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BE Department Annual Report 2017

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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 2017 highlights for the BE Department.

LHC:

BE-ABP Group

The most important innovation in 2017 was the use of a new optics, the Achromatic Telescopic Squeeze (ATS), after its successful validation in several machine development studies in 2016. This is the baseline for HL-LHC and it was important to set it in operation already during Run 2, as a proof of principle and to gain operational experience with it. The ATS consists of an optics setup that allows controlling the chromatic aberrations, the off-momentum β beating, and the spurious dispersion deriving from the large crossing angle which is required at small β^* in the particular case of the HL-LHC. It is divided in two parts: a so-called pre-squeeze segment, which acts on the matching quadrupoles of the interaction region (IR) in a traditional way and which relies on additional phase matching conditions to be met on several sections of the ring; a telescopic squeeze, which acts in a more global way, making use of the insertions located on each side of the IR, creating β-beating waves in the arcs which are directly adjacent to the low-β insertions, with their maximum at the sextupoles of a same electrical circuit. Consequently, the chromatic correction efficiency of these sextupoles will drastically increase at constant magnetic strength, which offers a cure for the chromatic aberrations. In the first period of operation in 2017, only the pre-squeeze was used to push β* down to 40 cm; the following step to 30 cm was instead relying on the new telescopic squeeze.

In 2017, another major revision to the commissioning strategy for low-β^* optics was introduced. The objective of this change was to extend LHC optics commissioning into the nonlinear regime. Indeed, to ensure the smallest possible β^*-imbalance between the high-luminosity experiments, not only was it decided to attempt direct correction of the nonlinear sources in the IRs, but also to perform a linear re-optimization of the optics at the operational crossing scheme after all higher-order corrections were applied. For the first time, the LHC operated with dedicated corrections for nonlinear errors in its low-β^* insertions, and for the impact of the operational crossing- scheme on the linear optics.

No regular one-month heavy-ion run had been scheduled for the LHC in 2017. However xenon beams had been prepared in the injectors for the fixed-target programme and a proposal was made to take advantage of this unique opportunity to inject them into the LHC. A plan for a short pilot-run was modelled on the very successful p-Pb pilot run in 2012. On 12 October, collisions of fully stripped xenon nuclei were recorded for the first time in the LHC at a centre-of-mass energy per colliding nucleon pair of $\sqrt{}$sNN = 5.44 TeV. Physics data taking started 9.5 h after the first injection of Xe beams. During 6 h of stable collisions an integrated Xe-Xe luminosity of about 3 μb^{-1} was delivered to ATLAS and CMS. Because of the larger β∗ values, fractions of 1 μb^{-1} were delivered to ALICE and LHCb. These provided significant insights into the physics of dense QCD matter at a scale intermediate between the LHC's usual Pb-Pb, p-Pb and p-p collisions and had a major impact on results presented by the LHC experiments.

BE-BI Group

First test of transverse beam size measurements using collimator BPMs

First quadrupolar measurements with beam position monitors (BPM) embedded in tertiary collimators were taken during a Machine Development period. In Figure 1, the emittance growth generated via a controlled blow-up using the transverse damper is clearly observed with such BPM measurements in both the horizontal and vertical plane. This technique opens the path for continuous, non-intercepting emittance monitoring at the LHC.

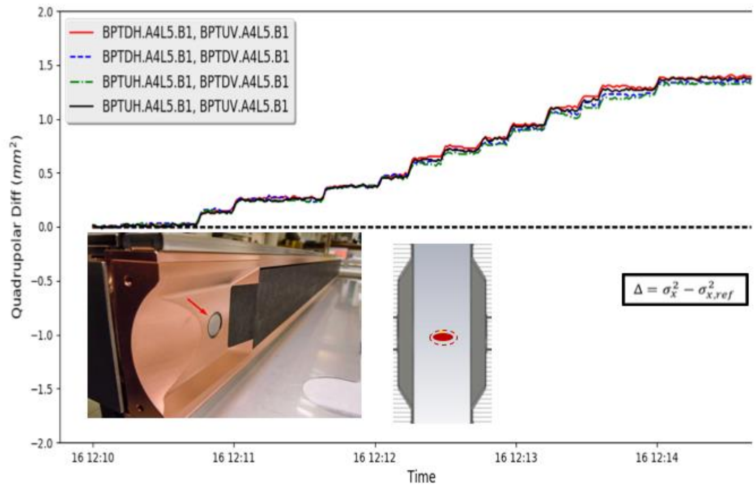


Figure 1: Evolution of the horizontal beam size during controlled emittance blow-up.

Latest results from the LHC Schottky system

Following major upgrades of both the pickups and the electronics, the signal quality of the LHC transverse Schottky system has been significantly boosted. A considerable amount of effort has also been put into the design and implementation of real-time software for both the control and data acquisition as well as the graphical user interface used for displaying derived parameters in the CCC (see Fig. 2). Early measurements noted a 1-2 unit discrepancy between the estimated chromaticity at injection energy measured by the Schottky monitor and the one predicted by the current offline model. An experiment was therefore carried out to further investigate the issue. The main conclusion was that both the RF modulation and Schottky chromaticity measurements agree fairly well with each other, with both indicating a discrepancy compared to the offline model (see Fig. 3). Further studies will be carried out in 2018, using both online and recorded data, in order to better understand the acquired spectra and further improve the chromaticity estimation algorithm.

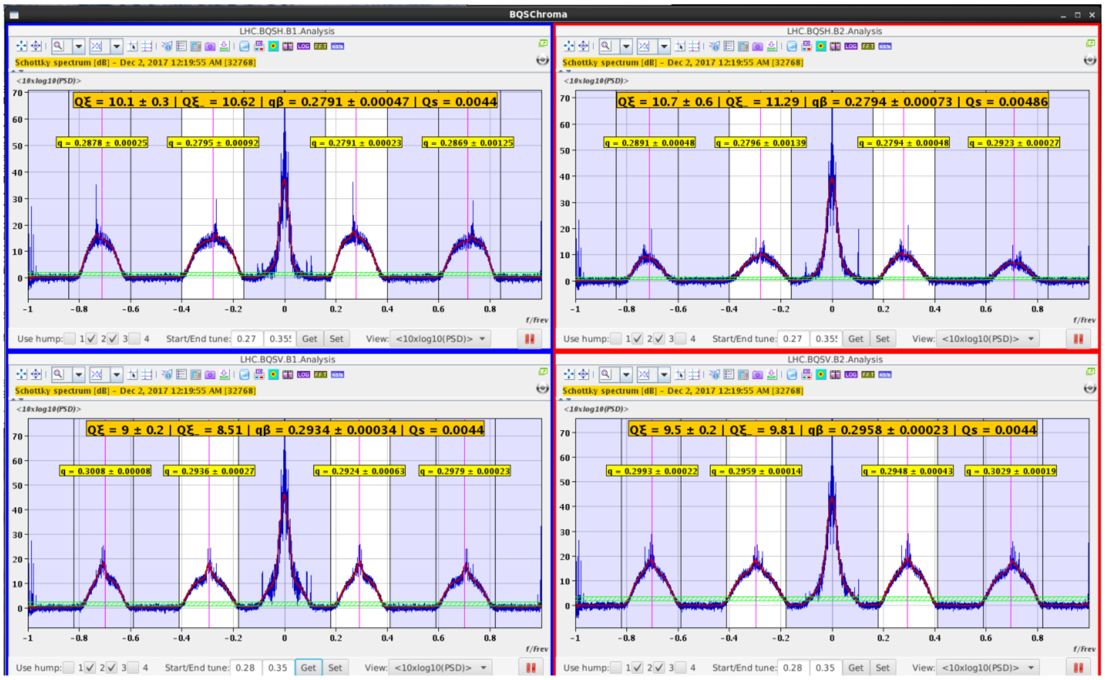


Figure 2: Schottky display GUI showing spectra from all 4 transverse planes.

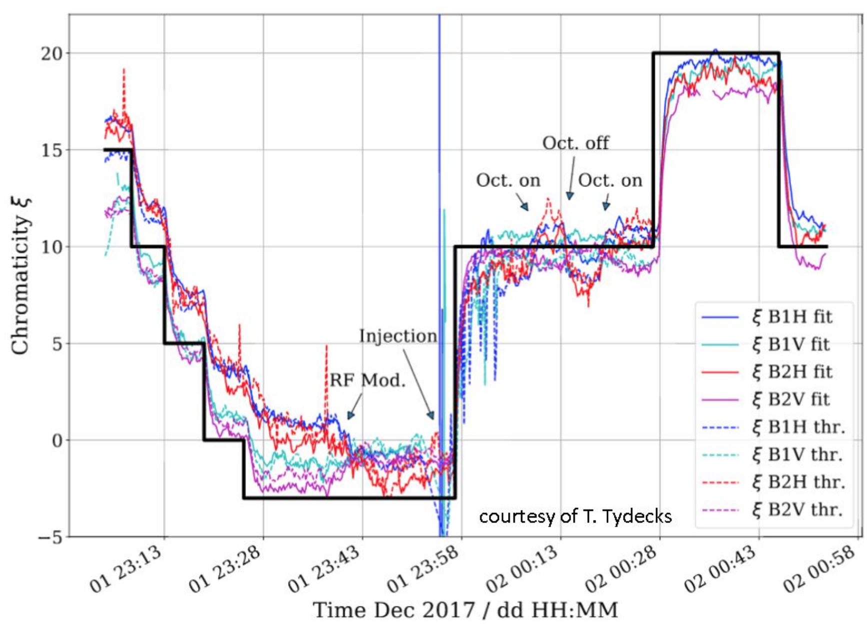


Figure 3: Schottky chromaticity estimates (colours) against prediction (black).

Investigations into the 16L2 problem

Recurrent beam dumps significantly perturbed LHC operation in the summer months of 2017. The beam dumps were triggered by fast beam losses that built up in the cryogenic beam vacuum at the half-cell 16 left of LHC-IP2 and were detected by the LHC BLM system either at that location or at the collimation insertions.

The ability to analyse losses near the 16L2 quadrupole during dump events was significantly improved during the run. First, 6 additional detectors and a mobile BLM system were installed at the location to increase the granularity of loss monitoring. This allowed the loss origin to be narrowed down to within 1.3 m in-between the quadrupole MQ.16L2 and the dipole MB.C16L2, thanks to fitting acquired data with simulation results of energy deposition from hadronic showers (see Fig. 4).

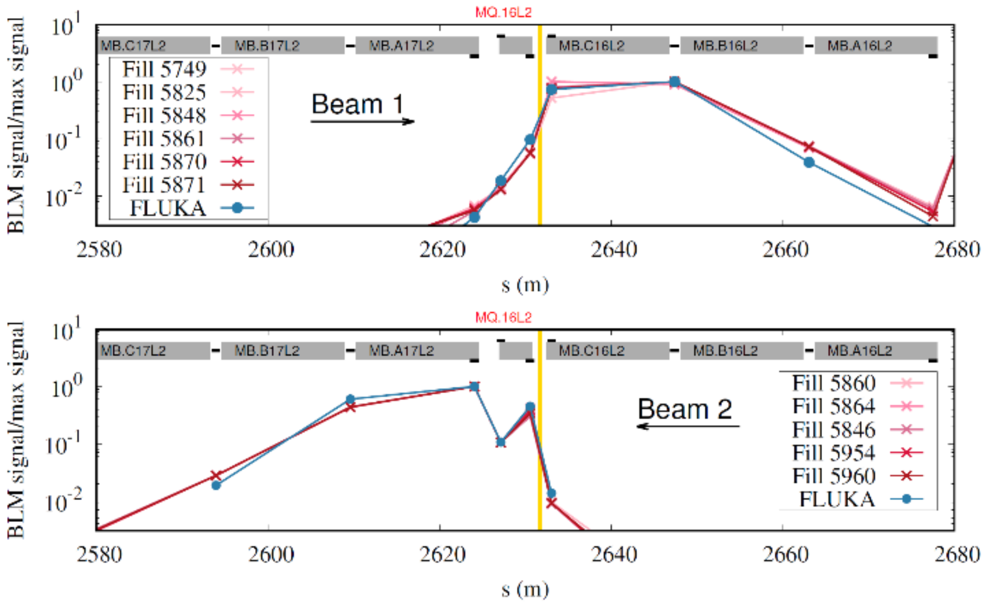


Figure 4: Loss pattern as a function of position along the machine for 16L2 dumps due to losses for beam 1 (top) and beam 2 (bottom). Measured data are displayed with red crosses and FLUKA [12] simulation best fit results with blue dots. The expected loss location providing the best fit to the measured data is indicated by a yellow line.

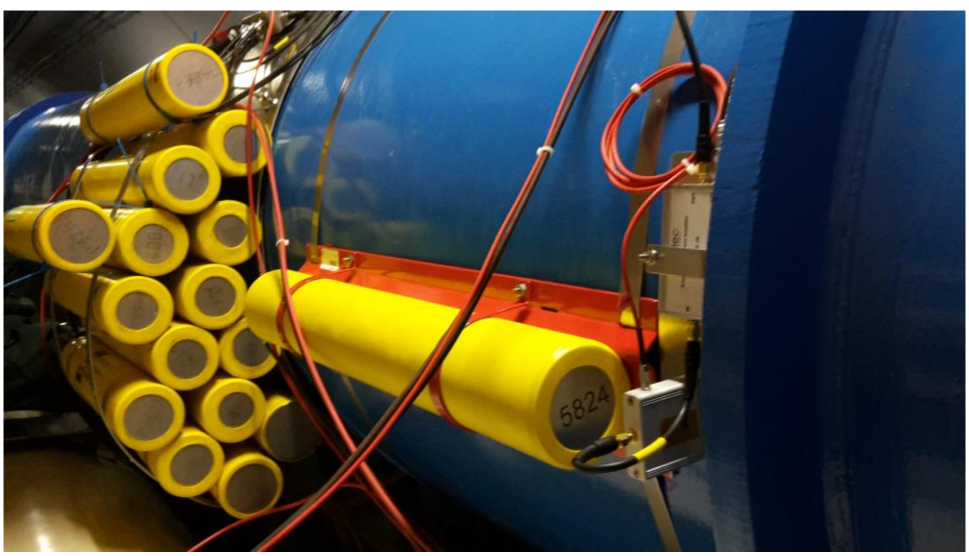


Figure 5: Bundle of 15 ionisation chamber beam loss monitors connected in parallel to observe losses at the LHC 16L2 location.

Later, to increase the sensitivity of the beam loss measurements, two bundles of 5 and 15 standard BLM detectors were installed (Fig. 5). The detectors on each bundle were connected in parallel to the same acquisition channel, allowing very low levels of steady state losses to be observed.

Finally, to provide on-demand, high frequency measurements, diamond detectors were installed and connected to dedicated, high-speed digitisers to observe bunch-by-bunch and turn-by-turn losses.

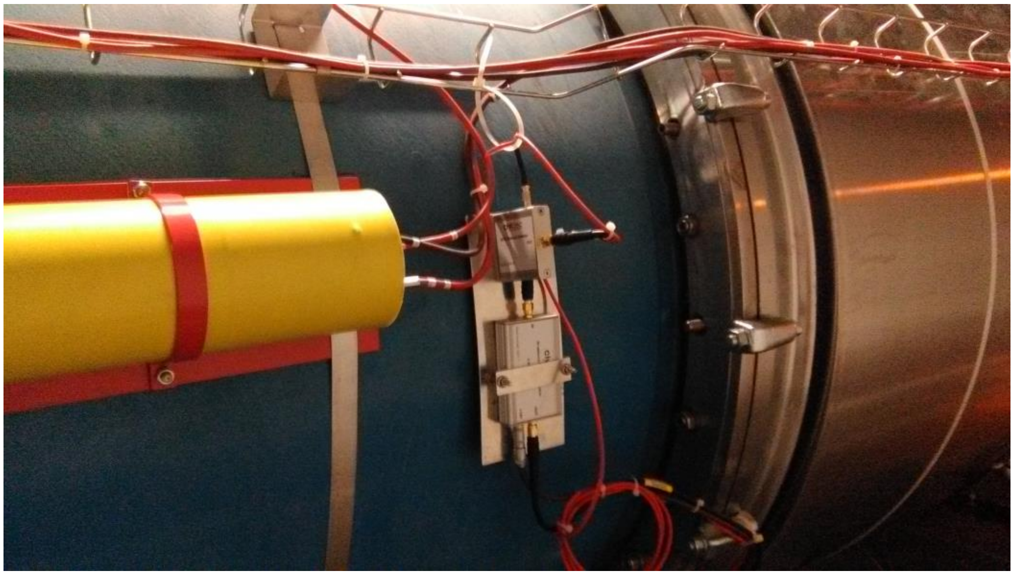


Figure 6: Diamond detector and signal amplification electronics at the LHC 16L2 location.

BE-ICS Group

LHC Cryogenics

During the year 2017, a long list of new features and corrections asked were deployed during the Technical stops. These include the change on controls of the QURCA of P8 as a prototype for the others points, change on the management of the HP compressor setpoints and many others to improve the operation of the installations. At the same time a number of new M580 PLCs were deployed in the LHC cryogenics control system within the upgrade campaign started in 2015 and ending by the end of LS2. Thanks to this campaign only one PLC crash was observed in 2017 (see Fig. 7)

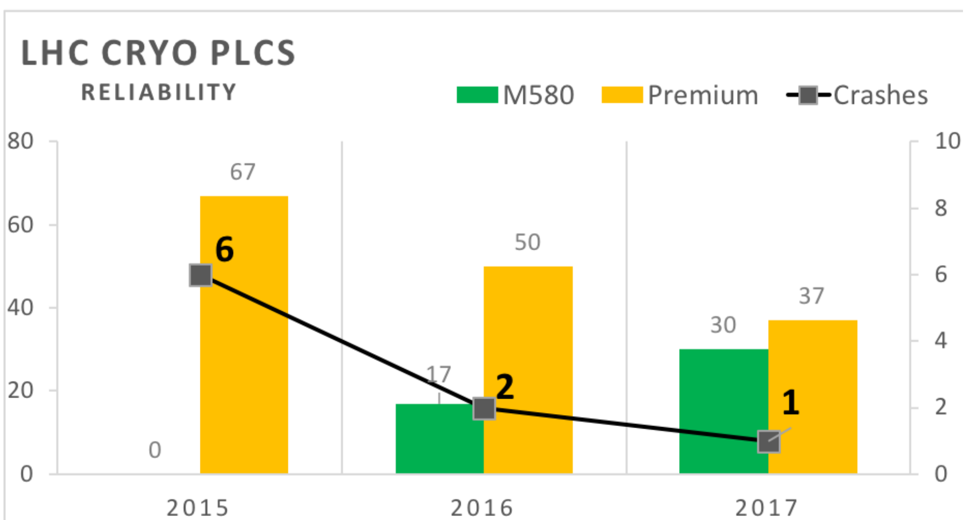
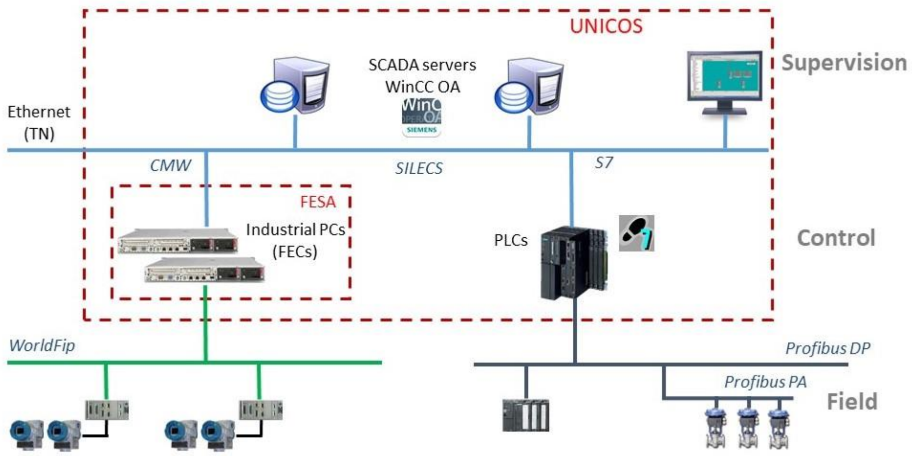


Figure 7

During 2017, the core of the activities for Cryogenics Instrumentation Expert Tool (CIET) were focused on three main topics; migration to the latest framework versions, including FESA, SILECS and UNICOS (for the SCADA layer), new developments to increase the availability and improvement of the preventive maintenance of the cryogenics control system. Among these new developments, it is worth mentioning to the automatic reset mechanism for the WFIP agents and the algorithms to compute statistics, like the relative standard deviation of the measured values of the WFIP sensors.

These new developments and upgrades were successfully deployed in the LHC and HIE-ISOLDE accelerators.



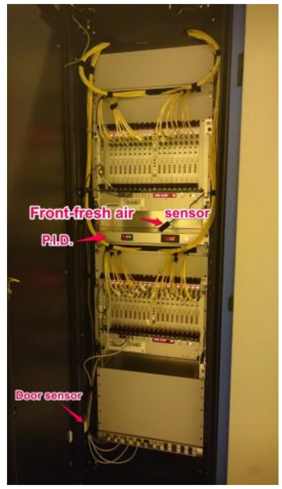
LHC GCS (Gas Control Systems)

The ICS group provides development, support and maintenance for the 32 Gas Control Systems for the 4 LHC Experiments, NA62, 904 CMS Mixers, LINAC4 accelerator complex and CLOUD Experiment.

During 2017, several upgrades were successfully made on the GCS during the TS and EYETS. Those include the migration of the GCS Data Servers to CentOS7 and new version of the SCADA to WinCC OA 3.15, the upgrades of several gas systems detectors of Alice, CMS and Atlas, and finally the development and integration of two new gas systems for CMS GEM and Atlas TRT. Moreover, a Java based tool was developed to replace the existing tool for the automatic generation of the GCS Human Machine Interface instances.

BI Rack monitoring

A new monitoring application was developed to show the status of the LHC racks containing beam instrumentation equipment, essentially temperature of the air and water are monitored. The application is based on standard UNICOS CPC-COMM solution and uses known and supported protocols to access the hardware (e.g. SNMP) and, based on alarms, allows the experts an early detection of problems in their instrumentation.



Machine Protection systems

Much of the work in the domain of the LHC protection was devoted to the conceptual design of the Powering and Protection Testbed in building 272 in collaboration with TE-MPE. This testbed incorporates different control systems such as the QPS (Quench protection system), PIC (Powering interlock controller) and the LHC Circuit. By the end of 2017 an initial setup of controls applications was in place on the Technical Network, but the decision was taken to move all testbed software to the GPN in order to minimize the risk of interaction of testbed systems with LHC systems.

BE-RF Group

The LHC Low-level RF (LLRF) systems for the 400 MHz RF system as well as for the transverse damper worked very reliably. The LLRF system needed to be switched to taking the spare antenna signal from cavity 1 on beam 1 due to an unreliable signal from the principal antenna used previously. The MD efforts concentrated on understanding the persistent longitudinal oscillations at injection and the study of the longitudinal blow-up, both these studies were conducted in preparation of higher intensities. For the setting-up, the code development in collaboration with SLAC was reviewed and migrated from MATLAB to Python, a significant effort which was paying off for the 2018 start-up. The full detuning method, modulating the phase following the bunch filling pattern to cope with increased intensities and reduce RF power needs, was also successfully explored and deployed in operation. Bunch length control and blow-up has been provided, in particular during long fills to limit the pile-up density in LHCb.

The ObsBox system provided online diagnostics both for the recording of the beam synchronous phase as well as the transverse oscillations at injection, for instability diagnostics and tune measurement. Following the encouraging results, further development of online tools is planned for the 2018 run. For the transverse damper development, work on a new beam position detection hardware with increased sensitivity advanced well through 2017.

The LHC RF power system was again remarkably reliable. The high voltage connections of the klystron gun tanks had been replaced during the previous YETS, which successfully helped avoid ionization and arcing problems. One half the klystrons is approaching the 50’000 operating hours, the formal “average life expectancy”. Although these tubes show no signs of aging or perveance change, we started working on possible replacements: A detailed study of a high efficiency 400 MHz CW klystron was conducted with the aim of achieving higher efficiency than in existing Thales TH2167, whilst preserving the klystron modulator parameters. This could allow a plug-in replacement of existing tube, anticipating that these renewed power stations could generate up to 400 kW in CW without modulator modifications.

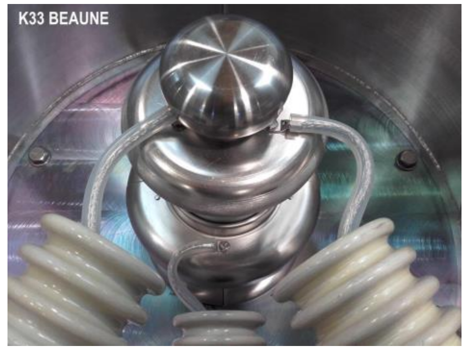


Figure 8: Inside the LHC klystron gun tank

High Luminosity LHC (HL-LHC) – LHC Upgrade

BE-ABP Group

The optimization of the optics and of the layout of the interaction regions around the high-luminosity interaction points (IP1 and 5) has continued in 2017. A new optics has been developed with optimized phase advance between the beam-dump kicker (MKD) and tertiary collimators (TCT) opening the way to tighter collimator settings. In addition, detailed and realistic beam-beam simulation studies together with the experience gained during the LHC machine run in 2017 have allowed reducing the crossing angle in IP1 and 5 by approximately 20%. These developments have reduced the requirements in terms of triplet aperture, thus leading to a reduction of the minimum achievable β^* from 20 to 15 cm. This restores the performance to the level before the 2016 re-baselining and recovers, and exceeds, the HL-LHC yearly integrated luminosity goal of 250 fb^{-1} even for the initially assumed performance efficiency of 50%.

The impact of the implementation of a fully remote alignment system allowing beam-based realignment of most of the elements of the final focus and matching section has been analysed. The study has demonstrated that the required strength of the orbit correctors of the matching section can be substantially reduced and therefore the existing LHC Q4 and Q5 magnet assemblies can be re-used and operated at the temperature of 4.5 K as it is presently the case in the LHC.

Progress has been made in the development of the optics measurement and correction techniques evidencing the possibility of suppressing a trim power converter allowing controlling separately the strength of the two Q2 triplet magnets, provided precise transfer function and magnetic measurements can be achieved and magnet sorting can be applied. However, the unprecedented accuracy in the knowledge of the beam size at the IPs, required to control the luminosity at the two high luminosity experiments, needs the implementation of K-modulation at the first magnet of the first final focus quadrupole Q1. An in-depth review of the new circuits has been carried out, and the requested performance assessed in detail.

A thorough review of the operational scenario has been made identifying the detailed machine settings and beam parameters for each of the phases of the HL-LHC cycles, both for the nominal and ultimate luminosity. Beam-beam simulations have confirmed the solidity of the operational scenario for nominal luminosity operation and the feasibility of operating at ultimate luminosity although with reduced margins.

During LHC machine studies two impressive results have been obtained, which are of significant importance for HL-LHC:

- The experimental validation of Molybdenum coating of Molybdenum Graphite (MoGr) collimators as a means to reduce collimator impedance. This has been demonstrated by measuring the reduction of the tune shift induced by the impedance as a function of the collimator aperture for Mo-coated MoGr collimators as compared to uncoated MoGr or CFC collimators (see Fig. 9). This has demanded the development of extremely precise (10^{-5}) tune measurements.
- The demonstration of beam-beam long range compensation by means of current-bearing wires that were installed in IR1 during the 2016-2017 Extended Year End Technical Stop (EYETS), which opens the path to an option to further enhance the HL-LHC performance

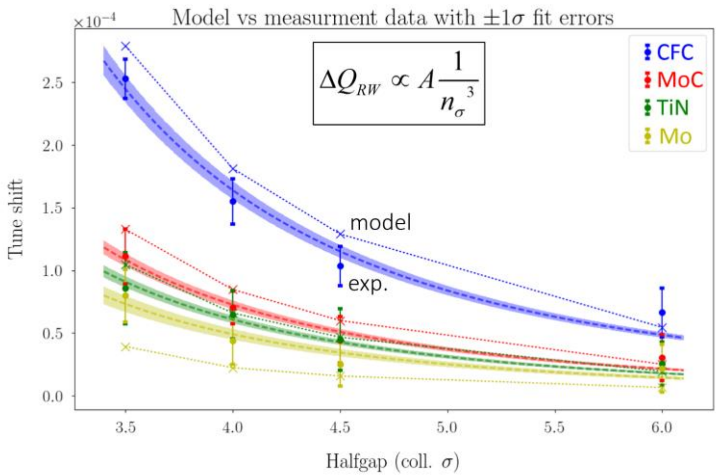


Figure 9: Dependence of the Tune shift as a function of collimator aperture for different collimator materials and coatings.

BE-BI Group

Mechanical design of the HL-LHC BPMs in the inner triplet of IP1 and IP5

The inner triplets in IP1 and IP5 will be replaced during LS3 with the installation of new, larger aperture and higher field superconducting quadrupoles. A series of new strip-line beam position monitors (14 per point from Q1 to D1) will be installed in the interconnections between cryostats. The design of these BPMs (equipped with Inermet inserts to absorb collision debris) has been studied for energy deposition and cooling as shown in Figure 12 and a prototype BPM is now under preparation.

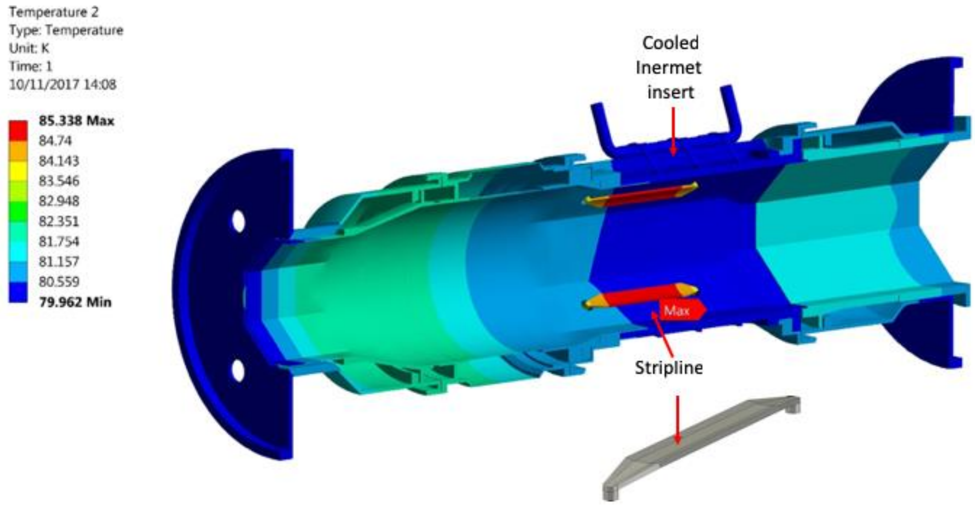


Figure 10: Thermal simulation for the newly designed strip-line BPM that will be located in the interconnections between cryostats in the HL-LHC inner triplet regions at IP1 and IP5.

Beam-gas jet diagnostics for HL-LHC

A collaboration agreement was signed between CERN and the Cockcroft institute in the UK in the framework of instrumentation for HL-LHC with the aim of developing non-invasive profile measurements capable of simultaneous monitoring of high intensity (~10 A) electron beams and high energy LHC proton beams. The aim is to provide diagnostics for either an electron beam based Beam-Beam Long-Range (BBLR) compensator or a hollow electron lens for collimation. This will be based on a gas jet luminescence device, and use existing experience at the Cockcroft Institute in this field, with an initial experimental set-up already available there for the project. A complementary collaboration agreement has also been agreed with GSI to benefit from their competence in optics and fluorescence measurements.

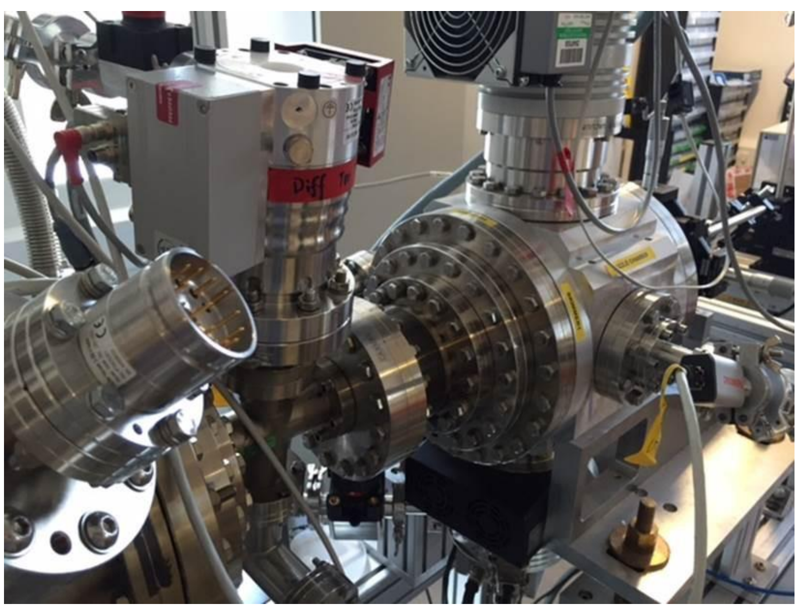


Figure 11: Gas-jet set-up at the Cockcroft Institute (UK).

Beam Gas Vertex (BGV) Detector Results

A beam gas vertex detector is being investigated as a possible addition to the suite of LHC beam size measurement devices, aiming for non-invasive measurements throughout the acceleration cycle for HL-LHC. After initial data taking in 2016, upgrades to the BGV read-out firmware as well as an increase of computing capacity by adding two CPU blades allowed the data processed to be increased by a factor of four. At the same time the fraction of good data could be increased to over 70% by applying better cuts to the data (Fig. 12).

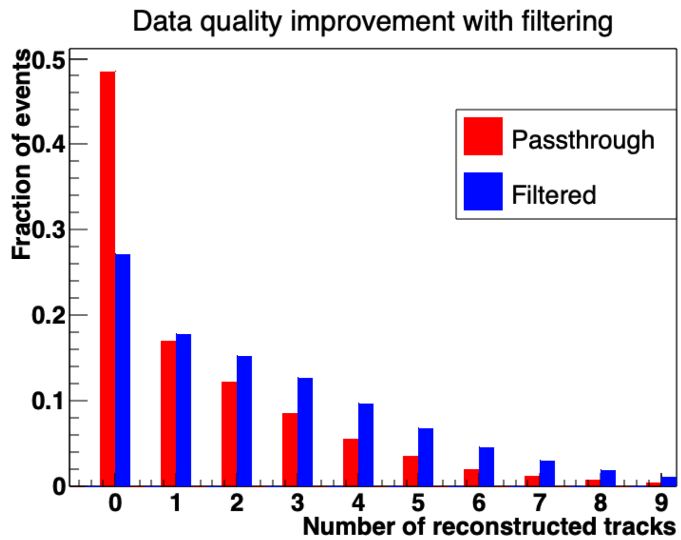


Figure 12: Quality improvement of BGV data through filtering.

Following this, 2017 saw the first long and very successful data-taking campaign of the BGV with acquisition at both 2.5 TeV and 6.5TeV. With this large amount of data two key areas for improvement in 2018 were identified: calculation and implementation of the measurement error and applying the new found precision to perform a rudimentary detector alignment.

BE-RF Group

The studies of longitudinal beam dynamics led to the change in baseline parameters of the HL-LHC. The bunch length of Gaussian bunch was increased from 1.05 to 1.2 ns to ensure beam stability in a single RF system of the HL-LHC.

Development of the BLonD code permitted to study the scenarios for HL-LHC with respect to the available parameter space for bunch length and voltage for given available klystron power. For the high bandwidth damper albeit not foreseen in the HL-LHC baseline, slotted kicker structures were proposed and scenarios simulated with the head-tail code in collaboration with the ABP group. Emittance growth due to crab cavity amplitude and phase noise was studied as well as the impact of the phase modulation induced by the main RF system beam loading and set-point modulation on luminosity in presence of the crab crossing.

Crab Cavities

After the descoping of HL-LHC in 2016, the new baseline with 8+8 crab cavities at IP1 and IP5, along with updated manufacturing strategy for the prototypes and the series production, was finalized and documented in an updated version of the TDR. Two double quarter wave (DQW) cavities, destined for beam tests in the SPS, were successfully fabricated and tuned to their final frequency. The 3D bead-pull test stand was used to perform field mapping for the two bare cavities, which subsequently were compared to the metrology measurements to validate the pole symmetry and electrical centre to be within 200 μm. The data were used for the intra-cavity alignment during the string assembly and the rest of the cryostating. RF tests of the bare DQW crab cavities were performed at 2 K in the SM18 facility reaching transverse deflecting voltages in excess of 5 MV, significantly above the nominal 3.4 MV. Following the successful vertical tests, the cavities were dressed with their Helium vessel and assembled with HOM couplers and field antennas. The dressed cavities reached only 3.3 MV; this limitation was later attributed to insufficient chemistry of the HOM couplers. Using a precision alignment trolley, the two dressed cavities with their respective power couplers, tuning systems and vacuum interfaces were assembled in the SM18 clean room. The cavity string was hermetically sealed in the ISO4 clean room before the cryostating phase.

Figure 13: String assembly of the SPS-DQW dressed cavities in the SM18 facility.

A special overhead assembly structure was built in the SM18 facility to assemble the cavity string into the cryostat, using a top loading scheme by the EN-MME team. Throughout the cryostating assembly, the inter cavity alignment was monitored to keep it well below the 500 μm specification. After the successfully cryostating and vacuum validation, the cryomodule was installed in the SM18 horizontal facility for a cool-down cycle to its operational temperature of

Figure 14: Cryostating of the 2-cavity string (left) and horizontal testing (right) in the SM18 facility

2 K with low power RF tests of up to 600 W including HOM measurements at 2 K. The complete tuning range was validated for the SPS tests with very little back lash and hysteresis.

For the planned crab cavity tests in the SPS, the infrastructure in point 6 of the SPS was prepared (Faraday cages, signal transmission to SPS BA3 and LLRF racks, vacuum chambers, movable table, high power RF system, cryogenics, electrical and other services) and prototype electronics were tested in SM18. The schedule for the preparation of the SPS tests is extremely tight (13 weeks!), but important not to miss since the 2018 run is the only available time window before 2021.

A detailed machine development program was developed to identify the four main phases for the validation of the crab cavities with proton beam. The required interlocks and safety procedures for a safe operation of the SPS crab cavities without perturbing the proton operation were implemented and tested. The program was approved with an initial request of 10 dedicated MDs over the run 2018.

Significant progress was made in establishing the collaboration with US-AUP to fabricate and provide 10 RF Dipole (RFD) dressed cavities towards the series production as part of the US in-kind contribution to the HL-LHC project. This included a detailed functional specification, interfaces and detailed timeline to be in accordance with the HL-LHC master schedule foreseen with the project. The UK-CERN collaboration agreement towards building the SPS-RFD prototype was finalized with detailed requirements, responsibilities and a timeline compatible with the manufacturing of the dressed cavities at CERN.

LHC Injector Upgrade

BE-ABP Group

To achieve the beam brightness and intensity required by HL-LHC, which are both roughly twice the present values, the LHC Injectors Upgrade (LIU) project has put in place a series of upgrades that will be mainly implemented during the Long Shutdown 2 (LS2).

Achieving double brightness for the LHC beams in the injectors relies on the reduction of the slope of the PSB brightness line by a factor two thanks to Linac4, as well as on the mitigation of the space-charge effect and other potential sources of emittance blow up at the PS injection. Concerning the former item, the PSB brightness line with half slope will be made possible with H^- charge exchange injection from Linac4 into the PSB at 160 MeV. An unchopped beam current of about 20 mA within 0.3 µm transverse emittance at the PSB entrance has been shown to be sufficient to meet the LIU/HL-LHC intensity and brightness targets (injecting about 40 turns), compatibly with the recovery of the PSB fixed target (ISOLDE) beams to the pre-LS2 performance. The first reliability run for Linac4 took place in the second half of 2017 and allowed the definition of the 2018 work program to achieve the required operational goals in terms the desired beam parameters and desired beam specifications (pulse flatness and pulse-to-pulse stability). Concerning the PS, its injection energy will be increased to 2 GeV and the longitudinal beam parameters at the PSB-PS transfer will be optimised to maintain the space-charge tune spread at PS injection at present levels, but for the twice higher brightness of the future beams. Intensive machine development campaigns took place throughout 2017 to gain an insight into the mechanisms of emittance blow up at the PS injection and prove the viability of the new longitudinal parameters. These studies will have to be continued in 2018 and combined with simulations to project to post-LS2 performance.

The production of double-intensity LHC beams in the injectors will rely on the longitudinal stabilisation of the beam along the PS cycle, as well as on the SPS capability of accelerating these beams thanks to the main RF system upgrade, the impedance reduction, and the electron cloud mitigation. The principal limitation for LHC-type beams in the PS comes from longitudinal dipolar coupled-bunch instabilities. A dedicated broadband feedback system using a Finemet cavity as a longitudinal kicker was installed in the PS during LS1 and it has been commissioned over the successive runs to combat these instabilities. Nevertheless, due to longitudinal quadrupolar instabilities and incoherent emittance growth, the maximum intensity achieved with nominal longitudinal emittance in 2017 was limited to 2.1×10^{11} p/b at PS extraction. The beam was found to be transversely stable along the PS cycle up to this intensity and a new operational setting with low chromaticity and transverse damper was tested at injection energy and over the 2.5 GeV energy plateau in order to further improve the transmission and free the tunes from the constraint of proximity to the main diagonal to induce linear coupling. The high-intensity beams produced by the PS in 2017 (up to 2.1×10^{11} p/b) were also tested in the SPS in dedicated machine studies in spite of the RF power limitation. Coupled bunch instabilities at 26 GeV have been observed, both in the horizontal and in the longitudinal plane. The horizontal instabilities exhibited clear intra-bunch modes with the number depending on the chromaticity settings, see Fig. ABP2. The nature of these instabilities still needs to be understood in detail, and thus further studied in 2018, so that the post-LS2 SPS operational scenarios can be defined based on numerical simulations.

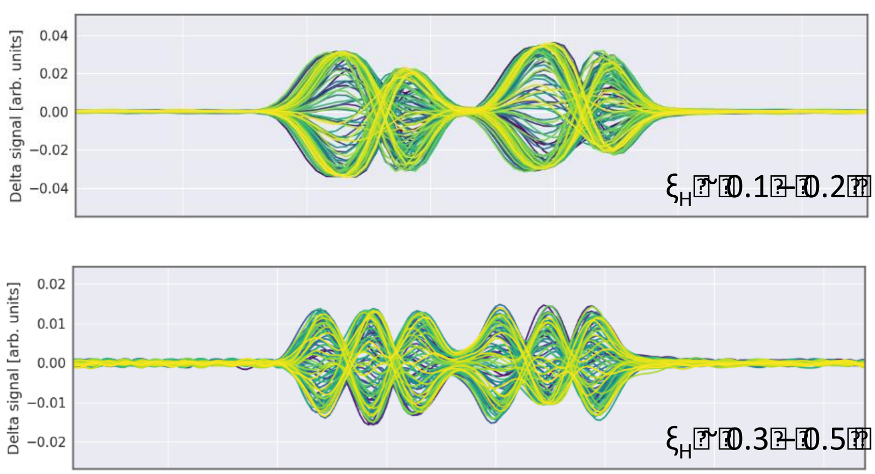


Figure 15: Horizontal beam position for selected bunches at the end of 48 bunch trains measured with the Headtail monitor in the SPS. Low chromaticity (top) and high chromaticity (bottom).

Also the electron cloud can be a potential limiting factor for operation with high intensity in the SPS. Accelerating the present LHC beam without significant degradation from the electron cloud required several days of dedicated scrubbing distributed over a few years in the first decade of 2000. Scrubbing is preserved from year to year in the SPS regions not exposed to air during the technical stops, while it is partially lost, but usually quickly recovered, where there has been air exposure. Studies of electron cloud build up in the different SPS chambers have revealed that the Secondary Electron Yield (SEY) thresholds will not change significantly for most geometries, when doubling the bunch intensity. However, this beam may suffer multi-bunch instability from the electron cloud in the dipoles, because the high electron density stripes will move further out to regions previously unscrubbed. Fortunately, extrapolating from the present experience and based on our understanding, it can be assumed that beam induced scrubbing, although potentially time consuming during beam commissioning in Run 3, will be applicable up to the future bunch intensities.

BE-BI Group

A radiation tolerant digital Front-end board for Beam instrumentation

Developed in the context of the LIU project, a radiation tolerant digital acquisition board, the S-GEFE, was designed and prototyped. It will be one of the building blocks of the new SPS orbit system but is also foreseen as a generic acquisition board for several other systems CERN-wide. As depicted in Figure 16, the board is split in two parts, an FMC carrier board (C-GEFE) featuring commercial components qualified up to 750 Gy and an FMC communication board (L-GEFE), based on radiation-hard components developed by the EP-ESE group (GBTx, VTRx) that can withstand an integrated dose as high as 10 kGy. The C-GEFE has a second FMC connector for an application specific FMC board which, in the case of the SPS BPM system, is based on radiation hard 40MHz ADCs.

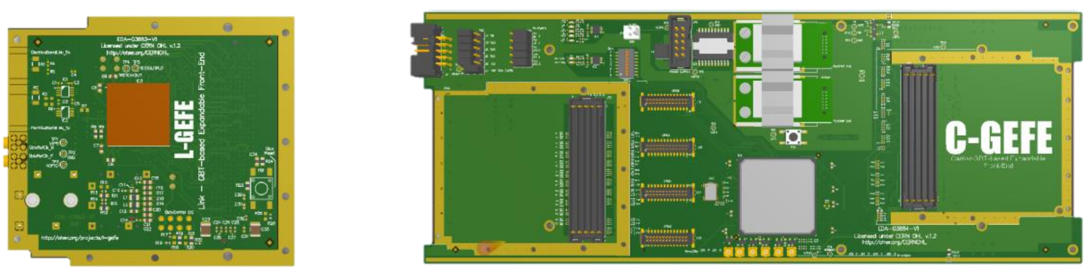


Figure 16: **The S-GEFE is composed of a Carrier board (C-GEFE) and a Communication board (L-GEFE).**

PSB orbit system upgrade

The upgraded PSB orbit measurement system was successfully commissioned and made operational with beam during 2017. The existing dual-plane BPMs (16 for each PSB ring) had new cables, front-end electronics and a new digital acquisition system with a dedicated FESA server. The BTMS (Booster Trajectory Measurement System) offers bunch-by-bunch trajectories over the whole cycle as well as orbit measurements on the 4 rings simultaneously. An example of orbit measurements using the BE-BI expert GUI can be seen in Figure 17.

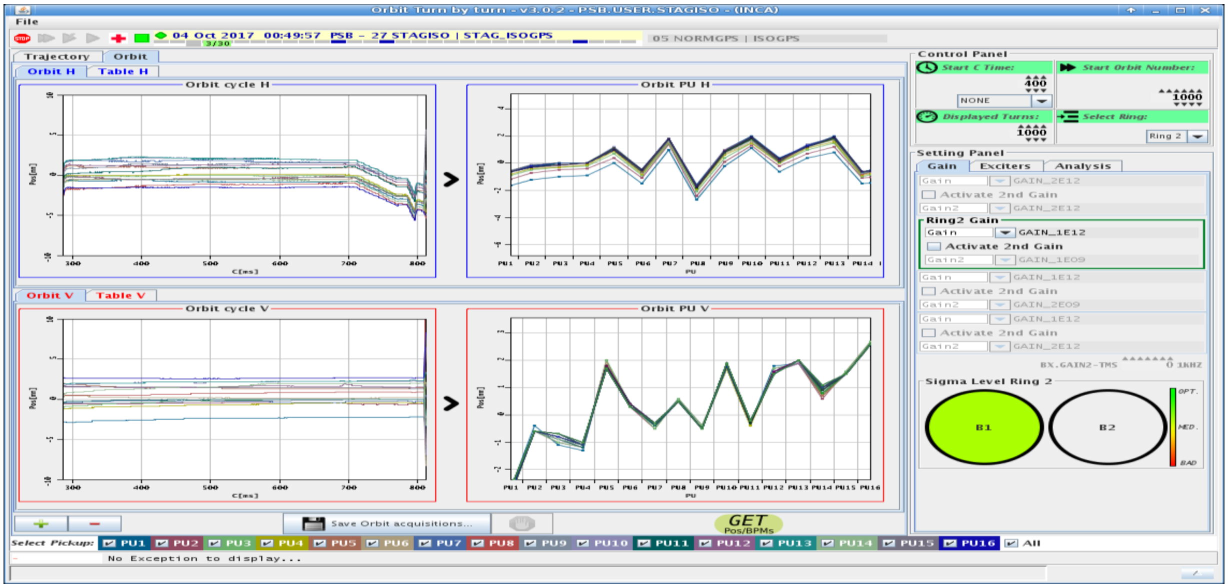


Figure 17: BTMS orbits shown with the BI expert GUI.

PSB injection Beam Current Transformers (BCTs)

As a part of LN4 Machine protection system, the intermediate or semi-fast BCTs in section 8L1, were updated with new toroid windings and new front-end electronics. The aim is for each ring to compare the beam intensity in the BI lines with that of the circulating beam. The bandwidth of the system was adapted to cover the full intensity range from the LHC pilot to ISOLDE. The interlock logic should inhibit injection of subsequent pulses if the observed loss is above a pre-set threshold. An oscilloscope image of the first measurements can be seen in Figure 18.

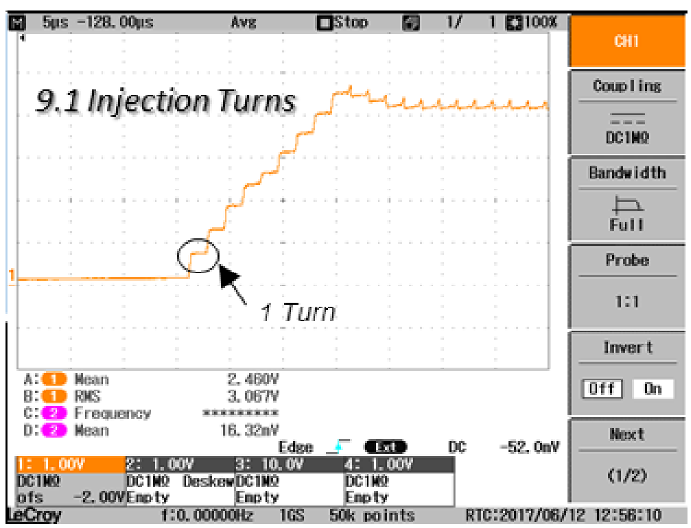


Figure 18: Multi-turn injection into the PSB as seen by the semi-fast BCTs in section 8L1.

LIU Beam Wire Scanners (BWS)

A new generation of BWS are under development for LIU, planned for installation in the next long shutdown in PSB, PS and SPS rings. A first prototype was installed and successfully tested in the SPS, however this design was not sufficiently compact to integrate into the four-ring structure of the PSB. A new mechanical design was therefore made, using the same concept as the SPS design. A prototype of this design was produced and successfully installed and tested in the PSB during

2017 (see Fig. 19). 2017 also saw the final design review of the BWS mechanics, with financial approval being given by the LIU project for series production.

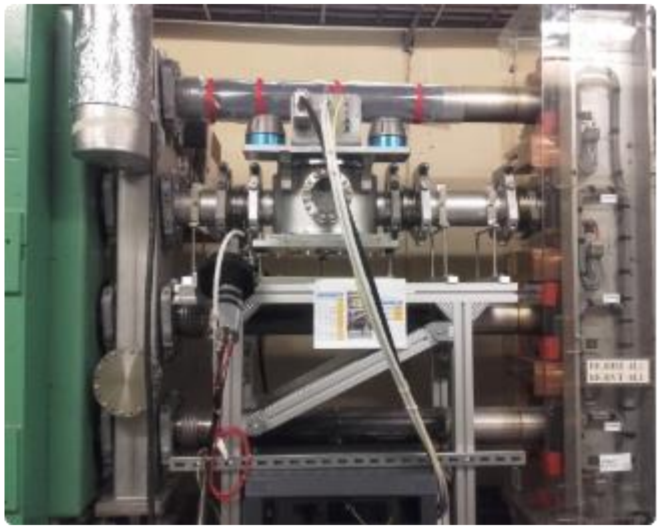


Figure 19: Prototype LIU wire scanner installed in the PSB ring 3.

In parallel, a new secondary particle acquisition system was developed, produced and tested in the PSB. The existing BWS acquisition systems consist of a scintillator for particle to light transformation, connected to a photo-multiplier and single photo-detector to produce an electrical signal. The photo-detector is equipped with a mechanically moveable filter to scale the light flux to the different particle intensities from the beams. The new system removes the need for the optical filter and varying the gain of the photo-multiplier by using four parallel acquisition chains linked to four photo-multipliers fitted with different filters. This allows the instrument to capture a much broader range of intensities without the need for physical change of filters, in a similar way to how a "high dynamic range" photograph is taken using a modern digital camera. This new system produced very promising results, as can be seen from Figure 20. The image shows BWS scans of different intensity beams in the PSB, with new and existing acquisition signals overlaid. The signal from the existing system is saturated at high intensity and would require a filter change, whereas the new system is able to correctly acquire the signal for all intensities.

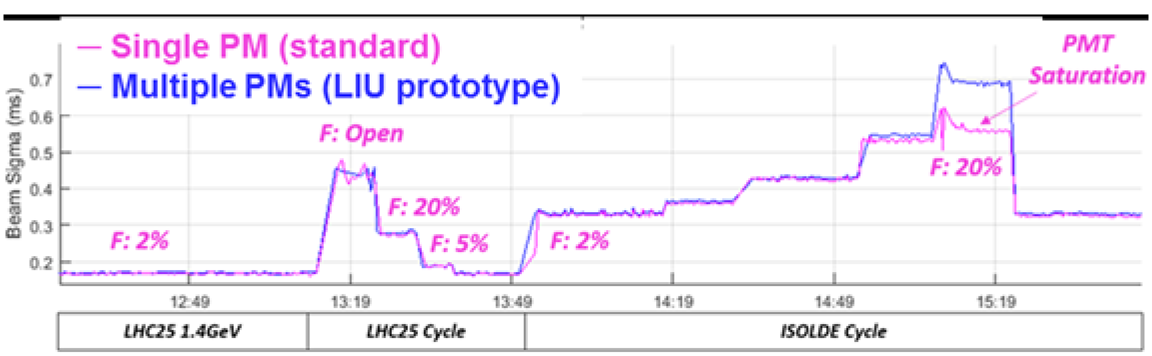


Figure 20: Measurements of beam size (sigma) for different PSB beams for both the operational (single PM) and prototype wire scanners.

Upgraded Ionisation Chamber based BLM systems

Supported by the LIU project, a new BLM system with more performant electronics and ionisation chamber type detectors will replace the legacy (ACEM) systems in both the PSB and PS. The new system offers much higher dynamic range (10 pA to 200 mA) and is complemented by adding several diamond detectors for bunch-by-bunch measurement at strategic locations.

The BLM system, through its direct connection to the beam interlock system, will have the ability to block upcoming injections when the loss thresholds are exceeded.

Specifically for the PSB upgrade and based on FLUKA simulations, it was found that it would be of great advantage to have additional BLMs installed in the L3 locations of each sector in the PSB ring. To fulfil this requirement, a Flat Ionisation Chamber (FIC) detector was designed and produced to fit the strict space restrictions. This very compact design (Fig. 21-22) made it possible to install two detectors per period, one monitoring beam losses from ring 1-2 and the other from ring 3-4, giving 32 FIC detectors in total.

Figure 21: 3D drawing of the assembled support together with the FIC BLM detector.

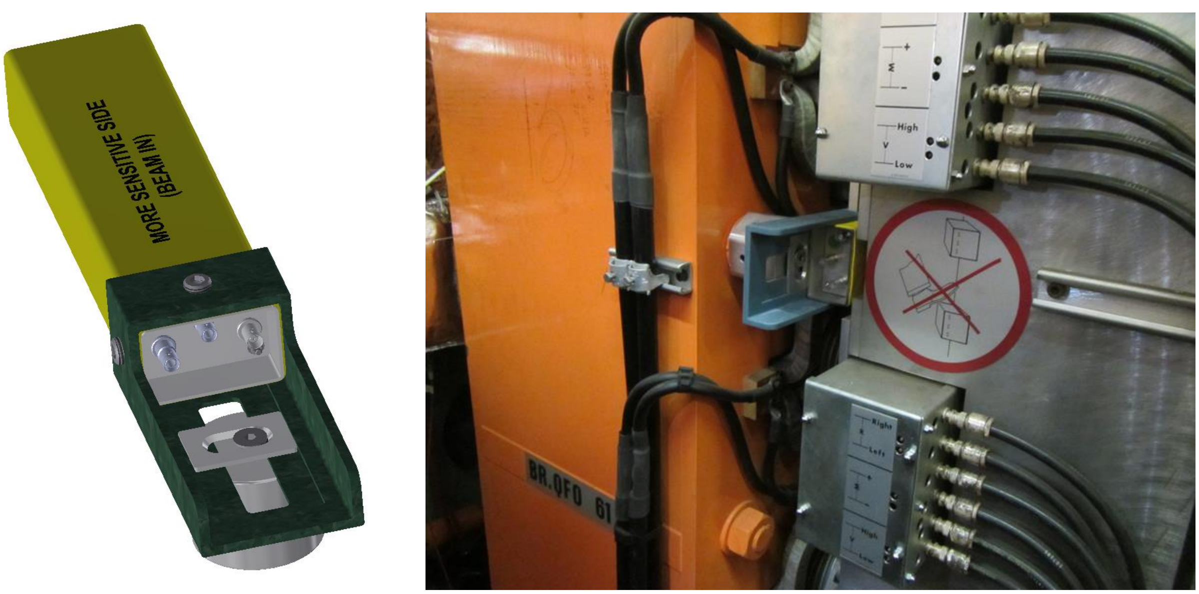


Figure 22: 3D drawing of the FIC BLM on its support, and the detector installed in the PSB.

A similar upgrade program of the BLM system in the PS Ring took place during the year-end stop, this time using LHC type ionisation chambers (IC) as detectors. The 100 IC detectors were put on top of each main magnet. In addition, at 17 of these locations, where bunch-by-bunch measurements would be beneficial, a diamond detector was installed just below the IC on the same support.

First Results from the PS Beam Gas Ionisation (BGI) Monitor

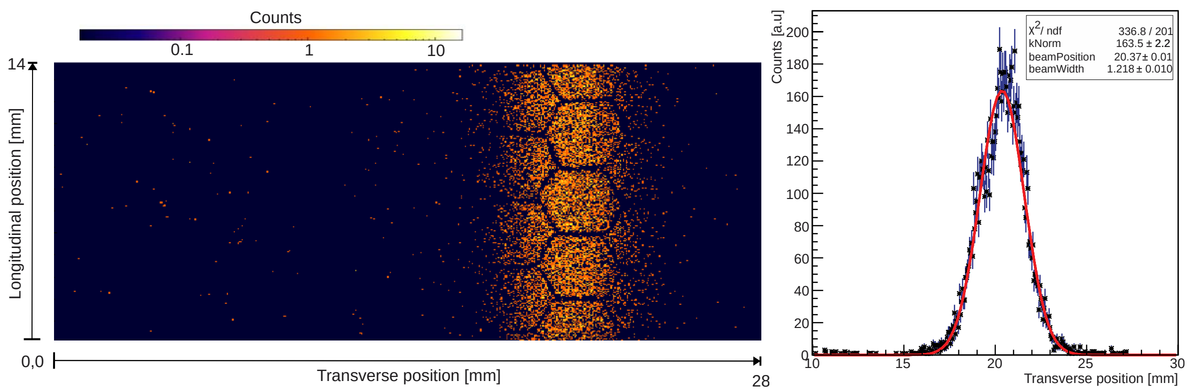


Figure 23: Rest gas ionisations electrons detected by Timepix3 hybrid pixel detectors (left) and the horizontal beam profile (right).

A novel rest gas ionisation beam profile (BGI) monitor is under development for the PS to provide continuous, non-destructive, bunch-by-bunch and turn-by-turn beam size measurements. The instrument consists of an electrical drift field to transport rest gas ionisation electrons onto a measurement plane. Uniquely for this type of instrument, ionisation electrons are detected by hybrid pixel detectors. These consist of pixelated silicon sensors bonded to a Timepix3 readout chip, which promises to significantly improve the time and spatial resolution of beam size measurements compared to existing instruments. A prototype Beam Gas Ionisation (BGI) profile monitor was installed in the PS during the 2017 winter shutdown. An image of the ionisation electrons detected by the hybrid pixel detectors is shown in Figure 23 for an LHC cycle in the PS acquired during a 10ms window at extraction energy.

BE-RF Group

LIU-PSB

Due to large bandwidth of the PSB Finemet® cavities, it is possible to supply voltage across three harmonics, which should decrease transverse tune spread at injection reducing blow-up. This was successfully demonstrated and allowed 0.1 µm and 0.2 µm lower emittance in horizontal and transverse planes to be extracted for LHC 25 ns type beams.

RF phase noise, which is routinely used for controlled longitudinal emittance blow-up in both the SPS and LHC, was successfully tested for the first time in the PSB and has shown to produce acceptable results, equivalent to the current method to inject a single-frequency, phase modulated high harmonic. The phase noise method has the benefit of requiring fewer parameters, giving the potential to simplify operation.

The Finemet® based RF system project for the PSB proceeded at full steam in 2017. European industry started the delivery of large number of parts and components produced according to CERN design or specifications. All delivered parts went through full characterization and acceptance tests. Most of cavity fabrication, assembly and cabling was performed at the RF workshop in Meyrin. Complete characterization and testing of amplifiers and assembled cavities was performed in the PSB Lab; the first seven cavities (of a total of 24) were fully tested and validated. The manufacture of the multi-ceramic gap vacuum chambers experienced significant difficulties that could be overcome by the end of the year thanks to the tight follow-up of EN-MME and BE-RF.

Figure 24: One of the new Finemet® based cavities of the PSB during its assembly at the RF workshop Meyrin

PS/PSB Transverse damper RF amplifiers upgrade

For the PSB and PS transverse damper systems, new 800 W power amplifiers were developed, prototyped and successfully tested in the group. In the PSB, these 800 W modules will drive the electrodes in each plane (eight in total). The contract for the production of these amplifiers was

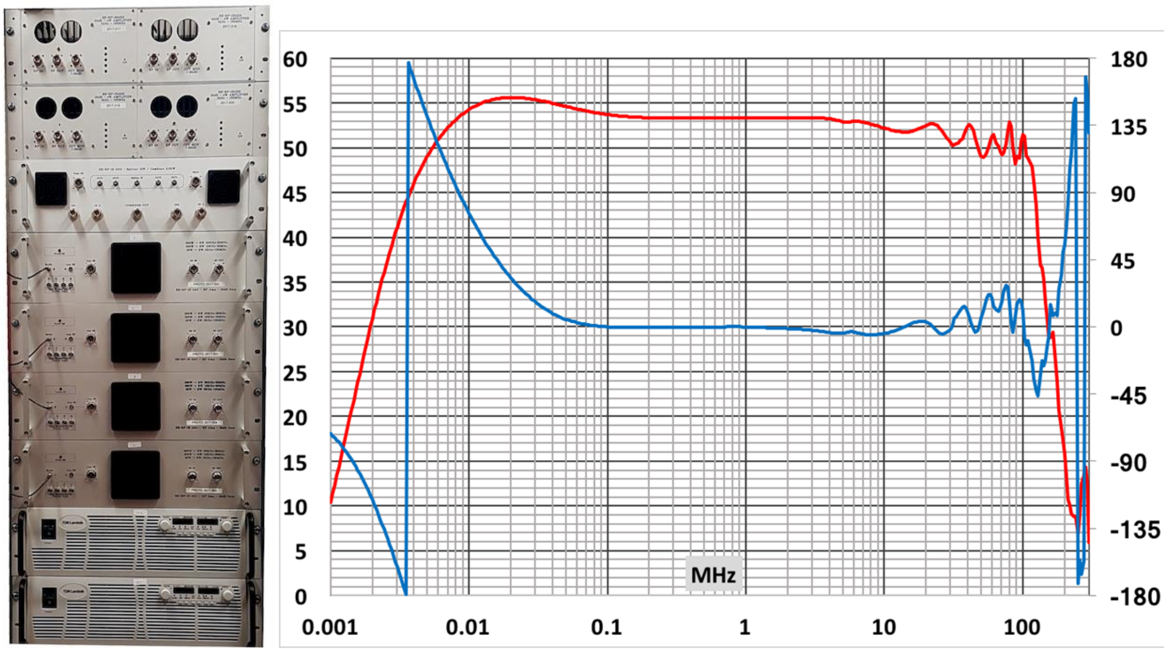


Figure 25: The 2.4 kW RF unit feeding the PS transverse damper plates (left) and its transfer function (right)

placed with industry and delivery was completed during the year. To reach the 2.4 kW required in the PS, four such 800 W modules are conveniently combined. Work advanced on the combiner and impedance matching transformer. A prototype has performed well at low power and a full test stand in building 864 is in preparation for full validation in 2018. The PS damper power amplifiers will be fully deployed in LS2, for which a study of the new location was also carried out.

LIU-PS

The longitudinal impedance model of the PS has been significantly improved, in particular thanks to MDs, cavity measurements as well as electromagnetic simulations. Various machine elements

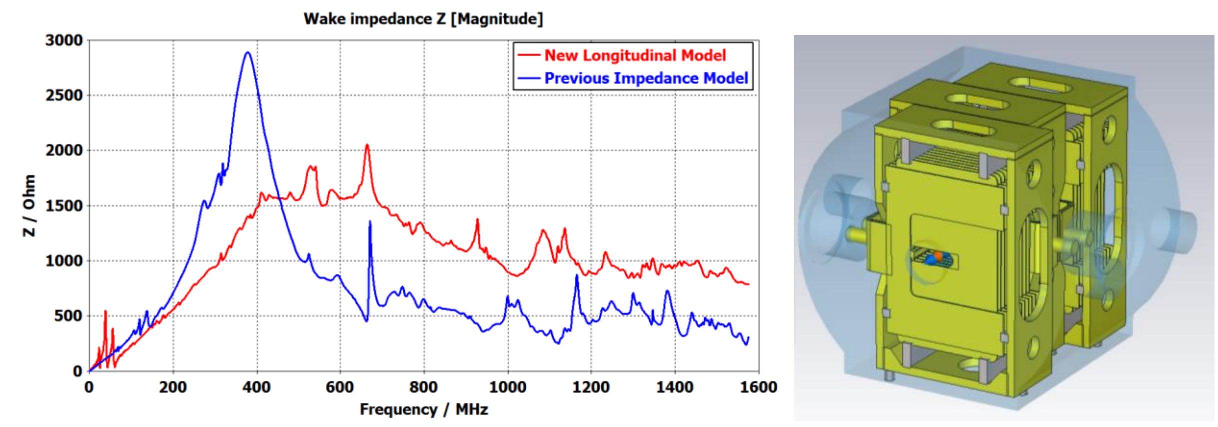


Figure 26: Longitudinal impedance contribution of KFA79 calculated from previous simple model and from new detailed geometry (left). Illustration of detailed model in EM-simulation code (right)

were re-evaluated for their impedance contributions. Injection kicker KFA45 and ejection kicker KFA79, e.g., were simulated with a more detailed geometry, resulting in a significantly higher broadband contribution in longitudinal beam impedance, better describing reality.

Highlights for the PS LLRF upgrade were the tests of the multi-harmonic feedbacks for the 40 MHz and 80 MHz cavities, as well as the use of a 40 MHz RF cavity as Landau cavity to test beam stability limits. A study group has been set-up to study the needs and the design of a dedicated Landau RF system. New results with feedbacks and power system upgrades planned for 2018 will provide fresh input on the needs of such an additional cavity system. As part of the beam control upgrade, new multi-harmonic sources are now operationally deployed for all beams. For the main 10 MHz cavities, this completed the extension of the 1-turn delay feedbacks to a full cavity controller. The RF signal is generated locally for each cavity. A new implementation of the cavity return vector sum has been validated and will be brought into operation during the 2018 start-up. This will further streamline the beam control system.

LIU-SPS

Intensive studies of particle losses on the SPS flat bottom led to better understanding of loss mechanisms related to the shape of bunches rotated in phase space at PS extraction, together with beam loading and momentum aperture limitations in the SPS. Measures to remove these limitations were proposed and partially implemented. Advantages and drawbacks of a possible low-harmonic capture RF system (80 MHz) in the SPS were studied in detail.

Longitudinal phase-space tomography, a vital tool in the PS for many years now, was for the first time actively used in many beam studies in the SPS.

A new approach using a vertical $\lambda/4$ stub for the fundamental power coupler (FPC) of the 200 MHz SPS TW cavities was studied. Varying loop shape while respecting the constraints imposed by the high power interfaces, transmission in the 200 MHz band was optimized. Spectra of the exited higher-order modes (HOM) were measured for different, typical SPS cycles and beams via the cables connected to the 630 MHz couplers and data were compared to the simulated impedances of the 630 MHz passband modes. Due to the different boundary conditions in the 3-section-cavity and the 4-section-cavity, individual HOM-damping schemes had to be developed in order to reach the targeted additional damping of a factor of three in the 630 MHz range for both types of cavities. For the 4-section-cavity, the "fork-coupler" concept was revived, one cavity in the tunnel was equipped with these couplers in addition to the existing HOM-couplers and the scheme was validated with beam. For the 3-section-cavity, the required damping can be reached by means of installation of resonant posts in the pumping ports, together with additional couplers. The effectiveness of this newly proposed damping scheme was demonstrated using RF-measurements on a single section.

In the framework of ongoing SPS beam impedance mitigation, the areas upstream of the QFAs were identified as locations with large variations of cross-sectional changes in the vacuum chamber. An impedance reduction was obtained by layout optimization, sorting of the existing machine elements to reduce the overall contribution to longitudinal impedance.

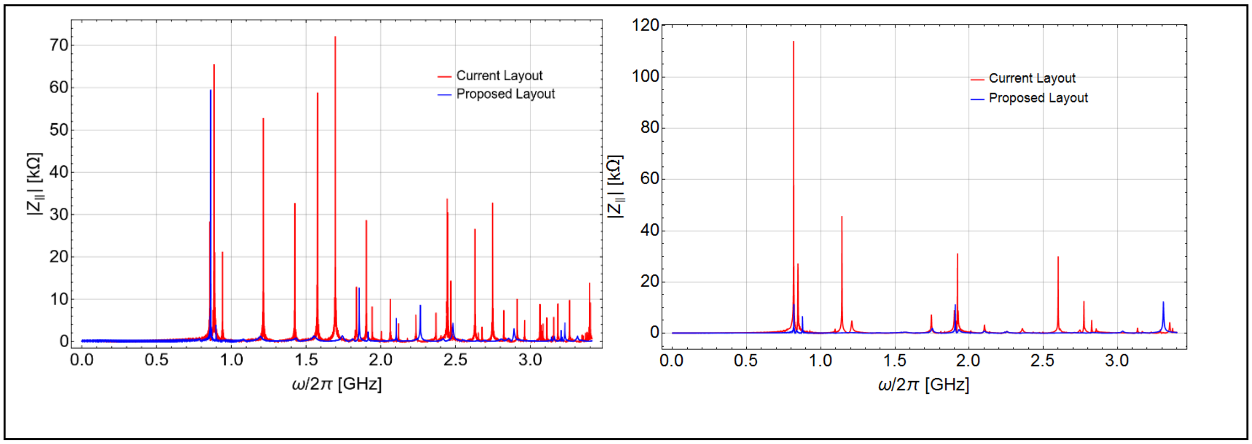


Figure 27: Longitudinal impedance of areas upstream of QFAs: QFA.218 (left) and QFA.418 (right) versus frequency before and after layout optimization of the existing machine elements

The SPS transverse damper, already upgraded during LS1, faced challenges with the increased intensities. A more advanced software interface helped to tune the system to new operational requirements and allowed making tests with ions. Even if not retained in the LIU-SPS baseline, interest remains in the possibility of intra-bunch damping using a wide-band damper system, both in the vertical plane (to fight TMCI like instabilities) and in the horizontal plane, where an intra-bunch oscillations were observed when multiple batches are injected. Intra-bunch damping could be clearly demonstrated with prototype hardware developed in collaboration with SLAC. Further tests with increased bandwidth, using the newly installed slot-line kicker are planned for 2018.

The SPS LLRF system will be completely renewed during LS2, based on the μTCA standard and fixed frequency clocks, and the first hardware modules for the cavity controller were procured. A full validation test is planned for this cavity controller together with other modules based on the new standard with the cavity in BAF3. Collaboration with the CO group has started for the integration with the WhiteRabbit system and for the regeneration of low phase noise RF signals.

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

BE-ABP Group

Linac 2 and 3

Linac2 had a good year, especially compared to the year before. The uptime was 99.1%. Due to the hard work of the source team the year before and during the 2016-17 EYETS the Duoplasmatron had no fault at all along the whole year.

Linac3 ran with xenon ions for the fixed target experiments in the North Area of the SPS, with LHC taking the beam for one day for collisions with xenon. A $^{129}Xe^{22+}$ was produced by the ECR source using isotopically pure xenon gas as a feed, mixed with oxygen. At the linac exit an intensity of more than 30 µA of Xe^{39+} was produced by stripping. Tests were made with diamond like carbon stripper foils as well as the standard amorphous type, and a campaign of measurements and simulation throughout the Linac could establish beam conditions at the spectrometer outlet, and how that beam was transport with improved accuracy compared to previous years.

In the frame of the consolidation a new microwave generator for the GTS-LHC ion source was bought, commissioned and off-line tested. This generator will allow to run the source in the frequency range of 14.0 – 14.5 GHz (frequency remotely changeable).

LEIR

The LEIR machine studies with xenon in 2017 were mainly devoted to the improvement of the machine understanding and performance in view of the 2018 Pb run. Joint Linac3-LEIR MDs were performed in order to characterize the dependencies of the Linac3 parameters affecting the injection efficiency into LEIR. For these studies, the longitudinal Schottky system was used to determine the change in injected momentum as a function of the main Linac3 RF parameters (tank3, ramping/debunching cavities). It was found that the machine operates close to the optimal value in the explored range of parameters. Additionally, studies were performed concerning electron cooling, space charge and impedance. Cooling maps were performed for the first time in LEIR, which allowed identifying the machine settings bringing to the fastest cooling rates. For these settings, the cooling force was as well measured and is comparable with numerical simulations assuming a lower electron density. Space charge studies were devoted to the resonance identification by means of static and dynamic tune scans: 6th and 8th order space charge driven resonances were identified and, in addition to what was done in 2016, the blow up was measured. Lattice resonances were partially compensated using chromatic sextupoles. A tune ripple of amplitude up to 0.007 was identified but the source could not be located by the end of the run. Impedance studies were focused on the measurement of the imaginary part of the longitudinal and vertical impedance showing good agreement with expectations. Beam Transfer Function studies were also performed to try to identify the source of the fast vertical instability present in LEIR when the damper is switched off and high intensity is accumulated. At last, but not least, RF studies were performed to further exploit the multiple harmonic capture extending it to h=2+4+6 to mitigate the space charge induced losses at capture, and to h=3+6 as future possible alternative to the SPS slip stacking. The frequency modulated capture method, first deployed in 2016, was further validated in 2017 and was proven to be extremely useful in improving capture's repeatability.

PSB

In the first part of 2017, the ABP work for the PSB was concentrated on the possibility to correct the chromaticity in both planes at the same time. A study has been performed to evaluate if the additional L1 sextupole family would allow to perform a two-plane chromaticity correction. From this analysis it was shown that this would be possible in principle, however, in the present set-up a factor of 10 is missing in the strength of L1 sextupole, even at the lowest injection energy after LS2 (160 MeV). It was also shown that the natural chromaticity in the PSB is very well predicted by the MAD-X model, at 160 MeV.

Moreover, a study was performed in order to re-compute the functions of the 2 Qstrips (QD3 and QD14) that will be used for the beta-beating correction during the fall of the chicane, for the new injection scheme. The tools were developed for the definition of the functions for any working point and the impact of a possible delay between the start of the fall of the chicane and the start of the function was quantified.

Finally, the studies to characterize the new turn-by-turn BPM system in the PSB and eventually measure the optics of the 4 PSB rings were initiated. In this respect a series of machine studies were performed.

PS

In addition to the studies related to LIU, the activities of the BE-ABP group focused on further improving the Multi-Turn Extraction (MTE). The implementation of new FGC3-based controls for the power converters of the Pole-Face Windings (PFW), which had been decided following the 2016 efforts, allowed to significantly decrease their ripple and to introduce a synchronisation between them, thus improving the overall beam quality. These improvements paved the way for studies to optimise the MTE process itself, an important step towards evaluating the MTE performance at high beam intensities, which might be operationally requested by future experiments, such as the Search for Hidden Particles (SHiP) facility. Following the optimisation phase at the PS, dedicated machine development sessions at the SPS were organized and potential show stoppers for high-intensity MTE beams could be successfully excluded. The success of these studies led to the decision to discontinue the former Continuous Transfer scheme and to remove the related hardware from the PS ring during Long Shutdown 2. Additional studies were related to improving the injection scheme, where a tune and chromaticity modulation during the collapse of the injection bump was observed. Eddy currents generated in the metallic vacuum chambers of the injection bumper magnets were understood to be at the cause of this phenomenon. Subsequently, the design of the new injection bumpers was modified to include dedicated compensation circuits. Furthermore, a new scheme to correct chromaticity with the PFW at injection energy of LHC-type cycles could be successfully tested. This correction relies on using the transverse feedback, which becomes indispensable to damp horizontal head-tail instabilities in this configuration. In collaboration with the BE-BI group, the commissioning of the new horizontal Beam Gas Ionization

(BGI) monitor was also advanced, allowing to measure for the first time the beam size evolution within a PS cycle.

SPS

The characterization and understanding of the losses encountered for the high intensity LHC beams with 25 ns bunch spacing on the long injection plateau of the SPS remained the main focus of beam studies in 2017. As concluded from the measurements in 2016, a large fraction of the flat bottom losses are explained by particles escaping the RF buckets due to longitudinal impedance and insufficient beam loading compensation with the present RF system. An important finding in 2017 was that the SPS momentum aperture in the Q20 optics is smaller than expected. In particular the momentum aperture was found to be asymmetric, with less acceptance for negative momentum offset. This could be traced back to a design flaw in the transition pieces between the MBB and QD vacuum chambers. They have an eccentric circular aperture to accommodate for the horizontal offset of the MBB chambers, but introduce an aperture restriction for the Q20 optics. The limited momentum aperture explained why a larger RF voltage on flat bottom would not improve but rather degrade transmission, as in this case even particles within the RF buckets would reach the momentum acceptance of the machine. To restore the momentum acceptance, the QD-MBB vacuum transitions at the critical locations with high dispersion will be modified as part of the LIU project during LS2.

Another highlight was the successful commissioning and full validation of a new SPS optics with intermediate transition energy. This so-called Q22 optics is a compromise between the Q20 optics with low transition energy and the Q26 SPS design optics. Similar intensity and transmission of LHC beams with up to 1.3×10^{11} protons per bunch could be achieved up to 450 GeV in machine development studies as with the operational Q20 optics. The Q22 optics can thus be considered as valid option for future high intensity LHC beams in case of remaining RF power limitations after the LIU upgrade of the 200 MHz main RF system. Furthermore, chromaticity measurements in the Q22 optics provided additional input for the nonlinear optics model of the SPS, which describes the nonlinear chromatic behaviour of machine consistently in all three optics.

Finally it should be mentioned that a high intensity version of the fixed target beam with Multi-Turn Extraction from the PS could be successfully injected and a total intensity of 4×10^{13} protons per pulse achieved at SPS flat top. This was an important proof of principle in view of the future high intensity operation of fixed target beams considered in the Physics Beyond Collider studies.

BE-BI Group

Secondary Emission (SEM) Grids with new in-vacuum cabling

As part of the continued activity to improve beam instrumentation design, reliability and maintainability, a new type of Ultra High Vacuum (UHV) compatible cabling for wire grids has been designed and prototyped. This brings the electrical signal from the detector wires to the vacuum feedthrough. As shown in Fig. 28, the new concept is based on flat multi-wire cables ending with multi-pin connectors. A first prototype was adopted for a wire grid in the PS injection region. After its validation with beam, this type of cable is foreseen to be adopted in all future designs instead of multiple single wires that need to be mounted individually.

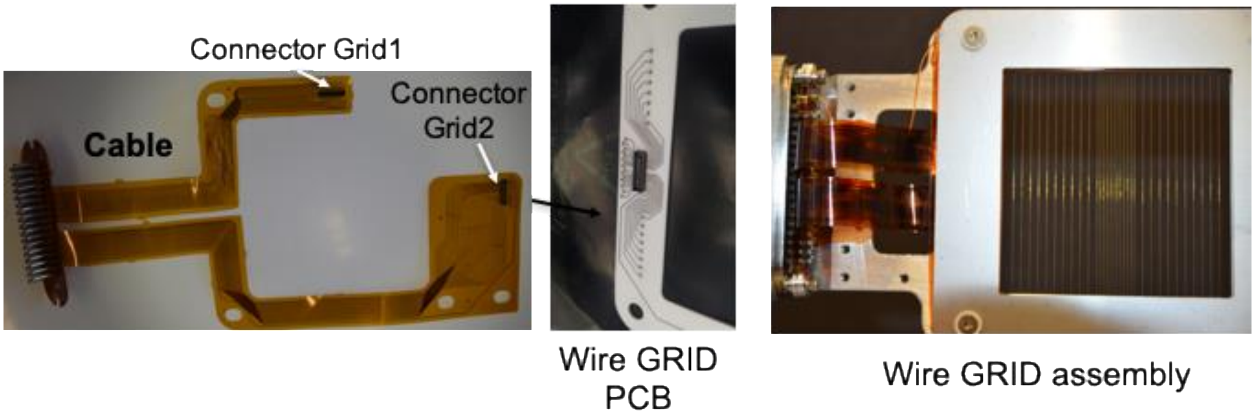


Figure 28: New, UHV compatible multi-wire cables for SEM-grids.

R&D to replace VIDICON tubes for beam profile imaging in high-radiation areas

In order to cope with the future worldwide unavailability of the VIDICON tube cameras traditionally used at CERN for beam imaging systems in high radiation zones, the BI group started an R&D programme on imaging via radiation tolerant optical fibre bundles. One end of the fibre bundle is optically coupled to the image to be acquired (e.g. scintillating screen in an accelerator), and the other end coupled to an imaging sensor such as a CCD camera, which can then be located in a much lower radiation area. An example of target imaging in the laboratory via this method is shown in Fig. 29. This successful proof of principle will now be followed by detailed sensitivity, resolution and radiation hardness studies.

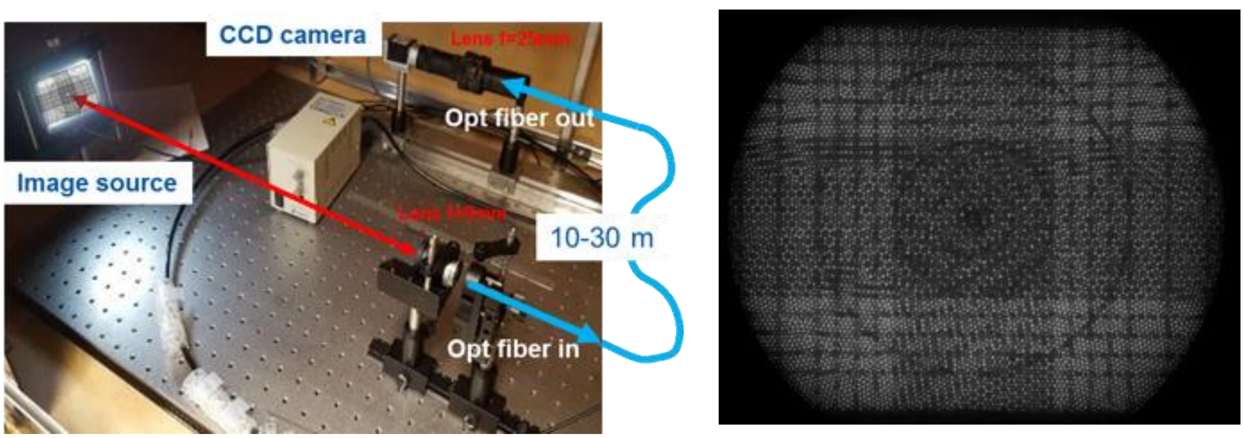


Figure 29: Laboratory setup (left) and target imaging example (right) via a radiation tolerant optical fibre bundle.

LEIR injection line BPMs

The two first BPMs out of a total of nine were installed in the L3 ITE line and tested during the 2017 run with Ar^{11+} beams. The signals from the first beam tests showed perturbations due to both EMI and low-energy secondary particles hitting the electrodes. Suspecting secondary electrons either from ionisation of the rest gas or desorption from the vacuum chamber, the front-end electronics was modified to enable a repelling voltage to be added on each electrode. This significantly improved the quality of the observed signals. When scanning the clearing voltages, it was possible to find a setting where the primary beam pulse is unaffected by charging, see Fig. 30. Further increasing the voltage results in positive charging of the electrodes, which is believed to be due to the attraction of ions from rest gas ionisation. Adding magnetic solenoid and/or dipole fields close to the BPMs further improved the situation. Unfortunately, the ideal settings of clearing potential and magnetic fields are different for each electrode and BPM, and was seen to depend on both the beam and LN3 parameters. This is therefore not a final mitigation for this issue and studies will continue during 2018.

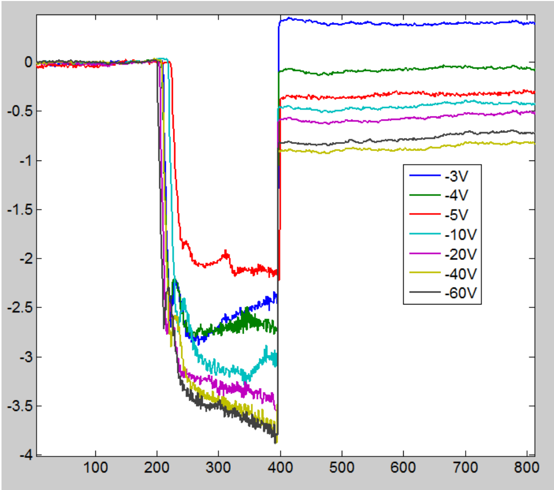


Figure 30: Sum signal charging along the beam pulse as a function of repelling voltage.

BE-ICS Group

External Conditions Refurbishment

During LS2 we plan to replace the existing system for LHC injector chain external conditions with a new system based on PLCs and Industrial Ethernet fieldbus technology. During 2017 a survey of all existing external conditions was completed, and the design of the new system commenced.

BE-RF Group

LEIR

A proof of principle demonstration of 3-bunch operation (rather than the nominal 2-bunch scheme) was carried out with Xe beams; the splitting was implemented using both Finemet® cavities simultaneously. Extracting with $h = 3$ from LEIR allows the PS to supply 3 bunches with 75 ns spacing, as compared to the usual 4 bunches with 100 ns spacing, allowing for increased luminosity in the LHC.

Linac4

The work on Linac4 cavities has been completed in 2017 with the installation of the debuncher cavity – in fact a PIMS cavity operated at lower power and 90° out of phase – in the Linac4 transfer line. The function of the debuncher, together with PIMS cavities 11 and 12, is to compensate

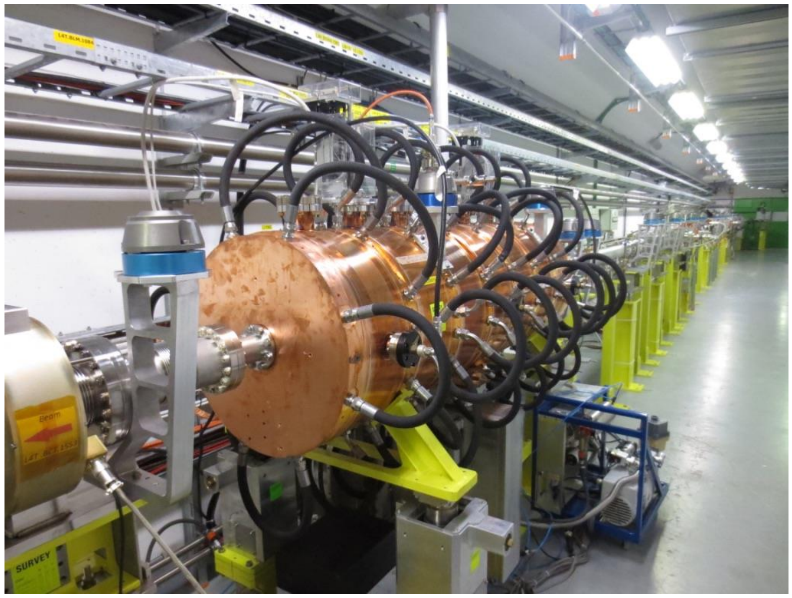


Figure 31: Debuncher cavity in the Linac4 transfer line looking upstream.

energy spread of a beam simultaneously varying in energy. The amplifier has been fully commissioned in 2017 and the coaxial line transferring the RF power from the klystron gallery to the cavity has been minimized in RF losses in order to transmit the maximum output power from the amplifier to the cavity.

The year 2017 also saw the successful reliability run of the Linac4 high power RF system, supported with a new version of the LLRF under test in parallel. One of the three pairs of LEP klystrons was replaced by a new, state-of-the-art klystron to allow a sufficient margin of RF power. Despite some initial teething problems, the system proved robust and reliable eventually. Modification of the klystron gun tanks will be implemented during LS2.

SPS

SPS RF operation was smooth through the year. In addition to setting up and following up operation for the standard SPS physics and LHC programs (including North Area p+ physics, AWAKE, HiRadMat, UA9, …), support was given to numerous machine studies, which now routinely take place in parallel to the physics programs.

Special in 2017 was the Xe ion run, using fully and partially stripped ions. It served the North Area with slowly extracted beams of different energies for about 4 weeks of operation, and was also taken in the LHC for machine developments and a short physics run.

In parallel to guaranteeing regular operation, part of the time was dedicated to preparing for LS2 and the LLRF upgrade that will follow.

AD

The AD stochastic cooling system was running reliably through the year. A new RF transmission line was installed and commissioned which will permit testing of a new optical delay line notch filter with beam during 2018.

ELENA

BE-ABP Group

The main activity related to ELENA throughout the year was commissioning of the ring as far as possible without the (not yet available) electron cooler. At the beginning of the year, ELENA commissioning started with H- ions from a dedicated ion source with an energy lowered from the nominal 100 keV to 85 keV due to technical problems with an insulation transformer. Commissioning of the RF system to rebunch the injected beam was essential to demonstrate beam-life-times of a few 100 ms, which could be increased only in autumn with the successful commissioning of the phase loop as well for H- ions. Poor reproducibility of the injection of the beam from the source was a frequent issue slowing down progress. Nevertheless, it was possible to commission all basic systems as the RF system, beam instrumentations etc. The machine was ready at the end of the run to send first H- beams to GBAR, the only experiment already connected to ELENA.

From August onwards, tests with antiprotons from the AD took place, typically during one day shift per week in parallel to setting-up with H- ions on other days. The antiprotons could quickly be transported to ELENA and injected into ring. Deceleration efficiency of antiproton beams was modest due to imperfections of the transfer without proper correction of injection oscillations and due to lack of cooling. Nevertheless, after various partly empirical optimisations, a small number of antiprotons could be decelerated down to the final energy of 100 keV and was lost at the transition between the ramp and the final plateau. An automatized procedure to correct injection oscillations was put in place only at the end of the run as preparation for the completion of ELENA ring commissioning during 2018.

ELENA commissioning activities were interrupted at the end of November for the installation and bake-out of the electron cooler, which had been mounted during autumn, at a time when manpower was available for this activity before the start of the shutdown of operational installations.

BE-BI Group

ELENA commissioning with H^- ions at 85 keV started in March with particular emphasis on the different beam diagnostics systems. First signals from the secondary emission monitor (SEM) situated at the source exit were observed on an Oasis scope with each individual wire connected to an input channel of the scope. Despite extensive measurements and modifications to the gain settings, the interpretation of the traces was too difficult to be used for beam steering.

For the setting-up of the transfer lines, the intercepting screens (BTV) proved to be a more useful tool. Three such systems were available and, along with the GEM monitor at the AD ejection, enabled a relatively fast tuning of the line to have the first antiproton beams circulating in the ELENA ring by the end of June. An example of images and related projections can be seen in Figure 32 below.

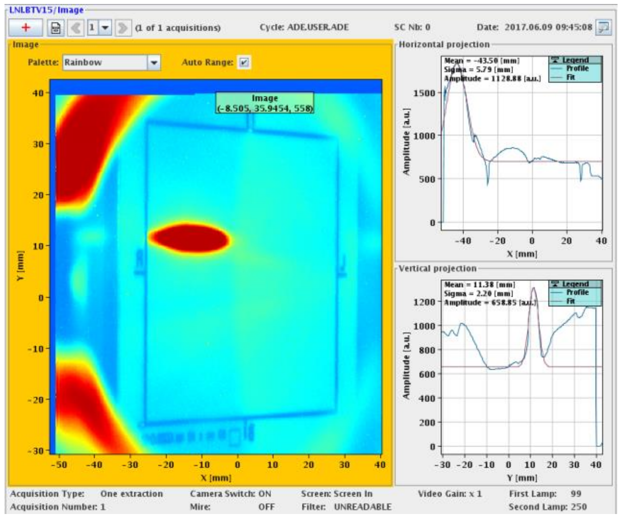


Figure 32: BTV image of the first antiproton beam injected into ELENA.

Once circulating beam was established in the ring, the orbit (BPM) and tune (BBQ) measurement systems were commissioned and provided closed orbit and working point measurements along the injection plateau. After correction, the first attempts at decelerating antiprotons to lower energies were made possible. The scraper system to measure the circulating beam profile was put into operation but problems with the synchronisation between the blade movement and the acquisition of the secondary particle shower took some time to resolve. Once the source of the problem was identified and corrected, profiles of the circulating antiproton and H^- beams were made available for the optimisation of the ring (Fig. 33).

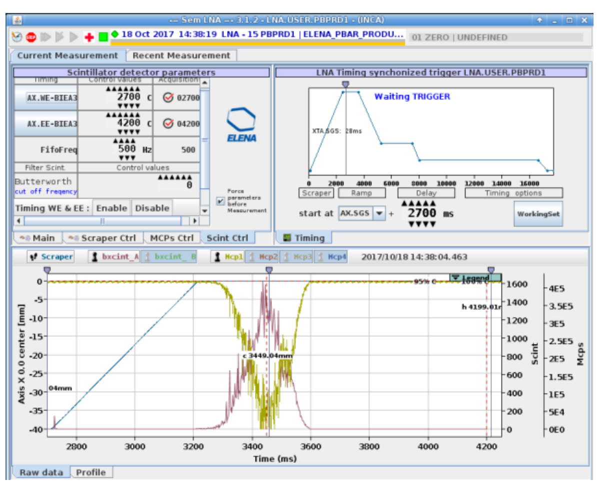


Figure 33: MCP and scintillator signals of an antiproton beam obtained with the scraper system.

The recombination monitor also provided an indication of the beam size of the circulating beam. This system detects neutral hydrogen atoms created when the loosely bound electron of the H^- ions is stripped by residual gas molecules. The image of the neutral atoms is recorded on a CCD camera at the exit of one of the bending magnets from which one can infer the horizontal and vertical dimensions of the beam (Fig. 34).

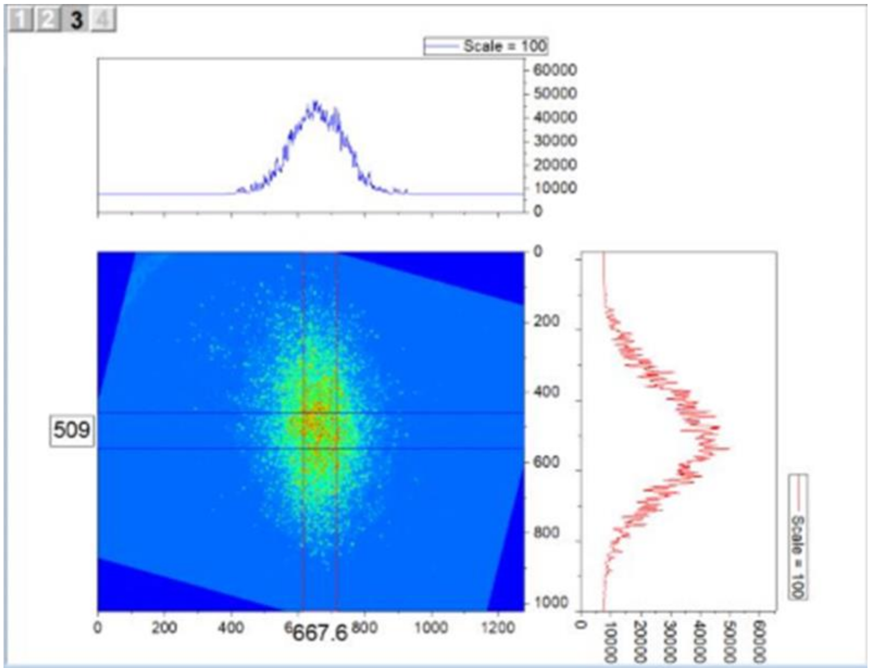


Figure 34: Beam profile measured with the recombination monitor.

After a long and difficult campaign of measurements, the magnetic system of the ELENA electron cooler was delivered to CERN during the summer of 2017. The full assembly of the device was delayed due to problems with the NEG coating of the vacuum chambers but the device was finally connected to the ring before the Christmas break, ready for the first bake out (Fig. 35).

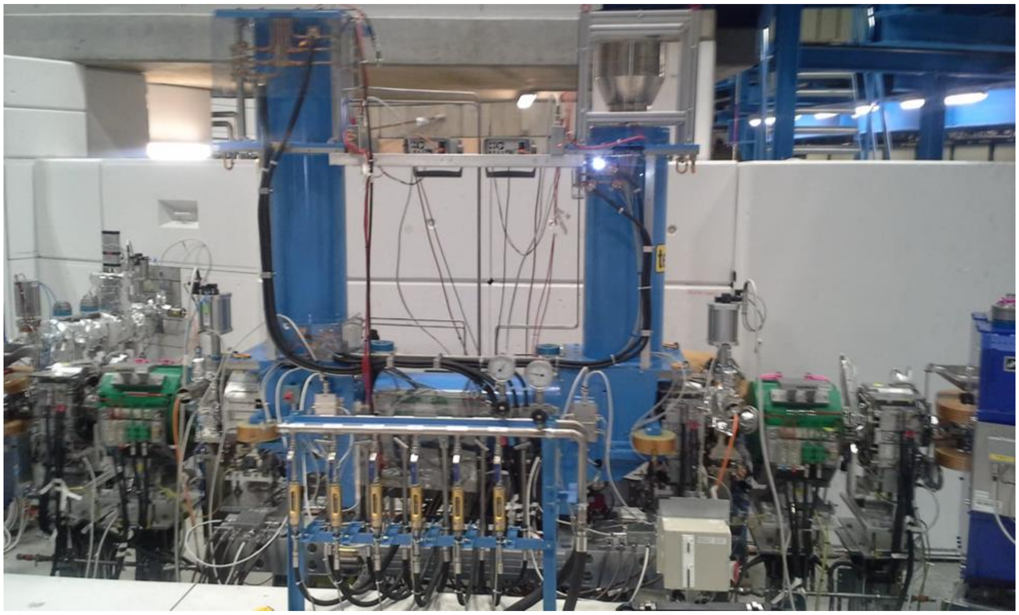


Figure 35: The electron cooling device installed on ELENA.

BE-CO Group

InCA/LSA

Support for new machines

The CLEAR machine was integrated into InCA/LSA, and support for CTF was removed. Based user requirements, a new InCA/LSA server was installed for CLEAR, and necessary extensions were developed for the LSA software, in particular to support obsolete GM devices. Configurations were created for CLEAR device types, device instances and parameters types, as well as for Workingsets and Knobs for the control room. A careful but thorough clean-up campaign followed to remove support for non-existing CTF equipment and devices.

The AWAKE Electron line can now also be controlled from LSA and steered by YASP, thanks to the configuration power-converters together with high-level K (strength) and MOMENTUM parameters. In AWAKE, OP need to manage the settings of non-PPM devices in a PPM manner - a requirement that was not easy to satisfy. In collaboration with OP, the LSA team have analysed several potential solutions and picked one, which - although it required more effort to implement - had a clean design and did not force them to take undue shortcuts.

Improvements to settings management:

Following the performance problems experienced in 2016, the LSA team introduced a flexible settings archiving functionality. The settings archive typically contains historical settings from previous years, which are not used actively but must still be available for reference and comparison.

The main challenge was to archive millions of settings within a reasonable time. With a simplistic implementation, this would have taken months rather than minutes. It took the LSA team several iterations to tune the queries, the database execution plans and statistics. They took special care not to impact the database performance for other users during the archiving process. The final solution takes from as little as a few seconds to a maximum of a couple of minutes to archive all settings of an LSA cycle. This work on settings archiving solved all performance problems experienced in 2016.

InCA/LSA improvements for quality assurance and smooth upgrades

Several improvements were made for smooth upgrades of InCA/LSA.

One regards version control for structural database changes. It is common practice to put the whole software under version control, so as to know exactly who did what changes. This was always the case for (Java) software, but it was only introduced in 2017 for all (structural) changes to the database schema. The LSA team have defined a workflow and evaluated tools to automate it. They selected Liquibase for DB version control and combined it with Ansible to automatically apply changes to all database instances. No structural DB changes are done outside of this workflow anymore.

Another improvement was made to automatically test LSA before new functionality is put into operations. One key aspects was to isolate test environments and make integration tests totally independent from operations. Technically, this is achieved by packaging the LSA server and a minimalistic LSA database in Docker containers, and deploy them in CERN OpenStack machines, where integration tests can be executed automatically and in parallel.

CO-OP collaboration

In June 2017, a collaboration between APS, OP and ABP team finished the first version of the Coupling Correction application. The goal of this application is to measure and correct the coupling between the horizontal and vertical beam planes in LHC so that they can be steered individually. The system uses the ADT device to excite the beam in both planes, and the BPMs to measure the resulting beam movement. This information is then sent to a Python script developed by BE-ABP which calculates the coupling and the necessary correction. Based on this result, the operator can trim the beam directly through LSA with one button click. This application is now used with success during operations.

One interesting technical aspect is the integration between Java and Python. The Python calculations are packaged in a Docker image which is built automatically. The communication with the Java server is done with gRPC, an open-source library for cross-language remote procedure calls and data streaming. The implementation was carefully crafted to produce clear error messages in case of failure, which enable OP to call the right expert when something fails. In other words, this solution guarantees clear boundaries between the controls system and the Python code, and facilitates operational support and long term maintenance. This application has been used operationally for each LHC fill since August 2017.

CESAR

During the North Area start-up 2017, the integration of the new COMPASS spectrometer into CESAR was successfully commissioned. This is the first and only equipment in CESAR controlled by an FGC. So far, CESAR supported only FESA devices, and the integration of an FGC in CESAR was challenging. This work paves the way for the renovation of the East Area during LS2, when all power converters in the area will be replaced and controlled through the FGC framework.

Also the micro-collimators are now fully controlled by CESAR, after being controlled by a legacy application for many years. Micro-collimators are used to precisely filter a full intensity beam coming from the SPS. CESAR now controls not only the jaw width, but also the positioning of the micro-collimator in all three axis.

Java Devtools

Commonbuild to CBNG migration

During YETS 2016/17, the Java Devtools Team successfully migrated all ~180 Java developers and their ~1000 projects from CommonBuild to CBNG, and eradicated CommonBuild with its 14 years of history and legacy. As part of this migration, the developers had to release the 1000 projects in the right order, which was a difficult procedure to organize. To support this, the team made a tool available that automatically analyses the dependencies between the 1000 projects, stores them in a Neo4J Graph Database, and visualizes them in graphically Web Interface. Thanks to this tool, the 180 Java developers were able to determine the order and point in time at which they had to release their projects, which made the whole migration campaign far more efficient than expected.

CBNG and the migration effort was presented at the Gradle Summit 2017 in San Jose, CA. Presentations from Netflix and LinkedIn show that they tackle similar use cases in a similar way we do.

SVN-gitlab migration

In 2016, the IT department announced that they would phase out the SVN version control service and replace it by gitlab, a new service that supports the entire software development cycle. The CO3 committee created a task force for "Future Version Controls Systems", headed by BE-CO-APS, to elaborate and implement the best migration strategy for the whole accelerator sector. In 2017 first steps were taken, such as gathering requirements of all software teams and matching them against the features of gitlab, comparing gitlab with the current setup (SVN and Atlassian tools) and evaluating tools (e.g. SubGit) for the migration of projects. The DevTools team and the InCA/LSA team have joined forces to practically evaluate git/gitlab for LSA. LSA is particular interesting because it involves not only the core team of software engineers in BE-CO, but also around 10 operators who contribute code to LSA. 38 LSA SVN repositories have been merged into one gitlab repository. The code was synched back to SVN, which remains the reference repository for all operational code. The joint team has also integrated BE-CO JIRA into gitlab, and set up Jenkins for Continuous Integration, including automatic creation of individual build plans for all live branches. The evaluation was positive and the team decided to officially do all development directly in gitlab. However, like other teams (e.g. MPE), the LSA developers laments the lack of global code search and versatile code review tools. Other shortcomings of gitlab were also identified, such as the inability to store huge binary files as needed for PLC development in BE-ICS. The APS devtools team and the chair of the task force will follow this up with IT in 2018.

SIS

Work started on an initiative to remove the physical timing cards from the SIS backend computers. Timing cards require special hardware, and prevent the migration to standard blade machines. As a first step, the SIS team developed an application that gathers statistics to compare the reception of events sent by CTIMs (using the physical card) and XTIMs (using standard middleware subscriptions), with the aim to compare both for their reliability. Several month of statistics yielded an unexpected result: timing distributions using standard middleware subscriptions is slightly more reliable than the physical timing cards! This finding paves the way for the eradication of timing cards, which is however postponed to LS2 on request of LHC-OP.

Concentrators: There is a new concentrator for PS. It is used to log the energy & field from the PS when a dump is inserted in the beam. The collected data will help the dump expert to design the next version of the PS dumps. This concentrator is built on a fully reactive stack that was prototyped in the UCAP study.

LASER

End of June, the review of the integration of LASER Alarms with FESA and CCDB was completed and approved, c.f. https://edms.cern.ch/document/1817871/2. The document defines a roadmap for the changes required in the three systems to improve and simplify the related configuration aspects. Most important planned changes are: (1) the "alarms flag" in CCDB will be automatically derived from the FESA design; (2) alarm priorities and fault codes will be taken as they are declared in FESA, and no longer translated into LASER specific concepts (3) it will be possible to declare PPM and non-PPM alarms for the same device. Another important evolution happened in 2017: the developers of the FGC framework have adopted the new C++ alarm library, which replaces an old version dating from 2001, and has only 50% of lines of code to be maintained.

In 2017, the TI alarms migration (aka TIAM) project has been brought to a successful end. A major milestone was reached in September when the Phoenix GUI was certified by TI-OP as the official operational console on top of the new TIM alarm infrastructure. After running for 3 months in parallel to the TIM service, the old LASER-1 server was shut down after 12 years in production.

BE-RF Group

For the ELENA Ring, a new LLRF system was deployed based on the PS complex family of hardware, with new firmware featuring fixed-frequency sampling. Beam commissioning with beam (both H^- and $\bar{p}$) started and phase and radial loops were successfully commissioned. Anti-protons were injected from AD using a bunch-to-bucket transfer and decelerated to nearly extraction energy. The magnetic pick-up for the extraction line LNE50 to Gbar is being prepared for use in 2018. Given the good quality of the electrostatic pick-up signals, the LLRF system could be configured for operation with either the magnetic or the electrostatic pick-up signal.

LINAC4

BE-ABP Group

The Linac4 project was officially finished on 31 January 2017 with the transition to commissioning and operation under the responsibility of ABP. The Linac4 was officially inaugurated on May 9th in presence of the Director General and the Director of accelerators. During 2017 the Linac4 served the Half Sector Test until the beginning of April allowing to collect many data on the behaviour of the stripper foil and injecting diagnostics. After a phase of preparation of about two months the Linac4 restarted with its first reliability run with the purpose of insuring a smooth transition from commissioning to operation including the training of operators, the development necessary software, and learning to deal with the increased flexibility. The purpose of this 24 hours/7 days continuous run was also to find any weak points and mend them in time for the connection. The aim for beam-availability for the PSB was to be above 90%: Linac4 was integrated in the Accelerator Fault Tracking system of CERN, in view of the connection. The reliability run was divided in two phases, for a total of 19 weeks during 2017. The average availability during this period was 91.5%, a very good start. Most importantly, the reliability runs highlighted the weak spots of the Linac4 that could be mended during the following year. The routine peak current at the end of the linac was above 20 mA, a quantity that allows the PSB to produce all the beam produced nowadays and in particular to produce the LHC beam of 3.4×10^{12} protons per ring with 45 injected turns.

Meanwhile at the Linac4 test stand experiments to understand beam formation and emittance control continued throughout the year, including the test of the sources to be installed and ready for the reliability run

BE-BI Group

The 2017 LINAC4 runs were essential for advancing with beam diagnostics commissioning and performance assessment.

All instrumentation foreseen in the LINAC4 project baseline up to the Half Sector Test (HST) temporary dump was installed and most of it successfully tested and operated. Wire scanners and wire grids were extensively used to monitor the beam profiles and to check the trajectory steering. Six wire grids in the L4T and L4Z lines suffered from excessive heating which caused the loss of a number of measurement channels. This issue will be investigated in 2018.

All Beam Loss Monitors were installed and connected to their acquisition system, and were extremely useful for accelerator setup, especially during HST operation.

Finally, two beam imaging systems (BTV) were installed and were important for the stripping foil test stand and HST operation.

Time of flight (BPMs)

The Linac4 beam trajectory measurement system consist of strip-line BPMs that provide information on beam position, relative beam intensity and beam energy via time of flight (TOF). A total of 15 BPMs are placed in the drift tubes between the LN4 accelerating structures, while another 27 units are spread along the 177m long transfer line towards the PSB. For setting-up phase and amplitude of the RF cavities, experts rely on charts representing beam energy gain versus cavity phase. Measurements from BPMs are then plotted against simulations for machine model validation purposes. This technique was extensively used in 2017 for RF fine tuning to reach the nominal beam energy for the commissioning of the Half Sector Test. Figure 36 shows the good agreement when comparing simulations with measurements at 160MeV.

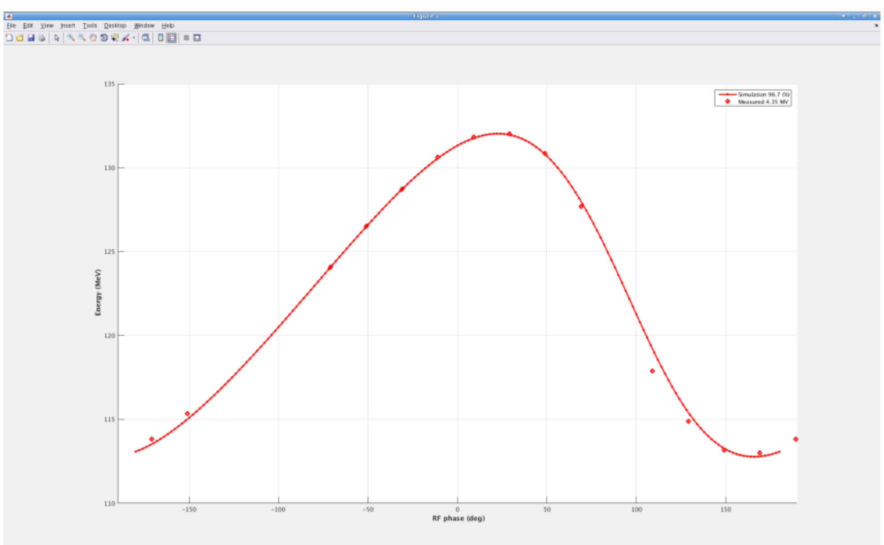


Figure 36: Simulated versus beam measurements at 160 MeV for a set of BPMs.

Bunch Shape Measurement (BSM)

A figure of merit for efficient linac operation is the longitudinal beam emittance. The latter is reconstructed from phase profile measurements provided by the bunch shape monitor (BSM) which has been used since the early commissioning stages of Linac4. The BSM is based on transforming the longitudinal structure of the beam under study into a transverse distribution of low energy secondary electrons. In 2017, S. Feschenko and his team from BINR (Moscow) came to support the successful commissioning of the second BSM in the transfer line.

LN4 Beam Current Transformers (BCT)

The LINAC4 BCTs consist of magnetic cores with a 20 turn secondary winding and a 1 turn calibration winding. They are designed for the nominal LINAC4 pulses of 400 μs with a droop that does not exceed 1 %. In order to minimize the transformer sensitivity to external magnetic fields, 3 layers of μ-metal and 1 layer of Armco magnetic shielding are employed. The 11 installed BCTs are regularly used to monitor beam transmission along the different LINAC4 sections and trigger the interlock system inhibiting the next pulse in case of poor transmission. Their use for high precision transmission measurements during the PSB HST brought to light pre-amplifier saturation effects due to a strong 352 MHz RF component well outside the presumed passband of the transformer. This effect was responsible for positive transmission values between two consecutive BCTs of up to 25%. Appropriate low-pass filters to suppress both monopole (EMI) and difference mode signals (beam) were added and the problem resolved.

Laser emittance meter

During 2017, the laser emittance meter design was completed (see Fig. 37) and the first of the two final stations, each consisting of a laser station and a downstream H0 monitor, was installed. Several beam tests were carried out during the autumn run, which allowed the system to be successfully commissioned and to record the first beam profiles and phase space distributions.

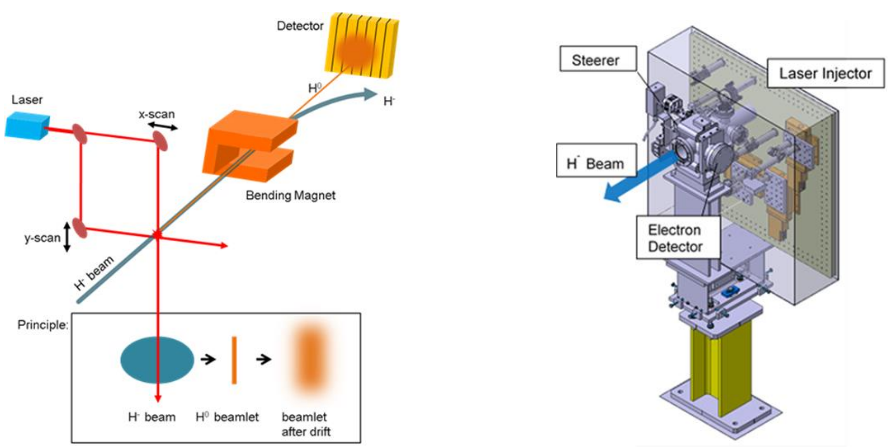


Figure 37: Laser Emittance meter concept and 3D drawing of the final laser station.

H^0/H^- detector

As part of the new PSB injection foreseen for connecting LINAC4, the H^0/H^- beam current monitor consists of 4 titanium plates mounted 2 cm upstream of the H^0/H^- dump, designed to absorb all particles that will emerge partially stripped (H^0) or unstripped (H^-) from the stripping-foils. The 1mm thick plates fully strip all particles, allowing the measurement of the charge deposited by the stripped electrons to be used to infer the stripping foil efficiency. Extensive tests, with and without stripping foil, allowed calibration, sensitivity and linearity checks on the detector.

A sketch of the design and a picture of the first dump-plates assembly together with an example of stripping efficiency measurements for two different stripping foil types is shown in Fig. 38. The interlock channel, yielding the integral of the charges collected on the four plates, designed to be part of the interlock system to protect the dump, was also tested and validated.

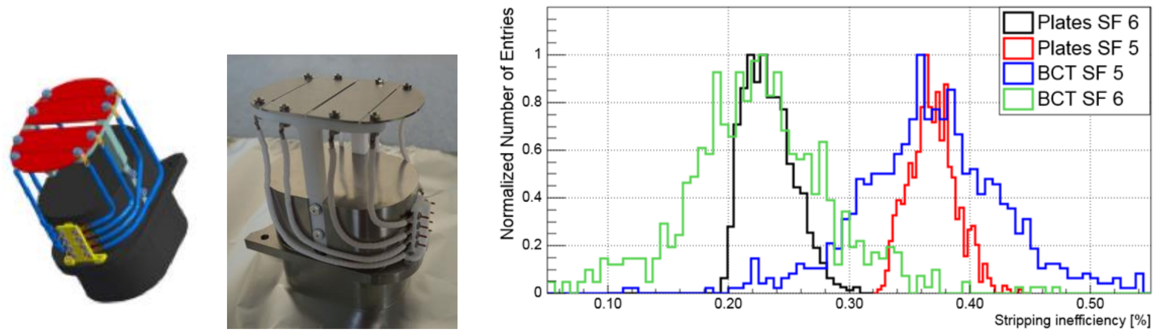


Figure 38: Design and assembly of the H^0/H^- dump equipped with measurement plates, along with and example of stripping foil efficiency measurements performed with two different stripping foils during the HST run.

COLLIMATION PROJECT:

BE-ABP Group

The LHC collimation system performed extremely well in 2017. This was another year without experiencing quenches from circulating beam losses and with a safe operation with stored beam energies for protons that exceeded 300 MJ. Despite this stored-energy challenge, the collimation system worked with very high availability, being one of the systems with lowest impact on the machine downtime in 2017. An efficient operation was also achieved thanks to the continuous follow up by the ABP team of the system setup and validation, and thanks to further developments of the collimator alignment techniques. In MD, pioneering studies of machine learning applied to collimation alignment were also performed, with the plans to deploy these new techniques already for the 2018 commissioning. In 2017, tighter collimator settings were also deployed to achieve a β^* of 30 cm, i.e. about half of the LHC design value for 7 TeV. This was also possible thanks to the usage of the BPM collimators to interlock orbit movements, which allowed ensuring the protection of the inner triplets in these unprecedented conditions.

In 2017, several new collimators were installed in the machine and tested successfully with beam: 2 new crystal primary collimators, mounted on beam 2, a low-impedance secondary collimator prototype (see also above) and a new primary collimator with integrated BPMs were installed. In addition, we also installed in IR5 two new collimators with wires, integrated in the jaw for long-range beam-beam compensation studies mentioned earlier, which can carry up to 300 A. The new hardware performed overall very well and allowed a number of tests that are important both for the present operation and for the HL-LHC upgrade of the collimation system. For example, measurements of the impedance of the low-impedance collimator prototype demonstrated the gains expected from the new design, confirming the present baseline choice to coat all the secondary collimators of IR7 by Run 4.

The short xenon beam run to 6.5 Z TeV was a unique opportunity to test beam collimation with this new species. In MD, we achieved for the first time crystal channeling of Xe beams at this unexplored energy range. An improvement of collimation cleaning by more than a factor 10 was achieved with crystal collimation in comparison to the performance of the conventional collimation scheme. This is an important milestone, in particular in view of assessing the possibility to use crystal collimation of ion beams at the HL-LHC.

In 2017, important works to prepare the production for the first upgrade of the collimation system were also carried out. The HL-LHC upgrade of the collimation system starts in LS2, with the implementation of a first stage of the low-impedance upgrade in IR7, with the addition of dispersion suppressor collimators around IR2 (without 11 T dipoles) and IR7 (with 11 T dipoles) and with the addition of 4 low-impedance primary collimators. The latter are funded by the Consolidation project, with HL-LHC contributing to the procurement of the material of the jaws. By the end of 2017, the production strategy was defined and all the major tendering completed, with all the main contracts for the production being signed or ready for signature. This involved the industrial production of a total of 20 new collimators, 16 for installation and 4 spares. The HL-LHC studies continued for the upgrade scenarios that will take place in LS3.

The collimation team was also very active in studies of collimation systems in other accelerators, in particular for the SPS and for the FCC-hh and HE-LHC. The SPS study, funded by the LIU project, aims at designing a collimation system to mitigate activation around the ring driven by losses at injection. A first conceptual design was elaborated and assessed in simulations, showing a performance that appears adequate for the SPS needs. The design for future accelerators also continued, collecting most of the results that will be used for the preparation of the Conceptual Design Report, or identifying areas where more studies are needed.

REX/ISOLDE/HIE-ISOLDE:

BE-ABP Group

The EBIS at REX-ISOLDE was restarted already in January for the final set of transverse emittance measurements. In April, also the Penning trap was made operational and the low-energy stage began delivering stable beams for the commissioning of the HIE-ISOLDE cryo-modules. In the beginning of the summer the radioactive beam campaign started. Between the physics experiments stable beams were provided to the operating team at ISOLDE for investigation and improvement of the slow ion extraction from REXEBIS, among other things. Ending the operation at the beginning of December made 2017 the longest running period so far.

ISOLDE, in combination with the REX low-energy part, were used to explore the potentials and limitations of charge breeding ^{11}C for use in a possible cancer treatment facility. During these tests it was found that the applied rotating wall cooling inside the Penning trap is not functioning as predicted, even though the cooling effect on the ions is satisfactory for normal operation. It is believed that the buffer gas pressure prevents the ion cloud from spinning sufficiently fast to be properly compressed. Furthermore, it was demonstrated that it is impossible to make use of the full electron beam space-charge potential for accumulation and charge breeding of ions, both when they are injected in pulsed mode from the trap (standard), and in continuous injection mode into REXEBIS. The result is of importance for future extremely high-intensity beams.

At the end of the year the halt of demineralized water resulted in a freeze-out of a cooling mantle located within the EBIS superconducting solenoid. The vacuum tube and with internal structure were undamaged, but the cooling mantle had to be replaced. An improved protection system has since then been implemented.

BE-BI Group

Renovation of ISOLDE instrumentation

2017 saw the start of a major renovation of ISOLDE beam instrumentation systems. Instruments that were designed in the early 1990's for limited use have recently had significant reliability issues with multiple interventions required in a difficult, high-radiation, work environment.

A new combined wire scanner and Faraday cup was designed and prototyped and fitted with new control electronics (Fig. 39).

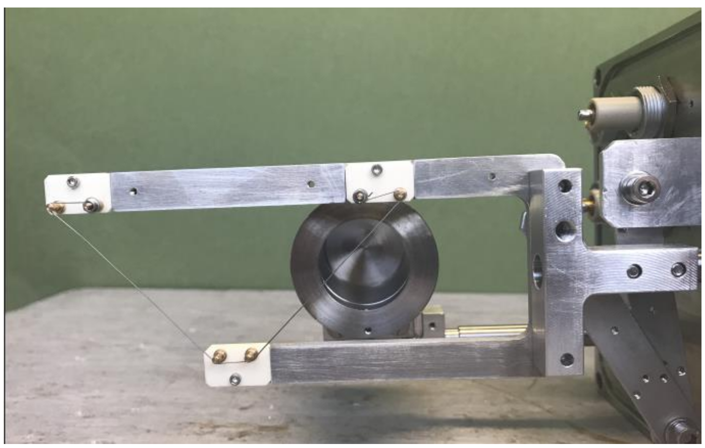


Figure 39: A new combined scanner and Faraday cup for ISOLDE.

The Faraday cups, SEM grids and needle scanners across the complex will gradually be re-engineered using modern methods and materials with the aim of significantly improving reliability and maintainability in the framework of the consolidation project.

BE-RF Group

HIE-ISOLDE had its first physics run with three operational cryomodules at 8 MeV/u. At the same time, the fourth cryomodule was completed for installation in early 2018. Due to difficulties with the Nb coatings around the welds, a new seamless cavity was designed, and the first such cavity was completed, coated and tested. The vertical tests at 4.5 K showed a performance on par with the best cavities measured so far. Lowering the temperature to 2.3 K and compensating external magnetic fields, a remarkable accelerating gradient of 13 MV/m could be achieved, corresponding to a magnetic surface field of ≈ 65 mT with very small Q-slope. This represents a

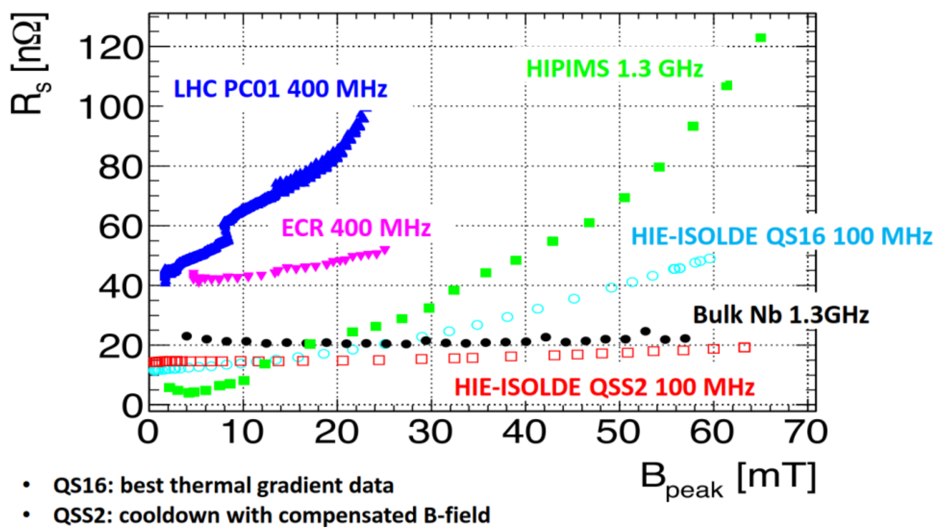


Figure 40: Surface resistance at 2 K of seamless HIE-ISOLDE cavity QSS2 in comparison with other cavities tested at CERN.

new world record for niobium-coated copper cavities and is in fact comparable with the performance of bulk niobium 1.3 GHz cavities.

Operational support was provided for the HIE-Isolde LLRF systems. The flexibility of the LLRF system and operational interface permits the users to phase the linac with little intervention by the LLRF expert. For REX Isolde a consolidation of the LLRF was studied for implementation in a future shutdown using the same VME technology.

CTF3/CLIC:

BE-ABP Group

The CLIC design and parameters team obtained several important technical results in 2017 aimed at a full update of the new CLIC baseline, with a first stage at 380 GeV centre-of-mass energy followed by an upgrade path in stages up to 3 TeV c.m. The Ring to Main Linac design and performance was updated for the 380 GeV machine and fully documented. The studies on optimized positron capture and acceleration were completed, and a consequent full re-optimization of the positron source design, with large power and cost reduction potential, was started. The Beam

Delivery System (BDS) studies saw also progress, with an improved BDS design at 380 GeV and a larger range of imperfections, including dynamic effects, added to the tuning simulations. The optimized design of the alternative CLIC option powered by klystrons has been refined. The activity on dynamic magnetic fields measurements reached important milestones, showing that for natural sources field levels are acceptable or infrequent and exploring mitigation techniques. The Horizon2020 Compact-Light proposal to the EU, for the design of innovative light sources based on the CLIC X-band high gradient technology, has been approved, with the official start in January 2018. An activity exploring novel acceleration techniques and their potential for linear collider applications was also launched. A proposal of an electron beam facility at CERN to explore Hidden Sector Physics (based on a 3 GeV CLIC technology electron linac and the re-use of SPS) was also put forward, and a more detailed study initiated.

The CLEAR facility was approved at the end of December 2016 as a 2+2 years project, with the main goal of enhancing and complementing the existing accelerator R&D and testing capabilities at CERN. The transformation of the CALIFES linac into CLEAR took place in the first half of the year, and beam operation started in September. After a fast re-commissioning, a total of 19 weeks of operation was recorded in 2017, and a number of experimental results were achieved:

- In the VESPER irradiation facility were carried out several measurement campaigns over a wide energy range (60 to 200 MeV) on radiation effects to electronics, in collaboration with the R2E team in CERN and a first successful official irradiation campaign with direct participation of personnel from the European Space Agency and their sub-contracting firms. Extensive measurements on electron energy deposition in water phantom at different beam momenta were also performed in VESPER in collaboration with Manchester University, in view of possible medical applications. Very good agreement was found with expectations, confirming the potential interest of the Very High Energy Electrons (VHEE) technique for cancer treatment.
- CLIC studies: the main linac beam position monitor prototypes were put back in operation and Wake Field Monitors (WFM) measurements were carried out. Issues with the BOM electronics were identified and partly fixed. WFMs were also improved with a phase shifter.
- Diagnostics and THz studies: Two Cherenkov radiators and the corresponding diagnostics, in vacuum and in-air, were installed and their exploitation started in both locations. Preliminary measurements in the sub-THz spectral range started as well.
- Plasma lens experiment: plasma lens and associated diagnostics were installed and commissioned, the beam transport optimised and the lens focusing effect was observed and quantified. By directly measuring the kick over the aperture the lens full linearity was assessed, a result which contradicted previous studies and prompted further investigations. The linear dependence on HV and current was also verified, and the first evidence of a non-linear wake excitation by the beam in the plasma after the current signal was detected.

BE-BI Group

First beam imaging measurements using incoherent Cherenkov Diffraction radiation

With the aim of developing non-invasive transverse beam size measurements, there were first observation of the emission of Cherenkov diffraction radiation in the visible range, produced by a

5.3 GeV positron bunch in a dielectric made out of fused silica [*R. Kieffer et al., Phys. Rev. Letters **121** 054802 (2018)*]. Contrary to classical Cherenkov radiation, the charged particle is not travelling through the material but at a distance of a few mm from the surface. The light intensity produced is large enough to allow the measurement of the horizontal beam profile using an intensified camera as shown in Fig. 41. Further studies have already been initiated in order to investigate what would be the resolution limit of such imaging systems.

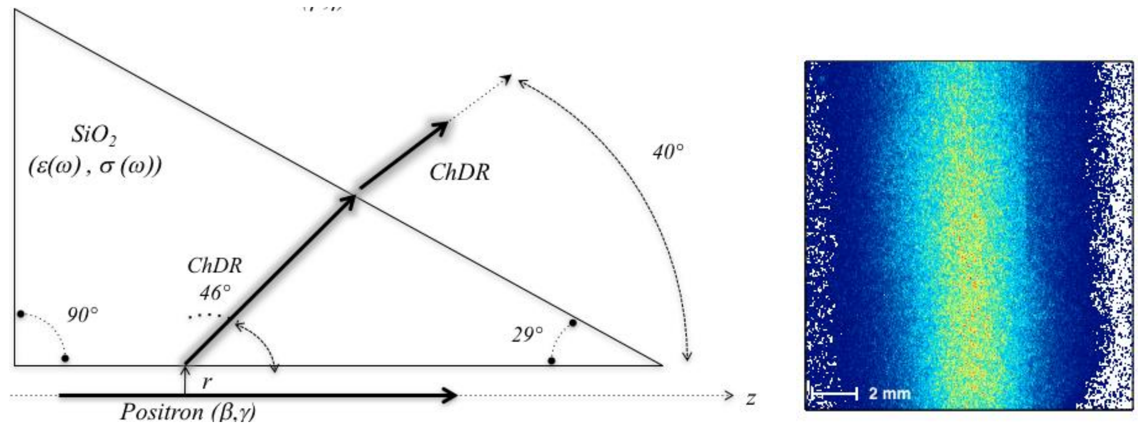


Figure 41: First observation of incoherent Cherenkov diffraction radiation emitted by 5.3GeV positrons in a 2cm long prism made out of fused silica.

BE-RF Group

The first two full-fledged CLIC prototype accelerating structures including all damping capabilities (TD24_SiC) were tested during 2017. While the first structure developed a hot cell as the consequence of a control failure, the second one was operated at almost 100 MV/m unloaded gradient, meeting CLIC requirements.

Two further CLIC prototypes (T24_PSI), manufactured by PSI with the same technology as used

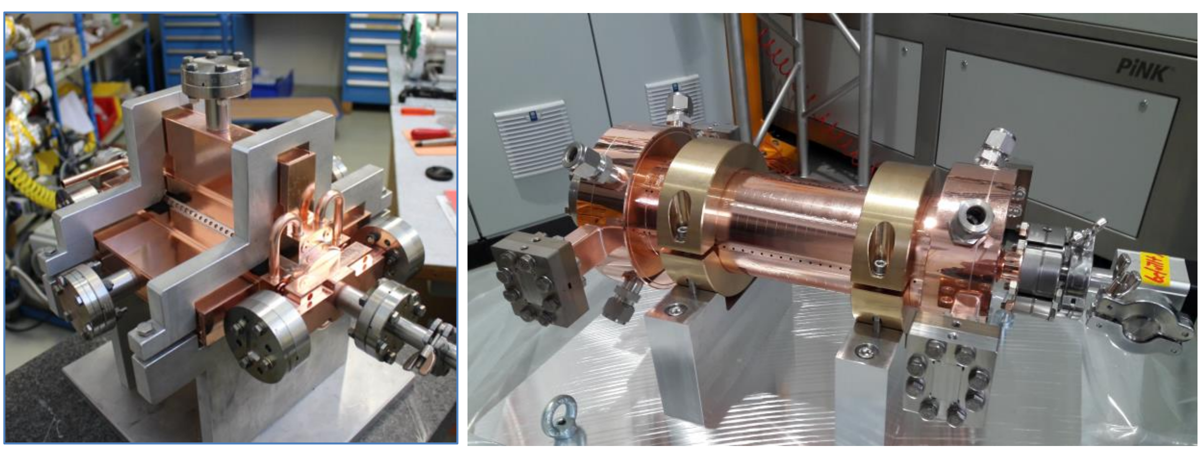


Figure 42: Full CLIC prototype TD24 SiC (left) and vacuum brazed T24_PSI structure (right) tested in high power.

for the Swiss FEL accelerating structures, were successfully tested with excellent results both in gradient and conditioning time. Both structures reached over 100 MV/m unloaded gradient. This opens the door to simplified manufacturing based on vacuum brazing, which may potentially be cost-effective without compromising CLIC performance.

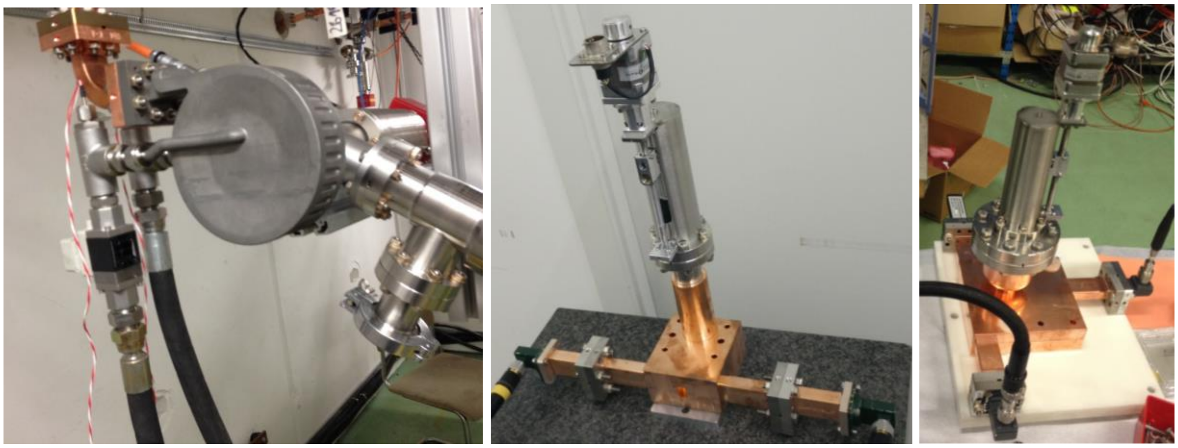


Figure 43: From left to right: spiral load fabricated by additive manufacturing, variable phase shifter and variable power splitter

Interest in CLIC X-band technology grew outside CERN, thanks largely to the excellent results measured in the test facilities at CERN on high gradient and high power components. In particular, high-power loads were designed and built using additive manufacturing, and initial tests proved the spiral geometry to work well even above 30 MW peak power, limited only by the capabilities of the test facility. This load and other components like directional couplers, pumping ports and pulse compressors are now being manufactured by DESY, STFC and Eindhoven University. Equally a variable power splitter and a phase shifter were designed and manufactured.

Future machines and EuCARD

BE-ABP Group

EuCARD-2 successfully concluded in May 2017. Over the previous 4 years the EuCARD-2 network on Extreme Beams (EuCARD WP5 XBEAM) organized a large number of workshops (35) covering all aspects of frontier accelerator performance; it defined a European strategy in four critical fields for future accelerator development: colliders, hadron beams, superconducting linacs, and polarised beams (published as a monograph in 2017); it continued the study of a new very large circular electron and hadron collider in Europe, which resulted in the Future Circular Collider (FCC) study at CERN and in the EuroCirCol Design Study in Horizon 2020; and it originated and promoted new ideas and developments in many accelerator fields, as extreme energy frontiers, muon collider designs, advanced photonics applications, etc.

Addressing open questions in particle physics calls for collisions at higher luminosities and/or higher energies. The next important step for e+e- colliders is the commissioning of the SuperKEKB B-factory in Japan, along with the design work being carried out for the “Higgs, Z, top, W” factories FCC-ee, hosted by CERN, and CEPC, its Chinese twin project. EuCARD-2

XBEAM has demonstrated that the design of these accelerators can exploit the lessons learnt at past and present colliders.

Following EuCARD-2, a new EC-cofunded Integrating Activity "ARIES" started in May 2017. WP6 Accelerator Performance and Concepts organised seven exciting workshops, including one on slow extraction, one on LHeC/FCC-eh, and one on photon beams. The "Photon Beams" workshop reviewed the state of the art of gamma-gamma colliders, Compton sources, and Gamma factories and fostered synergies between the different communities.

The FCC Week 2017 brought together more than 500 leading minds in engineering and science from 147 institutes to discuss the study progress and to lay the foundations for FCC design report. The accelerator, technology, and detector studies cover FCC-hh, ee, and a he hadron electron collider, giving diverse scientific programs for the proposed future large-scale research infrastructure. The FCC study is also designing an energy upgrade of the LHC (HE-LHC), based on the FCC-hh magnet technology. Topics covered at the week include cryogenic beam vacuum system, which has to cope with an unprecedented amount of synchrotron radiation, and the new layout of the FCC, which defines an overall tunnel length of 97.75 km, compatible with the existing CERN accelerator complex, allowing the use of the existing LHC or SPS as injectors, and optimized for the geographical conditions in the Lake Geneva basin.

Similar to the previous FCC meetings, special emphasis was placed on public engagement and outreach activities. For example, "Small particles, big machines" was the theme of the public hands-on exhibition run in parallel to the FCC Week 2017

The future heavy-ion operation at the HL-LHC was reviewed and updated to follow the evolving needs of the experimental community. Studies of future machines such as HE-LHC and FCC, including both their nucleus-nucleus and electron-nucleus collision options also continued.

In the framework of the Physics Beyond Colliders (PBC) study programme, several machine studies have been conducted in the PSB, PS and SPS to assess the potential of non-LHC beams after the LS2 interventions and the implementation of the LIU upgrades.

Higher intensity ISOLDE beams in the PSB could be limited by a known coherent horizontal instability, which has been further characterised with the goal to identify its culprit. For the moment, HOMs from the ferrite RF systems and EM ringing in the external circuits of the extraction kickers remain the main suspects. Machine studies in 2018 will be aimed to complete this analysis.

The vertical instability at PS transition crossing, which limits the intensity on the TOF beam, has been studied in detail by means of numerical simulations including the PS impedance model as well as space charge. The impedance of the kickers has been identified as the main driver for the observed instability. Although some obsolete Continuous Transfer (CT) equipment will be removed from the PS during LS2, PyHEADTAIL simulations with the updated post-LS2 PS impedance model have shown no significant change of the instability threshold. However, there is still margin for intensity increase and reduction of losses with the operational TOF beam in the PS, which will be the focus of machine studies in 2018.

An MTE beam with 2.3×10^{13} protons per PS extraction was injected into the SPS (about 45% more than in regular FT operation for the NA), proving the accumulation of the desired 4×10^{13} p per spill to a Beam Dump Facility (BDF). This high intensity MTE beam is also expected to benefit in the future from the LIU upgrade for the reduction of the vertical emittance delivered to the SPS, thanks to Linac4, and the capture and acceleration losses, thanks to the SPS RF upgrade.

BE-BI Group

AWAKE

In the course of 2017, the 16 MeV electron beam line was installed and equipped in the AWAKE facility. The BI group contributed with the installation of a set of instruments along the line. Two imaging systems (BTV) were recuperated from CTF3 and installed with refurbished screens, along with a Faraday Cup, designed by TRIUMF (Canada). There was also participation to the development of instrumentation for the detection of the accelerated electrons and of the proton bunch modulation. The optical line for the spectrometer to measure the energy of the accelerated electron bunch has been designed in collaboration with experts from the European Southern Observatory (ESO), and was installed in the second half of 2017. Two further BTVs were also modified to accommodate a beam halo instrument.
During the summer of 2017 TRIUMF (Canada) delivered 12 BPMs to be installed in both the AWAKE electron and common beam lines. Experts from TRIUMF helped to install, connect and test this system. A CERN developed FESA class and expert GUI was also available from October. All the installed instruments were successfully commissioned in the August, October and December 2017 AWAKE runs, where electrons were successfully transported to the entrance of the plasma cell and the mechanics of proton bunch modulation was studied systematically.

BE-RF Group

FCC

The power losses due to HOMs in the proposed 400 MHz cavity designs were evaluated for various energy options (Z, W, H, and $t\bar{t}$) of the FCC-ee. The constraints obtained for the cavity design are dictated by the Z-pole machine with the lowest beam energy, but the highest beam current. Different possible bunch and bunch train filling patterns were studied for these different machine versions, including the resulting HOM excitations.

A detailed study of HOM coupler options for the FCC-ee machine was carried out in collaboration with Rostock University. LHC-style HOM couplers were implemented on the 400 MHz cavity to

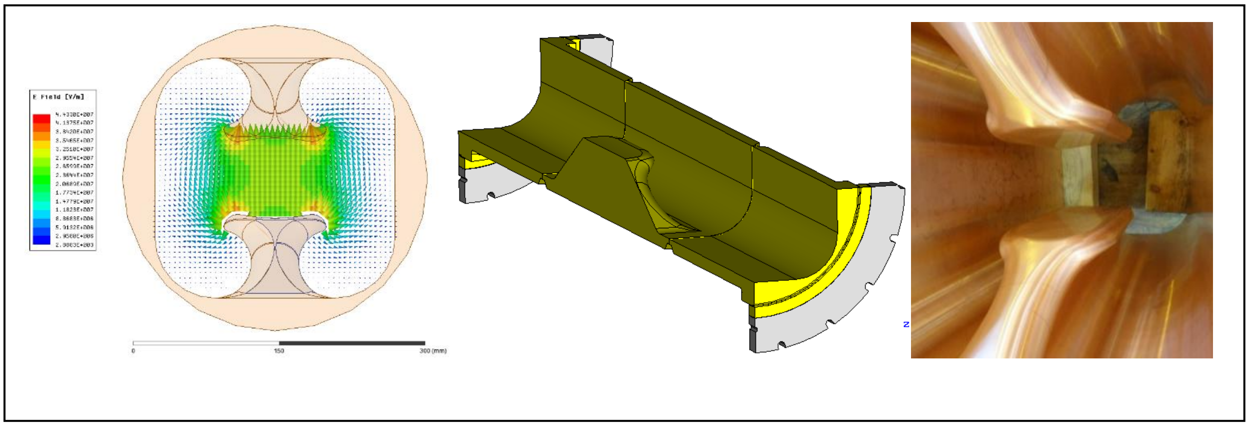


Figure 44: Wide Open Waveguide crab-cavity – from left to right: electric field distribution, mechanical assembly and inside view of cavity prototype

demonstrate that sufficient damping could be obtained even for operation at the Z-pole. A 5-cell 800 MHz cavity was proposed and optimized as a potential building block for the high energy regime of FCC-ee ($t\bar{t}$ operation). Scenarios for the staging of the different energy options of the FCC-ee were proposed and are being evaluated.

Detailed studies were carried out of the microwave and coupled bunch instability limits for the different versions of the FCC-ee and for FCC-hh. Since the FCC-ee aims at operating with large synchrotron radiation losses (50 MW per beam), which requires CW RF power of at least this power, another important aspect of this machine is to optimize the overall energy efficiency. The promising candidates for this optimization are the klystrons converting power from DC to RF, and intensive work was invested to bring a new class of klystrons, using novel bunching schemes (COM, BAC, CSM) closer to reality.

The "wide open waveguide" (WOW) crab cavity promises excellent mode purity, and the development of its prototype made excellent progress in 2017.

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 centralised organisation of the administrative assistants in the BE-ASR-AS section had remained unchanged since the birth of the BE Department almost a decade ago, and even before in the AB department. In May 2017, the model was changed whereby all administrative assistants were hierarchically assigned to the respective groups and the central secretariat to a dedicated section in BE-HDO. Independently of this decentralisation, the activities remained unchanged, although increased in volume. Throughout the year, a gradual increase in the departmental staff continued, resulting in an overall total of 852 (i.e. 427 Staff Members, 129 Fellows, 87 Students, 209 Associates). In addition, 199 employees of CERN contractors contribute to the departmental undertakings. Finally, through a partnership contract with A.D.A.M. SA developing an accelerator for medical applications, 64 of their employees 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 (32 new recruits in 2017) and the CERN contract review board (6 in 2017). The number of staff recruitment was high, mainly due to the 13 additional post openings in BE, authorised by the Director-General. In the Standing Concertation sub-group modifications of two Administrative Circulars were prepared, namely on Education Fees (AC-12A Rev.3) and Special Leave (AC-21 (I) Rev.2).

Resources & Logistics

The activities under this heading are related to the Departmental Planning Officer (DPO) on budgetary and financial matters, and to the Departmental Space Manager (DSM) for space and storage management, follow-up of small works and related logistics.

In order to overview, plan and control the departmental resources over the medium term period, the BE-ASR group leader has also the role of DPO. The departmental recurrent material budget was kept under control with *underspending* of 8.9% and an *over-commitment* of 8.4%. The personnel budget was substantially underspent by 6.14 FTE. The manpower planning was seriously challenged by a number of unforeseen events (11 resignations, 2 deaths, 2 departures for internal mobility, 8 new requests for reduced work time) combined with the high volume of posts opened (37) of which one selected candidate refused the offer.

The *financial and budget related activities* concern primarily 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. Following the resignation and early retirement of the DPO assistant, this workload had to be absorbed.

Within the activities of *space management*, work started on the evaluation for space requests for LS2: storage, workshops and the so-called *bases de chantiers*. The organisation of office moves is recurrent, involving modifications on electrical outlets, installation of ecological lighting, furniture and paint jobs if required. The BE-BI labs as well as three conference rooms were renovated, while the conference room reservation was reviewed to optimise occupancy. Two additional bike sheds have been constructed in the frame of soft mobility. The funding of the reconversion works of the auditorium in building 864 into a new RF workshop was secured.

Safety Unit

The BE Safety Unit counts four staff, one fellow plus a part-time contribution from a BE-BI staff member, 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" (LHC, SPS and PS) 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 acts also as scientific secretary for the DSO Committee (DSOC).

Safety of Personnel

The 2017 statistics on *occupational accidents* implying BE personnel or occurring in BE premises remained reasonable (8-10% of the 237 CERN accidents). Contributing to the working group on accident & incident management, a report has been finalised, presented by HSE to SAPOCO. The implementation will follow with continued implication of the DSO.

Preliminary risk analysis have been performed about hazards that can be addressed by the *Personnel Protection System* of the SPS. Rationalisation and simplification will lead to a reduced number of the so-called *safety chains*. A concrete proposal to improve access control to surface buildings of beam facilities was submitted to the Extended Directorate.

Radiation Safety

In close collaboration with HSE and EP, procedures have been improved or established, such as the *Safety Approbation Process for Solid State Physics Activities*, concerning the sample collections in ISOLDE.

In a continuous quest of the ALARA principle and in the framework of the SPS access system upgrade, the optimal locations of the SPS sector doors in LSS1 and LSS2 were investigated. It turns out that no displacement of the doors is required, mainly due to the future removal of the LSS1 beam dump and the new beam dump installation in ECX5, reducing significantly the dose rate in those regions.

BE personal doses were all below 1 mSv for 2017.

Safety of Installations

In line with the stage of each project, the required documents of the safety files have been established. For LIU, the descriptive part of the safety files for LIU-PSB, LIU-PS and LIU-SPS have been acknowledged and approved as released EDMS documents. The preparation of the demonstrative part is in full swing. For the SPS-FIRE Safety project, the Launch Safety Agreement (LSA) has been established with HSE, and the descriptive part is ongoing for each of the four work packages.

The *System Safety Assessment Form*, for the inventory of dangerous situations, has been fully revised and is also to be used to record the dangers of instruments. This has been successfully tested out on the hollow electron lens work package, in collaboration with the equipment engineer.

The safety review of the GBar experiment in the AD hall was held in March and revealed important issues to be addressed – namely related to the installation of the electron linac –, requiring close collaboration between BE, EP and the experiment's management. Finally, the beam permits were signed by the end of the year.

BE-ABP Group

The ABP Computing Working Group has been created in 2016 to coordinate the computing resource of the BE-ABP group with partners inside and outside CERN, and to share the available expertise within the group focusing on the developments for advanced optics and beam dynamics. In 2017, the CWG started a review of 35 in-house codes from ABP through periodic meetings and presentations, and created a TWiki webpage (http://cern.ch/abp-computing) to centralize and keep up to date the relevant collected information. This webpage became quickly a reference entry point for the newly hired students and fellows about the computing matters and resources in the BE-ABP group. The CWG was also in charge of coordinating the ABP migration from LSF to HTCondor, which ended in June 2017 after the successful transfer of the LSF groups used for tasks allocation and prioritization to the HTCondor new e-groups system. The CWG triggered a survey run across ABP during 2017 to feed IT with clear information about the significant impact of the migration from AFS to EOS.

Code name	Category	Development
LHC Online Model, MAD-X, MapClass, PyOptics, SixTrack, SixTrackLib	Optics and single particle tracking	In-house
ABCI, ACE3P, CST Particle Studio, GdFiDl, HFSS	Electromagnetic solvers (wake functions, beam coupling impedances)	External
ImpedanceWake2D, TLWall		In-house
IBSimu, Ninja, ONIX	Plasma discharge, low energy tracking	External
DELPHI, BimBim	Vlasov solver, circulant matrix	In-house
NHTS, MOSES		External
COMBI, FASTION, GuineaPig, PyECLOUD, PyHEADTAIL, PyPARIS, PyPIC, PySSD, RF-Track, SIRE, TRAIN	Tracking with collective effects (including space charge, beam-beam, electron cloud, impedance, ions, IBS, electron cooling)	In-house
PyORBIT		External
PLACET, PLACET2, PATH	Tracking for linear accelerators and linear colliders	In-house

Figure 45: Summary of the simulation codes developed or used by ABP.

Medical Applications

The highlight of 2017 was the MeDeGun test, high-compression electron gun for an Electron Beam Ion Source based on a novel gun design concept that was commissioned at the Twin EBIS test stand, giving an electron current of 1.5 Amperes at 10keV. This result demonstrates a sufficiently bright electron beam for a EBIS source to produce carbon 6+ ions, a necessary requirement for a linac-based carbon ion facility. The preliminary study of the facility will be included in the PIMMS2 study. The record results can also be used for the upgrade of the HIE-ISOLDE charge breeder.

In parallel simulations studies for extending the 750MHz RFQ design for protons, to the acceleration of particles with charge/mass 1/2 continued with the completion of a study for a 4 m long RFQ for able to accelerate carbon 6+ to 5 MeV.

BE-CO Group

The Accelerator Fault Tracking

The Accelerator Fault Tracking (AFT) project advanced significantly during 2017 with a major release in February followed by 11 feature releases during the year. Most importantly, AFT for the injectors was delivered on time, ahead of operation and was successfully used throughout the year. The AFT user count increased from ~160 to ~300. Lots of new features were delivered during the year, including:

- New data-driven Accelerator-specific properties (e.g. impacted destinations, affected PSB rings, scheduled cycle, destination, user, etc.) and System-specific properties (e.g. TI major event ids, failure type, JIRA issue key, etc.).
- Improved dynamic and fixed time selection controls, Integration with ASM (Schedules), Time period exclusion (e.g. to skip technical stops from statistics).
- User configurable dashboards, lots of dashboard components, and the possibility to share with colleagues.
- New statistics and reports (particularly for LHC related to turnaround times, operational modes, and physics availability summaries).
- Enhanced fault notifications.

Efforts were also made to ensure the alignment of fault assignments made in the TI Logbook and used for TIOC analysis with AFT fault categories. Combined with use of new AFT system specific properties (major event ids, equipment failure types etc.), there is now fully consistent TI availability data from AFT and TIOC perspectives and TIOC foresees to rely on AFT for reporting / statistics in the near future.

In addition to providing easy to access availability / performance related data, AFT is now saving the time of a lot of people via features which facilitate data completion and corrections, presentation preparations and bringing consistency to reporting across the machines – for example all content for the FOM report of each machine is available with a single click in AFT and is consistent across all machines.

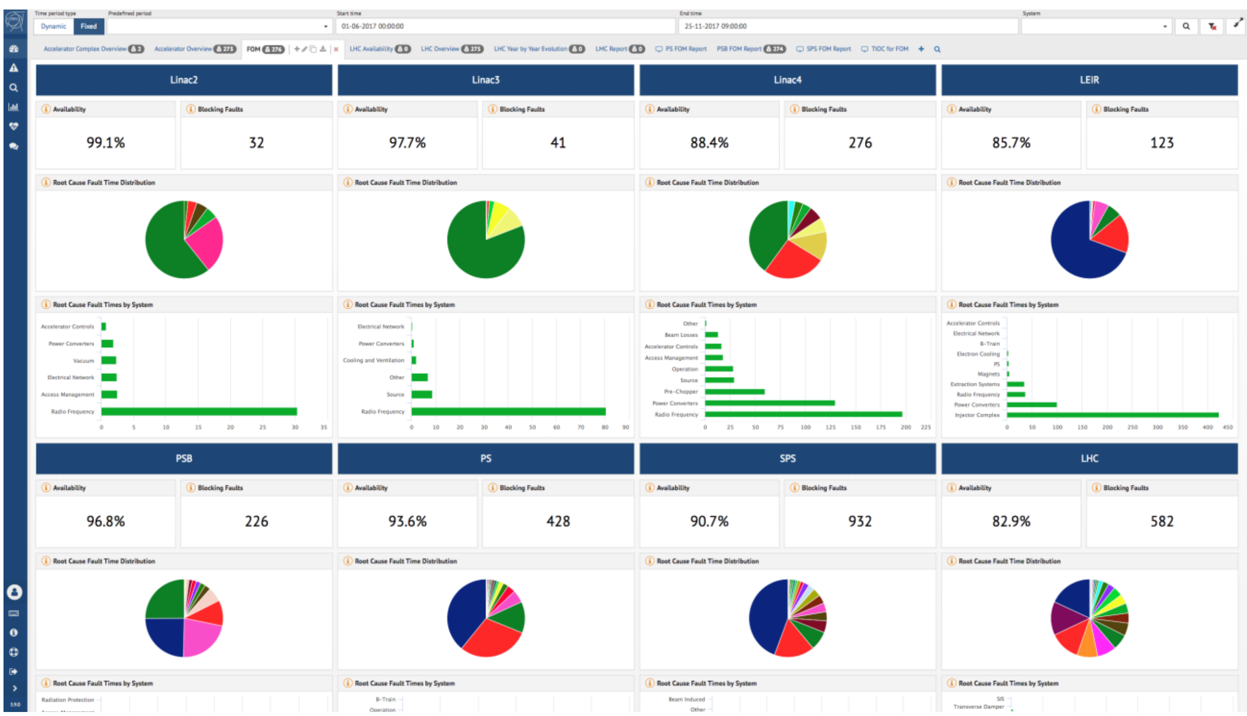


Figure 46: AFT screenshot of a public dashboard showing a performance overview of all machines.

Accelerator Performance Statistics

In order to maintain user confidence in the LHC Luminosity data shown in the Accelerator Statistics Web application, the underlying data calculation sever was extended to periodically obtain the updated "offline" integrated luminosity data from a common location shared by the LHC experiments. The data was then used to replace the less accurate "online" data obtained via the CALS Logging Service, and subsequently shown in the Web application. A number of other developments were also conducted to deliver a better user experience and / or facilitate future developments, including:

- Improving the Injector Performance Emittance plots and adding support for new LHC beam types (requiring modification of the calculation server for beam brightness).
- Migrating from the legacy IT-hosted Middleware-On-Demand service to the new OpenShift infrastructure.
- Configuring automatic deployment to OpenShift using the standardised DevOps approach for BE-CO Data Services.

Accelerator Schedule Management

A new project titled Accelerator Schedule Management (ASM) was launched in March 2017, where the aim was to provide a system to manage schedules related to accelerator operation and expose this to other applications such as AFT and TIMBER to facilitate various analyses that depend on the schedule. The new Web application was delivered in production in June and included a public REST API to allow other applications to programmatically integrate schedule data.

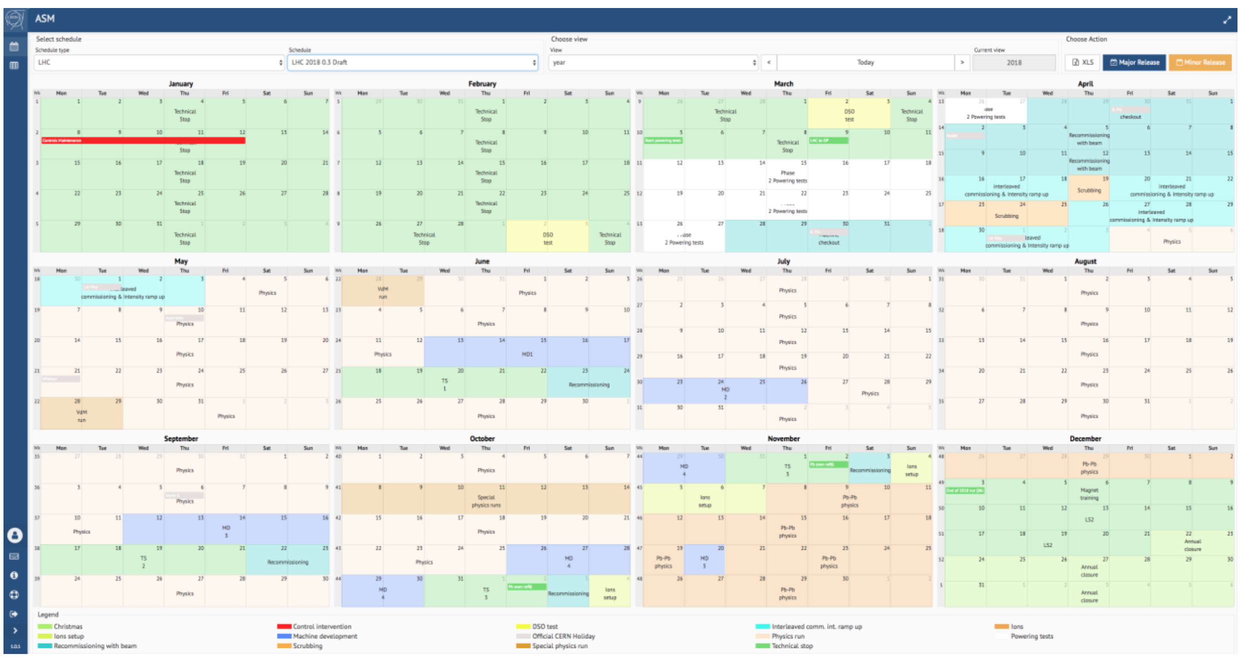


Figure 47: screenshot from ASM showing the latest draft LHC schedule.

Subsequently with the BE-OP group leader and the BE-CO exploitation manager - the opportunity to extend ASM to streamline and improve the process of managing changes to the Control system was identified. The ASM application was then extended and deployed in production to support the registration and follow-up of all Controls Changes, facilitating the data entry by equipment groups, validation by Operations and data browsing by all users. ASM was then used by the SUWG (Smooth Upgrades Working Group) to successfully plan and follow-up all Controls related changes during the 2017 TS2 and TS3 technical stops.

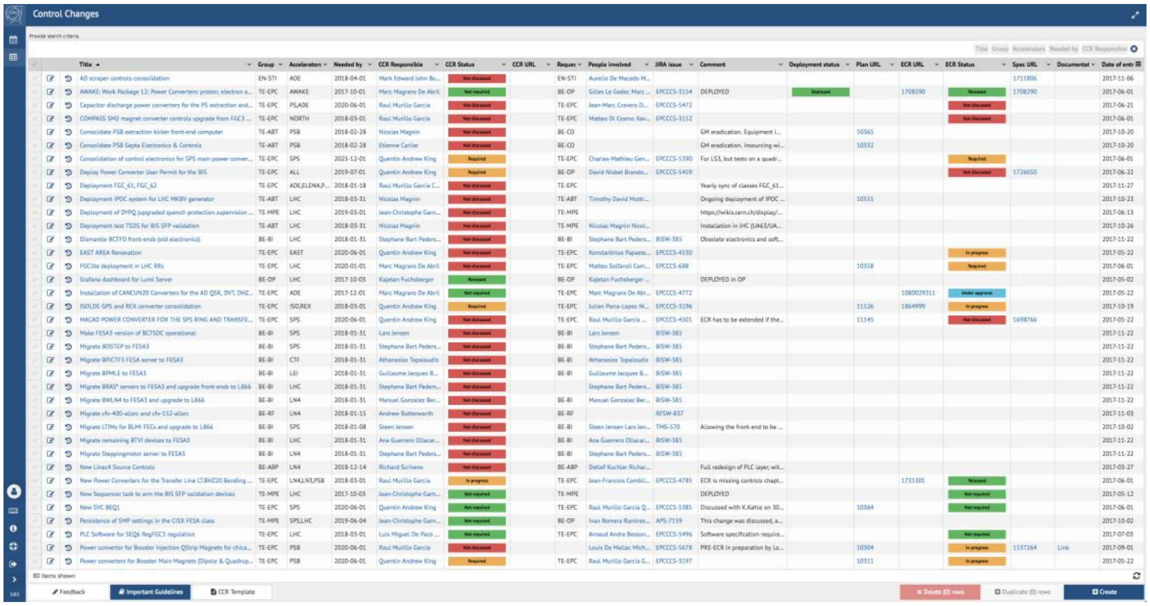


Figure 48: screenshot from ASM showing registered Controls Changes.

The other foreseen ASM extension to register, schedule and follow-up MD requests (for LHC and injectors) made significant progress and will be deployed in early 2018 for use in the 2018 run.

Controls Configuration Service

The Controls Configuration Service (CCS) was stable throughout the year for the large and diverse user community, despite a significant advance in the foreseen developments and consolidation. In particular, the first production version of the new Controls Configuration Data Editor (CCDE) was released which will eventually replace the old Oracle APEX applications. This first release included the modules to configure: hardware, NXCALS subscriptions, WhiteRabbit switches, and CMW servers and proxies.

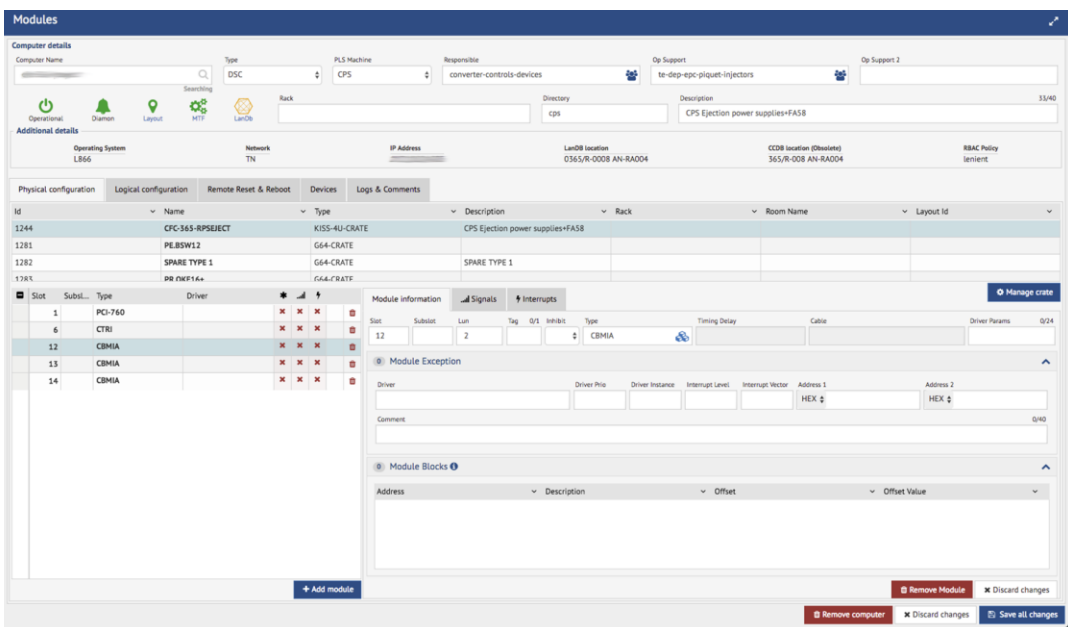


Figure 49: screenshot from the CCDE showing the edition of hardware modules configuration.

Concerning the Controls Configuration Database (CCDB), various aspects of technical debt were addressed, such as the removal of obsolete database accounts, tables triggers etc. and migration of non-CCS specific data outside of the system.

The integration between the CCS and Layout and LanDB concerning management of racks and equipment codes was improved, and support for new FESA features and workflows was added.

A CCS testing environment was established on appropriate database servers, including as part of the BE-CO-wide test bed infrastructure on the GPN.

DevOps for Data Services

A suitable DevOps environment was established and then used by all BE-CO Data Services activities. This was based on industry standards such as Artifactory, NPM, Gradle, Gitlab, Jenkins, and Monit –running on IT-provided infrastructure where applicable.

The Layout Service in the A&T Sector

The development of the new Layout database and associated Web application progressed well, and in September a first production version with a lot of core functionality was deployed (https://layout.cern.ch).

In particular, concerning the database developments, the synchronisation of data from the current Layout database to the new Layout database was implemented for powering circuits, circuits and segments, connections and powering sectors. Likewise, the synchronisation of responsible data for buildings, floors and rooms from AIS Foundation database was added. The new Layout is time oriented (supporting past, present and future layouts) and in 2017, improvements were made to the management of validity periods (expiring, expanding lifetime or deleting a record if it is timewise incoherent) in order to cascade modifications between parent and child elements, relative positions, dimensions and connections.

For the Web application, new user searching capabilities were introduced, supported by navigators for Powering Electrical circuits and Field buses (covering WorldFIP, Timing and White Rabbit circuits). Editing capabilities were added for managing layout element dimensions, geometric transformations and magnet types properties. Facilities to bulk upload both electronics data and circuit contents into the Layout database was also provided. A 3D interactive electronics schematics editor was also developed, which can be used to visualise and edit the electronics data in addition to the aforementioned bulk upload tool.

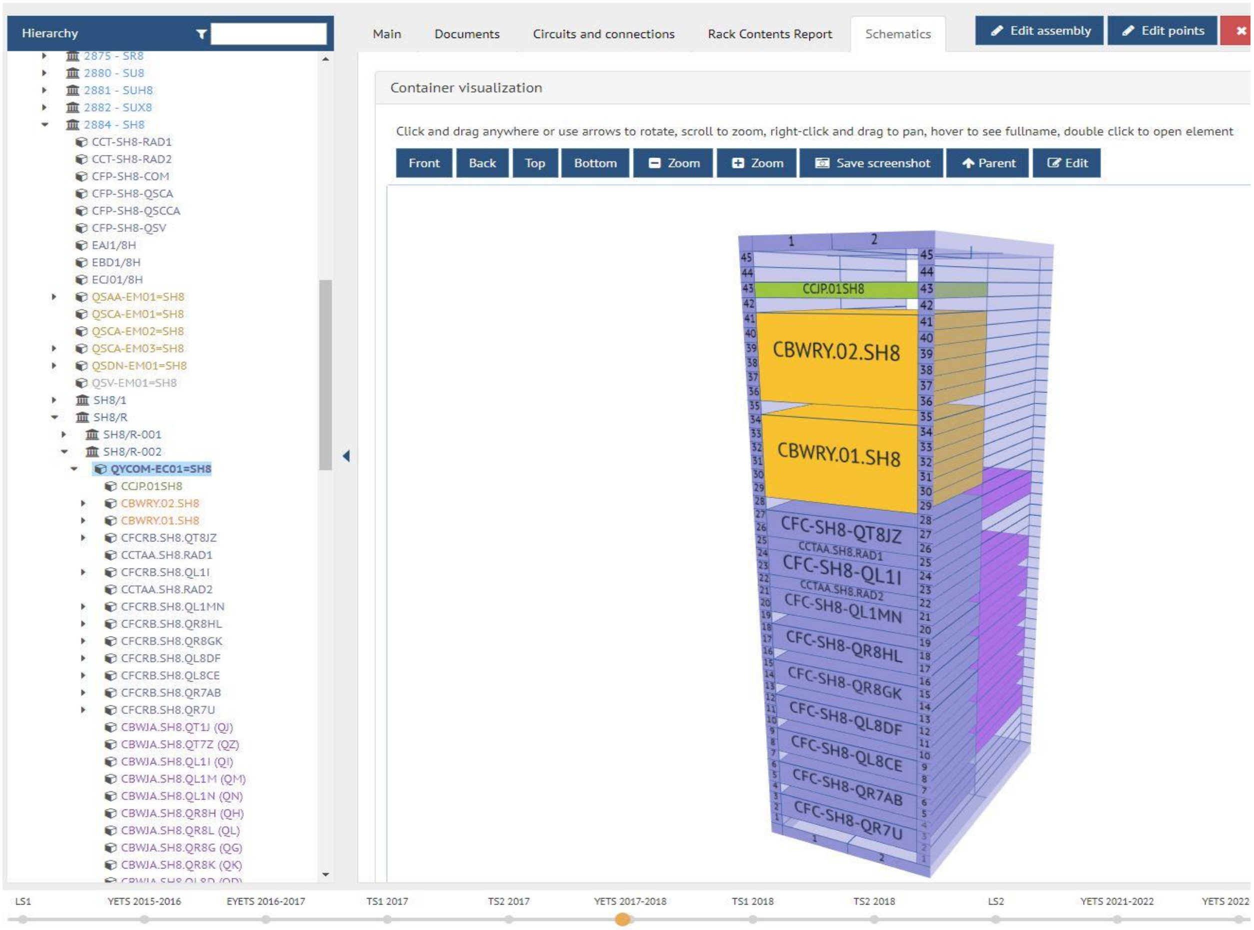


Figure 10: screenshot from Layout showing an editable electronics rack.

To avoid unwanted data modifications, an improved, fully data-driven authorization mechanism was implemented, based on associations between Layout classes and corresponding RBAC roles.

Meanwhile, for the legacy production Layout database, quite a lot of work was done as necessary, including: migrating the synchronisation process for CERN location data from the legacy GEOSIP database to the new AIS Locations database, updating BI Equipment reports as input to the annual CERN audit, and implementing a first simplified version of the PS MAD sequence file generation with Straight Sections and Main units as requested for the LIU project.

The Logging Service across CERN

The Logging Service continued to be heavily solicitated throughout 2017, reliably supporting operations of all CERN accelerators and experimental facilities. In parallel, a significant effort was invested in the new NXCALS project aimed at replacing the existing CALS logging system. On this topic, important progress was made on solidifying the overall system architecture, and the development of the core of the system in terms of: data storage strategies, compaction and de-duplication of captured data, and full system monitoring.

In order to reliably ingest data acquired via CMW into the NXCALS system, a sub-project was launched to develop a highly scalable data logging process architecture based on the Akka framework. This new Java software was stringently tested in terms of performance and functionality, with over 80% code coverage via automated tests. The software was then deployed in production on new hardware towards the end of 2017, and complemented with appropriate monitoring.

Beyond the pure NXCALS development, one of the main areas of investment was in identifying, planning and conducting work necessary to ensure backwards compatibility for CALS users and data continuity by migrating data from CALS to NXCALS. Data migration is a much more complex task than it appears, with the final goals being to migrate around 1PB of data, in a robust manner that transforms data representations between systems as required and ensures no data losses. The work required was organised as a dedicated NXCALS sub-project and a first production-ready version of CMW-acquired data migration was up and running by the end of the year for around 2000 device /properties. The data migration also required the development of advanced monitoring, plus coordination with several stakeholders in order to handle a number of corner cases.

In light of the development of a new Post-mortem (PM) system, a collaboration was established with TE-MPE with the aim of using NXCALS as the PM data archive. Two developers from TE-MPE joined the Logging team during several months, which proved to be a positive experience for all involved and resulted in the confirmation that NXCALS will be used for the future PM system.

With the aim of promoting the use of the SWAN service (Web-based Jupyter analysis notebooks developed in EP-SFT) to the Logging Service user community as one of the new means of analysing data, the NXCALS team formalised and presented the need for a stable, production quality service to be provided by IT and EP-SFT. Subsequently by the end of 2017, IT put in place a beta version of NXCALS data access via SWAN.

White Rabbit

The first White Rabbit Tutorial Workshop took place in Barcelona, as a pre-conference workshop in ICALEPCS 2017. The event was meant to help potential users of WR understand how this technology can solve some of their problems in different types of distributed real-time controls and data acquisition systems.

At CERN, the most important development using WR was the renovation of the BTrain system in the injectors. This new, message-based, system is meant to replace the legacy system based on pulse distribution. As such, it enables higher precision in the real-time distribution of magnetic field values and provides improved diagnostics. For example, in the future there will be a flow of magnet current information back to the master node so that models of the correspondence between current and magnetic field can be improved. Most of the initial deployments happened in the PS, including distribution to the RF electronics in the beginning and incorporating the Main Power Supply later on.

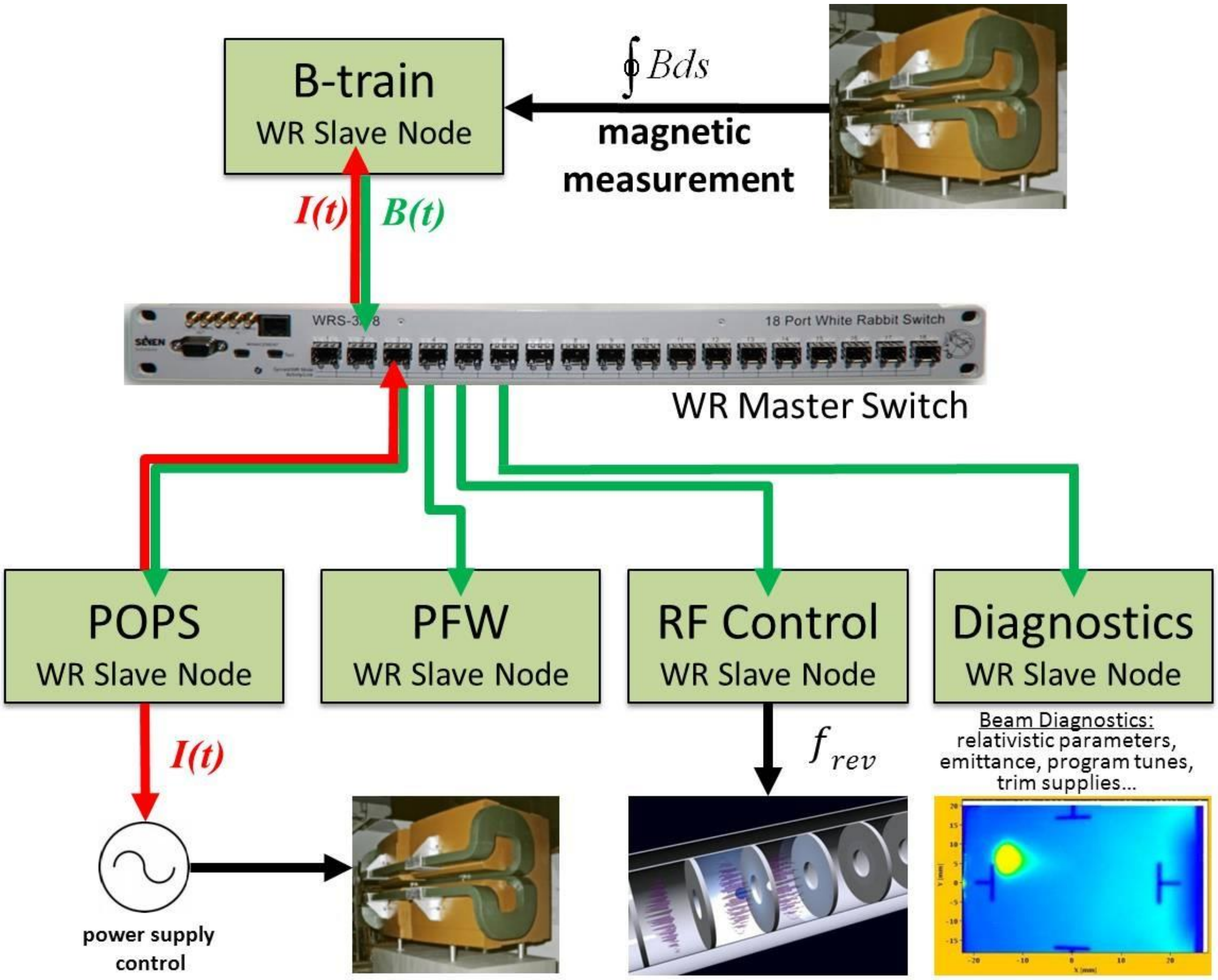


Figure 51: Simplified block diagram of a White Rabbit network for real-time distribution of the bending field in a synchrotron.

WorldFIP

The year saw the final stages of the masterFIP development and testing. This is an FMC (VITA 57) mezzanine which, used in conjunction with the SPEC carrier, provides a WorldFIP master board in PCIe format. This development was critical for two reasons. On one hand, the current generation of Alstom PCI boards showed signs of instability which, although extensively studied, could not be fully understood. In particular, more and more instability was noticed after the switch to multi-core industrial PCs. On the other hand, new PCs with PCI slots are hard to come by, and a PCIe solution will allow us to move forward with the deployment of new-generation industrial PCs with confidence. After extensive testing throughout the year, a good number of masterFIP boards were installed in the LHC for assessing their reliability during 2018.

Level Converters and Pulse Repeaters

Pulse conversion and distribution is the workhorse of synchronisation in the injectors. There are thousands of pulses travelling through long coaxial cables in all directions. For a long time, we used blocking technology (~24V) for medium-distance (a few hundred meters) pulse distribution. The repeaters were designed in the early 90’s, so we decided to start an upgrade project in the beginning of the 2010’s. This project involved the design of a number of boards to ensure distribution of pulses in TTL, RS-485, blocking and optics, and the conversion among the different standards. The year 2017 saw the end of the development and validation for most of the boards. In particular, the TTL-blocking translation and distribution module was finalised and deployed extensively in all injectors.

Figure 52: The new TTL-blocking converter module.

The new electronics is much more versatile and modular, as well as extensively documented and tested. It also provides remote diagnostics so that basic information can be used to assess if a physical intervention for a replacement is needed, and where. It uses a VME standard form-factor without any need for a CPU module sitting next to it. Diagnostics information flows through the I2C interface in the backplane to the crate management controller, which makes it available through the Ethernet management interface of the crate using SNMP. This allows for the configuration of simple pulse repeater assemblies using 1U and 3U VME crates, as well as the inclusion of a pulse repeater in a free slot of an existing VME crate.

Support for new machines

To support the migration of part of the CTF3 machine to CLEAR, several front-end device classes had to be migrated to a solution based on generic FESA3 classes and missing classes had to be provided.

General

Improve testability for the Control System

To support different release environments, as required by this group-wide initiative, the FESA framework Eclipse plug-in was modified to allow the developers in the equipment groups to test their software in isolated environments, separated from production. Also, the

CO Middleware services was modified to enable this dedicated test infrastructure.

CO Middleware (CMW) KT collaboration with South Korean company, LG Display

After discovering CMW from a presentation at an ICALEPCS conference, LG Display expressed an interest in using CMW in their Manufacturing Execution System. After some initial feasibility work between the CMW team and representatives from LG Display, the two parties together with the CERN KT group agreed on a license. As a consequence, 4 South Korean Engineers came to CERN for two weeks of consulting with the CMW team to help the former adapt their software to use CMW. After some additional trials on site, LG Display decided to pay for the license to use CMW.

JMS

The JMS service underwent a major consolidation effort in order to improve its reliability. Most of the important JMX metrics for all ActiveMQ brokers were imported to a dedicated Prometheus instance, which periodically polls for new metric values. Next, alerts were set up for early notification about an abnormal state of a broker. The alerts can be about warnings or critical errors. The latter are sent additionally via SMS to several people. Additionally, a dedicated monitoring agent was developed to perform additional checks on the configured brokers: message delivery performance and connectivity to a broker. The agent exposes the results of checks, which are also integrated into Prometheus. These additional checks will help the support team to spot a service degradation and give early warnings about the detected problem before it affects operational clients

OASIS

New systems were deployed for:

1. ELENA RF Tomoscope;
2. ELENA Prototype profile monitoring;
3. PSB BPM Orbit monitoring;
4. PSB BTP Wide Band Pickup (LIU);
5. PS FGC data sources monitoring;
6. PS Wide Band Pickup 90B (LIU);
7. SPS Quality Check system.

The SPS Quality Check proved technically challenging due to very demanding requirements with regard to the performance, quality and extensibility of the final solution. Several prototypes were prepared and tested in the OASIS testbed, an exact copy of the operational environment, before finding a satisfactory solution that was implemented and commissioned with operations.

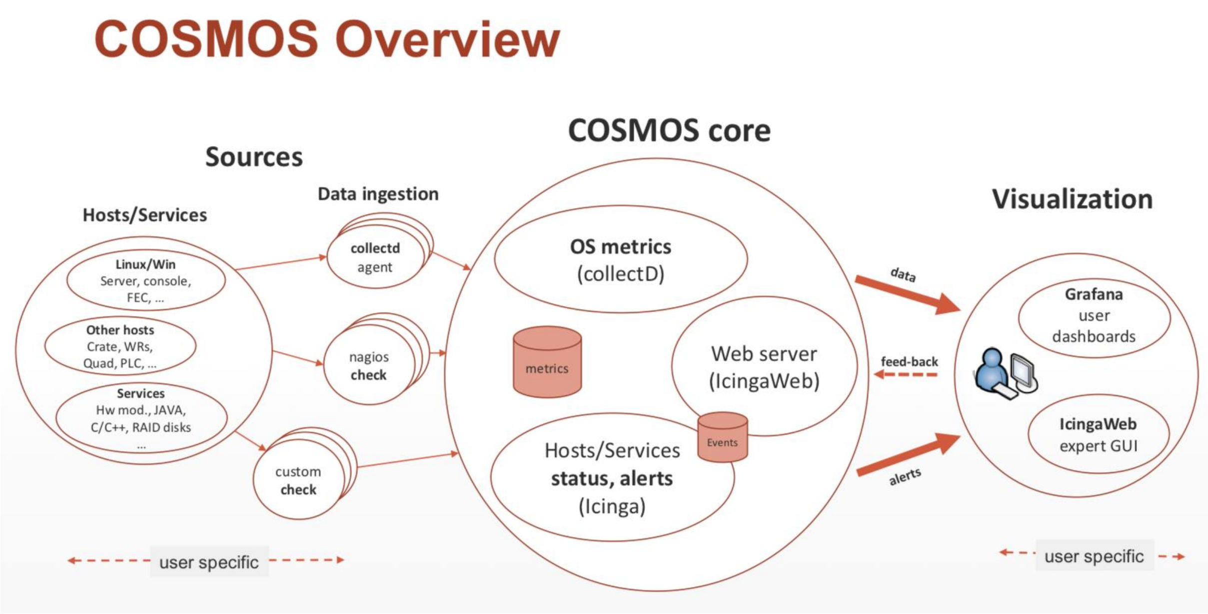
COSMOS: The Control System Monitoring 2.0

The BE-CO invested significant efforts in 2017 in order to design and deploy the very first open-source based Infrastructure monitoring system.

A large number of core operational components of the Accelerator control system infrastructure are now fully monitored through the new COSMOS system:

- All Linux Back-end systems of the Accelerator Data Center
- Storage systems
- White Rabbit switches
- WorldFIP communication fieldbuses

In the new paradigm, COSMOS proposes a very high level of flexibility by empowering the equipment specialists who can now specify and visualize monitoring data of their systems in a very powerful and flexible way.



The efforts are currently pursued in order to cover the front-end systems (Industrial PCs, VMEBus, mTCA.4) and the core software processes required to operate the Accelerator complex.

Here are some typical examples of operational dashboards currently deployed in operation:

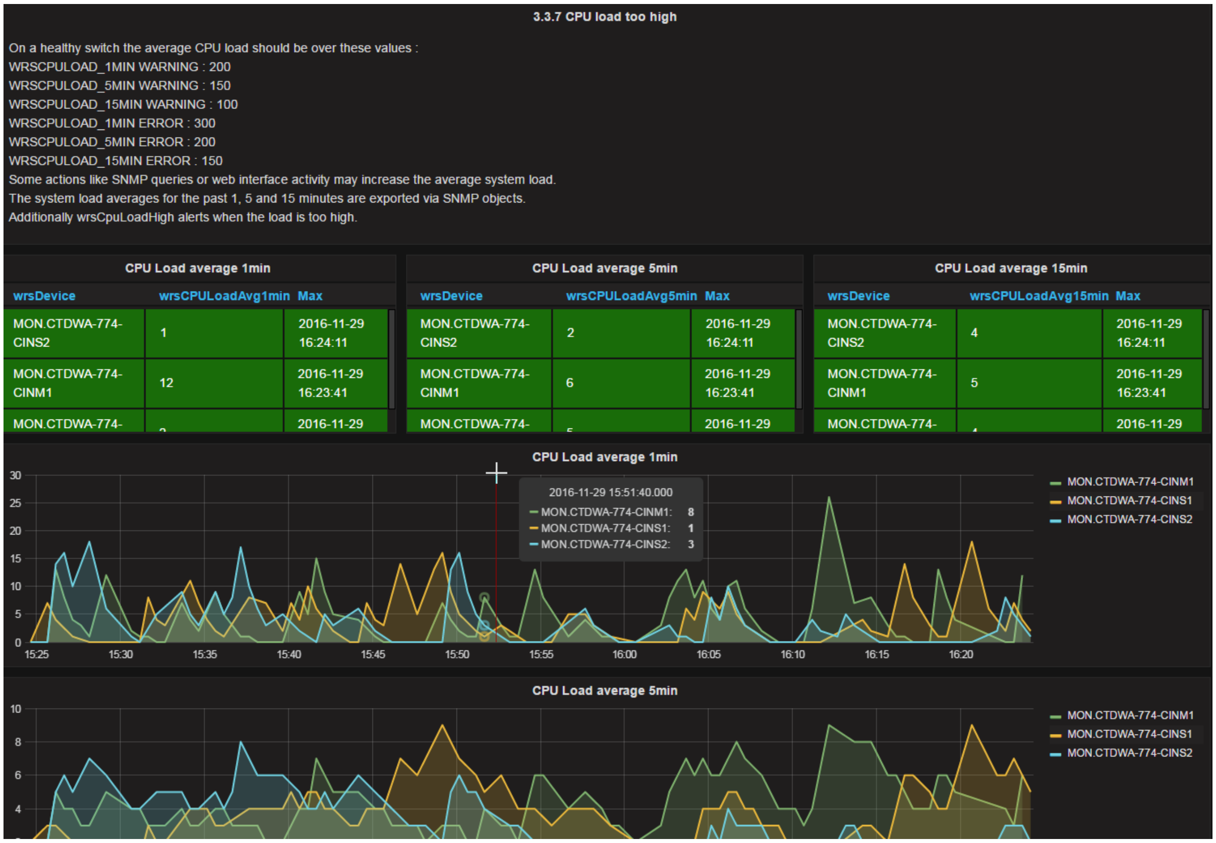


Figure 53: Dashboard for the monitoring of White Rabbit switches.

Figure 54: Global Control System Infrastructure dashboard.

BE-ICS Group

SCADA Application Service

Main activity for SCADA Application Service of 20107 was an upgrade campaign of SCADA software WinCC OA to go from version 3.11 to 3.15, it was accompanied by updates of the UNICOS framework and operating system from SLC6 to CentOS7. It required coordination across many teams responsible for controls as well as IT infrastructure months before and also during the upgrade. Due to the large number of WinCC OA applications (230) spread across many machines (120) it took a lot of time and resources – The campaign finished after 3 months and was a success.

Another important task was to centralise WinCC OA log collection as well as database statistics generated by a vast number of applications. A new implementation of central logs help the service diagnose and assess the scale of a problem occurring. Database statistics are used to monitor data production by the application and also help telling if something is wrong.

Quality and assurance: PLCverif

In recent years, a considerable amount of research effort was spent on improving the quality assurance of critical PLC software by using formal verification in addition to the typical testing-based verification and validation. This resulted in PLCverif, a proof-of-concept PLC software verification tool. Many parts of this research have been summarised in a PhD thesis written by a CERN doctoral student, defended in 2017. PLCverif has already been used successfully on several CERN PLC programs. The project reached a new stage during 2017 with the goal to develop a robust, extensible, automated PLC software verification tool that can be used not only at CERN but also in industry. The project was funded by KT, following a successful application in 2016. The development of the re-engineered tool should be finished by mid-2019.

The innovative, more thorough, formal verification methods have been applied this year to the interlock system of the new switchboard located in Building 311 and to the new vertical magnet test benches (cluster D) in SM18. In both cases, several errors were revealed by PLCverif. The project also attracted external interest, resulting in a collaboration with Siemens on the analysis of the potential of this method. Furthermore, we have applied formal verification to analyse a critical PLC program component that will be used by ITER in their experimental fusion reactor's control system. In the frame of the collaboration with the Budapest University of Technology and Economics, external support was provided to our tool development.

In addition to formal verification, we were working on other methods to improve the quality of our PLC-based systems. A summer student project targeted the testing, simulation and visualisation of PLC programs based on x86 code generation.

Detector Safety System: DSS

During 2017 there was a major effort on refactoring the control system to be able to cope with a larger number of inputs. Originally designed for a fewer number of them, this implied a change in the user interface and incorporated new functionalities as the cascade events. The operation of such system was rather smooth during the year and only had two hardware issues, one in ALICE and the other in ATLAS which were rapidly corrected to avoid experiment downtime.

FAIR: Magnet test bench

The cryogenics test facility for the SUPER-FRS* magnets as well as quench protection and energy extraction system were designed for a later deployment in 2018. Extensive works on cabling happened during the year. The final design of the control system is based on standard UNICOS projects and homogenised all the human-machine interface around interconnected projects allowing a single and unique operator panel.

Electrical Network: PSEN

The main activities related to the development of the supervision system for the CERN electrical network (PSEN) were related to the migration of the previous system from Linux SLC6 and WinCC OA 3.11 to Linux CC7 and WinCC OA 3.15. Compared to all other WinCC OA system deployed at CERN, the particularity of PSEN is the requirement to never have any downtime thus preventing the usual way of upgrading the systems. A completely redundant architecture was put in place for the migration to cater for this requirement. The development of new functionalities for PSEN lead to the deployment of 4 new releases in 2017. In order to maintain the quality of the release with the many different architectural changes, a formal definition of the release procedure was defined with EN/EL and TIOC. (See Fig. 55)

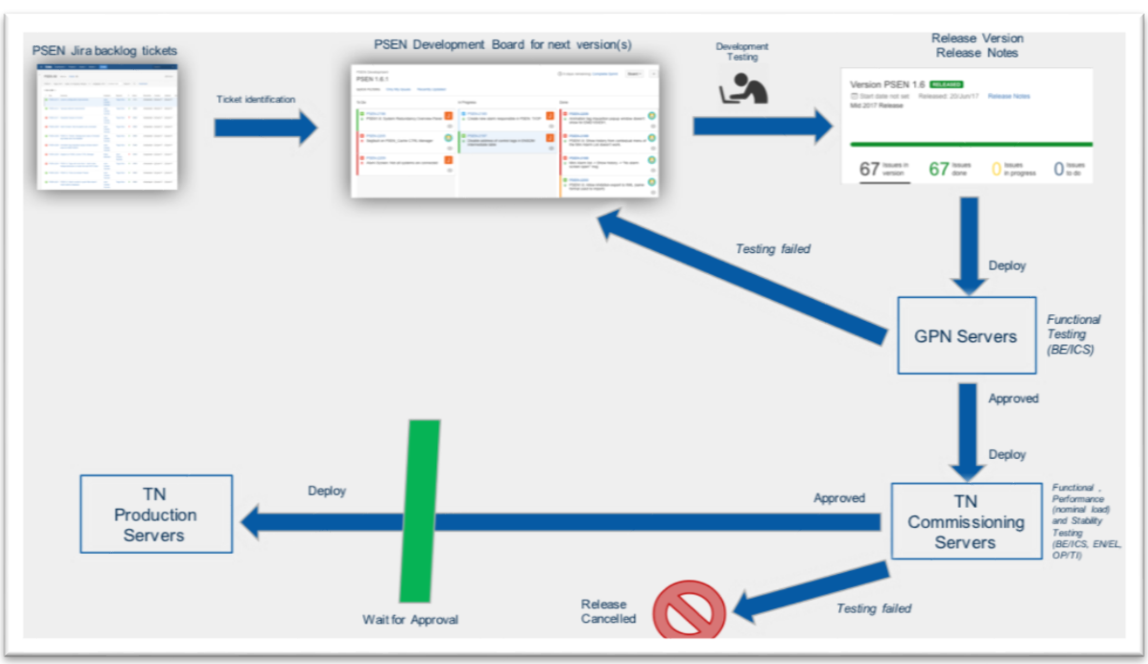


Figure 55

SM18 Test benches

A new vertical cluster D Interlock system, used for new HiLumi magnets test, as commissioned in 2017. The control system, like for all SM18 horizontal test benches was designed by using fail-safe technology provided by Siemens PLC controllers, integrating in one single CPU the UNICOS standard together with a Safety Instrumented System (SIS).

The development of the SIS was based on the recommendations provided by the IEC 61508 and IEC 61511 standards. The goal is to standardize all the activities described in the safety life cycle, such as risk analysis, safety functions specification, testing activities, etc. and apply them to the SM18 test benches.

Technical Infrastructure Portal

The portal allowing the TI operators have a global overview of the technical facilities control and alarms extended its functionality comprising 42 WinCC OA SCADA machines in distributed mode and totalising 230 UNICOS control systems. The portal also included the electrical network control system (PSEN)

B311: Switchboard controls

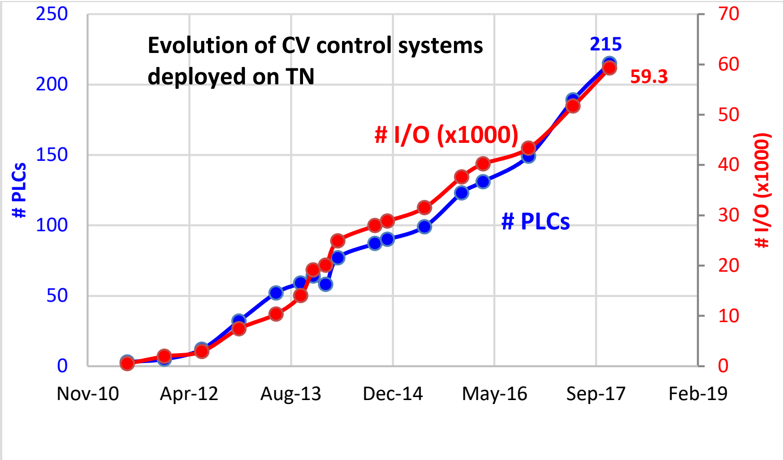
Fail-safe interlock control system has been designed to control the new magnet test bench facility that has been created in building 311. Support started from the hardware selection of the components with the full electric diagram design of the control unit, with UNICOS software development, keeping in consideration the risk analysis constraints. A close cooperation was maintained with the external supplier of the main power switchboard who integrated part of our control system directly in their control cabinet. In this particular project, a wide use of remote IOs technology allowed a significant reduction of the field wiring and therefore a reduction of the commissioning time.

AWAKE Plasma-cell

Following the 2016 commissioning of the experiment, in 2107 new requirements and implementation were developed: improvement of safety automation control during the procedure of rubidium refilling, inclusion of the oil pump in the automatic control system that improve the remote automatic control.

Cooling and Ventilation control systems

During the period from EYETS 2016 through Dec 1st 2017 the Cooling and Ventilation application development team in BE-ICS, in collaboration with the EN-CV group, commissioned a total of 60 PLCs – a new yearly record – see chart below, showing the evolution since the beginning of the development program in 2011.



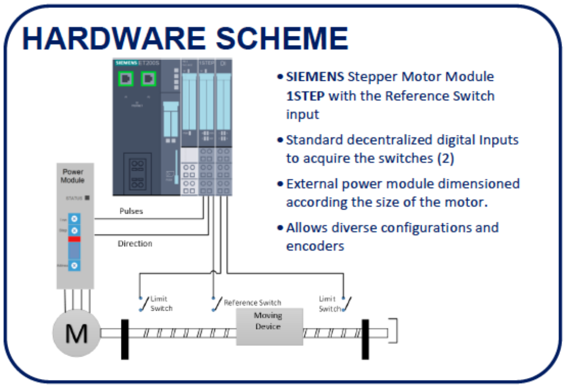
This included a number of critical applications which were re-engineered: the ventilation and cooling of building 513 (to replace the old Wizcon supervision) – a total of 15 PLCs; the ventilation of TDC2/TCC2 in the North Area; the ventilation of the LHC SR buildings (housing the power converters) of points 2, 3, 5, 6 and 7 – a total of 10 PLCs; and the ventilation of the LHC Surface buildings of points 1, 18, and 5.

In addition control systems were delivered for various new projects including 5 PLCs for the various ventilation, extraction and cooling systems in building 107 - see pictures below; the ventilation of the new ITHub buildings 773 and 924; the ventilation of the new EHN1 extension and the argon extraction and supply units; the ventilation and cooling systems of 2 new buildings on the Meyrin site (311 and 245); and a new detector cooling project for the ALICE ITS sub-detector, which will be tested on the surface until deployment in the cavern during LS2.

Finally, the team has begun preparing for YETS 2017 and beyond, including the development and lab testing of the control systems for the chilled water production and distribution in BA81 and building 355 in Meyrin. And the critical development of the CMS ventilation applications has begun, with a total of 5 out of 9 already prepared and lab tested.

Eurocircol

The European Circular Energy-Frontier Collider Study had one of its goals to validate the baseline of the preliminary design of the FCC-hh arc vacuum system for the prototype and develop the technical design concept for the beam-pipe. There were tests at ANKA (synchrotron light source facility) in Germany to validate the concept. BE-ICS helped TE-VSC with the automation development & commissioning of the control system based on UNICOS-CPC standard objects with **stepping motors functionality.**



The "Gas control system panel generator" used to generate HMI panels for WinCC OA was rewritten from scratch in Java. It replaces a hardly maintainable C# version. A total of 33 gas control applications are currently in production in the LHC Experiments and the CERN accelerator complex. Each application contains around fifty synoptic views and hundreds of plots. The model-driven approach simplifies the creation of these graphical interfaces; allowing the propagation of changes to all visualizations at once in a coherent manner, thus reducing the long-term maintenance effort. The generation tool enables the creation of files of similar content based on templates, specific logic (rules) and variables written in simple user-defined XML files.

In September, the legacy alarm system LASER got replaced by the new PHOENIX alarm console. PHOENIX uses the Technical Infrastructure Monitoring (TIM) service as backend which is based on the Open Source C2MON framework (http://cern.ch/c2mon). At the same time, all alarm configurations are now submitted via MODESTI (https://modesti.cern.ch) that provides domain related user workflows (see Fig. 56). All alarm requests are first reviewed and later tested by the Technical Infrastructure (TI) Operators. Furthermore, with the Grafana instance of TIM (https://timweb.cern.ch/grafana) operators now have a sophisticated dashboarding tool in place to create detailed alarm statics.

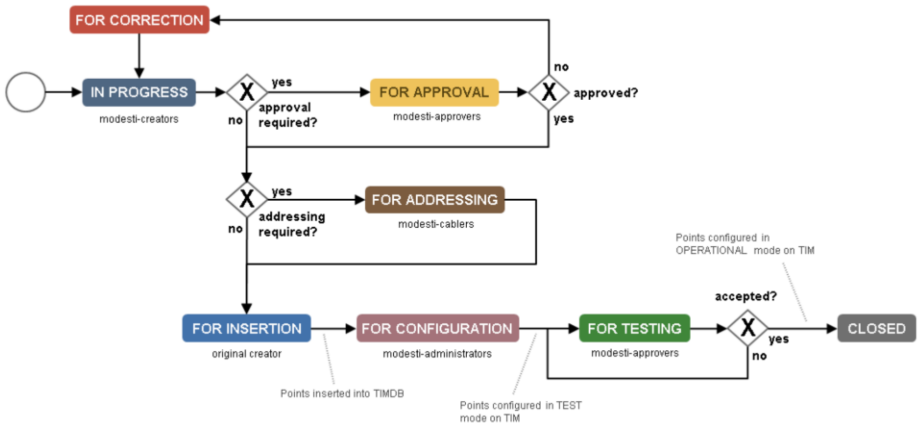


Figure 56: Example of a MODESTI workflow for alarm integration.

It is planned to include all 110 thousand electrical alarms from PSEN in a second phase which should be achieved until 2019 Q2.

Industrial Controls Frameworks

The CERN Industrial Controls Frameworks (JCOP and UNICOS) are used in more than 650 critical controls applications in multiple domains (LHC Experiments, Cryogenics, Machine Protection, CV, etc.) at CERN. This has allowed for an unprecedented level of homogeneity of industrial controls at CERN. In 2018, these frameworks have been enriched with new functionality and a number of improvements. In parallel, a major effort has been started, the so-called Framework Consolidation and Redesign project, which aims a simplifying the long-term maintenance of these frameworks, which are now 18 years old, as well as to prepare them for the new challenges of the High Luminosity LHC. The first steps in this direction have comprised the consolidation of the backlog, major improvements to the QA process, deprecation of obsolete code and functionality, organization of the work into work-packages as well as some major new developments like the Next Generation Archiving and Alarm Screens for WinCC OA. The Framework Consolidation and Redesign project is expected to be a major activity in ICS for the coming years. On the middleware frontOn the PLC front, obsolescence plans have been prepared for both Siemens and Schneider equipment. Moreover, new modules like the Schneider PXM Profinet coupler have been successfully validated for their deployment in critical Gas and Cryo control systems during the LS2 upgrades. The Siemens S7-1500 PLC family is currently being integrated in the Industrial Controls Frameworks since it is also envisaged to play a major role during the LS2 upgrades. On the R&D front, the Data Analytics and Machine Learning activities carried out by BE-ICS in the context of the openlab project in collaboration with Siemens, have continue to product results. In this respect, important new use-cases like the ion beam source optimization for LINAC 3 and 4 have been identified and are planned to be tackled in 2019.

BE-RF Group

AWAKE

In the SPS, the achieved acceleration of the electron beam and its synchronisation with the proton and laser beams permitted the experiment to take its first data with electronics. Reliable extraction of the proton bunch from the SPS was achieved. Collaborative work to measure the quality of the synchronisation between RF and laser has been set-up with Cockcroft Institute and Lancaster University.

Figure 57: The prototype of the 24 kV power converter, developed by TE/EPC in collaboration with the RF Group, expected to upgrade the performance of the LHC-dedicated 40 and 80 MHz RF systems in the PS.

PS High Power RF System consolidation

In the PS, the first prototype of new high voltage power converters, which was developed by TE/EPC in collaboration with the BE-RF-IS team to consolidate the power stage of the 40 and 80 MHz RF systems, has been tested in operation with beam for the first time, showing the potential to considerably increase the performance of the LHC-dedicated systems in the PS in the perspective of reaching the LIU beam performance after LS2.

LHC Spare Cavity program

The first simplified prototype cavities of the LHC spare cavity program reached nominal. This milestone was reached in close collaboration with EN-MME (cavity fabrication) and TE-VSC for (cavity coating). The cavities were produced using old Bonitempo half-cells and the next challenge is now to i) work on the spinning and hydroelectroforming procedures with two supplierw in order to fulfil shape and yield strenght requirements, ii) to make complete cavities including cut-off tubes with all necessary ports, iii) re-establish the welding procedure for helium tanks, iv) re-establish and test the cryomodule assembly procedure using a ¼ short model.

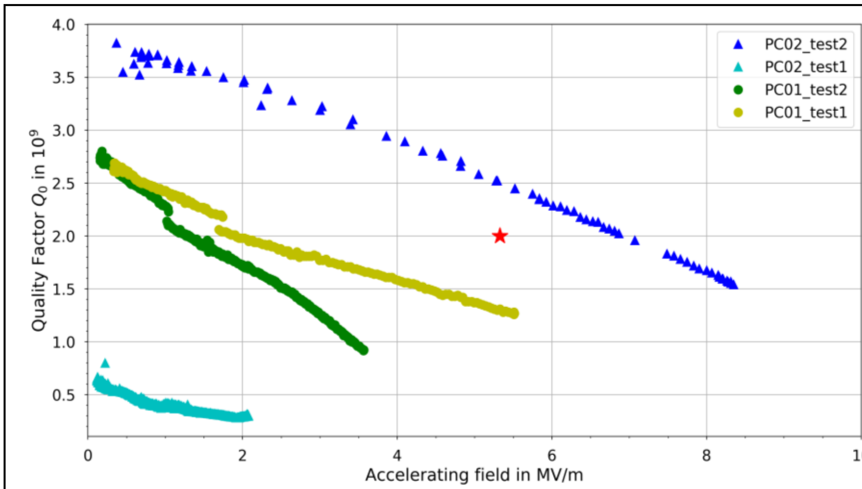


Figure 58: Quality factor vs accelerating field for LHC spare prototypes