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BE Department Annual Report 2018

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Abstract

The Beams Department hosts the Groups responsible for the beam generation, acceleration, diagnostics, controls and performance optimization for the whole CERN accelerator complex. This Report describes the 2018 highlights for the BE Department.

LHC:

BE-ABP Group

In 2018 another step was taken to lower the value of β^* in IP1 and 5 down to 25 cm, which could be achieved by including β^*-levelling for the first time in operational conditions, in addition to the already well-established crossing angle anti-levelling, guided by multi-parametric dynamic aperture simulations. The strategy of the optics commissioning was derived from what had been done in 2017, i.e. with full consideration of the non-linear effects since the beginning of the beam commissioning. In spite of the reduction of β^* the global optics corrections computed in 2017 could be re-used for the 2018 run. A major milestone consisted of the novel procedure of setting the strength of the skew-octupolar correctors in the triplets of the low-beta insertions. In fact, their strength had been successfully computed based on the measurements of the resonant driving terms, which is another step towards an approach suitable for the HL-LHC era. It is worth noting the challenge involved with the LHC special runs, i.e. the high-beta run at injection energy. A brand-new version of the optics was designed, including unequal β^* value in the horizontal and vertical planes at the IPs to fulfil the higher luminosity requested by the experiments. A number of tests were needed to find the configuration that could mitigate the high background observed by the experiments. A suitable solution could be found, based on numerical simulations, which provided an essential guidance towards the definition of the optimised settings. It is also worth stressing that during this special proton run crystal collimators were used operationally with excellent results in terms of background reduction to the experiments.

Electron-cloud effects have been scrutinised in detail, showing that they are the origin of the measured heat load variation in the LHC sectors and that such variation appeared only after LS1. They were also found to impact significantly emittance evolution and lifetime through the whole cycle. Numerical tools for the monitoring of luminosity evolution enabled a fill-by-fill follow-up and re-calibration of beam instrumentation. A rich programme of MD studies was carried out in 2018. A strong emphasis was given to the study of two variants of the ATS optics, including also a flat version, both relevant in view of the choice for the Run 3 configuration, and even more for the HL-LHC. In this context several studies were carried out using high-intensity beams to probe collective effects, thus obtaining much relevant information for future years. The impact of noise on the instability threshold has been clearly observed for the first time. A detailed validation of the crystal collimation for ions was achieved in MDs and commissioning. The long-range beam-beam MD with wire collimators provided very clear indications of the effect of the compensation even with trains and reduced crossing angle.

LHC Run 2 concluded with the fourth one-month Pb-Pb run of the LHC. This was also the culmination of the first phase of the LHC heavy-ion programme. The original goals had been to reach the design Pb-Pb luminosity of $1\times10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and achieve an integrated luminosity of 1 nb^{-1} in two experiments. Since 2011, the programme had been extended to include p-Pb runs, the 2017 Xe-Xe pilot run and reference p-p runs and luminosity is now provided to all four large experiments.

Following the tendency to reduce dependencies on the configuration of the preceding proton run, a completely new optics cycle with the strongest ever focussing at the ALICE and LHCb experiments was designed and rapidly implemented, demonstrating the maturity of the collider's operating modes. Performance increased rapidly despite a failure of the heavy-ion source and an initial problem with the optics at the ALICE interaction point. A switch from a basic bunch-spacing of 100 ns to 75 ns was made as the beam became available from the injector chain. A new record luminosity, over 6 times the original design and close to the operating value proposed for HL-LHC, provided validation of the strategy for mitigating quenches due to bound-free pair production (BFPP) at the interaction points of the ATLAS and CMS experiments. Most of the beam parameters of the HL-LHC Pb-Pb upgrade were attained during this run and the integrated luminosity goals were also substantially exceeded.

BE-BI Group

Diamond BLM acquisition system

Efforts were made to deliver an operational diamond-based BLM system in the LHC. Previously, diamond beam loss detectors were only installed after the horizontal primary collimators. To identify the loss plane (Horizontal/Vertical) however, additional detectors were installed downstream of the vertical primary collimators TCP.D6L7.B1 and TCP.D6R7.B2. Fulfilling this request enabled fast, bunch-by-bunch, time-resolved beam loss measurements at these locations. Examples of the losses observed for a single LHC bunch on different collimators over several hours can be seen in Figure 1 below.

In addition a new data acquisition system was deployed, taking advantage of the Group's generic

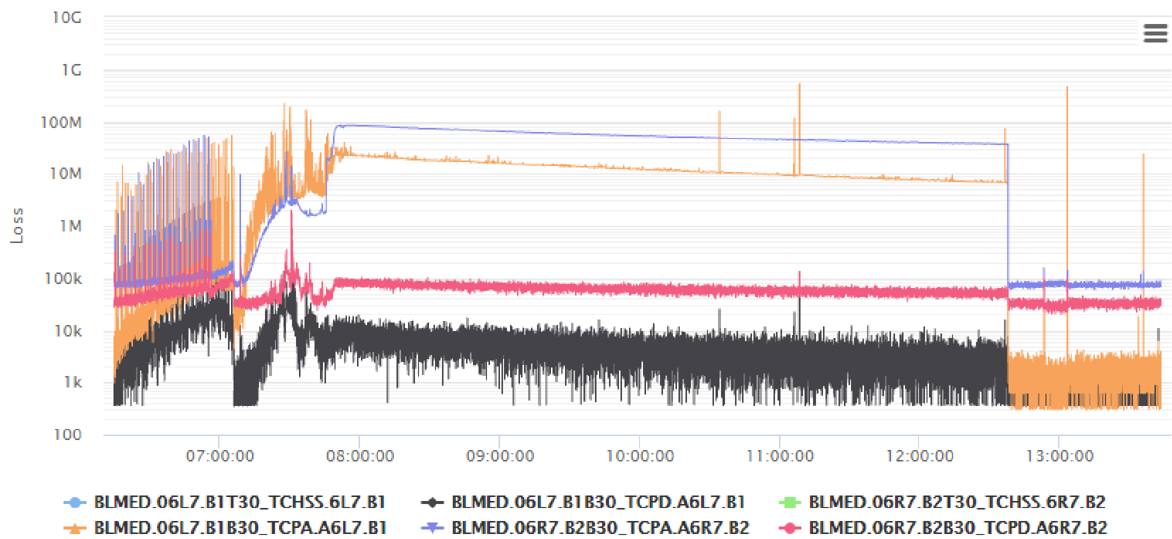


Figure 1: Losses observed for a single LHC bunch over several hours for 6 different diamond detectors.

carrier board (VFC-HD) and an off-the-self 14-bit ADC mezzanine sampling at 650 MS/s. This new system quickly showed its unique abilities and superior performance compared to the old oscilloscope-based acquisition system, and for more than half of the operational year these data were inserted into the new Logging database (NXCALS).

Upgrade of the BLM detectors around the LHC Beam Dump

For monitoring the beam extraction process a set of seven Secondary Emission Monitors (SEM) were positioned inside the two LHC beam dump blocks. During Run 2, early signs of detector degradation were observed through the self-test mechanisms of the BLM system and three serious issues contributed to a total downtime of 14 h. The inability to access the location of the detectors required a manual reset of the tunnel acquisition modules and it was therefore decided to disconnect these detectors. During 2017-18 YETS, a set of seven new detectors, six Ionisation Chambers (IC) and one Little Ionisation Chamber (LIC) were installed around each of the two beam dumps, along with radiation tolerant insulated cables. Figure 2 shows the position of the new detectors, which are now located outside of the dumps. The complete installation was prepared in advance with detectors placed on portable supports allowing a swift installation and minimising

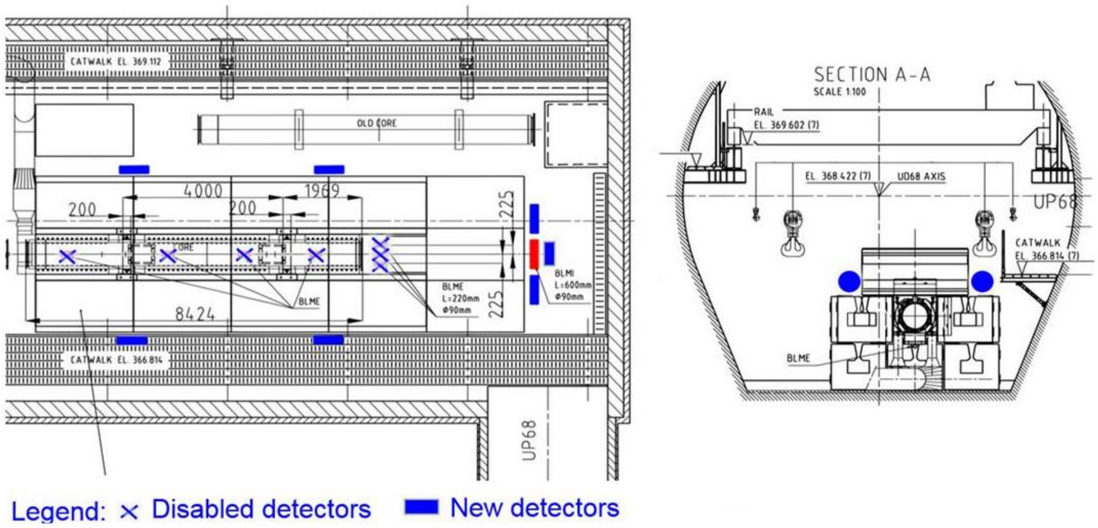


Figure 2: Configuration of the new BLM detectors around the LHC Beam Dump.

the radiation dose taken by the installation team.

BLM support for heat-load investigations in the LHC

Following the recommendations of the beam-induced heat-load taskforce, additional BLM detectors were installed in the vicinity of the magnet interconnect between MB.A31L2 and MB.B31L2 (cf. Fig. 3). The aim was to provide a better localisation and monitoring of the beam loss, and to potentially provide an insight into the beam-induced heating in this specific half-cell.

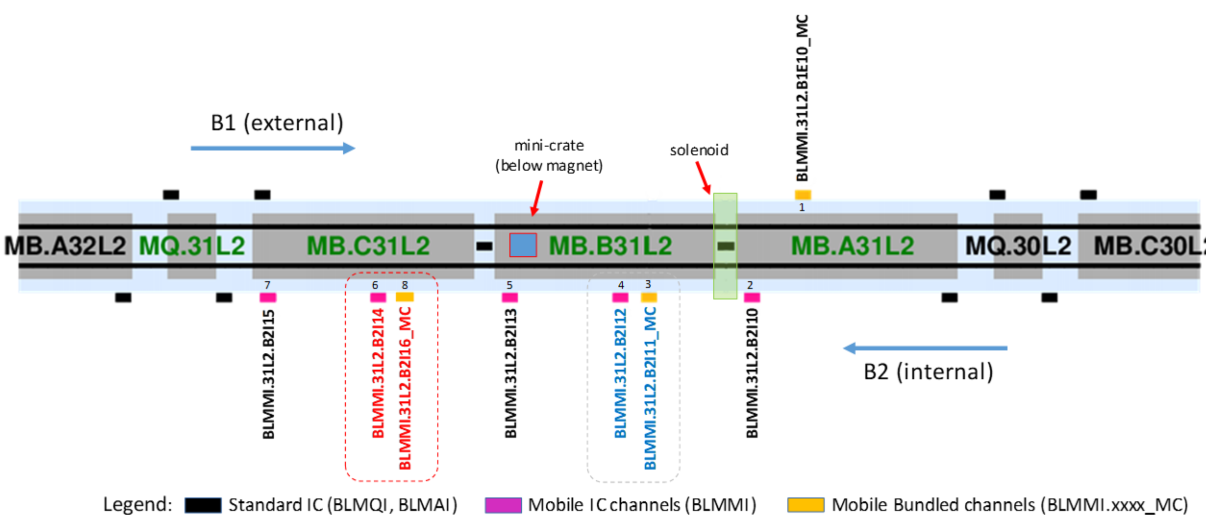


Figure 3: Final configuration of the BLM installation around half-cell 31L2.

The first installation, performed at the beginning of 2018, consisted of a portable BLM acquisition system placed under dipole MB.B31L2. This type of BLM system has the capacity to acquire data from up to eight channels and makes use of spare BI optical fibres, available at various locations around the LHC rings, to transmit the 40 µs integrals from each channel. The detectors installed included two IC bundles (one per beam) at a distance of 5 m from the QBBI.A31L2 interconnect. Each bundle consisted of 15 detectors connected in parallel to increase the sensitivity. In addition five individually connected, single ICs were installed along the three dipoles in 31L2 to determine the spatial distribution of beam-gas collisions along the cell.

The installation was modified later in the year with a third IC bundle installed at a distance of approximately 4.5 m from the QBBI.B31L2 interconnect to provide direct reference measurements to the detectors adjacent to the solenoid installation (cf. Fig. 4).

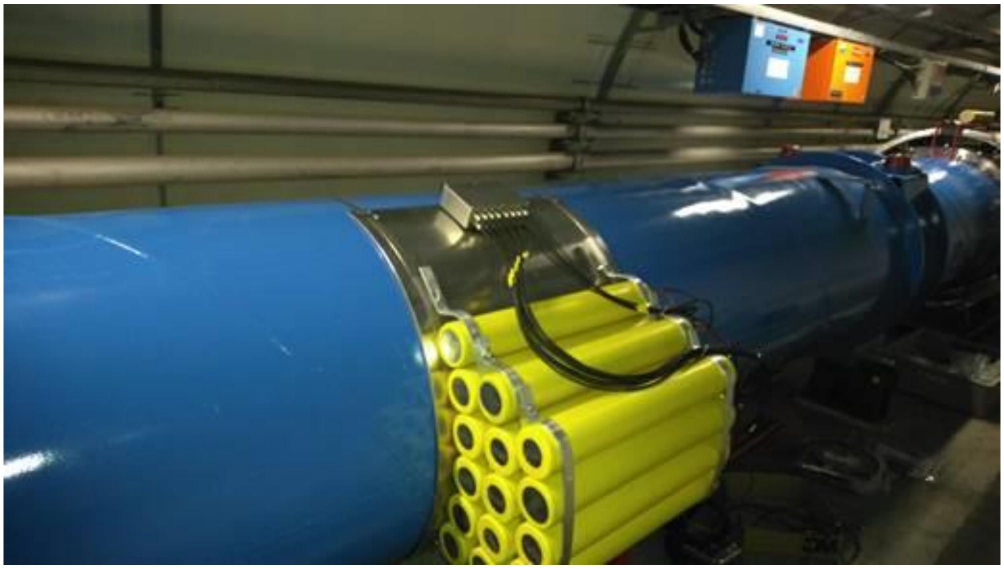


Figure 4: Photo of the 15xIC bundle (BLMMI.31L2.B2I11_MC) at dipole MB.B31L2.

Fast Beam Loss Monitor based on a Timepix3 hybrid pixel detector (BLMPX) for rapid deployment in the LHC tunnel

Fast, bunch-by-bunch, beam loss monitoring is currently provided by diamond-based particle detectors. Due to the relatively high cost of diamond detectors and the associated data acquisition and cabling infrastructure required, these detectors are only installed at a limited number of critical locations around the accelerator. When unforeseen problems arise at locations not covered by these detectors it is therefore necessary to install new diamond detectors – a process which is both time-consuming and expensive.

As an alternative to diamond detectors, a prototype fast beam loss monitor, based on a Timepix3 hybrid pixel detector, was designed for rapid deployment in the LHC tunnel. A prototype detector was installed in the TI18 service tunnel (~ 500 m from IP1) for the purpose of measuring background particle rates for the new FASER experiment. The detector was installed in less than half a day and the readout was done using the existing LHC optical fibre network, to back-end electronics located in Prévessin. The detector was used to measure particle count rates both before and during collisions at IP1, from which it was possible to conclude that the main background in TI18 is from collisions at IP1 and not beam-gas interactions – useful information for the design of the future FASER experiment.

BE-ICS Group

Preparation work started for the renovation of the 12-years-old LHC Personnel Protection System (PPS). This important refurbishing aims at fulfilling the requirements of the LHC lifts upgrade program and at replacing the obsolete Access Control product *Evolynx*, and requires hardware evolutions in the numerous control cabinets. The Personnel Safety interlock is upgraded to cope with the HL-LHC and the new SPS PPS interfaces. The reliability and availability of the system will increase. The installation takes place during LS2. For the work execution, an extension of the existing B1221 contract was approved at the December 2017 Finance Committee. The detailed system design and prototyping was done during 2018 and the installation works started in November 2018.

In the scope of the LHC access renovation project, the Web Viewer (see Fig. 5) of the Technical Infrastructure Monitoring (TIM) system (https://timweb.cern.ch) got updated and now provides a

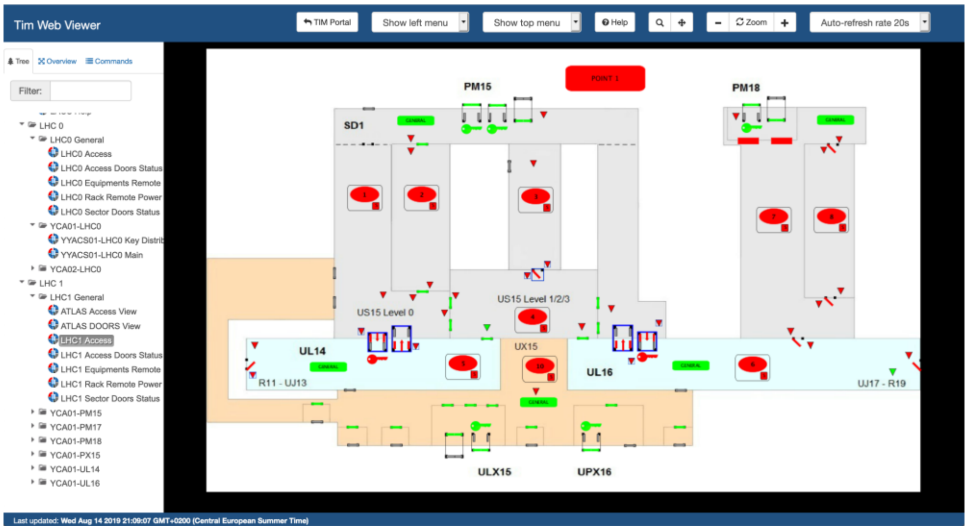


Figure 5: The TIM Web Viewer.

new responsive design with Single-Sign-On authentication and support for command execution with RBAC authorization. The TIM Web Viewer is used as the main SCADA for LHC access dashboards and replaced the outdated *Evolynx* solution. Also, the synoptic views of the SPS access system will be fully based on the TIM solution, not at least because of its stability, simplicity and long-term maintainability. In total, more than 200 views are provided via TIM for many user groups at CERN. To learn more about TIM, please contact tim-support@cern.ch.

LHC Cryogenics

A full set of new features and improvements was deployed at the YETS and TS during the year. The campaign to replace the faulty PLCs controlling the cryogenics production continued and reached the 61% (cf. Fig. 6) of the total foreseen (41 out of 67). The year 2018 was really good in terms of reliability as only 1 beam dump was caused by a PLC crash.

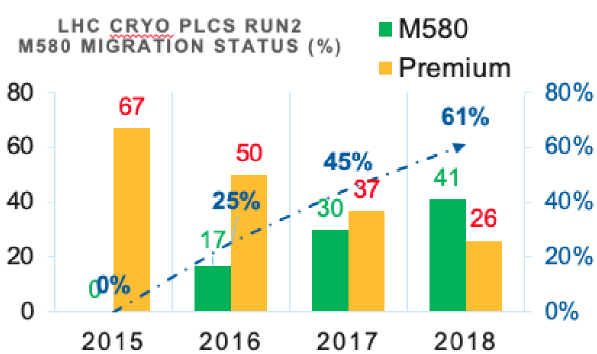


Figure 6: Cryo PLC migration.

LHC Cryogenics – CIET (Cryogenics Instrumentation Expert Tool)

During the first half of 2018, the LHC cryogenics control system was upgraded with the latest software components developed during 2017 and the continuous improvements proposed by the cryogenics experts.

The second half of 2018 focused on the reengineering of the real-time software. The business logic and software architecture of the Cryogenics FESA classes were largely refactored to improve readability, testability and maintainability. Technology upgrades have been carried out to keep up with the state of the art. An improvement was integrated into the Cryogenics FESA software to simplify the deployment procedures.

At the supervision level, the development effort was focused on improving the ergonomics for the user and give access to all the new functionalities implemented at lower levels of the control system.

LHC Gas control Systems

BE-ICS provides development, support and maintenance for the 34 Gas Control Systems (GCSs) for the 4 LHC Experiments, NA62, 904 CMS Mixers, Linac4 accelerator complex and CLOUD Experiment. During 2018, several gas system (cf. Fig. 7) upgrades were successfully accomplished during the technical stop. Those include new version of the SCADA components and the upgrades of several gas systems detectors of Alice, Atlas, CMS, LHCb and CLOUD.

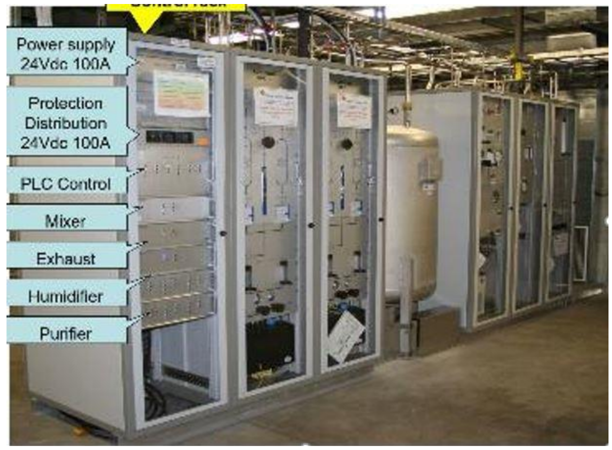


Figure 7: GCS control cabinets.

MACHINE PROTECTION

QPS

The WinCC OA/UAB Software Stack was extended in order to support a new QPS hardware device, DQAMGNUMP, used by the QPS team in the FAIR installation for protecting the magnets under test.

Additionally, a lot of preparatory work was performed towards analysing, understanding and documenting the current QPS system architecture. Subsequently, the preliminary design phase for the evolution of the QPS system for Run 3 took place. This includes the refurbishment of the FEC-to-WinCC OA Interface (removal of the CMW Driver APMs) and the possibility of sending logging data directly from the FECs to NXCALS, effectively bypassing WinCC OA, and thus reducing the load on WinCC OA and the database cluster. The potential benefits of such an action include cost savings in infrastructure.

LHC Circuit

The LHC Circuit application (cf. Fig. 8), which provides the LHC operators with an overview of

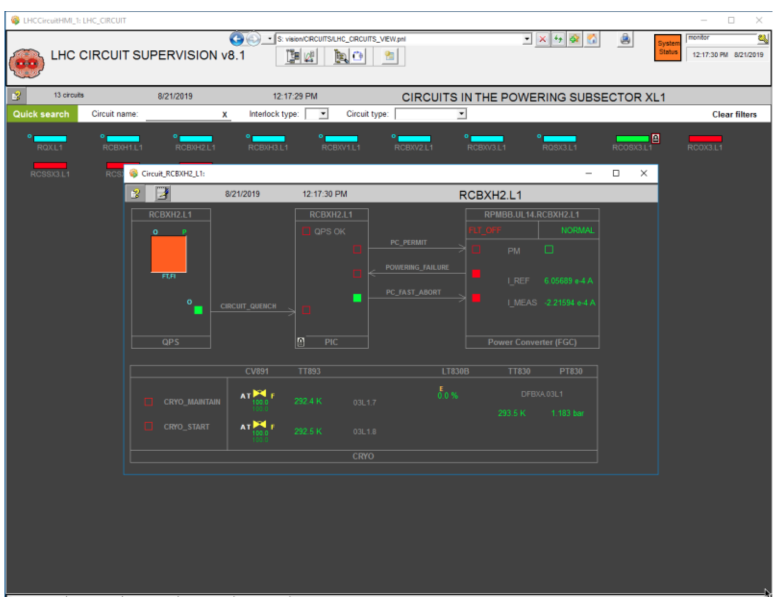


Figure 8: LHC Circuit supervision

the status of LHC powering and protection equipment, underwent a considerable consolidation during the YETS. The communication interface with the power converters was refurbished, and changes to the machine configuration during previous runs were consolidated in the application configuration.

BI Rack Monitoring

Several visual enhancements in the UI were performed during this year. Additionally, the system was prepared in order to be able to send alarms to the CCC operators (to be completed in 2019).

Finally, the LHC Beam Loss Monitor system was added as a new application on the BI project.

BE-OP Group

The 2018 LHC Schedule

The 2018 run was the final run before the start of LS2. During the Chamonix 2018 LHC performance workshop that was held in the last week of January, the goal for the integrated luminosity for 2018 was set at $60\ \mathrm{fb}^{-1}$ for ALTAS and CMS and $2\ \mathrm{fb}^{-1}$ for LHCb, under the assumption 131 days would be dedicated to 25 ns physics. The second target in order to reach this goal was to keep the stable beam time ratio at 50%.

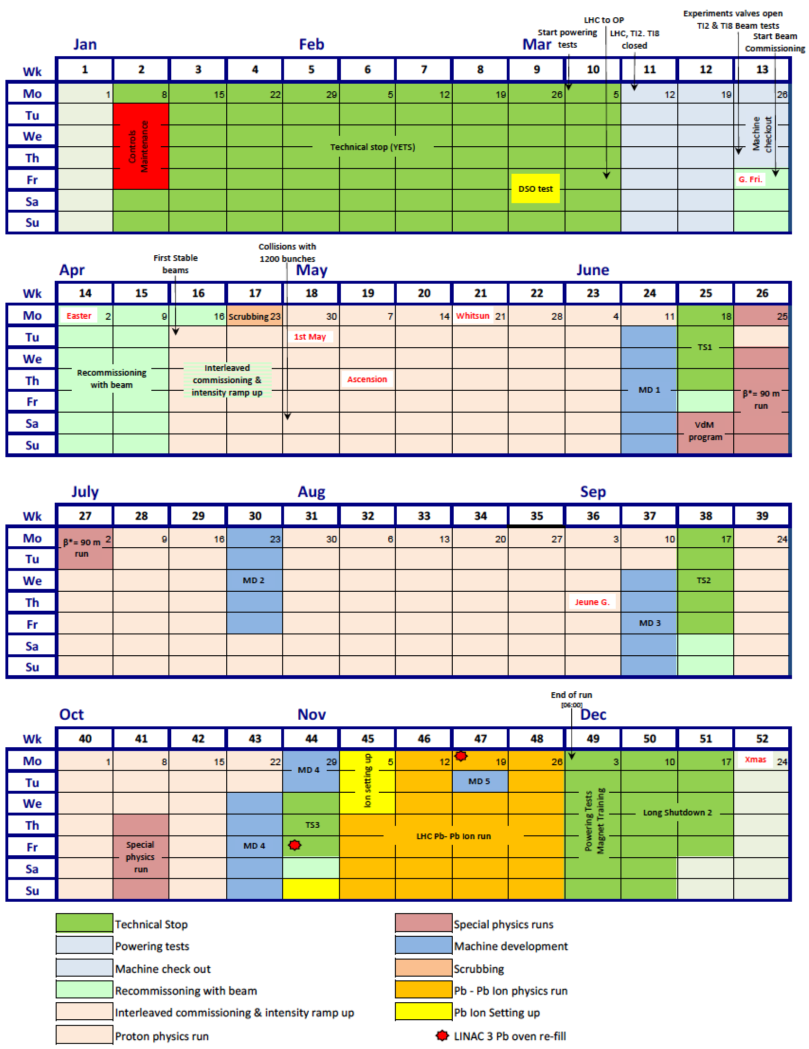


Figure 9: LHC schedule for 2018 version 1.6.

Initially the start of beam commissioning was foreseen on 2 April (Easter Monday). However, following a meeting with CMS and the CERN management it was agreed to move the opening of the valves for the LHC experiments from 26 March to 30 March, delaying the start of beam commissioning to 5 April. Finally the opening of the valves could be advanced by one day and the machine cold check-out period could be compressed, allowing for the beam commissioning to start on 30 March (Good Friday), as can be seen from the 2018 LHC schedule given in Fig. 9.

Following careful analysis and optimisation of the LHC re-commissioning with beam and subsequent discussions during the Chamonix 2018 LHC performance workshop, an update for the beam commissioning was integrated in the planning. It was decided that meaningful collisions start with 1200 bunches per beam which was then scheduled for 11 May. This explains the increase from 28 days to 33 days for the commissioning and intensity ramp up between version 1 and version 1.6 of the LHC schedule, as can be observed in Table 1.

Table 1: Summary table for the LHC schedule 2018, versions 1 and 1.6.

Activity	Schedule Version 1		Schedule Version 1.6	
	#Days	Ratio	#Days	Ratio
Comm. & Intensity ramp up	28	11.4%	33	13.4%
Scrubbing	4	1.6%	1	0.4%
25 ns proton physics	138	56.3%	130	52.8%
Pb ion setting up	4	1.6%	4	1.6%
Pb ion physics	24	9.8%	24	9.8%
Special physics runs	9	3.7%	14	5.7%
Machine Development (MD)	20	8.2%	24	9.8%
Technical stops (3)	13	5.4%	12	4.9%
Technical stop recovery (3)	5	2%	4	1.6%
Total	245	100%	246	100%

Out of the total machine time, 68.3% was dedicated to the actual physics run and 21.9% was used to set up the machine and the beams and to perform the necessary technical stops. The time spent for machine development represented only 9.8% of the total time.

Figure 10 provides an overview of the 2018 run with the major events on a time line. Although the planning foresaw collisions with 1200 bunches only on 5 May, in reality this was established

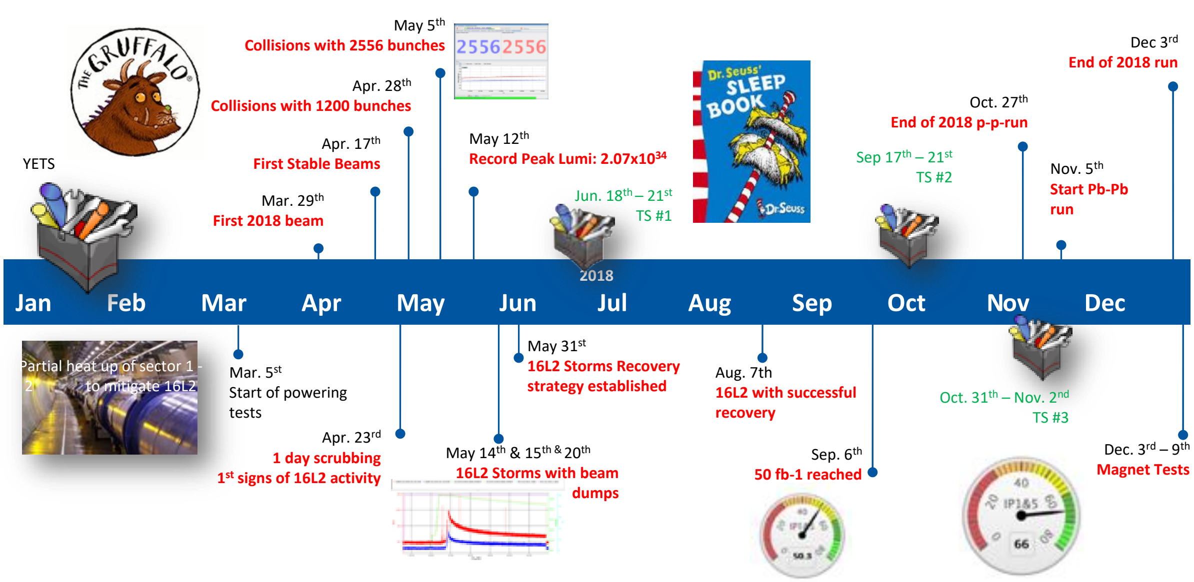


Figure 10: 2018 LHC event time line.

already on 28 April and – thanks to the good machine availability – collisions with the full machine, 2556 bunches per beam, were reached on 5 May.

During the intensity ramp-up, beam losses induced by 16L2, although much lower than in 2017, reappeared despite the partial warm up to 90 K and evacuation of gases from the cell. Occasional beam dumps due to 16L2 losses occurred a few times until early August, but a recovery recipe based on a few hours running with only 900 bunch could be established. Two novelties were introduced on the luminosity levelling front: continuous crossing angle levelling in steps of 1 μrad and β^*-levelling in two steps from 30 cm to 27 cm and from 27 cm to 25 cm. β^*-levelling was used in essentially all fills long enough for it to be applied, proving the operation concepts for Run 3 and for HL-LHC. The peak luminosity routinely reached $(1.8 \div 2) \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (Fig. 11). The 2018 proton run ended on October 24th and accumulated 66 fb^{-1} of integrated luminosity (cf. Fig. 12). The availability for stable beams was 49%, similar to 2016 and 2017. Over Run 2 a total of around 160 fb^{-1} were delivered to ATLAS and CMS.

Two successful special runs took place in 2018: a one week run with 50 ns beams at 6.5 TeV and at β^* of 90 m and a few days run at 450 GeV run and β^* of 100 m.

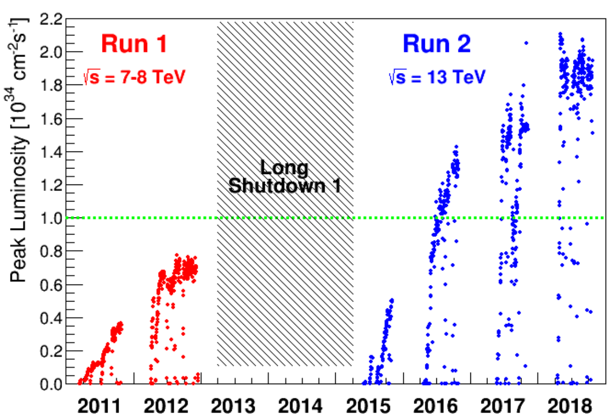


Figure 11: Evolution of the peak luminosity per fill between 2011 and 2018.

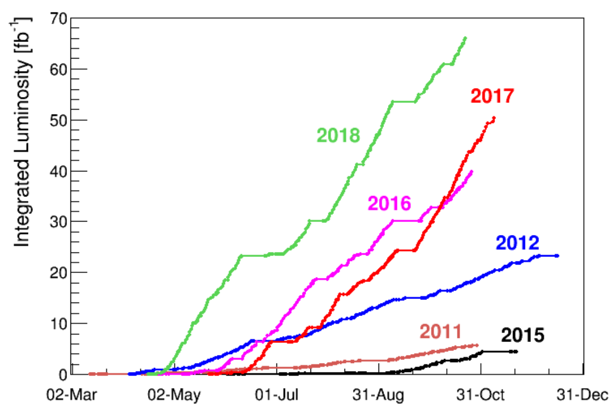


Figure 12: Integrated luminosity of the LHC between 2011 and 2018.

The year ended with a 24-day lead-lead ion run at 6.37 TeV. Beams with 100 ns spacing were used in the first part of the run, then the bunch spacing was reduced to 75 ns in the second half of the run. The ion bunch intensity reached 2×10^8 ions per bunch, with 733 bunches per beam the peak luminosity reached 6×10^{27} $cm^{-2}s^{-1}$ which corresponds to 6 times the design luminosity. The machine delivered around 1.8 nb^{-1} to ATLAS and CMS, and 0.9 nb^{-1} to ALICE. During one of the MDs, a first successful test at 6.5 TeV was performed with Pb^{81+} partially stripped ions (PSI) in the frame of the Physics Beyond Collider project.

BE-RF Group

Contributing to the good performance of the LHC in 2018, the LHC RF systems had an accumulated down-time of only 55 hours and thus demonstrated an impressive overall availability. Thanks are due for the different standby services.

The LHC cryomodule "America", which was removed from the LHC in 2014 and swapped with the module "Europe", was equipped in 2018 with new, improved pumping crosses, followed by

Figure 13: Left: Preparing ACS module "America" in the Clean Room; centre: "America" in the test bunker in SM18; right: test results demonstrating the reach of each cavity up to 2.3 MV.

installation in the SM18 test bunker M9 and a full re-validation at acceleration voltages of up to 2.3 MV, well above nominal voltage of 2 MV (cf. Fig. 13).

Another effort through 2018 concerned the construction of new spare cavities for the LHC – difficult since safety rules and fabrication methods have changed. The manufacturing of new LHC cavity half-cells via spinning at Heggli was fully qualified in 2018 with "practice cavity 5" (PC05), which exceeded specifications significantly (Fig. 14). A simplified cavity with electro-hydroformed (EHF) half-cells (PC03) also exceeded specifications, but is not yet considered a

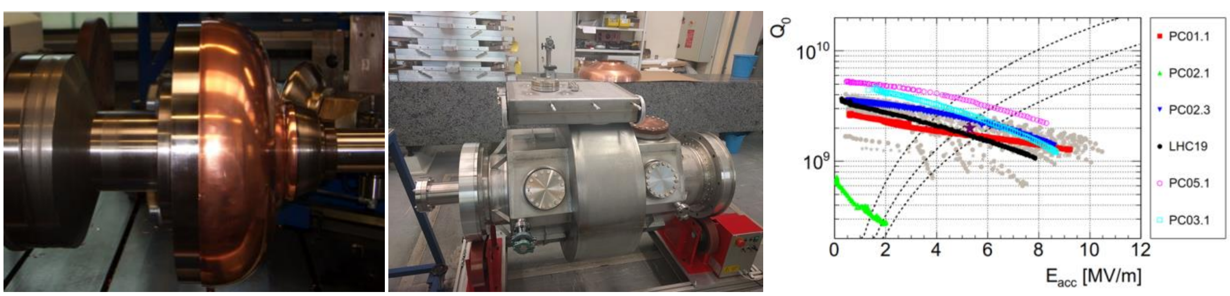


Figure 14: Left: Half-cell spinning at Heggli; centre: first new fully dressed production cavity (MC01); right: cold test results of practice cavities. Recent results exceed the specified 5 MV/m, 2E9.

valid reference test, since the inner surface had to be ground significantly. Another simplified EHF cavity is under preparation (PC04) and will be the reference test for EHF of LHC half-cells. The production of the first dressed cavity (MC01) (Fig. 14, centre) with fully qualified spun half cells was progressing well.

The assembly of a ¼ LHC-type cryomodule has started in 2018 and is expected to be completed before the end of LS2, together with the dressed spare cavities. This single-cavity cryomodule serves to re-establish and verify the assembly procedures and to train the technical team, but is also a relevant test object to improve procedures for operation (e.g. vacuum, cool-down, warm-up, etc.) and to help development and debugging of the next generation of LLRF electronics and associated controls during Run 3.

For the LHC ACS LLRF systems, the migration of the commissioning tools from MATLAB to Python was completed in 2018. The tools permit fast setting-up of the feedback loops of the cavity controllers and are essential for an efficient start-up and to verify the correct functioning of different loops. A large variety of Machine Developments (MDs) were carried out and data analysis continues. Persistent oscillations at injection are among the observations that are receiving most attention in preparation of Run 3. The LHC run finished with a very successful lead ion run.

Concerning the transverse damper (ADT), the ObsBox system continued to provide essential data for both machine operation and during MDs. 4.6 TB data were stored since 2017, and an upgrade program was launched for implementation during LS2 to move the system to more powerful servers. New prototype electronics are used with a set of additional pick-ups, permitting more flexibility and an improved signal-to-noise ratio. Highlights of the MD program for ADT include studies of a new signal processing for larger tune acceptance and of the active excitation for coupling measurements.

The LHC RF power system was remarkably reliable. The high voltage connections of the klystron gun tanks were replaced during the 2017-18 YETS to avoid ionization and possible arcing problems.

About half of the LHC klystrons TH2167 are now approaching 50'000 operating hours, corresponding to their nominal life expectancy. Although they have not shown signs of ageing or purveyance change, we are prepared if they start to show their age. In addition to the provision of a sufficient number of spare tubes, we have launched in 2018 a study of a possible higher efficiency, drop-in replacement of the TH2167, which could deliver 15% more power from the same modulator (see below).

Fine-tuning the power circulators in order to ensure both the klystron protection and optimum power transfer over the full klystron power range is very challenging and still requires further optimisation. The systematic replacement of outdated equipment in the LHC RF systems continued: the klystron heater power supplies, still from the LEP era, were replaced by new, fully programmable units, and a new klystron modulator, not relying on the discontinued tetrodes anymore, is under development. It shall also include precise klystron current measurements and a fast diagnostic detection system.

For the RF system controls and software, migration from Matlab to Python continued and the modern user interfaces using Inspector were written and deployed through 2018.

High Luminosity LHC (HL-LHC) – LHC Upgrade

BE-ABP Group

Following the revision of the HL-LHC baseline configuration of the high luminosity interaction regions which occurred in 2017, a new layout and optics have been produced. The new optics version (HL-LHC V1.4) incorporates improvements required by the beam instrumentation and collimation systems, as well as low-beta solutions for the LHCb experiment. The proposed solution features characteristics compatible with the possible implementation of a Hollow Electron Lens (HEL) in the long straight section 4. As a result of this process, the specification of the power converters for the new magnets has been revised in collaboration with the power converter and circuit experts.

With the consolidation of the layout, optics and operational scenarios, efforts have been focussed towards the contribution to the finalization of the specifications and acceptance criteria for the new pieces of equipment that are going to be installed for the HL-LHC Project:

- The beam dynamics considerations underlying the acceptance criteria for the triplet quadrupole MQXFA magnets and LMQXFA cold masses (e.g. alignment and mechanical tolerances, field quality, etc.) have been provided.
- The specifications of the strength of the linear and non-linear triplet correctors have been revised taking into account the results of the magnetic measurements and simulations performed for the triplet quadrupole short models.

- The impact of the expected flux-jumps observed in the new Nb_3Sn magnet models has been evaluated both in terms of orbit control and emittance blow-up based on experimental data obtained for the 11 T dipole short model.
- New techniques have been developed for the qualification of the resistivity of the molybdenum coating of the Molybdenum-Graphite jaws of the new low impedance collimators to be installed during LS2.
- The validation of the HL-LHC operational scenario has continued with the quantification of the dynamic bunch-to-bunch orbit, tune, beta-beating coupling and chromaticity shifts resulting from beam-beam effects and in particular from long-range beam-beam effects (PACMAN effects) allowing to constrain operational parameters like dispersion at the interaction point and tolerances on the orbit of the two counter-rotating beams in the interaction region.
- The simulation studies have been complemented by a vigorous experimental programme covering some of the key challenges expected for HL-LHC:
  - Measurement of observables related to the dodecapolar component and measurement and correction of the skew octupolar component of the triplet quadrupoles' magnetic field in view of establishing accurate beam-based measurement and correction procedures for the HL-LHC commissioning,
  - Study of the dipolar excitation observed on the beam, of its sources and of its effect on beam stability. This has revealed that Landau damping can be lost due to external noise leading to instabilities characterized by a latency time depending on the amplitude of such external noise. This instability mechanism could explain the larger (by a factor two) strength of the Landau octupoles required to stabilize the beam as compared to expectations for a noise-free machine,
  - Continuation of the studies for the compensation of the beam-beam long range effects by means of current bearing wires, allowing to validate new and more effective configurations that could open the way to the installation of realistic configurations in HL-LHC. A reduction of the beam 2 losses induced by long-range beam-beam effects by at least 20% was visible also for the smaller crossing angles indicating the possibility to reduce the crossing angles when operating the beam-beam wire compensator,
  - Tests and validation (e.g. by optics measurement and correction and collimation setting-up) of new optics configurations based on different values of the beta functions at the interaction points (flat optics) that could be used to further enhance the HL-LHC performance, and
  - Contribution to the test of a Crab Cavity prototype in the SPS in collaboration with BE-BI and BE-RF teams with the setting-up of the required beams and the participation in the measurement of some of crab cavity properties (noise, field quality, high order modes, etc.).

BE-BI Group

Cherenkov monitor for HL-LHC luminosity measurement

The choice of Cherenkov-based detectors for the HL-LHC machine luminosity monitors has been successfully validated. Prototypes based on air (with aluminium mirrors) and different types of fused silica rods have been installed in the neutral absorber (TAN) at IP1 and tested during LHC p-p operation. The former suffered from continuous degradation (reduced reflectivity) throughout 2018 and has been discarded as a viable solution. The fused silica rods, which have been installed since 2016, exhibited initial transmission loss during the first 5-10 fb^{-1}, which has since remained stable during 2.5 years of LHC operation. Post-irradiation measurements indicate that most of the transmission loss occurs in the UV-region, whereas the visible spectrum is largely unaffected (see

Fig. 15). During bake-out, the BRAN photo-multipliers need to be removed from the neutral

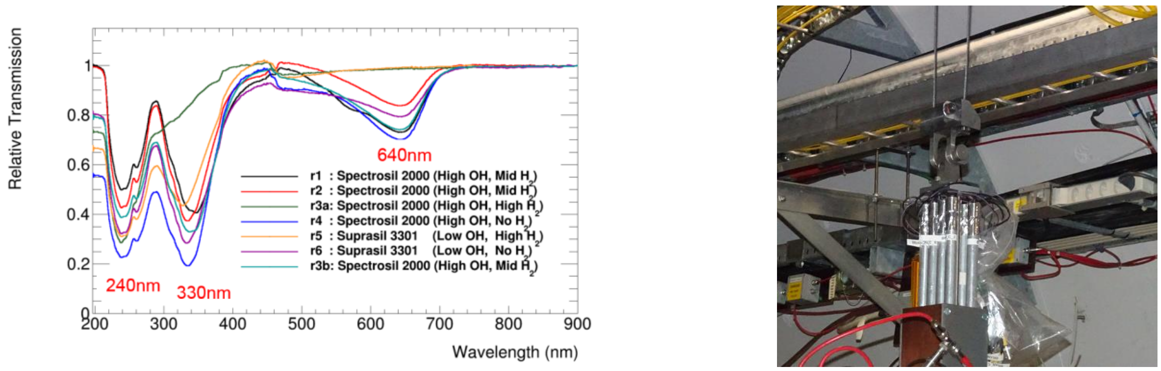


Figure 15: Optical transmission of different types of fused silica rods after up to 3 years of LHC operation (left) and crane-installation of the HL-LHC prototype into the TAN (right).

absorber to avoid damage. To minimize manual intervention in this highly radioactive area, the mechanical design has been revised such that all active electronic components are contained in a single removable module, using a modular quick-connect system (see Fig. 16). This makes the installation/removal compatible with the use of a remote-controlled robot.

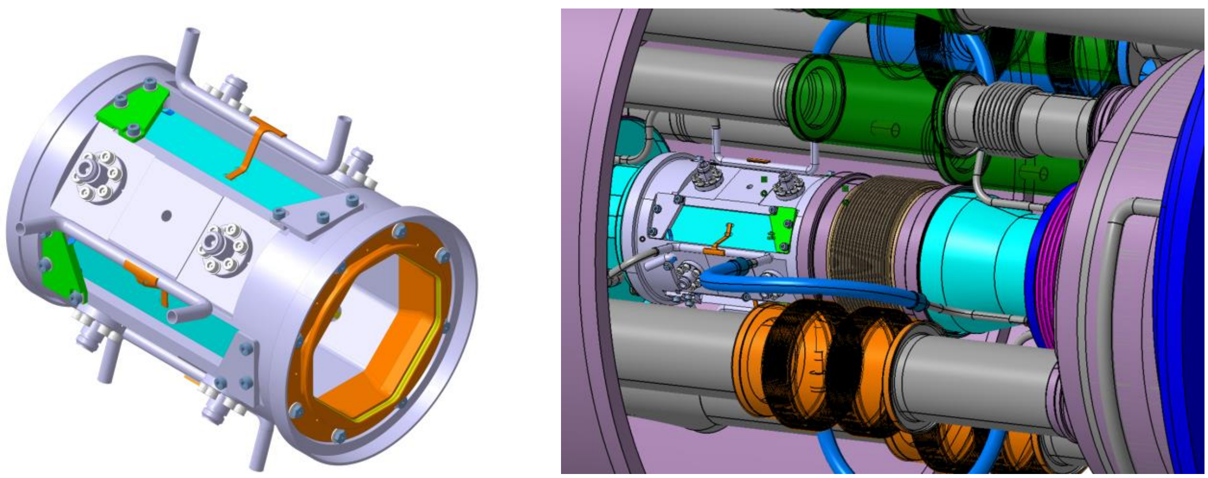


Figure 16: Design and integration of a cryogenic, tungsten-shielded, directional coupler BPM for HL-LHC.

Beam Position Monitor developments for HL-LHC

Four types of Beam Position Monitors (BPMs) are under development for the IP1/5 Inner Triplet region for the High Luminosity upgrade of the LHC. During 2018, major progress was made on the mechanical design and integration studies. EN/MME performed a set of thermomechanical simulations to verify the appropriate thermalisation of the cryogenic BPMs, prototyping of crucial mechanical pieces was launched and the procurement procedure for specialised RF components was started.

An internal HL-LHC Inner Triplet BPM Conceptual Design Review was held in May 2018 with an interdepartmental review panel. The reviewers gave four recommendations and proposed twenty actions (EDMS 2021763), all of which were followed-up and completed.

A comprehensive BPM test program was prepared and presented during the HL-LHC IT String Day in October 2018. The final decision was not to include BPMs in the String Test, but instead to test the BPM integration in a full magnet interconnection mock-up.

Gas curtain monitor

A gas curtain monitor is under development through the HL-LHC project. The principal objective is to provide a device to monitor the overlap between the LHC proton beam and an intense hollow electron beam that will be used for beam halo depletion in a ‘Hollow Electron Lens’. This monitor is a collaborative development between the Cockcroft Institute (University of Liverpool) in the UK along with GSI in Germany. It combines a highly directional supersonic gas ‘curtain’ with detection using beam-induced fluorescence to produce a 2D visible light image of the beams that can be seen using a conventional camera system.

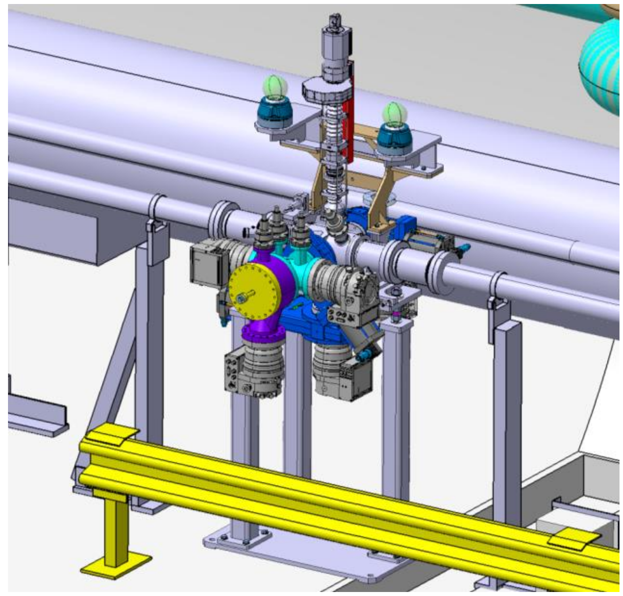


Figure 17: Integration of the beam gas curtain prototype with fluorescence detection in LHC Point 4.

2018 saw the installation of a new experimental set-up at the Cockcroft institute, with optics designed and supplied by GSI, which rapidly demonstrated images of electron beams from gas jets of nitrogen, neon and argon. This year also saw approval by the HL Technical Coordination Committee and LHC Machine Committee for installation of the first phase of a demonstrator instrument in the LHC during LS2 (2019-2020). Fig. 17 shows the proposed integration of the full prototype instrument in LHC Point 4.

BE-ICS Group

The group is involved in the coordination and preparation of the HL-LHC sub-work packages WP17.4 related to the safety systems and more particularly access, alarm and radiation monitoring, and WP17.5 related to technical monitoring and network infrastructure. In 2018, the work focused on the integration of the systems in the new cavern and in the evacuation galleries (UPR) located between the new HL-LHC galleries and the LHC tunnel. The work will include new safety sectors for the LHC Access Safety System, as well as the deployment of Fire and ODH detection systems, Red telephones, and Radiation monitoring systems and deployment of a network infrastructure. The installation is foreseen to take place mid-2020.

BE-RF Group

Work package 4 of HL-LHC concerns the crab cavities, which will allow to compensate for the luminosity losses resulting from very thin beams crossing at an angle. In 2018, an essential part of the HL-LHC crab cavity program was the test of these cavities in the SPS. The prototype cryomodule with two superconducting double quarter wave (DQW) crab cavities was successfully installed in the SPS, following a very tight planning during the 2017-18 YETS. The cryomodule is placed on a movable table along with its proximity RF and cryogenic equipment to allow for a horizontal movement in and out of the beam at its nominal operating temperature of 2 K (cf. Fig. 18, left). When in park position, the beam traverses through a standard SPS vacuum chamber. A long campaign of RF conditioning was needed to bring the cavities to stably operate at 1 MV. The majority of the MDs took place at this voltage.

Seven MDs were successfully carried out over the period of 6 months during the 2108 run. The first beam (single low intensity bunch) was injected and circulated in the SPS with crab cavities on May 23, 2018 at 26 GeV. Several important measurements were carried out during subsequent MDs including demonstration of crabbing with protons, cavity transparency, energy ramping, intra-cavity alignment, beam loading, high order modes, proton emittance growth, RF multipoles and high intensity operation of up to 2×60 bunches and 4×48 bunches. Some important limitations were identified, notably the maximum voltage reach at 2 MV (nominal voltage 3.4 MV) – this limitation of the prototype cavities were known beforehand and considered acceptable to meet the tight installation deadline. In spite of these limitations, the tests of crab cavities in the SPS were the first ever use of crab cavities with protons and clearly were a great success.

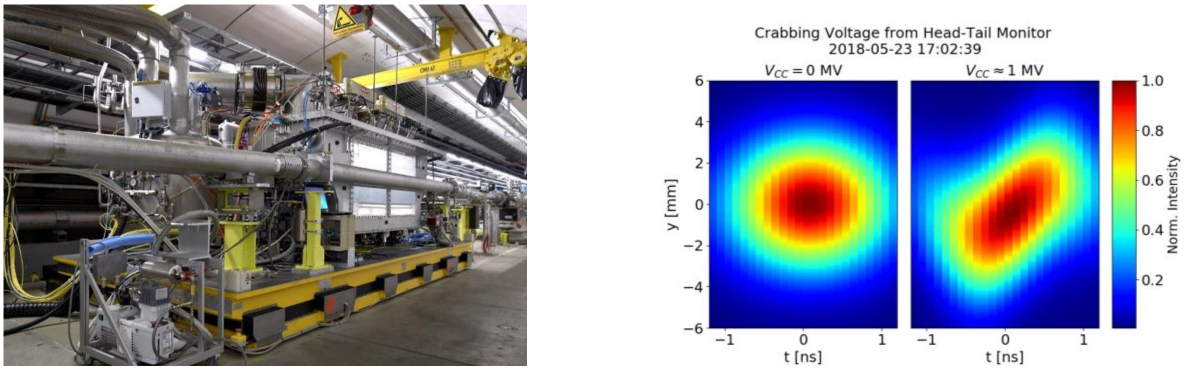


Figure 18: Left: DQW prototype modules installed on a movable table in the SPS-LSS6 for beam tests with protons. Right: Head-tail monitor measurements demonstrating the crabbing effect on the beam, without (left) and with crabbing voltage (right).

Prototype electronics permitted tests with beam in dedicated MDs with synchronization of the beam to the SPS RF and the crab cavity system. A number of issues were identified such as the direct coupling of beam to the cavity field probe antenna and ponderomotive oscillations at 210 Hz. These issues are addressed for the HL-LHC production systems by implementing improvements in the cavity design and in the LLRF systems (sequence of tuner, RF feedback and ramping-up of voltage). Studies on the blow-up of beam by artificially injecting noise into the crab cavity system near the betatron sidebands continued and implications for the feedbacks in LHC are analysed. No fast failures at the operable voltages with beam in the SPS were seen and the implemented RF and beam interlocks were found sufficient to protect both the cryomodule and the SPS. Numerous preparatory studies and simulations were necessary to carry out these MDs, including special machine protection approval to inject high intensity beams through the crab cavities.

In parallel, the RF dipole (RFD) crab cavity for horizontal deflection was updated to comply with impedance specifications, and the final RF design is being finalized for fabrication of two prototypes at CERN for its eventual installation in the SPS in the 2021-22 YETS. Important updates on the RFD prototype module were implemented to adapt it to the final HL-LHC design including all interfaces (RF, cryogenics, vacuum, survey and other services). Significant progress was made with the collaborations with the US (US-AUP) the UK and Canada. The technical specifications for the dressed cavities and cryomodules now include improvements learnt from the SPS beam tests and will be basis for the collaborations for fabrication to CERN and European standards.

The “full detuning” method, which makes the RF power required at 400 MHz independent of the beam current, was deployed in operation already in 2017 and was used through 2018 very successfully. Studies in 2018 concentrated on the injection of high current beams in the LHC during flat bottom, when the RF systems still runs in “half detuning”. The simulation code BLonD is instrumental for these studies. It was found that RF power is still marginal during this process, a problem to be mitigated with a combination of measures including optimisations of klystron performance and operation, circulator and transmission line matching and LLRF improvements. Also the development of higher efficiency klystrons will mitigate this problem.

LHC Injector Upgrade

BE-ABP Group

The achievement at the SPS extraction of the beam brightness and intensity required by HL-LHC (trains of 72 bunches with 2.3×10^{11} p/b and 2.1 μm transverse emittances) relies on a series of upgrades to be implemented across the whole injectors chain in the framework on the LHC Injectors Upgrade (LIU) project. Most of the hardware specified, designed and constructed under this project is being installed during the Long Shutdown 2 (LS2). Beam dynamics studies continue being crucial to steer the project priorities through this final phase as well as to prepare the post-LS2 operational scenarios for the injectors and the mitigation strategies for the known risks.

Using the H^- charge exchange injection from Linac4 into the PSB at 160 MeV is expected to lead to LHC beams with double brightness with respect to the values attained with Linac2. A beam current of about 25 mA within 0.3 μm transverse emittance out of the RFQ will be sufficient to meet the LIU intensity and brightness target with 40 turns injection, ensuring at the same time the full performance recovery of the PSB fixed target (ISOLDE) beams. Two Linac4 runs in 2018 helped improve the quality and the reproducibility of the beam parameters, as well as assess the global system availability. One more Linac4 quality and reliability run is planned to take place in the last three months of 2019.

The mitigation of the space charge effect and other potential sources of emittance blow up at the PS injection will be also instrumental to achieve the LIU beam brightness. The PS injection energy will be raised to 2 GeV and the longitudinal beam parameters at the PSB-PS transfer will be optimised to maintain the present level of space charge tune spread at the PS injection for the twice higher brightness of the future beams. However, since a significant horizontal emittance blow-up was measured in operation at the PS injection during Run 2, intensive machine development campaigns took place throughout 2018 aiming at explaining the discrepancy between emittance measurements with different instruments (PSB wire scanners, PSB SEM grids, PS wire scanners) as well as at disentangling the potential contributions to this emittance blow-up from all mechanisms (space charge, transfer line mismatch, extraction/recombination/injection kickers, collapse of the PS injection bump). The importance of the accurate measurement and control of the optics parameters in both the PSB and the PS has turned out to be fundamental to limit measurement uncertainties and move safely into the new parameter space.

In 2018, the production of LIU beams has been proven up to the PS extraction thanks to the successful beam stabilisation against longitudinal coupled bunch instability along the PS cycle. These intense beams were then also injected into the SPS and exhibited high losses and longitudinal instabilities at 26 GeV mainly due to the limitations of the current main RF system. In the transverse plane, large tune shifts in both planes and horizontal coupled bunch instabilities at 26 GeV were also observed. Several machine development sessions were devoted to the experimental characterization of tune shifts and beam instabilities. First attempts were also made to reproduce all these effects in numerical simulations by means of the PyHEADTAIL code. The large vertical shift observed with long trains of about nominal LHC beams has been reproduced remarkably well with the current impedance model of the SPS (see Fig. 19). Most of the features of the horizontal instabilities are also being captured by simulations, although the study is complex and still ongoing.

The performance of the Pb ion beam throughout the injector chain was further improved in 2018 with respect to previous years. The intensity extracted from LEIR saw a further 10% increase, which led the PS close to the longitudinal instability threshold upon transition crossing. The overall reliability of Linac3 and LEIR was greatly improved thanks to the identification of the main

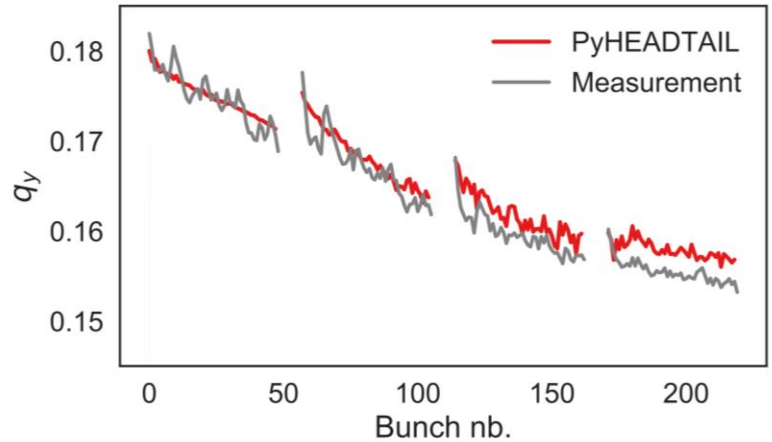


Figure 19: Tune shift along four trains made of 48 bunches in the SPS: measured (grey) and simulated with PyHEADTAIL (red). Here the bunch intensity was 1.35×10^{11} p/b.

sources of drifts and the implementation of automatic checks and procedures. An alternative to the baseline production scheme, based on PS batches of 4 bunches spaced by 100 ns, another scheme based on the PS-SPS transfer of trains of 3 bunches spaced by 75 ns was deployed operationally and it demonstrated its potential to produce 70% of the HL-LHC integrated luminosity target without slip-stacking.

BE-BI Group

PSB injection watchdog

For verifying the Linac4 to PSB intensity transmission, watchdog instances are required to protect the accelerator and its equipment. They will monitor the PSB injection efficiency by comparing the beam intensity measured in the injection line (after the distributor) with that measured inside each PSB ring. Each injection takes several turns so timing triggers derived from the distributor are used to identify the region of interest. The number of charges measured in the ring is compared with the intensity measured before the injection and trigger a software-based beam interlock in

Figure 20: Linac 2 injections (turn by turn) into the PSB acquired with the new injection watchdog.

case of high losses in any of the 4 rings. Figure 20 shows an actual measurement in the PSB with beam from Linac2, where we can see the intensity measurement over several PSB turns.

LEIR injection Beam Position Monitor electronics

The Beam Position Monitor (BPM) acquisition system installed in the LEIR injection line suffered from charging of the electrodes leading to corrupted beam position measurements, most likely caused by secondary particles impacting the BPM plates. Several different counter-measures were attempted but none solved the issue satisfactorily. A new acquisition system was therefore investigated, based on detecting the 101 MHz Linac3 bunching frequency. Despite significant debunching, this 101 MHz bunching frequency component is still present along all the injection line with a signal level at the BPMs sufficient to allow precise beam position measurements. Before entering LS2, three out of the nine BPMs were equipped with a new, custom-developed acquisition system, which proved to be immune to stray charging of the electrodes. The fully implemented acquisition chain from these monitors allowed OP to systematically monitor the injection to LEIR. This led to finding and correcting a temperature dependence of a bending magnet, resulting in a significant increase in the injection efficiency.

Beam Gas Ionisation monitors for LIU-PS

During the 2017-18 YETS, a second horizontal prototype of the Beam Gas Ionisation (BGI) monitor for non-destructive beam profile measurements was installed in the PS ring, including a new high-speed radiation tolerant control and data acquisition system. Measurements taken during the 2018 run demonstrated the capability of the monitor to acquire continuous, non-destructive, beam profile measurements. Example images captured by the BGI Timepix3 hybrid pixel detectors during a complete acceleration cycle are shown in Figure 21.

Beam images are processed to extract the ionisation electron signal from the beam loss background and then the ionisation electron counts are summed in each column to form the beam profile. The beam size is determined by means of a fit to the beam profile with a model which is a convolution of a Gaussian beam profile and a function which includes all known detector effects. The beam size evolution for a single LHC bunch is shown in Figure 22.

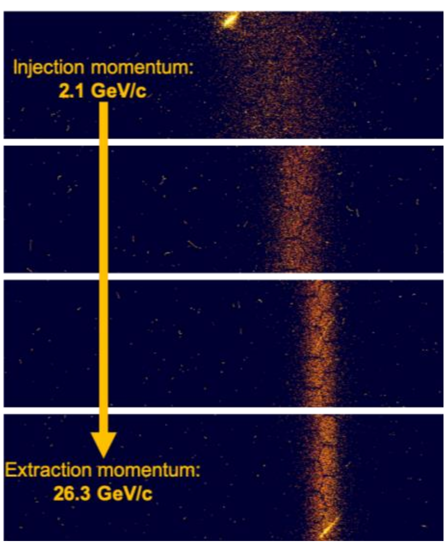


Figure 21: BGI images of a single LHC bunch in the PS. Each horizontal line is formed by integrating data from the Timepix3 hybrid pixel detectors for 10 ms.

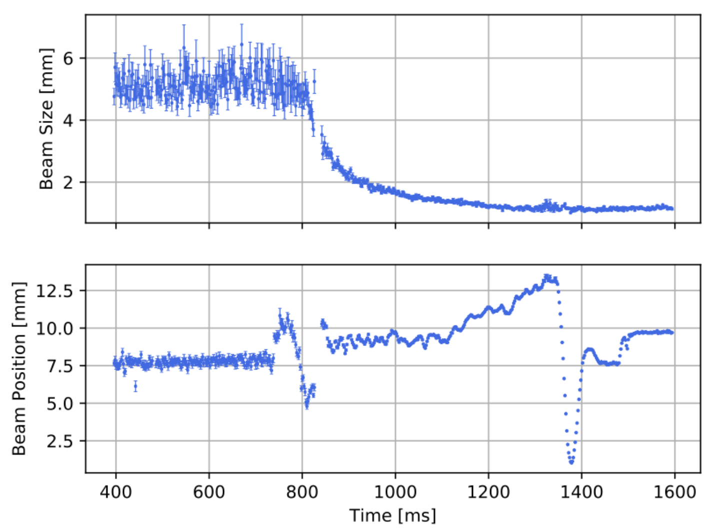


Figure 22: Evolution of the horizontal beam size (top) and position (bottom) of a single LHC bunch as measured by the new PS BGI.

Beam Wire Scanner upgrade

After a development carried out for several years, the PSB, PS and SPS will be equipped in LS2 with a new generation of Beam Wire Scanners (BWS). After testing prototype units in the SPS and PSB in previous years, the 2018 run was essential to validate the new PS prototype. This system consisted of the latest kinematic unit (Fig 23, left) with the most important difference with respect to previous version being an optical encoder based on a metallic disk. It was accompanied by the almost final version of the secondary shower detectors, featuring 4 PMT channels driven by a custom made PCB base (Fig. 23, right). The PS prototype allowed extensive reliability and performance tests to be carried out and, towards the end of the run, to probe for the first time the VME-FPGA based control and acquisition system, including a basic version of the FESA acquisition server.

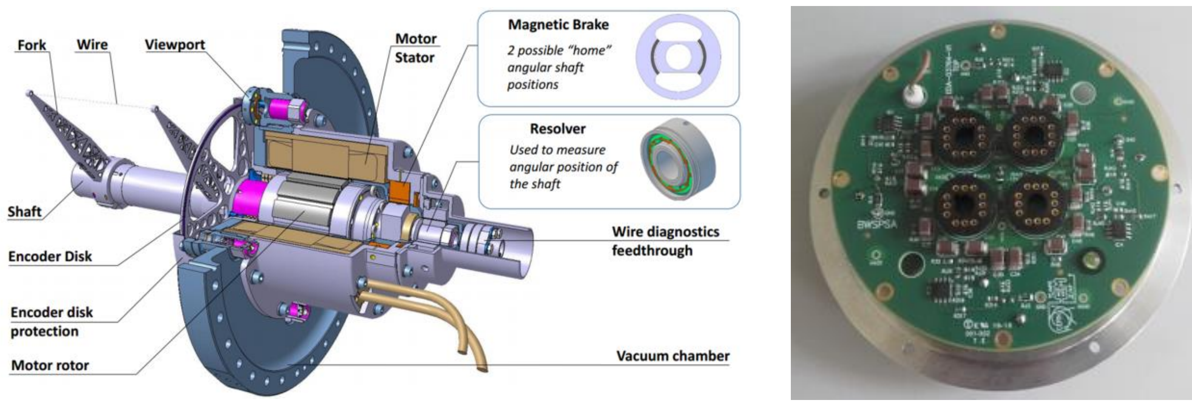


Figure 23: New LIU BWS design (left) and the new, custom-made, acquisition PCB, designed to drive the 4 Photomultiplier Tubes coupled to each BWS scintillator (right).

Turn-by-turn measurements from secondary emission monitors

The first prototype of the new fast electronics designed to record wire grid data during PSB and PS injection was successfully tested in the PS. A measurement example is shown in Figure 24. The beam size beating visible is typical of optical mismatch between the injection line and the accelerator.

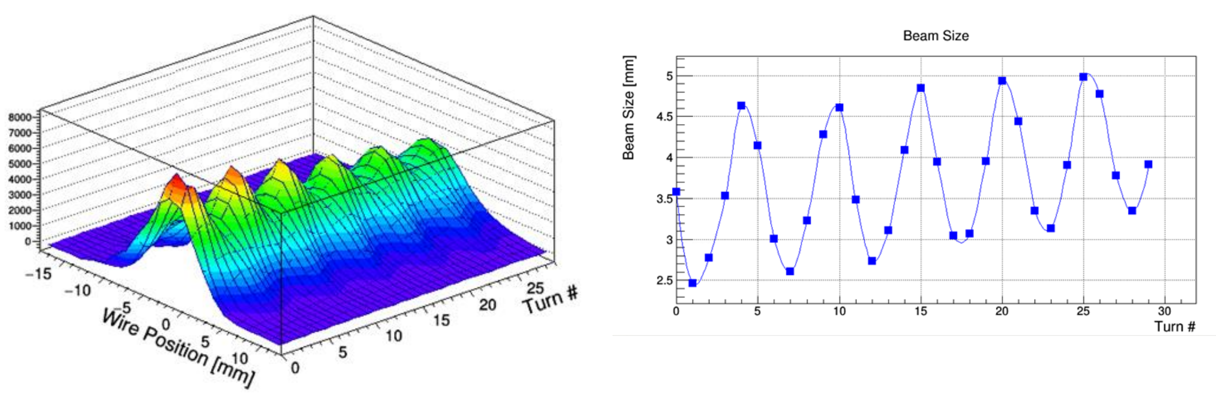


Figure 24: Wire grid turn by turn data during PS injection.

Software for SPS Beam Gas Ionisation Monitors

A new FESA server was developed for the SPS Beam Gas Ionisation (BGI) monitor, providing beam profiles and Gaussian fits for user configurable "time windows" (Fig. 25). By managing settings such as high-voltage power supplies, this software enforces consistent and safe sequences

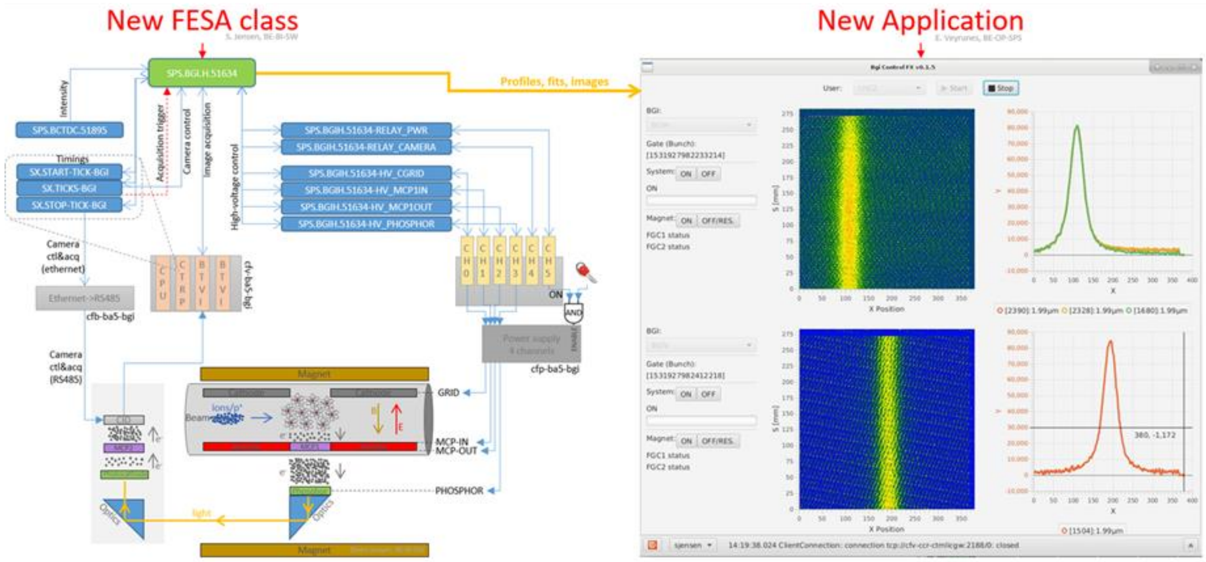


Figure 25: System overview (left) and expert application (right).

for system start-up and shutdown as well as automatic system shutdown after a configurable time. In case the detectors are at risk due to too intense beams, the software initiates an emergency system shutdown. With this, the SPS BGI systems are now fully integrated in the control system. With a dedicated GUI application (see Fig. 25, right), the system is now operational.

SPS Orbit System Upgrade

The present beam position monitoring system of the SPS (MOPOS) is foreseen to be decommissioned during LS2 and replaced by a new system (A Logarithmic Position System – ALPS) answering to updated specifications. ALPS is based on a logarithmic compression of the signal and relies on radiation-tolerant analogue and digital front-end electronics. The logarithmic compression simplifies the system operation by removing the need for many programmable attenuation stages, as presently used in MOPOS. The radiation-tolerant front-end electronics allows the use of short cables followed by fibre-optic transmission, replacing the need for the long cables used in MOPOS, which require regular dedicated calibration campaigns to compensate for radiation-induced deterioration. A vertical slice of the ALPS system, connected to 12 existing BPMs, was installed in Point 6 of the SPS in parallel to MOPOS in the second half of 2018. The tests performed with proton and ion beams confirmed the good results obtained in the laboratory and allowed the entire new acquisition chain to be verified. The ALPS system proved capable of covering the wide dynamic range required for SPS operation (~ 90 dB), with an orbit resolution

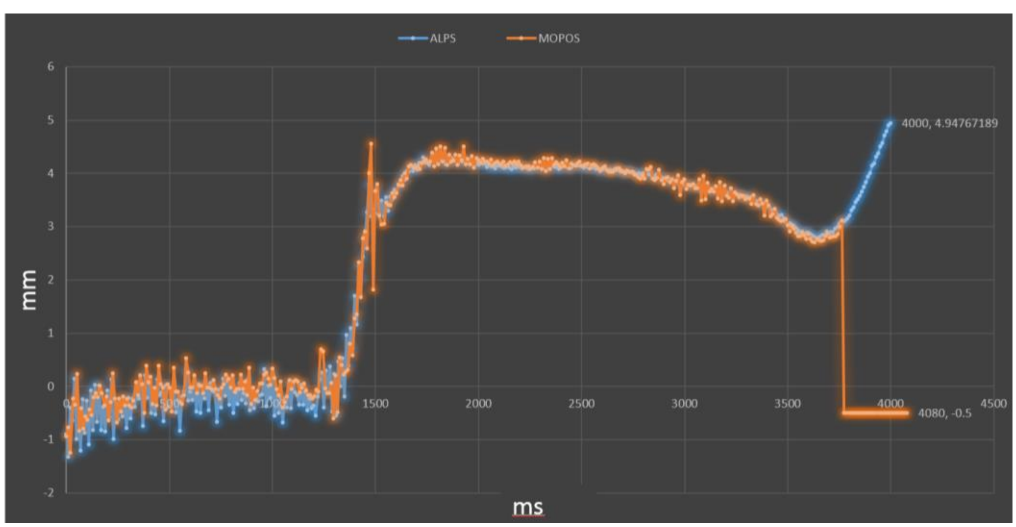
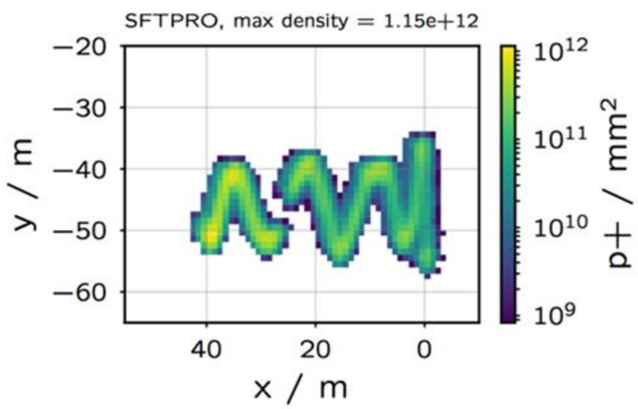


Figure 26: Horizontal orbit for a full proton cycle as measured by ALPS (blue) and MOPOS (orange).

(averaged over 1 ms) better than 50 μm for typical 25 ns bunch trains. Figure 26 compares the horizontal beam positions from ALPS and MOPOS during an SFTPRO cycle, showing very good agreement.

New Beam TV system for the New SPS Beam Dump

Within the new SPS Beam Dump System (SBDS) project, the BE-BI group is heavily involved in developing an online imaging system to monitor the 2D distribution of the beam extracted to the



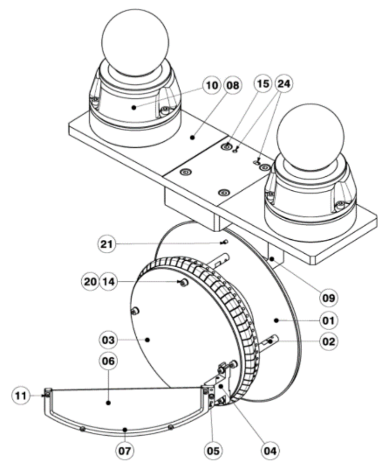


Figure 27: Simulated image of the diluted beam (left) that will be captured by a BTV system using a large scintillation screen for which the support design was optimised for machine impedance (right).

dump. For measuring the diluted particle distribution, such as the one simulated in Figure 27 (left), it was necessary to design a rather special BTV system. The design (see Fig. 27 right) was optimized to minimise beam impedance, to ease installation and to reduce maintenance in such a high radiation area.

FLUKA simulations led to the decision of designing a 17 m long optical line to allow the installation of the imaging detector far away from radiation, and of adding dedicated shielding. This allows the use of a modern, high performance, digital camera without the worry of single event upsets. The line was carefully designed with 5 high quality mirrors. Figure 28 shows the simulated optical ray tracing through the mirrors, which yielded the mirror quality specifications, and the full integration of the BTV components.

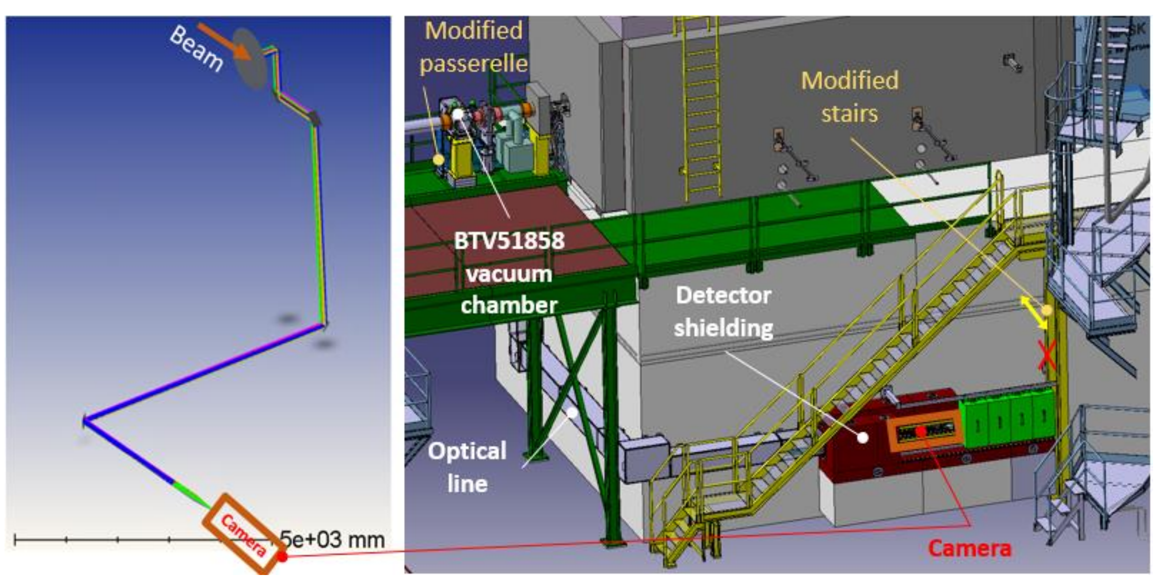


Figure 28: Optical line as simulated with OS ZEMAX (left), taking the CATIA 3D integration (right) as input. The camera will be located inside a shielding equipped with 4 doors on rails for easier and faster maintenance.

BE-RF Group

PSB

The PSB Finemet® project, which replaces 40-year-old RF systems of the PSB with a new wideband RF system in 2019, has progressed as expected in 2018 (see Fig. 29). All equipment parts were assembled and validated, 3 groups of cavities were mounted on their respective supports, pre-cabled, equipped with water and air-cooling infrastructure, and made ready to be moved in the Ring during LS2 (cf. Fig. 29, left). All power racks and ancillary electronics racks were also fully equipped, pre-tested and prepared for installation in their final locations. The removal of the old systems started in the surface equipment rooms at the end of 2018.

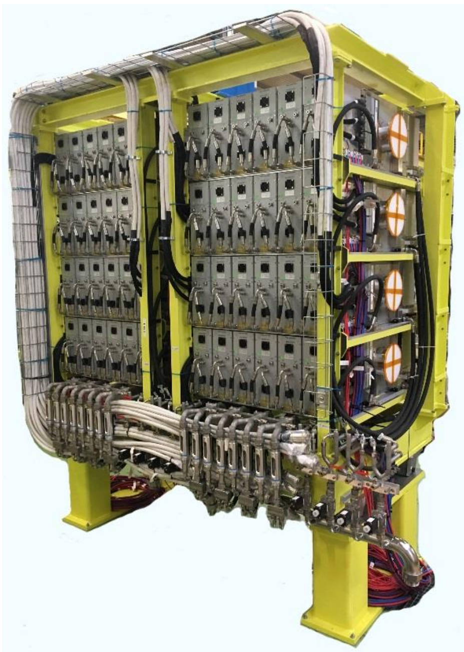


Figure 29: Left: One of the three fully equipped supports with new PSB Finemet® based cavities and solid-state amplifiers; right: one six-gap Finemet® cavity with individual solid-state amplifiers.

After successful validation tests in 2017 of controlled longitudinal emittance blow-up in the PSB using band-limited noise, this method was operationally implemented in May 2018 on all beams (notably BCMS, LHC25 and MTE cycles). Thanks to this improvement, now also the old C16 system, previously used for controlled longitudinal emittance blow-up, can be removed, since now all beam manipulations are possible with the Finemet® system.

A reliability run was carried out with the new LLRF system driving the Finemet® test cavity and using White Rabbit (WR) for the B-train distribution. The successful validation now allows full implementation in the new Finemet® system, which will allow driving these cavities at different harmonics at the same time. Firmware and software is being designed in a flexible way as to permit distribution of the different signals to the Finemet® cavities for optimised use of the available power and peak voltage.

For the PSB transverse feedback system, new solid-state 800 W power amplifiers and new digital electronics were successfully commissioned.

PS

PS 10 MHz System upgrade

During 2018, the final version of the 10 MHz upgraded feedback amplifier was tested with beam in the PS, confirming the impedance reduction provided by this technical solution. The production of amplifiers has started and is expected to be ready for installation in due time during LS2. Figure 30 shows a view inside the upgraded 10 MHz amplifier.

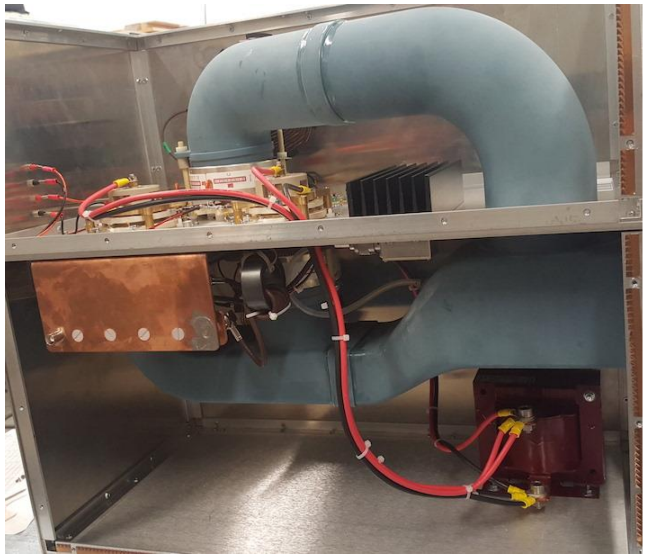


Figure 30: Inside view of the new 10 MHz feedback amplifier, still based on the YL1056 RF tetrode, providing increased fast feedback gain to the 10 MHz system.

PS Longitudinal damper

The final system design of this Finemet® based cavity was produced, assembled and tested on dummy loads. New electronic modules solved the problems experienced during the prototype tests in 2017. Beam tests confirmed the effectiveness of the coupled modes instabilities damping. The system was also successfully tested to generate barrier buckets described below.

Beam intensity reach

At the end of the 2017 run, the intensity of LHC-type beams with 25 ns bunch spacing and batches of 72 bunches at extraction from the PS was limited to about 2.1×10^{11}p/b. Above this intensity, longitudinal coupled-bunch oscillations were observed, as well as uncontrolled longitudinal emittance blow-up along the batch. While a bunch intensity of 2.1×10^{11} protons is already well above the present needs for the LHC, it remains well short of the LIU baseline of 2.6×10^{11}. Two

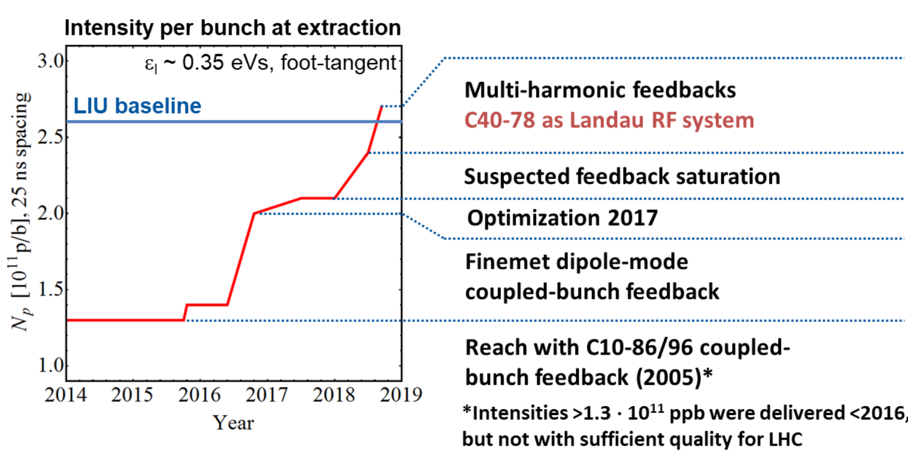


Figure 31: Evolution of the beam intensity reach in the PS with the partial LIU RF upgrades in place (25 ns bunch spacing a batch of 72 bunches.

major improvements could be implemented in 2018: Firstly, the anode power converters of the high-frequency cavities at 40 MHz and 80 MHz were upgraded (see below) – this allowed to counteract beam loading up to about 2.3×10^{11} protons per bunch. Secondly, prototypes of new multi-harmonic feedback systems were installed around the 40 MHz and 80 MHz cavities to further reduce the beam induced voltage, along with a partial use of the 40 MHz cavity as Landau cavity. With these additional measures in place, the LIU baseline intensity 2.6×10^{11} p/b at extraction from the PS has been achieved with excellent longitudinal beam quality.

Figure 31 illustrates the increase of the bunch intensity with 25 ns bunch spacing since 2015. The main contributors to achieving the intensity for HL-LHC are firstly the longitudinal coupled-bunch feedback with the Finemet cavity as wideband longitudinal kicker. The upgrades of the feedback amplifiers for the main accelerating cavities described above will provide additional margin for the longitudinal beam quality.

Landau RF system study

Before the implementation of the improvements described above, and guided by the double harmonic RF operation in the SPS, proof-of-principle beam tests using an existing 40 MHz cavity as a higher-harmonic RF system during the final part of the cycle had demonstrated in 2017 its beneficial effect on longitudinal beam stability. A working group had been set up to study a dedicated Landau RF system, covering the entire frequency range from flat-bottom to flat-top. The basic requirements for this new RF system are summarized in Table 2. Although different harmonic number ratios h_2/h_1 were considered, the ratio $h_2/h_1 = 4$ was chosen as a default configuration, identical to what was used for the initial beam tests. It is also the harmonic number ratio of the double harmonic RF in the SPS.

Table 2: Specifications for a dedicated Landau RF system in the PS

	$\Delta f/f$ [%]	$h_2/h_1 = 3$, $h = 63$	$h_2/h_1 = 4$, $h = 84$
2 GeV to 26 GeV	5.3	28.49…30.04 MHz	37.98…40.05 MHz
Transition to 26 GeV	1.3	29.65…30.04 MHz	39.53…40.05 MHz
Fixed target option	6.8	28.49…30.51 MHz (h_2 = 63 and 64)	
RF voltage		60 kV ($V_2/V_1 \approx 0.3$)	40 kV ($V_2/V_1 \approx 0.2$)

Three different RF system options were suggested and studied in detail. The first option is based on a shortened $\lambda/4$ coaxial resonator with a perpendicularly biased garnet tuner. The second option again consisted of the coaxial cavity, but using parallel-biased ferrite material to achieve the 5.3% tuning range. As third option, and innovative approach considered a wideband Finemet® cavity in the unprecedentedly high frequency range around 40 MHz, driven by a solid state power amplifier located outside the tunnel. For this last option, a shroud as a test set-up for multiple Finemet® rings was built and, following initial measurements at CERN, shipped to KEK to perform tests with new core material.

With these possible designs for a possible dedicated Landau RF system, this study concluded, since the improvements described above made it unnecessary to reach LIU beam parameters. The results however are interesting and may become relevant in the future.

Improvements of the PS longitudinal beam control

The improvements to the longitudinal beam control of the PS included the operational exploitation of a universal cavity return vector sum. It allows for any harmonic to correctly de-phase the gap signals of all 10 MHz cavities, according to their azimuthal positions in the ring before adding them up. With additional phase switching integrated in the digital signal processing, a massive simplification of the beam control could be achieved, thanks to which a novel, compensated phase flip of the RF voltage at transition crossing could be implemented and validated with beam.

For the detection of the radial position offset, the signal processing of a fully digital receiver as part of the radial loop was developed and successfully commissioned with beam. It features significantly larger dynamic range than the previous system and the possibility to measure spectral components at two revolution frequency harmonics simultaneously. The combination of signals from various pick-ups, together with the increased dynamic range will close the intensity gap for the radial loop, resulting in higher flexibility for intermediate beam intensities after LS2.

75 ns bunch spacing with lead ions in the PS

The $h = 3$ cycle in LEIR was deployed operationally in 2018. Three instead of four bunches in LEIR allowed for 30% higher bunch intensity in the injectors. To generate 75 ns bunch spacing, the 3 bunches from LEIR are first captured in buckets at harmonic 24 in the PS. Since accelerating on this harmonic would exceed the largest frequency of the ferrite loaded cavities, the harmonic is changed from $h = 24$ to $h = 21$ through a single-step batch expansion at an intermediate plateau. This results in 3 bunches spaced by 100 ns at the arrival on the flat-top. The bunch spacing is then

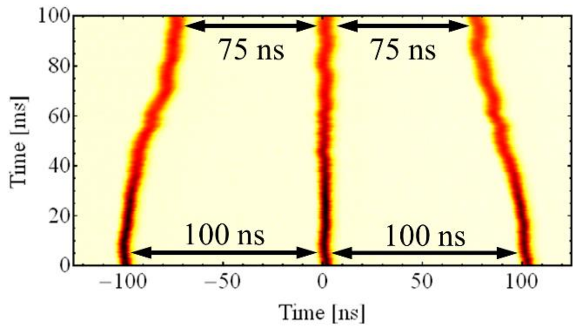


Figure 32: Re-bucketing of three ion bunches at PS flat-top from harmonic, $h = 21$ to $h = 28$. The bunch spacing is reduced from 100 ns to 75 ns.

decreased to 75 ns by a further batch compression from $h = 21$ to $h = 28$ (cf. Fig. 32), achieved by switching a 20 MHz cavity to 13.2 MHz. The batch is then re-bucketed to $h = 169$ (80 MHz) for bunch shortening prior to the transfer to the SPS. 75 ns bunch spacing for ions was used operationally in the 2018 Pb run and led to almost twice the nominal peak luminosity.

SPS

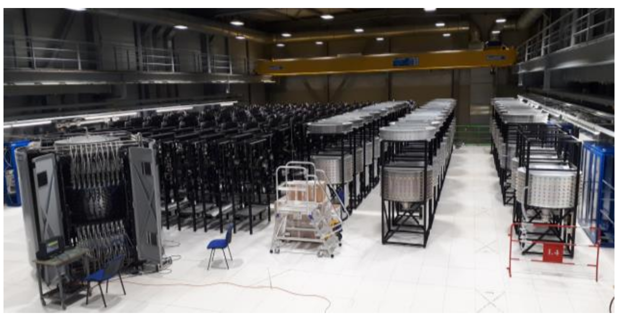
New 200 MHz solid-state power amplifier

The year 2018 was an exciting and crucial period for the new solid-state power amplifier (SSPA), to be added to the existing Siemens and Philips 200 MHz plants, adding almost 4 MW of RF power. Along with the re-arrangements of the cavities in LSS 3 and the reduction of their HOM impedances, this upgrade is key to coping with the increased beam current. The project went through critical phases during early 2018, when at times success was severely put in doubt and we had to seriously consider details of our plan B. An extraordinary personal effort, going through more than 5 versions of the RF power electronics in the amplifier boards, understanding and solving the underlying problems, which were sometimes subtle, much discipline in the careful implementation of the improvements in tight collaboration with Thales/Gerac, along with a lot of persistence, finally paid off: a full validation of the technology was achieved in August after a successful endurance run of a fully equipped 140 kW tower under realistic conditions for 1000+ hours without failure – a remarkable success!

The tower was also exposed to more severe tests – like running at full power on a full reflection, mimicking a short circuit in a cavity or an RF line. The short circuit is realized inside a coax line

a) Set-up for RF short circuit tests

b) Test-stand for "accelerated ageing" of SSPA modules



c) The 1st floor of building BAF3 in Q2/2018

d) The prototype 140 kW tower

Figure 33: The LIU-SPS 200 MHz SSPA.

with three movable fingers, controlled by an electro-pneumatic system. This test was carried out in September 2018 – the tower passed again. In parallel, a dedicated test-stand was used to check and validate that each and every module (eventually a total of 2560!) satisfies the tight CERN specifications in gain and phase. Another test-stand was used to check the lifetime of the SSPAs with RF-accelerated ageing (a factor 500 faster than normal operation!)

LLRF upgrade

MicroTCA has been chosen as standard for the new LLRF systems to be implemented in LS2 for the upgraded RF system, then consisting of six 200 MHz cavities. The project has been structured in work packages, specifications are agreed with all stakeholders for the individual beam loops and RF manipulations. A cavity controller was successfully tested in BAF3 on a test cavity to validate the scheme with a fixed sampling frequency. Frequency distribution with White Rabbit (WR) could also be validated. For this project, the RF group relies on full support from CO group, both for the implementation of this new standard, for the centralized purchase of crates and for software tools and environment.

Cavity re-arrangement and impedance reduction

In 2018, the SPS 200 MHz system consisted of four cavities – two 5-section cavities and two 4-section cavities (a section consists of 11 cells). After LS2, the system will consist of six cavities, two 4-section cavities and four 3-section cavities. This re-arrangement allows to cope with the larger beam current, but in addition the damping of higher order modes (HOMs) has to be further improved. Several HOM measurements with different SPS beams were carried out during 2018 to

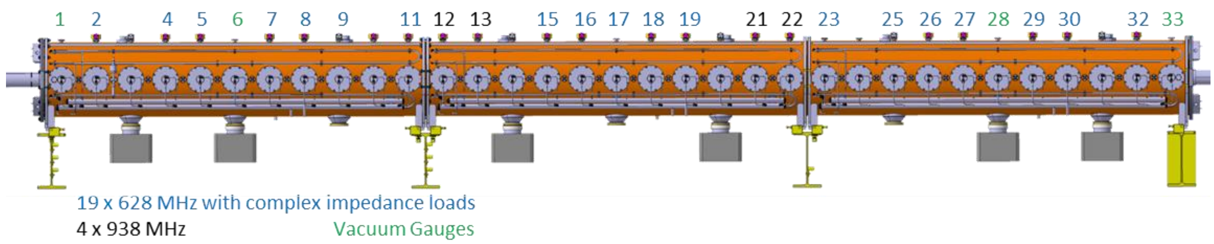


Figure 34: Schematic of 3-section 200 MHz travelling wave cavity with positions for nineteen 630 MHz and four 938 MHz HOM couplers as well as vacuum gauges.

characterize the difference between the two 4-section cavities, one of which already featured additional new HOM couplers; this allowed to validate the effectiveness of the proposed new HOM damping on those 4-section cavities.

For the new 3-section structures, the damping of the 630 MHz HOM could be considerably improved by implementing complex impedance loads on the existing couplers, leaving the actual coupler geometry untouched. The required HOM damping is obtained by adding 7 more HOM couplers in addition to the existing 12 (4 per section) previously.

LHC injector operation (Linac2, Linac3, Linac4, PSB, LEIR, PS, AD, SPS, Experimental Areas and Associated Facilities)

BE-ABP Group

Linac4

In 2018, Linac4 made very important steps toward operation and demonstrated to be ready to provide the all variety of beams required for the post LS2 run.

The machine was operated for a total period of about 6 months, split into the second part of the reliability run, which had started already in 2017, from mid-February to mid-May, and the beam performance and quality run from September to December. Between those two runs, during spring and summer, an extended technical stop was dedicated to equipment repairs, preventive replacements and upgrades planned since the beginning of the Linac4 project or whose need arose during the different operation periods.

The transition from commissioning to operation became very concrete. Most of the beam characteristics and quality targets (pulse to pulse stability, current flatness, emittances, etc…) were achieved. The machine set-up procedures and beam measurement techniques were once again validated and improved. Multi-user and multi-destination operation were successfully introduced, and Linac4 joined the family of the machines surveyed by the Accelerator Fault Tracking system with a very promising 95% availability during the last 2 months of 2018.

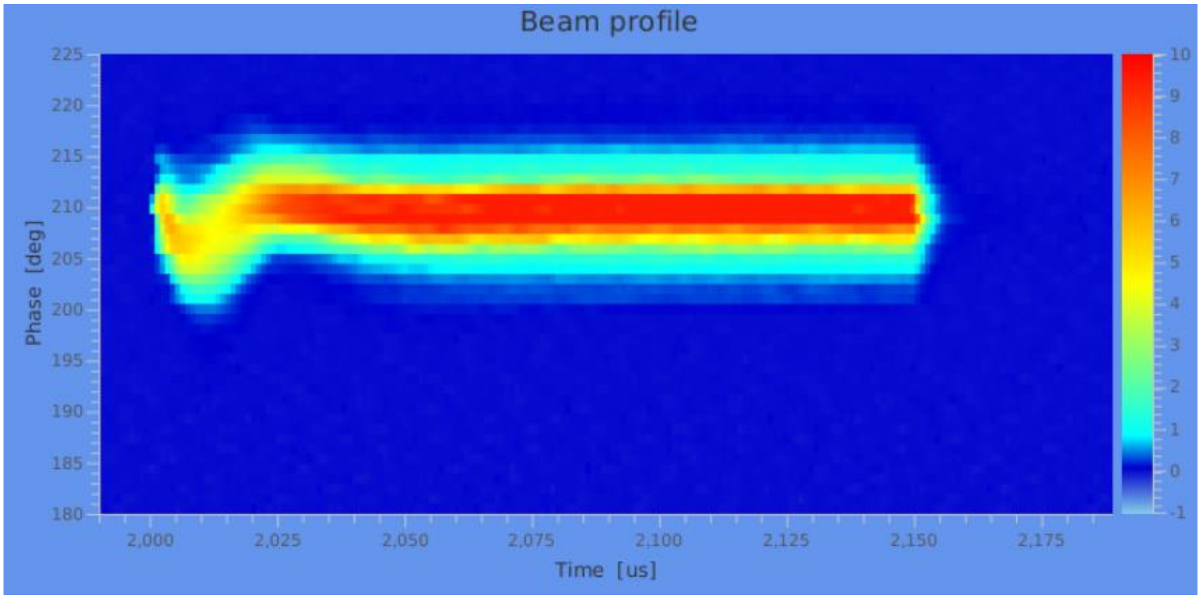


Figure 35: Phase profile of a 150 us beam pulse at 160 MeV beam measured at the end of the linac. After a transient of 30 us, the reduced longitudinal beam size and its stability are proof of the all machine stability and tuning quality.

Beside this very good year on the machine itself, studies and development were carried out in parallel at the Linac4 test stand, where different versions and setups of the H^- ions source extraction were extensively measured and characterized. A novel type of diagnostic, the RFQ acceptance box, was installed during the summer, and revealed to be an extremely useful, simple and accurate tool in the view of low energy beam optimization and characterization.

PSB

Various beam dynamics related studies were undertaken in the PSB during 2018. One of the main activities of the year was the optics measurements campaign. Optics measurements were performed in all four rings at 160 MeV and at 1.4 GeV. Unfortunately, the combination of 90° phase advance between the BPM and the small kick amplitude for higher energies led to large uncertainties in the optics measurements at 160 MeV and 1.4 GeV. Two new working points (Q4Q3 and Q3Q5) were set up and used for measuring the BPM calibration factors and eventually reduced the uncertainties at 160 MeV. Dispersion measurements were also carried out for the 4 rings and the BTM line.

Towards the second part of the year, the loss maps were measured at 160 MeV for all the 4 rings. Based on these measurements the excited resonances (mainly 3rd order) per ring were identified and optimal choice of correctors and current configurations were proposed for their compensation for each ring. This was a joint effort between BE-ABP and BE-OP.

In the context of understanding the sources of emittance difference between the PSB extraction and the PS injection, the last part of the year was dedicated to the emittance measurements at PSB extraction. Systematic brightness curve measurements were performed simultaneously in the PSB and the PS, using wire scanners and BTM SEM Grids for different beam and machine configurations. The outcome of these studies was that the PSB brightness curve measured with the wire scanners approaches the one given by the SEM grids using the measured optics, within the large uncertainty in the beta function measurement.

Finally, one of the highlights of the year was the experimental proof that the impedance source of the horizontal instability observed at 160 MeV is due to the extraction kicker's unmatched termination.

PS

In the beginning of 2018 the activities of the BE-ABP group focused on commissioning a new beam production scheme for LHC beams, which is based on correcting the chromaticity already at low energy. The operational implementation of this configuration was an important milestone in view of operating LHC beams with large longitudinal emittance after the Long Shutdown 2. This new low-chromaticity configuration relies on correction of the linear coupling as well as an efficient transverse feedback (TFB) system to damp horizontal head-tail instabilities. Starting from LHC fill number 7123, the operational LHC Batch Compression Merging and Splitting (BCMS) cycle had been using this configuration and the beam production using the TFB along the flat bottom could therefore be fully validated. Excellent beam performance was achieved up to the LHC using this low-chromaticity configuration.

A new beam production scheme for the beam serving the n-TOF facility has been developed and operationally implemented in order to mitigate slow beam loss after injection in the PS. The improvements on this specific cycle consisted of moving the blow-up of the longitudinal emittance from injection energy to an intermediate magnetic plateau to reduce beam loss by avoiding aperture restrictions due to a large dispersive contribution to the beam size at injection energy. As a result, beam losses from injection to transition energy could be reduced by more than 50%. This is very important in view of future high-intensity beam operation at the PS, considering that beam losses on the n-TOF cycle constitute one of the main reasons for radioactive activation of ring equipment. Related to high-intensity beams, progress has also been made in improving the Multi-Turn Extraction (MTE). Recent developments by BE-RF (see below) allowed the creation of a barrier bucket using the PS Finemet cavity. Subsequently, such a bucket was implemented on an MTE cycle and significant beam loss reduction of up to a factor 10 (depending on the bucket size) could be demonstrated during extraction by properly aligning the barrier bucket and the rising part of the extraction kicker wave form. The combination of these two techniques therefore has great potential for further loss reduction in the future.

SPS

A series of machine development studies was performed in 2018 with high intensity LHC beams in preparation of the LIU project (see above). The beneficial effect of scrubbing was clearly observed through an improved emittance preservation along the SPS injection plateau, when operating the BCMS beam for a couple of days with more than 1.8×10^{11}p/b. From the initial emittance growth of up to 40% in both planes, the blow-up could be reduced to less than 15%. This level could be maintained over a period of a few weeks with only occasional usage of the high intensity LHC beam for machine development studies. This gives hope that scrubbing will be sufficient for mitigating the e-could build-up in the SPS with the LIU target parameters, as foreseen by the LIU baseline.

The second focus of the studies with LHC beams was the characterization of the horizontal head-tail instability observed with 4×48 bunches of the 25 ns BCMS beam for intensities above 1.8×10^{11} p/b, which is not supressed by the transverse damper. Stabilization with high chromaticity could be achieved, however at the expense of slightly enhanced incoherent losses. Since the usable octupole strength for Landau damping was limited in the Q20 optics in the past, due to incoherent losses resulting from the large second order chromaticity induced by the octupoles themselves, the octupole scheme of the SPS was modified in 2018. By using the already installed ones but inverting the polarity of some octupoles during the second injector technical stop, the induced second order chromaticity could be significantly reduced. This allowed using the octupoles in mitigation tests of the horizontal instability, such that its onset could be fully characterized, as a function of chromaticity and octupole settings. These data will serve as input for identifying the driving impedance for this instability and the development of mitigation strategies during the long shutdown in preparation of the LIU beam commissioning.

A highlight in 2018 was also the successful test of the LHC crab cavity prototype with beam in the SPS. A rich program of measurements was performed in close collaboration with colleagues from BE-RF (see above). In addition to the experimental verification of the crabbing and the measurement of the crabbing voltage from beam-based observables and the nonlinear multipole components of the crab cavity, the emittance growth induced by crab cavity noise could be successfully measured, as well.

Finally it is worth highlighting that the performance of LHC ion beams was again significantly improved. In the first half of the LHC ion run the nominal scheme with 4 bunches per PS batch was used and the intensity achieved in 2016 could be slightly exceeded. In the second half of the run, a new scheme with 3 bunches per PS batch with 75 ns bunch spacing was commissioned, which resulted in an increase of the total intensity and luminosity in the LHC by about 50%.

LEIR

The LEIR machine experienced another year of deep improvement in performance from both extracted intensity target and stability of operation point of view. In 2018 it was possible to extract 10% more beam from the NOMINAL cycle and guarantee on average a stable operation above the LIU target. This remarkable achievement was possible thanks to the strong LEIR and Linac3 team efforts. The machine operation was largely improved thanks to innovative ad-hoc tools (like the LEIR optimizer) and the identification of possible systematic (e.g. ETL.BHN10 sensitivity to temperature, machine tune ripple due to XFW circuits) and non-systematic performance degradation sources (e.g. stripper foils degradation). On the machine development side, several studies were done on impedance, space charge, and electron cooling: the source of the fast transverse instability was identified (old BTF pickup) and suppressed; the IBS was observed to play an important role at capture together with space charge; the electron cooler was further characterized. Studies were also done to extend the injection plateau to accommodate eight injections with a faster ramp rate, and on the new transfer line optics to better match the PS periodic solution. Last but not least, 2018 has seen the NOMINAL beam operating with 3 bunches in harmonics $h = 3 + 6$ (75 ns in the PS) which allowed LHC to achieve 67% of the LIU target on total intensity compared to 58% for the $h = 2 + 4$ case (100 ns in the PS).

BE-BI Group

The 2018 Linac4 run relied heavily on all the beam diagnostic systems. In particular, beam current transformers (BCT), beam position monitors (BPM) and the bunch shape monitor (BSM) were essential for machine setup and optimisation. The BPM time-of-flight measurements were

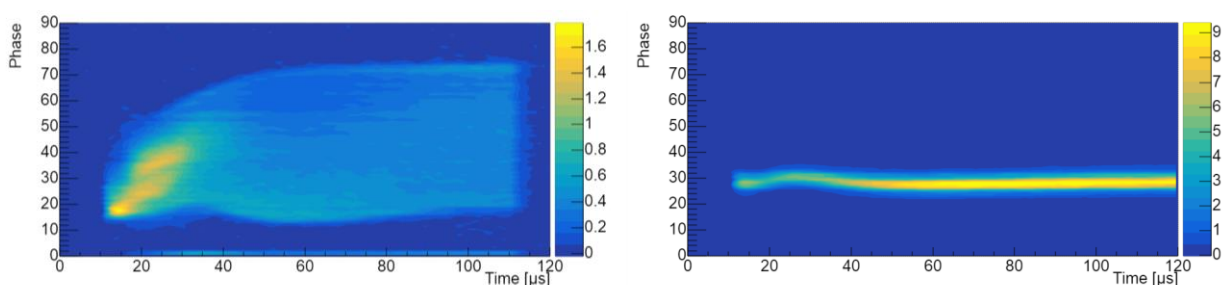


Figure 36: BSM measurements before (left) and after (right) adjusting RF cavity phasing to reduce the energy spread at 160 MeV.

repeatedly exploited to tune RF cavities, with the improved lowlevel and high-level software considerably reducing the measurement time and improving the accuracy of the results. The BSM system diagnosed abnormal beam debunching at 160 MeV that, at a certain point, prevented beam to be sent to the L4Z transfer line. Measurement examples before and after optimising the RF are shown in Figure 36.

With the L4T and L4Z wire grids undergoing extensive tests to understand their failure in 2017, wire-scanners were instead used by OP and ABP to measure the transverse emittances at 160 MeV. This was complemented by the installation and commissioning of the two final laser emittance meter stations. Measurement examples from the laser systems can be seen in Figure 37. These will in future be able to provide online, non-destructive profile and emittance measurements of full beam pulses.

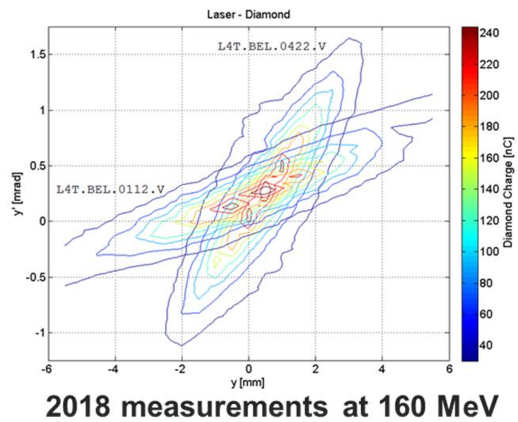


Figure 37: Linac4 vertical phase space as reconstructed by the two laser emittance systems installed at 160 MeV.

Linac4 pulse intensity flatness measurements

In order to evaluate and improve the efficiency of the Linac4 chopper, it is now possible to monitor the intensity flatness of beam pulses accelerated in the linac with the use of Beam Current Transformers (BCTs). The BCT electronics employs triggers to identify which part of the beam pulse will be distributed to the four rings of the PSB, allowing the flatness and destination of each part of the pulse to be determined. Figure 38 shows an actual measurement where the destination

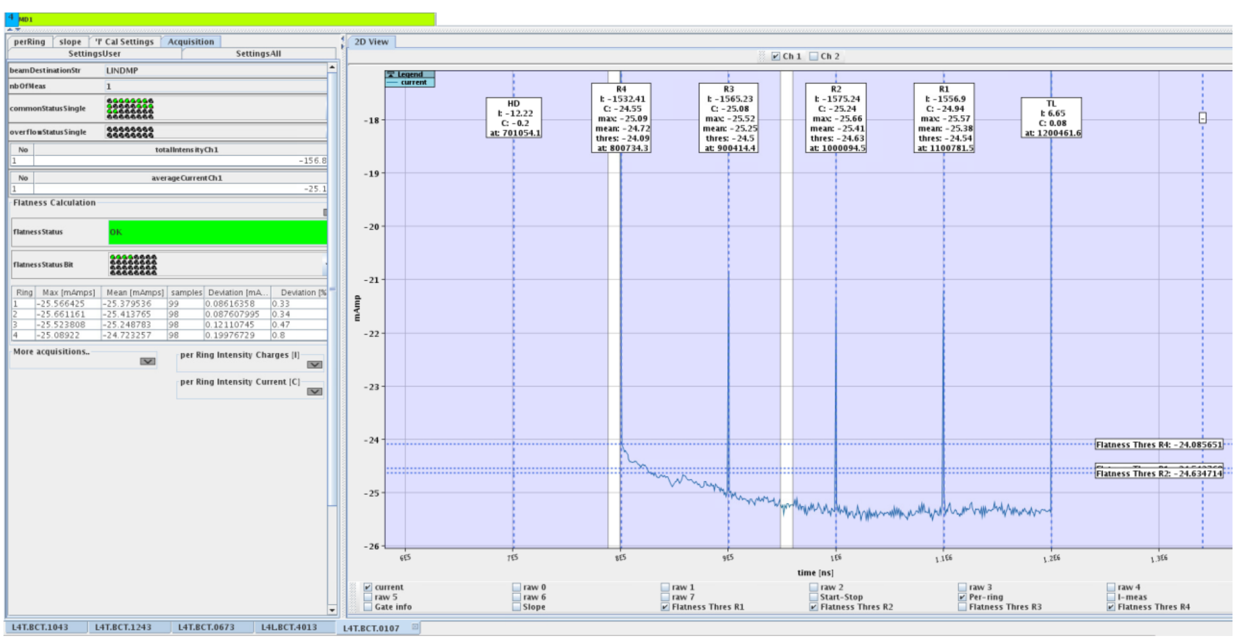


Figure 38: The Linac4 intensity flatness monitoring application.

is identified with vertical markers and the flatness threshold identified with horizontal markers. The calculated flatness values are shown in the table on the left side of the figure.

Quadrupolar oscillation measurements in the PS

All circular accelerators at CERN are equipped with a tune measurement system using beam position monitors to provide information about the frequency content of beam position oscillations. Recently, the tune measurement system of the Proton Synchrotron (PS) was upgraded with a new, dedicated channel allowing observation of beam size oscillations. As these oscillations provide very small signals with respect to the position signals, they are usually very difficult to observe. The PS tune measurement system employs electronic circuits developed at CERN to meet this challenge. Figure 39 presents three beam spectra: two spectra correspond to standard beam

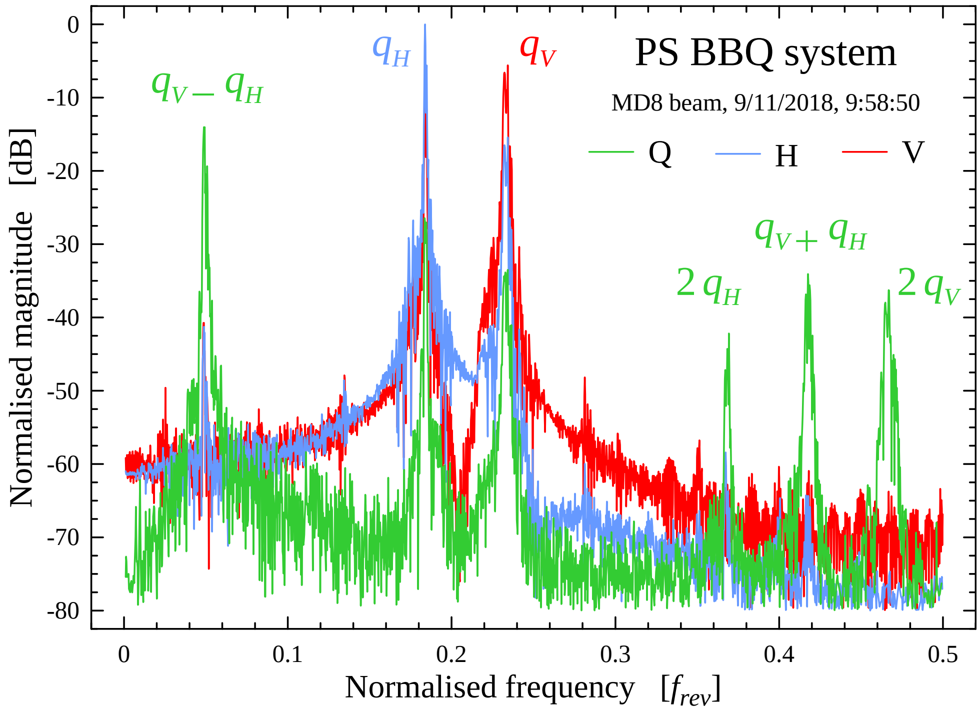


Figure 39: Horizontal (blue) and vertical (red) tune spectra and the quadrupolar oscillation spectrum (green).

position oscillations (tune measurements) in the horizontal (H) and vertical (V) planes and the third corresponds to beam size oscillations (Q). The frequencies of the peaks, expressed in terms of the tune frequencies q_H and q_V, together with the amplitudes of the peaks, can be used to calculate many beam and machine parameters. The PS is the first accelerator worldwide equipped with an operational tune measurement system that also provides information about beam size oscillations. During LS2 such a system will also be built for the PS Booster.

LEIR Schottky measurements

New acquisition hardware was installed to allow a standard and more convenient FESA-based interface as an alternative to the commercial Windows-based spectrum analysers previously in use.

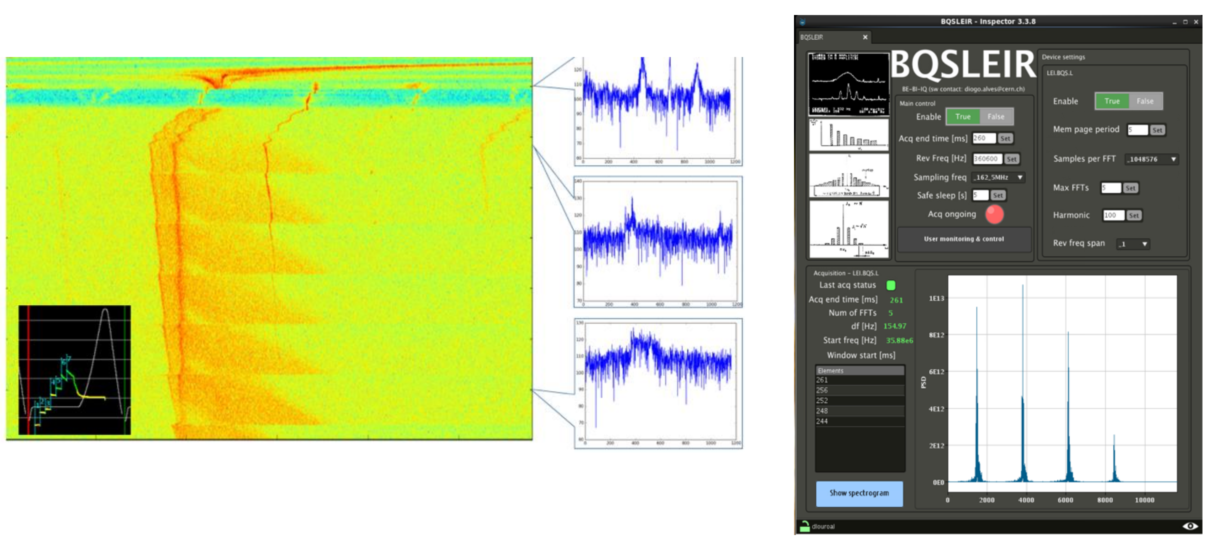


Figure 40: Spectrogram composed of 400 spectra centred at harmonic 50 (left) and the expert configuration tool based on ‘Inspector’ (right).

The hardware is based on the BI VME FMC carrier board (VFC-HD) equipped with 650 MS/s, 14-bit ADCs sampling the longitudinal Schottky signal from a low-beta pick-up. The system can be configured to acquire data from multiple time-windows per cycle with a sampling frequency that can be set from 40 MHz to 650 MHz, covering the multi-turn injection and cooling phases. The subsequent FFT analysis is also performed by the FESA class. The frequency resolution, spectral harmonic and spectral span of interest are also configurable, thus making the system sufficiently flexible for both computationally demanding machine studies and day-to-day operation. An example of a spectrogram obtained from the system, showing the multiple injections and beam cooling, is shown in Fig. 40, left. Both, an expert GUI (Fig. 40, right), based on the "Inspector" framework, and an operational GUI for day-to-day operation were also developed.

DC BCT Normalisation with White-Rabbit

To calculate the number of charges circulating in a machine from the measurement of DC beam current as provided by a DCCT, requires normalisation to the instantaneous beam velocity. This is usually determined from the magnetic flux density (B) of the main bending magnets. In the past this signal was distributed by dedicated "B train" cables, but will in future be distributed over new White Rabbit links.

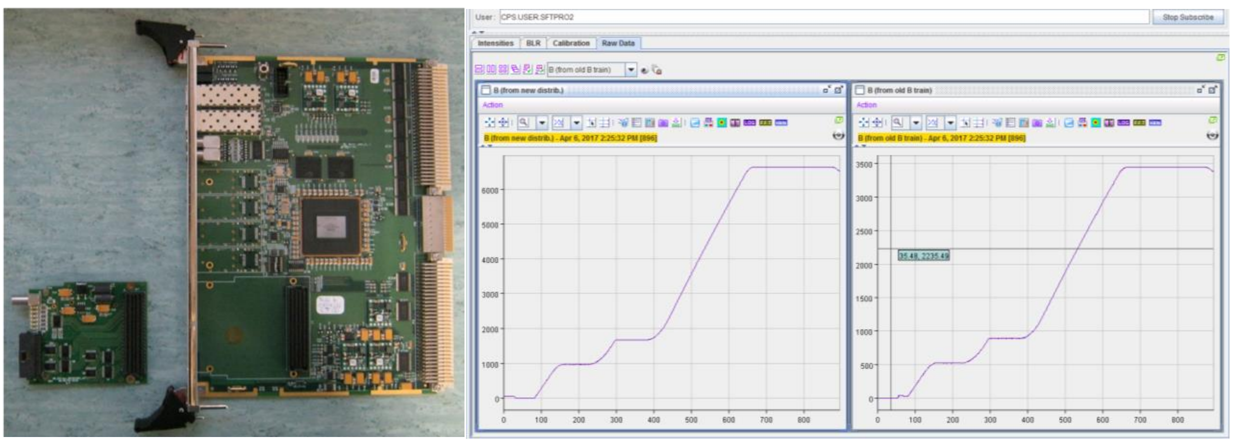


Figure 41: White Rabbit B-train receiver (left) with excellent agreement between the monitoring signals of the old B Train receiver (middle) and the new White Rabbit receiver (right) on a PS SFTPRO2 cycle.

In collaboration with BE-CO and TE-MSC a White Rabbit B-train receiver was designed using the BI VME FMC Carrier board (VFC) and a dedicated FMC mezzanine (Fig. 41, left). The new system is now operational for DCCTs in the PSB, PS and LEIR and a comparison of old and new systems can be seen in Fig. 41, right.

Consolidation of PSB BTV mechanics

The present PS Booster beam imaging systems (BTV) were designed and installed between 1970 and 1990, resulting in a range of different mechanical designs in different locations. Considering

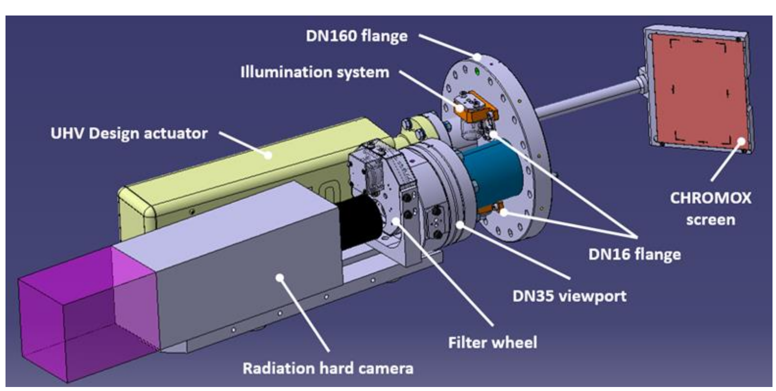


Figure 42: New PSB BTV system design based on a bellowless magnetically coupled actuator.

the age of these systems and the lack of mechanical spares for most of the monitors, a consolidation programme started in 2018 to replace all monitors with a common design. The new screen insertion device, shown in Figure 42, is based on a magnetically coupled actuator not requiring any vacuum bellow. After the successful test of a prototype in the PS injection line, this simple and robust system was integrated into the new design of all the 17 BTVs in the different PSB rings and its transfer and measurement lines (BI, BR, BE, BT and BTM).

Most of the consolidation will be implemented during LS2 and then completed in the period between LS2 and LS3. Apart from the innovative mechanical conceptual design, a major change is that each PSB ring will be equipped with 4 independent BTVs, thus replacing the complex unique mechanism presently installed. This should simplify maintenance as well as allowing an improved optical resolution. The integration of one of the PSB BTVs before and after consolidation is shown in Figure 43, highlighting the compactness of the new design.

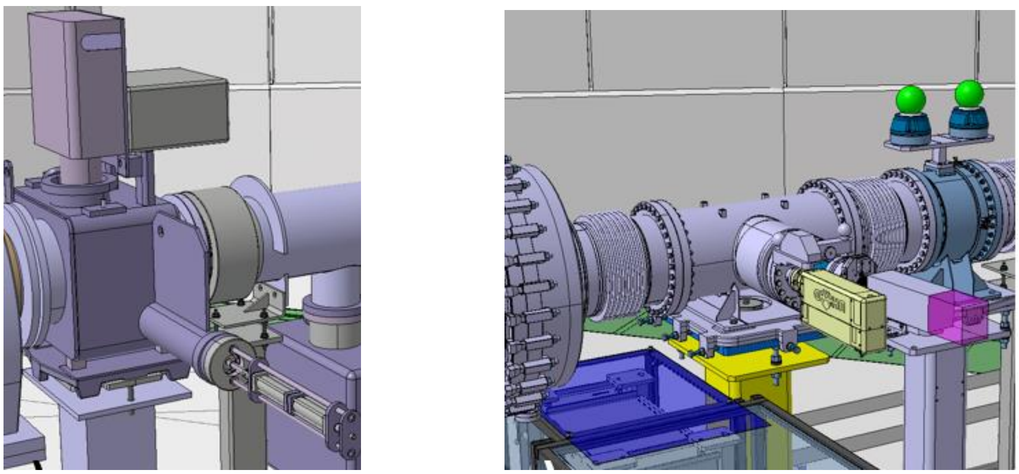


Figure 43: 40 year old BTV equipped with obsolete vacuum elements (left) and new, compact BTV (right).

Radiation-Hard Optical Transmission using Optical Fibre Bundles

This R&D project, aimed at studying the possibility of beam imaging via radiation tolerant optical fibres to replace obsolete VIDICON tubes cameras, advanced significantly in 2018. In particular, it was possible to evaluate the optical performance and radiation hardness of a complete setup consisting of a bundle of 10000 pure silica fibres optically coupled to a target on one side and a digital camera on the other. Irradiation in a dedicated facility at IRMA-CEA in Saclay, France (Fig. 44) showed a degradation of about 50% in terms of total collected light after an integrated

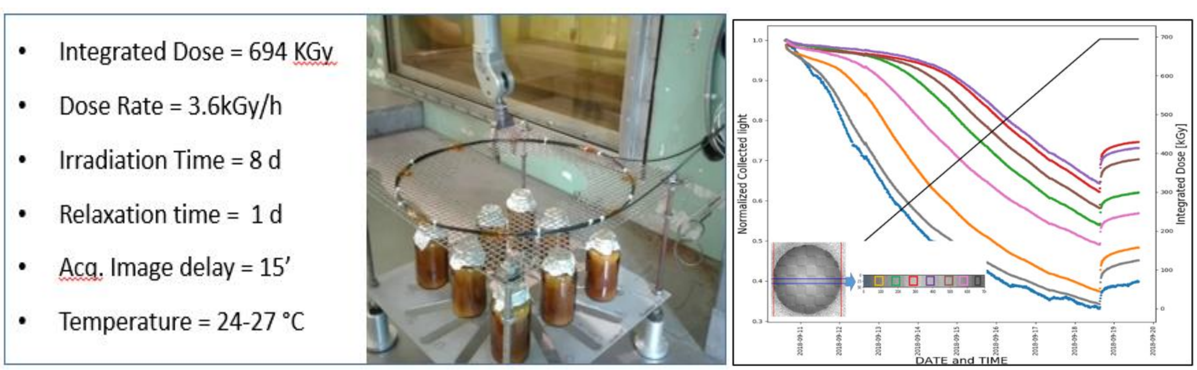


Figure 44: Specifications of the irradiation test performed in IRMA (CEA Saclay, Paris) (left), picture showing the fibre inside the irradiation bunker (centre) and the transmission evolution up to 700kGy with the different colours corresponding to fibres at different distances from the bundle centre (right).

dose of about 700 kGy, corresponding to about 10 years of operation for a CERN BTV in a high radiation zone. It was discovered (and not yet fully understood) that the degradation is stronger on the outer fibres compared to the inner fibres of the bundle.

A test system was also installed on a BTV in the TT2 line and the imaging results compared to a standard camera system. This showed an unexpected large optical cross-talk between fibres that resulted in a poor resolution for beam size measurements. After a debriefing on this issue, the fibre manufacturer is now studying modifications to the production and assembly process aimed at minimising this cross-talk.

New AD target BTV

As part of the AD target area renovation, a new BTV system was developed. Integrated into the new target trolley as shown in Figure 45, the BTV monitor will feature an independent alignment

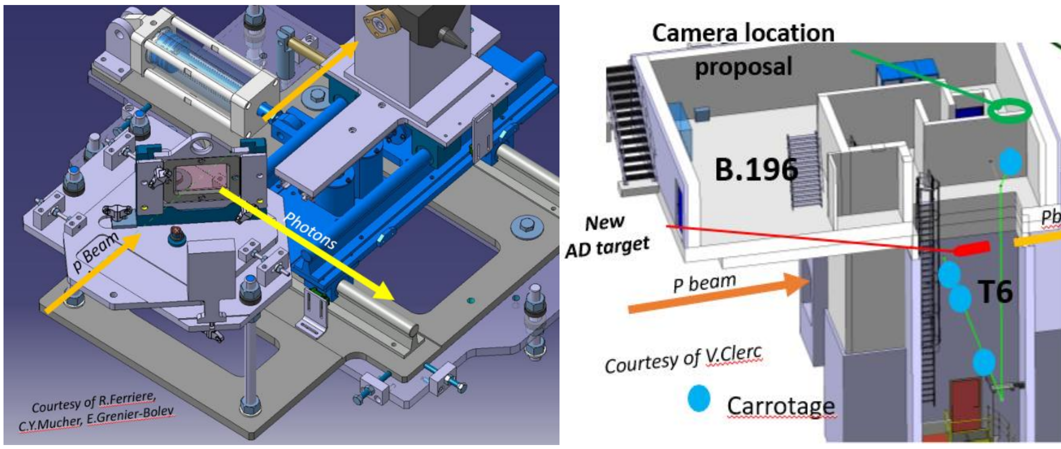


Figure 45: 3D drawing of the BTV screen integrated in the new target trolley of the AD target area (left) and the optical line (in green) to allow imaging of the screen with a digital camera inside building 196 (right).

system and a fast positioning mechanism, resulting in a design conforming to the ALARA recommendations for this high radiation level area. A 20 m long optical line (see Fig. 45), designed with high optical quality mirrors, will allow the screen to be imaged with a digital camera sitting far away from the high radiation area.

ProtoDUNE tests with XBPF / scintillating fibres

The recently created Neutrino Platform in the North Experimental Area has been equipped with a new scintillating fibre monitor developed by BE-BI. Both instrumentation and beam lines were successfully commissioned in September 2018, followed by the successful commissioning of the NP04 ProtoDUNE experiment. Despite the tight production schedule (March 2018 to August 2018), all monitors were produced on time, along with all the necessary control and acquisition software. Two versions of the monitor with a slightly different readout were produced: a version in which every fibre is read-out individually, called XBPF (Fig. 46), and another one in which the fibres are bundled and read-out by fast photomultipliers, called XBTF. The XBPF is capable of

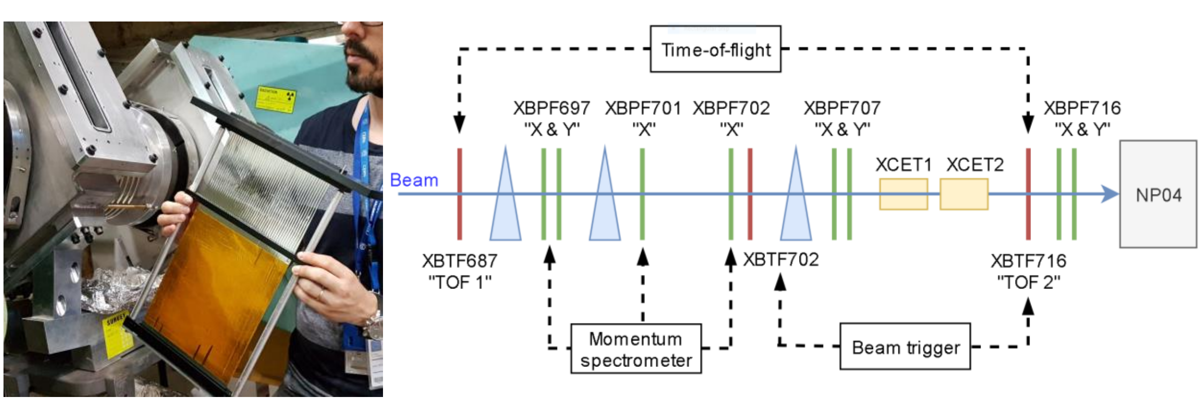


Figure 46: Installation of an XBPF in its vacuum tank at the H4-VLE beam line of the Neutrino Platform. Layout of the H4-VLE beam line with the XBPF and XBTF indicated in green and red respectively.

individual particle tracking and is used to measure the profile and position of the beam for reconstructing the tracks of particles entering the ProtoDUNE detectors.

The good timing properties of the XBTF are exploited to produce trigger signals used by the XBPF and the experiments, and to measure the time-of-flight of the beam particles, which is used to determine the particle composition of the beam. Both beam instrumentation and ProtoDUNE share a common clock distributed over White Rabbit, which allows the information from the monitors to be precisely correlated with the events recorded by the neutrino detector. There was no significant down-time of these detectors during the 2018 data taking run, and they provided very useful information to the ProtoDUNE physicists, helping them to successfully characterise the NP04 detector.

AWAKE spectrometer

During 2018, the AWAKE project reached the main goal of Run 1: demonstrating the acceleration of an electron bunch in a proton-driven plasma wakefield. Several systematic measurement were performed showing that the 18.8 MeV electron beam could be accelerated up to energies ranging from 0.6 to 2.0 GeV in a 10 metre long plasma-cell. The final energy of the witness electron bunch was measured by the electron spectrometer (Fig. 47), for which the BE-BI group designed the optical line in collaboration with experts from the European Southern Observatory (ESO). The optical line was tested and commissioned at the beginning of 2018, delivering the first data from accelerated electrons in the course of the May-June 2018 runs.

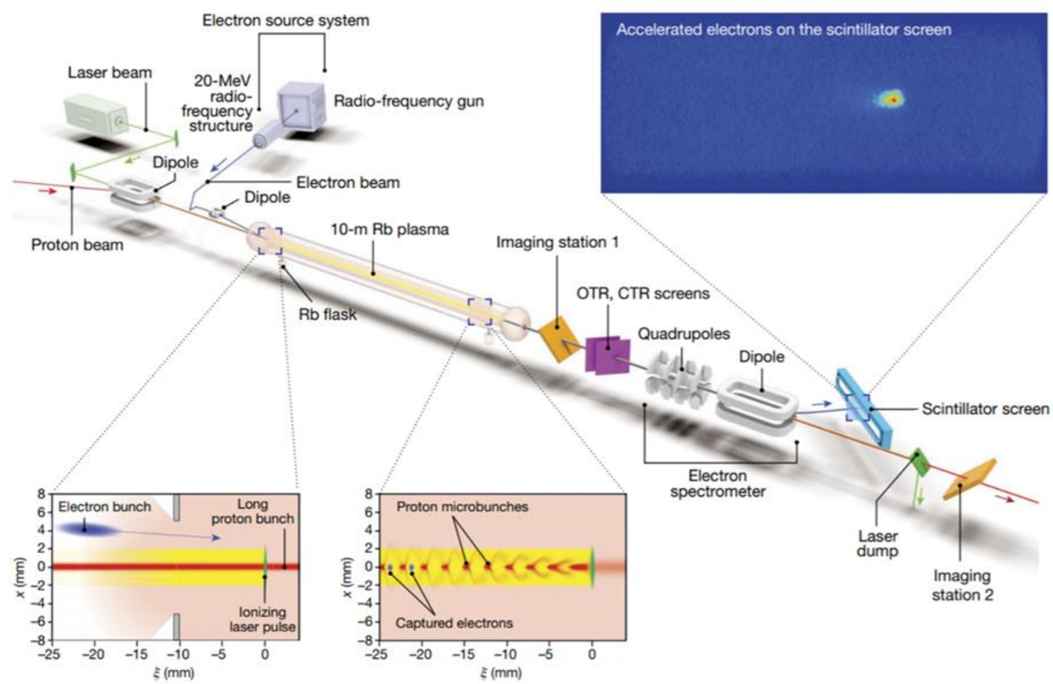


Figure 47: Layout of the AWAKE experiment with the spectrometer in the lower right corner. The image in the top right corner shows an accelerated electron bunch as acquired from the scintillating screen of the spectrometer.

BE-OP Group

Contrary to Linac2, where the PS Booster section played a more front-line role in terms of operation and BE-ABP was responsible for the operation of Linac2, Linac4 was handed over in 2018 from the BE-ABP group, responsible for the Linac4 project, to the BE-OP group that is now is responsible for its operation.

Besides many preparatory activities and a workshop "Linac4 towards operation", where the aim was to review the readiness of the Linac4 for operation post-LS2, the PS Booster section organised and manned the Linac4 autumn reliability run. The aim of this reliability run was to increase the Linac4 beam quality, performance and availability, but also to address all operational aspects before the post-LS2 restart as new first accelerator in the CERN LHC proton injector chain, replacing Linac2 that has provided excellent service for 40 years.

Main results of the Linac4 autumn reliability run

After a summer break during which several upgrades were implemented, Linac4 was running continuously with beam from 1st of October until 7th of December 2018. The main goals of this run were to improve the Linac4 reliability and the beam quality and to prepare Linac4 for its operation as injector for the CERN proton accelerator chain after LS2.

Concerning the availability numbers, faults were suspended during nights and week-ends if piquet/specialist service was needed (no piquet service available yet for Linac4). Thanks to several improvements after the start of the reliability run, the Linac4 availability reached 94.1% in average throughout the entire period (see Figure 48).

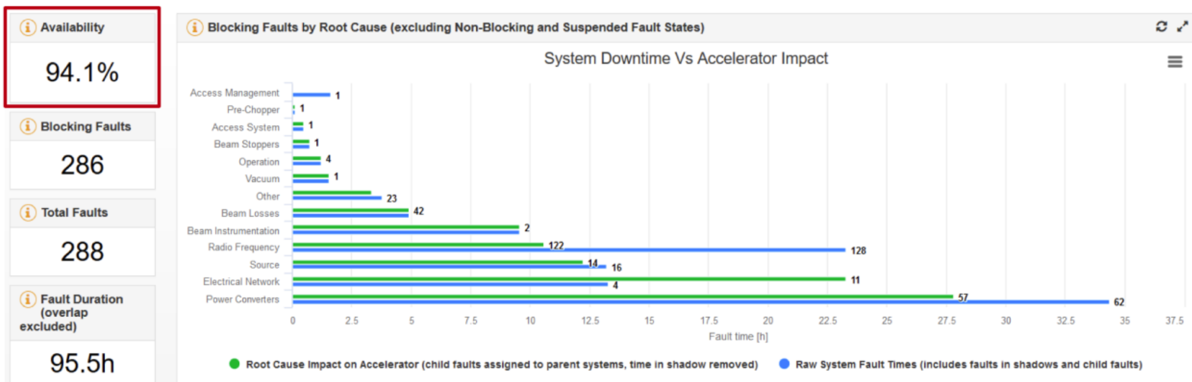


Figure 48: Fault distribution and Linac4 availability extracted from AFT for the Linac4 2018 autumn reliability run.

Thanks to the excellent collaboration with the various groups involved, Major steps ahead could also be made concerning the beam quality. As shown in Figure 49, beam currents reaching 25 mA could be achieved at the end of the Linac, practically loss-free from 3 MeV along the accelerating structures.

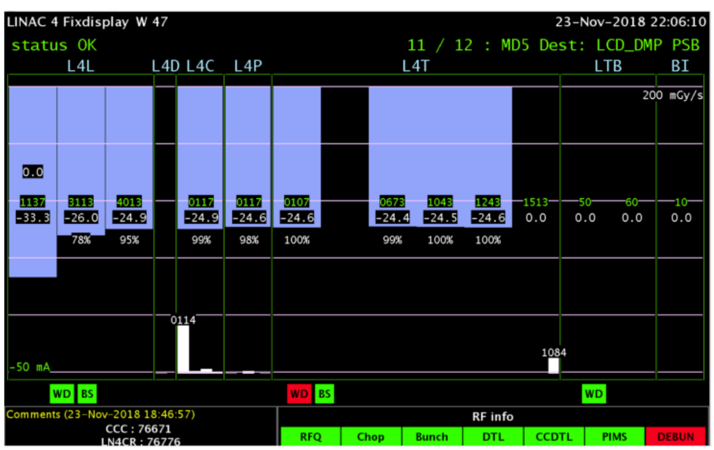


Figure 49: Linac4 current measured by beam current transformers from the source to the Linac4 dump.

The pulse flatness could also be improved considerably, as can be seen in Fig. 50 for the longest possible Linac4 pulse of 600 µs, required to produce high-intensity beams like ISOLDE after LS2 with the current source performance.

Stripping foil tests were conducted at a specific test stand to probe different stripping foil materials in order to choose the optimum foils for the PSB injection point for the new post-LS2 charge-exchange injection. The run was also used to prepare operational applications and to test multi-user operation.

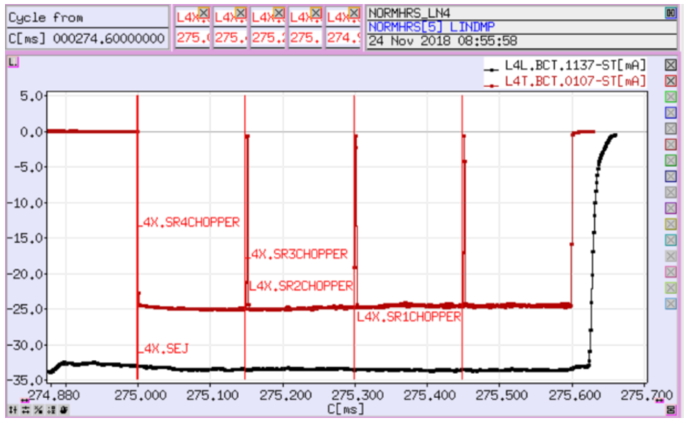


Figure 50. Linac4 beam current of 25 mA for each of the four PSB rings (red curve; 150 μs per ring)

In addition, the transverse emittance could be measured at Linac4 exit and corresponds to the expected values. The phase spread could also be determined and some beam loading effects from the cavities were visible, which will be improved by implementing additional low-level RF loops, to be tested during the 2019 LBE line run.

The 2018 Injectors Schedule

The 2018 run was the final run before the start of LS2, during which the LHC Injector Upgrade (LIU) project will be deployed. Besides the production and delivery of the large range of different types of physics beams an impressive amount be machine development studies had to be completed in order to be able to conclude on some of the studies required for the LIU deployment. As for every run the majority of the Wednesdays were allocated to dedicated MDs. However, with the aim to produce more protons for the SPS North Area, a stricter schedule had to be applied for the parallel MDs in the SPS. Therefore the concept of a parallel MD days was introduced on Thursdays, allowing for scheduled MD cycles in the super cycle in addition to the physics production cycles, but accepting a reduced duty cycle, while minimizing the parallel MDs during other days, nights and weekends.

The Injectors schedule in **Error! Reference source not found.**1 illustrates the re-commissioning period of the injectors starting with the Linacs followed by the PS Booster, PS and SPS. The first physics beams for the setting up of ISOLDE, PS East Area and nTOF became available in week 13, quickly followed by beam for the other facilities such as the SPS North Area and AD that had a delayed start due to vacuum issues. The proton run ended on 12 November with the definitive shutdown of LINAC2, celebrating at the same time 40 years of faithful service.

The AWAKE and HiRadMat runs were scheduled according to the needs while the COLDEX and UA9 runs were scheduled such that they would not impact on the SPS North area physics time.

The 4-week ion run for the LHC started on 4 November and the 4-week ion run for the SPS North area started one week later on 12 November. In order to prepare the ion beams throughout the injector chain and increase further the its performance for the LHC the LEIR machine started taking beam already on 16 April, allowing for advanced studies mainly in LEIR and the SPS.

Monday morning at 06:00 the beam stoppers were entered, announcing the start of LS2.

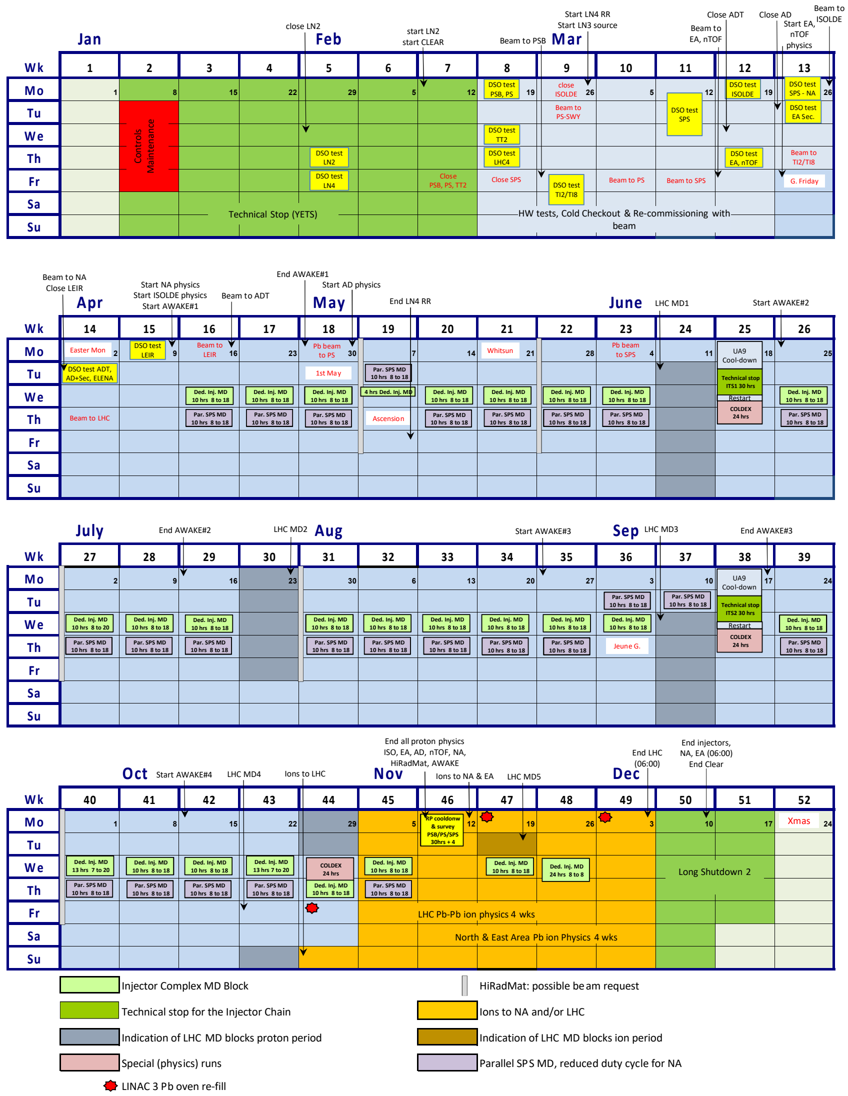


Figure 51. Injectors Schedule for 2018 version 1.6.

Technical Infrastructure

During 2018, the technical infrastructure operation team coordinated 98 major events as well as 121 minor events (Fig. 52).

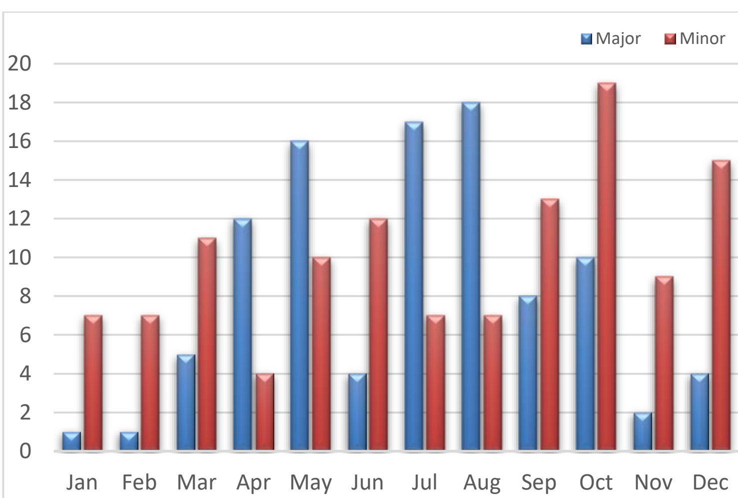


Figure 52: Distribution of minor and major events by month.

A year rich in events with a higher proportion than other years in terms of floods and climate related events, affecting both the accelerator complex, experimental infrastructures and tertiary buildings. These interventions were managed jointly by the TI operator, firefighters and standby services from the various groups and departments. It should be noted that the consolidation of the sumps performed by EN/CV has resulted in a considerable improvement of the situation.

From the electrical point of view, 32 electrical disturbances, resulting in a major or minor event were recorded. This represents an increase compared to the other years. However, the overall impact on the accelerator complex has decreased thanks to measures put in place. Other incidents related to technical failures had more significant impact on the accelerator complex and its associated equipment. The explosion of a transformer on 13 April at point 5 of the LHC is one of these incidents. The repair was an example of very good coordination between the various on-call services with as result a complete change of the transformer in less than 8 hours.

As in previous years and despite the protections put in place around some of the electrical stations, the visit of animals has hindered the smooth progress of the operation on 17 April at 22:30h. The EHT1 400kV/66kV transformer stopped due to a ground fault of 1400 A, caused by a weasel (Fig. 53). After the animal was removed by the fire brigade and the electrical installations was repowered, the accelerator complex was restarted in only a few hours during the night. Figures 54 and 55 illustrate some of the more serious water leaks in the different buildings.

Figure 53: Weasel in the electrical station.

Figure 54: Water leak in SF8.

Figure 55: Water leak in EHN1.

All service desk interventions are recorded as maintenance orders (ODM). For 2018, a total of 8212 troubleshooting requests were created by the TI operators. Of these 8212 requests, 1880 repairs were carried out by the TI operators themselves, either on site or remotely via the supervision tools that are continuously being developed and updated. Figure 56 illustrates the distributions of these ODMs by service.

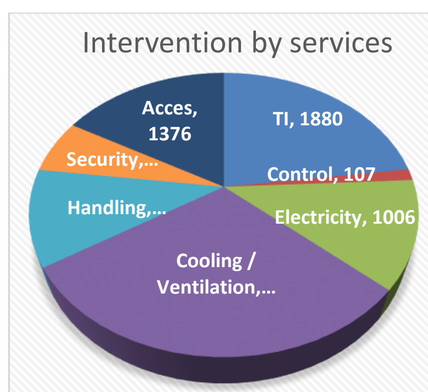


Figure 56: The distribution of the ODMs by service.

In order to reach the different intervention teams, one of the most important tools is the telephone. In 2018 a total of 53,217 incoming calls and 29,146 outgoing calls were registered which gives an average of 225 calls per day. This large number is directly related to the number of alarms received from the infrastructure equipment (cf. Fig. 57). In 2018 a total of 475,871 alarms were received, of which 94% come from electrical systems.

Towards the end of the year, the Technical Infrastructure operation changed face, the accelerator complex was stopped to start LS2 and the TI operation was reinforced with a second operator on shift to handle the increased work load due to all interventions in and around the accelerator

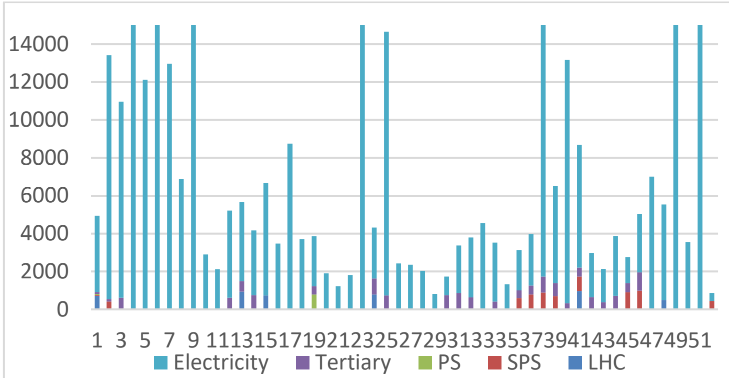


Figure 57. The number of alarms received per week.

complex. The goal for LS2 is to allow smooth maintenance and work on the equipment while ensuring the safety of all. In addition, access to the accelerators are managed in close relationship with the coordination team.

Linac2 and PSB

Two main events marked 2018 operations by the PSB section members and the PSB supervisors: the upcoming LS2 and the hand-over of Linac4 operations from the BE-ABP group to BE-OP-PSB.

As 2018 was the last beam production year before the long shutdown, which will result in a PSB renewed almost from its roots, it implicated a vast program of machine developments to provide all necessary beam studies, of commissioning and reliability runs for equipment installed ahead of LS2 and of reference measurements towards the end of the year. All of this of course in parallel to the delivery of physics beams to all downstream machines and experiments with highest possible availability and beam quality.

In addition, the PSB section was organising and manning the Linac4 2018 autumn reliability run, aiming at increased Linac4 beam quality and availability before the post-LS2 restart as new first accelerator in the CERN LHC proton injector chain, replacing Linac2.

PSB availability during 2018

2018 saw a small decrease in overall PSB availability from 97.2% during the 2017 run to 95%, which can be explained by a few long-lasting faults. 565 faults blocked operation during 2018,

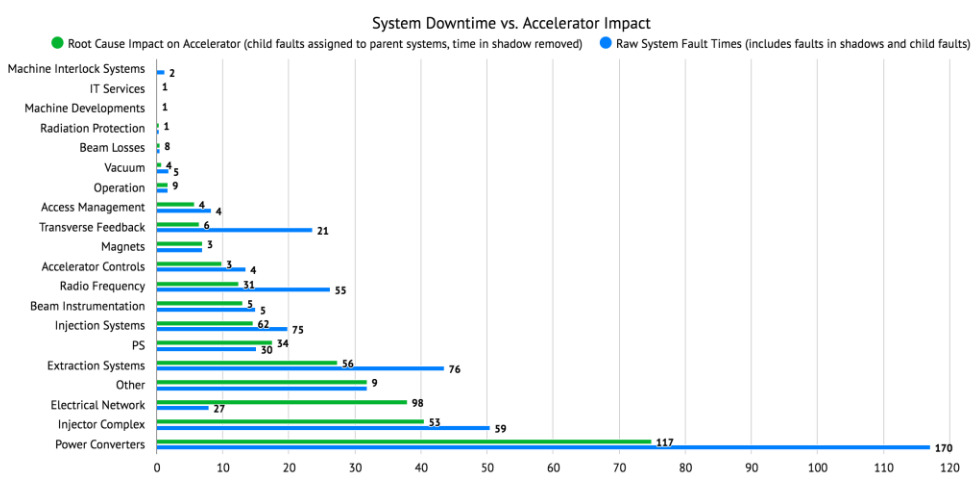


Figure 58: Downtime by system for the 2018 PSB run.

with power converters corresponding to most of the downtime (Figure 58). The weekly machine availability for the destinations PS and ISOLDE are shown in Figure 59.

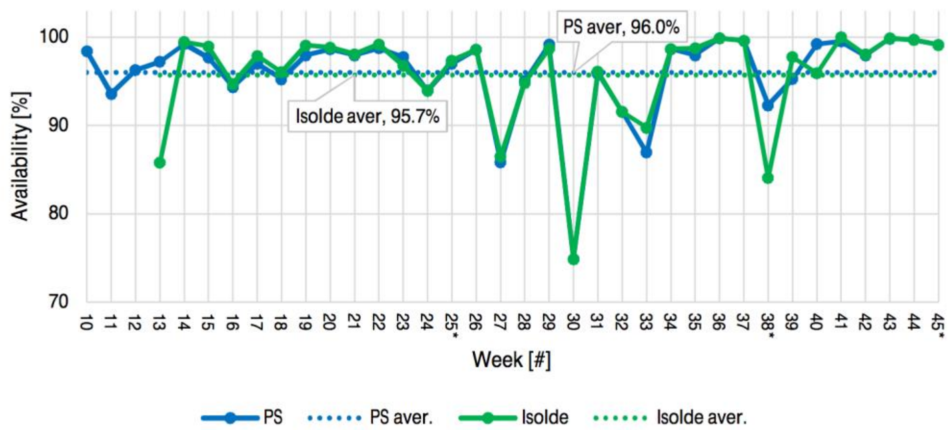


Figure 59: Weekly availability of the PSB split up by destination.

PSB Highlights

Throughout the 2018 run, the PSB delivered all proton beams to the downstream machines and experiments, maintaining and optimising about 65 operational beams and ~570 beams for machine studies. The biggest fraction of the protons was sent to the two ISOLDE targets, HRS and GPS, amounting to $> 10^{20}$ protons, $\approx 5 \times 10^{19}$ protons to the PS and $> 10^{19}$ protons to the PSB dump for beam setting up and studies. The proton share for the LHC was only 0.2%, but the LHC beams required very strict follow-up of its beam quality throughout the year. The brightness of the LHC beam is one quality factor, and Figure 60 shows the evolution of this parameter along the year for the four PSB rings.

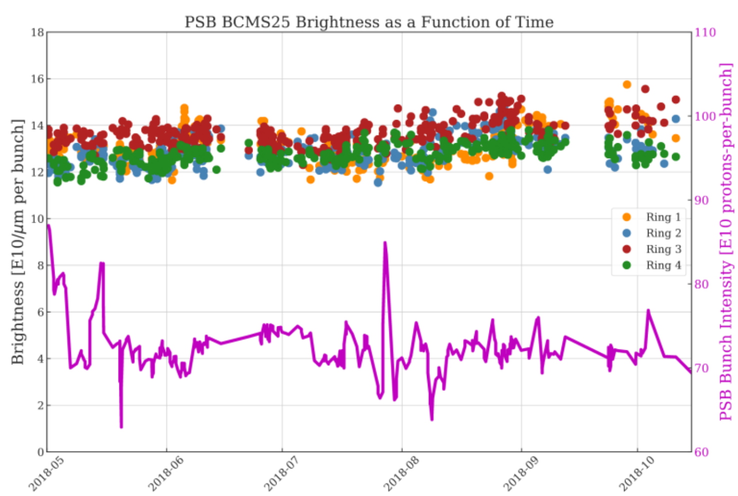


Figure 60: PSB bunch intensity and brightness evolutions for the four PSB rings along the year for the LHC production beam (BCMS25).

Once more the prototype Finemet® system was extensively tested throughout the year; the cavity and its controls were used with 100% availability from 07/08 until 29/10 for a reliability run on ring 4 for the ISOLDE production beams. In addition, various tests were conducted, one example being injection synchronisation studies for the bunch-to-bucket transfer from the Linac 4 160 MeV beam to the PSB after LS2. Other important subjects concerned controlled longitudinal blow-up studies using band-limited RF phase noise compared to the operational high-harmonic blow-up, for which a successful reliability run took place for the BCMS25, LHC25 and MTE beams. An example for the blow-up along the PSB cycle for a BCMS25 beam is shown in Figure 61.

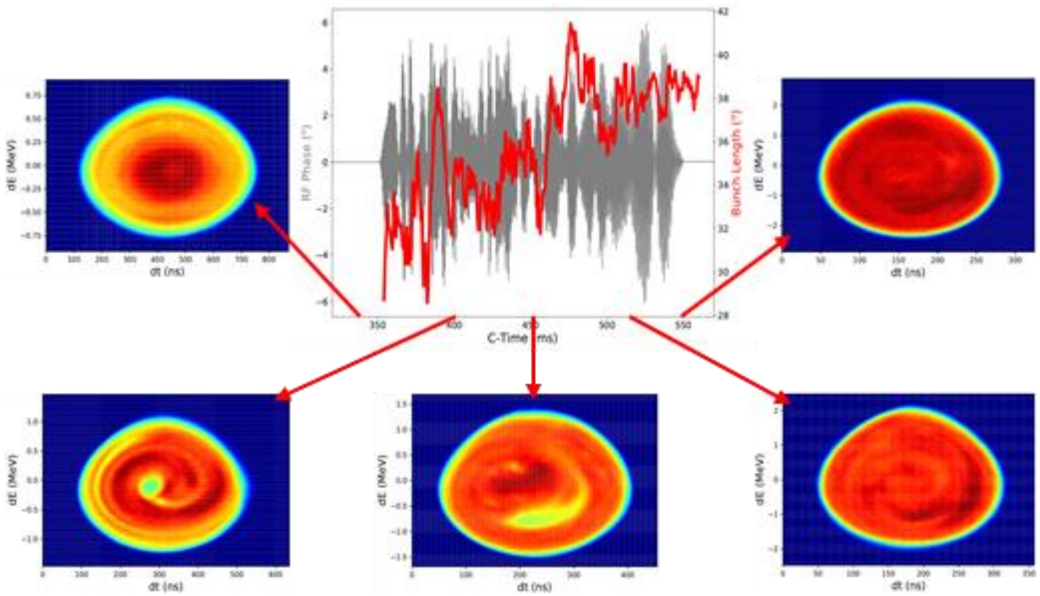


Figure 61: RF phase modulation along the PSB cycle and corresponding longitudinal particle distribution.

In the transverse plane, a multitude of machine development sessions prepared the road to the post-LS2 era, for example optics studies, tune scans for all rings to identify and cure machine resonances, transverse emittance studies to better understand systematic effects of the measurements etc.

Other important milestones concerned the successful commissioning of the new Transverse Feedback system and the new White-Rabbit B-train system – for the latter a reliability run took place as well, accelerating all beams with the White-Rabbit protocol since mid-July.

Towards the end of the run, everybody contributed to collect reference measurements for representative beams and most systems, and in case of the PSB this will be historic data at the same time, as it was the last year with 50 MeV proton beam injection from Linac2.

PS

The start-up of the Proton Synchrotron after the 2017-18 YETS was smooth and rapid. The 2018 run being the last one before Long Shutdown 2, both the physics and Machine Development (MD)

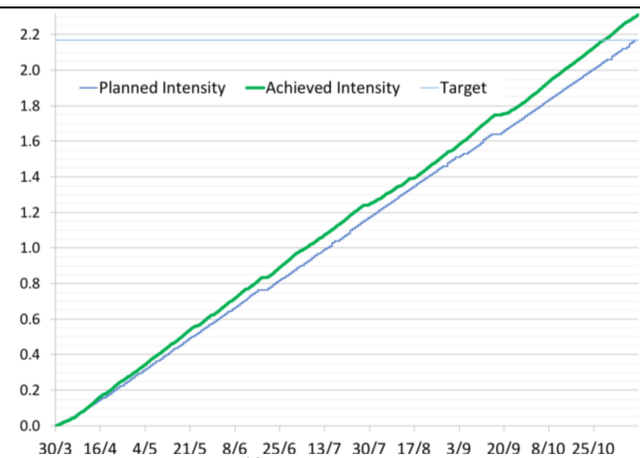


Figure 62: Integrated number of protons ($\times 10^{19}$) sent to the nTOF target throughout the 2018 run.

programs were very dense.

As LHC injector, the PS delivered on a reliable basis the different flavours of beams and thus contributed to the successful LHC run. A new production scheme for the BCMS beam was deployed successfully. The main proton user, the nTOF facility, received $2{,}31 \times 10^{19}$protons on target, a figure 6.4 % higher than theoretically predicted (Figure 62). A new magnetic cycle helped to reduce beam loss along the cycle. The PS also delivered protons and ions to the East Area, the Antiproton Decelerator AD and to the downstream Super Proton Synchrotron.

On the Machine Development side activities were driven by the commissioning of newly installed equipment in the frame of the LHC Injectors Upgrade (LIU) project, as well as a wealth of theoretical studies. New diagnostics such as a turn-by-turn injection matching monitor, a beam gas ionization monitor and a new-generation wire scanner were commissioned and already used. Figure 63 shows the horizontal beam profile measured with the new Beam Gas Ionisation Monitor (BGI).

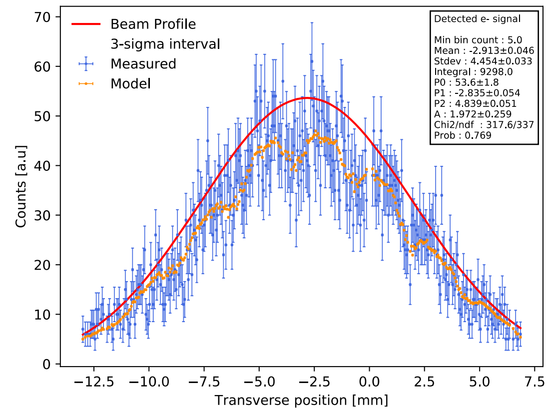


Figure 63: Horizontal beam profile measured with the new Beam Gas Ionisation Monitor (BGI).

Use of the Accelerator Fault Tracking (AFT) tool allowed both to extract the overall statistics as well as to assign faults to the various subsystems and ensure follow-up. In summary the overall availability of the PS machine during 2018 is found at a very good value of 90.5% (Fig. 64)

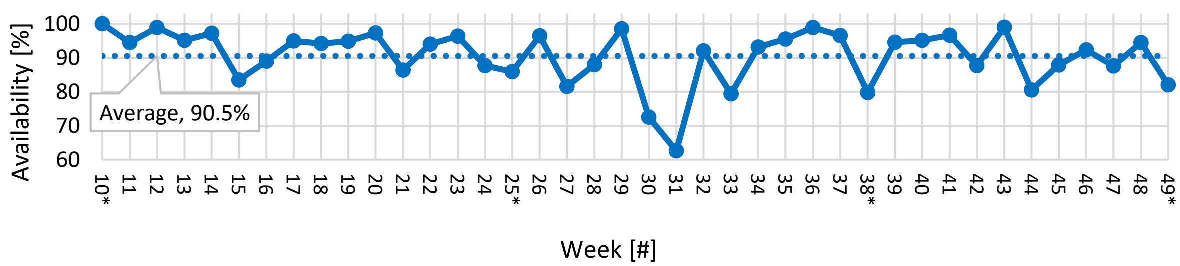


Figure 64: Availability of the PS throughout 2018 and the average value.

The PS was switched off on 19 December 2018 to enter into Long Shutdown 2 where this now 60 year old machine will undergo massive upgrades in order to prepare it for LHC Run 3 and the High-Luminosity LHC (HL-LHC) era.

AD

2018 was a very important year for the AD, not only due to the demand for high quality $\bar{p}$ (antiproton) beams by the experimental community for their final year of physics before LS2, but also for supplying $\bar{p}$s to ELENA, the latter being crucial since the decision whether to install the new AD-ELENA transfer lines was depending on a successful ELENA beam commissioning.

The first $\bar{p}$ beams were delivered for physics on the 30th of April, 3 weeks later than initially foreseen. This was mainly due to a vacuum leak in one of the injection kicker tanks, a lengthy commissioning of the new FGC63 power converter controls and a small water leak at the production target cooling system.

As well as supplying beams to the ATRAP, ALPHA, ASACUSA, AEGIS and BASE experiments during 8-hour shifts, the schedule also included three morning shifts per week for ELENA commissioning. This was initially planned for the first half of the run but was later extended to continue until the end of the year.

Running with good performance and beam quality, AD was interrupted several times by machine problems. Three periods with significant down time can be mentioned in particular:

- 15 – 24 June: A fire in the Magnetic Horn power supply in a surface building was caused by a faulty HV junction box in the target area, this was replaced by a recently constructed spare unit.
- 23/7 – 9/8: The electron cooler electron beam collector sprung a water-to-vacuum leak and was replaced by the spare unit. After bake-out of the cooler AD could be restarted and physics resumed after fine-tuning.
- 6/9 – 11/10: A new, smaller, water-to-vacuum leak appeared in the recently installed e-cooler collector. Du to non-availability of a spare unit, several unsuccessful attempts to repair in-situ were done. As soon as the unit removed in July was repaired, vacuum was broken again for installation. AD could then re-start after being down for over a month.

The target water cooling leak gradually worsened over the year, which prompted the operators' teams to somewhat reduce intensity of the primary proton beam. Finally, towards the end of the run, the cooling system was converted from water to air as cooling medium and after improvements in the PS, full intensity could be restored i.e. 1.5×10^{13} protons on target. The final weeks saw excellent AD efficiencies with a peak number of extracted 3.95×10^{7} $\bar{p}$ per cycle.

Overall, the AD beam availability over the year was down to 65% of the scheduled 4700 hours. Nevertheless, ELENA beam commissioning was successful and progress was made on the physics side.

Immediately after turning off the machine as planned on 12th of November, dismantling started in many areas. Both AD consolidation (ring magnets, target area, etc.) and replacement of the AD ejection lines with new electrostatic lines from ELENA to the experimental area will take place throughout LS2.

Figure 65 shows the intensity of extracted beam over the year. Note the 3 long down-time periods, the lower intensity during the summer (target cooling) and the higher intensity during the last weeks (full proton beam intensity)

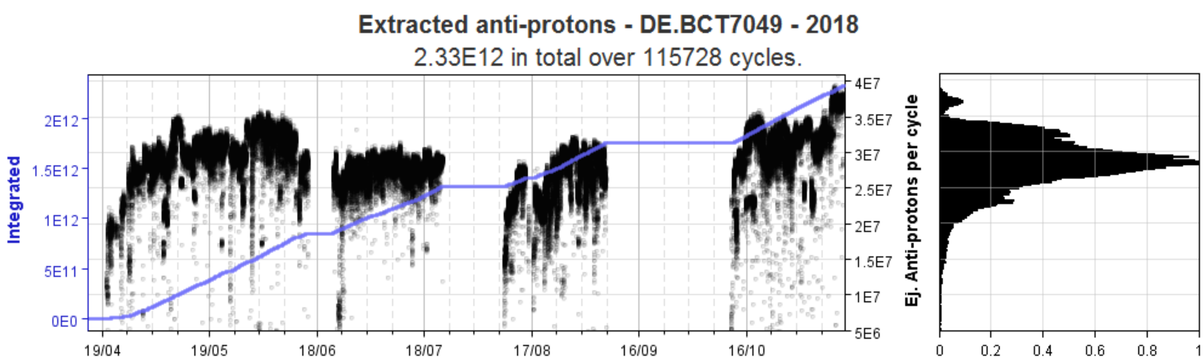


Figure 65: Intensity of extracted beam over the year. Note the 3 long down-time periods, the lower intensity during the summer (target cooling) and the higher intensity during the last weeks (full proton beam intensity).

SPS

In 2018 the SPS ring was closed on 23 February and first beam was in the machine on the 16 March. Fixed target physics started on 9 April and the first beam was injected into the LHC 30 March (pilot beam). AWAKE setting up started on the 17 April with first beam to AWAKE on the 27 April. Ten HiRadMat experiments with up to 288 bunches extracted with bunch intensities of typically 1.2×10^{11} protons were executed. Six experiments were CERN internal and four external. The scheduling and organization of HiRadMat was even more difficult in 2018 due to a broken feed-through on ZS4. As a consequence, sparking was to be avoided under all circumstances not to lose any of the other four remaining ZS tanks. Operation with 288 bunches led to an increased spark rate. Hence 288 bunches HiRadMat could only be done standalone without FT physics in parallel. In total 7.7×10^{15} protons were delivered to HiRadMat.

The duty cycle for NA physics was much increased in 2018. It was decided to not do any parallel MDs during nights and weekends and in addition the production super cycle was modified. The cycle between two subsequent fixed target cycles was reduced to 3 Basic Periods. No beam can be taken on this cycle, it is purely there for hysteresis and to match RMS power limit on the main power supply. With this the highest integrated number of protons in the history of the NA was slow extracted from the SPS for the FT physics programme. At well over 1.2×10^{19} protons on target (POT), this represented the highest annual figure for almost two decades, since the West Area Neutrino Facility was operational. Figure 66 shows the activation in LSS2, 30 h after beam stop as a function of POT per year.

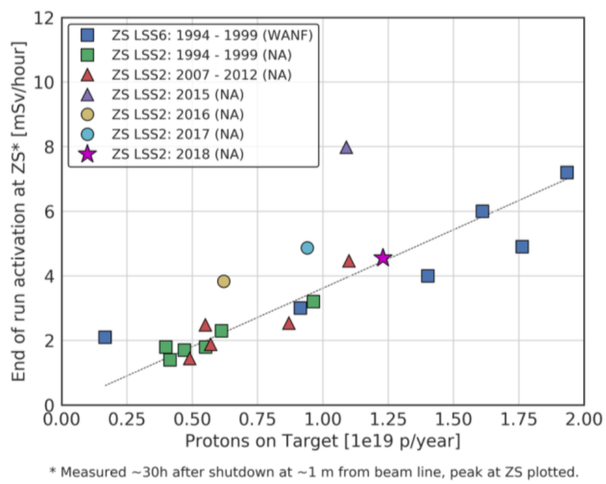


Figure 66: Activation in LSS2 30 hours after beam stop as a function of POT per year.

Figure 67 summarises the percentage of a given operation (cycle time in super cycle) allocated in time per year. MD1 is the hysteresis cycle mentioned above that follows a fixed target cycle.

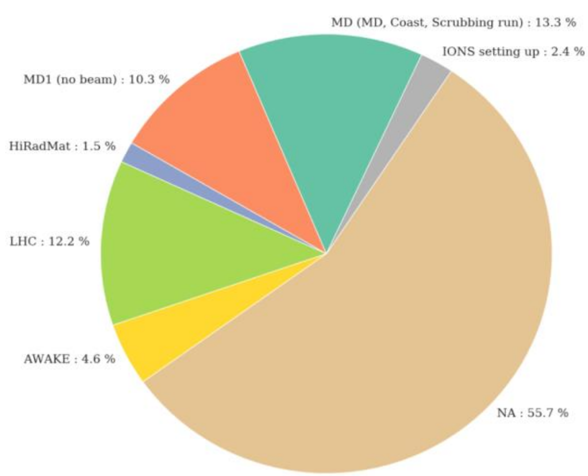


Figure 67: Distribution of different users in the super cycles in the 2018.

Despite the intensity record to the North Area, the objective of the year could not be achieved. This is due to several major break-downs, mainly affecting NA physics (ZS4 feed through breakdown, ZS high voltage cable, MBE2103 auto-transformer).

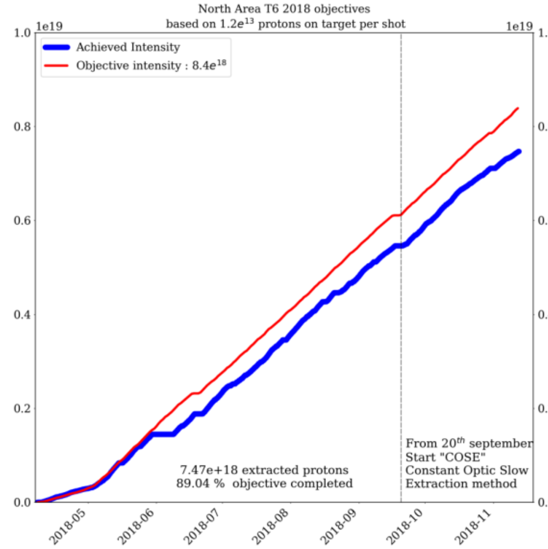


Figure 68 shows the achieved versus expected intensity on the T6 target (COMPASS).

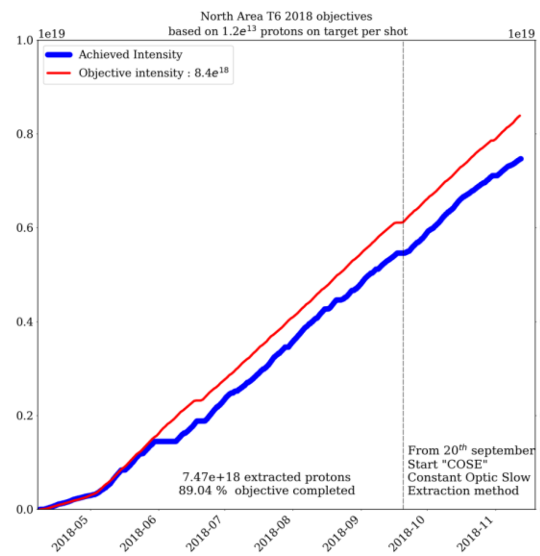


Figure 68: The planned and achieved integrated intensity on the T6 target (COMPASS).

The mean availability for 2018 for NA was 82.8 % and for LHC 92.8 %.

On 6 November, the first nominal ion beam was injected into the LHC for the LHC ion run, consisting of 9 injections with 4 bunches per injection (100 ns spacing). Later on, 14 injections with 3 bunches per injection (75 ns spacing) were used. For the 2018 LHC ion ions were run with Q26 optics in the SPS instead of Q20. The transmission in the SPS with the long flat bottom was < 55%.

The end of the proton run for fixed target was 12 November, which was followed by setting up for fixed target Pb82+ ions at two momenta (380Z GeV/c and 36.8Z GeV/c for the last week only). The run finished on 10 December.

Highlights

Progress was made on several fronts during the 2018 run. One of the big open questions for PBC projects such as ShiP, BDF was whether the losses in LSS2 during slow extraction could be reduced to be able to run with even higher numbers of POT per year (typically a factor 5 more than previously). Several concepts were studied in MD: loss reduction with diffusers and crystals as well as octupole phase-space folding to reduce the density on the ZS wires. All the proposed schemes rely however on a constant separatrix throughout the spill. With the conventional quadrupole driven slow extraction the separatrix unfortunately rotates in phase-space. The SPS team came up with a solution for this problem in the form of Constant Optics Slow Extraction or COSE. COSE was used as the operational method for slow extraction from TS2 in September. With COSE in place, a loss reduction of about a factor 4 could be achieved applying the aforementioned loss reduction techniques: bent crystal combined with octupole phase space folding to reduce the density on the ZS wires. Also, the BDF prototype target was successfully tested with beam with an adequate optics in front of the T6 target and the SHiP like super cycle.

Partially stripped ions were tested in the SPS and sent to the LHC. The highest intensities and transmission were achieved with Pb81+. Also AWAKE profited from the experiment with partially stripped ions: they used this beam to calibrate their spectrometer.

Crab cavities were successfully tested the first time with protons in the SPS in 2018 (see above).

Several mini-scrubbing runs were carried out throughout the year also partially profiting from unscheduled downtime. The efficiency of the scrubbing was monitored this time with the evolution of the emittance blow-up on the injection flat bottom (over 10.8 s). During the scrubbing run around the 3 June with high intensity of up to 2×10^{11}per bunch in 48 bunches, the emittance blow-up was reduced from 40% initially to 15% after one day of scrubbing.

Linac3 and LEIR

The LEIR machine experienced another year of improvement in performance from both extracted intensity target and stability of operation point of views. As shown in Figures 69 and 70, in 2018 it was possible to extract 10% more beam from the NOMINAL cycle and demonstrate an average stable operation above the LIU target of 9×10^{10} extracted charges during the LHC ion run.

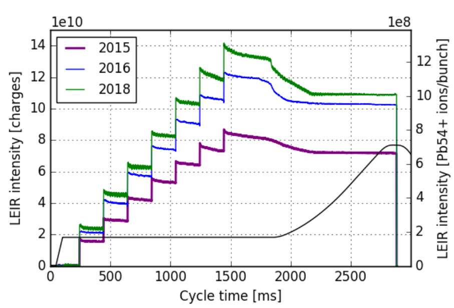


Figure 69: Pb intensity versus time for a typical NOMINAL cycle in LEIR from 2015 to 2018.

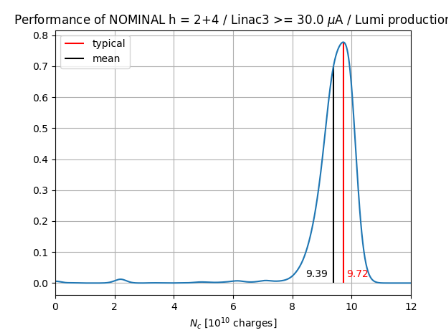


Figure 70: Statistical distribution of extracted NOMINAL intensity for LHC fills during LHC run.

This remarkable achievement was possible thanks to the strong LEIR and Linac3 team efforts done in order to better characterize the machine and to understand the dependencies on operational parameters. As an example, the LEIR longitudinal Schottky system allowed monitoring the momentum distribution after injection into the machine: the mean and standard deviation of the momentum distribution were tracked and their change correlated and corrected with the Linac3 RF settings (namely Tank2, Tank3, ramping and de-bunching cavities) in which respect the settings were optimized. This was possible thanks to the joint work of members of the BI, CO and OP groups to develop an alternative Schottky system, which allowed better integration in FESA than the present Agilent spectrum analysers.

The LEIR machine optimization was done with innovative tools developed ad-hoc to ease the machine operation: the LEIR optimizer, released since 23 May and based on Powell optimization algorithm, allowed quick injection/cooler bumps and injection line trajectory optimization. The

LEIR equalizer and autopilot, which were developed later in the year, allowed for the optimization of injection efficiency for each of the seven Linac3 injections into the machine. These tools allowed for a faster performance recovery in case of unexpected performance drifts and were essential during the LHC run. Further development was done on applying machine learning algorithms to the data collected by the LEIR optimizer.

A significant effort was put on understanding the source of performance degradation: thanks to the use of the newly installed BPMs in the injection line to LEIR, it was found and mitigated the large trajectory drift due to the ETL.BHN10 sensitivity to temperature; in April, the source of the machine tune ripple was identified in the XFW circuits and removed by disabling them; the effect of the stripper foils degradation on the injected beam was characterized and the observations suggest to exchange foils every 2 weeks in the future.

On the machine development side, several studies were done on impedance, space charge, electron cooling. Concerning impedance, the source of the fast transverse instability (occurring when the machine is operating without damper) was identified as being induced by the termination mismatch of the (unused) BTF pickup and with adequate matching it was suppressed. The intensity loss and emittance blow-up at capture were further analysed and IBS was also observed as a potential player together with space charge. The LEIR electron cooler was characterized with direct measurement of cooling force at different electron currents/profiles, cooling “maps” were produced versus horizontal and vertical bump position/angle, and the effect of the horizontal angle on the ion beam horizontal profile was found to be as an essential knob to improve stability and lifetime after each injection. Bunched beam cooling, as well as electron beam driven ion acceleration (dragging), were studied in order to explore a possible reduction of the losses occurring at capture, which unfortunately was not possible to achieve. Part of these studies substantially profited from the improved orbit and trajectory system made by BI. Studies were also done to extend the injection plateau to accommodate eight injections with a faster ramp rate, and on the new transfer line optics to match the PS periodic solution.

Last but not least, 2018 has seen the NOMINAL beam operating with $h = 3 + 6$, which allowed LHC to achieve 67% of the LIU target on total intensity compared to 58% for the $h = 2 + 4$ case. The machine availability with respect to PS destination during the LHC and NA61 run was excellent: respectively 95.9% and 93.7% with the largest components being the source/Linac3 and the electrical network.

BE-RF Group

Linac2

Linac2 saw its last year of successful running, was very reliable in spite of its advanced age and was officially switched of on the 12th of November 2018.

Linac4

The Linac4 RF systems saw a major debugging and completion campaign during 2018. Failing RF probes with vacuum windows inherited from LEP were replaced by new probes with coaxial feed-throughs, prototyped and tested successfully earlier (cf. Fig. 71).

Figure 71: RF probes of LEP type with ceramic window (left) and new probes with coaxial feedthrough (right).

The two LEP klystrons installed on CCDTL 5 and 6 have been replaced by one new, 3 MW klystron (cf. Figure 72), along with major upgrades of the linked RF control and LLRF systems. The gained power margin allows higher beam currents to be accelerated. The chopper high-power amplifiers were upgraded to handle beam pulse length up to 950 µs. All RF systems were tested for longer chopped beam pulses of 600 µs. The RF control system was upgraded to the latest versions of the evolving controls infrastructure and with further LLRF features and tools implemented.

Considerable effort has been invested in the development of the low-level RF systems. Kalman filters were implemented, optimized and tested on some cavities, full deployment on all cavities and further improvements will need to be implemented and tested during the LBE run in 2019 and during the 2020 start-up. Modern software tools with user-friendly interfaces are being developed in tight collaboration with OP group.

All improvements implemented led to a considerable reduction in downtime due to RF faults in 2018 and could be recorded during the 2018 reliability run, while further improvements are still on their way. But with the now acceptable availability of Linac4 after initial teething troubles,

Figure 72: The new, state-of-the-art, Linac 4 klystron (Thales version), providing 3 MW at 352 MHz.

these further improvements will address beam quality. Given that sufficient time is reserved for MDs, considerable improvements are to be expected in 2019 and 2020.

LEIR

LEIR has provided record lead ion beam intensity with the 3-bunch scheme to LHC and allowed for 75 ns bunch spacing described above. Improvements during Run 2 included modulation of the RF for a smooth recapture after cooling and an optimization of the transverse feedback.

PS

PS 40 MHz and 80 MHz operation

A major improvement for the PS RF systems was the upgrade of the 24 kV power converters for the the 40 MHz and 80 MHz amplifiers, implemented by TE/EPC during 2017-18 YETS and ready for the 2018 start-up (cf. Fig. 73, left). This was rewarded by the good LIU results described above.

Figure 73: Left: New 24 kV power converters delivered by TE/EPC, feeding the final power amplifiers of the 40 MHz and 80 MHz RF systems in the PS; right: Measured evolution of the bunch profile from 16 bunches (0 ms) to one long bunch kept in a barrier bucket (50 ms).

The use of barrier buckets in PS to reduce losses for MTE

Residual beam losses during the Multi-turn Extraction (MTE) of fixed target beams from PS are observed when the field of the extraction kickers rises while the beam is debunched. Promising beam tests were conducted towards the end of 2018 to significantly reduce these losses by means of preserving a kicker gap with a so-called barrier bucket. Using the new, Finemet® based longitudinal damper described above, a single sinusoidal RF pulse per turn is generated at the accelerating gap of this cavity, such that all particles are kept in one long bunch and a particle-free region (Fig. 73 right, dark blue zones) at the azimuthal position of the pulse. This allowed the reduction of extraction losses by more than one order of magnitude.

Combining two complex beam manipulations, namely the MTE transverse splitting and the longitudinal barrier bucket scheme, may pave the way to higher beam intensity for present and future fixed-target experiments.

SPS

SPS RF operation was smooth through 2018 – the "Accelerator Fault Tracking" system AFT testifies a remarkable availability of 99.5% through 2018. Setting up and following up operation for the standard SPS physics and LHC programs was guaranteed, in addition to participation in and support to numerous MDs that took place daily, parallel to physics. Ion beams came in many different flavours: different extraction energies, different ion species, different optics for LHC (Q20 and Q26), and different numbers of injections. Even AWAKE required a dedicated setup with stripped ions (Pb81) for the spectrometer calibration! As 2018 was the last year of operation before a Long Shutdown, particular care was given to taking "reference measurements" for standard beams to ease the next restart. Other studies include participation in crab cavity MDs, impedance measurements with long bunches, preparatory studies for slip stacking, and the 800 MHz system was used with ions for the first time.

Careful beam dynamics studies in the SPS, combining MD results and BLonD simulations, allowed optimization of the voltage program for the 800 MHz Landau system, which had traditionally been kept at a constant 10% of the 200 MHz voltage. This allowed for the first time acceleration and extraction to the LHC of HL-LHC intensity beams, limited before the full LIU upgrade of the SPS however to 12 bunches. A new online bunch length measurement system, referred to as “ABWLM” was equally commissioned in 2018.

Since Richardson Electronics had announced the end of production of tetrodes YL1440, YL1520 and YL1530, which were used in large quantity in the Philips 200 MHz system, and in connection

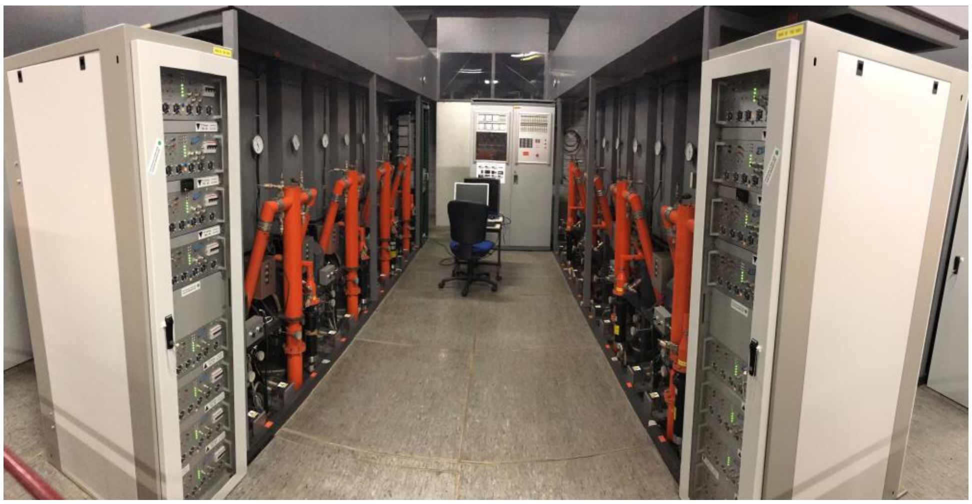


Figure 74: The new 1.25 kWp SSPA Driver amplifiers TTi Norte (Spain) in operation in the Philips 200 MHz system.

with LIU (see above), all drivers had been upgraded to solid-state drivers (cf. Fig. 74), which operated reliably through 2018.

AD

The amplifiers for the decelerating RFQ in ASACUSA were dismantled by the end of 2018 to provide space for the modifications of the experiments in view of the commissioning of the new ELENA machine.

Consolidation in AD continued with preparations of the upgrade of the analogue LLRF system to the CERN standard digital system for small synchrotrons. For the stochastic cooling system, a notch filter with optical fibre delay was successfully tested with beam. At the end of the 2018 run, the entire power system of the stochastic cooling was removed from the AD roof shielding blocks to gain access to the machine for magnet consolidation and a modification of the shielding walls. Careful measurements were carried out to ensure a smooth reinstallation in 2019.

BE-ICS Group

The connection of Linac 4 to the PS complex requires several modifications of the PS Personnel Protection System. In November 2018, the current Access Point located in Linac 2 was dismantled and relocated to the new extended switchyard safety sector. The connection of Linac 4 also required the definition and preparation of new Important Safety Elements to protect the Booster and the Switchyard and a safety requalification of the PS Personnel Protection System.

ELENA

BE-ABP Group

The main activity during the year was the installation of the electron cooler followed by the completion of ELENA ring commissioning with antiprotons from the AD and H^- ions from the dedicated source.

Contrary to initial plans, most of the progress has been made with antiprotons from the AD. In spring and early summer, work concentrated on setting up and optimizations of the magnetic cycle with careful measurements and corrections of the closed orbit and evolution of the working point and setting up of the RF system. A long-standing issue was a significant beam loss along the second decelerating ramp from an intermediate energy close to the final energy of 100 keV. With careful adjustments based on observations or empirical and, in particular coupling, allowed to reduce this loss, but not to supress it completely even with electron cooling at the intermediate plateau. Later on, the electron cooler has been commissioned and electron cooling of antiproton beams has been both at an intermediate plateau and at the final extraction energy of 100 keV. Bunched beam electron cooling prior to extraction to generate short bunches with sufficiently small energy spread required by the experiment has been set up successfully. At the end of the run, beam characteristics, although not yet nominal, clearly improving the conditions for the experiments have been obtained. Whereas nominal longitudinal beam characteristics have been demonstrated, the transverse emittances were still larger than expected and the overall efficiency lower than nominal.

Antiproton and H^- ions beams have been delivered in summer and autumn to the GBAR experiment, the first ELENA user.

At the end of the year, preparations for the installation of the electro-static transfer lines from the ELENA ring to the experiments in the old experimental zone started immediately after the end of the AD antiproton run with the dismantling of the magnetic AD extraction lines.

BE-BI Group

Electron cooler in operation

The installation of the electron cooler in the ELENA ring was completed in January 2018. Unfortunately, after the bake-out, a vacuum leak appeared on a feedthrough of one of the beam position monitors. A complete dismantling of the device was required to replace the faulty element, after which a second, successful, bake-out was made. As the vacuum level in the cooling section improved, the power supply connections to the magnets were completed and by early May all circuits were tested and ready for powering tests.

For the first stage of commissioning, perturbations due to the magnetic system of the cooler had to be compensated. The closed orbit distortion and transverse motion coupling were corrected using compensation solenoids and corrector magnets installed on either side of the electron cooler. Over the following weeks electron beam conditioning was performed during nights, when the sector vacuum valves could be closed, to ensure that the initial outgassing from the cooler did not pollute the rest of the ring. Operational values of 355 eV/5 mA and 55 eV/1 mA were quickly

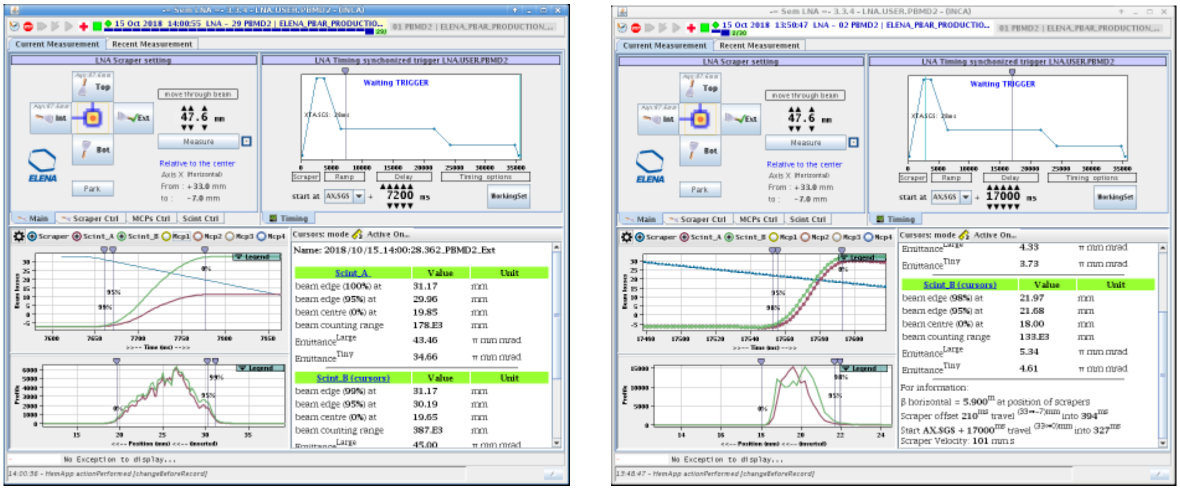


Figure 75: Horizontal emittance measurement of the circulating antiproton beam at 648 keV before (left) and after (right) 4 seconds of electron cooling.

obtained with electron beam collection efficiencies better than 99.99%.

First signs of cooling were visible on the bunched beam signals during deceleration between the two cooling plateaus; the enhancement of the signal level in the BPMs indicating an increase of the phase-space density of the re-captured beam. After some adjustment of the alignment between the circulating antiproton beam and the cooling electrons, both transverse (Fig. 75) and

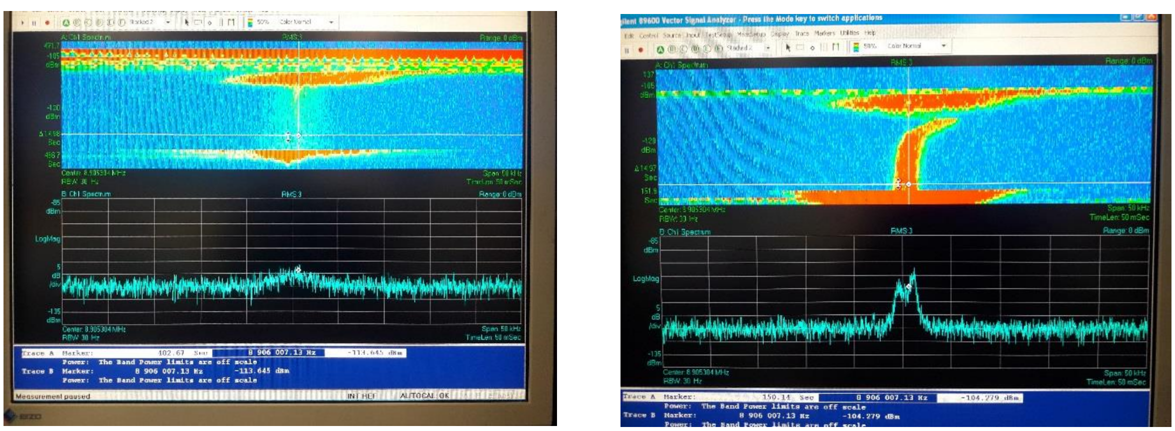


Figure 76: Longitudinal Schottky signal of uncooled (left) and cooled (right) antiproton ($\bar{p}$) beam at 648 keV.

longitudinal cooling (Fig. 76) was observed on both cooling plateaus, confirming the excellent performance of the device.

BE-OP Group

2018 has been a fruitful year for ELENA commissioning, started end of April after the completion of the ring installation with the insertion on the electron cooler. To optimize the commissioning time without impacting too much the physics program of the AD machine, 3 shifts per week were planned to send the 5.3 MeV antiprotons ($\bar{p}$) from AD towards ELENA, and use the rest of the time the 100 keV H^- provided by the dedicated source installed into the ELENA zone. Significant progress have been made during the first part of the year, with the first $\bar{p}$ beam arriving on the 100

KeV plateau end of May, the first observation of longitudinal and transverse beam cooling beginning of July and the first extraction to Gbar experiments on the 20 July.

The progress was slowed down throughout the year by the unavailability of both $\bar{p}$ from AD and H^- from the source. 2018 was a very bad year for AD with a beam availability down to 65% because of issues with the electron cooler collector and a leak on the target, reducing the commissioning time with $\bar{p}$ when most of the progress were made. As a problem never happens alone, the H^- beam was available at 100 keV until end of May, but then the beam energy had to be reduced to 85 keV after a breakdown of the HV insulation transformer. To allow continuing setting-up despite the lower energy and the source instability, a full acceleration cycle has been set up with H^- (cf. Fig.

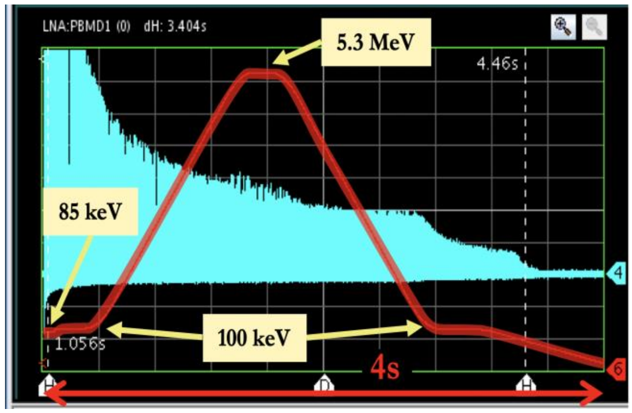


Figure 77: H^- acceleration cycle.

77), allowing optics studies, beam instrumentation tests and extraction of H^- to Gbar at 100 keV. Progress with H^- was stopped end of September with another breakdown to the HV insulation transformer stopping source operation for the rest of year.

Optimization of the $\bar{p}$ cycle went on after summer in parallel with the Gbar shift, allowing optimizing the transmission over the cycle, to set-up the RF gymnastics along the cycle, fine tune the e-cooling on both plateau. At the end of the run in November, ELENA commissioning stopped with an almost nominal cycle (cf. Fig. 78) and very close to nominal beam parameters: deceleration

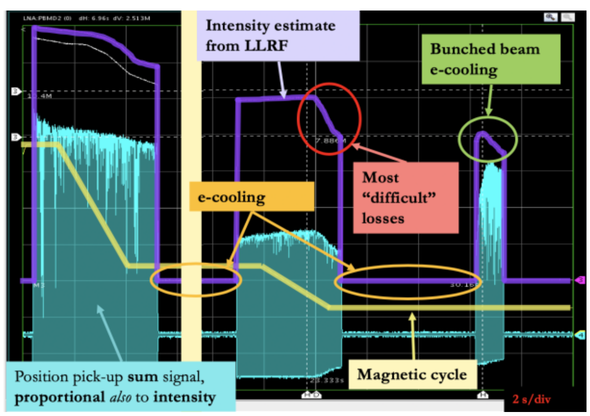


Figure 78: Nominal cycle for antiprotons.

efficiency of 50%, a clear emittance reduction in all three planes due to electron cooling (up to 80% in transverse plane), production of four bunches on extraction plateau and very good reproducibility. These good results despite the little beam time available gave confident that ELENA can improve the conditions for AD experiments and connect of all AD experiments to ELENA during LS2 has been approved at the end of the year.

BE-RF Group

Elena commissioning continued with new features implemented in the LLRF systems including the extraction synchronization. Beams of decelerated antiprotons were for the first time delivered to the Gbar experiment. A magnetic pick-up for the LNE50 transfer line was used for the measurement of the extracted beam intensity.

COLLIMATION PROJECT

BE-ABP Group

The proton cleaning performance of the LHC collimation system throughout Run 2 is shown in Fig. 79. Data from the validation loss maps done regularly in each operational year are used to generate this graph. In 2018, the system produced in both beams and planes cleaning inefficiencies

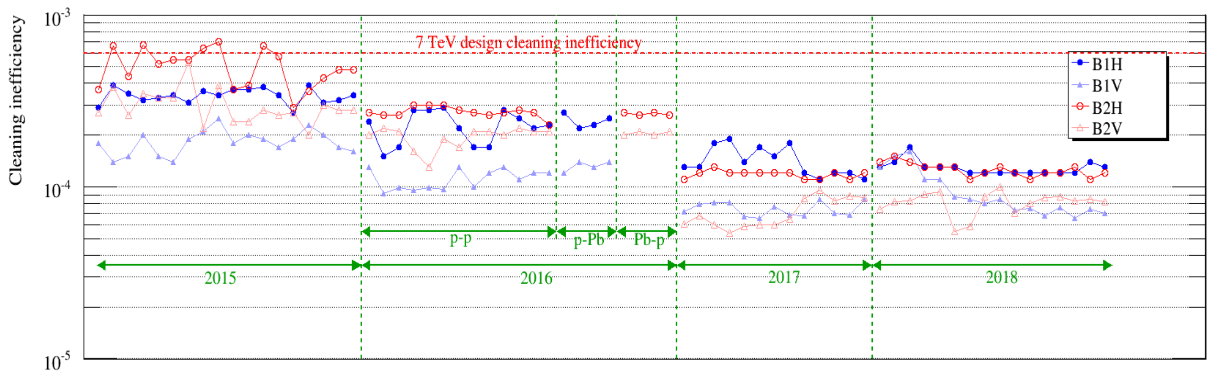


Figure 79: Proton betatron cleaning inefficiency for both beams and planes throughout Run 2.

with protons in the range of 10^{-4}, confirming the previous excellent results and enabling another year free of quenches from collimation losses with stored proton beam energies routinely up to 300 MJ. The collimation hardware and the controls systems worked with extremely high availability, being one of the systems with lowest impact on the machine downtime. The ABP collimation team followed up the system commissioning and validation efficiently for all the relevant configurations in standard operation, in special runs and in MDs. In 2018, a further improvement of the collimator setup techniques was achieved thanks to the application of machine learning to the algorithms for automated collimator alignment, which made the beam-based alignment procedure faster than in previous years. The transverse hierarchy of the collimators in IR1 and IR5 was tightened further (IR7 remained as tight as in 2017) to enable a record β^* of 25 cm, i.e. less than half of the LHC design value for 7 TeV. Collimators were part of the orchestration of various levelling schemes deployed in 2018 in preparation for the HL-LHC era. Furthermore, the ABP collimation team was deeply involved in the commissioning of the Pb ion run, where detailed simulations and experiments were used to adapt and optimize the operational collimator settings to keep all local losses at an acceptable level. This was necessary in order to handle the challenging Pb ion loss conditions, with a cleaning efficiency about two orders of magnitude worse than for protons, due to the nuclear breakup of the beam ions in the primary collimators that create a large range of effectively off-momentum nuclear fragments.

The collimation team participated also very actively to crucial MD studies, in particular to the new ATS optics developments in preparation for Run 3 and HL-LHC. This required the preparation of multiple high-intensity beam tests that entailed several dedicated collimation setup and validation campaigns. The team worked also on future developments, for example participating actively to the first tests of partially-stripped ions at the LHC.

New collimation schemes and developments were also implemented for the special run at high β^* at 450 GeV. The feasibility of this run was put in question because preparatory tests revealed critical background conditions for the Roman pot experiments in IR1 and IR5. A key ingredient to perform the run, strongly requested by the experiments, was the development of two new schemes with tight collimation that reduced, in different ways, the background by orders of magnitude. The first scheme was based on the conventional system with settings below 3σ, but with the tightest and most challenging hierarchy retractions ever of only 0.2σ, whereas the second one used for the first time the crystal collimation concept in a physics run. The two forward-physics experiments had specific constraints that favoured one or the other collimation scheme, so both were used and were instrumental for the successful completion of the run. Crystal collimation developments also continued for the high-intensity operation with ions, demonstrating for the first time a significant improvement of cleaning performance for lead ion beams at 6.37 Z TeV compared to the present system. This is an important achievement in view of the possible implementation of crystals for the HL-LHC.

The collimation project team followed up the HL-LHC upgrade that entered in full-steam production mode because the collimation upgrade starts already in LS2, with the industrial production of 20 new collimators, 16 of which will be installed in the ring and operational in Run 3. In 2018, most critical production contracts were placed and the production of the first pre-series collimator – a TCLD collimator to be installed in the dispersion suppressors around IR2 and IR7, respectively without and with new 11 T dipoles – was completed (delivery to CERN planned for January 2019). Other important developments involved the definition of a coated material for the new secondary collimators that will be installed in IR7, to prepare the LHC to the higher-brightness LIU beams. The present baseline is based on Mo-coated MoGr, which is a new material developed for the HL-LHC collimators, and improved further in 2018 thanks to the collaboration with the TE and EN departments.

The collimation team was also very active in studies of collimation systems in other accelerators. A first conceptual design was elaborated and assessed in simulations for an SPS collimation system to control beam losses and activation at injection.

REX/ISOLDE/HIE-ISOLDE

BE-ABP Group

The schedule for the REX/HIE-ISOLDE post-accelerator was extremely dense in 2018 as several experiments desired to benefit from the higher beam energies available with the HIE-ISOLDE upgrade before LS2. Among other beams, ^{228}Ra was accelerated, the hitherto heaviest element, and an energy of 9.5 MeV/u was reached for ^{28}Mg, partly thanks to the relatively high charge state provided by the REXEBIS charge breeder. Numerous shifts of stable beams from the EBIS were delivered for among other things characterisation of low-intensity detectors installed along the linac.

During the year the feasibility study on using a Penning trap–EBIS system for preparing ^{11}C for injection into a medical synchrotron was concluded. It was found that this kind of setup is not suited for low-repetition rate treatment facilities, and an alternative bunching method, possibly involving a cryogenic trap, is required. Furthermore, the practical use of dielectronic recombination resonance for manipulation of the charge state distribution within the EBIS was evaluated. For example, KLL and KLM dielectronic effects on the charge state distribution for highly charge potassium were demonstrated and excellently reproduced by simulations. The practical use of these resonance effects is however limited to few-electron systems, which translates to unwanted long charge breeding times.

In June the LaB_6 cathode installed at REXEBIS started to exhibit fluctuations in the emission current. With time the fluctuations increased in amplitude and it was decided to exchange the cathode end of August when there was a window in the experimental campaign. The removed cathode was inspected with a SEM and a clear fracture of the crystal could be observed. A new cathode of the same type was installed, but already after a few weeks it showed the identical current fluctuation symptoms. By operating the cathode at a constant moderate power it survived until the end of the run. When taken out, also this crystal was found broken at a similar place. These repeated failures underline the need for a more reliable cathode at REXEBIS. The design of a new non-adiabatic electron gun, with an aim of providing a higher electron current density, has started, and two alternative cathode types have been identified.

BE-RF Group

Phase 2b of the HIE-ISOLDE project was completed with the installation of the 4th cryomodule (CM4, see inset in Fig. 80); first beam through the full linac was achieved on the 29th May. During hardware commissioning it became clear however that Cavity 3 of CM4 had a problem with the connection to the fundamental power coupler. As a consequence, this cavity was not powered during the 2018 runs to avoid any risks of contamination. This module will be taken out, repaired and re-tested in SM18 during LS2. Most cavities reached $6\,\mathrm{MV/m}$ with a $Q > 5 \times 10^8$ – one cavity was limited by field emission to $\approx 2\,\mathrm{MV/m}$.

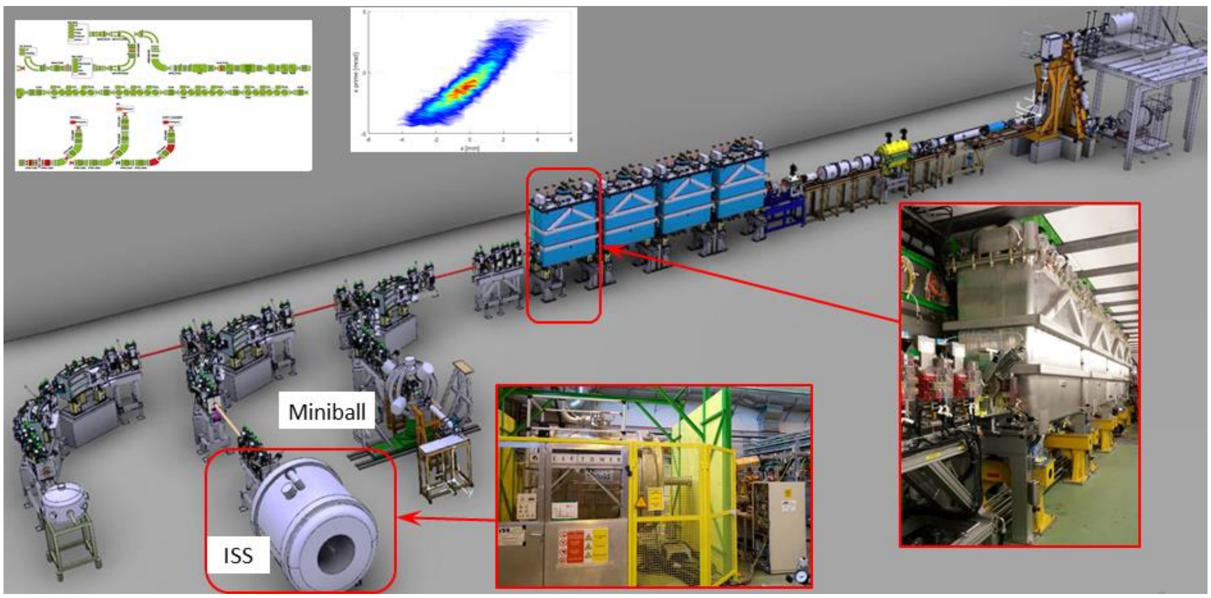


Figure 80: Layout of the REX/HIE-ISOLDE post-accelerator and most relevant developments in 2018.

BE-OP Group

The 2018 operations campaign of ISOLDE started in early March after the supply of cooling water was re-established and many of the systems in the facility could be powered-up. During that month, the machine checkout of the low-energy lines was completed. The initial beam commissioning started later that month using stable beams produced by the GPS and HRS front-ends. The low-energy Physics campaign started at the beginning of April (week 15) when the first Radioactive Ion Beam (RIB) was delivered to the CRIS experimental station. The campaign continued uninterrupted until the beginning of July (week 28). Several additional low-energy experiments were scheduled in parallel or in between high-energy experiments in the last part of the year.

In parallel, during the first half of the year, phase 2b of the HIE-ISOLDE project was completed as described above (cf. Fig. 80). Among other important tasks, the fourth (and last) cryomodule (CM4) and all its ancillary equipment was installed, the superconducting cavities were conditioned, the different systems in REX, the HEBT lines and the experimental stations (including the new ISOLDE Solenoid Spectrometer) were tested and the beam commissioning of the whole post-accelerator complex was completed.

The high-energy Physics campaign started on July 11th (week 28) when the first RIB was delivered to the Miniball experimental station. The campaign continued until Nov. 21st, a week after protons from the PSB had stopped, using a pre-irradiated target. At that point, REX/HIE-ISOLDE was stopped in preparation for the LS2. During those weeks, the thirteen experiments that were conducted required eighteen different RIBs with energies as high as 9.5 MeV/u (cf. Table 3). Beams were delivered to the three experimental stations and, for the first time, two experiments were successfully completed using the recently commissioned ISOLDE Solenoid Spectrometer (ISS). In addition, multiple stable beams were provided to test and calibrate different experimental systems throughout the whole campaign. In total, approximately 1322 hours of radioactive beams and 369 hours of stable beams were delivered to the high-energy users.

Table 3: List of Radioactive Ion Beams delivered during the high-energy Physics campaign.

Experiment	Isotope(s)	Energy [MeV/u]	Exp. Station	Time [hours]
IS644	^{96}Kr	4.7, 5.3	Miniball	178.2
IS506	^{212}Rn	3.8, 4.4	Miniball	49.0
IS552	$^{222, 228}$Ra, $^{222, 224, 226}$Rn	4.3, 4.2, 5.1	Miniball	31.3, 82.9
IS553	^{142}Ba	4.2	Miniball	38.5
IS562	^{106}Sn	4.4	Miniball	91.4
IS616	^{8}B	4.9	SEC	97.2
IS655	^{11}Be	7.5	OTPC	117.5
IS654	$^{134, 132}$Sn	7.4, 7.2	Miniball	67.5
IS651	^{28}Mg	9.5	Miniball	116.0
IS621	^{28}Mg	9.5	ISS	116.8
IS631	^{206}Hg	7.4	ISS	98.0
IS561	^{9}Li	8.0	SEC	103.0
IS554	^{7}Be	5.0	SEC	135.0
			Total	1322.3

In addition, multiple MDs were conducted during the year. Most of them were focused on the post-accelerator and many of them were related to the phase space characterization of very weak beams. During these MDs, novel techniques were developed to measure the transverse and longitudinal emittances of sub-femtoamp beams. Several software tools were also developed during 2018. Most notably, additional capabilities and improved views of the Fast Beam Investigation (FBI) software were introduced and regularly used during the operations campaign.

As seen in Figure 81, the weekly availability of the facility was typically higher than 90% (more precisely an average availability of 97.5% and 96.6% for the low-energy experiments using beams generated in the GPS and HRS targets and an average availability of 93.3% for the high-energy

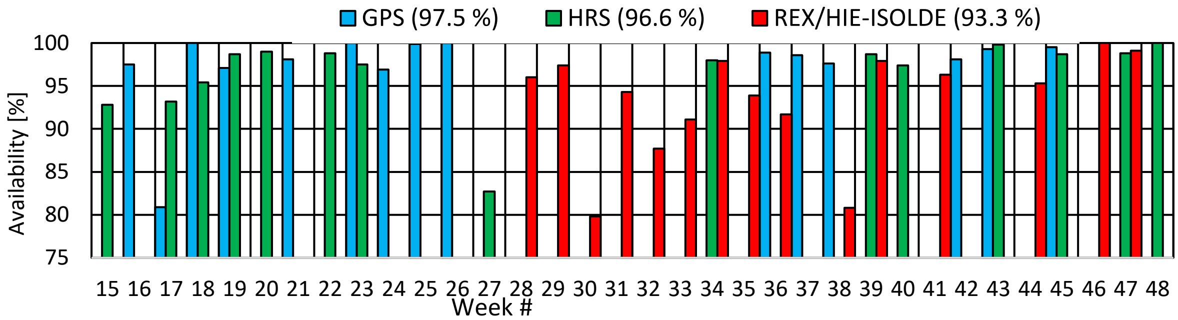


Figure 81: Availability of the ISOLDE facility by week number.

experiments). The main sources of downtime were related to two of the CERN-wide power cuts suffered during the year, occasional problems in the injection chain and trips of the superconducting cavities of the post-accelerator sometimes caused by instabilities in the cryogenics system.

CLEAR/CLIC/CALIFES

BE-ABP Group

In 2018 the CLIC study completed a fundamental milestone, with the completion of the new CLIC staged approach and its full documentation in a series of documents submitted to the European Particle Physics Strategy Update (EPPSU). In particular, the accelerator first stage at 380 GeV centre-of-mass (c.m.) energy and the subsequent upgrade path up to 3 TeV c.m. have been described in the CLIC 2018 Summary Report (CERN-2018-005-M) and the CLIC Project Implementation Report (CERN-2018-010-M), including a full costing and evaluation of the overall power consumption. The more recent technical contributions of the group to the CLIC study include the achievement in simulations of the goal tuning performances of the Beam Delivery System, with both beams and realistic luminosity signals, the identification of a proper mitigation techniques for time-varying magnetic stray fields, including a workable scheme of magnetic shielding, the consolidation of the evaluation of emittance growth from static and dynamic imperfections in the CLIC main linac at 380 GeV c.m. and the full documentation of the improved positron production scheme. The proposal of an electron beam facility at CERN for Light Dark Matter detection (e-SPS), including a 3.5 GeV linac based on X-band CLIC technology, was also submitted to the EPPSU process and documented in an EOI. The studies are now continuing towards a CDR. Another CLIC spin-off, the Compact-Light European Project, started in January and the design in now reaching maturity, with the group contributing with beam dynamics and simulation expertise in particular analysing the full X-band injector with Ka-band linearizer option.

The CLEAR facility ensured 36 weeks of operation in 2018, almost twice as much as in previous years. Since the beginning of operations in 2019, CLEAR has developed a wide and diverse user community, both within and outside CERN; a total of 26 institutes from 9 countries participated in the 19 experiments concluded so far and 14 scientific papers (6 in peer-reviewed journals) have been published. Six PhD students were as well involved in CLEAR. The main activities were: 1) high-gradient X-band studies, related to CLIC, 2) beam instrumentation R&D, with potential application on present and future accelerators, 3) irradiation of electronics components for space applications (collaboration with ESA) and particle detectors and accelerators, 4) dosimetry studies for medical applications (VHEE and FLASH cancer radiotherapy), 5) Plasma acceleration and focusing (active plasma lenses) and 6) THz radiation generation with electron beam for various applications.

In 2018 the CLEAR team made the first direct measurement of thermal aberration in an active plasma lens, finding it to be consistent with theory. More importantly, it was shown that this aberration can be suppressed using heavy gases (e.g., argon) in the plasma capillary. The use of heavy ions slows down the heat transfer, resulting in ideal, degradation-free focusing. This represents a significant step towards making active plasma lenses a workable accelerator component. Other highlights in 2018 were the intense medical dosimetry activity, which showed the possibility to control dose depth deposition by transverse focusing of the electron beam and the feasibility of FLASH irradiation tests, the development of diffraction Cherenkov diagnostics with the potential to be used to monitor beam position and bunch length, and the coherent production of radiation in the THz and sub-THz frequency range, reaching peak powers beyond the MW level. CLEAR contributed as well to the AWAKE collaboration, testing and calibrating AWAKE electron diagnostics.

BE-BI Group

Coherent Cherenkov diffraction

With the aim of developing non-invasive beam diagnostics, the emission of Cherenkov Diffraction

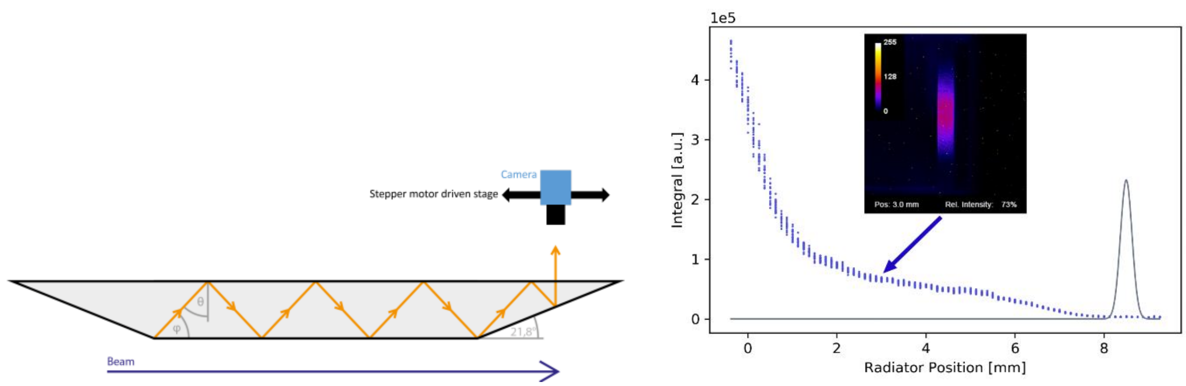


Figure 82: Sketch of incoherent ChDR emission in a long dielectric (left) and a scan of light intensity as a function of beam distance from the dielectric obtained with a 500 pC electron bunch and using a 600 nm optical band-pass filter (right).

Radiation (ChDR) has been studied during 2018 at CLEAR. ChDR appears when a relativistic charged particle moves in the vicinity of a dielectric medium. This radiation has very interesting properties, among which the emission of a large number of photons in a narrow and well-defined solid angle, providing excellent conditions for signal detection with very little background. The

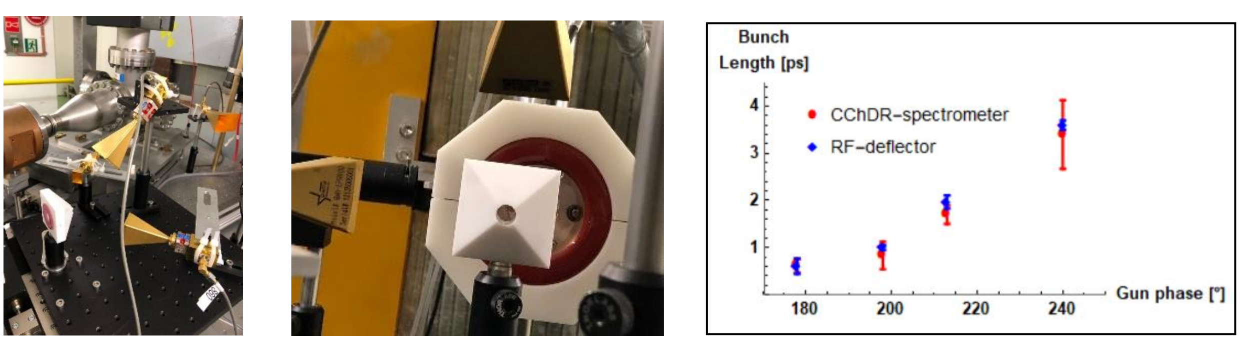


Figure 83: Pictures of the hollow pyramidal teflon radiator with 3 diodes (60, 84, 113.5 GHz) coupled with horn antennas and results comparing ChDR and RF deflector bunch length measurements.

emission of incoherent ChDR in the visible range through a long dielectric (fused silica) radiator has been investigated to monitor the beam position (see Fig. 82).

Furthermore, the observation of coherent ChDR emission in the frequency range from tens to hundreds of GHz was exploited to measure both the beam position as well as the bunch longitudinal profile. A hollow pyramidal teflon radiator (Fig. 83) was used to generate the coherent ChDR and a set of diode detectors coupled to horn antennas used to measure the emission at 60, 84 and 113.5 GHz. Measurements were acquired with bunch lengths ranging from 1 to 5 ps, and compared to longitudinal profiles measured at CLEAR with an RF deflector. The two methods showed very good agreement (see Fig. 84). This set-up was also used to test the ability of such a system to measure beam position, by comparing the output of diodes placed on opposite sides of the pyramidal radiator, with promising initial results.

BE-ICS Group

A preliminary technical feasibility and price estimations for a Personnel Protection System for both options of the CLIC was done covering all surface building, services and accelerator galleries.

BE-RF Group

X-band test stands:

The family of test facilities for CLIC prototypes working at 12 GHz was extensively used to test CLIC prototypes in view of the EPPSU. An additional test-stand was created in Xbox2 (Fig. 84, left), equipped with a new BOC pulse compressor and linearizer cavities in order to exploit the full power of the existing klystron.

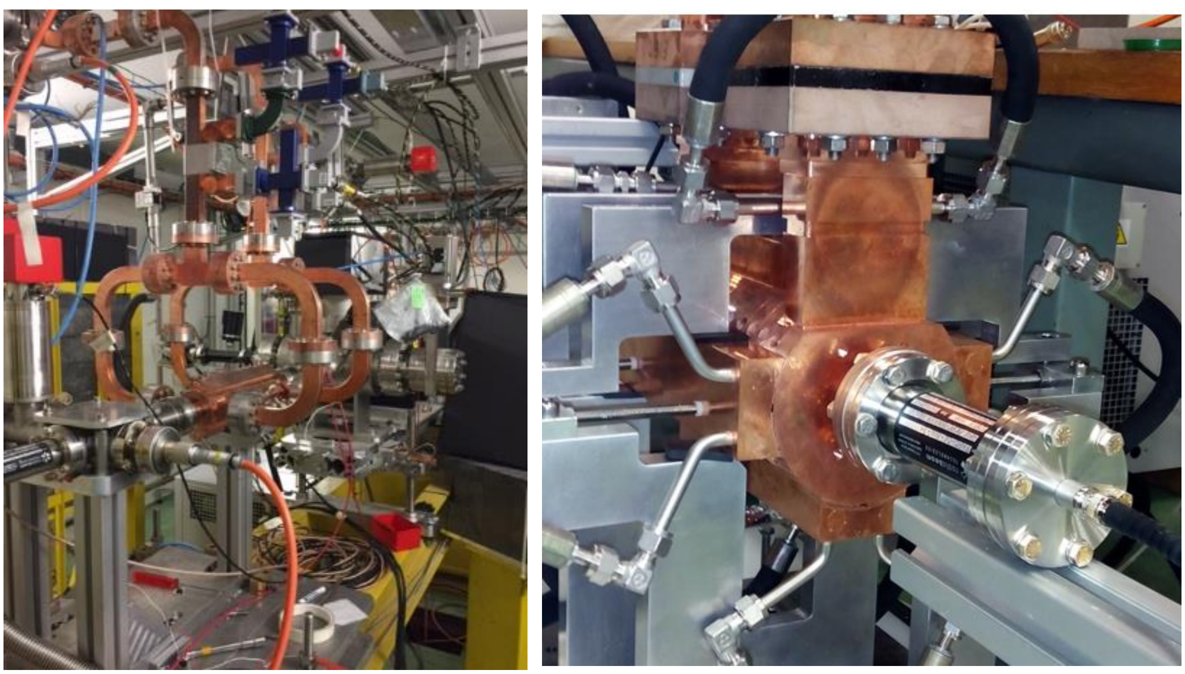


Figure 84. Left: high gradient X-band structure under test in Xbox2; right: S-band backward travelling wave structure for a medical linac.

In parallel, the development of the X-band accelerating technology has moved forward on different fronts. With the help of IPT/KT, a large effort was made on the technology transfer of the fabrication procedure and assembly parameters to companies and to other accelerator laboratories. High power components operating at 12 GHz are now under open hardware license for all the world to use. This industrialization effort is of major importance in the preparation phase of the CLIC machine, which will require the manufacture of thousands and thousands of high-technology parts.

In this regard, high gradient activities have allowed knowledge transfer from CERN to be used to design accelerating structures for other applications, for example a high-gradient S-band backward travelling wave accelerating structure for medical applications (Fig. 84, right). This structure was built and successfully tested in the CTF2 facility, achieving an accelerating gradient of 50 MV/m.

Future machines

BE-ABP Group

Medical Applications

The highlights of 2018 are the thorough investigations on $^{11}C+$ charge breeding during three MD sessions at ISOLDE and REX-ISOLDE. The results of these MDs could show that a reasonable high neutralization factor of 30% could indeed be obtained, half of what is expected from gas injection, but significantly higher than previously demonstrated for continuous ion injection into the EBIS. It was also shown that if a trapping device could provide the necessary trapping and bunching of the $^{11}C+$, the capacity and efficiency of a high-current EBIS would be sufficient for preparation of $^{11}C+$ bunches, even for a demanding single-spill treatment using a synchrotron. The results are of major importance for the conceptual design of a preparation stage linking an ISOL-production of $^{11}C+$ with a treatment accelerator, something that is pursued by CHIBA, Japan, and of interest for carbon treatment centres in Europe. The survey invalidated the initial idea (from 2014) of using a trap-EBIS-like charge breeding concept, and points instead in the direction of employing a cryogenic trap in close connection with an EBIS. The results will serve as a base for one of the chapters in a CDR on a $^{11}C+$ cancer treatment facility, that is under preparation by the MEDICIS-Promed collaboration.

In parallel simulation studies for designing a linac based on the 750MHz RFQ and continued with an IH/DTL and a 3 GHz structure have moved forward. The beam dynamics design, including a bent section to make the layout more hospital-friendly, is now completed, with the RF design by the RF team is the next step. The 750 MHz RFQ design has been further improved, reaching now a degree of maturity that is a base for a CDR.

Physics Beyond Colliders (PBC)

The BE-ABP activities in the PBC framework during 2018 covered essentially: 1) Studies of injectors' performance for fixed target beams after the LIU upgrades, 2) Electric Dipole Moment (EDM) ring, and 3) Various fixed-target implementations under consideration for the LHC.

In order to investigate the future intensity reach of the PSB, the horizontal instability at 160 MeV in the PSB was systematically characterized and its source was searched both theoretically and experimentally. Applying the Sacherer formalism and PyHEADTAIL simulations with the full PSB impedance model clearly pointed to the external circuits of the extraction kicker as responsible for this instability. An experiment, in which the kicker was disconnected from the generator and terminated on a matched load, proved the suppression of the instability in these non-operational conditions. While post-LS2 operation of the PSB will still rely on the transverse feedback system to cope with this instability in the known intensity range, an option for kicker impedance reduction is kept in store for future operation, if necessary for higher ISOLDE intensities.

One of the future projects considered under PBC is the measurement of a possible EDM aligned with the spin of protons. The scheme foresees to circulate proton bunches polarized in longitudinal direction in a fully electric ring. To fulfil the "frozen spin" condition, such that the spin remains parallel to the direction of motion, the ring has to be operated at the so-called magic energy of about 232.8 MeV. This constrains the minimum circumference of such a machine to be around 500 m. A signature of a possible proton EDM is a rotation of spin from the longitudinal into the vertical direction. Studies on systematic errors due to machine imperfections, like misalignments and stray magnetic fields, of the measurement of a possible EDM in a fully electric "frozen spin" ring have been carried out, leading to a deeper understanding of the effects to be taken into account.

In 2018, important progress was made on the feasibility demonstration of the "double-crystal experiment". This involves a first crystal, which is part of the collimation hierarchy and extracts onto an in-beam target a fraction of the circulating beam halo, and a second crystal adjacent to the target that channels the interaction products, enabling studies of precession for very short-lived baryons. The study focused on the layout optimization in IP8 and other IPs and on the achievable protons on target at the LHCb. The feasibility of the SMOG2 experiment, which in 2018 was approved for implementation in LS2, was also demonstrated, addressing aspects related to aperture tolerance and losses from proton-gas interactions.

FCC

Almost 500 scientists and engineers from around the globe gathered at the 2018 FCC Collaboration Week in Amsterdam. During discussions from 9 to 13 April 2018, these experts identified the key contents and objectives for the FCC Conceptual Design Report (CDR), which was released at the end of 2018. The four volumes of the FCC CDR cover the physics landscape and opportunities, the energy-frontier lepton collider (FCC-ee), the 100 TeV hadron collider (FCC-hh), and the High Energy LHC (HE-LHC), respectively. Cost estimates and implementation schedules were developed in parallel. The ten-page summary documents, plus addenda, directly submitted to the European strategy group for the EPPSU process describe an integrated FCC programme consisting of both FCC-ee and FCC-hh, which will extend through most of this century.

In 2018, WP6 of the European Integrating Activity project ARIES organized or co-organized a total of 11 workshops, which were aimed at improving the performance of existing accelerators and at optimizing the design of future facilities. The topics addressed ranged from accelerator reliability and availability, via performance limitations in hadron storage rings and energy-recovery linacs, to future circular colliders and, in particular, muon colliders. Several novel concepts could help the muon collider become a reality. These concepts include parametric ionization cooling, low emittance muon production by positron annihilation (LEMMA scheme), production of low-emittance muon or positron beams using the Gamma factory concept, and strategies to upgrade large accelerator complexes, like the LHC or the FCC, into a highest-energy muon collider. The muon collider workshop organized by ARIES WP6, APEC in Padua in July 2018, gathered the international community in order to review the recent progress and to formulate a common R&D strategy. At the workshop, a general consensus was reached that the steps forward include: 1) the design and implementation of a 6-D cooling experiment for proton-based muon colliders, 2) target tests for positron-based muon production, 3) the Gamma factory development, and 4) the establishment of particle-physics programme based on a reasonably intense, high-energy muon beam, e.g. NuSTORM.

BE-RF Group

FCC

An optimized and consistent proposal for the staging of RF systems for the different FCC-ee machines and the FCC-hh was elaborated in collaboration with Rostock University, carefully reviewed and presented in the FCC week in Amsterdam and in the FCC CDR. In the proposed hybrid scheme, one would first operate for about 4 years with single-cell 400 MHz cavities, optimized to run at the Z-peak with very high beam currents. In a subsequent phase, lasting about 6 years, one could use 4-cell 400 MHz cavities to study W and Higgs particles. After a 1-year shutdown, one would subsequently add 800 MHz cavities to reach single pass acceleration voltage of about 11 GV to reach the $t\bar{t}$ resonance at around 365 GeV. It was found to be most economic to use Nb sputtered Cu cavities at 400 MHz, which can be run economically at 4.5 K, while the

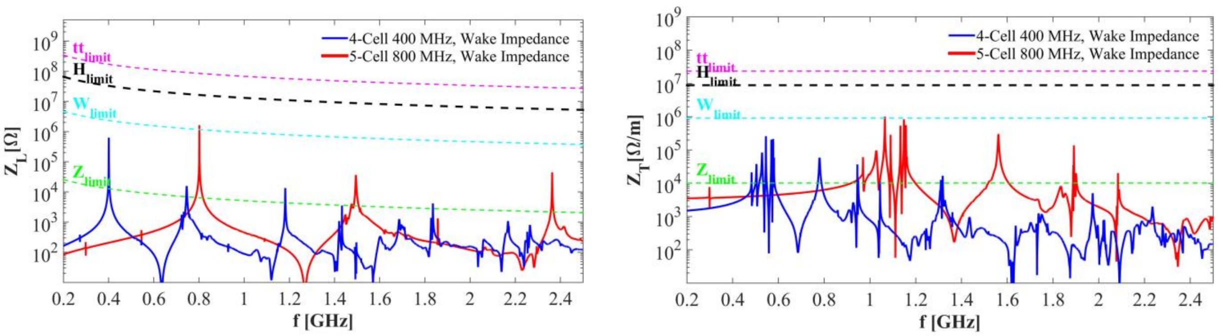


Figure 85. Impedance spectra for 4-cell 400 MHz and 5-cell 800 MHz cavities for the W, H and $ttbar$. The Z-pole uses a 1-cell 400 MHz cavities to reach the very tight thresholds.

800 MHz high-gradient cavities would be 5-cell bulk Nb cavities operated at 2 K. The FCC-hh is less challenging for the main RF system, but noteworthy here are the design of the beam loading compensation scheme and the challenging transverse feedback systems. The latter was simulated with new dedicated code, including intra-bunch feedback in the presence of the full impedance model of the machine.

Several damping schemes using different types of HOM couplers were studied for both baseline and hybrid scenarios and shown to be compatible within the impedance budget (cf. Fig. 85).

Other Group Activities and Cross Departmental Activities

BE-ASR Group

The Administration, Safety and Resources (ASR) group is a service group to the Beams Department. The group is mandated to provide overall assistance to the department head, to each individual group and to each member of personnel in the department. The heterogeneous services are to be delivered in the smoothest and most unobtrusive way while minimizing the inevitable overhead associated with administrative work, resources planning and control, and safety.

Administration

The reorganisation in May 2017, whereby all administrative assistants were also hierarchically assigned to the respective groups and the central secretariat assigned to a dedicated section in BE-HDO, went through a smooth and successful transition.

Throughout the year 2018, a gradual increase of the departmental staff continued, resulting in an overall total of 872 (i.e. 443 Staff Members, 116 Fellows, 98 Students, 215 Associates). In addition, 248 employees of CERN contractors contribute to the departmental undertakings.

Finally, another 88 ADAM S.A. employees developing an accelerator for medical applications, are administratively attached to BE-ASR.

Specific responsibilities concerning human resources and administrative matters have been mandated to the BE-ASR group leader, by delegation of the department head. Departmental representation is hence ensured in staff selection committees (19 in 2018), the CERN contract review board (10 in 2018), and the Standing Concertation sub-group dealing with modifications of the Staff Rules & Regulations, Administrative Circulars and Operational Circulars. The preparation of OC11 on Data Privacy Protection took significant efforts to get the final version approved by CCP in October.

Resources & Logistics

The activities under this heading are related to the Departmental Planning Officer (DPO) on budgetary and financial matters, but also to space management, follow-up of small works and related logistics, vehicles, printers and drinking water.

In order to overview, plan and control the departmental resources over the medium term period, the ASR group leader has also the role of DPO. Both the departmental personnel budget and recurrent material budget were kept under control with *underspending* of respectively 0.01 FTE on staff, 6.5% on fellows and 3.3% on materials. The DPO is assisted by his deputy (DDPO in BE-HDO), who assures planning of fellows, students and special associate programs, and has also the role of deputy project planning for the HL-LHC project.

The *financial and budget related activities* concern primarily implementing, authorizing, monitoring and reporting on material budgets for all BE Groups and projects, monitoring and follow-up of the invoices and yearly accruals, maintenance of budget codes and signature rights. This includes externally funded budgets such as EU projects, the collaboration with ESS (European Spallation Source) and the partnership with ADAM S.A. (Applications of Detectors and Accelerators to Medicine).

In addition to the normal, recurrent activities of *space management,* the effective occupation of office space was scrutinized in the frame of a CERN-wide evacuation plan. Two meeting rooms were fully refurbished, for which the management of the AV equipment was transferred to the IT department, in line with our strategy for centralized support.

The BE Newsletter

After seven years and seventeen issues, the editorial leadership was handed over to Lars Jensen (BE-BI) to give a fresh view on the publication of the BE Newsletter, introduced in 2011. The content remains varied, from scientific and technical to practical, social and safety information, provided by each group via its correspondent. Under the motivated push of the new Editor-in-Chief, seven BE Newsletters were published during the year.

Safety Unit

The BE Safety Unit counts four staff, one fellow, plus a part-time contribution from a BE-ICS staff member (as the new DRSO), representing a total of 4.9 FTE throughout the year. They fulfil departmental safety roles as well as project safety roles – namely for LIU, HL-LHC and the SPS-FIRE Safety project – and have also a presence in the *CERN Crisis Coordination Team*. A crisis response organization is fully operational to be able to react and manage a crisis, should it happen at CERN.

All members of the BE Safety Unit are committed in the three *Complex Safety Advisory Panels* (CSAP), respectively for the LHC, the SPS and the PS complex. These panels are composed of members from all technical departments, report to the IEFC & LMC, and make recommendations in matters of safe operation of CERN Accelerator Complexes. The BE DDSO who had been acting as scientific secretary for the DSO Committee (DSOC) for five years, handed over this function.

Safety of Personnel

The 2018 statistics on *occupational accidents* implying BE personnel or occurring in BE premises remained reasonable (8% of the 654 CERN accidents). Only a few days-off were to be deplored, from 4 accidents.

Radiation wise, BE personal doses were all below 1 mSv for 2018, with a maximum of 0.7 mSv.

Based on an initiative from the BE DSO, approved by the CERN Management, the access control to surface buildings of beam facilities started to be improved, in collaboration with the EN Safety team.

In view of LS2, the mandates and responsibilities of work & services supervisors (WSS), of technical contacts (for contractors), and of safety link-persons (SLP) were clarified. A workshop was organized to help WSS and technical contacts to write proper safety prevention plans. A checklist was proposed to the TSOs to help them in their tasks.

A new Cryogenic Safety Officer, as well as a Chemical Safety Officer have been nominated at the level of the A&T Sector.

Safety of Installations

HIE-ISOLDE has come to an operational state, and with the end of the project phase, safety responsibilities have been redefined in the ISOLDE complex. A member of BE-OP is now technical coordinator for HIE-ISOLDE, and deputy technical coordinator for ISOLDE. This nomination eases the collaboration with the BE Safety Unit.

A safety assessment of the experiments proposed at CLEAR was included in the selection process. Safety aspects are followed-up by the GLIMOS.

Following a new version of the procedure to prepare more readable and usable Safety Files (SF), the guidelines to help editors has also been reviewed. The new version was presented and explained to SF editors, and also integrates the SF editors' feedback.

Safety in Projects

The safety documents concerning the LIU project came close to completion. Among the proposed safety measures, one appeared to be very useful. The Project Safety Officer (PSO) required pre-visits from HSE to judge the conformity of delivered electrical equipment before they are installed in the beam facilities. These pre-visits revealed that most of the delivered equipment was not conform. Modifications could be done by equipment groups before the installation of the equipment into the machines. The result is a gain of time for the project, safer working conditions, and safer beam facilities.

The first stage of the works related to the SPS-Fire Safety project was presented to an ALARA-3 committee, which gave its go-ahead with a warning for sprinklers installation and the work dose planning. The process will therefore be optimised for the 2nd stage.

Meetings between the HL-LHC PSO and HSE are organized on a quarterly basis, and aim at clarifying HSE's requests in view of the safety clearances. It was also proposed to include safety aspects in MoUs. The PSO helps the work-package leaders to produce sound Engineering Change Requests (ECR), and uses clear procedures to check the safety aspects of their deliverables.

BE-HDO Group

The BE Head Office comprises, the Department Head, Deputy Department Head and the Central Administration. The Group provides overall assistance to the Department Head and is responsible for the general administration for all categories of members of personnel and visitors, including letters of invitation and the related visa requests. The central secretariat is responsible for the onboarding of all newcomers to the BE Department, including welcome events and the communication of all arrival formalities. All contract statuses are also overseen by the central secretariat, ranging from the initial contract, to status changes/personal schedules and end of contract formalities and all special leaves (maternity, paternity, accident home leave etc.). The central administration is also the link with the HR Department for the Fellows, Associates and Student committees and oversees the selection procedure. The scope of the activities also covers the administrative support for the advancement and promotions exercise, the payment of subsistence for visitors to the Department, the Department's overtime payments, along with trainee and summer student placements. Bi-monthly BE seminars on topics covering the Department's activities are scheduled and organised and the office is also responsible for the entire organisation of BE participation in HEP conferences and educational schools. The BE Department has collaboration agreements with many Member and Non-Member States and the central secretariat is also responsible for the administrative content and follow-up of the agreements, the liaison with legal and financial services and the establishment and follow up of project associate contracts.

BE-ABP Group

Computing for Accelerator Physics

The activities of the CWG in 2018 ranged from the distribution of the information related to computing matters within the group and direct connection to the IT department (link to the ABP-CWG Twiki), to the assessment of software and hardware needs for in-house beam dynamics code development and the consequent deployment of resources. In order to consolidate the present status of know-how in numerical simulations and avoid repetitions on the long term, the CWG has identified a main guideline in the creation of a robust set of common tools to serve as a general framework for future accelerator physics studies. This relies on the construction and/or extraction from existing codes of shareable library modules, such that any embedded functionality will no longer remain the exclusive property of the original code, but can be handily re-used also in other contexts. Efforts in this direction have been already made in the development of the PyECLOUD-PyHEADTAIL suite for collective effects or SixTrackLib as a particle tracking engine.

New frontiers of code development are gradually becoming reachable thanks to an important ramp up of the hardware resources dedicated to High Performance Computing (HPC) to support parallel computation. In 2018, a strong increase has been recorded in the exploitation of the large HPC infrastructure deployed at CERN, made of 2 Infiniband clusters of 1440 cores and a batch cluster of about 2000 cores with low-latency Ethernet interconnects. Besides, an additional 448 cores and a GPU server were installed in the HPC cluster at the CNAF-Bologna, so that the cluster is now running full steam with 832 cores and 4 Nvidia Tesla V100 7 TFlops (double precision) GPUs. The new HPC infrastructure as well as the awareness spread across the group of the existing activities and resources have been already the cornerstone in 2018 to generate an important upgrade of the existing computational tools for beam dynamics (e.g., multi-bunch evolution with impedances and electron cloud, large scale space charge simulations, massive beam stability studies with beam-beam interactions and interplay with other effects) and are expected to serve the purpose to foster continued progress in this direction during LS2 and well beyond.

In 2018, a major effort has been devoted to preparing the migration from AFS to the EOS shared file system, in collaboration with IT. In order to save resources scheduled for LS2 and involved or impacted by the migration, the CWG has proposed a strategy consisting of providing to IT services a set of ABP use cases critical for beam dynamics studies, which should run as-is on EOS to ensure the non-disruption of the typical ABP workflows.

BE-BI Group

FESAweb for fixed displays

The BE-BI software section is testing a new approach to providing lightweight fixed-displays to replace existing GUIs. Through a dedicated Tomcat web server running on a trusted application

Figure 86: Examples of FESAweb graphs showing data in various formats.

server, it is now possible to acquire data from any FESA server and to display it in real-time. Options for the displayed data include single scalars, tables of 1D arrays and even full 2D images (see Fig. 86). An accompanying Java application was developed for creating and storing display configuration files allowing different users to reload and share displays.

BE-CO Group

CMW – Controls Middleware

New major version of the CMW Directory Service

During technical stop 2 (TS2), the CMW team deployed a new major version of the CMW Directory Service. This deployment marks an important milestone to eradicate the old, ADA-based version of the service.

The Directory Service is a core part of the BECO Controls Middleware (CMW). It is a naming service used to identify and locate all RDA (Remote Device Access) servers (e.g. FESA, FGCD) present in the Control System. Moreover, it is responsible for resolving the location of the physical server for a given logical device name. Additionally, based on the provided configuration, the service can route the client to an intermediate server that either provides high-level services or acts as a proxy, thus, shielding the target server from a high load from multiple clients. The Directory Service must run with high availability (as every initial device access needs it) and serves approximately 220 requests per second.

The previous version of the service was implemented in ADA and deployed in 2009. Even though it was stable and functional over many years, it was neither extensible nor scalable. Scaling the service was impossible without significant source code changes and over the years, the service accumulated significant technical debt. Additionally, it was difficult to put in place a proper monitoring solution. In the second half of 2017, the CMW team performed a market survey examining possible solutions for the next generation of the Directory Service. There are various products on the market, however, in addition to useful features, each one introduces many constraints. The Directory Service has many CERN domain-specific requirements and it is difficult to find a product that meets them all. Ultimately, the decision was made to develop a custom

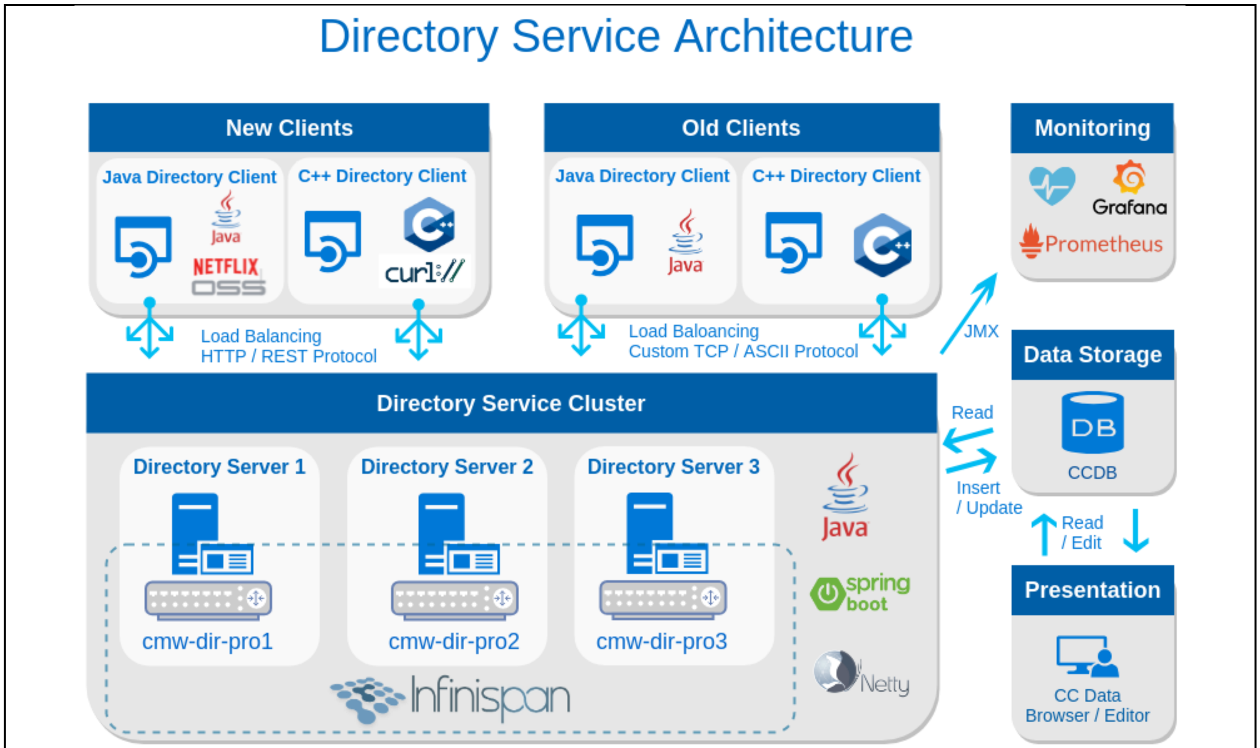


Figure 87: Architecture of the new CMW Directory Service.

solution based on industry standards: Java, Spring Boot and REST API. Using this approach, the new service can be customised and extended, and delivers exactly what is needed.

The new architecture (cf. Fig. 87) follows the microservices approach. The new Java Directory client uses the Netflix open-source software stack *Feign* for REST communication and *Ribbon* for client-side load-balancing. The new C++ Directory client uses the *libcurl* library for REST communication and provides custom load-balancing. The server-side is written in Java on top of Spring Boot and uses *Netty* as a TCP channel for old Directory clients. To provide the required scalability and availability the service is deployed as a cluster on three separate machines, as presented in the figure below.

All nodes in the cluster are connected via a distributed cache, based on the Red Hat *Infinispan* product. The cache provides a distributed, in-memory key/value data-store with automatic synchronisation between nodes, and it can scale horizontally to several hundred nodes. Additionally, each server instance has a local file backup containing the entire contents of the cache. All nodes expose runtime metrics through JMX, which are acquired and analysed periodically by the monitoring system. According to the registered monitoring rules, warnings and alerts are sent to team members in case of abnormal behaviour or malfunction.

Key characteristics of the new service:

- Contract and interoperability: the service is described through HTTP and REST and it is interoperable as it uses standard message exchange protocols.
- Loose coupling: As a micro-service, it is self-contained, independently deployable.
- Statelessness: It is stateless with no shared or conversational state. All business states are maintained in a database and in memory.
- Discoverability: When an instance of the service dies, the Directory client, equipped with load-balancing facilities, silently falls back to another server instance in a transparent way.
- Even when the database is unavailable, the service is able to serve and update the data on time. Additionally, each server instance provides a local data backup.
- Retro-compatibility: The new Directory Service is compatible with old Directory clients operating through the old TCP/ASCII protocol.

The new Directory Service has successfully passed many testing phases, including integration, performance and stability testing. Before the final deployment in production, the test setup ran continuously for several days without any problems, proving that the new service can reliably handle twice the expected production load. It was successfully commissioned and deployed during TS2 in September 2018.

Getting ready for major LS2 GMT Infrastructure Renovations

Major efforts were concentrated in 2018 for the design, manufacturing and qualification of the new technical solutions for the renovation of the General Machine Timing (GMT) RS-485 and Pulse Repeaters distribution networks for the entire Accelerator complex.

After 30 years of loyal service, it was high time to develop new infrastructure solutions in order to

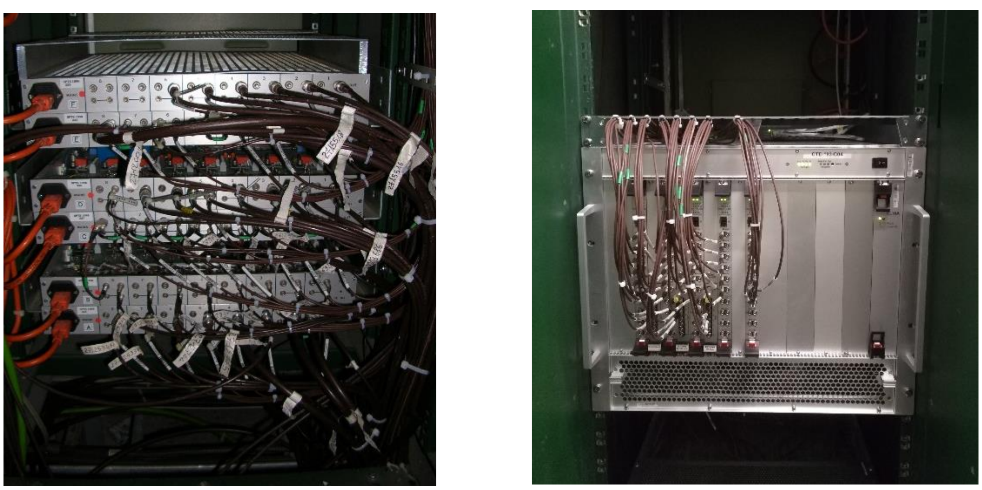


Figure 88: GMT VMEbus modules, before renovation (left) and after renovation (right).

prepare for LHC Run 3. A full collection of VMEbus modules were designed, manufactured and tested under operational conditions for full deployment in 2019. Several hundreds of these new modules hosted in small VMEbus subracks will allow for a rationalization of the legacy distribution network while offering at the same time on-line remote monitoring and early fault detection via the COSMOS system (see Fig. 88).

Accelerator Data Centre renovation

Phase II of the Accelerator Data Centre renovation took place as planned in 2018 with the installation of a new batch of about 100 new servers and the associated network infrastructure.

These servers grouped in QUADs enclosures are progressively replacing the legacy Hewlett-Packard servers. The full renovation of the Data centre will finish by the end of LS2.

A new generation of Industrial PCs (IPC) for Run 3

In 2018 the BE-CO group was evaluating potential Industrial PC platforms in view of the replacement of the operational Kontron PICMG1.3 machines used for the control of major LHC systems such as Cryogenics, QPS and Power converters (about 750 machines in total).

A full market investigation was done which led to the conclusion that time was arrived to move away from the PCI standard in favour of PCIe. This move will allow for improved performance and better compliance with industry board manufacturers (COTS).

CERN requirements were considered by Siemens and integrated in their brand-new state-of-the art IPC platform. All aspects related to the introduction of this new platform in the CERN Accelerator infrastructure were addressed (networking, security, remote monitoring, operating system, etc.) and several pilot machines were installed under operational conditions for final validation (Fig. 89).

Figure 89: The new generation of PCIe-based Siemens IPC.

Evaluation of Container technology for Accelerator control

The CERN Accelerator Data Center runs historically with a 100% bare-metal approach. In 2018, BE-CO decided to undertake a study and evaluation of the container technology in view of its potential usage for Accelerator control.

The potential benefits of containers (Docker) and containers orchestration (Kubernetes) technology are currently evaluated in close partnership with the IT department and several application developers in the BE department. Containers may allow for an easier and safer deployment of software components while containers orchestration would allow for better Data Centre resource usage and easier maintenance. More studies and evaluation will continue in 2019. Stay tuned!

White Rabbit

The year 2018 saw the last touches to the new version of the IEEE 1588 (Precision Time Protocol, PTP) standard. This new revision includes a generalisation of White Rabbit (WR) concepts under the so-called "High Accuracy" (HA) profile. This means that in the future, WR devices will just be IEEE 1588 nodes which implement the HA profile. One consequence of this generalisation is that existing WR building blocks need to be migrated to comply with HA. In particular, the WR team in BE-CO-HT worked on implementing HA in the WR switch, and successfully demonstrated it in the ISPCS 2018 conference, which was held at CERN. A WR workshop immediately followed the conference, allowing ISPCS attendees to extend their stay at CERN and attend it. The workshop was a good occasion to see how WR technology is now used in domains as different as finance and telecom.

A lot of work was devoted to generalising the ideas embodied in the LHC Instabilities Trigger distribution system (LIST) so that similar projects can easily reuse them. The result is the WR Trigger Distribution (WRTD) project. This development needed a serious clean-up and upgrade of the Mock Turtle hard real-time processing core, migrating the underlying processors to a RISC-V architecture and adding support for remote debugging using GDB.

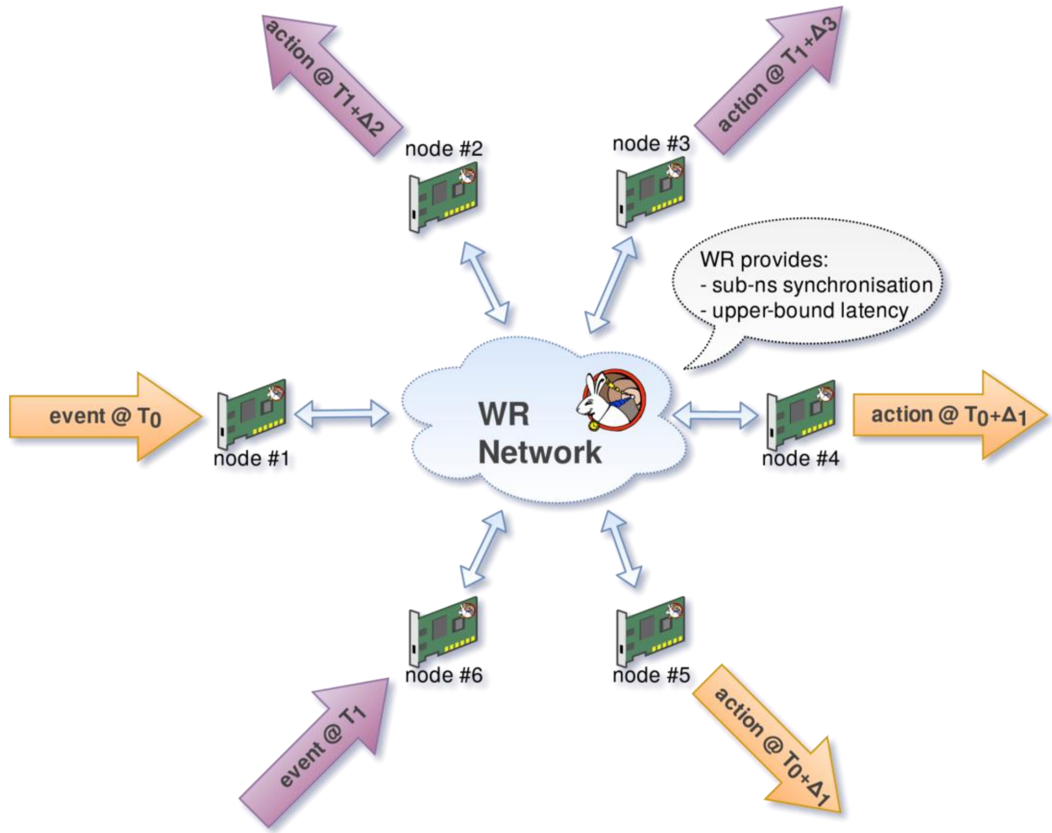


Figure 90: A high-level view of WRTD (White Rabbit Trigger Distribution)

Figure 90 depicts the general architecture of a WRTD-based system. WRTD-capable nodes can emit and consume events (which physically exist as accurately time-stamped messages on the WR network). The emission of a given event can be pre-programmed to follow the occurrence of some external trigger. Conversely, consumption of a certain event can result in the production of an external trigger to synchronise nearby equipment.

Development tools for Gateware and low-level software

The Cheby project saw its first release in 2018. Cheby aims at automating some of the most repetitive tasks in HDL/FPGA development and capitalises on past efforts in equipment groups such as Gena and Cheburashka. The idea is not new: take in a text-based description of the memory map of a hardware module and automatically generate a number of HDL and software files so that a designer can concentrate on the non-automatable part of the design.

As Figure 91 illustrates, Cheby hardware description files can also be used to generate Linux device driver code and even FESA classes through a plug-in developed in BE-RF. Driver generation is done with EDGE, a new tool succeeding Encore which adds features such as PCI/PCIe support and hardware emulation. This allows software developers to start writing code to support a piece of hardware even before it actually exists.

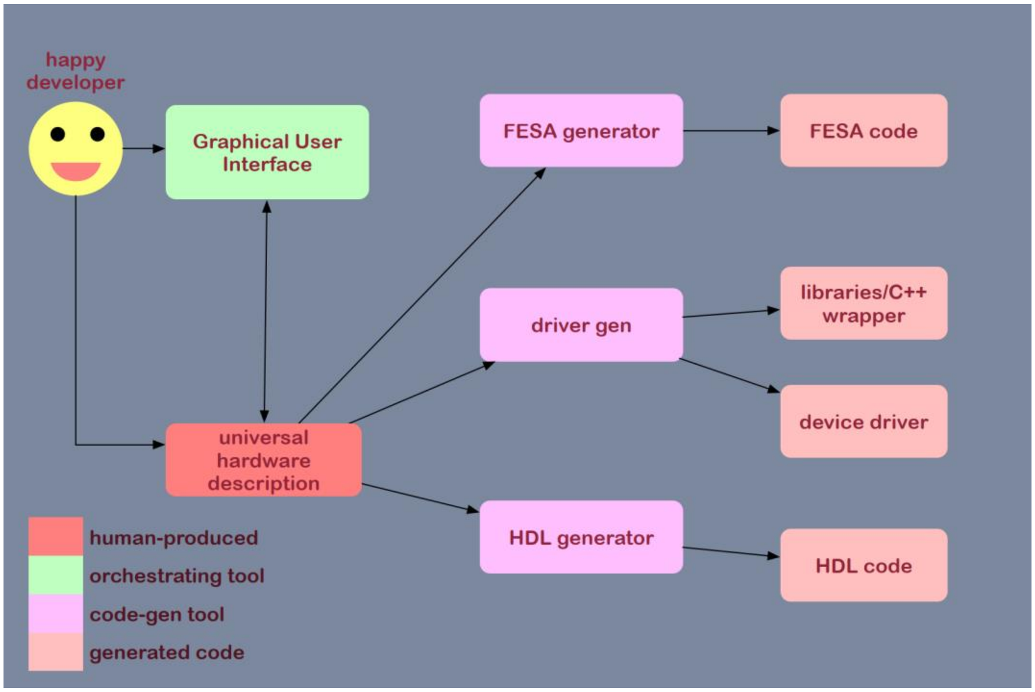


Figure 91: A schematic view of the different generated components from a single hardware description file in Cheby.

Hardware developments in HL-LHC WP18

Work package 18 in the HL-LHC project covers new controls technologies developed to cope with HL-LHC requirements. This includes NXCALS, the new-generation logging system, as well as the development of a new modular hardware platform to be used by equipment groups to build radiation-tolerant systems. The Distributed I/O Tier (DIOT) crate will feature radiation tolerant power supply, remote management support and a system board to control peripheral cards and exchange data with higher layers of the control system through a variety of communication channels.

Good progress was made in 2018, in particular proving the feasibility of the concept by developing a demonstrator based on a commercial off-the-shelf (COTS) crate and power supply. This demonstrator was used to control current loops such as those used in the Warm magnets Interlock

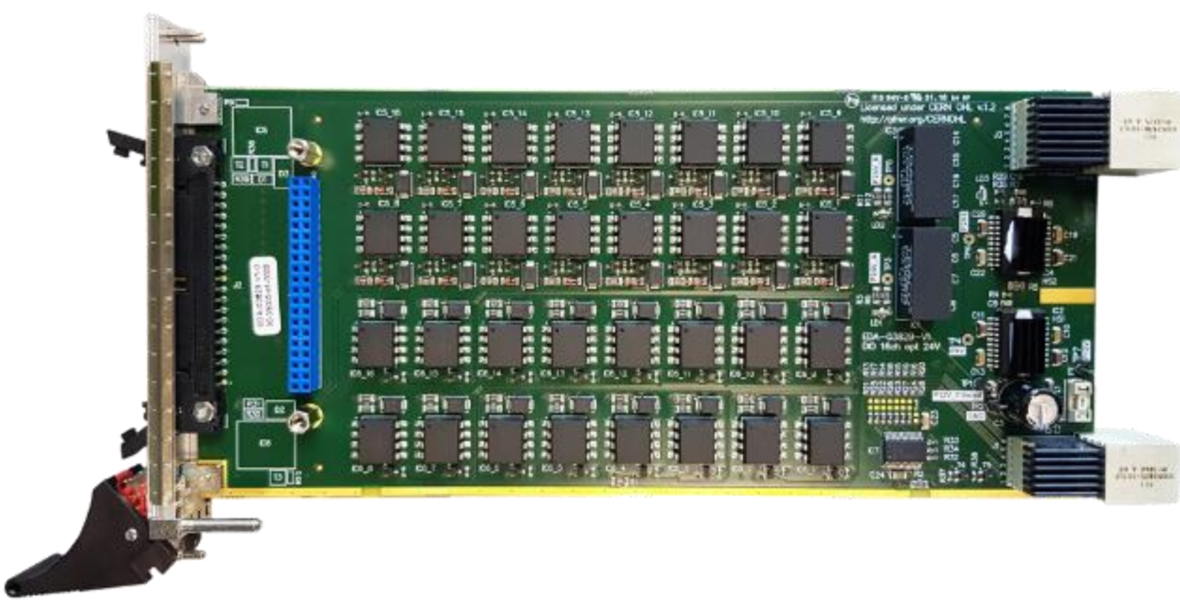


Figure 92: Picture of the rad-tol 3U WIC peripheral board used in the DIOT demonstrator.

system (WIC), using radiation tolerant (rad-tol) electronics. Figure 92 shows the peripheral board used in the system, specifically designed for the demonstrator. The system board was an evolution of the GEFE board developed in BE-BI.

Progress was also made on the development of a rad-tol implementation of the Powerlink Ethernet-based fieldbus to boost bandwidth beyond the few Mb/s available with WorldFIP.

A new processor board for VME64x systems

As the PCI-VME64x bridge chip (TSI148) in the MEN A20 Single-Board Computer (SBC) became end-of-life, a new SBC was selected after a market survey and call for tender. The MEN A25 is basically a PC running Linux, seeing the whole VME64x bus as a peripheral. The PCIe-VME64x bridge is this time based on an FPGA design whose sources are licensed under a free and open source licence. This ensures we will not suffer from obsolescence problems in the future, as the bridge is the only exotic component in this otherwise standard PC board.

After a lot of work in 2017, the task of completing the HDL design of the bridge in collaboration with MEN was completed in 2018, with first deployments of A25 units in April. After identifying some performance issues with the users, fixes were made so now the A25 is faster than its predecessor for all types of VME64x bus accesses. A wrapper was developed around the Linux device driver provided by MEN so that the A25 can be used as a drop-in replacement of the A20.

WorldFIP

After the development of the masterFIP, the successor of the WorldFIP master board discontinued by Alstom, a large effort was undertaken with the users to extensively test it and program its progressive deployment in the LHC. In addition, a mezzanine was designed with the nanoFIP chip on it (see Fig. 93). This will allow users, e.g. those basing their designs on the DIOT platform, to easily design slave boards which interface with a WorldFIP bus in radiation.

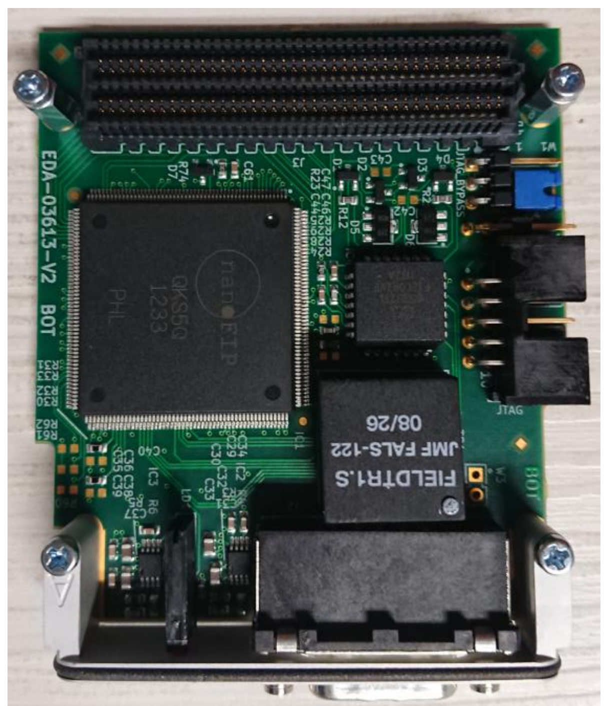


Figure 93: NanoFIP mezzanine.

MTCA.4 support

Two new Front End platforms were evaluated with the aim of establishing whether they can be supported by BE-CO in the future. The tests for PXIe showed that we will need to work on a number of shortcomings before fully supporting this technology. On the other hand, MTCA.4 proved to be a well-adapted platform for those who need high performance in the FEC layer. After this positive result in the proof-of-concept stage, and taking into account the existence of a reasonably large LLRF community using MTCA.4 in other laboratories, it was decided to base the upgrade of the SPS LLRF electronics on MTCA.4, in a collaborative effort between BE-CO and BE-RF (more details above).

The Accelerator Fault Tracking

The Accelerator Fault Tracking (AFT) project advanced significantly during 2018 and the user count increased from ~300 to ~500. The AD machine was also introduced to AFT, completing the coverage of the CERN accelerator complex. With 12 feature releases during the year, lots of new functionality and usability improvements were delivered, including:

- The integration with the Layout Service, in order to search for elements to assign faults to. This then allows to have statistics for elements and element types in fault. It also gives links to InforEAM (to reach the assets) and the GIS, giving the foundations to plot faults by location on a map in the future.
- The possibility to put faults into a "Suspended" state, to produce statistics which exclude the time when a fault could not be worked on due to a lack of out-of-hours support (this is generally the case for Linac4 and ISOLDE). In addition to having *meaningful* downtime data by system, it will also allow to understand the cost (in terms of availability for physics) of not having an out-of-hours support in place.
- Bulk edition of faults – to allow machine supervisors and equipment experts to efficiently update or complete fault attributes.
- Cross-accelerator fault searching (much more complicated than it sounds, since different accelerators have different systems and properties to filter by), accompanied by completely redesigned search controls to increase usability given a growing number of filters.
- New and updated Accelerator & Destination Statistics and Reports, new Data Consistency Reports (highlighting Faults with no impacted destinations, and Injector Complex faults with no intersecting faults in upstream machines) and a new graphical representation of fault states and times.

User training, titled "Getting the most out of AFT" was also provided – showcasing all of the available functionality with a focus on the many features added during 2018.

Behind the scenes, consolidation and update of dependencies and framework versions was conducted to facilitate future maintenance and evolution. Internal instrumentation was also improved, so we know more about how the system is performing and are immediately notified in case of any problems encountered by users.

Accelerator Performance Statistics

The Accelerator Statistics Web application was unchanged during 2018 (a full re-write is foreseen during LS2), however, behind the scenes the calculation server was re-factored to use RDA3 following JMS-related problems that blocked certain statistics updates.

Accelerator Schedule Management

The Accelerator Schedule Management (ASM) was used throughout 2018 to expose schedule events for use in AFT and to register and follow-up all Controls changes planned and executed by BE-CO and equipment groups in the sector.

The module for managing Controls Changes received numerous usability improvements, including inline edition of scheduled changes and new advanced searching capabilities.

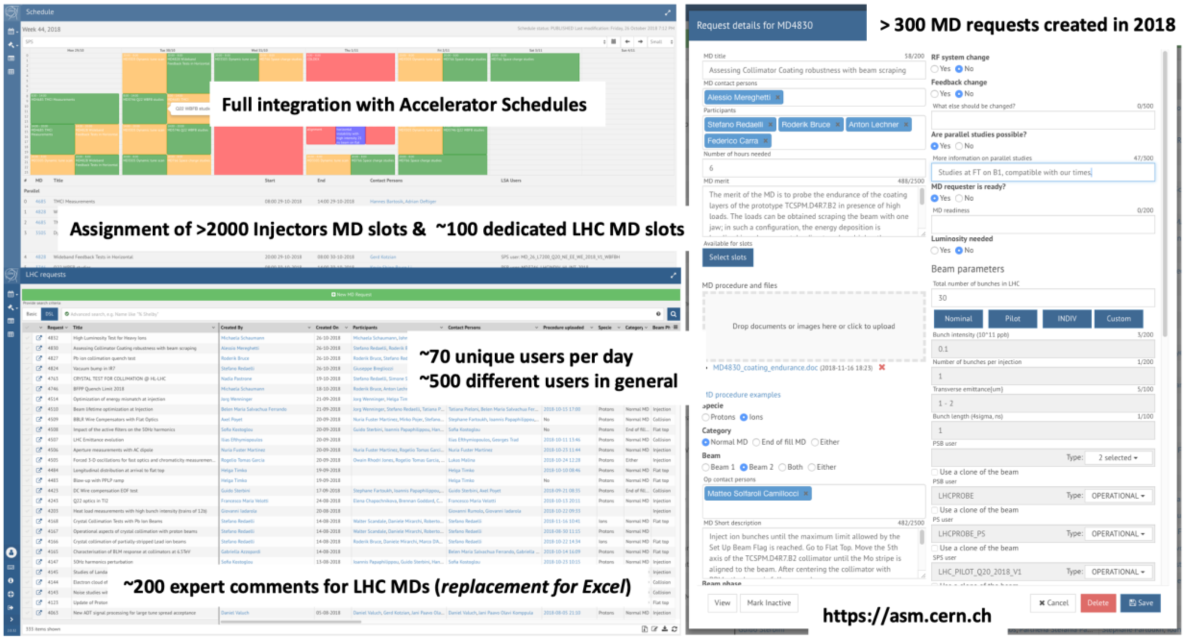


Figure 94. Screenshots from ASM showing the new MD Planning tool used throughout 2018.

For the first time, the Accelerator Schedules module was used by operators to plan and follow-up both hardware and beam commissioning for the restart of all of the injectors. This was possible due to a collaboration between BE-CO and BE-OP to integrate ASM with the existing OP-developed Machine Checkout Web Application.

Following several development iterations and feedback sessions with the Injectors and LHC MD coordinators, the new Machine Development Planning module was deployed in March and successfully used throughout the year by the MD community to request, organise and follow-up MDs for all machines. cf. Fig. 94.

The full history of past MDs, their scheduling, plus pending MD requests were also imported from the legacy tool/database to ASM.

Controls Configuration Service

Following a support intensive YETS period with hundreds of devices being migrated to FESA3, development and consolidation of the Controls Configuration Service (CCS) saw significant progress. For example:

- The CCS components were incorporated into the new Controls Test-Bed environment.
- The Controls Configuration Data Editor (CCDE) was heavily developed, providing new modules and extending existing ones to manage and consults configurations of computers, drivers, devices, classes, device relations, RBAC rules, etc. All of these modules replaced equivalent legacy Oracle APEX applications.
- Development throughout the CCS to support other projects such as White Rabbit as an Operational Service (WRaaOS), CHEBY and EDGE for management of drivers, UCAP device configurations, and NXCALS CMW data source configurations.

In addition to the above, a key area of development was the new Controls Configuration Data Access (CCDA) API, which allows people to perform language independent, programmatic interactions with the Controls Configuration data. The architecture follows industry standards based on so-called "Spring Cloud" technologies which combine to provide lightweight, load-balanced, highly available and fully instrumented data access.

Another major achievement was the development of tools to enable smooth and robust migration of devices from legacy/End of Life platforms towards the latest version of FESA. In CCDE a new Device Migration module (to replace the old APEX one) was provided to allow users to migrate devices from one class (or class version) to another, including across device frameworks e.g. FESA 2 to FESA 3 (cf. Fig. 95). Behind the scenes of the application is a device migration orchestrator engine, which automatically migrates the devices at the time selected by the user, including validation for non-breaking changes in related systems (e.g. LSA and NXCALS), generating new RBAC access maps, deploying and restarting corresponding FESA processes (based on FESA team scripts), updating the LSA configuration and transforming parameters and settings (using the LSA API), and updating the configurations of the NXCALS CMW data source processes.

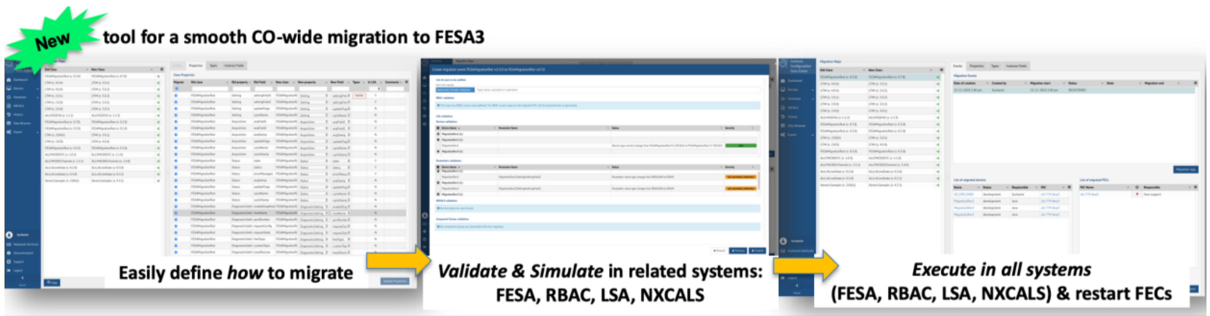


Figure 95: Screenshot from the CCDE showing the tools to easily configure and automatically execute controls-wide migrations of devices to FESA 3.

Training on how to use the new CCDE interface was provided to a large user and received a lot of positive feedback. Overall the initiative to put in place CO-wide (CCDB, FESA, RBAC, LSA, (NX)CALS) migrations was well timed and executed, such that it will surely be of great benefit to many equipment groups as they deal with the End-of-Life for GM and FESA2 during LS2.

Work to integrate the CCDE Hardware editor with the Layout (part of the CHDM initiative) also advanced significantly resulting in the possibility for HW experts to link CCS configuration data to crates and modules in the Layout, or even directly register new crates and modules in the Layout without having to leave the CCDE application (cf. Fig. 96).

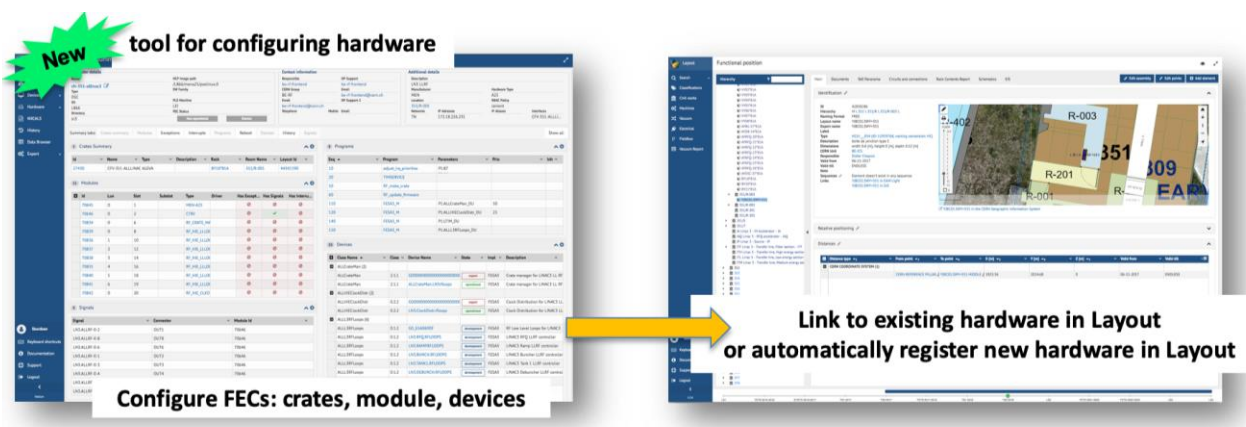


Figure 96: Screenshots from the CCDE and Layout tools showing the integration concerning Controls hardware

In addition to this improved usability/convenience – the overall data quality will also improve due to coherency across distributed systems. More work will be conducted on this topic in 2019.

DevOps for Data Services

The common Data Services DevOps infrastructure established in 2017 was successfully used throughout 2018. Furthermore, it was extended to incorporate HAProxy to ensure even higher availability of all of the Web applications, including enabling zero-downtime deployments of new releases.

The Layout Service in the Accelerator and Technology Sector

The development of the new Layout database and associated Web application progressed well, to reach the objective of providing the tools necessary for various CERN teams to manage their Layout related data themselves in function of the changes to be conducted during LS2 and for initial preparations for HL-LHC (cf. Fig. 97).

There were many developments to improve the usability or add new features based on user feedback, as well as configuring more access rules/restrictions and improving application performance. Some key new features included:

- Integration of EDMS documents for element types
- Support for bulk operations to update elements, deep cloning of element types, and total or partial cloning of Assembly Breakdown Structures (ABS).
- Many new types of searches.
- Fine-grained access control integrated with RBAC and e-groups and configured in a data-driven manner.
- Editor for machine sequences (lists of adjacent sequential elements such as LHC Beam 1, LHC Beam 2, LHC vacuum inner aperture pipes, etc.).
- Many new reports e.g. to extract circuits and connections in a given Powering sector (Used by TE-MPE to document in more detail the description of the injectors circuits, starting with Linac4 and the PSB); or to produce a summary of BI equipment for the CERN annual audit of assets.
- Full support to manage EIS (Element Important de Sécurité) elements was developed.
- A dedicated LHC Vacuum Layout Editor was also developed. This is used to design the vacuum layout of the inner and outer beam pipe sequences in the LHC Long Straight Sections (LSS). This edition of aperture profiles, aperture types, specific vacuum properties, cloning of vacuum sub- assemblies, and some important validations (apertures continuity, overlaps/gaps by beam apertures, etc.). Overall this can help ensure that LHC optics can be properly generated, leading to coherent generation of settings in LSA and also providing a basis for the Survey team to align the beam line elements. This means that the Vacuum team can start to define the new LHC vacuum configurations for post-LS2 operation and even HL-LHC – thanks to the time oriented features of the new Layout.
- The latest 360 panorama API was integrated into Layout so that panorama images of CERN's accelerator installations, taken over time, now match to a given layout version, and navigation in the panorama view is synchronised with the Layout user interface. This is essentially like a time-oriented Google Street View inside CERNs installations. To match the panoramas to Layout elements, an automatic synchronisation was put in place to match the positioning in the CERN Coordinate System (CCS) of some shared machine elements from the Survey database and Racks (+assimilated elements) from the GIS database.
- New functionality was also developed to allow end-users of the Layout application to directly publish functional positions and their structures from Layout to InforEAM (from where they can manage corresponding assets). A mechanism to import functional positions from InforEAM to Layout was also included. These features will greatly facilitate the work of people using (or planning to use) Layout and InforEAM. As a first test case, this mechanism was used to publish all BI functional positions and ABS representing BPM electronics (FEC crates, modules...) located in SR2, UA23 and UA27 to InforEAM.

- The schematic view in Layout which displays connections between elements got a major overhaul and now integrates with the COSMOS Grafana API to support a display of live statuses of the different nodes in a network or circuit (e.g. WorldFIP agents). This should help validate new installations and diagnose related infrastructure problems.

In order to get people up to speed with the new tools, various training and documentation of key

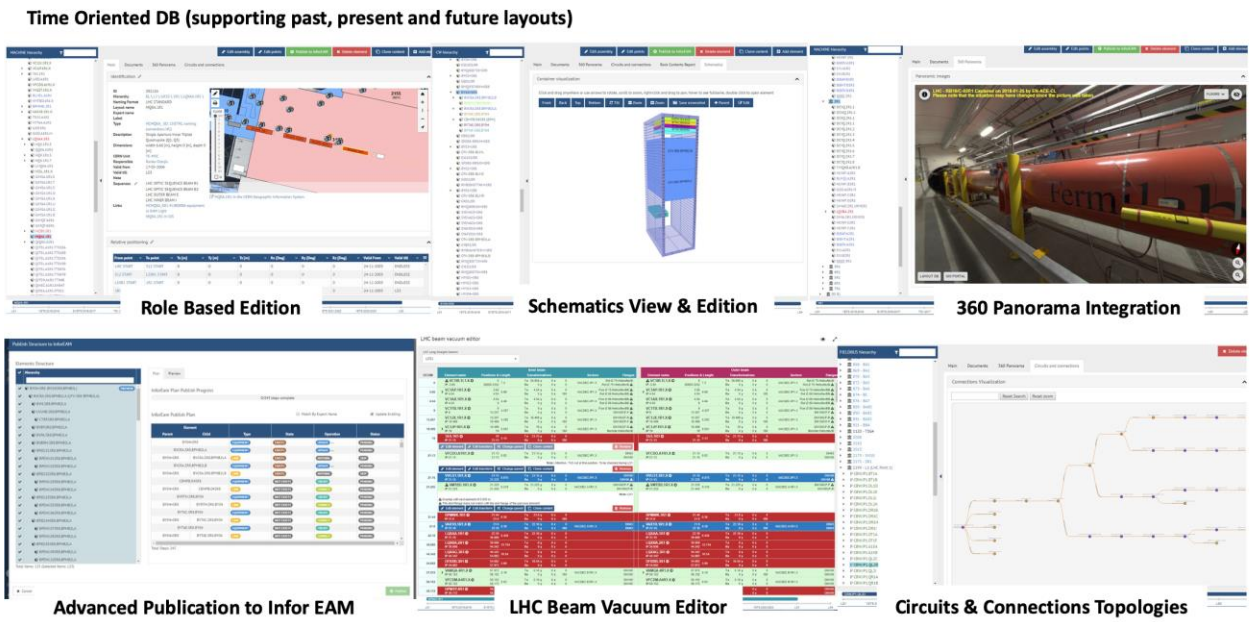


Figure 97: Screenshots from the Layout application showing the new tools ready for LS2-related work.

use cases was provided to the different user communities as needed during the year.

Controls Hardware Data Management

A new initiative was launched to facilitate controls hardware data management, starting by focusing on BE-CO-IN's needs, and in particular, the installation of White Rabbit networks and Pulse Repeater renovations foreseen to take place during LS2.

The initial goal was to be able to manage both physical and logical configurations of racks, crates and modules, using the Layout and CCS tools as appropriate, with a smooth, user-friendly exchange of data between the systems. Application workflows were designed to move data between Layout and CCS in a way that matches how users work in real-life. The aim being to facilitate the work of the installation teams whilst ensuring a coherent definition of both physical and logical infrastructure configurations in the distributed systems.

A huge effort was made to clean-up the crate related data in the CCDB which involved a lot of interaction with various groups in the sector who are responsible for the different controls crates. Once this was done, it was possible to start to precisely define the position of Front-End Computer (FEC) crates in racks and add other passive equipment that was never defined in the CCDB. As a result, it was then possible to have full schematic views of the various equipment using the tools developed in the Layout and CCS related applications. Knowing what is positioned where and connected to what can greatly simply maintenance, installations and dismantling – a key requisite for LS2.

Tracing Service

Coming into 2018, the BE-CO Tracing Service was quite unstable, running on legacy hardware and heavily outdated software. An initiative was launched to consolidate this service to base the BE-CO Tracing Service on the Elasticsearch (ES) infrastructure provided by IT, rather than continuing to maintain an ES cluster in-house. Following the agreement from IT, the project was launched, starting with significant DevOps related tasks, including adapting existing Tracing projects to use Gitlab and introducing Ansible to manage everything in a way common to other BE-CO-DS systems.

To use the latest IT provided solutions, a lot of effort was required to update the legacy BE-CO Tracing data ingestion chain – removing dependencies on JMS and unsupported libraries. One of the main activities was to introduce Kafka as a replacement for JMS in the data ingestion process, by writing code that performs an ETL process – reading data from Kafka and sending it to IT Elasticsearch cluster via a provided REST API, in a transactional manner. End-to-end tests were then developed, which produce data and read it back again – thus validating the full chain.

The initiative was completed on schedule before the end of 2018. As a result, the maintenance costs for the BE-CO Tracing Service have been significantly lowered (thanks to using IT ES), reliability has increased, and monitoring is in place. This gives a stable platform that users from the sector can rely on to diagnose data gathered from their systems which will be heavily renovated during LS2.

Additional work was also carried out to have a fully working setup of the new Tracing Service in the standalone Controls Test-Bed.

The Logging Service across CERN

The Logging Service continued to be heavily solicited throughout 2018, reliably supporting operations of all CERN accelerators and experimental facilities. In parallel, a significant effort continued to be invested in the new NXCALS project aimed at replacing the existing CALS logging system. On this topic, important progress was made as described below.

In April, the NXCALS service was moved to the new production computing cluster located in the CERN Computing Centre. From this point onwards, NXCALS has been considered as a production system in terms of user support, monitoring and ensuring availability. At the same time, NXCALS moved to use the standard Apache Hadoop distribution (moving away from Cloudera Company's distribution favoured thus far by IT). Concerning code quality, Sonar source software was fully integrated into the NXCALS CI/CD pipeline, to automatically detect bugs and fail new builds. A big clean-up effort was made in advance to get down to 0 detected bugs with 80% code coverage.

During the year, one of the key topics was the migration of historical data from CALS to NXCALS, for which there is more than 1PB in total for some 2.6 million signals. Not only is it critical to preserve the data logged so far in the CALS system, but the act of migrating data is also an excellent test of the stability and performance of the new system – as the data ingestion mechanism used to capture live data is also used to receive historical data from the migration process – thus placing huge loads on NXCALS. Throughout 2018, many performance and stability issues were solved and following the development and deployment of the new software to also migrate WinCCOA (industrial controls) data, migration rates increased from $\approx 100\,\mathrm{krecs/s}$ to $> 10^6\ \mathrm{recs/s}$. Up to 100 IT-provided Openstack machines (virtual computers) are being used for migration processes, however they regularly become overloaded and stop responding. To work around this, NXCALS migration process resources (e.g. queues, threads, etc.) needed to be carefully configured and tuned throughout the year. This was further complicated by the fact that the logged data is skewed across both entities and over time. Additional features also needed to be introduced to handle events such as device/property "renames" that are subject to appear during on-going migrations (since migrations can sometimes take several months to complete). The dedicated Migration Verifier application that was developed in 2017 to identify holes in the data, was further developed during 2018 and successfully found missing data during periods where it was actually foreseen (due to infrastructure failures). Missing data will be re-migrated in 2019.

As expected, the massive load generated by data migration highlighted the need to tune the NXCALS data ingestion API. Re-factoring was made to increase the level of asynchronous processing, in turn allowing for a correct backpressure implementation to avoid instabilities.

On a similar note, the BLM concentrator software was adapted to produce data in a format considered acceptable for NXCALS and started to log the large volume LHC BLM data. This exposed a bottleneck in HBase on the Hadoop side that was eventually solved in collaboration with IT-DB, using a more advanced configuration to split the data destinations, which in turn required more logic in the NXCALS code.

Also concerning data ingestion, a fruitful collaboration was established between BE-CO and BE-ICS to co-develop the new WinCCOA-NXCALS Data Source software, with BE-ICS agreeing to take on the responsibility for the maintenance from the moment it is deployed in production. As the name suggests, this software is used to send data from WinCCOA data archives to NXCALS for long-term storage. Following the end of the run, scalability tests were launched for a backlog of QPS data (the biggest CALS system by far). Following further configuration tuning, the full integration testing was successfully completed by the end of the year and now awaits production deployment in 2019.

On a less positive note, the NXCALS ETL (Extract, Transform, Load) process which moves data already ingested into Kakfa to HBase could not deal with the massive load generated by the QPS logging tests. A new horizontally scalable in-house developed ETL process was prepared and tested to replace the off-the-shelf software in early 2019.

On the topic of data extraction, numerous improvements were made in collaboration with IT to the process to integrate NXCALS updates with SWAN, including automatically publishing the NXCALS software bundle to EOS when it changes and gets built, where it can then be picked up by the SWAN distribution process.

The NXCALS Python and Java extraction APIs were heavily developed throughout the year. A lot of efforts were also made to tune data extraction performance by adapting the daily data compaction process to arrange data in an optimal way with respect to data extraction patterns. For some cases, users reported that a regular analyse that took 1 hour to process 1 day of numeric data in CALS, can now return a week's worth of data, instantaneously. After further investigations and testing, a solution was also deployed to improve extraction times for systems whose data exceeds GB/day by adapting storage partitioning intervals to be hourly (instead of daily) and applying sorting to the data within the partitions. This resulted is a ~10x improvement in extraction times for such cases. To benefit from this optimisation, older data will need to be re-compacted, but this task will only be performed on demand due to other priorities. Despite these encouraging advances, there is still a long way to go to tune the performance further and cater for the wide variety of use cases and data structures.

With a growing number of NXCALS users, efforts were made to improve the documentation including examples of CALS-equivalent calls using Spark. The MkDocs software was used for the documentation, as it allows to actually build the documentation as an integral part of the overall development pipeline. This allows to ensure that documentation is provided or updated as part of each relevant merge request – otherwise the build will fail.

In addition, quite some efforts were made to provide features required for the new Post-mortem system such reducing the latency for extracting the most recent logged data from HBase.

New strategy for operational GUIs

There are more than 500 operational Java Graphical User Interfaces (GUIs) used in the CCC and other control rooms, of which around 90% were written in Java Swing, and 10% in JavaFX. Unfortunately, after almost two decades of loyal service, Java GUI technology is declining (while Java on the server side continues to thrive!). In March 2018, Oracle, the company backing Java, stated in their Java Client Roadmap Update that JavaFX has become a "niche" technology with a "market place [that] has been eroded…" They also announced that they will not provide JavaFX as a part of the Java platform anymore, but instead let it live on as an open-source project maintained by the community.

We assessed this new situation for a few months by analysing Twitter feeds, discussions groups and the activity on the JavaFX github repository. We also talked to experts and participated in a workshop "JavaFX beyond 2022" in Munich, to meet with an official Oracle representative and with other companies using JavaFX. Based on all this, we finally concluded that we should not count on JavaFX as our future GUI technology.

We elaborated a new strategy for the development of operational GUIs based on Python and PyQt. Over the last few years, Python has been exploding in popularity. Worldwide, it is amongst the most popular programming languages and the number one "want-to-learn" language. In the Accelerator Sector, it is increasingly popular amongst physicists (for data analysis and MDs), equipment specialists (for GUIs, and prototyping/testing) and in controls (for code generation, DevOps tools and system administration). Python GUIs are typically written using PyQt, a Python binding to Qt. Qt is a popular GUI framework implemented in C++ and used in desktop applications such as Linux KDE and WinCC OA, and also in medical and media appliances, car dashboards, IoT devices and other embedded systems. Both Python and PyQt have existed for almost 30 years; Python is on the rise, and PyQt shows no signs of decline.

We decided to develop a GUI framework for Python similar to the one we already provide for Java Swing. We also plan to provide a Rapid Application Development (RAD) toolkit, which will enable users to develop dashboards and simple applications, with little or no Python coding.

The above considerations and the new strategy were presented in October 2018 in the CO3.

Device Lifecycle and Automatic Settings Migrations in LSA

In 2018, the LSA team contributed to a group-wide initiative called the "device life cycle", by developing software that automates the migration of operational settings. So far, the LSA team had to do this by hand, with careful analysis and tedious and error prone database manipulations.

Equipment specialists regularly make changes to FESA classes, normally to provide new functionality to Operations. All FESA devices have their configuration stored in the CCDB, and their operational settings stored in LSA. Therefore, changes to FESA classes have to be propagated through the controls system layers from FESA to CCDB and to LSA. From an LSA perspective, when the structure of a FESA class is modified, the LSA parameters and operational settings of the corresponding devices must be adapted too. This is a process called "settings migration". There are many different ways in which a device class can be modified (as illustrated hereafter), which makes automatic settings migration a surprisingly challenging task.

When a FESA class is modified ("migrated"), the new LSA settings migration software checks the consequences of these changes on the corresponding LSA parameters and settings. FESA developers can rename devices or properties, which triggers renaming of the corresponding LSA parameter names without changing the settings. FESA developers can delete devices or device properties; this scenario requires an interactive feedback from OP to confirm the deletion of devices and corresponding settings. FESA developer can also change properties of a given device class. If the type of a device property change in a “convertible” way (for example, from Integer to Long or to String), the corresponding settings can be automatically converted (rather than being deleted). If the FESA developer provides a so-called Migration Map (a recipe for handling non-compatible changes), this is used to correctly adapt the corresponding settings. Otherwise, migration is not possible and the FESA developer has to be notified.

For every change, the system sends notifications to the initiators of the change (the equipment groups) and to the responsible OP person in the accelerator(s) where the migrated devices are used.

Settings migration is a delicate task that can break operation. That is why the system provides functionality that enables the FESA class developers to simulate the impact of a FESA migration on LSA before the actual migration. Even with that, things can still go wrong. Therefore, our system implements functionality to roll back migrated settings, e.g. when an equipment specialist or operator notices that they have made a mistake.

UCAP

The UCAP project was launched in 2018 and presented in a CO Technical Meeting. UCAP stands for "Unified Controls Acquisition and Processing", and is sometimes defined as a "Virtual Device Service". The purpose of the project is to enable users to develop and deploy virtual devices with transformations written in Java or Python. This shall be possible for users with limited software expertise and without requiring the help of CO experts. UCAP aims to provide a platform for the transformation of data acquired (mainly) from devices. It shall also centralize and simplify the way this data is processed, and make the processed date suitable for further use in the controls system, e.g. in GUIs, fixed displays, server processes, logging etc.

Key elements of the project are:

- the UCAP project team provides tools for development, test and deployment of transformations, as well as the infrastructure required to run the transformations,
- the tools make it easy to create, deploy and monitor "transformations" to UCAP,
- the code stays under the responsibility of the developer.

The team started by tackling the requirements of the NXCALS system, where data acquired from devices is pre-processed before being stored in NXCALS.

By the end of 2018, they successfully deployed to production a first version of the "UCAP transformation server", which runs the over 950 transformations that already existed in the old CALS system. In this case, all transformation are written in Java.

In 2019, the UCAP project shall amongst others, cover more use cases, e.g. concentrators, fixed displays and the LN4 source control, and it shall support users who want to use Python instead of Java to write their transformation algorithms.

BE-ICS Group

SPS Fire Detection

In the context of the improvement of the fire safety of the SPS machine, BE-ICS took the responsibility to equip the SPS with several new safety systems: a new fire detection, a new public address system replacing the actual sirens and intercom, a new emergency call network installed all along the machine and a new safety interlock systems. For the work execution, a contract with the French company DEF specialized in fire protection was signed and approved by the 2017 December FC committee and started in January 2018. The 2018 objectives were to design and to validate all equipment of the project and more particularly the specific CERN Long Distance smoke aspiration system that has to cope with the SPS topology. The fire detection performance of this new system has been validated in a large scale pilot installation in the TAG41 tunnel. All the control cabinets were manufactured and 50% already passed the factory acceptance tests by the end of the year.

In parallel of the system design, important work was made to integrate the system in the 3D model of the shaft, access gallery and tunnel. The integration models have been validated in SPS 4 and SPS 6. The first ALARA committee was passed.

For consulting and conformity verification purposes a support contract has been signed with the French company CNPP (*Centre National de Prévention et de Protection*).

SPS Fire Protection system

It consists of refurbishing the SPS automatic fire extinguishing system. The upgrade of this system became necessary to comply with latest safety standards and is part of the objectives given to the SPS Fire Safety project. To this effect, a dedicated network of pipes and sprinklers will be installed in the shaft, TA tunnel and in the main ring up to the first Fire doors.

The contract with the Spanish company ARCECLIMA started in January 2018 with the general system design, followed by the detailed design of the BA4 and BA6 SPS sites. In parallel the efforts focused on the 3D modeling of this complex pipe network.

For verification and certification, we use the services of CNPP. The Engineering Change Requests, functional specifications, work package analysis, installation procedures and the work safety documents have been prepared and approved, allowing a quick start of the installation work as soon as the SPS sites are accessible during the LS2. A first ALARA committee has been passed.

Apart from the major SPS Fire Safety project, the focus for fire detection systems in 2018 was the introduction of a ticketing system to manage fire detection and emergency evacuation requests based on a workflow recognizing roles and responsibilities of the main project actors: HSE (authority prescribing personnel and environment protection), BE-ICS-AS (implementer) and Requestor (responsible of equipment, personnel and environment protection and guarantor of process and premises knowledge).

In October 2018, the Director-General launched a review of CERN's policy in matters of fire detection. HSE was asked to lead the review and limit it to surface buildings in a first stage. BE-ICS took a very active part in this work, providing all data about installed equipment, maintenance procedures and costs. The outcome of the review was very positive and allowed additional budget to be allocated to fire detection maintenance.

Many new fire detection installations where deployed in 2018, in the Polymer Lab (B771), the POPS Booster (B245), the FLEX Storage (B947), the Cooling Station (SFA181) and many others are in preparation for the LS2 such as the new ALICE & LHCb Data centre, the extension of SX5 (SXA5), the NanoLab (Extension of Medicis), the fire protection for kickers in ECA5 and fire protection in SPS electrical substations BM1, BM2, BM4, BM6, BE2, BE1. Several renewal projects were launched in SM18 area, Meyrin Diesel area, CTF3 area, Main Building and surrounding Public areas. Many others are in preparation for the LS2 in the AD Target and in the PS infrastructure.

Gas Detection

The focus for gas detection systems in 2018 was the new installation for cryogenics leak detection in the SPS Crab Cavities area and in the EHN1 Neutrino Platform, as well as the new installation for flammable and toxic gases leak detection in the Electronics' Surface Treatment B107.

During 2018, the renovation effort was put on the Heating Plant of Prévessin, the area surrounding the B107, and the Experimental areas of the EHN1 Salève side. Other projects were in preparation for LS2, such as the manufacturing of spare electronic cards for the SNIFFER systems to be able to keep those systems operational until LS3. In LS3, obsolescence will need to be addressed implying a complete refurbishing of those systems to maintain the same functionalities over the HL-LHC era.

Alarm Transmission

For alarm transmission, the focus in 2018 was on the user requirements review to define clear objectives for an upgrade of the CERN Safety Alarm Monitoring system, CSAM for the HL-LHC era.

A new database for alarm cabling traceability, R3Web, was ordered and development was be completed by the end of 2018. As built information is being collected in the SPS, Prévessin and LHC to update the new database.

SPS Personnel Protection System

The design of the new SPS Personnel Protection progressed according to the plans, highlighting more particularly the installation of a large-scale test platform, which is a replica of the CCC and site equipment. It will allow integrating and validating each component of the system and more particularly the safety interlocks, which are regulatory requirements for the protection of the persons working in the SPS accelerator complex against the radiation hazards.

A first Access point, integrating ergonomics evolution from the LHC and PS experience was installed at ECA5, allowing to validate the production of the 16 other Access Point by the SAIMA manufacturer in Italy. In 2018, the efforts concentrated on the revision of the safety functions, and Important Safety Elements definition of the SPS Machine and its Experimental Areas and also on the study of the deployment of the new system on AWAKE during the summer 2019.

SM18

Following a request of BE-RF, motivated by the functional and technical obsolescence of the present safety system, the group conducted a project to equip the SM18 RF test zone with a flexible state-of-the-art Personnel Protection System.

Laser rooms

Following a request of the DSOC in 2015, to increase the safety of personnel in class 3b and 4 laser rooms and to standardize the laser Personnel Protection Systems at CERN, the group set up a service to provide guidance and support for laser safety system design and installation. The Isolde, GBAR, MEDICIS, and CAST Experiments were equipped in 2018.

East Area Renovation

The ECRs for all the safety systems designed to satisfy the new East Area machine layout have been documented. It integrates the functionality required by the new EA1 and EA2 areas, the new Beam stoppers and the Personnel Protection System Interface with the new ventilation system (EA1). New access sectors have been proposed to minimise dose rates.

In the Experimental Areas, the Neutrino Platform Access system was one of the major modifications to the North Area, the GBAR personnel protection system was deployed in the AD Hall.

Site Surveillance and Access Control

In 2018, we significantly increased the video surveillance installations and site security installations, including Access control to two new site entrances (Entrance E and SM18).

Control Systems

The decommissioning of old LASER alarm system got finalized as planned in June 2018 by integrating all existing PSEN alarms (110k+) in TIM and PHOENIX. This important milestone allows TI operators to monitor all Technical Infrastructure alarms from a single application (PHOENIX). Furthermore, the alarm definition is now fully managed via MODESTI which is providing customized workflows (see **Error! Reference source not found.**99) to better coordinate the configuration tasks of the different groups involved.

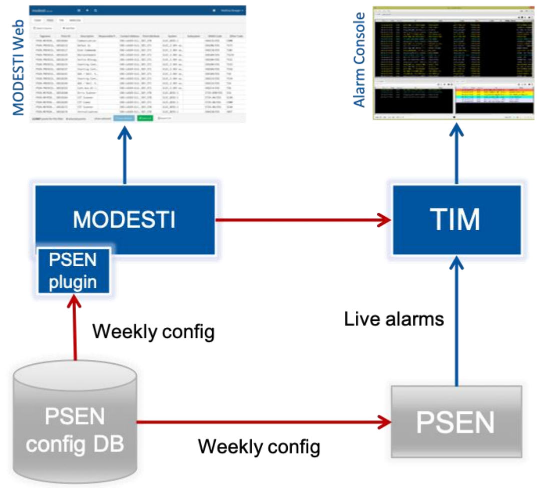


Figure 98: Synchronization of electrical alarms configuration with PHOENIX.

The central alarm information web pages (a.k.a. HelpAlarm: https://helpalarm.cern.ch) got re-developed from scratch to replace a 15-year-old implementation based on Oracle DB procedures generating HTTP web sites. This was a long standing request of the TI operators to improve the most used web site for technical infrastructure alarm handling. The new solution provides an intuitive search interface for browsing through more than 170k alarms with a fast and responsive design (see Figure 99). The user has the option to display the alarm search results with live updates either as list or on the GIS map. A detailed information page can be opened for every alarm which integrates nicely with PHOENIX, InforEAM and other standard tools at CERN.

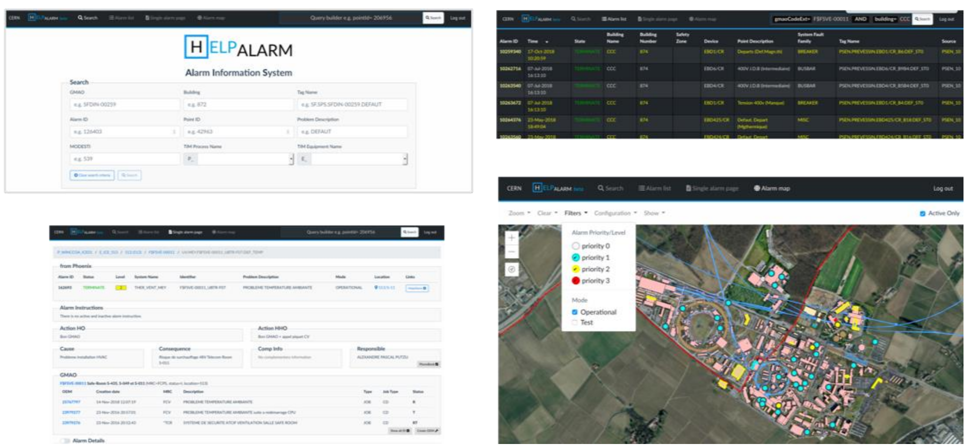


Figure 99: The new HelpAlarm interface.

The group's Jenkins infrastructure supports 668 build jobs and acts as the backbone of the BE-ICS software effort. This year the historical central monolithic instance has been migrated to the CERN Openshift cloud service, as the way to accommodate multiple BE-ICS software groups and ease the maintenance and upgrade of the infrastructure.

For AdaMS, a new mechanism was implemented to cope with urgent piquet IMPACT activities. This has cut significantly the delay to propagate urgent access rights, but implied serious modifications to ADaMS core functionality and philosophy.

Since summer 2018, external visitors have to print a badge at the reception before entering the CERN site. The user interface of the kiosk (cf. Fig. 100) software is an extension of ADaMS and supplies the guards with a practical and fast interface to locate reservations, print badges and consult the originating Service Now ticket for a visit. The kiosks print an average of 3500 access badges on a self-service basis per month. It is a major first glance that visitors have of the organization and it works just fine.

Figure 100: External visitor kiosk.

Industrial Controls Frameworks for WinCC OA

The CERN Industrial Controls Frameworks, JCOP and UNICOS, provide generic building blocks and a standardized methodology to implement industrial controls applications integrating a wide range of front-end equipment, including PLCs, commercial power supplies and the SCADA layer based on the Siemens WinCC Open Architecture (OA) package. The JCOP and UNICOS frameworks form the foundation of over 600 critical controls applications across the Experiments, the accelerator complex and CERN technical infrastructure, and these applications must be maintained throughout the lifetime of the LHC.

A major consolidation and redesign effort started in 2018 in order to minimize long-term maintenance cost and to modernize and prepare the Frameworks to meet the challenging upgrade plans of the LHC, including integrating new technologies (like the new Siemens S7-1500 PLC family and latest versions of TiA portal) and methodologies. The effort in 2018 focused on reviewing and standardizing the internal development process of the Frameworks, specifically the adoption of Agile methodologies and increased automation of many standard procedures in order to boost efficiency. In this sense, a new build system was developed, based on gitlab pipelines, to automate the build and release procedure for all software components comprising the Frameworks; these pipelines include execution of unit and integration tests and the production of documentation. Moreover, the frameworks benefitted from additional functionality at the request of the user community. Examples include the next generation archiving system for WinCC OA developed jointly with Siemens/ETM and the new alarm screen, the major refactoring of aging components of the Frameworks and the migration of the WinCC OA-CMW interface to RDA3 performed in collaboration with IHEP (Russia). This last project has been the first adopter of the new Device Server abstraction layer provided by BE-CO.

Another large part of the work in 2018 has been the preparation for LS2 upgrades. An important task in this context is the 2019 migration of the middleware used by all powering systems of the LHC Experiments to OPC Unified Architecture. In 2018, BE-ICS developed OPC servers for CAEN and ISEG power supplies through industrial collaborations with the manufacturers, and these servers were then thoroughly tested at the Experiments setups with help from the user communities. Furthermore, the collaboration agreement with Wiener was finalized in 2018, paving the way for joint development of an OPC UA server for Wiener equipment.

Finally, in line with the interests of external organizations like GSI and ITER, BE-ICS initiated a program to define a licensing model for the CERN Industrial Controls Frameworks. This activity (to be completed by 2020) aims to protect CERN Intellectual Property whilst promoting easy access to CERN software for external research centres and commercial companies.

Industrial Controls Applications

Cooling and ventilation control systems

During 2018, about 30 new PLCs were deployed in production. These PLCs were controlling the ventilation and HVAC of different installations as BAF3, BA6 BA surface buildings, BDF SKID, ALICE MFT, SR1B, POPS Dummyload, BMs, SU1, USA15…

A large effort was devoted to the preparation of the LS2 upgrades of large and complex systems as the HVAC of ATLAS and CMS, East Area renovation and P18 new buildings.

SM18 Magnet Test benches

CLUSTER G

During 2018, the reengineering of the Safety Instrumented System (SIS) for the SM18 Cluster G test bench started. This project follows a new development methodology designed to improve the traceability, testability and maintainability of the system.

The project development follows the recommendations given by the IEC 61508 standard and a new software specification method based on the Cause and Effect Matrix (CEM) formalism has been applied to this project. The goal is to provide an unambiguous and coherent specification and being able to generate test and verification cases from it. Both the safety requirements and operational requirements for this project have been specified using the CEM formalism.

CLUSTERS A-C-D

Cluster A and Cluster C have been upgraded to be able to test new HI-Lumi magnets, maintaining the compatibility with the previous magnet types, while cluster D (vertical) has been successfully upgraded with a new test type that provide an additional connection with to two new power converter units: 2K1 and 2K2.

FAIR

FAIR magnet test bench (see Fig. 101) has been fully commissioned, by testing on site all SIS (Safety Instrumented System) + BPCS (Basic Process Control System) control software. In

Figure 101: FAIR installation magnet test bench installation.

addition of SAT, the SIS software has been completely analysed and formally verified by our formal verification tool (*PLCVerif*).

The integration with the QPS + Energy Extraction systems has been provided using WinCC OA projects, by developing dedicated scripts for the interlock systems and dedicated faceplates for the operator interface.

MACHINE PROTECTION

WIC (Warm Interlock Controller)

Preparatory work for LS2 was performed along the year. Namely, several new projects were created and deployed on the LAB for the WIC team, including several new features for WIC SCADA: PS_AUX, LINAC4 to PSB TL, TT2-nTOF.

Machine Protection Testbed

By the end of 2018, the PIC, QPS and Circuit SCADA applications for the B272 machine protection testbed were in place and operational helping to make available a full testbed of the LHC magnet protection equipment.

PSEN: CERN Electrical Network Supervision System

Following the development and consolidation effort started the previous years, PSEN has been enriched with new functionalities based on the direct requests from the EN/EL users. These development lead to five different releases of PSEN during the course of 2018 providing the required improvements or new functionality. A new way of engineering the control system was created, the methodology allows performing all of the operations offline without impacting the production system. Another important hint was the release and update of PSEN to WinCC OA 3.15 P009 which required a four weeks phase of intensive testing and commissioning with EN/EL.

New extensions of the PSEN project allowed the natural integration of PSEN devices in the Power Converters control systems.

Waste Heat Recovery for LHC Point 8: Simulation Study

In close cooperation with EN-CV, a simulation study was carried out to assess the effects that the proposed waste heat recovery plant at Point 8 may have on the cooling towers and their associated controls. Using the simulation tool *EcosimPro* a model was engineered and validated with process data (Figure 102). When connected via OPC UA to a PLC running the UNICOS application for SF8, the study indicated that the installation of the waste heat recovery plant should not affect the cooling towers efficiency in cooling critical installations as the LHC cryogenics and no major changes are required in the current control strategy, on the contrary having a model of the process opens the possibilities of optimizing the controls to make substantial energy savings.

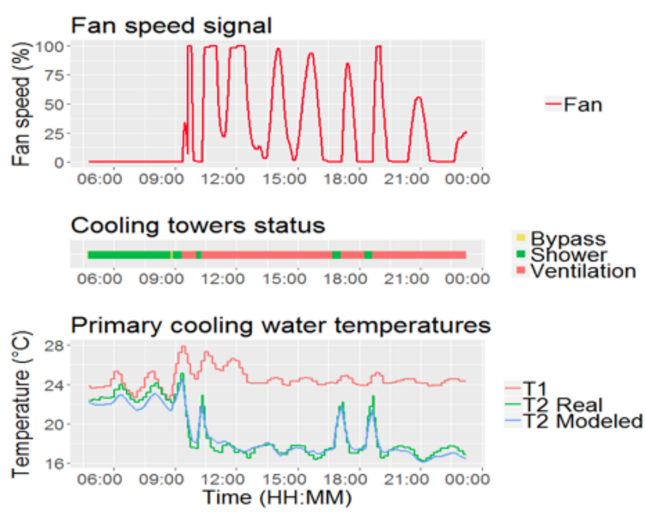


Figure 102: Cooling water towers model validation.

CERN Lifts

Some CERN elevators were integrated in a common supervision making a new domain standardized using UNICOS. The development allows the future integration of all new elevators being installed at CERN and with an Internet of Things architecture based on OPC-UA.

Large Magnet Facility (in collaboration with TE-MSC)

In the effort of standardize control applications around CERN, a new collaboration with the Large-Magnet Facility (TE-MSC) has been put in place. Their GLO furnaces had their own PLC-based controls developed by an external company. This situation brings two major issues: (1) External dependency of the evolution and (2) integration issues with the CERN services (e.g. Alarms, Long-term archiving)

To mitigate the second problem, a UNICOS-CPC project was put in place in order to collect data from the PLC and calculate deviations from the normal process of the machine and archive data of the magnets manufacturing, which will increase the possibilities to trace back fabrication problems. This allowed, for the first time, the archiving of data coming from magnet impregnations and a better capacitance measurement analysis.

PLCverif

PLCverif is an advanced tool developed at CERN to support formal verification of PLC (Programmable Logic Controller) programs and was awarded with a KT fund[1]. During 2018, the reengineering of the tool focused on essential features to create a turn-key tool usable by any project wanting to verify PLC programs.

In addition, in 2018 several CERN safety critical PLC programs have been verified using PLCverif. Some of the most relevant projects are the B311 switchboard facility and FAIR magnet test benches. In both cases, discrepancies between the specification and the PLC programs were found proving the importance of the tool on the development process of critical PLC programs. Today PLCverif is systematically used to verify the PLC programs of all the Safety Instrumented Systems (SIS) developed by the BE-ICS-AP section.

MONARC: Monitoring of SCADA Archiving Infrastructure

The SCADA Application Service manages two Oracle clusters of two nodes each to ensure the long-term archiving of all data coming from the 250 WinCC OA applications managed by BE-ICS-AP. While IT/DB is providing the Oracle infrastructure, the configuration, management and monitoring of the performance of the database is the responsibility of the SCADA Application Service. To address these needs, a new application called MONARC has been developed in order to monitor, configure and be notified of any performance issues related to the Oracle archiving infrastructure. It allows to have a high-level view on the status of the Oracle clusters, nodes and schemas and to configure the schemas individually or in batches without having to deal with low level and complex SQL queries.

BE-ICS Support Reorganization

The BE-ICS Support team (currently involving the AP, FD and, partly, the TI section) was reorganized under the umbrella of the new Operational Support Review Meeting (OSRM) in order to provide better and more efficient services to the Industrial Controls users.

The reorganization included the drafting of official support procedures and processes, a set of KPIs to be monitored along with the corresponding weekly reports, a new webpage and various JIRA Dashboards, in order to consolidate information, and various service scripts to automate support procedures. A clear distinction of the responsibilities of the three support lines was introduced,

[1] https://kt.cern/kt-fund/projects/automated-formal-verification-plc-code

with the goal of increasing development efficiency without compromising the quality of support services.

BE-RF Group

MB-IOT Tests in collaboration with ESS

In collaboration with ESS, two MB-IOTs (Multi-Beam Inductive Output Tubes), fabricated by industry, were tested at CERN in 2018. While normal IOT's operate at power levels below 100 kW, typically for TV transmitters, but at CERN also for the SPS 800 MHz system, the target for these 704 MHz devices was challenging 1.2 MW peak power.

The first device was developed and built by the American company L3, the second by a consortium between Thales (France) and CPI (USA). Both devices feature 10 beams, but subtle differences concern the ability to control the individual beams. Tests started in 2017, but both devices reached the specified performance in 2018; the L3 tube reached 1.2 MW peak, the Thales/CPI tube reached

Figure 103: Top row: L3 MB-IOT; bottomrow: Thales/CPI MB-IOT. For both devices, the 3-D rendering (left) and a photo (right) of the device under test at CERN are shown.

even 1.35 MW peak with pulses of about 1 ms rise- and fall-time and a 3 ms flat top. The efficiency reached remarkable 72% for the Thales/CPI tube, 68.5% for the L3 tube. Fig. 103 illustrates the

MB-IOT tests, showing their conceptual design and photos of the devices in the CERN test-stand in building 905.

AWAKE

After installation and preliminary conditioning of electron injector for AWAKE in 2017, the commissioning and improvement of the beam quality continued in 2018 in between experimental campaigns. The main focus was on improving the beam stability and beam emittance. Several improvements were implemented in the laser transport to the photo cathode, suppressing pointing jitter and improving the transverse laser spot profile. Consequently, the emittance of the beam for a charge of 600 pC was reduced from previously 40 μm to ≈ 10 μm in summer 2018. The emittance for the nominal charge of 200 pC was measured at about 5 μm, roughly still a factor 2 above the original specifications. It was found later though that, due to a too thick YAG screen, the measurements were overestimating the emittance. After exchange of the screen, beam emittances below 2 μm could be measured routinely for a charge of 200 pC. Beams over a large range of charge from 100 pC to 1 nC can be routinely produced and delivered to the beam transport. The good performance of the electron injector, which included significant improvement to its LLRF system, contributed to the successful experimental runs of AWAKE at the end of last year, regularly allowing stable acceleration and synchronisation of the electron beam with both laser and proton beam. A publication is under way to document the electron beam commissioning results.

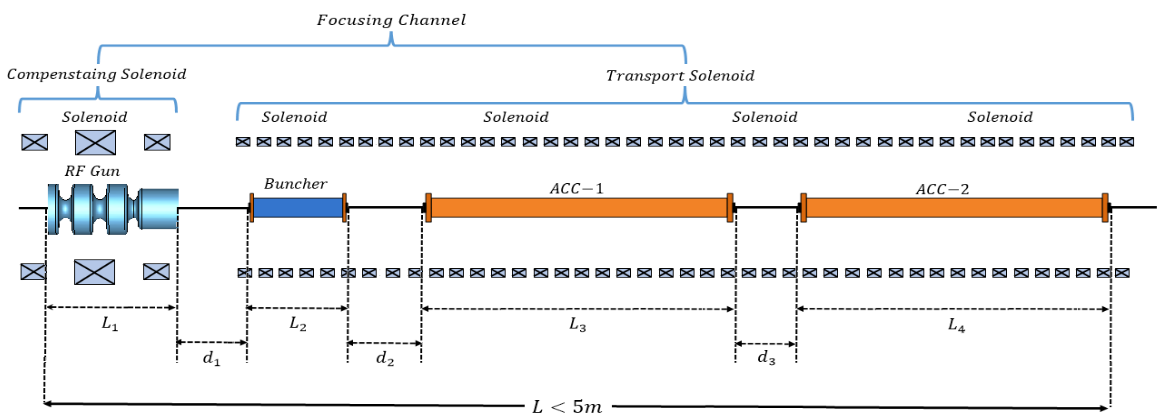


Figure 104: Schematic layout of the Run2 injector for AWAKE. Electron bunches are generated with an S-band RF- gun and then compressed longitudinally and accelerated using x-band accelerating structures.

The requirements and possible designs for a new injector for AWAKE run 2 were also studied in 2018. It turned out that the electron source needs a significant higher energy of ≈ 160 MeV and much shorter electron bunches of the order of 0.2 ps. This is needed to match the externally injected electron bunch to the plasma wake fields in order to achieve acceleration with a low energy spread and emittance preservation. The design of the new injector consist of an S-band RF gun, similar to the existing injector for run 1, followed this time by X-band velocity bunching and acceleration. Fig. 104 shows the conceptual schematic of this new injector.

PIXE RFQ

The design of a “portable” RFQ for the analysis of fine art and cultural artefacts, employing a technique called *Particle Induced X-ray Emission* (PIXE) to measure the elements present within a sample exposed to a beam of low-energy particles, was completed in 2018. The first vane of the RFQ has been machined and the manufacturing is progressing.

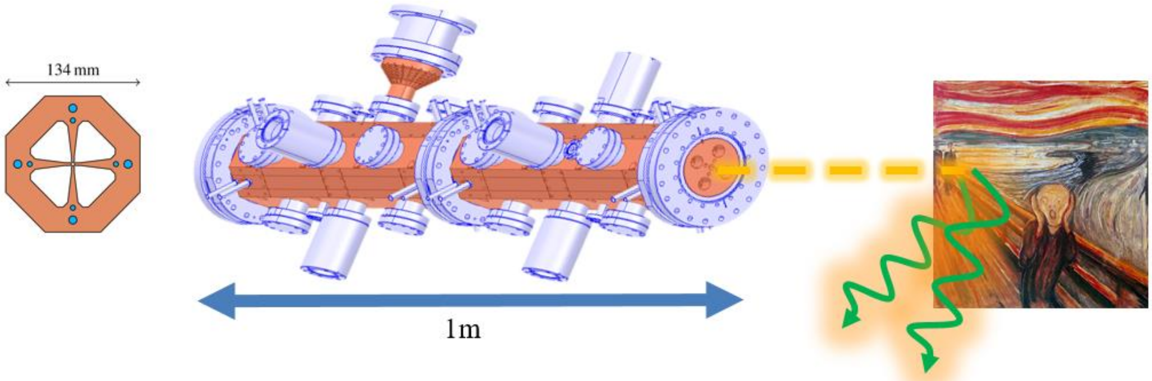


Figure 105: Artist’s view of a PIXE RFQ sending beam for probing art work.

High-Efficiency klystron R&D

The development of high-efficiency klystrons at CERN has considerably progressed in 2018. The efficiency of klystrons strongly depends on an efficient application of a technique called bunching, which aims at transforming a continuous beam into one containing discrete bunches of particles. New techniques for efficient bunching have since been established and evaluated, a new computer code for the fast and accurate simulation of klystrons (KlyC) has been developed, and a new scaling procedure was introduced. On this basis, klystrons for various frequencies and output power levels were developed at CERN in order to either increase their efficiency, their output power, lower their operation voltage or their size. Projects to build prototypes of these klystrons to validate the new concepts have been launched with industry.

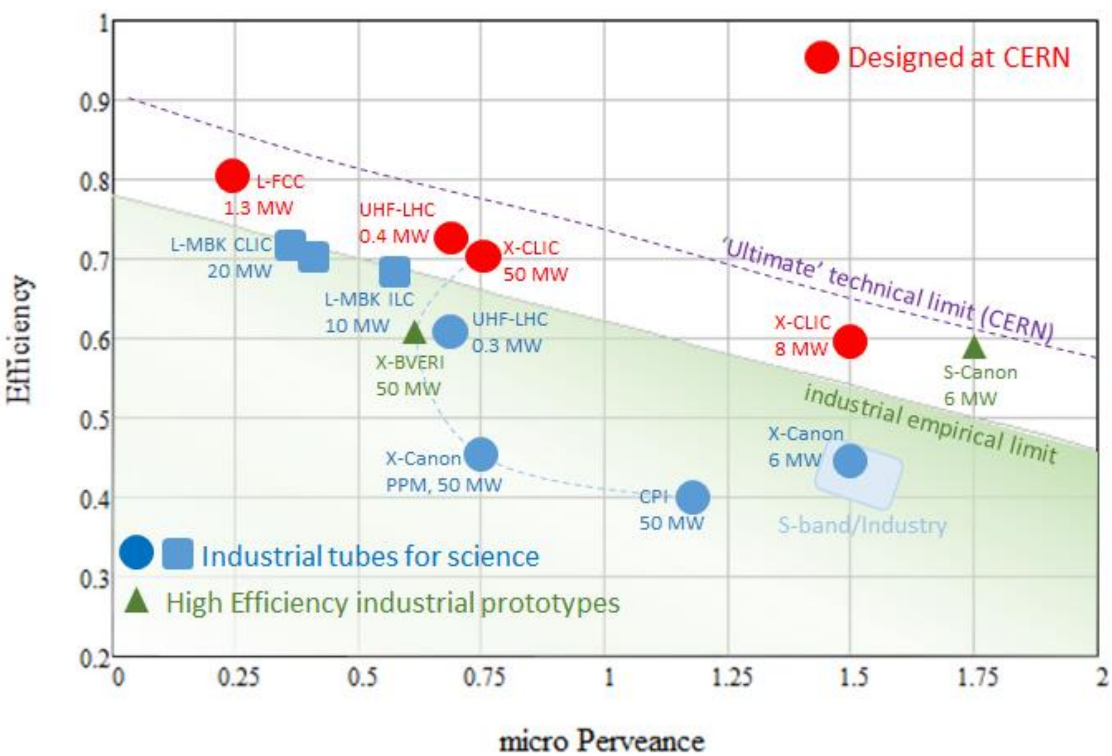


Figure 106: Latest klystron developments lead to higher output power, smaller size, lower power consumption depending on the optimization target and will be essential for any kind of new accelerator.

As mentioned above, part of this study aims at building a high-efficiency version of the LHC klystron TH2167, which could deliver 15% more RF power from the same modulator. It would directly serve the LHC and would allow to validate the so-called "core stabilisation method" (CSM), relevant for the FCC study, where energy efficiency is crucial.

SRF Infrastructure upgrade program

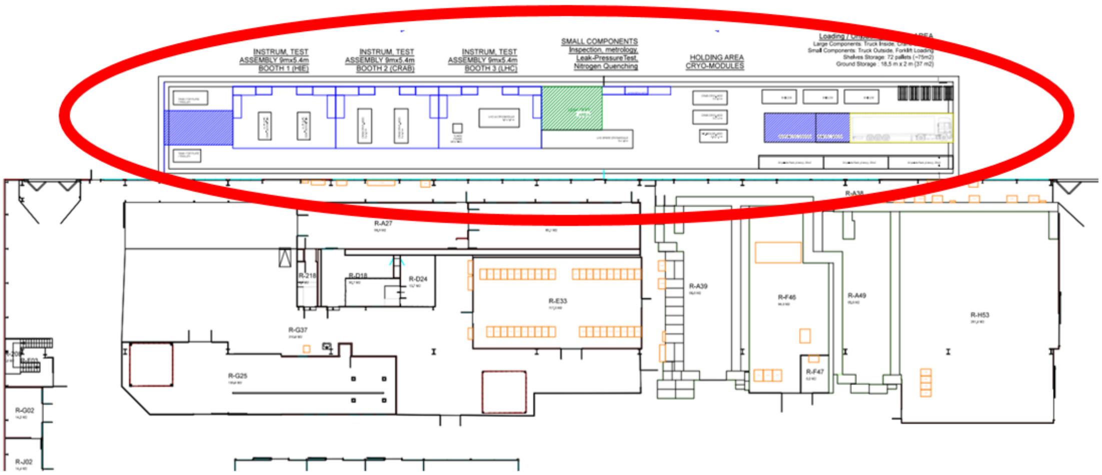


Figure 107: Layout of SM18 extension.

The effort on improving and consolidating the SRF infrastructure continued with the completion of the SM18 extension and the emptying of building 2002. Both buildings will be usable in 2019, urgently awaited to create dedicated workspaces for HIE-ISOLDE, HL-LHC Crab Cavity CMs, LHC ¼ module, secure storage of spare parts and spare cavities, and buffer storage for incoming material and cavities. A preliminary layout of the SM18 extension is shown in Fig. 108. For the new coupler test facility in building 864, the amphitheatre was removed and a new first floor built. Full completion is expected in 2019.

SRF R&D

CERN fell somewhat behind in SRF (Superconducting RF) R&D over the last decades. But a vigorous SRF R&D program has regained momentum some years ago, which allowed to successfully produce and maintain HIE-ISOLDE and LHC cavities, but also allowed to study new technologies and techniques in view of the FCC study. The aforementioned SRF Infrastructure upgrade activities are of course tightly connected to this effort. The following list summarizes the 2018 successes of this R&D program:

- The construction of the 2nd QPR (quadrupole resonator) for testing of bulk Nb and thin film material samples is completed and the device will be commissioned in 2019.
- A first promising Nb_3Sn sample with an intermediate Tantalum layer was measured with the old QPR and results were presented at the 2018 thin film workshop. Compared to previous samples, the residual resistance was reduced by one order of magnitude and is now comparable with Nb on Cu films, though with a strong *Q*-slope.
- The best result ever of a HiPIMS (High-Power Impulse Magnetron Sputtering) Nb on Cu sample was measured with very small *Q*-slope and a surface resistance comparable to bulk Nb.
- Bulk-Nb cavity tests on 704 MHz 5-cell cavities reached a performance comparable to the best results measured internationally.
- An international workshop on flux trapping and magnetic shielding was organised with support by ARIES and the TTC (TESLA Technology Collaboration).

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