CERN-ACC-2020-0034

BE Department Annual Report 2019

G. Arduini, R. Billen, P. Collier, E. Hatziangeli,

E. Jensen, R. Jones, E. Laderi, M. Lamont, A. Mackney, P. Sollander, R. Steerenberg

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 2019 highlights for the BE Department.

Table of contents

LHC

BE-ABP Group

Complete LHC operational scenarios were devised in order to maximize the machine performance over its third exploitation period (Run 3). In consultation with the various equipment groups, a target beam intensity of 1.8e11 p/b was agreed upon for Run 3, which should be available at SPS extraction towards the end of 2022, according to the LIU project roadmap. A new template for the LHC hypercycle was established, with the goal of adapting the machine configuration to prevent limiting the machine performance in Run 3, considering also constraints of different nature together with specific desiderata from the experiments. A new LHC optics version was constructed accordingly, and validated in terms of magnet strength, mechanical aperture, beam stability, beam-beam effects, etc. The proposed hypercycle includes, amongst others,

1. a new concept of anti-telescopic squeeze, deployed in the ramp, in order to lift possible intensity limitations coming from the machine impedance, but also and mainly to enable a levelling of β* in a purely telescopic mode over a wide dynamic range by a factor of 4 to 5, i.e., at constant quadrupole settings in IR1 and IR5, as requested by the forward-physics experiments;
2. a parametric variation of the crossing angle with β* in the two high-luminosity experiments, based on scaling laws and dynamic aperture simulation results, for operating the machine at the minimum possible crossing angle allowed by the long-range beam-beam interactions, and, optimizing in this way the lifetime of the inner triplets;
3. the possibility of rotating the external crossing angle in IR8, from horizontal to vertical, the same beam process for both polarities of the LHCb spectrometer, in order to preserve as much as possible the physics conditions of this experiment for the two configurations of the spectrometer, while minimizing the re-commissioning effort following each polarity reversal.

2019 was also used to review the LHC optics measurements and corrections performed during Run 2, by finalizing data analysis, developing new algorithms, and putting a critical view on the procedures and the tools used. All these activities materialized in the OMC-OP workshop in October 2019, where the various teams involved in the LHC commissioning identified key areas that required improvement. In particular the various MAD-X wrappers such as Jmad, PyJmad and cpymad reveal the need for such tools. Moving towards a unique solution should be envisaged.

The LHC model generation for use in studies or optics corrections remained an obstacle for the entire Run 2. A common model repository for OP and ABP with knob definition should be envisaged. ABP and OP agreed on maintaining a common optics repository and implementing automatic bidirectional data flow from optics models in MAD-X and LSA.

Furthermore, LHC operation should distinguish between target values and corrections on the different machine variables to allow constructing models based on target values. OMC software tools were in the process to upgrade to Python 3 and improve accuracy and speed.

The validation of the LHC beamline data, in particular vacuum aperture definitions, stored in the layout database is in progress.

For the LHC heavy-ion programme, one of the main activities was a continued and detailed analysis of the Run 2 performance. This served as a foundation for starting the work on reviewing the main machine parameters for future runs and updating them where needed. These studies, continuing in 2020, should lead to an updated heavy-ion operational scenario for Run 3 and HL-LHC. This was motivated partly by a recent request from LHCb for increased heavy-ion luminosity. Studies were thus carried out to find new injection schemes with significantly more collisions at LHCb with a minimal penalty for the other experiments.

Other important activities included studies for a proposed short pilot run with oxygen in Run 3, as well as preparation work for installing new dispersion suppressor collimators that should handle the increased luminosity and intensity foreseen in future heavy-ion runs. Exploratory studies were also carried out to understand limitations found in 2018 LHC beam tests with partially stripped ions, done within the Physics Beyond Colliders study.

BE-BI Group

Schottky signals

The LHC transverse Schottky system is designed to measure various parameters related to beam quality. This diagnostic is particularly appealing as it should in theory be able to provide a non-intrusive measurement of the chromaticity. In practice, this measurement has been found extremely challenging not only due to the deterioration of the signal quality, but also from a theoretical perspective when it comes to the interpretation of observed experimental spectra. In the course of our efforts to interpret the Schottky spectra in the LHC, a novel application for this system has emerged as a longitudinal profile monitor, in the absence of intra-bunch coherent motion. Furthermore, it has been shown how the longitudinal profile is related to the distributions of synchrotron amplitudes and frequencies, hence, how these can also be obtained. In addition, a framework for the simulation, fitting and comparison of Schottky spectra has been developed without the need of using computationally demanding Monte-Carlo methods. This work was selected for a contributed talk in IBIC'19 and has since been published in Physical Review Accelerators and Beams.

A subset of results from this work can be seen in Figure 1, where the simulated and experimental spectra are showing good agreement, and in Figure 2, where the experimentally estimated longitudinal profile is also showing good agreement with the one obtained from the Wall Current Monitor. Studies are underway to incorporate the transverse beam motion into the developed framework and analysis with the specific goal of improving the reliability of chromaticity estimates in the LHC.

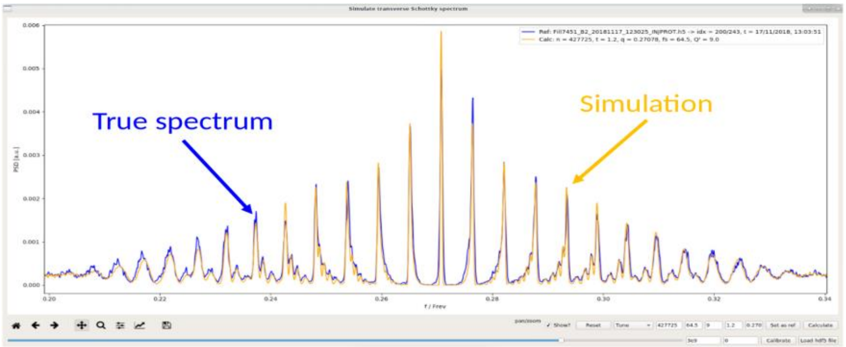


Figure 1. A comparison between a measured Schottky spectrum and simulation.

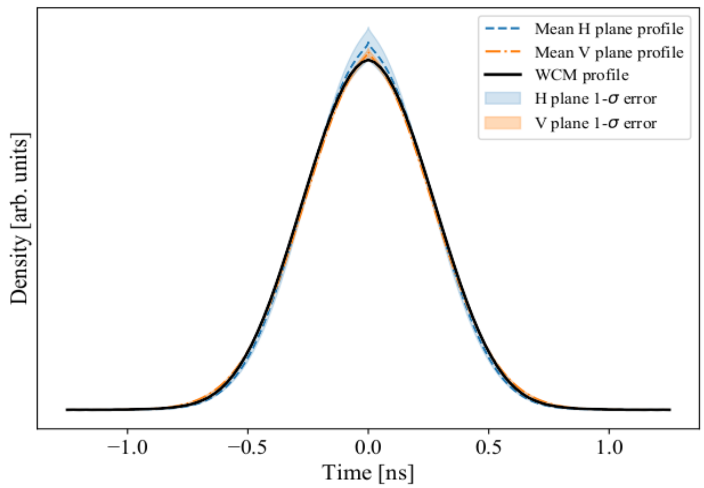


Figure 2. A comparison between a measured longitudinal profile and simulations.

Fast intensity loss interlock

The LHC is protected against potentially dangerous beam losses by a distributed system based on some four thousand beam loss monitors. To provide an additional level of safety, the LHC is to be operated with the Beam Current Change Monitor (BCCM) system detecting fast beam intensity drops, and triggering a beam dump if this exceeds a given threshold. The system has been designed to detect changes of 0.1 % of the beam intensity per turn for physics production beams, with a prototype successfully tested with the LHC beams at the end of the 2018 run. During LS2 the system performance has been further optimized using acquired beam data. An example of such an optimization is shown in Figure 3 presenting the noise of the system as a function of the observation window length. This analysis allows the windows giving the best system performance to be selected. A fully redundant BCCM system will be installed for the LHC start-up.

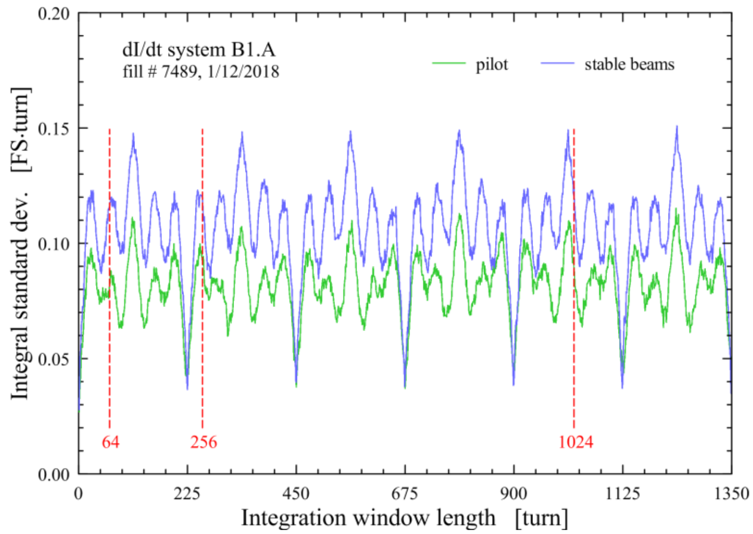


Figure 3. Measurement of the noise level in the dIdT acquisition system as a function of the length of the acquisition window.

Analysis of quadrupolar measurements for beam size determination in the LHC

Due to limitations with non-invasive transverse beam size diagnostics in the LHC, particularly during the energy ramp, there has been an interest to explore quadrupolar-based measurements for estimating the transverse beam size. This technique is especially attractive as it is completely passive and can use the existing beam position instrumentation. It is, nevertheless, a particularly challenging technique mainly due to the extremely low sensitivity of existing instrumentation to the quadrupolar moment of the beam. Furthermore, it can only provide relative beam size/emittance measurements if used on its own. This work was presented at IBIC'19), with an analysis of the method and a presentation of measurements taken during LHC Run 2 energy ramps. Quadrupolar-based measurements were compared with wire-scanner measurements and a cross-calibration strategy was proposed to overcome present limitations. The results revealed a reasonable agreement in the vertical plane with a poorer agreement in the horizontal plane, as shown in the Figure 4. An additional difficulty with absolute emittance estimates comes from the high sensitivity to the knowledge of the beta function which may change with time and from BPM to BPM. Studies will continue to assess the accuracy and applicability of this technique.

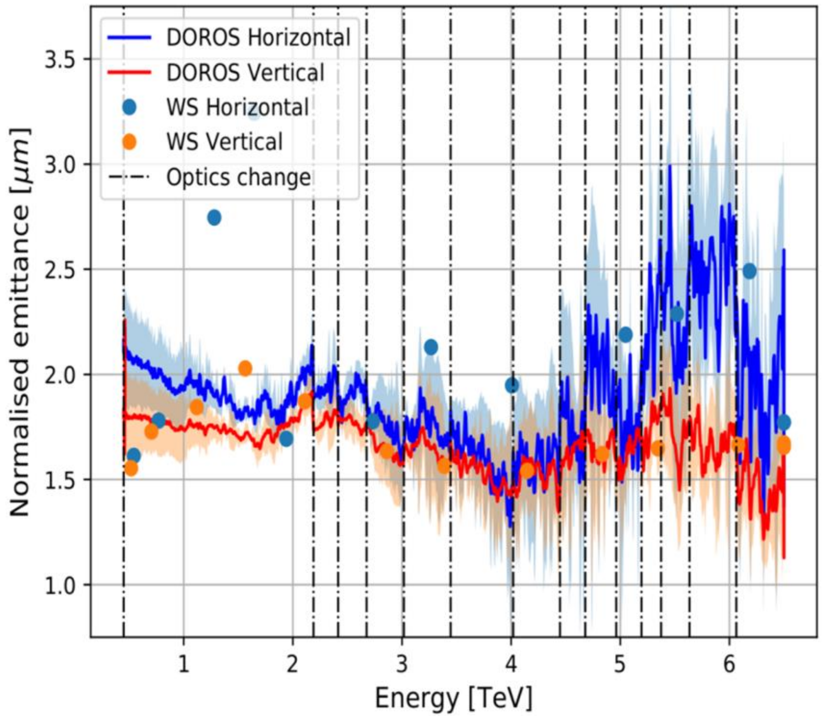


Figure 4. A comparison of beam size measurements using Wire Scanner and quadrupolar pick-ups during the LHC energy ramp.

BE-ICS Group

Industrial Controls

LHC Cryogenics

Refrigerators

In 2019, all the remaining Schneider Premium PLCs were migrated to the new platform M580 (Figure 5). This action finishes the consolidation campaign started in 2016 aiming to replace the 67 PLCs controlling the LHC refrigerators which caused several stops and machine downtime during in previous years.

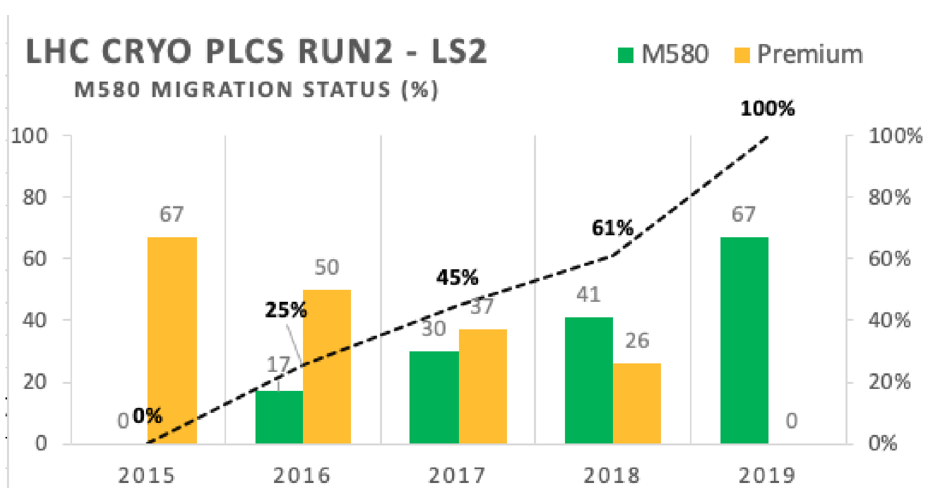


Figure 5. PLC upgrade campaign.

Also 40 critical Profibus networks were upgraded with new Profibus remote modules. Approximately 25% of the control applications were upgraded to the newest version of the UNICOS CPC framework incorporating many new features requested by the cryogenics colleagues.

The old QSCA LEP compressor room was equipped with a totally new control system architecture using Ethernet IP (Figure 6).

Figure 6. Cryo compressor station at Point 8 (QSCA).

The eight 1.8K coldbox control systems went through a severe retrofit campaign not only affecting the logic of the applications but also leading to modifications to the architecture. A great challenge for their commissioning at the start of the cooldown in 2020.

Numerous control logic modifications requested by Cryogenics operation team were implemented on critical PLCs: e.g. 1.8K Cold box, 4.5K compressor room (QSCB) and the cryogenic interconnection boxes (QUI).

Tunnel cryogenics

New features and bug fixes were included in the real-time software running in the cryo front-ends (FECs). These changes and improvements were deployed in the Cryogenics LHC control systems mainly in June and November of 2019.

A new FESA class was designed and developed in 2019. The goal was to replace an obsolete communication mechanism between the Cryo PLCs and the LHC power converters. The new mechanism based on a FESA class, CMW and the SILECs protocols, provides a simpler communication mechanism, easier to maintain and aligned with the existing controls architecture of the LHC cryogenics. This new mechanism is already deployed in one of the LHC sectors and the rest will be deployed at the end of LS2.

In addition to this, the new testing infrastructure created to improve the reliability of our real-time software was consolidated (Figure 6). This action has greatly increased the level of reliability of the LHC cryogenics tunnel control system which relies on the software running in these front-ends. As an added value, the development is adopted and integrated in the FESA framework so other CERN FESA developers can re-use and profit from unit and integration testing.

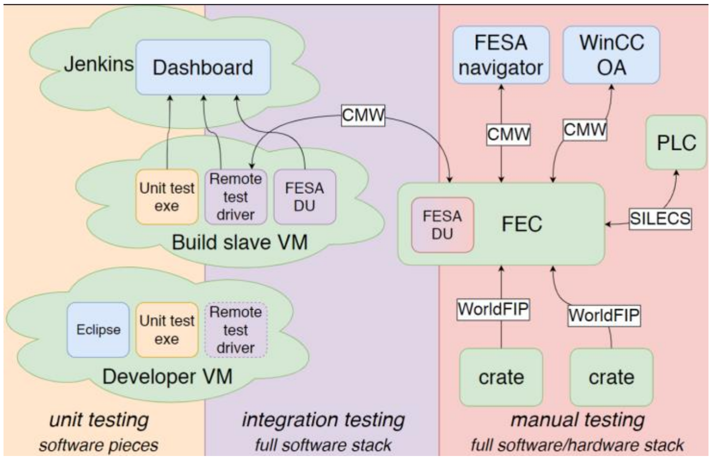


Figure 7. Testing infrastructure for the LHC cryogenics real-time software.

Machine Protection

QPS

While the QPS control and supervision layers have been running persistently and successfully for many years, the LS2 gives us the opportunity to re-engineer the QPS control layers in those areas where we identified weak points and we could make considerable savings in terms of material and/or maintenance.

The main changes are the following: (1) separate the generic CMW driver from the custom QPS code by redesigning the QPS FEC's FESA interface, (2) sending the data from the FECs to the NxCALS directly without an intermediate WinCC OA applications, dramatically simplifies the global architecture of the SCADA (15 servers) and leads to the removal of a specific expensive database (QPSr), (3) optimize NxCALS size of archived data and last, (4) the Powering Interlock controller will receive the QPS_OK information directly from the source (FECs) increasing the availability.

All these modifications will be done while maintaining backwards compatibility with existing external configuration and diagnostics tools (e.g. QPS expert) and other operational applications (e.g. LHC_CIRCUIT, Sequencer). Figure 8 shows the resulting architecture.

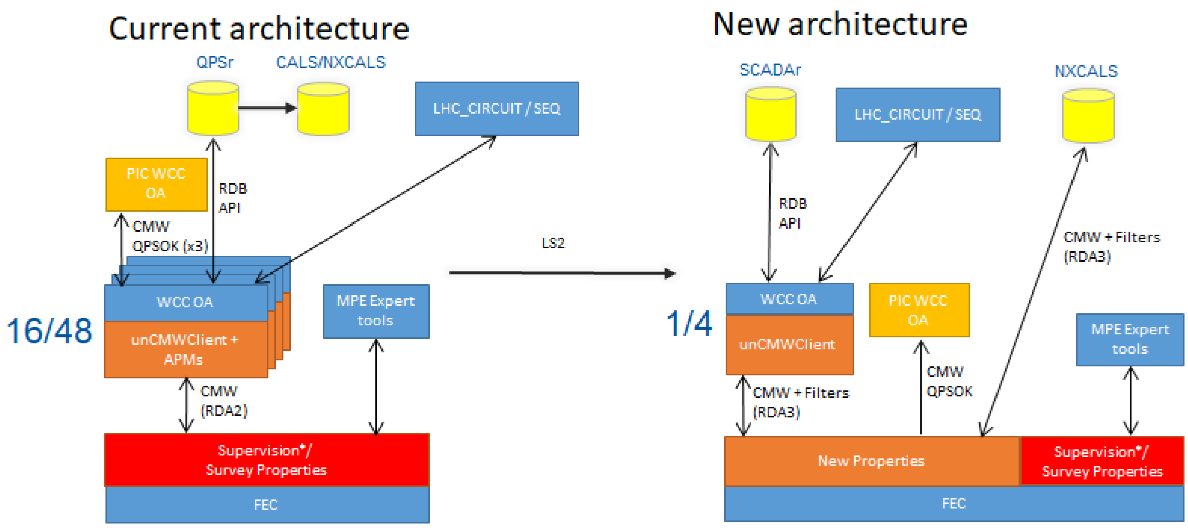


Figure 8. QPS control system from the pre-LS2 to the post-LS2 state.

Work completed during 2019

During 2019, the new architecture was defined, refined, tested and implemented in a lab environment. Near the end of the year, the FESA part of the new architecture was deployed on the FAIR installation/project, in order to allow for further validation of the solution in a production environment. The FAIR project, though, will still be operated using the old approach (this is possible since the new architecture also provides backwards compatibility).

Warm magnet Interlock Controllers (WIC)

The WIC devices/faceplates have been updated, according to the specification provided by TE-MPE. This includes a new widget, to be added on synoptics, that provides a project-global view for User Permits.

The WIC SPS and WIC LINAC4 projects were fully recommissioned for RUN3, using the latest widgets. The WIC Booster project configuration has been updated.

Powering Interlock Controller (PIC)

During 2019 the focus of development in the PIC project was the introduction of new functionality to automatically mask the global protection mechanism (GPM) for low energies. The goal was to reduce the number of unnecessary openings of the energy extraction switches for the 600A circuits. A study performed by TE-MPE had identified a larger than expected number of openings of these switches during previous runs, and since their lifetime in terms of total number of opening operations is limited, it was desired to reduce this number. The new mechanism of automatically masking the GPM at low energies requires providing the PIC PLCs with information about the currents in the main magnets. To do this, a new FESA class FGC2PIC was created to subscribe to relevant power converter gateways, obtain current information, calculate a mask value, and propagate this to the relevant PIC PLCs. This class was deployed and tested in the lab during 2019.

LHC Gas control Systems

The group provided support and maintenance for the 34 Gas Control Systems for the 4 LHC Experiments, NA62, 904 CMS Mixers, LINAC4 accelerator complex and CLOUD Experiment. The project underwent a large campaign of upgrades and consolidation actions.

During 2019, 4 Gas systems in Alice, CMS and LHCb were retired and 2 new gas control systems were deployed for the new LHCb Scintillating Fibre tracker detector (SciFi) and for the LINAC4 ION Source test. Also following the steps of the LHC cryogenics, a total of 13 Schneider Premium PLCs and profibus interfaces (PBY tpye) were upgraded to new hardware models respectively M580 PLCs and PXM profibus interfaces (Figure 9).

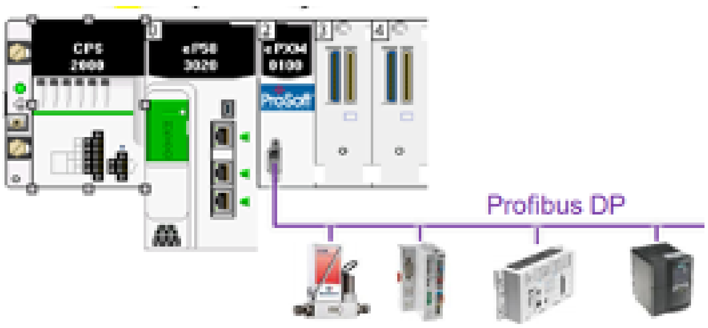


Figure 9. New architecture based on the M580 PLC.

Safety Systems

ICS started a major refurbishing project of the LHC Access system, aiming at replacing the LHC Access control software and to upgrade its Access Safety System to cope with the HL-LHC requirements, the upgrade of the SPS Personnel Protection System, and the LHC lifts program upgrade. The refurbishing started in November 2018 and was roughly halfway at the end of 2019, progressing according to the plan.

The fire and gas detection and emergency evacuation systems of the LHC Underground will reach the end of life by Long Shutdown 3. The renovation of these systems is a major project and the problem was presented at the LHC-CSAP.

The HostLab Phase II was launched covering the consolidation works to be performed in the surface and underground premises of the LHC Experiments. Fire risk assessments were launched with HSE to update the safety concept. Preliminary designs for fire and gas detection systems were done to prepare preliminary cost estimated. An overall project of 10 MCHF, including the refurbishing of the SNIFFER systems.

BE-OP Group

2019 Operation - introduction

Since 2019 was the first year of the two-year long shutdown, it was particular year for the Operations group. After having dumped the last beam in the CERN accelerator complex in the early morning of Monday 10 December 2018, the Long Shutdown 2 (LS2) had started. Initially powering and magnet tests were performed in most accelerators and facilities, but early 2019 dismantling and installation activities were in full swing in nearly all accelerators and facilities.

The BE-OP human resources were distributed over many different activities and projects, either within the OP group or in other groups and departments across CERN, making valuable contributions in a wide range of activities. Figure 10 illustrated the distribution of the OP resources to the various projects, groups and departments.

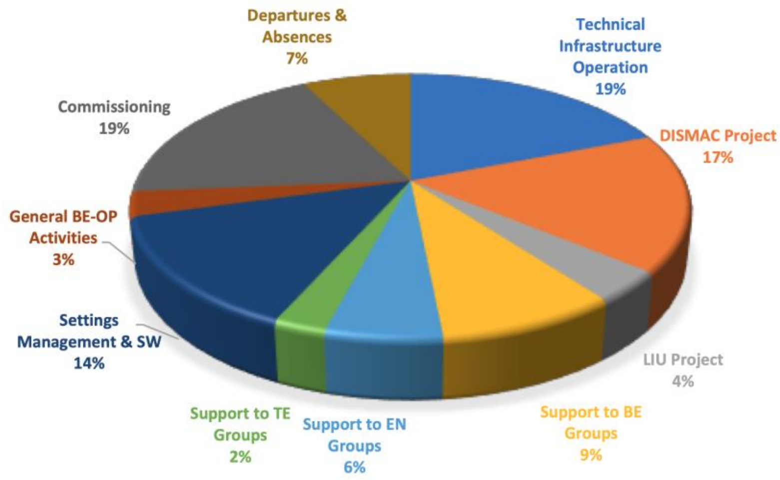


Figure 10. Distribution of the OP resources during LS2.

Despite the accelerators and other beam facilities being in shutdown mode, the Technical Infrastructure operation, as always, continued 24/7 and was reinforced with a second operator on shift coming from the accelerator sections.

With the deployment of the LIU project and the installation of many new or consolidated equipment in all the accelerators and facilities of the complex there was also the need to develop many new software applications to control the new equipment and the associated processes from the control rooms. Therefore, a substantial amount of the OP resources was dedicated to the settings management working group and the software development.

Although 2019 was only the first year of LS2, members of the Operations group in close collaboration with the equipment and service groups started working on the commissioning plans to be executed once LS2 finishes.

A substantial amount of the BE-OP recourses also made valuable contributions to the DISMAC project, taking a leading role in the project management and quality control, but also in performing the actual consolidation of the diode boxes in the LHC tunnel.

LHC

For the Operations group and thus also the LHC section, 2019 was particular. The last beams in the LHC, following a four-week long lead ion run, were dumped in the early morning of Monday 3 December 2018, signalling the start the two-year LS2. Immediately after the beam stop, the LHC went in powering test mode followed by a warm-up period before starting the LS2 activities in the LHC tunnel early April.

During LS2 the members of the LHC section were involved in different activities among which the DISMAC project, mainly focussing on the consolidation of the diode boxes and the associated quality control process. The LHC team members were joined in this effort by other members of the Operations group, resulting in slightly more than 17% of all the OP group resources contributing to the DISMAC project in different roles.

LHC section members were also part of the LHC Run 3 working group, with the mandate to prepare LHC operational scenarios for the third exploitation period of the LHC. These scenarios were then assessed in terms of performance reach and expected limitations and an operations-oriented action plan to mitigate some of these limitations was established.

Some members of the section worked most of their time to support important activities in other groups, such as BE-BI and BE-RF.

BE-RF Group

ACS Modules

The spare LHC ACS1 module AMERICA was cooled down in February at the SM18 facility to assess the static heat load, as previous tests done in 2018 had not given conclusive results. The final results were in line with expectations and with the values measured in the machine, and AMERICA was fully revalidated.

In May, an accidental partial venting of the beam vacuum occurred in the ACS unit ASIA. Since a possible contamination of the module could not be excluded, and in view of the upcoming long shutdown, the decision was made to take the ASIA cryomodule out, and to replace it with AMERICA. The latter was thus transported from SM18 to P4 in October. The two cryomodules were then swapped. All the disconnection and reconnection work in the tunnel was completed in November, and the transport of ASIA to SM18 was planned for early 2020, when the HIE-ISOLDE cryomodule was to be transported to ISOLDE, making space for ASIA.

[1] "Accelerating Cavity Superconducting"

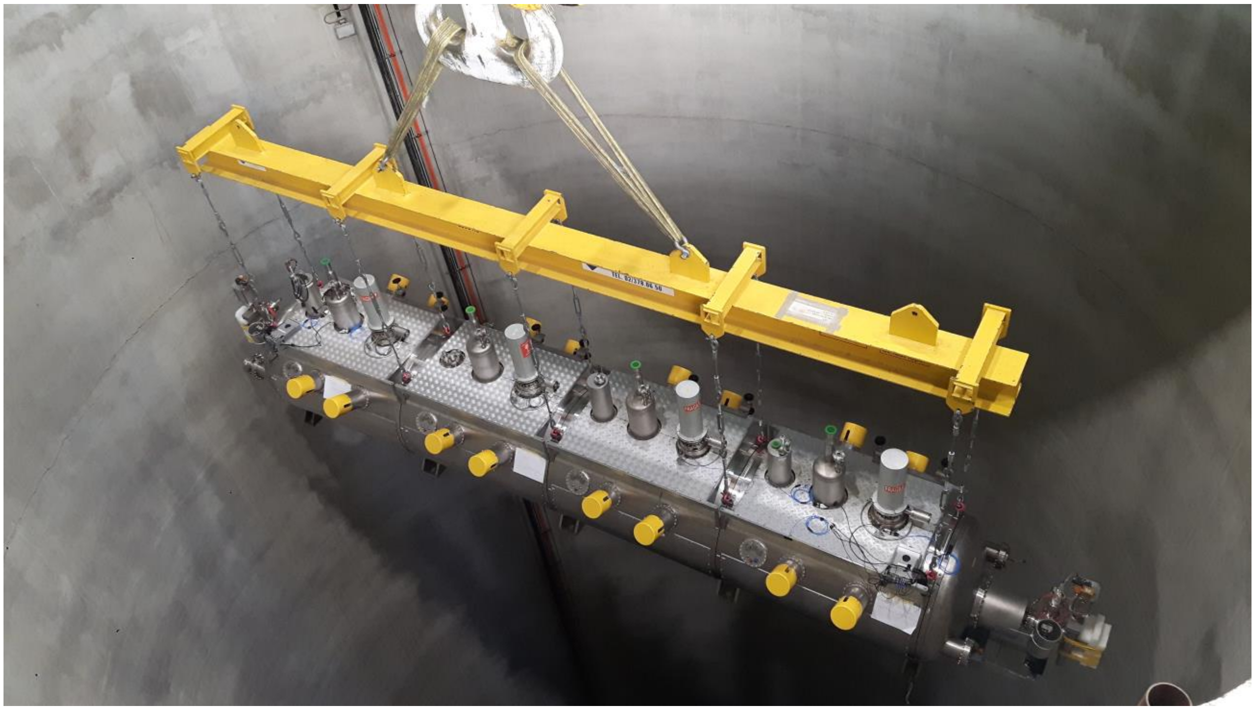


Figure 11. ACS module AMERICA being lowered at Point 4.

LHC spare cavities

Simplified so-called "practice cavities" with simplified cut-off tubes (no ports) were successfully tested in 2019 and showed promising results. This allowed verification of new fabrication methods, so practice cavity PC04 was the first one fabricated from "electro-hydroformed" (EHF) half-cells. PC04 turned out as the best CERN-made cavity ever (see Figure 12). Spun half-cells were fully qualified for LHC cavities and are now the baseline for cavity production. A first complete cavity with cut-off tubes (MC01) was completed and met specifications during the cold test. It will be used in the assembly of a ¼ LHC type test module. NC01, the next cavity with cut-off tubes did not meet specifications and will be re-coated. Figure 12 shows recent test results of the LHC spare cavity program.

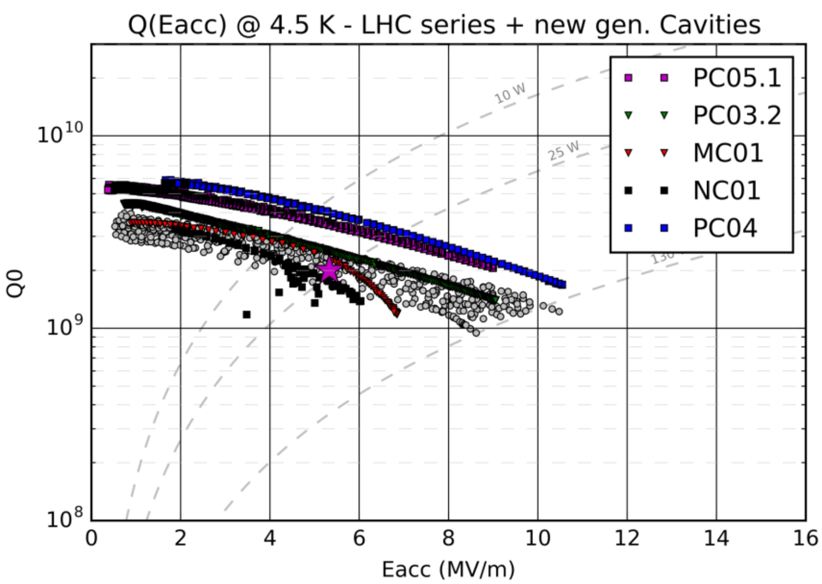


Figure 12. Performance of recent LHC cavities. The best-performing cavity PC04 was fabricated from half-cells produced with the novel EHF technique.

SPS to LHC transfer

On the LHC RF side, studies of minimum required injection voltage are ongoing. The aim is to determine the smallest affordable injection voltage for HL-LHC beam intensities within the budget of acceptable beam losses at SPS-LHC transfer. Along with the minimum voltage, the required transient RF power at injection is investigated in order to understand whether the present main RF system in the LHC will be able to capture HL-LHC beams within the loss budget. To this end, complex simulation models have been built and benchmarked with 2018 data. The simulations require modelling SPS batches at flat top with intensity effects, realistic bunch length spreads, and the SPS one-turn delay feedback and feedforward. Similarly, on the LHC side, intensity effects and the LHC one-turn delay feedback need to be modelled accurately. These models and the 2018 measurement data will allow us to estimate the voltage and power requirements for HL-LHC beam intensities.

LHC High-Power RF

Every year the RF system in UX45 is thoroughly inspected, repaired and upgraded as necessary and prepared for the next run. In 2019 for example, the old (LEP) generation of water flowmeters were replaced by more reliable ones.

Although the RF system performance has, so far, not been impacted by the ageing klystrons, special attention is paid to this potential issue. The result of the ceramic leakage measurements performed on all the LHC klystrons & spares, with age ranging from 1’000 to 50’000 hours, are shown in Figure 13. Luckily, no correlation between the leakage current and the number of operating hours of the tubes was observed. There is also no evidence of any ceramic metallisation, which would severely impact the lifetime.

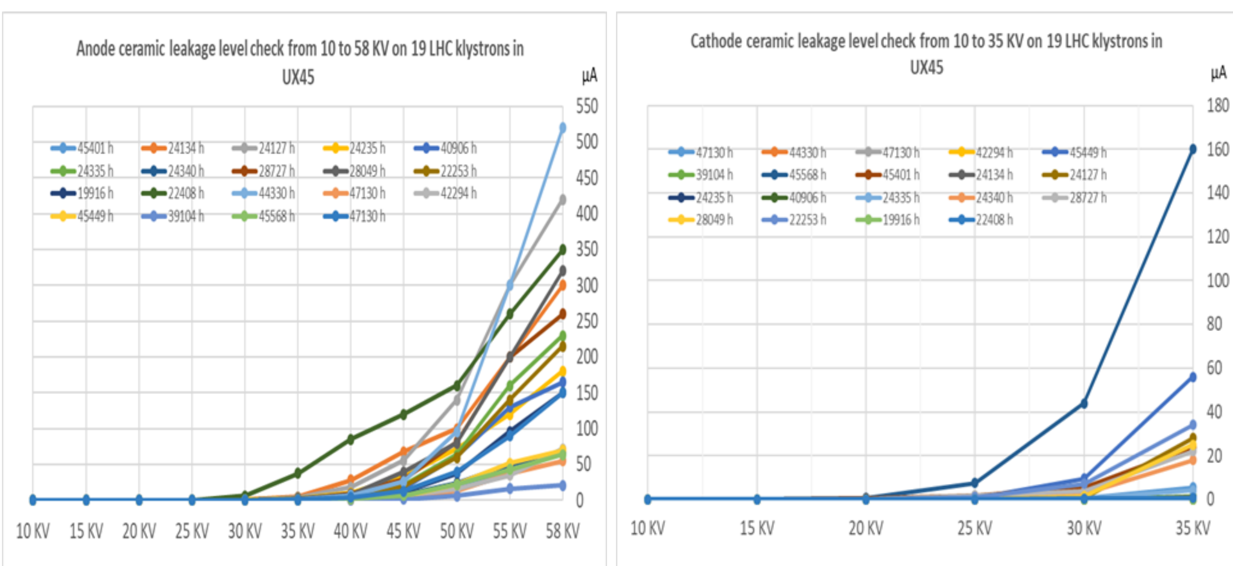


Figure 13. Anode and mode anode ceramic leakage measurements on all LHC klystrons.

The development of the klystron high-voltage mod-anode control modulator replacement has continued. The actual system is still based on a LEP design and uses obsolete tetrodes and DCCTs.

Figure 14 shows the new design, with a floating auxiliary high voltage power supply and its PLC control both at -58 kV, which successfully passed the first hurdle in high-voltage tests in 2019.

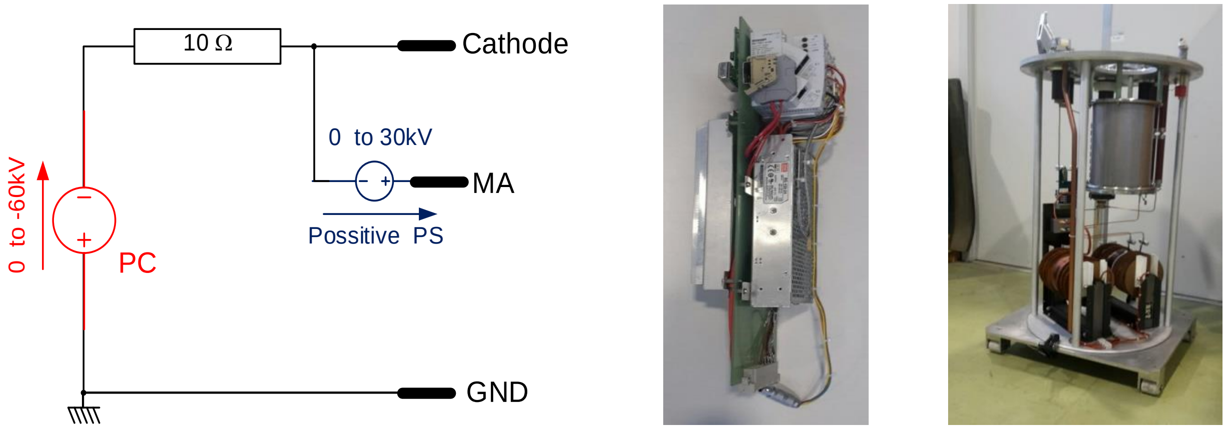


Figure 14. The new klystron high-voltage mod-anode control modulator replacement (Left: diagram, Centre: floating auxiliary high-voltage power supply & PLC, Right: assembly).

High Luminosity LHC (HL-LHC) – LHC Upgrade

BE-ABP Group

The analysis of the enormous amount of experimental data collected during Run 2, the study of the implications for the HL-LHC and their documentation have been the main emphasis in the contribution of the work package on Beam Dynamics and Performance to the HL-LHC Project.

It has been confirmed that the observed unbalance in the measured beam-induced heat load in the arcs of the LHC is consistent with different surface properties of the beam screens leading to different Secondary Electron Yields (SEY) and therefore to different levels of heat deposition due to electron cloud. This has been shown by the analysis of beam screens extracted from LHC magnets that were featuring high and low heat loads during Run 2. In addition, the analysis of the experimental studies with high-intensity 25-ns beams conducted in the LHC at the end of 2018 (with trains of 12 bunches with 1.9×1011 p/bunch) has confirmed the non-monotonic dependence of the electron cloud induced heat load on bunch population expected from simulation. This is also in agreement with the observed reduction of instabilities at injection for high bunch populations. Based on the present data, the cryogenic capacity should be sufficient to allow operation with nominal HL-LHC beam parameters provided that no further degradation of the surface properties is observed (to be checked with measurements during run 3). Hybrid filling patterns consisting of standard LHC beam trains with 25 ns bunch spacing interleaved with "8b+4e" trains could be used to limit the impact of possible deteriorations of the surface properties in some of the arcs, in case these are found.

Following the successful test of a prototype low impedance collimator featuring Molybdenum-Graphite (MoGr) jaws with different coating materials, Mo-coated MoGr jaws have been selected as the baseline for the reduction of the impedance of the secondary collimators. The resistivity of the Mo coating of the batches of the coated MoGr blocks delivered by industry has been continuously monitored throughout the production with an ad-hoc measurement technique using a 16.63 GHz RF cavity specifically designed and built for that purpose. The resistivity has remained well within the acceptance threshold and very close to the value of the pure Molybdenum (see Figure 15). This, together with the upgrade of the primary collimators with MoGr blocks, has allowed limiting the scope of the collimator impedance reduction campaign, decreasing the number of secondary collimators to be replaced from 11 to 9 per beam. The 9 collimators showing the highest contribution to machine impedance have been selected for this upgrade that has started during LS2 and will be completed during LS3. In parallel, the studies for the understanding of the difference between the expected and measured thresholds for transverse stability have continued, discarding some possible causes. In particular, these studies indicated the combined effect of noise and impedance to change the beam distribution and the related stability diagram and uncertainties in the estimate of the overall LHC transverse impedance (up to 50%) as the main sources of the above discrepancy.

A new layout and optics version (HL-LHCv1.5) has been released taking into account recent modifications in the hardware baseline (e.g. increase in the length of the non-linear triplet correctors, reduction of the length of the skew quadrupole ones and optimization of the crab cavity positions). Solutions have also been proposed to suppress an aperture bottleneck at the D1 exit appeared as a result of an increase in the length of the D1 separation/recombination dipole cryostat and beam screen. A simple dipole misalignment avoiding a more costly redesign of the beam screen with non-standard dimensions has been selected. The budget of the orbit corrector strength has been revised following a study including various effects like ground motion, alignment errors, and beam position monitor performance. In parallel the follow-up of the field quality of the new HL-LHC magnets has continued and the evaluation of the impact on the machine performance determined. The field quality of the triplet orbit correctors MCBXF remains a concern and will require corrective and/or mitigating actions. A preliminary study of the optics and beam parameters required for a possible operation of the LHCb detector at higher luminosity has been performed.

Progress has also been made in the understanding of the systematics errors in the measurement of the beam emittance throughout the cycle and of the sources of emittance blow-up. In particular it has been evidenced how burn-off (preferentially affecting the denser core of the beam) affects the transverse distribution introducing an unavoidable source of “emittance blow-up” during collision.

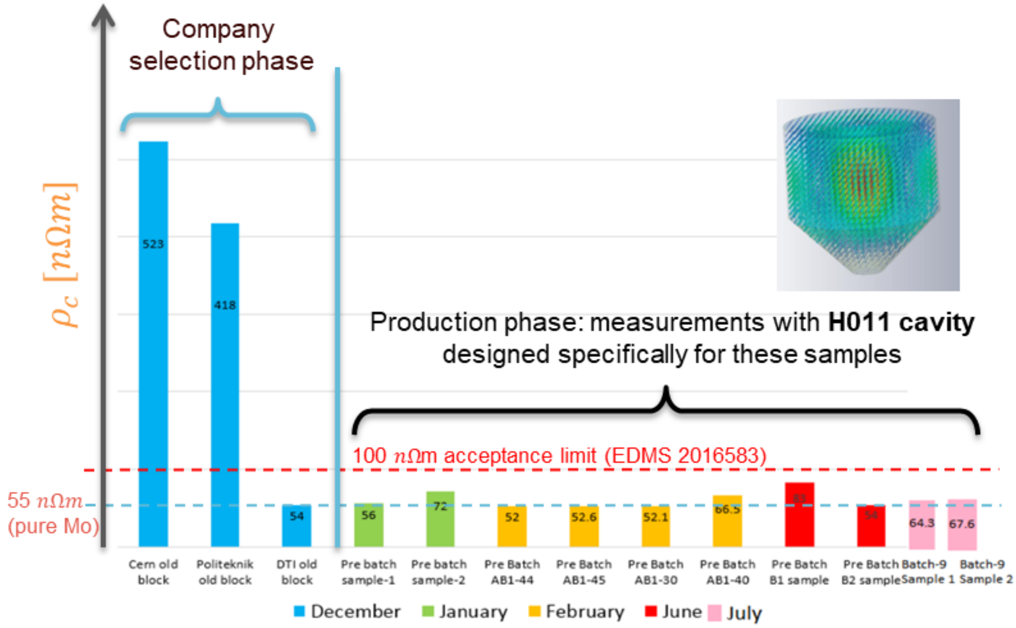


Figure 15. Resistivity of the Mo coating of different batches of Mo-coated MoGr collimator blocks throughout the first phase of the production. The resistivity has been measured using a H011 16.63 GHz resonating cavity. The resistivity of the samples produced by different companies during the qualification process is shown in light blue.

BE-BI Group

Beam position monitors with in-kind contribution from Russia

There are currently three types of Beam Position Monitors (BPM) under development for the LHC Interaction Regions (IR) 1 and 5 as part of the High Luminosity LHC (HL-LHC) upgrade. The first six BPMs on each side of the ATLAS and CMS experiments will be installed in the new, high-gradient, Inner Triplet (IT) quadrupoles, where both LHC beams circulate in a common vacuum chamber. Those BPMs must be able to independently resolve the transverse position of both counter-propagating beams. Moreover, they will operate at cryogenic temperatures and must feature tungsten absorbers to protect the IT magnets from the high-energy collision debris coming from the experiments. Initial designs of two types of directional coupler BPMs fulfilling the aforementioned criteria have been finalised, with Figure 16 showing the more complex type B. The BPM pickups feature four 125 mm long antennas (often called striplines) to sense the transverse beam displacement. Each stripline electrode is fitted with a connector on both ends via a UHV coaxial feedthrough. The antenna design is optimised to couple most of the beam signal at the upstream end with very little parasitic signal leaking to the downstream port.

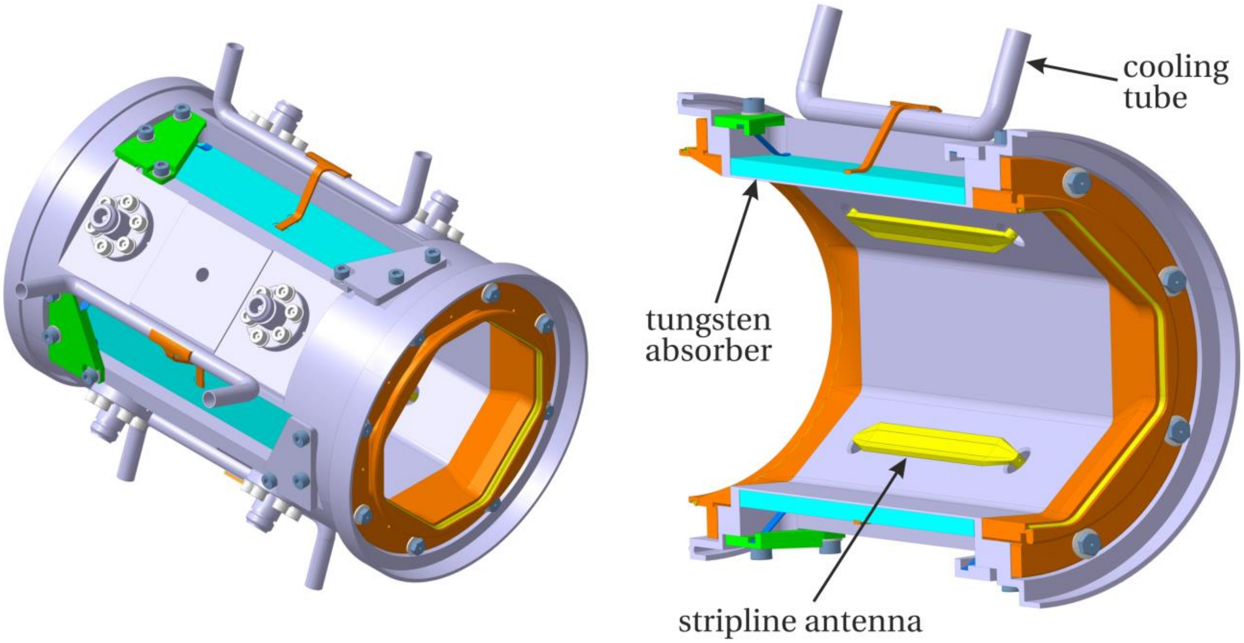


Figure 16. Design of a tungsten-shielded cryogenic directional coupler BPM for the HL-LHC.

Besides the directive coupler, a set of more conventional capacitive button BPMs is also under development for the new D2 separation/recombination dipoles. In total, the HL-LHC will require 32 new BPMs to be installed and an additional 6-8 spare monitors to be manufactured. Production of the BPMs will take place at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk, Russia as a part of the in-kind contribution of the Government of the Russian Federation to the HL-LHC Project. The pre-production phase at BINP is foreseen to start in the second half of 2020, and BPMs are expected to be delivered to CERN in several batches between 2022 and 2025 to meet the HL-LHC magnet production and installation schedule.

Beam Gas Vertex (BGV) monitor studies for HL-LHC

In 2019 BGV developments were focused on triple Gas Electron Multiplier (GEM) detectors, as a candidate for the future BGV instrument tracker. Experimental tests were conducted in order to gain experience with operating this technology and performing track reconstruction with multiple tracking detector layers. A test telescope was mounted in the Gaseous Detectors Development (GDD) laboratory, shown in Figure 17, with four 10 x 10 cm2 standard triple GEM detectors to acquire data from cosmic rays. Tracks could be reconstructed and the analysis raised the importance of detector alignment for a tracking analysis, as well as the need for the support of simulation studies to facilitate a better understanding of the experimental setup. In parallel, a new triple GEM detector structure was designed and shaped specifically for the BGV instrument application (Figure 18), with a reduced material budget compared to the standard triple GEM structure.

Both the telescope & new triple GEM studies were done with the support of the GDD and micro-pattern technologies service teams at CERN. This work has led to the conclusion that the GEM option seems promising for the BGV but should be compared to the possibilities that other technologies may offer. A simulation of the full BGV instrument will be developed to better understand the BGV target and tracker requirements, and to compare the performance achievable with different detector technologies.

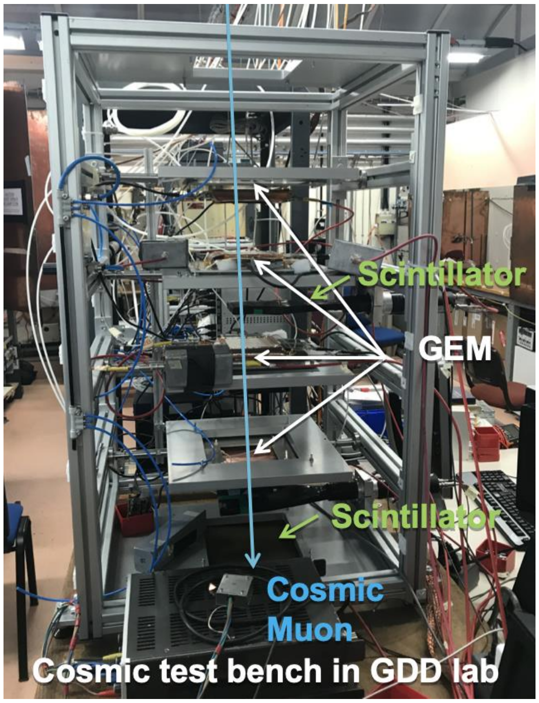


Figure 17. Triple GEM detector telescope installed in the CERN GDD laboratory.

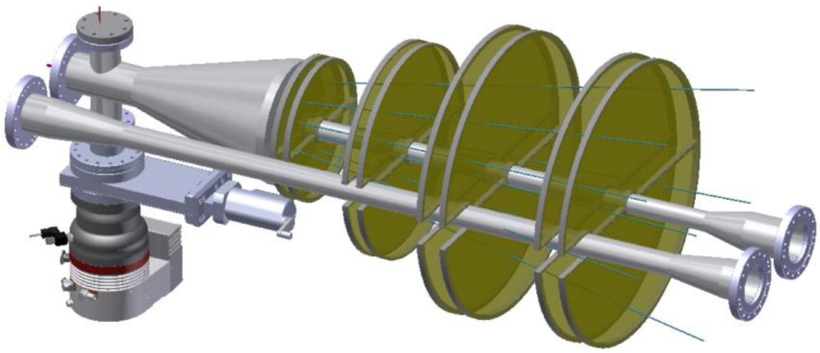


Figure 18. BGV instrument design proposal. The tracker modules are made with reduced material budget triple GEM detectors, shaped into half-moons.

Beam Gas Curtain (BGC) monitor for the Hollow Electron Lens (HEL)

The BGC is the baseline instrument for on-line monitoring of the overlap between the HL-LHC proton beam and the hollow electron beam, essential for ensuring the optimal performance of the HEL. The instrument, developed in collaboration with the Cockcroft Institute (CI) in the UK and GSI in Germany, functions as a 'virtual' screen, creating an optical image of the two beams by observing the light produced when the beams cross a diffuse gas 'curtain' which is projected across the beam aperture. 2019 saw a major step-forward in this collaboration, with the instrument becoming part of the HL-LHC baseline (along with the HEL) and the UK agreeing to the fully in-kind development and supply.

The key highlight on the scientific side came when analysis of data taken with optical observation of background gas injected in the LHC in 2018 showed clear images of beam-gas fluorescence and a beam profile from the LHC ion beam. Figure 19 shows successive measurements of vertical beam size (cropped due to mechanical misalignment) during one LHC fill with ions, fitted to Gaussian distributions. The changes in magnitude of these profiles were later shown to be consistent with measurements of beam intensity from the BCTDC current transformers (BGC Collaboration meeting).

On the technical side, an extensive experimental programme at CI provided the data to produce an optimised instrument design that is planned for installation as a demonstrator in the LHC during Run 3.

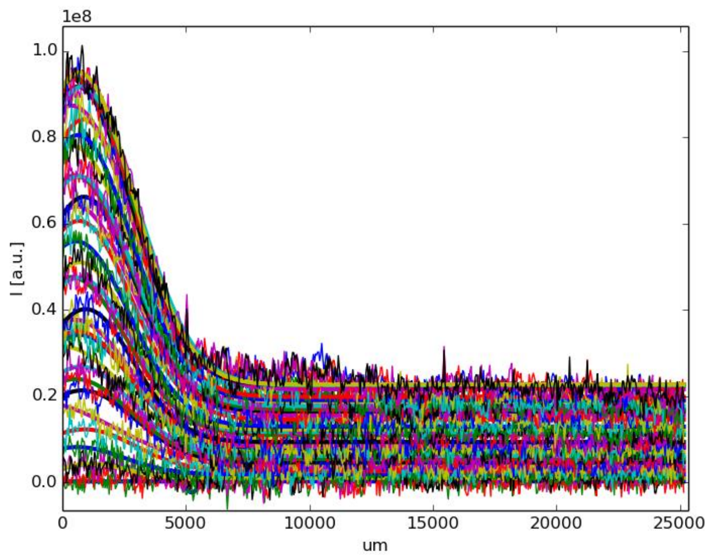


Figure 19. Beam induced fluorescence intensity as a function of vertical position across the (partial) beam aperture.

BE-ICS Group

ICS is responsible to deliver the WP17.4 covering Access and Safety systems as well as the WP17.5 dealing with technical monitoring and networking. The new evacuation galleries UPR have been equipped with Safety systems and the design of the ODH and Fire detection has been completed has well has the emergency telephone and the radiation monitoring functions. The installation of these systems, the emergency telephone and the radiation monitoring functions will take place as of mid-2020.

The interface between the smoke removal system, designed by EN/CV, and the Système de Mise en Sécurité, designed by BE, was discussed and the limits of responsibility defined. The need of having a Technical Protected Volume for each HL-LHC point where all safety racks are grouped on the surface was approved. A preliminary architectural design of Red Telephone and fire and gas detection system was done to be able to prepare the preliminary DIC, representing more than 600 cables for a total length of 40 km. The production of new Red Telephones was launched and the CSAM and cabled alarm infrastructure of Points 1 and 5 were extended.

BE-RF Group

Work Package 4: Crab Cavities & RF

Immediately after the successful completion of the DQW[2] crab cavity module for vertical crabbing and its successful test in the SPS in 2018, the construction of the RFD[3] crab cavity module for horizontal deflection was initiated (see Figure 20). Integrating lessons learned from the SPS tests, the RF design was updated to comply with impedance specifications, notably the frequency shift of the higher order mode at 760 MHz was implemented, which required for improved robustness a major concept change to coaxial lines and feedthroughs with 25 Ω characteristic impedance (see Figure 21). An important change in the antenna design was implemented to suppress the direct beam coupling observed in the SPS tests. The fabrication of two RFD prototypes at CERN was accomplished, with the final assembly stages to be completed in the first quarter of 2020. In parallel, significant design updates on the cryomodules and interfaces between RF, cryogenics, vacuum, survey and other services were implemented, leading to a conceptual design compatible with the final HL-LHC version. This effort was jointly carried out with UK-STFC, where the assembly of the RFD cryomodules will take place.

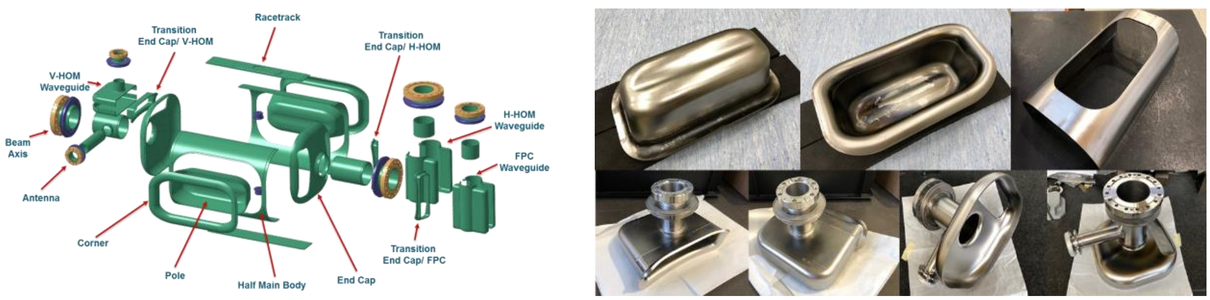


Figure 20. RFD cavity fabrication cut-out (left) and production status of the sub-assemblies (right).

After the successful manufacturing readiness review, the industrial production of the DQW series at Research Instruments (RI) has moved into the fabrication phase of cavity components. The first two pre-series cavities from RI will be cryostated at CERN, with the eight series cavities to be dressed at CERN and cryostated in the UK. All of the series RFD cavities will be manufactured by the US-AUP collaboration and cryostated at TRIUMF as part of an in-kind contribution to the HL-LHC projects from the US and Canada respectively.

[2] Double Quarter-Wave
[3] RF Dipole

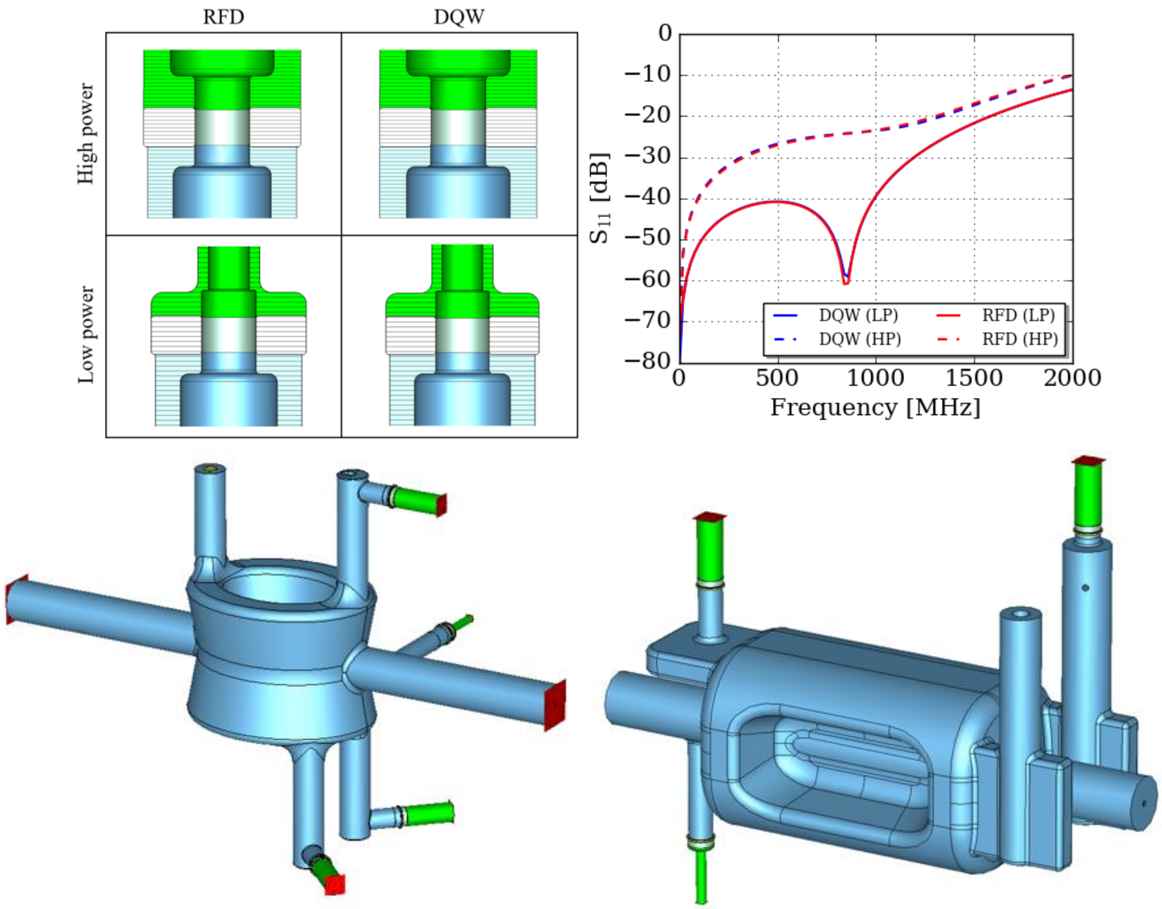


Figure 21. Re-designed crab cavity ancillaries to meet operational requirements using coaxial lines with the characteristic impedance of 25 Ω.

Figure 22. Trim tuning of RFD crab cavities (horizontal crabbing) to ensure they meet the correct frequency in their operational conditions. Tracking and analysis of Higher Order Modes (HOMs) to assess their effect on beam stability and heat-load.

LHC INJECTOR UPGRADE

BE-ABP Group

2019 has been the first year of Long Shutdown 2 (LS2) for the all the CERN accelerators except Linac4, with most of the hardware specified, designed and constructed under the LHC Injectors Upgrade (LIU) project being installed during this time. Beam dynamics studies have continued being crucial to prepare beam commissioning, further improve our prediction capabilities for the post-LS2 intensity ramp up as well as define the post-LS2 operational scenarios for the injectors and the mitigation strategies for the known performance risks.

Using the H- charge exchange injection from Linac4 into the PSB at 160 MeV is expected to lead to LHC beams with double brightness with respect to the values attained with Linac2. A beam current of about 25 mA within 0.3 mm transverse emittance out of the RFQ will be sufficient to meet the LIU intensity and brightness target with 40 turns injection, ensuring at the same time the full performance recovery of the PSB fixed target (ISOLDE) beams. In 2019 there was a dedicated Linac4 run from September to December to improve the quality and the reproducibility of the beam parameters, as well as to assess the global system availability. As notable outcome of this run, 40 mA were made stably available out of the source thanks to the deployment of an autopilot and continuous cesiation, resulting into 25.5 mA at the end of the emittance measurement line LBE with virtually 100% transmission between the RFQ and LBE line. The phase space of the beam was successfully reconstructed thanks to the profiles measured in the LBE line and the optics model of the Linac could be validated. Using the more realistic beam distributions coming from Linac4, detailed simulation studies have been also launched to assess the future production schemes for all types of beams in the PSB after connection to Linac4. This is a strong interdepartmental effort involving TE/ABT and BE/RF, to be carried out over more than a year, which is expected to lead to clear beam production guidelines by the time of the PSB beam commissioning.

From 2018 machine studies, it emerged that one of the potential limitations for LIU beams in the SPS will be horizontal instabilities for trains of bunches with intensity larger than 1.8e11 p/b. As a consequence, this instability has been the subject of an intense simulation campaign aiming at pinning down the source and the underlying mechanism. PyHEADTAIL simulations have been carried out using the SPS transverse wake model optimized for long range (i.e. to be used over trains of bunches and carrying a memory of several turns). The model includes the resistive wall impedance and narrow band resonators as well as the impedance of the kickers with its large broad-band contribution. These simulations have been used to reproduce the 2018 machine observations, which mainly showed single bunches typically at the end of trains of 25 ns spaced bunches going unstable with high order modes depending on the chromaticity value. The first remarkable result of this study was the discovery of a loss of stability induced by the reduction of the broad-band part of the kicker impedance due to serigraphy. Besides, simulations have been found to be able to reproduce to a very high degree of accuracy the behaviour of the horizontal instability as a function of the horizontal chromaticity and octupole settings, as shown in Figure 23.

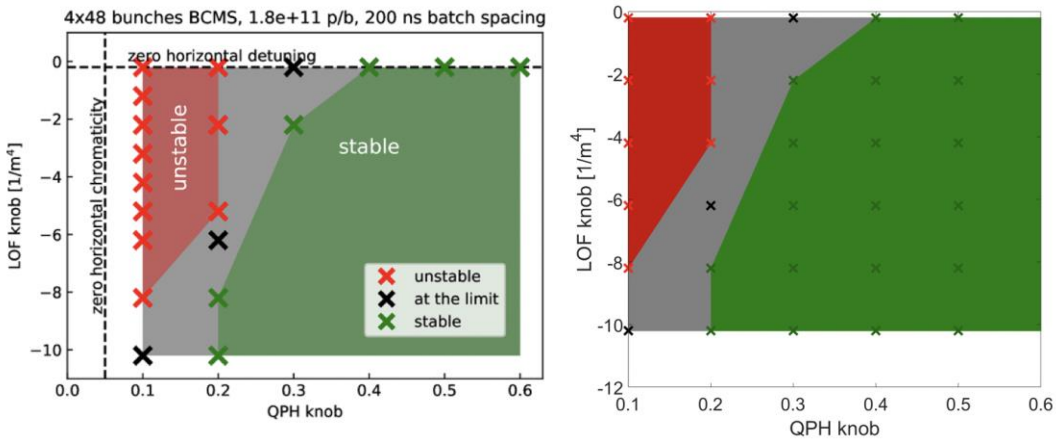


Figure 23. Stability map of the 4 trains of 48 bunches with a current of 1.8e11 p/b and train spacing of 200 ns: Experimental (top) and simulations (bottom).

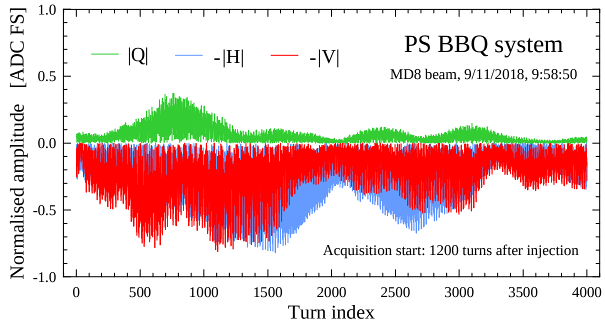
BE-BI Group

Dismantling of LIU related systems (PSB)

LIU was the major project activity for BI during 2019. 49 new instruments were constructed in the preceding years, mainly to upgrade existing instruments. These older instruments were removed at the start of 2019 and either stored for future use or disposed-of. In addition, many of the other LIU activities required extensive dismantling of the injectors, with approximately 100 in-vacuum BI instruments being temporarily removed. In particular, the Booster injection, PS switchyard, SPS LSS1 and 5 were completely dismantled. This proved challenging as many instruments had not been removed for some decades. However, it also gave the opportunity for major maintenance and consolidation activities to be planned and started.

PS quadrupolar beam spectra

Quadrupolar techniques can be used to extract information about the beam size from regular BPMs. Typically, these measurements are difficult as the signal is very small with respect to the position signal. The high dynamic range of the Base Band Tune (BBQ) system provides the opportunity to measure these signals in the frequency domain. New BBQ front-end electronics were installed in the PS during 2018 to allow measurements of the quadrupolar signal in addition to the regular tune signals. This data was analysed during 2019, with the measurements from injection oscillation studies proven to provide excellent results as depicted in Figure 24. During LS2 these new front-ends have also been installed in the PSB.



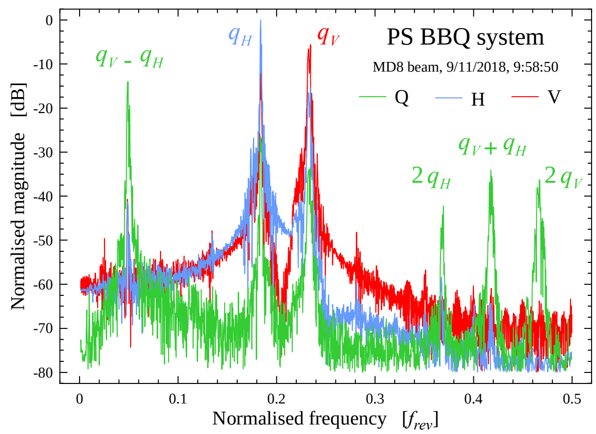


Figure 24. Injection oscillation (top) and corresponding spectra (bottom) acquired during a machine development study.

Beam Gas Ionisation (BGI) profile monitors for LIU-PS

During 2019 a new Beam Gas Ionisation (BGI) monitor to measure the transverse beam profile in the vertical plane was designed & manufactured. The complete monitor consists of: an impedance optimised vacuum chamber; in-vacuum instrument to guide and detect rest gas ionisation electrons and a 0.2 T self-compensating dipole magnet. Integration of the monitor in a PS straight section is shown in Figure 25.

In parallel a new ionisation electron detector has been developed for both the horizontal and vertical BGI monitors. This is based on a modular, single, Timepix3, hybrid pixel detector design (Figure 26). The new design will improve upon limitations identified during the assembly & operation of the prototype BGI monitor, in particular: the temperature stability of the in-vacuum electronics; power delivery to the Timepix3 chips and the production yield.

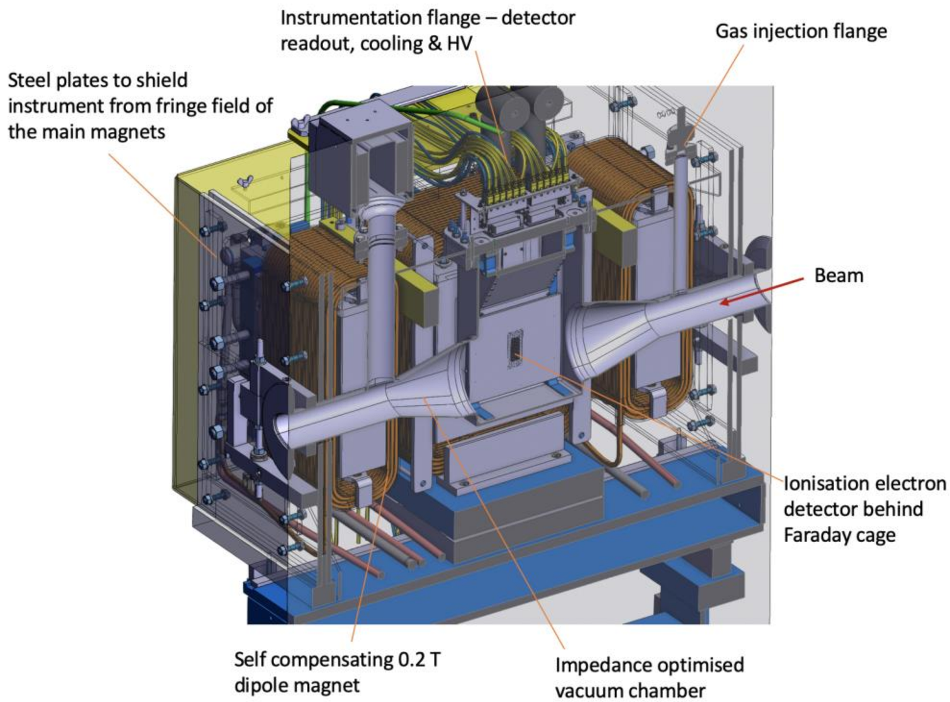


Figure 25. Cross-sectional view of new Beam Gas Ionisation (BGI) monitor for the PS to measure the transverse beam profile in the vertical plane.

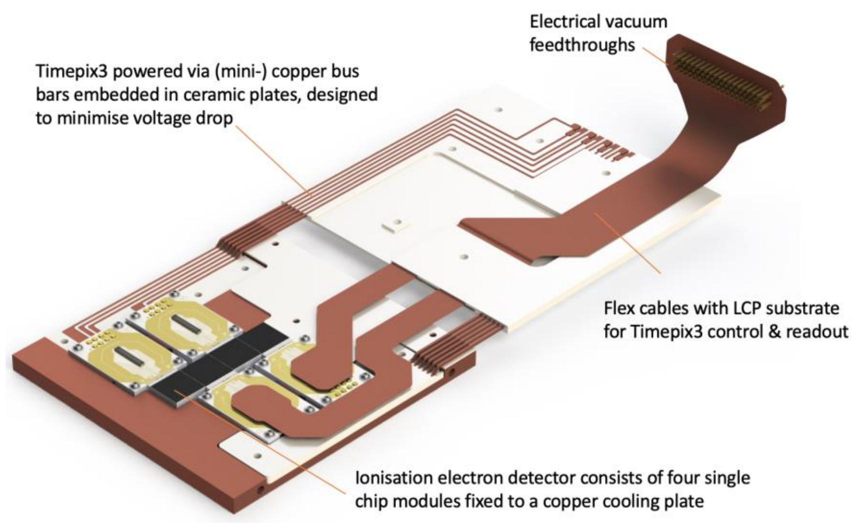


Figure 26. Design of the PS BGI ionisation electron detector based on individual Timepix3 HPD detector modules.

Injector wire-scanner upgrade with calibration

The beam wire scanner (BWS) upgrade project is the most important new electro-mechanical beam instrument for LIU. It will replace three different designs previously in operation in the PSB, PS and SPS with one new, higher performance design. This new design will bring significant improvements in scanning speed, allowing measurements of the higher brightness LIU beams whilst also giving higher precision. A series of 17 instruments is being prepared for installation during LS2, to be ready for operations at the start of Run 3.

2019 saw the start of electro-mechanics installation in the PSB (see Figure 27), while in parallel the series production of the control and acquisition electronics was started along with the firmware and software development.

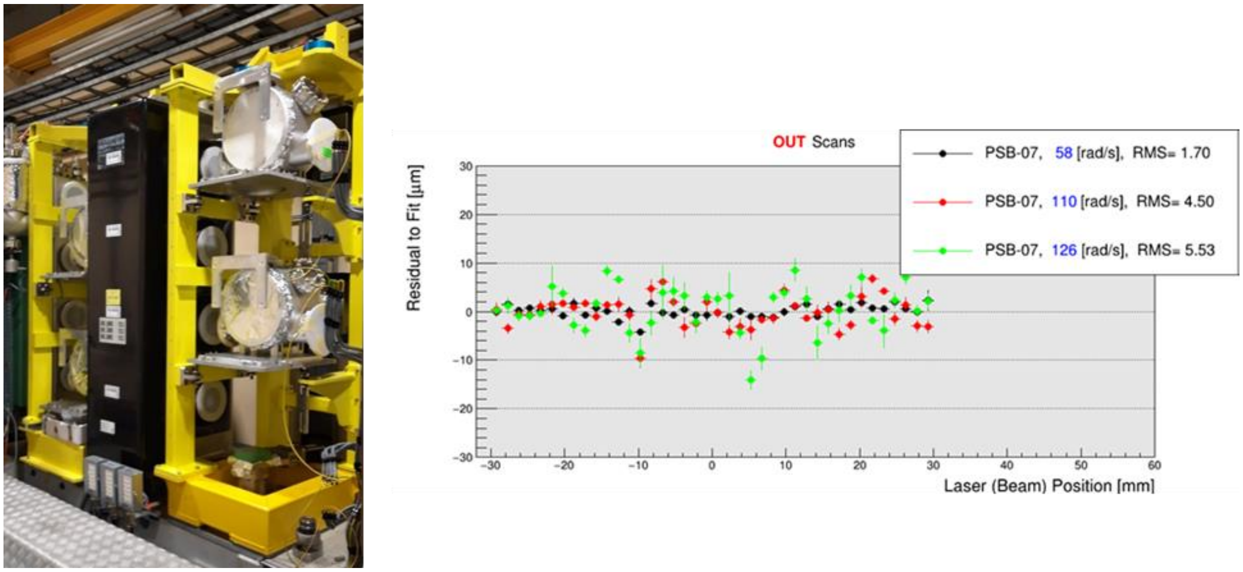


Figure 27. Left: LIU BWS support structures and vacuum tanks installed in the PSB, September 2019. Right: Example of LIU BWS calibration results, showing the residuals of the linear fit between the measured angular position and the projected wire position.

Six such instruments along with their control systems are also being produced for the European Spallation Source (ESS) in Sweden.

Each assembled wire scanner unit was calibrated on a dedicated test bench based using a laser beam to intercept the wire during a scan. The calibration determines the projected position of the wire for each measurement of the angular position of the rotor. An example of calibration results is shown in Figure 27. The RMS of the linear fit residuals show that for the 3 different speeds (corresponding to 10, 15 and 20 m/s) the error remains below 10 micrometres.

SPS orbit system upgrade

The new SPS BPM read-out electronics (A Logarithmic Position System - ALPS) was designed with the aim of covering 90dB of dynamic range in terms of beam / bunch intensity in the SPS, without the need of any intervention of the operators, e.g., to dial-in pre-settings to adapt the BPM sensitivity to the expected beam intensity, as is the case with the current system. ALPS uses a set of logarithmic amplifiers and acquires the detected beam signal from each BPM electrode simultaneously with 3 channels of different gains, with the most adapted for calculating the position selected automatically. The beam-format specific polynomial correction and the channel selection is realized on the fly based on algorithms implemented in the real-time operating FPGA.

Ten prototype ALPS electronics boards were tested and validated under realistic beam conditions in the SPS in 2018. Based on these 2018 tests the ALPS hardware received a few minor modifications, before the design was frozen in early 2019 to allow the production, test and calibration of over 300 ALPS hardware units to start. At the same time the update and modification of related infrastructure in the SPS was also performed. By end of 2019 an entire SPS sextant was equipped with a fully functional ALPS BPM system, which could be tested without beam thanks to the integrated calibration unit.

One of the main challenges was to reliably obtain calibration data over a range of ~70 dB for each of the various SPS beam formats, with an accuracy better than 0.01dB, for the correction of non-linearities. This calibration, achieved using a dedicated test bench, keeps the error with respect to signal intensity below 0.025dB, corresponding to a beam position error below the target precision of 100 μm (Figure 28).

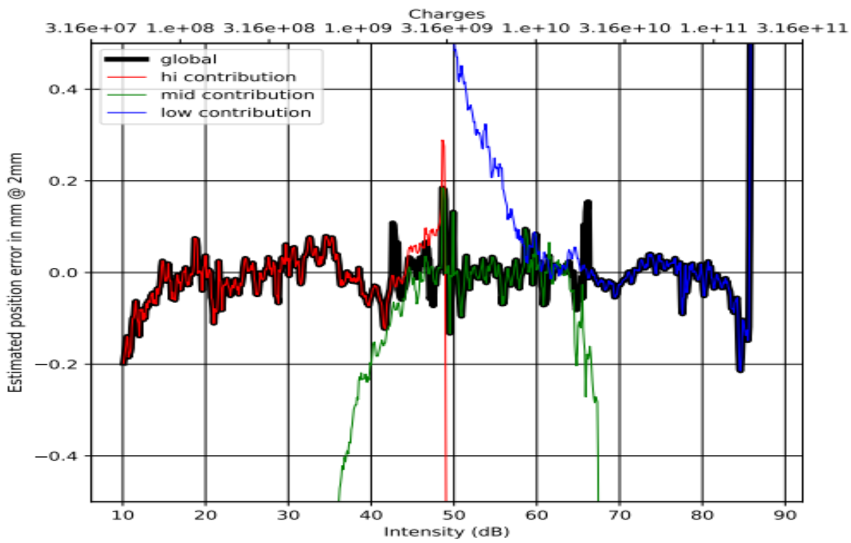


Figure 28. Calibration result example for the SPS ALPS BPM read-out system. In the relevant bunch intensity range (for 5ns spacing) from 5e7 to 1e11 the position error stays below the target of 100 μm.

Changes LSS1 and LSS5 due to the relocation of the SPS Beam Dump

A key part of the LIU project is a new internal beam dump in LSS5 of the SPS to handle the future high brightness beams. This has led to a number of requirements in terms of beam instrumentation. The old instruments in LSS1 (where the old dump is being removed) and in the new dump location in LSS5 have been removed to allow work on the beam dump to proceed and will then either be re-installed in their original positions or re-located. In addition, a new beam observation screen (BTV) is being prepared to sit in front of the new dump to monitor the beam impinging on the dump block. Although the screen itself is of a conventional design, the high radiation in the area means that a 20m long, light-tight, optical channel had to be designed to move the sensitive camera electronics away from the source of radiation.

An extensive effort also went into identifying obsolete cables in the SPS in view of their expected dismantling during LS3, with a total of nearly 180km of cables belonging to BE-BI tagged.

Fast Beam Current Transformer (BCT) electronics renovation

A new, dedicated pulsed current calibration system for beam current transformers in the SPS, LHC and their transfer lines is being prepared for Run 3. The system, shown in Figure 29, is suitable for both variants, wall current transformer and fast beam current transformer, and produces an exceptionally stable and reliable current source. A plot of system stability is also shown in Figure 29.

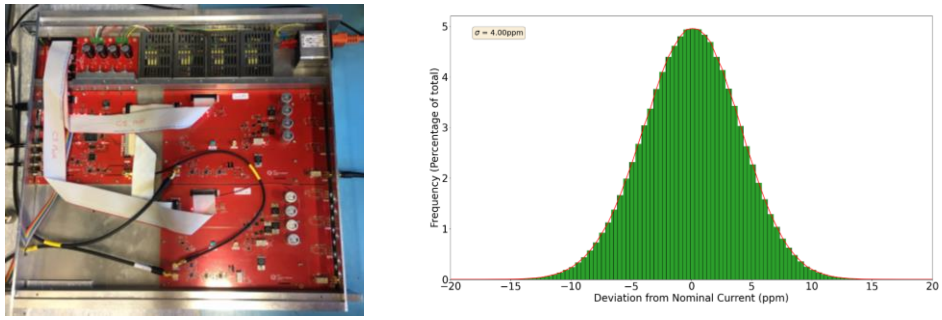


Figure 29. Left: Photo of the FBCT calibration system prototype. Right: 90 Hours Stability Measurement.

BE-RF Group

PSB

Finemet® Cavities

During 2019, the PSB Finemet® project proceeded as planned. All cavities were installed in the accelerator ring (see Figure 30 and 31), the ancillary equipment in the surface buildings and the cabling could be completed. A complete reorganization/renovation of the BRF1 (see Figure 32) and BRF2 equipment rooms was made. Although a temporary water-cooling system provided by EN-CV was available for starting the preliminary power testing, unexpected water pollution issues delayed this activity to 2020. Nonetheless, low-level RF measurements and characterisation of the system could begin according to schedule.

Figure 30. Support structure installation work for the Finemet® system in the PSB.

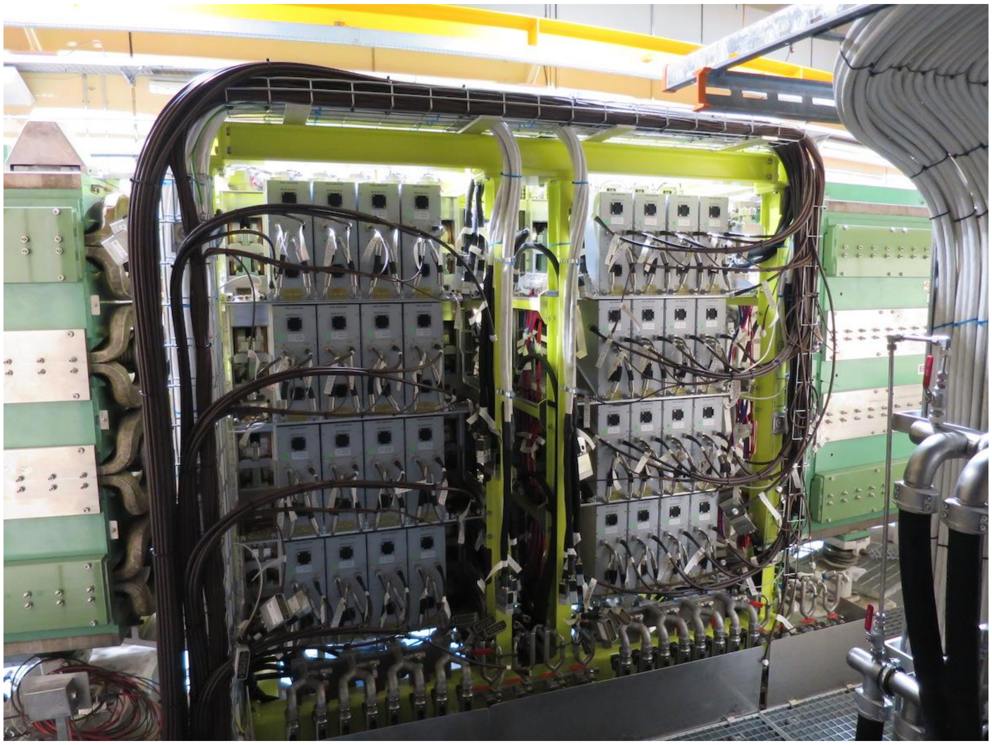


Figure 31. Details of the Finemet® cavities installed in one of the three PSB sectors dedicated to the RF systems.

Figure 32. View of the renovated BRF1 equipment room.

PSB injection tests from Linac4

For the injection of the Linac4 beam into the PSB, a new tool was developed for calculating chopping patterns for longitudinal painting, which allowed their first tests during the LBE line run. The chopping factor will vary with energy to match the shape of the bucket.

With the upgrade of the RF system and the change of the injection energy, new longitudinal production schemes of the LHC multi-bunch and single-bunch beams in the PSB have been developed. The single-bunch beam is designed to be produced with a single Finemet® RF cavity per ring, so it can be produced even before complete cavity commissioning is completed.

The 2 GeV magnetic cycle has been redefined to incorporate a flat bottom at injection. This will be used when restarting after LS2, with the original baseline of injecting on the ramp to be studied for optimisation in the future. In collaboration with BE-OP and TE-EPC, a new algorithm for cycle generation was developed and made available for the generic Function Generator and Controllers (FGC) driving the power converters.

PS

PS 10 MHz system upgrade

Production of the 10 MHz upgraded feedback amplifiers was completed in 2019; they are tested and ready to be assembled into the final amplifier chassis. The final stage of the amplifier was in turn upgraded with the latest improvements to provide the ultimate performance in term of cavity equivalent impedance reduction (see Figure 33).

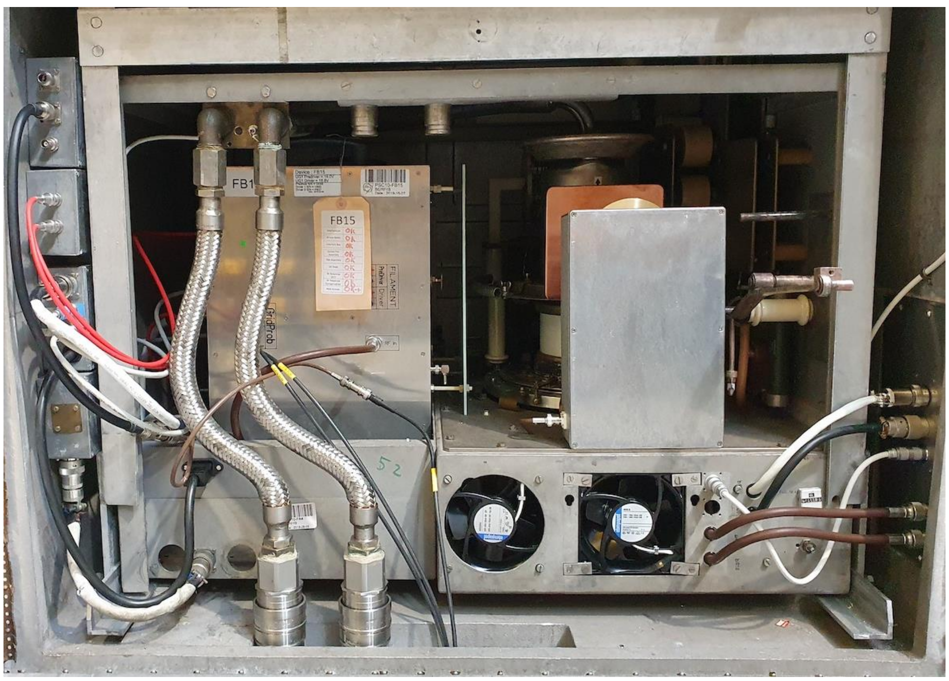


Figure 33. View of the 10 MHz amplifier, complete with the new upgraded feedback amplifier and the grid neutralization on the final stage.

Longitudinal beam dynamics and impedance studies in the PS

The short ion bunches present around transition crossing in the PS may couple to high-frequency impedances and are therefore an ideal probe for these impedances, most relevant for high-intensity proton beams. The longitudinal instabilities at transition crossing were therefore studied experimentally with the ion beam during the Run 2, for small longitudinal emittances (below the LIU operational value). In 2019, the observed instability was compared with particle simulations using BLonD simulation code (see page 89) and the latest PS longitudinal impedance model (see Figure 34). The simulations included realistic conditions with the gamma-transition jump scheme, the saturation of the magnets, intensity effects (space charge and impedance) and beam phase and radial loops. Based on simulations, it is confirmed that high frequency impedance sources (> 1 GHz) are responsible for the instability. The major contributors to the longitudinal impedance at high frequency are identified to be the unshielded pumping manifolds on the downstream ends of the main magnet units and the sector valves. Although not yet limiting for the ion and proton beam operation, this study can be used as a benchmark case to evaluate the influence of high frequency impedance source on the beam quality (e.g. uncontrolled emittance blow-up, generation of tails that could lead to losses, etc.) and to optimize the machine parameters at transition crossing as a mean to mitigate the instability.

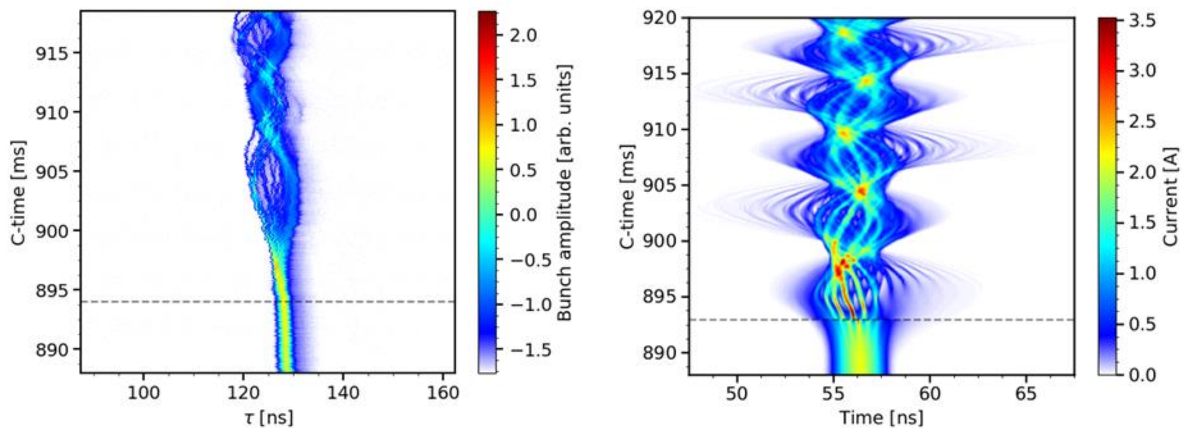


Figure 34. Measured (left) and simulated (right) longitudinal beam instability at transition crossing with the ion beam.

In the effort to understand the impedances driving the observed instabilities, several important machine elements have been modelled. Electromagnetic simulations of very complex 3D-geometries have been successfully completed, for example of the PS injection kicker KFA45. The impedance from these simulations agrees very well with RF measurements.

Additionally, one of the 80 MHz cavities had to be removed from the PS ring, offering a unique opportunity to characterise the resonator with a bead-pull measurement, a first since the initial its installation in the late 1990s (see Figure 35). These renewed measurements confirmed the expected characteristics from electromagnetic simulations. Additionally, detailed HOM spectra were recorded as an input to the refined impedance model of the PS.

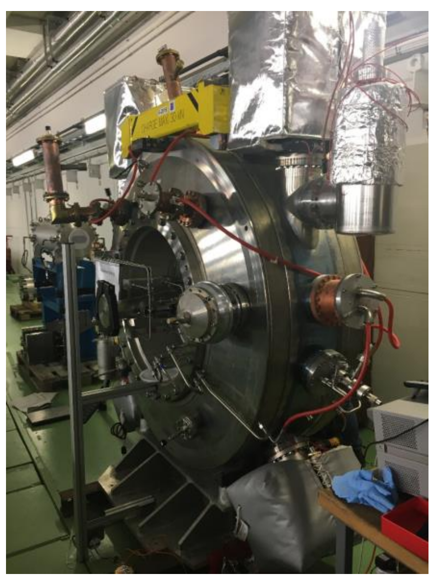


Figure 35. 80 MHz cavity with the bead-pull measurement set-up, temporarily removed from the PS ring.

PS low-level RF system upgrade

Major design choices for the upgrade of the longitudinal beam control of the PS were frozen. The detailed topology, based on a sweeping clock running at 256 times the revolution frequency, has bas been developed for all parts of the low-level RF systems. Following prototype validations in 2018, the VXS hardware platform, originally designed for the PSB, was also adopted for the post-LS2 LLRF system of the PS. A campaign of series productions for the required beam control hardware, covering about 120 electronic modules of ten different types, was launched and completed.

The firmware for the radial detection as part of the radial loop of the beam control has been finished. It features the simultaneous measurement of the radial position offset on two different harmonics, essential for smooth harmonic number changes during RF manipulations. Additionally, the dynamic range could be significantly increased. The experience with the radial detection will guide the firmware development for the double-harmonic receiver of the beam phase loop.

Prototypes of the fractional divider module, originally developed for the RF distribution of AWAKE, were completed and commissioned. In the PS LLRF, they will become part of the upgraded generation and distribution of the beam synchronous signals. The production of the fibre-optic distribution modules is also in full swing.

Upgrade of longitudinal tomography

Longitudinal phase space tomography is an essential tool in the PS Complex to qualify the longitudinal parameters of the beams. The tomography code was translated from Fortran to a modern mixed Python/C++ implementation. Besides assuring the long-term availability as an operational tool, the new version allows substantial flexibility in how the code is used and will make future developments much easier. By choosing reconstruction parameters to optimise for run time, it was shown that online tomography would be possible, with the potential to have a reconstruction of the longitudinal bunch distribution performed at every injection and extraction of each accelerator in the injector chain.

SPS

Longitudinal beam dynamics studies in the SPS

The work on LIU project included longitudinal stability studies of the LHC beam in the SPS. In particular, the effect of the HOM at 915 MHz in traveling wave of the 200 MHz RF system was identified and analysed in detail. Mitigation measures are now under study.

The problem of ion beam stabilization, required for successful momentum slip stacking, can be solved by the separate control of each of the 800 MHz cavities during slip-stacking.

SPS Traveling wave cavities HOM damping

The optimum HOM damping scheme for the 200 MHz traveling wave cavities was finalized to meet LIU requirements. As an alternative proposal, 5 mm longer antennas on the parallel-line dampers can be used to improve further the damping. A reduction in the number of 938 MHz-couplers on cavity 1 (4 sections) from eight to six showed no significant change, while it could reduce the frequency shift in the fundamental passband. Detailed measurements were carried out on all cavities before their removal from the tunnel. Each removed section was subsequently measured in standing wave mode, the results were found as expected, in good agreement with the simulations. A similar campaign was carried out on the 800 MHz traveling cavities on the surface.

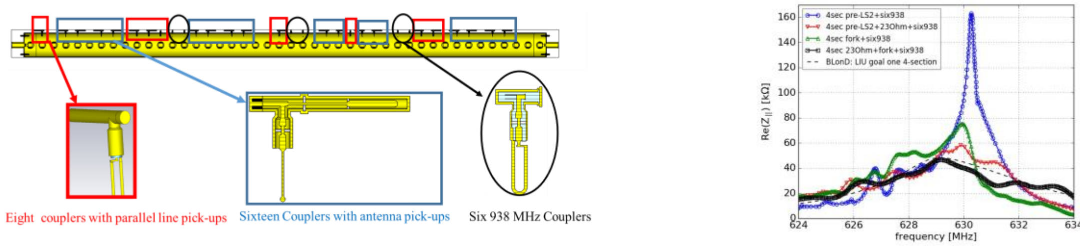


Figure 36. 4-section HOM damping scheme including the eight fork-type couplers (left) and the expected longitudinal impedance reduction post-LS2 at 630 MHz.

The new approach using a vertical $\lambda/4$ stub for the Fundamental Power Coupler (FPC) of the 200 MHz SPS traveling wave cavities was finalized and fabrication launched.

A new technique was developed and published to determine the RF voltage in long travelling wave structures, where conventional perturbation measurements are excluded due to their mechanical length. It is based on summing-up time delayed signals from each accelerating gap. The technique had been successfully applied to characterize the 200 MHz traveling wave structures of the SPS.

Infrastructure for LIU-SPS RF upgrade

The BA3 Faraday Cage was emptied right after the end of the 2018 run, and mostly infrastructure work was carried out during the year (including de-cabling and cabling campaigns, air conditioning and lighting renovation). Meanwhile, work focused on documenting functional requirements for the new LLRF system (e.g. on RF gymnastics) and on preparing the restart with beam, in particular codifying the logic to prepare make-rules (e.g. for the new internal ATIM timings, for RF synchronisation), identifying which parameters should be maintained in LSA in order to define the strategy to control the new RF systems.

Development of the front-end software for the new LLRF system continued, with FESA classes for embedded timings and function generators developed and tested. FESA classes for the surveillance of the SIS8300 board and the White Rabbit interface were also developed.

LIU-SPS RF Power upgrade: New Solid-State Power Amplifier

We checked and validated in the test-stand in BAF3 that all modules conform in gain and phase with the CERN specification. Another test-stand was set up to check the lifetime of the driver SSPA with RF accelerated aging. All 2560 modules for 32 Thales towers (plus about 400 spare units) were tested and validated.

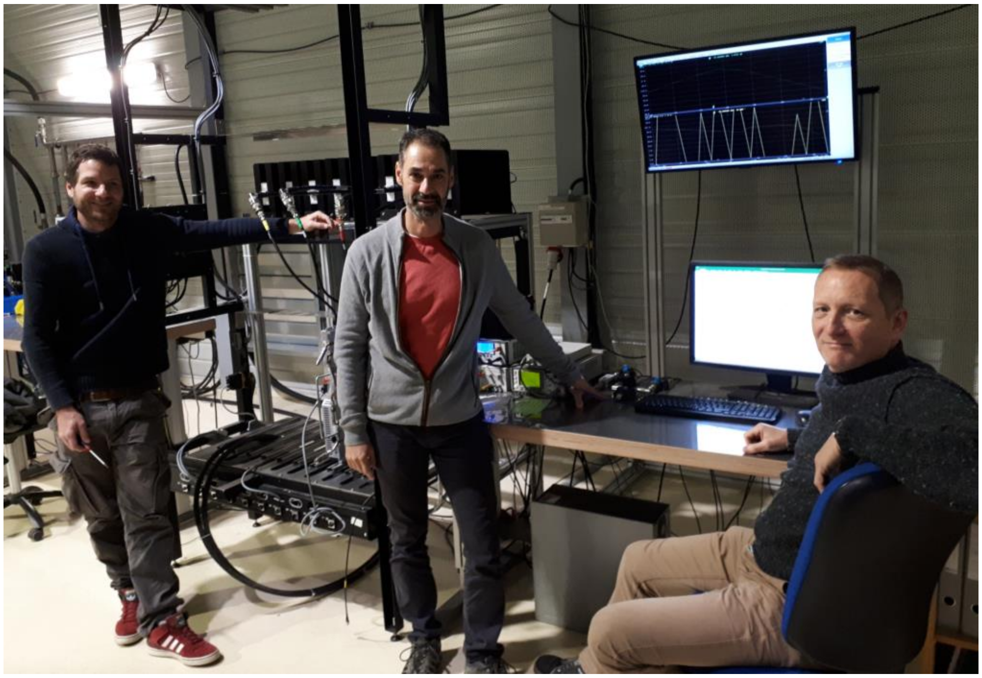


Figure 37. The test stand for Thales SSPA modules.

In parallel, all 32 Thales towers underwent significant RF stress tests, verifying BW, phase response, linearity with 10% less modules, with the difficult cycle of 5 s on – 5 s off, up to 144 kW and with the simulated SPS super cycle for over 100 hours.

At the end of 2019, one of the two full systems was successfully tested on a cavity in BAF3, with a power of 1.6 MW at low duty cycle (6 µs/16 ms) and 576 kW at high duty cycle (5 µs/5 ms).

Figure 38. The 32 Thales 144 kW SSPA towers on the mezzanine in BAF3.

The 32 PLCs controlling the SSPA towers were installed and commissioned. An initial version of the two cavity controller PLCs was also deployed. The four existing PLCs controlling the cavities powered by the Philips and Siemens amplifiers were also upgraded for compatibility with the new systems.

LIU-SPS RF Power upgrade: Hybrid combiner 3 dB

In the BAF3 building on the ground floor, there was also an impressive installation of the new 15 3-dB hybrids and 6 50-kW RF power loads.

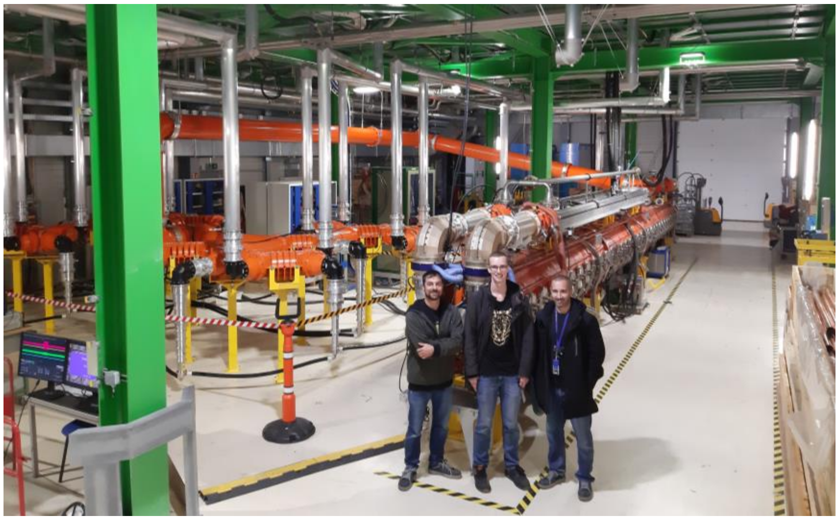


Figure 39. 3-dB-hybrids (left) and 3-section SPS TW accelerating structure (right) in BAF3.

LIU-SPS RF Power upgrade: Coax lines and cavities

During the year, the team installed about 300 meters of RF coax line 345 mm from BAF3 through the GT10 gallery, the PA3 tunnel, TA3 tunnel and LSS3 tunnel. The working conditions were very hard due the length and heavy weight of the line through a very small passage and due to many co-activities.

Figure 40. Installation of the coax line in TA3 tunnel.

All 18 sections of 200 MHz travelling-wave cavities (TWC) and all other devices in LSS3 were removed and transported to 867.

Figure 41. Transport of an 800 MHz cavity in LSS3.

Figure 42. Assembly of new drift tubes for the 200 MHz TWC in building 867.


Figure 43. Connection of the RF line and FPC on a 200 MHz TWC.

LHC INJECTOR OPERATION (LINAC2, LINAC3, LINAC4, PSB, LEIR, PS, AD, SPS, EXPERIMENTAL AREAS AND ASSOCIATED FACILITIES)

BE-ABP Group

Linac4

During 2019 Linac4 has undergone a reliability run on the main dump, a run at 3 MeV with beam on the chopper dump (18 March to 18 April), and a LBE run (7 October to 12 December) with the beam arriving at the beginning of the PSB injection line. Linac4 showed an overall reliability of 94 % with the source being responsible of only 3.5% of the down time. The LBE run showed that a beam of 600 microsec and in excess of 20mA could be routinely delivered within the needed specification to produce all the post LS2 PSB beams. The 3 MeV runs were extremely instructive for further studies of source and LEBT and gave insights on the limitation of the present configuration, in terms of emittance and sensitivity to steering. The source stability and reliability greatly benefitted from the implementation of autopilot in collaboration with BE-CO, and the continuous cesiation.

PSB

In 2019 the PSB studies were focused on the analysis of the data collected in 2018 and the preparation of simulations for the restart of the machine after LS2. In this respect, the reference orbit data collected in 2018 were analysed and large orbit excursions (up to 10 mm amplitude) were confirmed. Moreover, hot spots were reported around the rings by the radiation survey team. Based on these, a tool which can propose optimal quadrupoles' beam-based re-alignment, taking into account the four PSB rings and the fact that the elements share the same physical support, was prepared and will be used after the Long Shutdown 2.

The main power supply of the PSB will be upgraded as part of the LIU Project. Due to the higher operation energies, the main bending magnets will now operate in their saturation regime. One important task of the year was the preparation of a new tune control implementation procedure, which takes into account the saturation effects of the bending magnets and the reconfiguration of the main circuits as well as the additional complexity of the new H- charge exchange injection. The previous tune control algorithm was tested, and new tune control approaches were studied.

Finally, space charge simulations were conducted to produce the ISOLDE beam after LS2, where it was concluded that no longitudinal painting will be needed, at least for the production of the ISOLDE beam with pre-LS2 parameters.

PS

With the accelerator complex going into the Long Shutdown 2 (LS2), 2019 was the ideal moment to focus on simulation activities. An important achievement was the complete redefinition of the PS MAD-X model, updating especially the description of the main magnets in this optical model. The modifications aimed at incorporating the most recent understanding of the distribution of the field harmonics obtained with the 3D magnetic model. This magnetic model, built in OPERA by colleagues in TE-MSC, had been significantly improved to allow comparison with the MAD-X model. Furthermore, the layout of the straight sections and the positions and lengths of the elements installed there were updated, and the MAD-X sequence of the PS elements can now be obtained from the layout database.

Based on the data from a non-linear chromaticity measurement campaign in 2018, a new optics repository was established in order to continue towards model-based operation of the PS. For the different beams, injection, flat bottom, flat-top and extraction configurations were established based on the chromaticity measurements and the machine settings, and these optics are going to be uploaded to LSA.

The information about the optics was centralized in a new Gitlab-based optics repository, which also contains the optics information about the other accelerators in the chain. This new and common optics repository is accessible at http://acc-models.web.cern.ch/acc-models/.

Furthermore, space charge simulations were performed to evaluate the transverse emittance blow-up close to the integer resonances, in order to reproduce experimental results from 2018. The outcome of this study led to the understanding that the optics perturbation caused by the irregular placement of the low-energy quadrupoles is at the source of the emittance blow-up and a study is ongoing to improve the placement of the quadrupoles along the PS lattice.

SPS

For the SPS a focus was put on the characterization and understanding of the horizontal instability with LHC beams at injection as described in more detail in the chapter on LIU activities. Other subjects concerned beam coupling impedance studies of beam transfer systems. In particular, it was shown that the beam induced heating of the MKP-L will become a limitation for LHC type beams already during operation and machine development studies in the early part of the intensity ramp-up foreseen during Run 3, unless a serigraphy is applied on the kicker. Concerning the ZS extraction septum, simulation studies have shown that the beam coupling impedance and thus the beam induced fields play a role in the observed sparking and that a significant improvement is to be expected with the new shielded ZS that is being installed during LS2. On the beam dynamics side, studies of incoherent emittance growth for high brightness bunches in the SPS in the context of space charge induced periodic resonance crossing showed that the fast synchrotron motion in the SPS Q20 optics explains the high sensitivity to tune modulation induced by power converter ripple. Work was done on the SPS optics model to incorporate the machine layout changes due to the installation of the LIU hardware, including the verification of the layout database with mechanical drawings and cross-checks with the survey team. Finally, the analysis of experimental data from 2018 with the crab cavity prototype installed in the SPS showed that the RF multipole components have a similar magnitude as expected from the design. The crab cavity noise study was focused on investigating the discrepancy between the induced emittance growth, measured during MDs in 2018, as compared to the theoretical expectations.

Linac3

At Linac3, the main objectives of LS2 got underway, with the ABP Facility Coordinator managing the requirements for the major consolidation of the ventilation system, along with other works on the Linac.

For the GTS-LHC ion source the construction of a moveable puller system began, measurements were made of different micro-oven configurations, and preparation started to integrate automated tuning of the Linac3 GTS source into the software framework developed for the Linac4 source Autopilot. The Linac3 team also started planning the 2020 restart of the Linac both for an extended source test programme as well as commissioning the new Low Level RF system with beam, as well taking as processing and comparing data from many years of stripping and RF measurements. In addition, the possibility of producing an oxygen beam for LHC collisions was investigated, and the required modifications for Linac3 were documented

LEIR

A series of activities started at the beginning of LS2 for the LEIR machine. The experience of 2018 was reviewed under several aspects. In particular, the achieved LEIR performance, the outcome of the MD studies, the source and Linac3 operation were summarised drawing the pre-requisites for the post-LS2 restart.

Considerable simulation efforts were put in place in order to improve the understanding of space charge, IBS, electron cooling and impedance effects and benchmark the observables collected during 2018.

The hardware and software need for the restart were addressed. As an example, the LLRF parameters were included into LSA for a higher-level oriented operation, and the orbit system requirements were reviewed for the so called “first turn” and “turn by turn” operation. From this last, the analysis of the multi-turn measurements performed in 2018 allowed to define specifications for a dedicated optics kicker system.

The injection line optics measurements were reviewed and the strategy for compensating stray field effects was defined together with an update of the specification for the injection line BPM system.

The relevant beam performance parameters (like extracted intensity, injection efficiency, injected energy distribution, etc.) were defined in view of the centralized injectors beam performance tracking project.

The detailed work performed along the year provided input for the ATS note "Review of LEIR operation in 2018" eventually published at the beginning of 2020.

BE-BI Group

LEIR Schottky acquisition upgrade

The acquisition and FESA interface of the LEIR Schottky system was upgraded to run with a new commercial PCI express board. This allowed much faster data transfers of 3Gb/s (compared to 80Mb/s previously) to allow the real-time measurement of horizontal, vertical and longitudinal Schottky spectra from the low beta pick-ups (Figure 44).

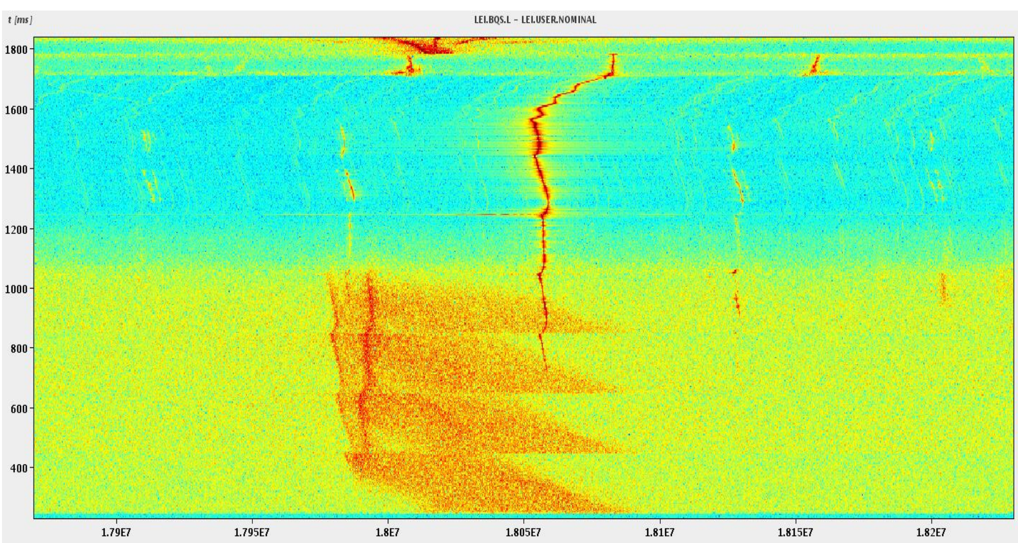
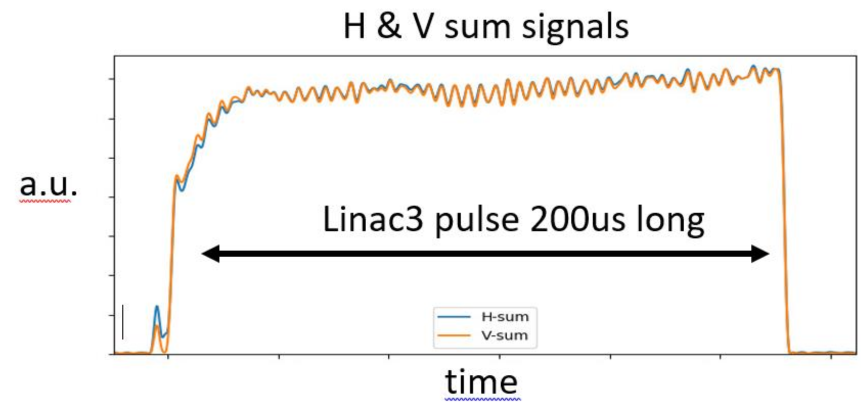


Figure 44. LEIR Schottky spectra during a nominal cycle with multiple injections and electron cooling.

LEIR injection line BPM electronics

New analogue front-end boards, operating at the LINAC3 bunching frequency of 101MHz, were produced and tested. This upgrade was necessary to overcome the difficulties with parasitic charging effects when using the original charge-based measurement method. The removal of the original head amplifier from the tunnel also makes the system compatible with proposed future oxygen ion runs, where radiation effects are expected to be an issue to any electronics in the tunnel.

The performance of the new system, and its robustness to parasitic charging of the pickup electrodes, was proven during a 2018 test run with 3 prototype boards. Figure 45 shows the stability of the measured beam position along the Linac pulse. The new system will be installed and commissioned during 2020.



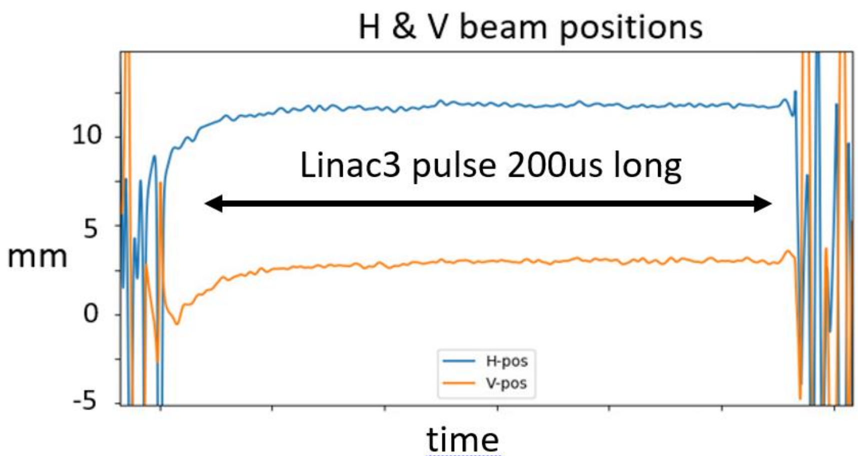


Figure 45. Typical LEIR injection-line BPM signals (sum and positions) acquired with the upgraded 101 MHz font-end electronics.

ISOLDE Beam Instrumentation Consolidation

The ISOLDE beam instrumentation underwent major consolidation in 2019, with a dedicated project launched to improve reliability and minimise access requirements in this radioactive area (Figure 46). The combined Faraday cup/scanner instrument has been replaced with a new design and 19 such instruments were installed. In addition, three new needle scanners have been completely redesigned using modern materials and principles, including 3D printed titanium alloy forks and bellows-free magnetically coupled actuators.

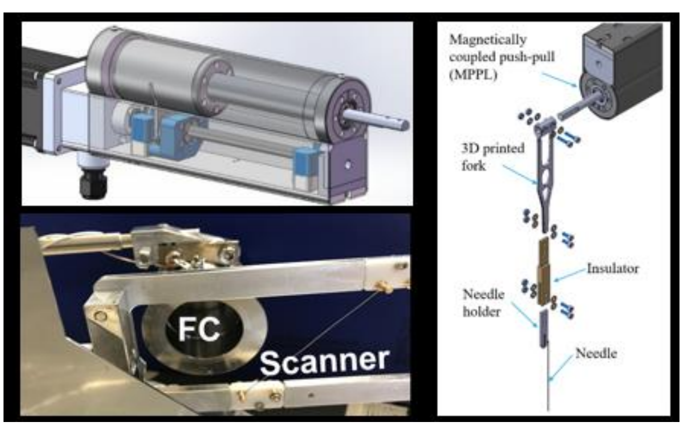


Figure 46. Consolidated mechanical beam measurement instruments for ISOLDE.

Consolidation of PSB BTV systems

The beam observation screens (BTVs) in the PSB injection and ring are key to the set-up of the injectors. The installed systems are decades old and suffering from increasing reliability issues. It was therefore decided to replace 17 instruments with new designs as part of the accelerator consolidation project. In addition, the extensive opening of the booster injection region during LS2 meant that these instruments were readily accessible.

The new designs take advantage of recently developed 'magnetically coupled' motion feedthroughs. These use powerful permanent magnets to move the screens in and out of the beam, removing the need for flexible bellows which limit the lifetime of existing systems. This activity was approved in early 2018 with design and production progressing rapidly and installation starting in late 2019 (see Figure 47).

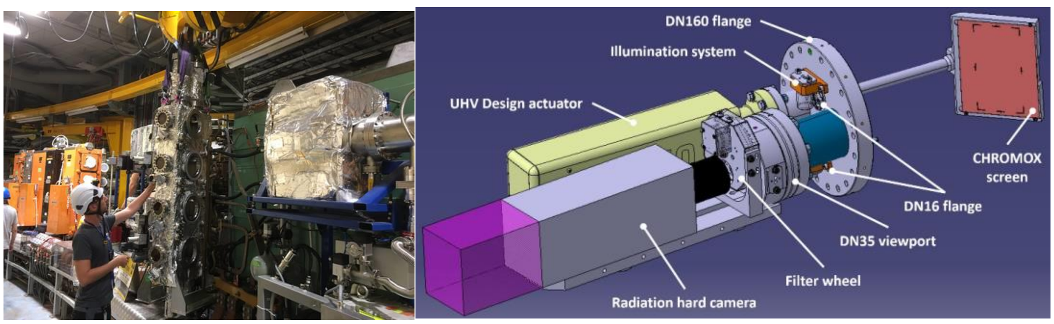


Figure 47. Left: removal of a stack of 4 BTVs. Right: UHV push-pull insertion device.

AWAKE Beam Instrumentation

In the course of 2019, a series of R&D studies for AWAKE Run2 beam diagnostics were initiated. The BE-BI group is contributing with a sub-picosecond bunch length measurement system based on the Electro Optical Spectral Decoding (EOSD) method. The aim of the project is to upgrade the existing EOSD test setup at CLEAR to improve and ease operation. First results with a picosecond-long bunches were obtained in November 2019.

To improve AWAKE electron line studies, new scintillating screens have been installed on the two BTVs of the TT43 line. The original Chromox screens have been replaced by thinner Ce:YAG screens which have a faster response and better resolution.

LINAC4

Transverse Profile Monitors (Wire Grids and Scanners)

Following the failure of some wire grids in the L4T and L4Z lines in 2017–18 and for equipping the LBE line, new detectors were produced and installed in 2019. This included a reviewed wire layout (minimum wire spacing 0.5 mm and equal wire spacing everywhere for the systems at 160 MeV), increased wire tension and the adoption of new flex-cables for the in-vacuum connectivity. Examples of the new grids, cables and connectors are shown in Figure 48.

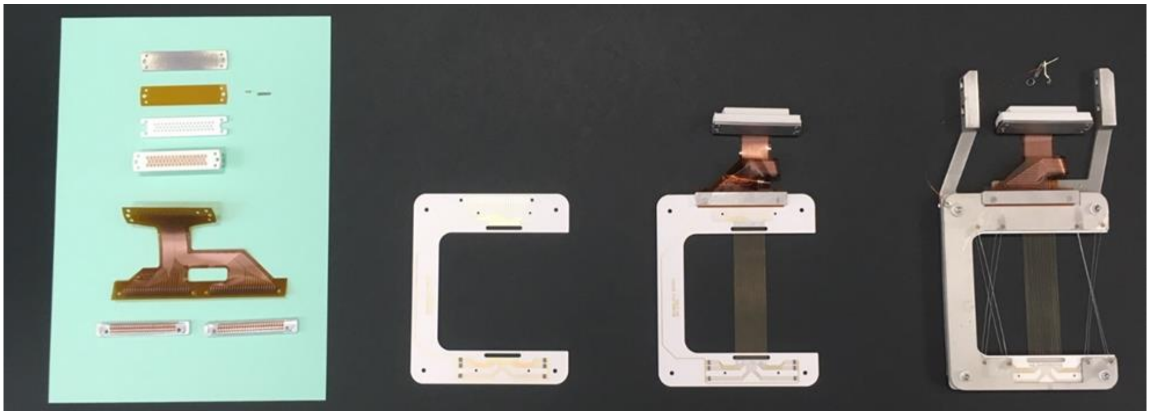


Figure 48. New wire grids as implemented for the L4T, L4Z and LBE lines in 2019.

During the LBE run in autumn 2019, the wire grids were extensively used both as support operation for characterize the beam steering / transverse profiles. Example of wire grids profile measurements in the L4T and L4Z lines, showing good agreement with wire scanner measurements at the same locations, are shown in Figure 49.

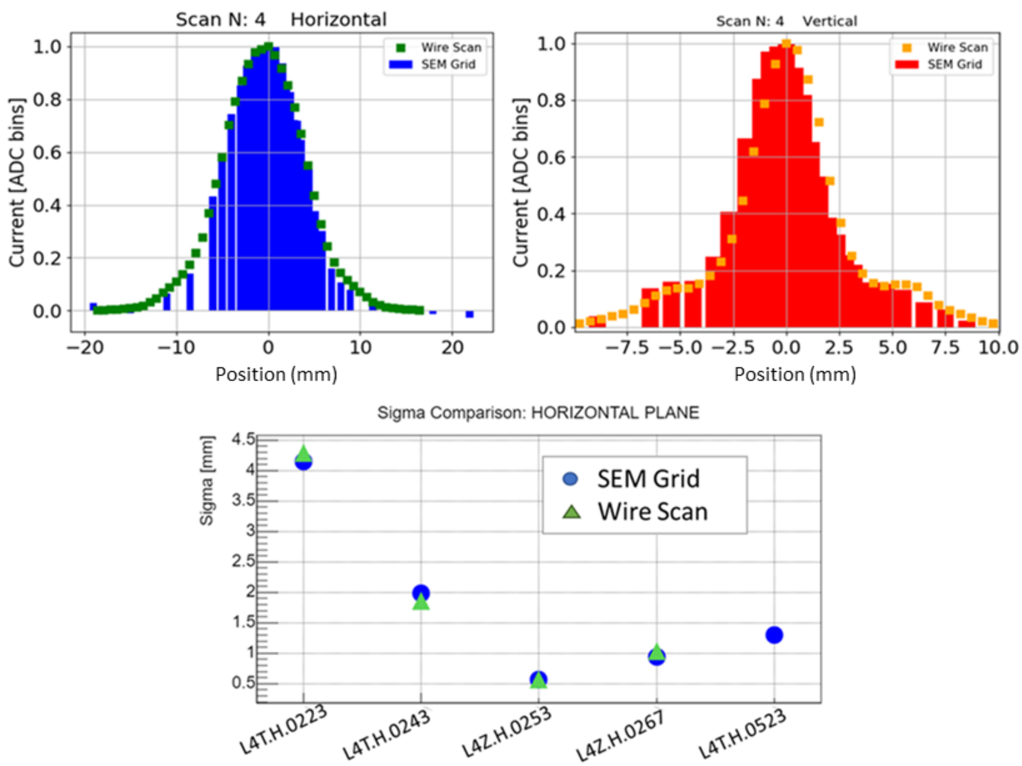


Figure 49. Example of wire grids measurements at 160 MeV with the new detectors installed in 2019 and comparison to wire scanner measurements at the same locations.

At the very end of the run, a dedicated set of measurements was performed with the aim of studying wire heating of the grids at different beam powers. The data analysis to benchmark and improve the available models is ongoing. Beam wire scanners were also very extensively used in 2019. In particular, the L4T, L4Z and LBE devices were the workhorses to characterize the transverse emittances of the Linac4 beam at 160 MeV and the matching to the PSB. It should be noted that before the 2019 run all scanners were equipped with the latest version of the VME electronics recently developed by BE-BI to unify the control of stepping motors across all CERN facilities.

BPM Time of Flight

The LINAC4 time-of-flight (TOF) system is based on the beam arrival time at the individual beam position monitors measured as its phase with respect to the RF reference signal. It is used for the accurate tuning of the LINAC cavities in terms of amplitude and phase. In the past, the cumbersome setup of the TOF measurement procedure required the presence of experts, but the software has now been updated and simplified to minimize the need for manual operation. The combined efforts of the BE teams involved (BI, OP, ABP and RF) led to an operational application (see Figure 50) that simplifies the TOF procedure, allowing a much faster machine optimisation. Nevertheless, unstable beam conditions are not uncommon during LINAC4 set-up, therefore a fully automatized TOF system for RF tuning remains challenging and will require additional improvements.

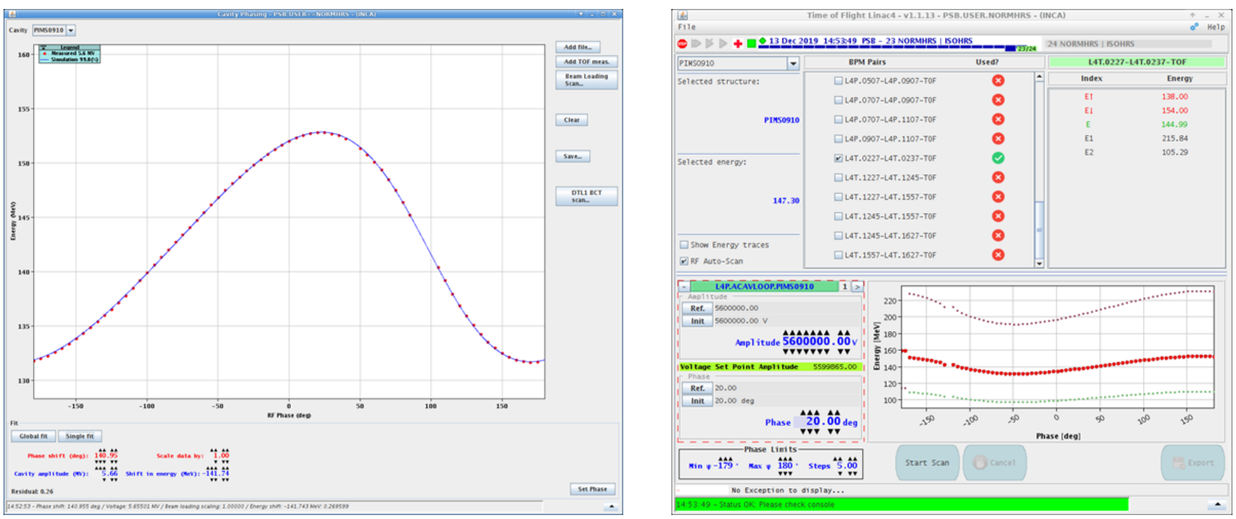


Figure 50. Improved Graphical User Interface for the BPM-based time-of-flight measurement.

BE-ICS Group

Industrial Controls

External Conditions Renovation

The renovation project for the External Conditions system continued in 2019. Much of the work this year involved, together with BE-CO and equipment groups, establishing which conditions could be migrated to CMW subscriptions (software inputs). Once this was done and the scope for the remaining hardware conditions was fixed, the final cabling requirements were submitted to EN-EL. Meanwhile, retrofitting of the existing signal collection chassis began, and verification of the Profinet network was made in the BE-ICS lab. The global architecture is seen in Figure 51.

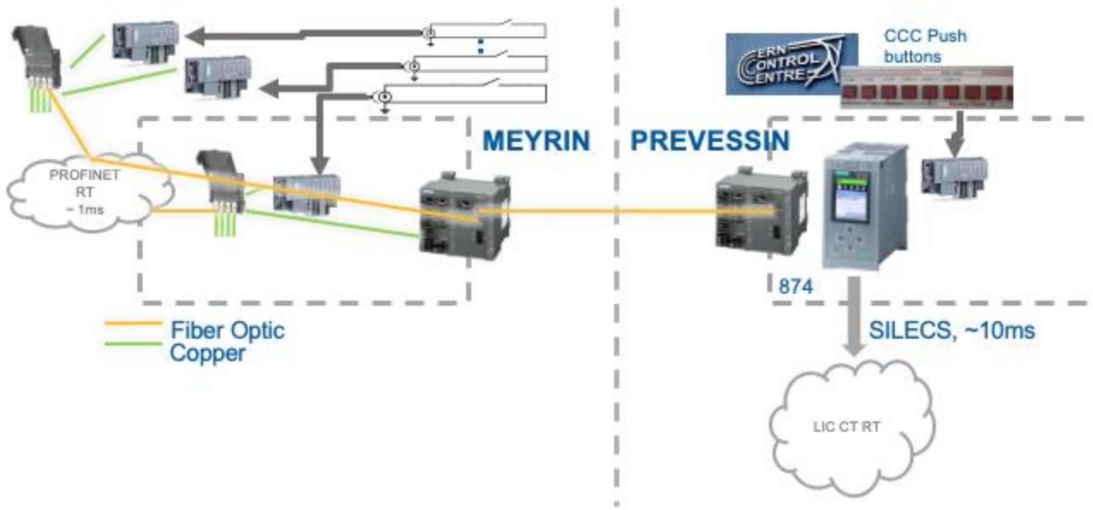


Figure 51. External conditions architecture.

Safety Systems

For the PS Complex, BE-ICS focused its work on the integration of the LINAC4, in the PS Access and Safety system, the integration of the POPS-B with the Booster Access Safety System, the installation of three large material booths to improve access of large equipment in the PS. The design for the refurbishing of the East Area primary and secondary Beam zones in the Personnel Protection System has been completed, the installation work will take place at the end of 2020. This refurbishing covers new access sectors to minimize dose rates, new interlock with the ventilations system, new access control to B157 RP buffer zones, control room and storage, and new safety alarm systems.

ICS was also leading the major safety refurbishing of the SPS Accelerator complex covering both SPS Personnel Protection System and Fire Safety.

Concerning Fire Detection, interlock and safety public address, at the end of 2019, 95% of the surface building equipment were installed and the tunnel installation was completed at 60%, the SPS 4 and 6 points have been commissioned. A test platform was deployed in B104 and maintenance teams were trained to the new technologies of Long Distance Air Sampling Detectors (LASD), Voice Alarm Systems and Système de Mise en Sécurité. In parallel, an enormous work was done to create the INFOR equipment data base and to define the OPC detailed alarm information required for the Fire Brigade.

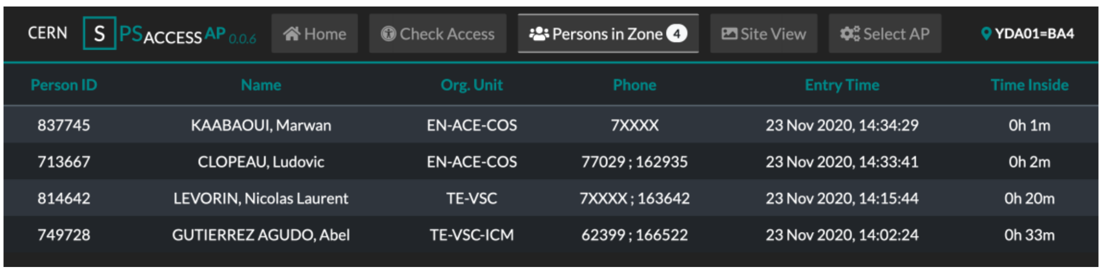
Concerning the sprinkler system all the detailed design work has been completed and the installation is completed at 60% and system was certified by the CNPP at BA4 and BA6.

The ALARA committee validated the work organisation for fire detection and fire extinguishing system for the BA1 and BA2 hot zones.

Concerning the new SPS Personnel Protection system, at the end of 2019, 10 of the 16 Access Points are installed and in operation, 5 of 16 Access Zones installed and tested, the TAG41 (AWAKE) Access and Safety systems has been put in operation during the summer, dealing with lasers and electron gun hazards. The efforts also focused on the formal verification process of the safety software including validation of compliance to Functional Safety standards, model checking using PLCVerif (http://www.cern.ch/plcverif) and automated testing techniques.

As part of the SPS Personnel Protection renovation project two new web applications were developed to provide information about persons in a given zone as well as to check their access privileges.

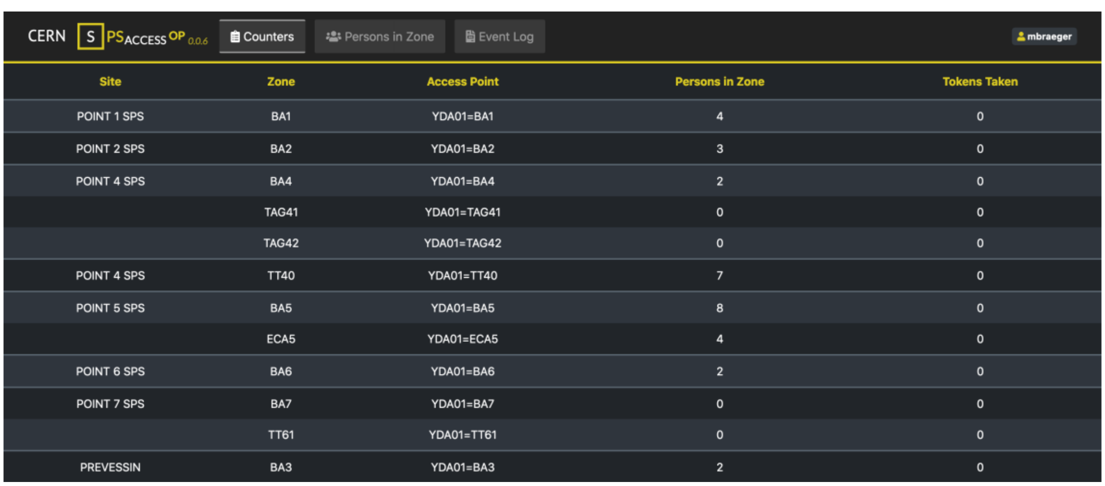
Both share similar features but were optimised for different use cases. Every new SPS access points (AP) will provide a touch display to get a quick overview about the site and access situation (see Figure 52). This is in particular interesting for persons who are about to enter the tunnel, but also for the firemen to see who is still in the zone in case of emergency.


CERN SPSACCESS AP 0.0.6 | Home | Check Access | Persons in Zone 4 | Site View | Select AP | YDA01=BA4

Person ID	Name	Org. Unit	Phone	Entry Time	Time Inside
837745	KAABAOUI, Marwan	EN-ACE-COS	7XXXX	23 Nov 2020, 14:34:29	0h 1m
713667	CLOPEAU, Ludovic	EN-ACE-COS	77029 ; 162935	23 Nov 2020, 14:33:41	0h 2m
814642	LEVORIN, Nicolas Laurent	TE-VSC	7XXXX ; 163642	23 Nov 2020, 14:15:44	0h 20m
749728	GUTIERREZ AGUDO, Abel	TE-VSC-ICM	62399 ; 166522	23 Nov 2020, 14:02:24	0h 33m

Figure 52. Display for Persons in Zone.

A second interface was developed for the SPS operators (OP) in the CCC, which are rather interested in getting a general overview about persons in the SPS Zones (see 53), or to consult the historical event log.


CERN SPSACCESS OP 0.0.6 | Counters | Persons in Zone | Event Log | mbraeger

Site	Zone	Access Point	Persons in Zone	Tokens Taken
POINT 1 SPS	BA1	YDA01=BA1	4	0
POINT 2 SPS	BA2	YDA01=BA2	3	0
POINT 4 SPS	BA4	YDA01=BA4	2	0
	TAG41	YDA01=TAG41	0	0
	TAG42	YDA01=TAG42	0	0
POINT 4 SPS	TT40	YDA01=TT40	7	0
POINT 5 SPS	BA5	YDA01=BA5	8	0
	ECA5	YDA01=ECA5	4	0
POINT 6 SPS	BA6	YDA01=BA6	2	0
POINT 7 SPS	BA7	YDA01=BA7	0	0
	TT61	YDA01=TT61	0	0
PREVESSIN	BA3	YDA01=BA3	2	0

Figure 53. OP application to provide a quick overview about persons in the SPS tunnel.

The Safety Review for the North Area was prepared and provided extensive cost and resources estimates. An overall project of 8.5 MCHF.

The renewal of the East Area was launched. Preliminary designs of fire and gas detection system was done to be able to prepare the preliminary DIC and start integration works.

ICS also provided several laser room personnel protection systems for Medicis, Awake, SMA18, Isolde B26 Lab, GBAR, etc.

BE-OP Group

For the LHC injector complex 2019 was also a particular year. The last beam in the injector complex was dumped in the early morning of Monday 10 December 2018. The members of the accelerator sections were then dispersed across CERN to make necessary and valuable contributions to projects and other activities in various groups and departments.

The Technical Infrastructure operation, as always, continued 24/7 and was reinforced with a second operator on shift coming from the accelerator sections. Long shutdown periods are also particular for the TI operation. Although they did not have the constraints of the accelerator complex running it was a busy period monitoring the infrastructure and ensuring masking and unmasking several types of alarms in areas where work was taking place, but most importantly responding adequately to all other alarms and coordinating interventions when minor and major events occurred. Some of the statistics for the Technical Infrastructure operation are given in Figure 54, Figure 55, Figure 56 and Figure 57.

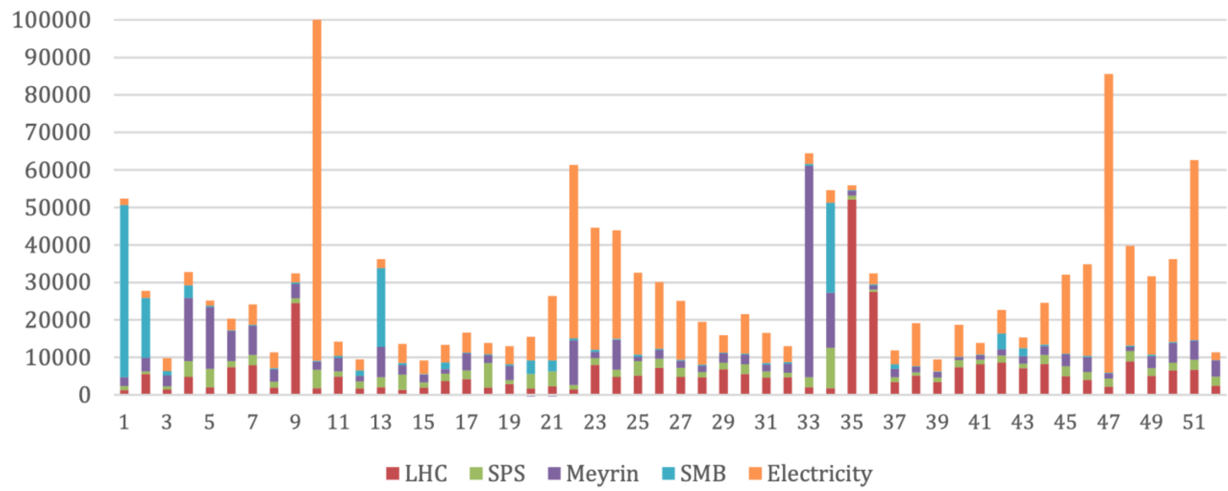


Figure 54: The number of alarms per category received weekly at the TI desk.

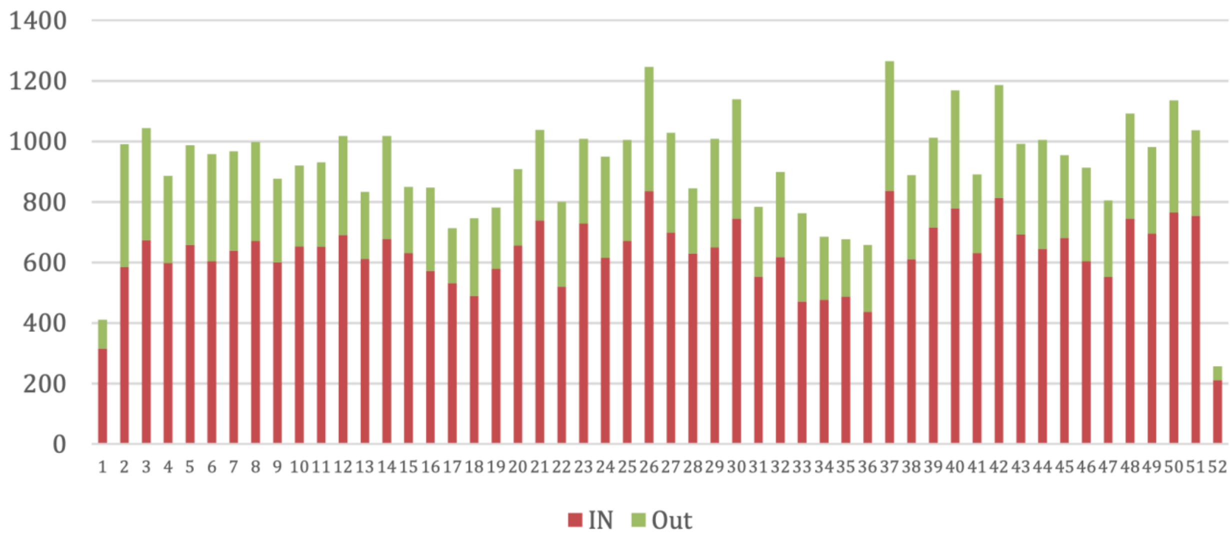


Figure 55: The number of incoming and outgoing phone calls per week received at the TI desk in the CCC.

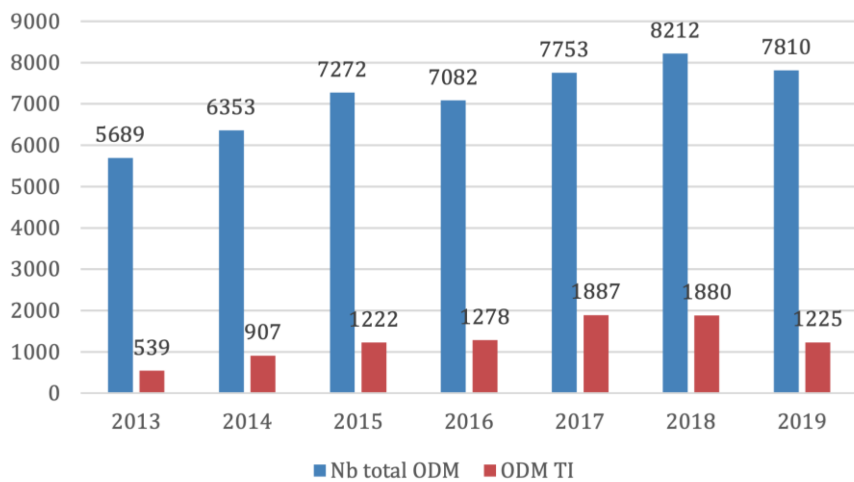


Figure 56: The number of ODM (ordre de maintenance) created by the TI operators per year since 2013.

The TI team dealt with 23 major events in 2019, ranging from erroneous gas detection alarms, through accidental activation of emergency stop buttons (AUG) to CERN-wide power cuts. A summary of the major events can be found in Table 1.

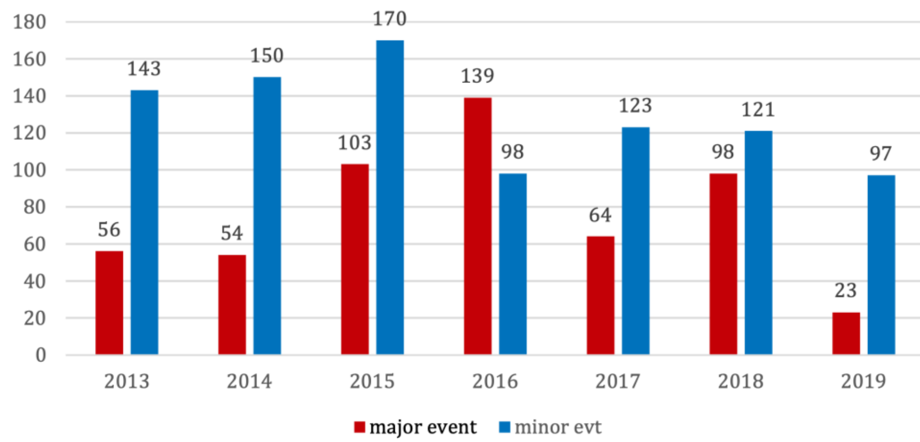


Figure 57: Number of major and minor event every year since 2013.

Table 1: Overview of TI major Events in 2019.

#	Date	Brief description of the major event
1	04.02.2019	Evacuation PX24 following a gas detection alarm.
2	05.02.2019	Evacuation SPS BA6 – Sextant 6.
3	12.02.2019	SPS stable loop cut as a result of a problem with an 18kV transformer.
4	13.02.2019	Trip of cold compressors LHC6 side B as a result of UPS overload.
5	09.03.2019	Fire alarm on a circuit breaker that cut the SPS stable loop.
6	29.03.2019	Accidental activation of an AUG in the SPS.
7	05.04.2019	Loss of 130 kV (SIG) at station ME10.
8	16.04.2019	CERN-wide electrical perturbation.
9	26.05.2019	Fire in UPS batteries in SCX5.
10	02.07.2019	Evacuation of EHN1 following ODH alarm due to loss of cryo in vacuum of NP02.
11	23.07.2019	Emergency stop of the BE substation as a result of a faulty relay on an AUG card.
12	04.08.2019	CERN-wide electrical perturbation following an earth fault in the ME9/ME24.
13	09.09.2019	An 18 kV power cut for Point 18 and BA7 as result of a digger that damaged cables.
14	15.09.2019	CERN-wide electrical perturbation.
15	24.09.2019	Activation of emergency stop (AUG) in PS octant 7.
16	02.10.2019	Power cut Prevessin and LHC loop.
17	18.10.2019	DSS-Rack CMS fatal error.
18	18.10.2019	CERN-wide electrical perturbation.
19	21.10.2019	Activation of emergency stop (AUG) in SM18.
20	01.11.2019	18 kV failure LHC loop.
21	19.11.2019	Power cut Point 1, as a result of bad connection on an 18 kV transformer.
22	27.11.2019	A 400 kV power cut causing a CERN-wide black-out.
23	17.12.2019	18 kV power cut in UJ67 due to a loose contact on a recently changed transformer.

The PS Booster section supported by operators from some of the other accelerator teams gathered in the CCC by the middle of September to start Linac 4 for an eight-week long run during which the beam was sent into the LBE lines. This allowed the re-commissioning of the Linac 4 itself, but also the commissioning of the renewed LBE lines after which beam characterisation measurement were made. The LBE run also enabled the commissioning of modifications made since the last Linac 4 reliability run that took place in Autumn 2018, revealing some issues for which mitigation measures had been developed and implemented. The run was successfully completed, after a few days' extension, just before the annual closure in December.

On the PS Booster, PS and SPS side the deployment of the LIU project was a major task, which will continue well into 2020. Members of the OP group led the project for the PS Booster and the PS, while many others contributed in an important manner to establishing the commissioning planning and the hardware commissioning checklists in close collaboration with the equipment and service groups. The integration of the newly installed equipment in the operational controls environment was also ensured by members of the different sections together with the development of many new software applications to control the new equipment and processes. In particular in the PS Booster and PS a next step in high-level parameter control through LSA was made with the help of the OP-run Setting Management Working Group.

In addition, the SPS was equipped with a new fire detection and sprinkler system and a new access controls and safety system. Members of the OP group made important contributions to both projects.

De-cabling in the LHC injectors was another major venture, before pulling the new cables required for the new or upgraded equipment. Although the work was under the responsibility of EN-EL, a substantial amount of these worksites was successfully supervised by members of the PSB, PS and SPS teams.

On 14 and 15 September the CCC was one of the major visit points for the CERN open days. Many members of the operations teams, but also other colleagues from elsewhere at CERN volunteered to guide people around and explain the workings of the CCC and the accelerators that are controlled from there. Members of the TI section were present in the Open days control centre that was situated in building 160 to ensure safe and orderly Open days.

BE-RF Group

Linac 4

In 2019 for the first time, Linac4 has successfully injected beam to the LBE measurement line in the PS switchyard, few meters from the injection point into the PSB. Considerable preparations and improvements of the Linac4 systems were required in the shutdown period during the year to achieve this feat.

The six 352.2 MHz, 33 kW SSPAs for Linac4 buncher and debunchers, built in 2011, were completely overhauled and upgraded to a new more robust transistor type. In addition, to improve the availability of the Linac4, an RF patch panel was installed that allows switching of any of the three buncher cavities to the spare amplifier, liberating its amplifier for repair during operation.

The Linac4 high-power RF system ran around 15'000 hours over that last years, overall quite reliably, corresponding already to about one third of the expected klystron lifetime! At this time however, the stock of LEP and new high-power klystrons seems sufficient for run 3.

To ensure compliance with the updated directives of Thales concerning the high voltage polarities and filament power supplies of the klystron, the gun tanks of all Linac4 klystrons and spares were modified. Figure 58 shows a view inside the emptied gun oil tank and the filament connections.

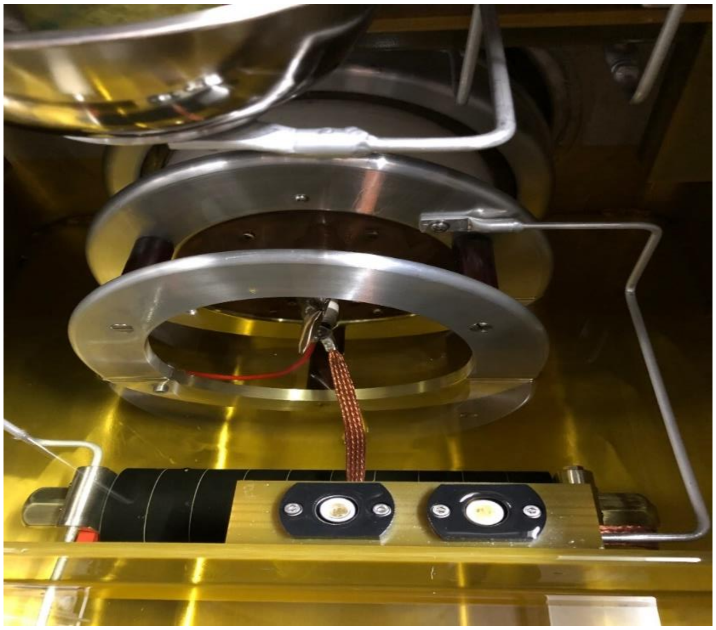


Figure 58. View inside the emptied gun oil tank and the filament connections.

PS

Consolidation of the 10 MHz interlock system

RF controls and interlocks for the 10 MHz system of the PS were completely renovated in 2019, converting them to a modern PLC-based infrastructure, allowing event-tracing post-mortem diagnostics.

AD

The Obsbox system, originally developed to record transverse oscillations in LHC, will also be used in the AD complex to record both beam intensity and Schottky beam spectra from the longitudinal pick-ups. For both AD and ELENA, a full new beam control system is operational for the restart with beam using the technology platform developed originally for the PSB LLRF.

Installation of the new C02 RF system

The AD C02 RF system with its infrastructure was completely replaced by the multi-cell, modular Finemet®-based system, as successfully deployed in the PSB. It actually employs Finemet® cores and solid-state amplifiers that have already assured a reliable operation in PSB ring 4 during many years.

Figure 59. The new C02 cavity in AD, an updated version of the PSB Finemet® prototype.

AWAKE

The AWAKE electron source was switched on again for beam studies, e.g. extensive bunch length measurements allowed to provide input data for simulations. In addition, preparatory parameter scans and simulations were performed to study machine-learning algorithms for beam set-up and optimisation. Requirements and design of the electron source for run 2 were intensively studied. It turned out that the electron source needs a significant higher energy and much shorter electron bunches to better match the externally injected electron bunch to the plasma wakefields, in order to achieve acceleration with a small energy spread and emittance preservation. The target parameters for the electron injector can be found in Table 2.

Table 2. Target beam parameters for the Run2 electron source.

Beam Energy	Energy spread	Energy stability	RMS bunch length	Bunch charge	Emittance	Beam size plasma focus
$(85 \dots 160)$ MeV	0.2%	$1 \cdot 10^{-3}$	≈ 200 fs	100 pC	$(1 \dots 4)$ µm	≈ 5 µm

The design of the new injector consists of an S-band RF-gun similar to the existing one. The bunches are subsequently compressed in an X-band RF structure using velocity bunching to achieve the final bunch length of 200 fs rms. Two one-meter-long X-band accelerating structures boost the energy to 160 MeV. The total length of the injector is only 5 m, fitting the compactness requirements of the AWAKE facility. The whole injector is bedded in a solenoidal magnetic field to preserve the emittance during the bunching and acceleration process. A schematic layout of the injector can be seen in Figure 60. The energy of 165 MeV can be obtained due to the high gradient X-band acceleration. The final bunch parameters resulting from the simulations using ASTRA are summarized in Table 3.

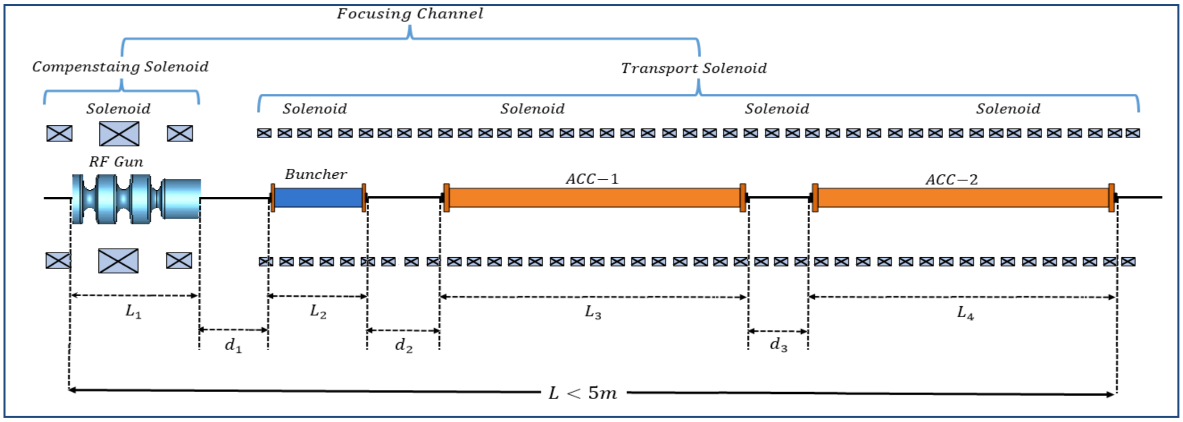


Figure 60. Schematic layout of the run 2 injector for AWAKE. Electron bunches are generated with an S-band RF-gun and then longitudinally compressed and accelerated using X-band accelerating structures.

Table 3. Beam parameters at the end of the injector from ASTRA simulations.

E_k[MeV]	σ_r[mm]	σ_t[fs]	ε_x[µm]	σ_E[%]	I_{av}[A]
165	0.14	207	0.44	0.09	168

In collaboration with the Cockcroft Institute, UK, a Mach-Zehnder Interferometer (MZI) phase detector has been installed at AWAKE. The MZI allows monitoring of the laser-to-RF phase deviation between the AWAKE mode-locked laser and the 3 GHz electron accelerator clock source. This design uses a unique square wave bias signal to set the correct biasing conditions on the MZI phase detector. A PXI-based control system monitors the MZI output and controls the bias voltage to allow drift free operation. The MZI has been used to identify problems with the currently installed laser-to-RF locking scheme and therefore can be used to improve the performance of the AWAKE experiment going forward.

ELENA

BE-ABP Group

The main activity of the ELENA project during the year was the connection of the ring to the experiments in “old” experimental zone, which were operated with antiprotons coming directly from the AD until the start of LS2. To this end, first the magnetic transfer lines from the AD to these experiments have been dismantled to free the space. Then, a new electro-static transfer line from ELENA has been installed. Electro-static elements are a cost-effective solution for beam transfer at the low energy reached by ELENA. This allows installing many quadrupoles and, in turn, to keep the beam sizes small and the design less sensitive to perturbations due to magnetic stray fields. By the end of the year, the installation had progressed well.

The diagnostics of the H- and proton source, which has been installed for commissioning and tests, has been improved and was used for systematic studies. As a result, settings allowing more stable and increased beam H- currents have been identified and are important as preparation of the commissioning of new transfer lines relying entirely on beams generated with the help of this source.

At the end of the year, the ELENA ring has been operated for a brief period with H- beam from the local source. The main purpose was to carry out tests with profile monitors, and to verify that they work well enough with the very low beam intensities expected. For short periods, H- beams have as well been sent to the GBAR experiment.

BE-BI Group

Measurement of the electron beam trajectory in the ELENA electron-cooler

Two electrostatic pick-up stations are installed in the ELENA electron cooler and are integrated into the closed orbit measurement system of the ring. As well as being able to measure the antiproton beam, they are also designed to measure the trajectory of the electron beam used to cool the circulating antiproton beam. The electron beam intensity modulation required for this measurement was achieved by coupling the modulation signal to the reference voltage of the electron gun grid electrode via a current transformer. The electron beam trajectory was then corrected to be as close as possible to the central position using the eight transverse correction coils in the electron cooler. This optimisation proved to be more complicated than expected as any mis-steering resulted in the pick-up signals being swamped with secondary electrons and ions created by the lost primary beam. The electron beam collector settings were readjusted to avoid these losses and increase the beam collection efficiency. Complementary simulations using COMSOL Multiphysics confirmed the enhanced performance of the cooler, in terms of collection efficiency, with the new settings obtained.

ELENA Secondary Emission Monitor Tests

Secondary emission monitors (SEM) will be used to measure the profile and position of the antiproton beam extracted from the ELENA ring. After numerous mechanical modifications to the original design, eight monitors were installed for this commissioning run. Because of the ongoing development of the front-end electronics, only two monitors were equipped with a full data acquisition and control chain. Initial measurements on the monitor at the ion source exit were problematic due to the large beam intensity resulting in saturation of the head amplifiers. It was therefore decided to move the electronics to the monitors installed on the LNE50 extraction line towards the GBAR experiment.

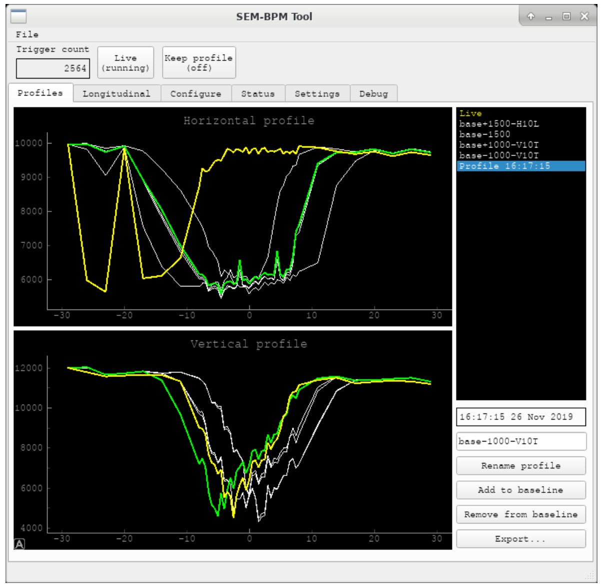


Figure 61. SEM profiles measured during a horizontal position scan in LNE50.

The profile monitors performed well during the run, giving reliable profile and position measurements despite problems with missing wires (Figure 61). The acquisition firmware was also modified to include new options to improve the setting-up of the signal acquisition. One particularly important option was the possibility to acquire the signal from any individual wire as a function of time. This greatly simplifies the setting of the delay of the trigger to start the acquisition and will be an invaluable tool in the future when up to four beamlines can be used quasi-simultaneously. Optics studies of the beamline using the SEMs resulted in a better understanding of the future challenges of operating the electrostatic elements in the extraction lines.

BE-OP Group

The commissioning period in 2018 was hampered on one side by the breakdown of the AD electron cooler and on the other side by the frequent break down of the high voltage transformer of the ELENA local ion source. Although beam was extracted to GBAR in 2018 it did not allow to conclude the commissioning of the ELENA machine before installing the electro-static transfer lines between the ELENA decelerator and the experiments during LS2. Installation of the new transfer lines meant removing the direct connection with AD and therefore disabling the possibility to send AD beam to the experiments. A difficult choice, but fully supported by the AD physics community. 2019 saw the start of the installation of the electro-statics transfer lines and the project is scheduled to finish by mid-2020.

Since the 2018 run ended with problems on the local ions source, time and effort was devoted to consolidating the source and replacing the transformer by a new improved version, which unfortunately also sparked. In September the source was successfully made working in pulsed mode, reducing the constraints on the high voltage transformer. This allowed many studies on the source itself, but also measurements on the profile measurement devices that revealed issues with discontinued wires, which were addressed.

The development of software applications to control and monitor the ELENA machine and the new transfer lines was an integral part of the AD section activities and was partly executed in collaboration with the Setting Management Working Group with the aim to make a first small step to LSA based high level parameter control and where possible to align practices with the other machines in the complex.

The preparation of the commissioning plans for ELENA and the new electro-static transfer lines in particular was also done between BE-OP, BE-ABP and the equipment groups concerned with the aim to start the commissioning, using H- beam from the local ion source through ELENA, in September 2020.

BE-RF Group

The last of the four longitudinal magnetic pick-ups for ELENA has been completed and installed in the new extraction line LNE00. A mitigation of interference from power supply spurious signals has been developed and is being gradually deployed on the four pick-ups for the restart with beam foreseen for 2020.

COLLIMATION CONSOLIDATION AND UPGRADE

BE-ABP Group

The year 2019 saw important progress on the collimation project activities, with a very successful continuation of various production contracts for the new collimators for the LS2 upgrade of the LHC. The upgrade includes items related to both the Consolidation and the HL-LHC projects. Specifically, four new collimator hardware types are planned for installation in the LHC:

- 4 new primary collimators in IR7 (TCPPM);
- 8 new secondary collimators in IR7 (TCSPM);
- 2 new passive absorbers in IR7 (TCAPM);
- 4 new dispersion suppressor (DS) collimators in the DSs around IR2 and IR7 (TCLD).

Together with the production of operational spares, a total of 22 devices (20 of which are movable) is being produced, with responsibilities shared across different groups in the ATS sector. The IR7 TCLDs rely on the new 11 T dipole developed for HL-LHC and being produced. Two important collimation milestones were reached in 2019, with the delivery of the first series-production units of the TCLD and TCPPM collimators. The latter use a new material as active component facing the beams – Molybdenum-Graphite (MoGr). The same material, with a thin layer of Mo coating, is used for the secondary collimators. Altogether, the activities proceeded well in 2019, and the team is on track for meeting the LS2 installation deadline: this work will continue with high priority in 2020.

The detailed analysis of the Run 2 performance of the LHC collimation system continued, addressing both proton and ion beam challenges. Studies addressed both the standard operation and the several dedicated MDs taking place in Run 2. Some examples are the completion of the performance analysis of crystal collimation MDs and the improved collimator impedance assessment through measurements of the TCSPM prototype used in the runs 2017/2018. These works provided crucial inputs for some important baseline changes for the collimation upgrade that took place in 2019, as discussed below. The documentation of some key achievements of 2019 was achieved through a number of publications.

In February 2019, a major technical review of the collimation upgrade project for HL-LHC was organized. An international review panel assessed the project status and plans. The outcome of the review was very positive, with the main conclusion being a full support for the upgrade strategy and with a few follow up actions for the team. These were addressed by the end of the year, in time for the Cost & Schedule review of the HL-LHC. At this review, the collimation work package was also reviewed. The upgrade plans were confirmed and supported by the reviewers, and additions to the upgrade baseline were endorsed. Indeed, one important achievement of the review processes was that, at the end of 2019, two new items were added to the collimation upgrade baseline: hollow electron lenses and crystal collimation of heavy-ion beams. These two items have been studied in the last years by the collimation team and matured to a level that enables the insertion in the baseline. Crystal collimation is being prepared in LS2 for the upgraded ion beam parameters in Run 3, as a mitigation of schedule risks with the 11 T dipoles that the IR7 upgrade relies on. Hollow electron lenses will instead be deployed in LS3 for an active halo control of the HL-LHC proton beams in Run 4.

REX/ISOLDE/HIE-ISOLDE

BE-ABP Group

A general demand from the experimental setups at the HIE-ISOLDE linac is a shortened charge breeding time inside the EBIS. That increases the repetition rate, thereby reducing the instantaneous particle rate during the beam pulses and allows access to even shorter-lived radioactive isotopes. For these reasons, a new electron gun, with the aim of providing a higher electron current density, has been constructed. The upgrade makes use of a novel in-house development, i.e., a so-called immersed non-adiabatic electron gun. The concept reduces the undesired superimposed cyclotron motion of the electrons by means of a local magnetic field, precisely placed with respect to the beam ripple, such that the resulting electron beam is laminar and easily compressible to higher current density. The idea may have applications also in other fields where laminar beams are desired, for instance electron lenses and coolers, as well as for RF tubes. After a careful evaluation of possible knock-off effects, such as beam contamination from new cathode types, degraded vacuum due to a higher current, increased space-charge potential and modified ion injection acceptance, a set of baseline parameters for the non-adiabatic electron gun could be agreed upon. The gun design was thereafter verified with beam simulations for nominal and lower electron beam currents. Subsequently, the technical design was carried out within the group. Tight constraints imposed by the existing REXEBIS geometry, high voltage gradients, high temperature and a small cathode led to a delicate design, with some objects resembling those found in the watch making industry. Two different cathode types will be considered for operation, a commercial IrCe cathode and a new BaO dispenser cathode from Beijing University of

Technology. The latter, with an expected exceptionally low work function, has been developed especially for CERN.

BE-RF Group

Rex-ISOLDE

With the LS2, the REX-ISOLDE RF installation has gone into a consolidation phase. New 101 MHz, 5 kW SSPAs were ordered to replace the aging Dressler units, and all 90 kW tube amplifier systems in operation since 2002 were taken apart for deep cleaning and maintenance. In order to improve the reliability of electro-mechanic variacs, solid-state replacements have been developed that will make do with the sliding contacts on the auto-transformer windings. This consolidation effort targets an increase in the meantime between failures and a reduction in the average intervention time on the systems during run3.

HIE-ISOLDE

One cavity in the fourth cryomodule was not powered during 2018 due to an RF short circuit at the fundamental coupler. In March 2019, the faulty cryomodule was disconnected from the beam line and transported to the SM18 test facility where the HIE-ISOLDE clean room had been requalified for the refurbishment. Venting was done applying an improved procedure, starting from the top plate. A diffuser, filtering particles larger than 3 nm, was installed in the line. The pressure was very slowly brought to atmospheric values for two days. Upon inspection, the fault was traced back to insufficient solder filling of the joint between the RF cable and the coupler antenna, in a recessed spot with difficult access. A new soldering procedure was then studied and validated, and all coupler lines were unmounted and redone according to the new procedure. Reassembly and the usual qualification tests followed. The cryomodule was then transported to the M9 bunker to be tested at cryogenics conditions. This was also the occasion to validate the full test bench, which had been built as a project deliverable, but never used up to then. All cryomodules had been tested in the linac to gain time for physics. The long shutdown however offered the possibility of a qualification test in SM18. The RF test was carried out successfully in November. The Q_0 measurements could also be cross-checked with the dynamic heat loads.

BE-OP Group

The last protons to the ISOLDE target were stopped already on 12 November 2018 following a successful run with experiment behind both the low energy lines and the superconducting Linac. In the ISOLDE facility, besides the regular preventive and corrective maintenance, the cryo module 4 of the superconducting linac was removed from the tunnel to receive a repair in SM18. Additional diagnostics boxes were also installed on the request of the ISOLDE OP team. New software applications were written while others were consolidated.

New target front-ends, high voltage power supplies and tape station were installed.

An additional commissioning and test period in 2020 was approved and the scheduling of the activities for this period were carefully done by the ISOLDE Operations team.

CLEAR/CLIC/CALIFES

BE-ABP Group

In 2019 further progresses were made in the CLIC study on the positron production scheme, again increasing the positron yield and thus making substantial gains in power consumption and target expected reliability. The present final yield is about a factor four higher than the initial evaluation. Simulation and optimization tools for positron production have been also finalized, and a design of the Adiabatic Matching Device realized in collaboration with Shandong University, with the aim of future prototyping. Integrated studies, mitigation schemes for magnetic stray fields and Ring-To-Main-Linac system studies were also finalized and fully documented. A milestone was reached in the assessment of the Beam Delivery System tuning performances, with the achievement in simulations (using two independent beams and realistic luminosity signals) of the goal of more than 90% of the simulated cases exceeding 110% of the nominal luminosity. As a follow-up of the European Strategy Upgrade process, an evaluation of a high-luminosity option for CLIC 380 was carried out and documented together with evaluations of luminosities at the Z0 pole and for an eventual CLIC gamma-gamma option. Beam dynamics studies relative to the CLIC technology were carried out also for spin-off projects like Compact-Light and e-SPS, whose X-band linacs were further optimized and assessed in terms of stability and beam performance.

CLEAR operation was extended to 2019-2020 after a successful CERN internal review which took place in February 2019. The CLEAR facility was operated in 2019 for 38 weeks (two more weeks than in 2018). The CLEAR user community expanded further, with 26 independent experiments/activities executed during the year. Several progresses were made on beam performance, stability and reliability. In particular, the reach towards short bunches, as requested by several users, was dramatically extended from about 1 ps r.m.s to 100 fs r.m.s., at the limit of the present bunch duration measurement system. Charge stability of a few percent pulse-to-pulse was also obtained. Consolidation work was performed on several systems, including the laser (to be completed), realignment of the experimental beam line, and addition of several beam diagnostics tools (e.g., inductive BPMs and digital cameras). From the experimental point of view, the program on dosimetry studies for medical applications (VHEE and FLASH cancer radiotherapy) were particularly intense, with several institutes applying for beam time and carrying out experiments. The CLEAR program on THz sources continued, testing several radiators and configurations, including 3D Smith-Purcell gratings (in collaboration with CEA-CESTA) and fully characterising their emission. A peak power in the MW level in the THz spectral region was reached in 2019. The plasma lens experiment performed several series of measurements, documenting among other thing a world record focusing magnetic gradient of 5.2 kT/m.

BE-RF Group

X-band activities

In February 2019, a novel MgB_2 solenoid built for the 50 MW X-band klystron by the CLIC-KEK collaboration was tested at the manufacturer Hitachi. After acceptance by KEK, it was shipped to

CERN where a first cool-down and magnetic measurements confirmed the original performance. This solenoid is a first step towards a green approach for power consumption. The prototype MgB2 superconducting magnet demonstrated a significant electric power saving at an operation temperature of 20 K with an AC plug power consumption of less than 3 kW for klystron solenoid (compared to 20 kW for normal conducting). It also demonstrated a very high stability and operational margin, which should guarantee reliable operation when working on the klystron (see Figure 62).

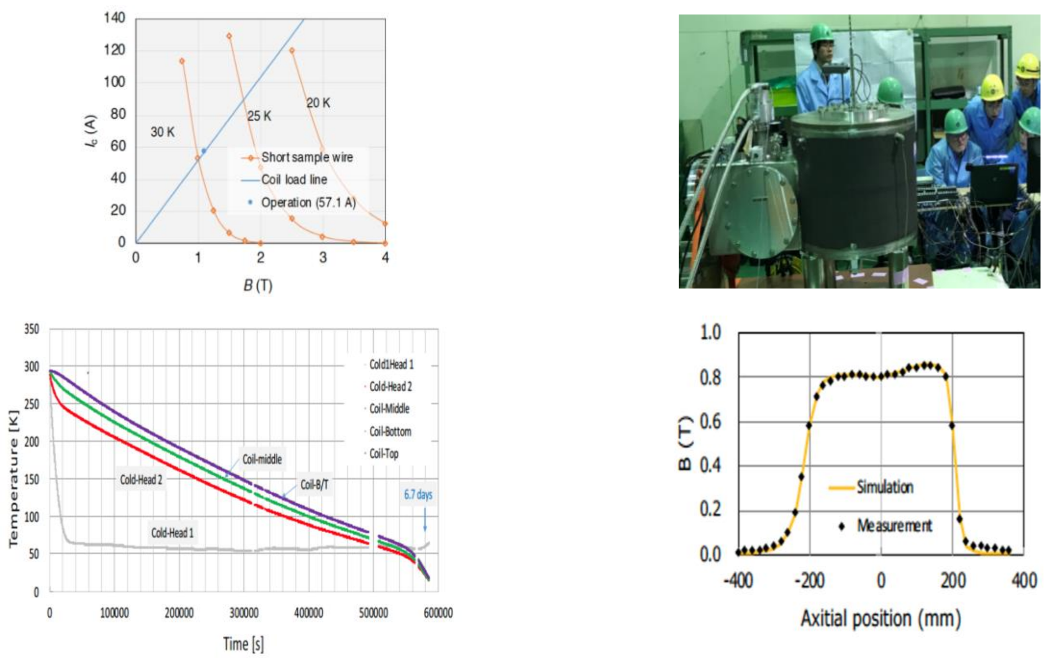


Figure 62. Prototype MgB2 superconducting magnet test results.

High-Gradient studies

A new test-facility for testing S-band structures was inaugurated in Valencia (Spain) as part of the CLIC collaboration on high gradient studies. In collaboration with DESY for the FLASH Forward experiment, the X-box2 test stand successfully tested the PolariX Transverse Deflecting Structure (constructed at PSI). The set-up was installed with a high-power phase shifter between the cavity inputs to allow change of the polarization of the field. In the limited testing time available, the PolariX was conditioned up to a peak power of 25.6 MW at 100 ns pulse width in one polarization and no clear power limit on the structure emerged (see Figure 63). PolariX was returned to DESY and has been operational in the FLASH Forward beam line since September 2019 operating at a peak power of 6 MW.

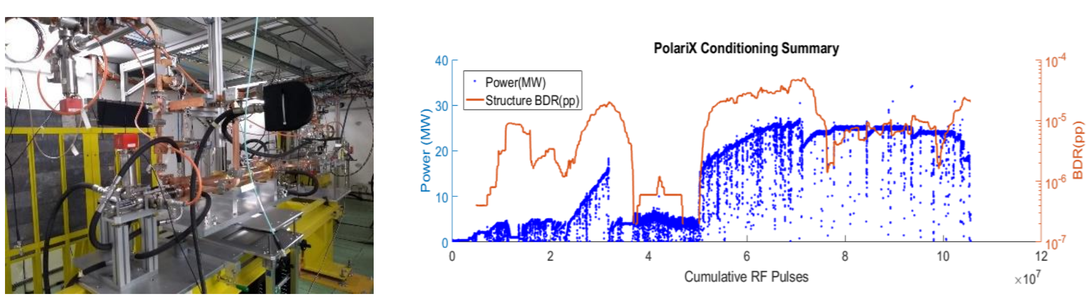


Figure 63. PolariX in the X-Box2 facility and conditioning summary.

CLEAR

After a long shutdown following the stop of the CTF3 facility in 2016, the Combiner Ring and its transfer lines and the dumps were finally dismantled in 2019. The 33 main quadrupoles on loan from the LURE facility have now been returned to Paris.

Figure 64. Combiner Ring quadrupoles on their way back to LURE, Paris.

CLEAR was operational all year in 2019 for user experiments and machine improvement studies. Upgrades continue to be made, in particular a new solid-state switch for thyratron replacement was developed and put in operation (see Figure 64). In addition, the CLEAR facility was backed up by the installation and commissioning of a klystron & solid-state modulator assembly for powering S-band cavities and the photo injector, as shown in Figure 65.

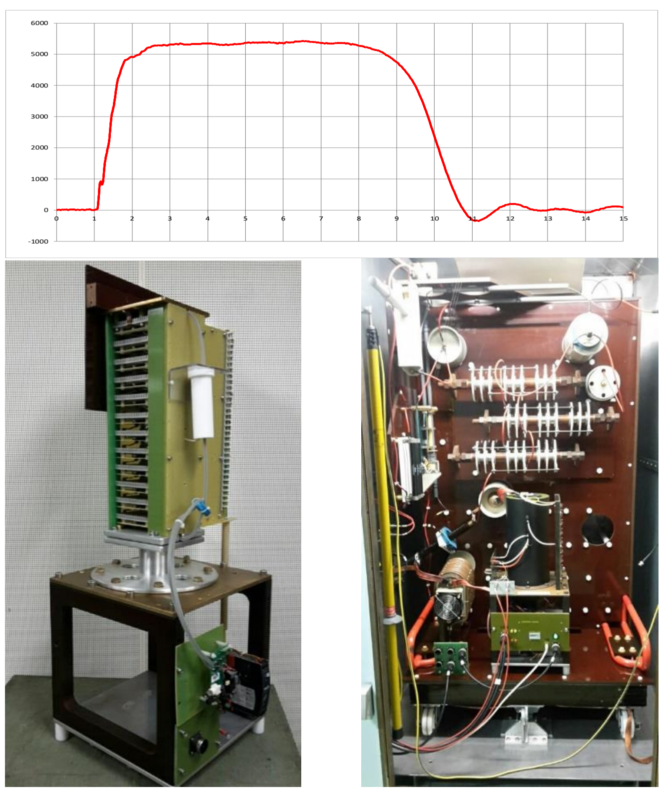


Figure 65. Solid-state switch for thyratron replacement in CLEAR. Top: pulse current (5.5 kA/8 µs, 50 Hz). Bottom left: Solid-state assembly. Bottom right: The CLEAR modulator and its thyratron (black cylinder) in the centre.

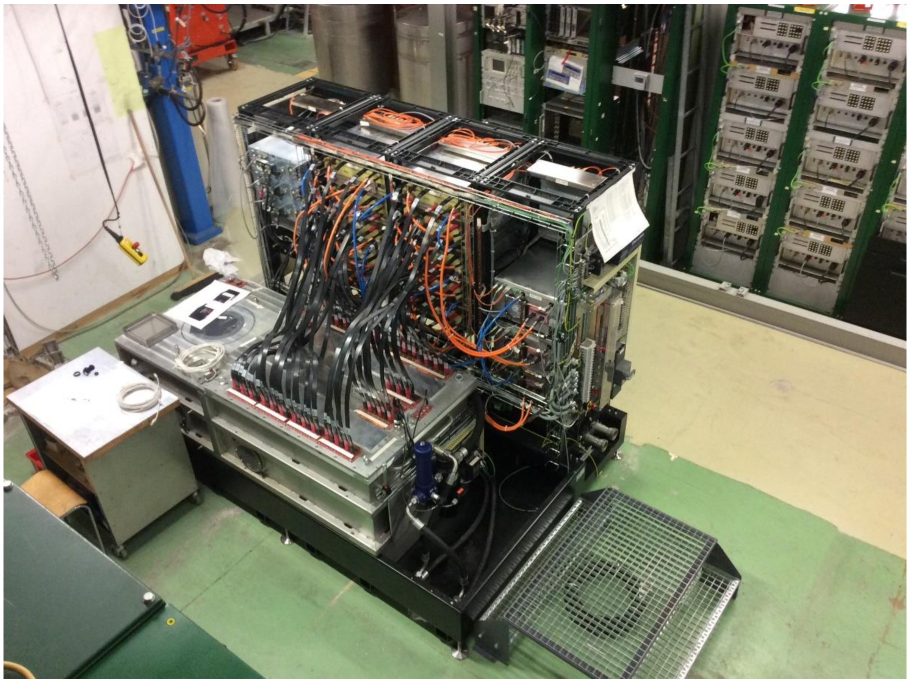


Figure 66. Klystron & modulator assembly for powering CLEAR S-band cavities and photo injector.

FUTURE MACHINES

BE-ABP Group

Medical Accelerators

The TwinEBIS test bench has evolved significantly during the year, with many of the auxiliary systems for ion extraction now in place. A scaled-down version of the ion extraction line, featuring a Mamyrin-type TOF system, is now operational and first ions have been extracted and characterized. In addition, the production of the mechanical pieces for the complete ion extraction line progressed during the year with many of the larger pieces delivered. The electron beam from MEDeGUN was restarted late summer and the system ran with a beam current exceeding the specification and first ions were extracted for commissioning of the TOF. Thereafter, following a full bakeout, the characterisation of the ion production could be initiated. Residual and injected Ar gas ions were studied by recording TOF spectra. Unfortunately, a series of technical problems hampered the progress and the initial results points towards a non-optimal beam optics configuration in the collector and ion extractor region.

On the accelerator design side, the layout of a linac-based q/m=1/2 hadron therapy facility was completed from the source to 400MeV/u, including error studies. The layout is based on the use of a 750MHz RFQ and a 3 GHz SDTL and CCL, integrated in a bending section that could facilitate to locate the linac in a hospital building without loss of real estate gradient. The tolerances on the magnetic element gradient and positioning as well as the RF jitter tolerances have been defined also in view of energy variability. The design is the base for the established collaboration with CIEMAT, of which ABP is the technical contact. This collaboration aims at the construction of the pre-injector for the medical facility, equipped with a MedeGun-like source (or a commercial alpha particle source) and an RFQ until 5 MeV. The realisation of such pre-injector is assigned to a consortium of Spanish industries lead by CIEMAT.

Physics Beyond Colliders

The BE-ABP activities in the PBC framework during 2019 covered essentially: 1) Studies of injectors performance for fixed target beams after the LIU upgrades, 2) Electric Dipole Moment (EDM) ring, and 3) Various fixed-target implementations under consideration for the LHC.

1. The study of the horizontal instability in the PSB, relevant to accelerate high intensities and to fully validate the new injection at 160 MeV without constraints on the choice of the working point, continued with PyHEADTAIL simulations. The results of these simulations exhibited an excellent agreement with the experimental observations, thus confirming our understanding of the underlying mechanism. As demonstrated in these studies, this instability is not expected to impose a limitation for future operation, given that it will not appear for values of kinetic energy above 1.3 GeV and will be suppressed by the upgraded TFB hardware at the lower critical values of energy.

   The chapter "Protons Beyond the LHC Injectors Upgrade Project" for the PBC CDR, covering not only high intensity beams in the PSB but the potential of all fixed target beams in all injector synchrotrons, was produced and released as CERN-PBC-REPORT-2019-004.

2. A scheme to measure a possible Electric Dipole Moment (EDM), aligned with the spin and the magnetic moment, of protons is studied within the PBC. The concept foresees to circulate proton bunches polarized in longitudinal direction in a fully electric ring with a circumference of about 500 m operated with "frozen spin". To this end, the machine is running at the "magic energy" of 232.8 MeV, where the spin is rotating with the direction of motion and remains polarized in longitudinal direction. The signature of a possible proton EDM is a rotation of spin from the longitudinal into the vertical direction. Studies to understand systematic effects, which generate as well a rotation of the spin into the vertical direction and, thus, limit the sensitivity, have been continued. Such effects occur in realistic machines with imperfections as alignment errors, magnetic stray fields and other imperfections.

3. The studies on possible integrations of fixed-target (FT) experiments in the LHC continued in 2019. The PBC-FT WG worked on the documentation of the work carried out, producing a final report as input to the ESPP. The report summarizes the main findings on three FT projects under consideration: (1) gaseous targets and halo splitting with bent crystals for (2) conventional targets and for (3) the "double-crystal" setup for MDM and EDM measurements of short-lived baryons. The SMOG-2, which plans injection of various gas types in front of the LHCb in a new storage cell enabling larger gas pressures, is being installed in the LHC and will be operational in Run 3. Various studies on the feasibility of using bent crystals to split part of the beam halos and steer it on an in-vacuum target also continued, addressing the compatibility with high-intensity operation at the LHC. The estimates of achievable protons on target in realistic machine configurations were improved. A new layout for a possible integration in the LHC P3 was elaborated in addition to the initial layout for P8, upstream of LHCb. The physics reach of both have been

comparatively assessed to identify optimum scenarios for the LHC. Improved simulation models for the channelling process in the long crystals used for the precession of short-lived baryons were compared to data collected in 2018.

FCC

Early in 2019, the FCC Conceptual Design Report was published in the European Physical Journal C and ST. The FCC Week 2019 was held in Brussels, 24-28 June 2019. It attracted about 410 participants. Its 240 talks and 50 posters highlighted the study progress and inspired new initiatives. US teams reported that a 15 T accelerator magnet had successfully demonstrated at FNAL and that two independent groups had achieved FCC target Nb3Sn conductor performance (current density 50% above the HL-LHC specification). A proposal in the frame of the Swiss CHART program was developed to jointly develop the FCC-ee injector complex with a beam test of a prototype positron source at PSI's SwissFEL linac. BNL colleagues proposed an upgrade of FCC-ee to an energy recovery linac configuration, allowing to reach substantially more luminosity (or, alternatively, save a large fraction of the electric power required by the baseline) and to boost the collision energy up to 650 GeV.

A project proposal "FCC Innovation Study" focusing on a 100 km Future Circular Collider infrastructure implementation & e+e- collider design was prepared and submitted to an EU H2020 design study call. It foresees the validation of key performance enabling approaches through beam tests at KARA, PETRA III, DAFNE, VEPP-4M and possibly SuperKEKB; user capacity building; collider and infrastructure CDR++; the layout and placement optimisation in collaboration with government authorities, the management of excavation material, transnational impact assessment, and communication and engagement strategy.

Activities related to the European Strategy Update process 2019-20 included presentations and discussions at the Open Symposium in Granada and, throughout the summer of 2019, the compilation of the "Physics Briefing Book" (CERN-ESU-004) from all the input received. This Briefing Book provided the foundation for the subsequent discussions and decisions by the European Strategy Group.

Beside the FCC Week, in 2019, the H2020 Integrating Activity ARIES' Work Package 6 APEC organized or co-organized five workshops: Beam Tests and Commissioning of Low Emittance Rings, KIT, 18-20 February 2019; High Intensity RFQ meets Reality, Heidelberg, 15-16 April 2019; Mitigation of Coherent Beam Instabilities in particle accelerators (MCBI2019), Zermatt, 23-27 September 2019; Electrons for the LHC, Chavannes-de-Bogis, 24-25 October 2019; and the Space Charge mini-workshop, CERN, 4-6 November 2019. The ARIES workshop at KIT manifested a renaissance of (low-emittance) storage ring light sources, in full synergy with FCC-ee. The RFQ workshop in Heidelberg reviewed the intensity limit of heavy ion beams due to the RFQ, and addressed the optimum balance between ultimate performance and reliable operation.

Using a new EU instrument, the Innovation Pilot, which is well adapted for super-advanced communities such as the European accelerator community, the project proposal "Innovation Fostering Accelerators Science and Technology" (I.FAST) was prepared and submitted. Its Work Package 5 "Strategies and Milestones for Accelerator Research and Technologies (SMART)" will develop a MUon collider STrategy (MUST), Push Accelerator Frontiers (PAF), and Improve Resonant slow EXtraction spill quality (REX).

BE-RF Group

FCC

Phase 1 of the study of the RF systems for FCC-ee and FCC-hh was completed, as well as the RF chapters for the FCC CDR. The baseline design as well as the installation and operational scenarios are defined, and a first draft of the resulting implementation studies (cost, powering, cooling, civil engineering and safety) has been produced. The constraints imposed by the machine parameters and operation schedule are challenging, and a detailed R&D plan shall be prepared in 2020.

Amongst the significant improvements, the quest for innovative bunching technologies for high efficiency klystrons, initiated at CERN in 2013, has reaped tangible results and the development of a highly efficient version of the LHC klystron, as demonstrator of this technology, will be built in collaboration with Thales.

RF cavities for FCC and eSPS

The study of a hybrid scheme using both 400 MHz and 800 MHz cavities was continued with Rostock University to demonstrate a feasible solution for the varying requirements of the FCC-ee operating points. A new concept to add a waveguide HOM coupler in addition to the coaxial dampers to extract the high frequency HOM power was found to be effective compared to only coaxial couplers.

A new proposal to use the 5-cell 800 MHz FCC-type cavities in a two-cavity configuration in the SPS-BA6 bypass to accelerate electrons in SPS (eSPS) was made and compared to the normal-conducting option at 200 MHz. This option is now adopted as the baseline for the eSPS RF system (see Figure 67).

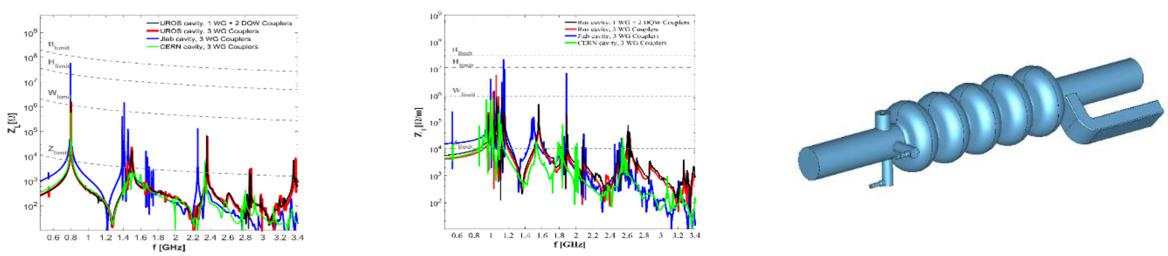


Figure 67. Impedance spectra for 5-cell 800 MHz cavities with different damping schemes (left, centre). The schematic of a combined HOM damping using coaxial and waveguide couplers (right) shows efficient damping and extraction of HOM power in the high frequency regime.

FE-FRT – Ferroelectric Fast Reactive Tuner

A first proof of principle test was performed with a prototype Ferroelectric Fast Reactive Tuner (FE-FRT). This is a non-mechanical frequency tuner, which can be mounted on the outside of a cryomodule. It couples out a fraction of the stored energy in the cavity, which is then reflected back through a ferroelectric to shift the phase of the RF wave, thereby changing the frequency in the cavity. For cavities with low beam loading (e.g. in ERLs or heavy ion accelerators) this kind of device can potentially be used to suppress microphonics and thereby significantly reduce the power needs from the RF amplifiers. In this first test, the device was connected to a crab prototype cavity and a frequency shift of 10 Hz was demonstrated (see Figure 68).

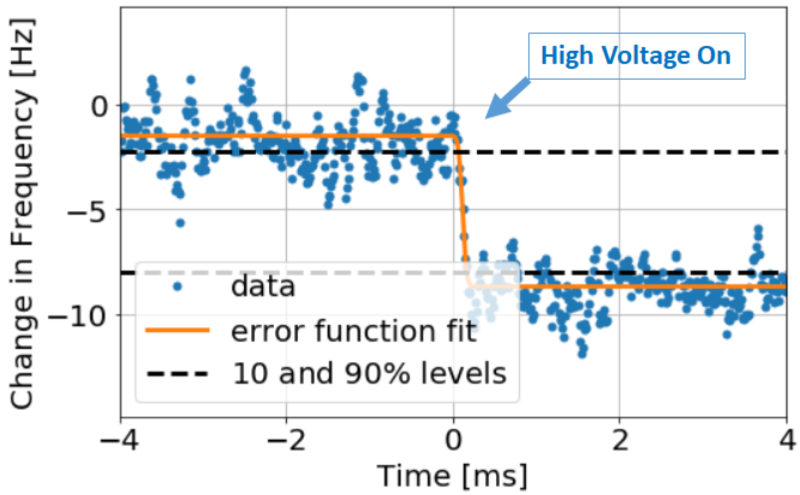


Figure 68. Proof of principle test to shift the frequency of a SC cavity with an FE-FRT

Testing superconducting materials for cavities

Superconducting RF R&D at the Cryolab continued. A Nb/Cu HIPIMS coating recipe, which gave good results on flat samples tested with the QPR, was applied to a spun 1.3 GHz cavity. The cavity was tested but first results were disappointing. In parallel, prototyping work for seamless substrates with different technologies was started. On the front of new SRF materials, R&D on A15 coatings on Cu continued in TE-VSC. The DC magnetic characterization of test samples was done in the framework of a collaboration agreement with the University of Geneva. For Nb3Sn, first samples of an optimised recipe were tested with the QPR, giving useful indications for the future work.

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

Throughout the year 2019, the tendency with respect to previous years inverted resulting in a reduction of staff from 872 to 794 (i.e. 431 Staff Members, 98 Fellows, 81 Students, 184 Associates). On the other hand, due to the long shutdown work, industrial support increased to a total of 303 employees of CERN contractors contributing to the departmental undertakings.

Finally, another 98 ADAM S.A. employees developing an accelerator for medical applications, are administratively attached to BE-ASR.

Specific responsibilities concerning human resources and administrative matters have been mandated to the BE-ASR group leader, by delegation of the department head. Departmental representation is hence ensured in staff selection committees (13 successful boards in 2019), the CERN contract review board (9 in 2019), and the Standing Concertation sub-group dealing with modifications of the Staff Rules & Regulations (SRR), Administrative Circulars (AC) and Operational Circulars (OC). The preparation of AC33 on Duty Travel took significant efforts to get the final version approved by CCP in November 2019 and is effective since January 1st, 2020.

Resources & Logistics

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

In order to overview, plan and control the departmental resources over the medium-term period, the ASR group leader has also the role of DPO. The departmental personnel budget was kept under control with a 0.3% overspending of the personnel budget in FTE units, but actual *underspending* in kCHF. Also, the slight underspending in the Fellow budget allowed some positive budget carry-forward to 2020. The DPO is assisted by his deputy (DDPO in BE-HDO), who assures planning of fellows, students and special associate programs, and has also the role of deputy project planning for the HL-LHC project.

The planning of the material budget was quite a rocky road, due to CERN's cost savings exercises, resulting in three consecutive budget cuts during the year. The established departmental cost-savings plan was accepted by the directorate, implemented and respected. On the other hand, by means of the medium-term plan, additional funds were secured for the recurrent fire detection maintenance and renovation, as well as a new R&D budget for high-efficiency klystrons.

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

In addition to the normal, recurrent activities of *space management*, the new tools were tested and scrutinized: *Locations* replacing GESLOC and the *conference room booking system* in Indico.

Safety Unit

The staffing of the BE Safety Unit remained stable with four staff, one fellow, and a part-time contribution from a BE-ICS staff member (as Deputy RSO), representing a total of 4.9 FTE. Throughout the year, the team had the welcome support of an administrative student. In addition to the departmental and project safety roles and the past roles, the Safety Unit also provides the PSO for the renovation of the East Area. The DDSO is still active in the *CERN Crisis Coordination Team*.

All members of the BE Safety Unit are committed in the three *Complex Safety Advisory Panels*, "CSAP" (LHC, SPS and PS; the Unit provides the scientific secretary for the PS- and SPS-CSAP). 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.

Safety of Personnel

The BE Safety Unit has carried out more than 30 safety patrols during LS2, mainly in the injector complex. Most of the safety issues identified dealt with safety equipment, for example the lack of fire extinguishers for worksites with hot works. The remaining safety issues concerned safety rules such as not wearing of personal protection equipment and disconnected cables not grounded.

The 2019 statistics implying BE personnel or occurring in BE premises remained reasonable. In 2019, our Department was involved in 66 safety events (11% of CERN-wide events). Among those events, 41 were occupational accidents while the others concerned hazardous situations or near misses. Twelve accidents on BE premises caused absences, for which the total was high (190 days), mainly due to two accidents with respectively 90 and 27 days off.

Radiation wise, BE personal doses were all below 1 mSv for 2019, the maximum was 0.9 mSv.

Safety of Installations

In order to allow the long-shutdown activities, most beam facilities were put in safe mode conditions for the personnel, whereby EIS were condemned. On the other hand, ELENA (the ion source), CLEAR (CTF3 Linac), GBAR Linac, LIGHT (ADAM), and AWAKE (with electrons and lasers) were operated 'with beams' in 2019.

Only RF tests took place in HIE-ISOLDE, and the Linac tunnel was closed for that purpose.

The DSO participated to the definition of the new scheme of emergency lighting in the Beam Facilities, to be implemented by EN-EL during Long Shutdowns. To save energy and improve the longevity of this lighting, it is now coupled with the Access Safety System, and switched-off during Beam operation.

The safety documentation for beam facilities was completed by several new operational procedures related to long shutdown activities.

Safety in Projects

A process of electrical pre-inspections of the LIU equipment by HSE was put in place. These pre-inspections allowed to identify non-conformities and address them at an early stage, prior to installation of the equipment in the accelerators. This is an improvement for safety and from planning point of view.

An Individual System Test (IST) risk assessment template has been produced for LIU and non-LIU ISTs. It is the first time that this process is put in place in the injectors. A total of 31 documents have been produced based on this template.

SPS-Fire Safety project: the 2nd phase of the implementation of the project in SPS-LSS1 and LSS2 was presented to the ALARA-3 committee. Due to the experience gained during the first phase, further optimization of the processes and dose-limiting measures were presented, after which the committee gave his go-ahead for planned execution in 2020. The collective dose for the project in

2019 was well below the initial estimations due to the optimization on the workplaces as well as the efficiency and thoroughness of the executing personnel.

The safety assessments for deliverables under BE-led work packages continued. The ones for the Beam Gas Curtain installation stage 1 (WP13) and for the TCSPM and TCLD collimators (WP5) were produced and released. Preliminary discussions took place to define the access conditions in the LSS during the conditioning of the crab-cavities.

During 2019, the East-Area renovation project had to face many safety challenges. The dismantling activities inside the hall 157 generated many co-activities that had to be coordinated and managed. This included a radiation protection challenge involving an ALARA Level 3 intervention for the primary area. The façade and the roof on the outside of the building was fully renovated, while the experiment CLOUD was operationally running from September to November.

BE-HDO Group

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

BE-ABP Group

The main tasks of the ABP-CWG in 2019 were the follow-up of the AFS phase-out and the upgrade of the accelerator logging system from CALS to NXCALS, focusing on their impact on the activities of ABP. A series of test cases were gathered from the different users of AFS within ABP and provided to IT for the testing EOS as a replacement of AFS. The ABP-CWG served as a platform to broadcast the status of the development of the new logging system within ABP, allowing the members for early testing and sharing their experience with the usage of the new API. In addition to these main tasks, the ABP-CWG maintained its role of interface between the users of high throughput and high-performance computing resources provided by IT (HTCondor and

HPC clusters) and INFN-CNAF clusters in terms of monitoring of the performance and optimization of the systems to the needs of ABP members. The working group also encouraged the development of modular and shareable codes for beam dynamics simulation by hosting discussions between developers of various codes. The development of a new particle tracking library SixtrackLib (SixTrack GPU engine) as well as the experience with its integration in the collective effect code PyHEADTAIL were particularly encouraging. The exploitation of the synergies between the similar yet different codes COMBI and PyHEADTAIL were also studied, showing a more limited potential due to incompatibilities in the parallelisation methods. The MAD-X developments were mainly focusing on the needs for the high luminosity LHC and the FCC-ee project. This included verifying the radiation modelling, implementing a tilted solenoid and the separation of dipole magnet strength from bending angle. The speed of the MAD-X tracking, for a single particle, was also improved by an order of magnitude. The year 2019 was concluded by the first (beta) release of the new code MAD-NG (Next-Generation) and its first application to LHC and HL-LHC studies.

BE-BI Group

Asset-management review and objectives

BI manages more than 400 in-vacuum instruments across the accelerator complex with moving parts that require regular preventive maintenance. The group is taking advantage of the long shutdown to implement an asset-based maintenance system. All instruments are identified with bar codes that link them to the layout database and the CERN enterprise asset management (inforEAM) database. A maintenance checklist has been prepared for each instrument and linked to this database which allows the on-site technician to perform and log all the required tasks. The maintenance history of all devices can then be easily tracked.

LS2 coordination

LS2 was the main focus of the group’s activities in 2019, with major upgrade and consolidation across the whole injector complex. There were some 200 machine interventions planned, which grew to over 240 during the year. The wide diversity of activities and people involved was managed with dedicated machine link persons and a group planning officer. Month-by-month schedules were prepared and updated across the accelerator complex using data from the global CERN schedules, which allowed successful management of co-activities across machines.

2019 Open-days

As in 2013, the BE-BI group hosted an exhibition during the 2019 CERN Open Days (COD). The venue was in front of building 866, where a 200 square meter tent was installed. With the help of different CERN service groups, the site was nicely prepared, and the tent with its wooden floor was installed a week a head of the event. A total of 11 different instruments where displayed together with acquisition systems especially designed for the COD event. In addition to well-known instruments such as the BPM, BLM and BCT there were newcomers such as the Beam Gas Ionisation monitor (BGI) and eXperimental Beam Profile Fibre monitor (XBPF). A special video game had also been prepared by a student, which allowed the visitors (both adults and children!) to steer the virtual beam and interact with beam instrumentation devices. The beam instrumentation video, showing the beam in the various injectors all the way up to the LHC was upgraded from the 2013 version, adding a section on beam position monitoring as well as speech and subtitles. The 45 BI-group volunteers greeted over 1000 happy visitors per day, explaining how the instruments work and how they are developed, tested and used in operation.

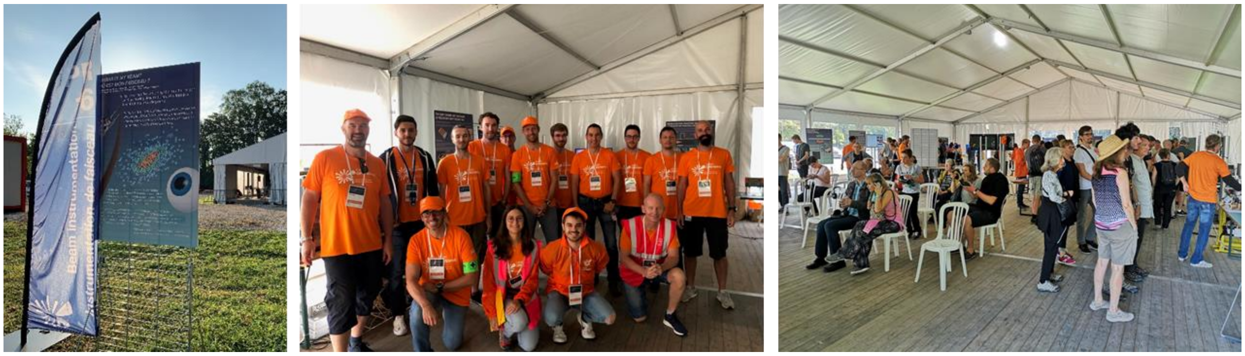


Figure 69. The BE-BI exhibition during the CERN 2019 Open Days.

BE-CO Group

LS2, LINAC 4 and End-Of-Life baselines

The 14th of January 2019 marked the end of the LS2 Baseline developments and was THE day for a massive release of many CO products in a synchronised, coherent way. The majority, if not all, of the backward-incompatible changes were released and new versions of our tools, with long-term support, became available for our partner groups to develop with during LS2.

A second coordinated release, the Linac4 baseline, was deployed on the 17th June. Contrary to what its name suggests, it did not only focus on Linac4-related work, but acted as a milestone for many activities in the group. This second baseline, focused on hardware and software elements needed for Linac4 beam tests; the SPS LLRF project; the migration to Oracle18; the migration to Git; the Post-ACCOR project with objectives for the B-Train renovation and features and modifications that could not be included in the LS2 Baseline. In addition, a special effort was made to move the whole Linac4 controls infrastructure to the post-LS2 version of the stack, that is to say CC7, RDA3 and FESA3.

The final public baseline in 2019 took place at the end of the year, and marked the end of life for many of CO's oldest technologies including the LynxOS, SLC6 operating systems and the FESA2, RDA2, GM and SLEquip frameworks.

MTCA4 and the new SPS LLRF system

In the context of the SPS LLRF renovation project, led by the BE-RF group, BE-CO participated by providing new low-level building blocks. Traditionally, the electronics in the LLRF system were a mix of different form factors, including NIM and VME64x. In 2018, it was decided that a new system will be developed, to replace ageing electronics and to cater for new needs, in terms of RF gymnastics for a range of new cavities to be deployed during LS2, that will allow the SPS to cope with the intense beams needed by the High-Luminosity LHC project. The new form factor for the electronics is MTCA.4, and the main reason for this decision was the possibility to capitalise on a number of existing LLRF developments from other labs in this form factor.

RF have also decided to move away from clocking their digital electronics with a sub-multiple of the RF clock itself, and will use a White Rabbit (WR) based scheme instead. The WR node that will deliver precise timing to the MTCA.4 crates in BA3 has the most stringent jitter requirements in WR to date (below 100 femtoseconds). The proposed solution involves sandwiching two modules, **eRTM14 and eRTM15,** and the initial results presented to the High-Precision Timing Distribution interest group, in September, already fulfilled RF's requirements. After a few months of fine-tuning the performance, series production will begin in early 2020, ready for the restart of the SPS.

In order to support this project and any future dedicated accelerator systems requiring high bandwidth and high-availability, in 2019, the MTCA.4 platform became a fully integrated member of the BE-CO control system.

White Rabbit

2019 marked the end of an 8-year effort to standardise White Rabbit (WR) under IEEE-1588 (Precision Time Protocol, PTP). The ideas of WR were generalised and made it into the standard under the "High-Accuracy (HA) Profile" heading. The WR team at CERN started working on porting the gateware and software in the WR switch and the WR PTP Core (WRPC) to comply with the new HA profile.

In the applications front, the most salient development was the release of White Rabbit Trigger Distribution (WRTD). This is a new building block which can be used in applications requiring synchronisation of remote equipment, e.g. for distributed data acquisition. In a WRTD network, one can declare producers and consumers for each trigger. The system translates input pulses into network messages and, conversely, network messages into output pulses, always guaranteeing a constant delay between input and output pulses. This constant delay can then be taken into account by the application in order to mimic the effect of simultaneous triggering.

Work started on the development of a new WR switch, to cope with component obsolescence and provide for more robustness in critical applications. The new switch will make use of System-on-Chip (SoC) technology, and include redundant power supplies and fans.

In the frame of the WR-Btrain project, a new modular approach was developed, whereby users can include Btrain functionality in their designs by using a dedicated mezzanine (CUTE-WR-DP) connected to their mother board. This decouples upgrades of the WRPC from those of user logic, and allows the CO group to conduct remote diagnostics of the WR network without any access from the host side, i.e. avoiding any interference with the user's system.

On the RF-over-WR front (RFoWR), a collaboration was launched with the stewards of the IEEE 1914.3 Radio over Ethernet (RoE) standard. As a result, RFoWR will be an annex of the standard, to be used at CERN and elsewhere in applications requiring the transmission of an RF waveform over WR.

DI/OT

The Distributed I/O Tier (DI/OT) platform is part of Work Package 18 in the HiLumi LHC project. The main deliverable is a crate with a controller board which can communicate with higher layers of the control system, e.g. the Front End Computers (FEC), through a fieldbus. This crate, along with the controller board, the communications mezzanine and any other board equipment groups add to suit their needs, must operate in radiation, and it is therefore very important to design all these components with high quality and robustness in mind.

The DI/OT project, has seen quite a lot of action in 2019. A first prototype of the DI/OT Monitoring Module (MoniMod) was produced, which can monitor voltages, current consumptions, read temperatures and drive fans, interfacing with the outside world through PMBus. The MoniMod is based on an AT-SAMD21 microcontroller, which has shown moderate radiation tolerance in tests. This is enough for a monitoring solution which furthermore exposes an external reset pin that can be driven by a part of the system more tolerant to radiation.

Progress was also made on the radiation-tolerant implementation of an AC-DC power converter for the crate. The DC-DC part of the design will now proceed as a collaboration with TE-EPC, who require a similar building block for future generations of their FGC platform.

It is important to already start planning how the DI/OT crates will communicate with higher layers of the controls stack. Some existing systems for which DIOT could be a good evolution (such as the WIC) make extensive use of PLCs, even for critical parts such as the computation of the state control for power converters based on interlock inputs. It was therefore important to discuss with BE-ICS, ways in which PLCs could communicate with a DI/OT crate. As work progressed on the development of a radiation-tolerant Powerlink interface, it was noted that the proposed solution was quite generic and that it might be possible to implement an Ethernet/IP interface on the same hardware/gateware foundation. This would be interesting because Ethernet/IP is easier to interface to existing PLC families at CERN than Powerlink

Discussions have continued throughout the year with committed and potential users of the DI/OT platform, as the different actors in the equipment groups decide which parts of the kit they can use to come up with good, efficient solutions to their problems for HL-LHC.

CERN Open Hardware Licence

The main development during 2019 for the drafting of version 2 of the CERN Open Hardware Licence (OHL), was the decision to split the licence into three variants, in order to cater for three different collaborative models frequently found in Open Source Hardware (OSHW):

- The strongly-reciprocal variant (CERN-OHL-S). Work released under this variant can be included in larger works, but then, upon release, the sources for those larger works need to be published under the same licence, thus creating a virtuous, ever-growing circle of sharing.
- The weakly-reciprocal variant (CERN-OHL-W). Work released under this variant can be embedded in larger works and these don't need to be published under the same licence. Modifications to the part under CERN-OHL-W, however, need to be shared back with the community.
- The permissive variant (CERN-OHL-P). Work released under this variant does not carry any obligations towards its users, beyond the usual requirement of keeping notices e.g. related to copyright.

There was an intense collaboration with the Knowledge Transfer group and an external legal expert in drafting the texts of the three variants, taking care to cover not only traditional hardware such as Printed Circuit Boards (PCB) but also designs expressed in Hardware Description Languages (HDL) for the purpose of designing Field-Programmable Gate Arrays (FPGA) and Application-Specific Integrated Circuits (ASIC). This drafting paved the way for review and publication in 2020.

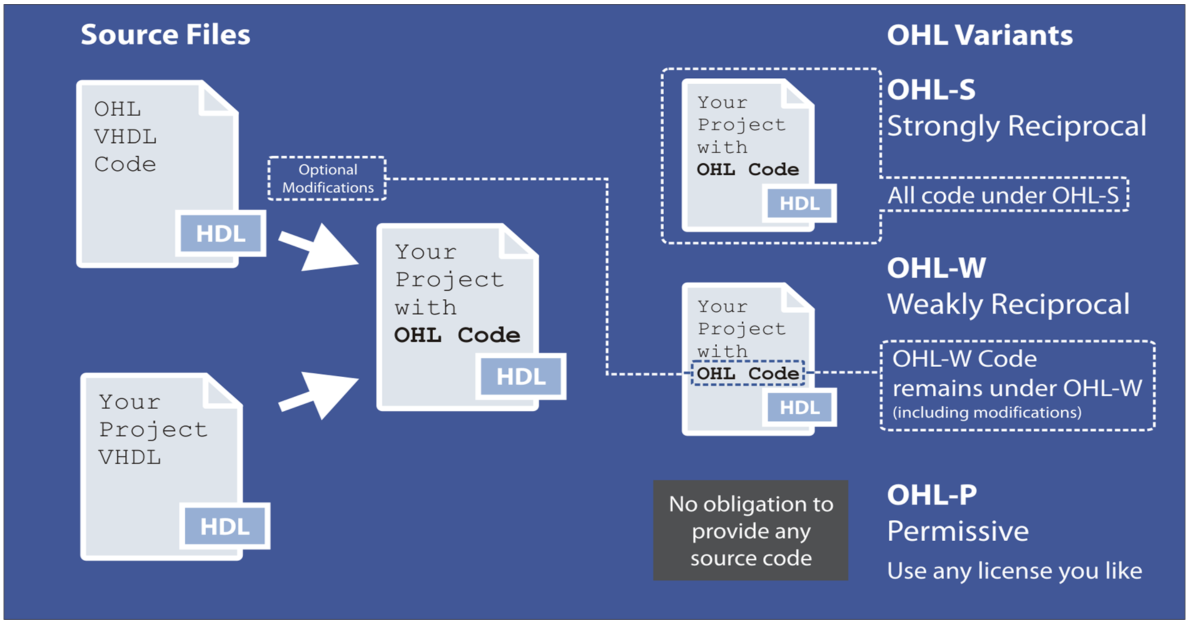


Figure 70. Effect of the different variants of the CERN OHL as applied to HDL designs.

LS2 Hardware Installations and supporting activities

The GMT and Pulse Repeater renovations

The renovation of the complete GMT distribution network in the injector complex was a key objective of the BE-CO group during LS2. After an extensive period of testing, both in the labs and in-situ, the new ELMA VMEbus crates, populated with the new VMEbus cards, developed by the HT section, were finally installed in the field in 2019. The installation process was quite complicated, as it was necessary to take into account the other interventions planned for electricity, powering and civil engineering.

The design of the new GMT distribution network is composed of both fibre and copper transmission links and required the installation of about 70 VMEbus crates, 350 VMEbus modules, 500 cables and 200 patch cords. These new crates and modules are fully monitored via the I2C bus. In addition, the IN section collaborated with the SRC section on a new remote diagnostic chain for the CTR-x timing modules in order to detect transmission problems (PLL errors, etc.) via CMX and COSMOS.

From CO's perspective, the connection to the PS Booster took place on the 17th June 2019, when the stand-alone LN4 central timing generator was dismantled and the Linac4 GMT distribution network was connected to the PSB, the complete chain having been renovated with the new generation of optical modules, provided by the GMT Distribution Renovation project.

The pulse repeater renovation project, also progressed considerably during 2019, with LN3, LEIR, PSB, AD and ELENA being finalised. Major refactoring was necessary on the PSB injection system, to take into account the requirements for the LN4 Baseline.

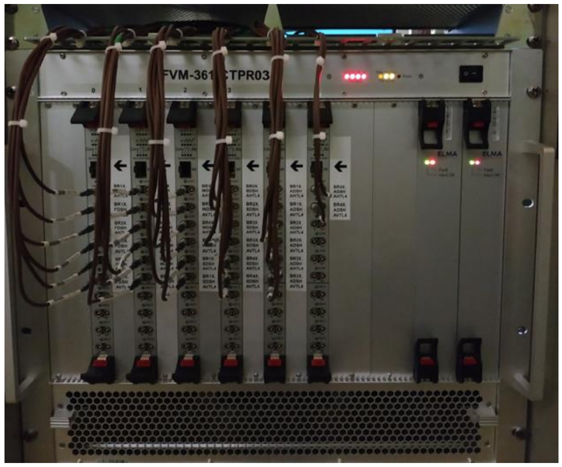


Figure 71. New Pulse Repeater installation.

Also, in the context of the Pulse Repeaters Renovation project, the back-bone of the LN4-PSB RF-synchronisation was deployed. PSB per-ring central triggers are being sent to the LN4, where triggers for key equipment, such as the chopper and low-level RF, are generated and being distributed with the new generation of modules.

Figure 72. Both sides of the LN4-PSB trigger renovation.

Industrial PC renovation

Following the extensive validation phase carried out in 2018, the first batch of 50 new 4U Siemens IPC847E Industrial PCs (IPC) arrived at CERN in January. These new IPC models, envisaged to replace the ageing Kontron machines, are the absolute latest technology on the market and some parts of the CO infrastructure had to be adapted and modernised to make them work in the CERN environment. Already adopted for several applications, the 4U IPC847E model was confirmed as the best solution for the B-train renovation project and after successful testing, the MasterFIP CTRIE cards, together with the 2U Siemens IPC647E computers, was the platform chosen for the LHC WorldFIP to MasterFIP renovation.

Bulk deliveries from Siemens continued throughout 2019, until all 250 machines were received. In order to streamline the initial setup, a very fast semi-automated mechanism was developed in order to perform the computer-specific settings. This involves the use of barcode scanners whenever possible to avoid typing mistakes during the procedure.

Figure 73. The first batch of Siemens IPCs.

The IPC 2.0 platform was gradually deployed during 2019 for Cryogenics, QPS, FGCs and BLM applications, in coordination with the equipment groups.

LS2 Hardware Installation requests

The Hardware Installation team have been gathering installation requests from equipment groups for LS2 since 2016. Fulfilling these requests required an immense effort from the team, especially with respect to coordination. Hardware installation activities took place in 76 buildings across CERN and had dependencies on both clients and other service providers (i.e. Cables from EN-EL, Ethernet Sockets from IT-CS etc..). The planning had to be adapted due to other interventions and accessibility issues, and often had to be pro-actively followed up. In total, 765 requests were made for LS2 and 80% of them were fulfilled by December 2019.

Data Centre Migration

BE-CO-IN is responsible for supporting the 24/7 operation of backend servers, fixed displays and operators' consoles, in the Accelerator Data Centre (CCR) and CERN Control Centre (CCC).

In 2016, the decision was taken to replace the obsolete HP Proliant systems with INTEL Quad server technology, and converge all backend hardware to a heterogeneous platform by the start of Run 3. In order to procure the new replacement server hardware, BE-CO joined IT's highly competitive tendering process. The contract was won by MAGUAY computers from Romania and in October, BE-CO began installing the new hardware in the CCR. All of the servers successfully passed the burn-in and acceptance tests, covering intensive memory and network checks, I/Os, SDD throughput etc. The new platform was also fully integrated into the new COSMOS monitoring system.

There are currently 427 servers installed in the CCR, with 7508 cores, 45'446 GB of RAM and 338 TB of NFS storage. This represents an investment of 2.7MCHF in server hardware, as well as an additional 60KCHF in network switches and cables. At the end of 2019, the migration from

HP is 75% complete and the team are confident that 100% of BE-CO operational servers will be on the Intel platform at the start of Run3.

Controls Hardware Data Management

In 2017, CO began the Controls Hardware Data Management (CHDM) initiative, in order to consolidate the data describing the hardware installations, both owned and managed by CO, appropriately in the CERN central databases (Layout, CCDB, InforEAM and Netops). In parallel, improvements to the workflows, tools and the integration between the different systems are addressed.

In 2019, the Hardware Installation Team made a considerable effort to define 270 different types of crates and modules, so that all of the Front-End computers could be fully documented in the Layout database as hierarchies of Functional Positions. Thanks to improved integration between the systems, this physical hardware description is seamlessly integrated with the corresponding configuration data stored in CCDB and the asset management data stored in InforEAM.

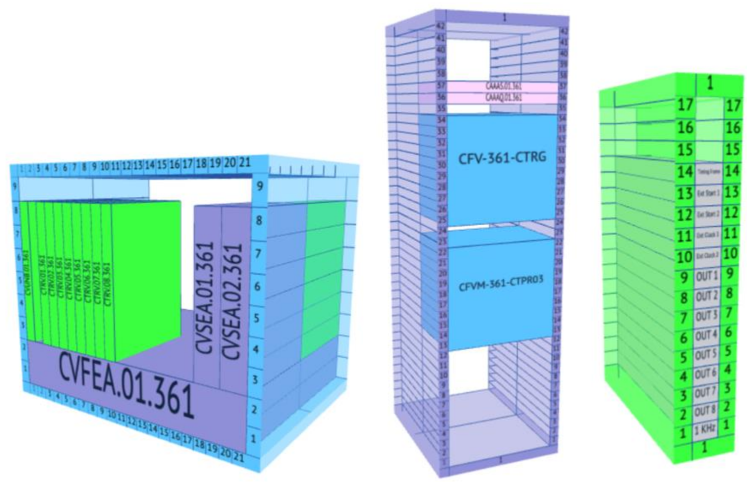


Figure 74. Layout schematics of crates, racks and modules.

The next logical step was to begin documenting the cabling for fieldbuses, trigger and signals, especially those appertaining to the new hardware installations taking place during LS2. However, it was first necessary to transfer data from the Controls Configuration Service's deprecated PSCables application into the Layout database and develop a new tool, the Controls Connections Editor, that would allow the large scale insertion and maintenance of cabling data.

Although, the improvements in integration and tooling performed in the context of CHDM initiative were designed with CO's needs in mind, other groups have also been able to benefit from these developments. For example, the Beam Instrumentation Group have used the new tools to fully document their instrumentation channels from the BPMs to the surface racks for the SPS and LHC.

COSMOS

After a year of design and development, phase 1 of the Controls Open Source Monitoring System (COSMOS) initiative was completed at the beginning of 2019. The monitoring infrastructure is fully operational on both the TN and GPN, and uses IT services for OS metrics (collectd), storage

(DBOD) and authentication (LDAP). For visualising the metrics, the COSMOS team setup their own Grafana instance in order to ensure availability, reliability and performance for its users. Monitoring of non-critical hosts and services is complete, with 6600 hosts and 21,300 services monitored, generating 138,000 collectd metrics. By April 2019, end-users had already implemented approximately 40 custom checks and 50 Grafana dashboards, themselves.

Phase 2 of the COSMOS project involved collecting metrics from all ACC hosts, including the critical systems. This also included the integration of checks for White Rabbit nodes, the new VME-based Pulse Repeaters and ELMA crates with redundant power supplies. The second half of 2019 focused on setting up the monitoring of C/C++ and Java processes.

One key aspect of COSMOS in 2019 was the migration of the DIAMON console, which had to remain in place for the operators. The underlying server was switched from DIAMON to COSMOS, but the console remains the same in terms of functionality and Layout. This new version was put into production in June. This milestone was important for two reasons: firstly, it means that COSMOS has become an operational service. Secondly, it enables the removal of the obsolete DIAMON infrastructure.

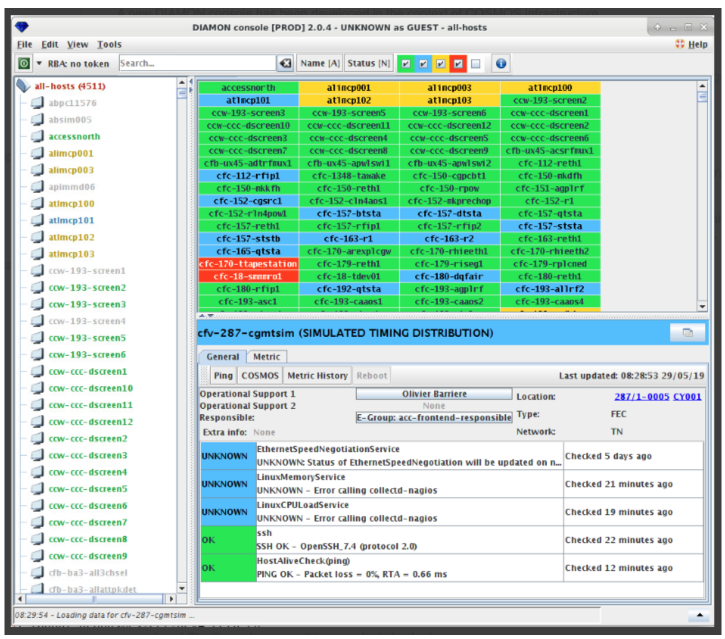


Figure 75. The new DIAMON Console.

Significant progress was made, in collaboration with the BE-ICS group, to use COSMOS for monitoring WinCC OA servers. Around 2 million records/day will be stored, with a data retention of 3 months. Given the nature and volume of the data, a dedicated BE-ICS Icinga satellite was put in place with its own resources. This first implementation will pave the way for the future integration of monitoring information for other equipment groups.

Finally, five COSMOS wall screens have been installed in the 774 building. This Grafana Carousel allows every member of BE-CO to keep an eye on the health of the control system and to be informed about important control system news and messages.

LUMENS

BE-CO's Systems Administration team have developed the Linux Units (aka processes) Management Service (LUMENS), in order to replace the current 30-year old in-house solution of wreboot and transfer.ref, with standard Linux solutions such as systemd.

All major features, both in the client and server-side, have been implemented and successfully tested. The LUMENS end-user tools are maturing and the first series of tests were carried out from October. A certain number of FECs (from CO and Eqp. Groups' labs) were selected according to their configuration and interest (FESA, TimService...). The objective was to replace the CCDB configuration of the "transfer.ref" file by a LUMENS configuration compatible with the current FEC interface (DSC Program). Although the project initially focused on FECs, in order to validate the LUMENS mechanism on a larger panel of machines, approximately 30 BE-CO servers are also running with the LUMENS service.

Future improvements will include better integration with the current sys-admin infrastructure (ansible, gitlab...) and the development of a new "systemdmon" tool to monitor the "systemd" service, which will be progressively used to control and manage all front-end processes. This new tool will replace the old DIAMON clic daemon to report the LUMENS service status to Icinga (COSMOS).

During Run3 the two solutions (LUMENS and wreboot/transfer.ref) will coexist and legacy tools will be adapted so that the user will not be impacted by this change.

LIC Central Timing renovation

The LIC Central Timing has been updated to work with the Linac4 accelerator. In addition, it has been programmed to allow the measurement of the emittance of Linac4 beams in the LBE line, as well as the measurement of the emittance, energy and energy distribution of ion beams from Linac3 in the LBE and LBS lines. Thanks to the multi-PPM programming of the LTB line, which is a shared line for both H- and ion beams, the ion measurements can be requested dynamically (on a cycle-by-cycle basis) and interleaved with a normal proton H- operation.

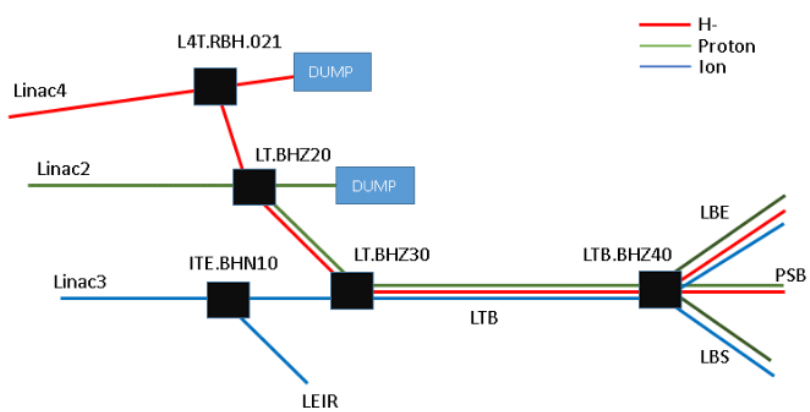


Figure 15. LN3 and LN4 post LS2 transfer and measurement lines, LN2 shown for illustration.

At the beginning of August, the Timing team deployed (in the Timing testbed) the first version of the renovated LIC Central Timing system. This version included many enhancements requested by OP, such as simpler switching between standalone and coupled modes (SPS, LEIR), and better handling of AD beams.

On the 18th of October, the LIC central timing software was migrated to FESA 7.2.0. The migration is not just an update to the latest version of FESA: seven FESA classes have been merged to a single FESA process. This will allow the possibility to easily switch back and forth to the new central timing architecture (by just starting the old binary or the new binary as needed), which is essential for its progressive deployment in early 2020.

Finally, this was also an opportunity to deploy an upgrade of the external conditions management. External conditions are boolean signals coming from equipment throughout the CERN complex. They are used by the central timing to decide which beam should be produced next. They used to be transmitted over wires attached to a specific module (ICV 196, now obsolete) present in the central timing FEC. They will be replaced with RDA notifications, giving greater flexibility to the providers of these signals.

Layout

Throughout 2019, the Layout team has made significant progress, adding new or improved features and functionality to the new Layout application. The LHC beam vacuum editor was improved based on user feedback, such that functional positions common to both LHC beams are now more distinguishable. The mechanism to publish Layout elements and assemblies to InforEAM was also enhanced. Furthermore, multiple features existing in the old Layout system were re-implemented in the new system, including: the 360-degree panoramas, EIS management, integrated history, user reporting and generation of the Cryogenics UNICOS specifications.

New tools were added to the Layout portfolio including the LHC distance calculator, a 3D graphical viewer showing distances such as the distance of a point from IP1, the closest IP, Half-cells distances etc.

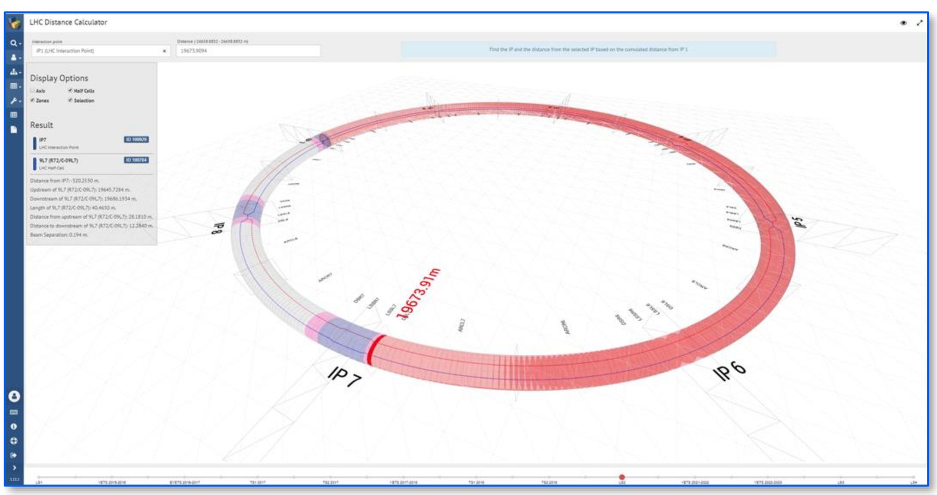


Figure 76. LHC Distance Calculator.

A first version of the new LHC apertures graph was also deployed, which represents the LHC's inner and outer beam apertures along the ring and allows users to zoom in on a section of the beam pipe, in order to view, and subsequently edit, details of the corresponding beam line elements. This tool helps experts diagnose incorrect aperture definitions or layouts.

Figure 77. LHC Apertures Graph.

Another accomplishment was the generation of the post-LS2 MAD-X sequence files for the PSB, PS, SPS and LHC from the new Layout database. A MAD-X file describes the layout of active and passive beam-line elements and is used by BE-ABP for optical validations, simulations and to establish initial settings for the accelerators. The data is also used by the surveyors to perform the critical operation of aligning everything along the beam-line. To speed up the generation process for users, new functionality has been developed to automatically generate and archive the files (per machine and version) in a dedicated GitLab repository, upon detection of changes in the source data. The Layout user interface then retrieves the files from Gitlab instead of generating them for every user request. This also has the advantage that users can use the GitLab tools to easily compare changes across versions.

Layout has generated a lot of interest within the Equipment Groups, both inside and outside the Beams department. Extensive hands-on training was provided to members of EN-ACE, TE-CRG, EN-MME, BE-CO, BE-BI and TE-VSC so that they were able to prepare their LS2 and HL-LHC layouts autonomously. In addition, groups who didn't previously use the service including EN-EA, EN-EL, IT-CF have expressed an interest in using Layout to define parts of their infrastructure.

NXCALS & TIMBER

By the end of 2019, the majority of the data from the CERN Accelerator Logging System (CALS) had been migrated to NXCALS, including all of the pre-LS2 Industrial Controls data and many corner cases including the proper handling of LHC Fills and beam modes. In parallel, TE-MPE and BE-ICS worked together with BE-CO to adapt the WinCC OA data transfer processes to send data to NXCALS with a view to putting this in production next spring.

Once the CERN accelerator operation resumes and all systems are sending data to NXCALS, the expected throughput is estimated to be around 250,000 records/second. Therefore, it was necessary to validate the performance limits of HBase in our environment and tune the cluster and the NXCALS system to achieve a stable write and read performance. New data generators were created to scale the load and simulate various types of data and the effects of changing the configurations were observed. Due to a lack of documentation, tuning HBase was extremely challenging, but several performance problems were discovered and addressed and although the situation is still not perfect, it has improved dramatically. Furthermore, it was also ascertained that it is possible to scale the performance horizontally by adding machines, which was an expected, but welcomed, result.

The NXCALS Extraction API was released in production in September. Shortly afterwards, a first version of the NXCALS-based CALS Backport API was released for user-feedback. This API is a backwards compatible CALS client library that uses NXCALS behind the scenes, thus allowing end-users to switch their applications to use NXCALS, without having to change their client-side calls.

Finally, towards the end of the year, the first version of the new TIMBER application, integrated with NXCALS, was released. The GUI was developed using Angular 8 with Material Design and already contains functionality for plotting and downloading user-selected signal within a time-window, as well as browsing variables and sharing links. The latest version can be found at timber.cern.ch

Figure 78. First version of the NXCALS-based TIMBER application on the Web.

Controls Configuration Service

Throughout 2019, the Controls Configuration Data Editor (CCDE) continued being extended and improved. Significant changes were made to the Hardware Editor, such that it is now integrated with the Layout database. In particular, the management of FECs, Crates and HW Modules has been adapted so that physical layout data (crates and modules) can easily be imported from Layout to CCDE and configured for controls. The opposite is also possible - registering a new FEC with crate(s) and modules in the CCDE and having the data automatically entered into Layout. The aim is to improve overall data quality and coherency, whilst minimising the number of tools a user needs to interact with. The Hardware Editor, along with RBAC and FESA Editors, were the final mainstream applications to be migrated from APEX to AngularJS. The remaining APEX applications, for specialist management of the BIS, WIC and PIC configurations were upgraded to use the latest APEX5 features, in place of legacy in-house code.

In parallel, the first major version of the Controls Configuration Data API (CCDA) was released in June, providing programmatic data extraction based on REST. It has full support for data paging so that queries for a large number of records will not provoke out-of-memory exceptions on server nodes. Furthermore, users are able to decide how they wish to load the data, which is particularly important when local client memory is a constraint. CCDA also includes a search mechanism based on RSQL; a powerful and intuitive query language. Extensive performance and throughput testing were carried out using Gatling, allowing the CCDA server configurations to be optimally tuned to reliably sustain heavy loads (e.g. 10k calls/sec to retrieve Devices by name). Ongoing developments are now being driven by feedback from key users who are migrating away from the obsolete ConfigDB Directory Service API.

To support the evolution of the EDGE device driver generation initiative, the CCDB schema was updated to support EDGE v2.0 and the changes integrated into the CCDE and the CCDA. EDGE integration with the CCDA allows the Python EDGE CLI (Command Line Interface) tools to directly read and persist changes in CCDB via REST calls. This marks the first case of supporting programmatic data entry into the CCDB.

Considerable progress was also made on integrating the registration of Logging Service Variables for NXCALS into the CCDE, which is the single entry point for users to configure CMW-based NXCALS logging. Subsequently, integration with the NXCALS Data Sources API feeds the logging system with events based on changes of the underlying configuration.

UCAP & LINAC4 Source Autopilot

This year, UCAP underwent significant refactoring towards a more flexible architecture. The Event building module was improved and support for transformations that re-publish data as many different Devices/properties was added. In collaboration with the DS section, the UCAP team also provided nodes that can run NXCALS array extraction transformations, which extract elements from arrays and republish them as new virtual Device properties. The virtual Device JSON file format has been finalized and a type-safe Java builder for creating virtual Device/transformation definitions was provided. The UCAP framework now also comes with a REST API, which allows users to query transformations and metrics and to start, stop, add or remove virtual Devices from a UCAP node. The REST endpoints are protected by RBAC and communication uses SSL encryption. The framework also provides a Java client to access the REST API and send definitions created by the builder. This is an important step to allow users to control their UCAP node in "self-service" mode.

The LN4 controls team in the APS section developed a microservice that extends UCAP so that it can execute transformations written in Python. While the main UCAP server is written in Java, this microservice is implemented in Python using Flask. The Flask server receives input data from the UCAP event builder through an HTTP POST request, executes a Python transformation and returns the result back to UCAP, which in turn publishes it over RDA3. The Flask server can also execute control loops, i.e. Python scripts that continuously receive data from UCAP transformations and control device properties of the LN4 source using RDA set actions. Two source experts in BE-ABP used the above framework to develop and deploy several transformations and control loops used to stabilize the source using the autopilot. The functionality was successfully validated during the 2019 LBE run. An additional effort focused on the development of a GUI for the Linac4 Source, which was fully written in Python, using pure PyQt for the GUI components, and an APS in-house product [AccPy]QtGraph for charting. Although it is not yet feature complete, the first version was used during the 2019 run to oversee the BCT Stabilisation task.

Accelerating Python

Python is a popular programming language because it is easy to learn and produces succinct, readable code. In 2019, BE-CO officially adopted Python as a supported language for operations. In order to make Python code fit for operations, it needs to be quality assured, maintainable, modular, interoperable and easy to use for everyone, not just software engineers. The aim is to build coherent applications following guidelines and best practices, which can coexist harmoniously and yet be isolated from one another for the purposes of operational stability. Python applications should be written as Python packages, rather than Python scripts, in order to improve testability, to support re-use and to allow sustainable sharing through standard Python package management tooling.

The foundation of a Python infrastructure is its distribution – the Python installation plus core libraries. The latest release of the Acc-Py distribution is a self-contained environment, which is easy to extend using virtual environments. It includes the Acc-Py development tools, which support the full development lifecycle of projects, as well as an extensible PyQt add-on.

There are several Python control libraries under development, including PyJAPC and PyCCDA, which are Python wrappers around existing APIs. The APS section has a mandate to provide a consistent style and central coordination for all CO Python APIs. However, they provide consultancy, focusing on the look and feel of Python interfaces, rather than their design or architecture.

Python GUIs & RAD

Over the last 18 years, more than 500 operational applications have been developed in Java Swing and JavaFX by software developers, physicists, operators and hardware experts. In 2018, PyQt was selected as an alternative GUI technology.

Users need to perform both standalone PyQt development plus Rapid Application Development, with little or no coding, for prototyping. With these requirements in mind, the APS section is providing tools to streamline PyQt development, as well as a framework on top of PyQt for RAD. This new framework is known as ComRAD.

The design goals of ComRAD are to be easy to use, follow good architecture and build on existing technologies. In addition, ComRAD should let prototype applications evolve into full PyQt products easily. In order to convert ComRAD applications into regular PyQt ones, equivalent widgets (Graphs, menus, lists etc) are required in both worlds. A project has been launched to compile a library of custom accelerator widgets, with contributions from users, in order to promote code reuse. One example of a custom widget is the Graph. It is a derivative of the PyQtGraph widget, augmented with features inspired by JDataViewer. The graph widget can plot live data on several Y-axis, using different representations e.g. bar graphs, line graphs or other primitives found in fixed displays. This widget has already been used in the LINAC4 source GUI.

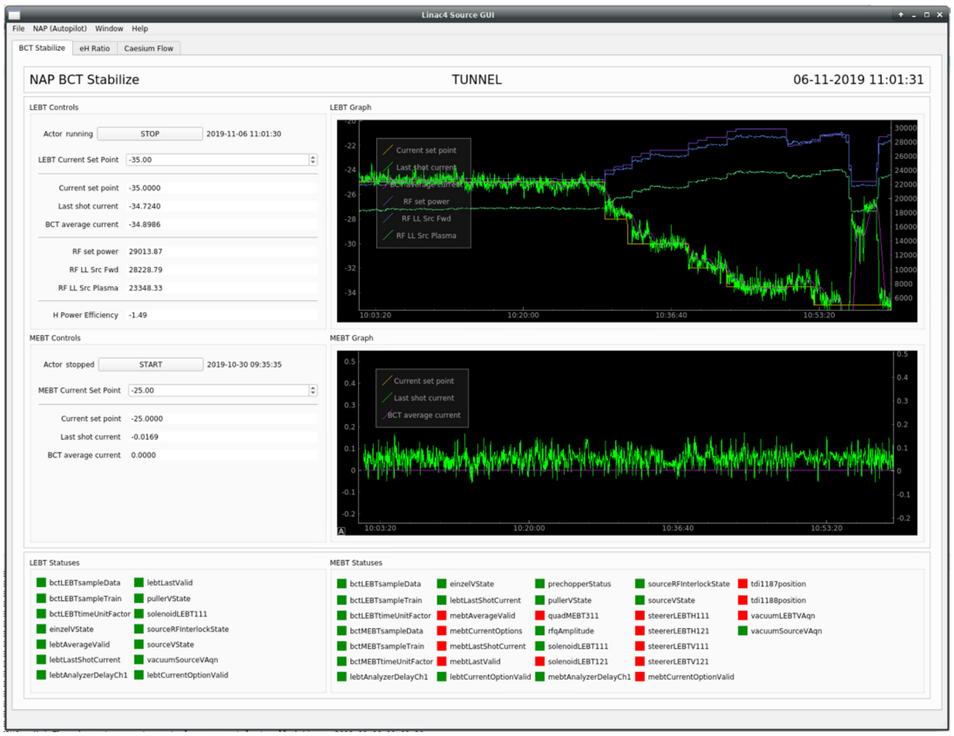


Figure 79. The PyQt-based LINAC4 Source GUI.

ComRAD is still under development and the Python team is working closely with other groups to gain feedback. TE-ABT have some applications that they would like to convert to ComRAD in 2020 and providing assistance for migrating from other frameworks is a long-term goal.

CO Development Tools

CO's Development Tools team is responsible for providing a coherent set of tools and services, as well as guidelines and best practices for developing, building and running Java and Python code. Its user community is comprised of full-time developers with a high-level of expertise and second-job developers who need simple tools. Satisfying the user's needs on a common level is a challenge, as well as finding a balance between industry standards and practicality, reducing in-house solutions where possible. Python became a member of the development tools portfolio in 2019 and where possible the same policies and technologies are applied, in order to profit from similarities and synergies.

One of the main tasks in 2019 was the move from SVN to GitLab for the whole ACC-CO code base. This involved migrating over 800 SVN projects in a single repository to 100s of individual GitLab repositories by November. The Development tools team prepared the required tools, helped project owners to make migration maps and performed the migration. As a result, all CO and TE-MPE code is now migrated, with its history, into GitLab repositories with coherent configurations. The transition appears to have been quite smooth and GitLab has been surprisingly well adopted by the users.

Common Build Next Generation, or CBNG, also took a major step towards Industry standards by aligning with Gradle. The latest version, CBNG3, is a Gradle distribution with custom CBNG plugins, which removes remaining technical debt from CBNG2. Several in-house solutions were replaced with default Gradle features, such as meta-build being replaced by multi-project and composite builds. The new version can be integrated with GitLab CI and also supports build promotion.

In 2019, preparations were well underway for replacing the previous Oracle Java distribution with the OpenJDK11 runtime. As a safety net, Java 8 remained available, therefore language features and byte code needed to be backwardly compatible. At the end of the year, Java 11 was made available on all CO machines and consoles to allow early testing and limited adoption ahead of a full migration campaign foreseen for 2020.

BE-RF Group

Training the next generation

BE-RF colleagues gave lectures on RF systems and non-linear longitudinal beam dynamics at the Introductory CERN Accelerator School in Vysoke-Tatry, Slovakia, as well as a new longitudinal tutorial introducing the students to calculations and longitudinal tracking. The lectures were complemented by courses on beam loading and RF feedback at the Advanced CERN Accelerator School in Slangerup, Denmark. A lecture on longitudinal beam dynamics was given at the Joint CERN-US-Japan-Russia Accelerator School in Dubna, Russia.

BLonD

The Beam Longitudinal Dynamics simulation suite “BLonD” is a core simulation tool for longitudinal beam dynamics in the RF group since 2014. In 2019, a new high-performance computing (HPC) version of BLonD has been deployed. As a result of several years of work, this new version contains, among others, intra-node optimizations, mixed data and task parallelism, dynamic load balancing between different workers, and approximate computing techniques that the user can choose to enable. The HPC version of BLonD has demonstrated a runtime reduction of two orders of magnitude compared to the initial BLonD code, and it has enabled us to simulate previously week-long simulations in a few hours. Through this speed-up, it has for instance largely contributed to LIU longitudinal dynamics studies that required modelling up to 288 bunches.

MedAustron

The RF group continued to provide support to MedAustron in the form of consultancy. In total 10 days of training was provided covering LLRF hardware including testing of hardware, firmware, DSP code, controls and beam control theory and practice.

BE-ICS Group

Industrial Controls

New Service Management processes were designed and implemented for applications and services in the industrial control domain (JCOP & UNICOS frameworks, ADaMS, TIM, MODESTI, HelpAlarm, etc.). These processes aim at collecting all required information from stakeholders and agree on software packages to deliver in time. An Agile methodology was used to plan the software development and delivery. Planned work is represented in Gantt charts and regular follow-up of progresses increases the confidence in delivering work on time as agreed with stakeholders.

All service incidents and requests are managed in JIRA ticketing tool with an ITIL approach allowing to improve communication with users and between support lines, ticket responsiveness and follow-up, work prioritization, and backlog reduction.

A large amount of work was done for the main control systems and applications provided by the group:

Electrical network supervision - PSEN

Two major releases together with four other minor releases were deployed in production during the year. The releases included, among several other features, the ability for the user to qualify alarms as *test* or *production*. This functionality alone required a 6 man-month development and testing effort to be fully integrated into the PSEN eco-system as well as the associated engineering tool.

During this year, the application continues to grow with more and more signals to monitor: as of November 2019, 283,686 signals were monitored by PSEN. This number has to be considered with respect to the original specification which envisioned no more than 100,000 signals to monitor leading to the re-design of many parts of PSEN as the system grew in order to handle such a large number or I/O in a single system.

Another important milestone for PSEN in 2019 is the development of a component allowing the users to create and configure all PSEN devices required to represent the energization state of an electrical network out of already existing UNICOS-CPC devices. The component has been actively used by the TE/EPC team for their UNICOS control systems (e.g. SEQ_SVC).

TIP - Technical Infrastructure Portal

During 2019 Technical Infrastructure Portal (TIP) continued to grow by adding new cooling and ventilation installations to the supervision system and the insertion of the cryogenics. TIP constitutes the main tool for TI operators to crosscheck different systems (e.g. Electricity, cooling, cryogenics…) in the technical infrastructure island in the CCC (Figure 80).

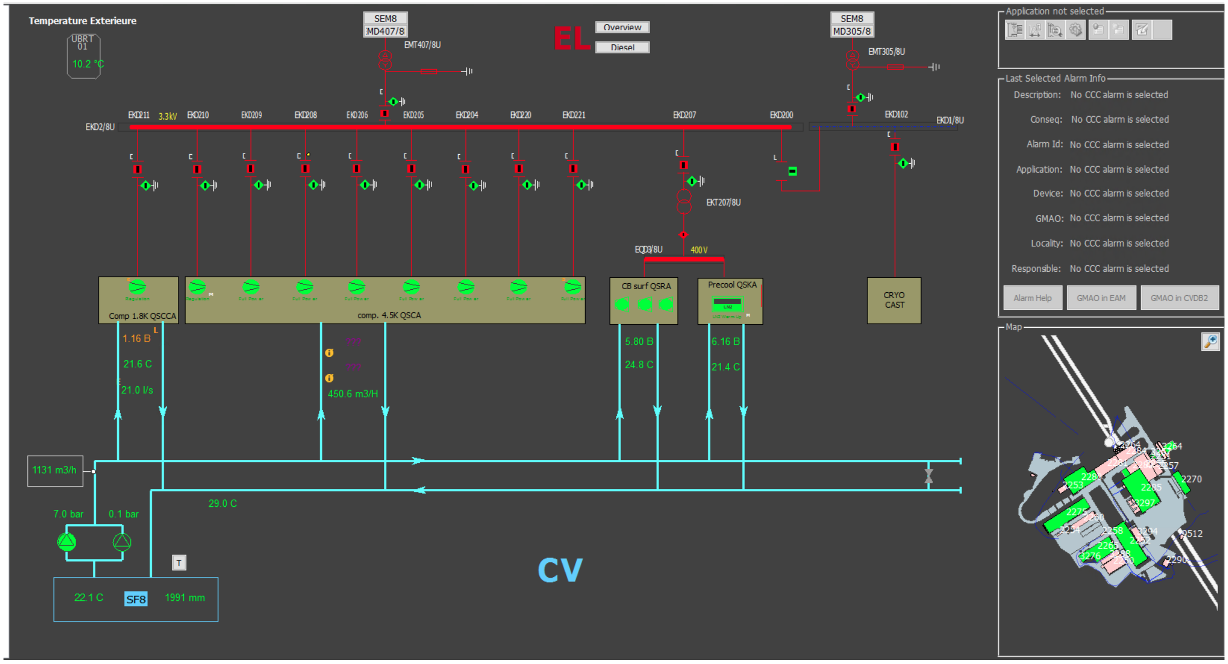


Figure 80. Electricity, Cryogenics and Cooling monitoring at P8.

Cooling and Ventilation controls

During 2019, about 40 new PLCs were deployed in production. These PLCs were controlling the ventilation of different important and complex installation as the ATLAS and CMS caverns, and cooling points like the CT2 towers in Prevessin or the new cooling towers of P18 among others.

A large effort was devoted to the preparation of coming upgrades of large and complex systems as East Area renovation or the SPS Cooling pump system.

To achieve this number of control systems per year without increasing the number of people working in the project, we started to identify and apply an increased level of standardisation in several process units, allowing us to develop the control of those units from an already validated set of code and in an automatic way. With this method we are able to reduce the working hours needed per project and increase the quality of the control system. Given the number of projects that we have in production right now, having standard functionalities around all of them also helps the operation to understand and predict better the behaviour of the cooling and ventilation plants.

SM18 - Magnet Test Bench

The magnet test benches (Figure 81) are a very dynamic installations requiring a very flexible approach allowing the different magnet test campaigns being adapted to particular conditions. During 2019 several clusters control systems required modifications, notably

1. Cluster A and C have been upgraded for High Lumi - 11T magnet test capability
2. Cluster G has been fully upgraded with a Fail-Safe PLC and new operator interface.
3. Cluster A2 was in preparation to be able to power SC-Link (in couple with Cluster G)

Particularly, the second point, in cluster G, triggered an activity with the aim of improving the safety and reliability of the installations. The following activities were performed: (1) Risk analysis together with TE-MSC group, (2) Safety Functions specification and (3) software verification including the usage of PLCverif and the SITE Acceptance Tests (SAT).

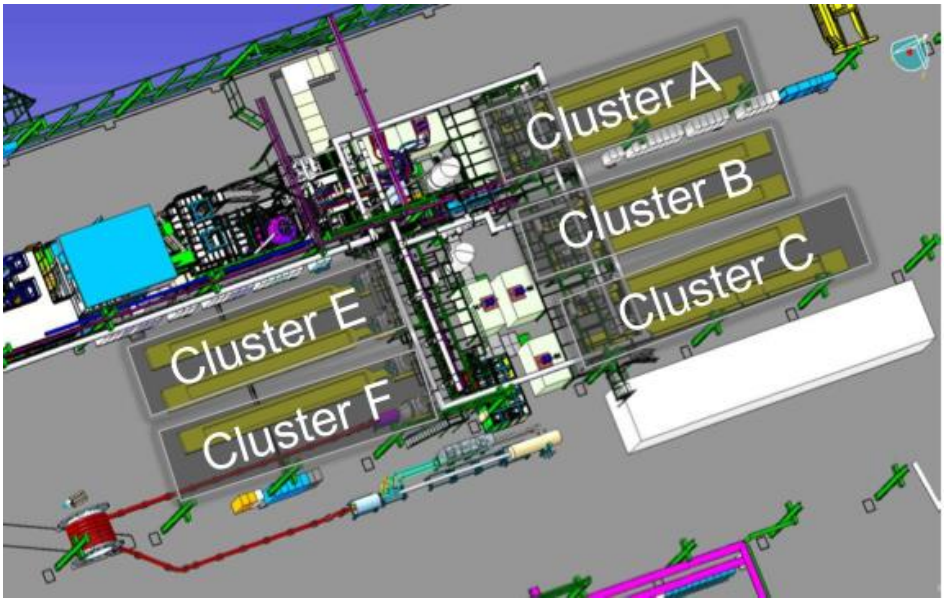


Figure 81. SM18 Magnet Test Benches.

Regarding the specification of the Safety Functions and the control interlock logic, the new tool SISpec, based on the "Cause and Effect Matrix" (CEM) method and developed by the BE-ICS group, was applied. SISpec allowed to automatically generate the verification and test cases out of the CEM specification.

The development of the safety PLC program was done using Siemens Distributed Safety library and the LADDER programing language by following strictly the Safety Functions specification. The development of the standard (operational) PLC program has been done using the UNICOS CPC framework.

FAIR – Magnet Test Bench

The facility is fully in operation after full commissioning of the control system. The FAIR QPS FECs are updated to the latest FESA code. This allows them to send data to NXCALS via CMW directly. This will be used to validate the new QPS architecture.

The production CALS/NXCALS logging will still follow the traditional path (through WinCC OA). However, the FAIR WinCC OA application was upgraded to the latest, RDA3-compatible WinCC OA CMWClient driver, since RDA2 will be discontinued in 2020.

Machine Protection Testbed (272)

The B272 testbed QPS FECs were recommissioned from scratch using the correct/actual 272 device names, and through our standard/official procedures (using UAB: UNICOS Application Builder).

Moreover, the 272 QPS FECs have been updated to the latest FESA code, that supports the new communications architecture, with the goal of attempting, for the first time, to log directly from

QPS FECs to NXCALS, via CMW, and to provide, for the first time in the 272 testbed, data logging in NXCALS to the users (TE-MPE)

The proper integration of the PIC/LHC_CIRCUIT applications with the new architecture will be performed in 2020.

CERN Lift Monitoring

During 2019, the focus was put on defining the software and hardware technologies to be used during the LS2 project consolidation for the monitoring of the LHC Lifts within WinCC OA and the UNICOS framework. These chosen technologies will be based either on modbus TCP or OPC UA depending on the equipment availability of the lift supplier. The solution based on modbus was tested in our lab and is ready to be deployed.

SCADA Application Service

In 2019 the SCADA Application Service (SAS) carried out several tasks affecting many industrial control systems and domains. This service hosts the major SCADA systems supervising processes from cryogenics, cooling, electricity to vacuum or the protection systems (e.g. QPS, PIC, WIC…). While some of them were not active others continued in production during the LS2.

At the beginning of the year an awareness campaign about a technical network router exchange was carried out. The impact on network connected industrial control devices was analysed and communicated to the control systems responsible. The exchange of routers was closely monitored, especially ones in CERN Data Centre (building 513) and 874 Data Centre. The campaign ended without incidents.

Another important task was to prepare and inform the users about the phase-out of RDA2 infrastructure, which was still used in several SCADA applications. This resulted in an update of selected applications so they could still publish data after RDA2 phase-out.

Another important activity was the evaluation of Linux Terminal Servers, together with IT and BE-CO, to improve quality, maintainability and performance compared to the existing Windows Terminal Servers.

At the end of the year the focus was on preparing for upcoming WinCC OA new versions, the upgrade from 3.15 to 3.16. Meetings with users were carried out and initial plan was drafted. The needed automated tooling was also developed for a smooth upgrade process.

Industrial Controls Monitoring - MOON

Major rework of the application to integrate with COSMOS – BE monitoring infrastructure. This has several benefits as the removal of duplicate monitoring data; less maintenance and a substantial lower load on central SCADA database.

The main interface has been switched to Grafana (Figure 82) web frontend and this action should allow different users to create their own monitoring panels in an easy and standard way.

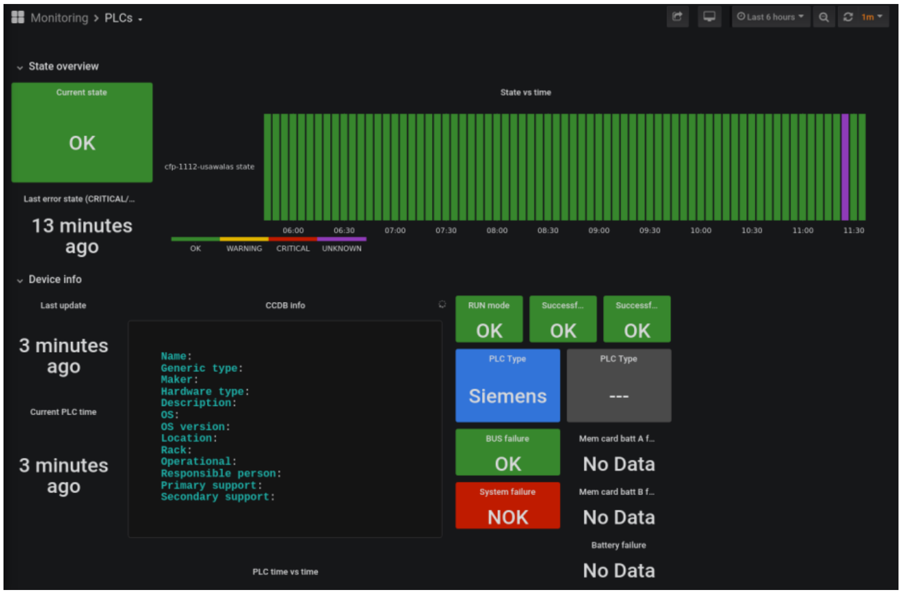


Figure 82. MOON user interface.

There was a new application developed to monitor the SCADA DB, the so-called MONARC, an application to monitor and administer Oracle databases for WinCC OA archives so we can give a close look to the performance of the DB with respect to the data introduced by the different clients.

External clients support

A large effort was put in to help TE-MSC group with the controls of their large magnet factory (LMF) and the magnet workshops in Prevessin. One of the existing press control systems was no longer supported (originally engineered by an external firm) and it was extremely difficult for TE-MSC to change the controls. With our help, TE-MSC refactored that control system using the UNICOS framework and using the new TIA portal-based PLCs.

At the B927 workshop, following an urgent request to our standby service, we performed a global status evaluation of the different machinery controls existing in that workshop. An urgent re-engineering was performed and deployed to ensure that the affected machine, the curing press (Figure 83), could be brought back into service and keep its tight schedule assembling the future LHC superconducting magnets.

Figure 83. B927 Curing press.

Industrial Controls Standby Service

In 2019 there was a consolidation of the standby services in BE. As a consequence of this it was decided to merge the industrial controls standby service with the TIM (Technical Infrastructure Monitoring) service. This process was completed during the year and resulted in adding two new members to the industrial controls standby service team, bringing the total to 10 members. New procedures were added to cover the new services. A total of 15 on-site interventions were performed by the team during the year (Figure 84).

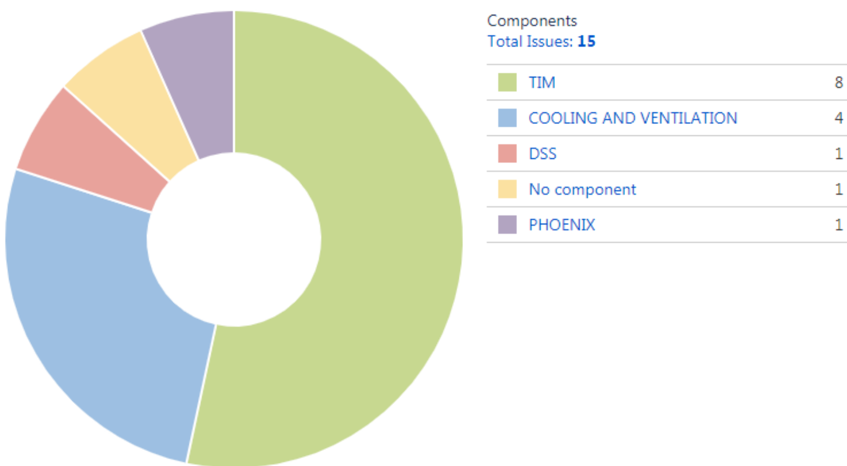


Figure 84. Industrial controls standby service intervention domains 2019.

Quality assurance

PLCverif

In 2019 the usage of PLCverif continued to spread among the safety-based control systems managed by BE/ICS such the new SPS access control project and the SM18 magnet test bench projects. It is worth noting that these projects are constantly evolving, e.g., SPS access control, and a significant effort to formally verify these systems in a fast and automated way is to be planned for the coming years.

While the usage of PLCverif increased, the development of the tool itself continued by adding new functionalities, e.g., generation of input test cases from counter examples.

Another improvement of PLCverif concerns the way specifications are defined by users. By realizing that making specifications is very complex, different approaches were developed depending on the domain:

1. A graphical tool was developed allowing the user to *draw* the specification instead of writing it explicitly. (https://cern.ch/grassedit). This was proven to be extremely useful when defining the logic of a complex accelerator access control system.

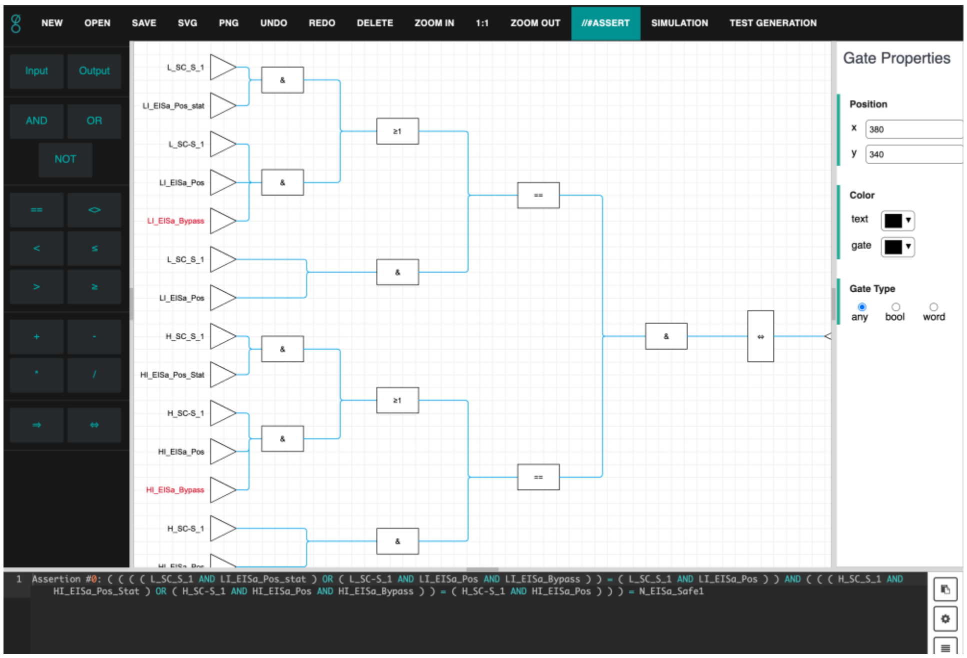


Figure 85. Grassedit specification tool.

2. Another example of high-level specification for the users is the *SISpec* tool (Figure 86), also developed in 2019. This tool allows the use of the "Cause and Effect Matrix" (CEM) method and automatically generates the PLCverif verification cases. CEM is particularly useful to specify the interlock-based logic of a control system or to specify the logic of Safety Instrumented Functions (recommended by the IEC 61511 standard).

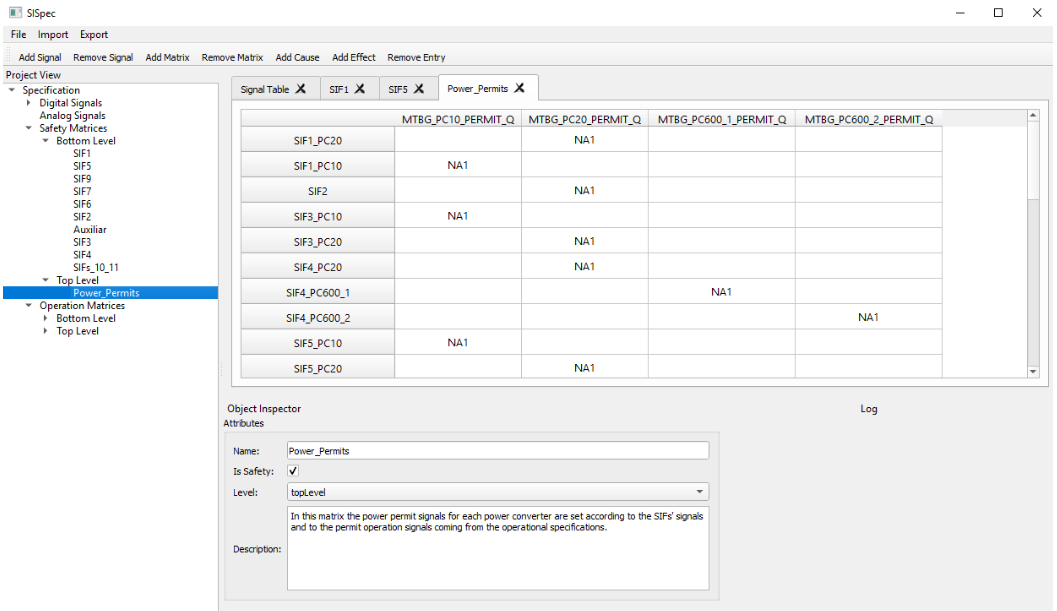


Figure 86. SISpec tool.

Automated PLC program testing

In order to enable refactoring of the aging PIC PLC code, and to enable the implementation of the new GPM masking functionality at the PLC level, an automated test setup was created. A PIC PLC was installed in the BE-ICS lab, and a Simatic NET OPC UA server set up on an openstack virtual machine to expose the PLC variables. A WinCC OA test project was created, and an OPC UA server added to expose operator commands and other SCADA variables. Finally, a Siemens Simulation Unit module was used to simulate the Profibus IO. A test suite was written in Python which was able to communicate with all three of these interfaces, and thus could implement complete system tests for the PIC. These tests were used both to verify the new functionality and confirm that the exiting functionality was not affected by the code changes.

Another approach developed during this year was the novel concept of unit-testing when applied to PLCs. Using the PLCSim advanced, a Siemens PLC simulation tool, we developed an application which can control the program execution and specify timing requirements at the PLC cycle level. A very accurate tool which allows to run a predefined configuration at a precise PLC cycle to perform tests with isolated pieces of code under test.

Continuous Integration/Continuous Deployment for PLC-based controls

During 2019 there was ongoing development work in creating automated build, deploy and test tooling for PLC-based controls. These tools took the form of improved command line tools for interfacing the three supported PLC engineering tools used at CERN, namely Siemens Step 7, Siemens TIA portal and Schneider Unity. A Python test environment was created to allow test suites to interact with PLCs using OPC UA. Test suites can interact with the PLC variables directly, but a UNICOS object layer was also implemented in Python to allow tests to be written by interacting with UNICOS objects rather than PLC data structures (Figure 87). The work was presented at the conference ICALEPCS 2019.

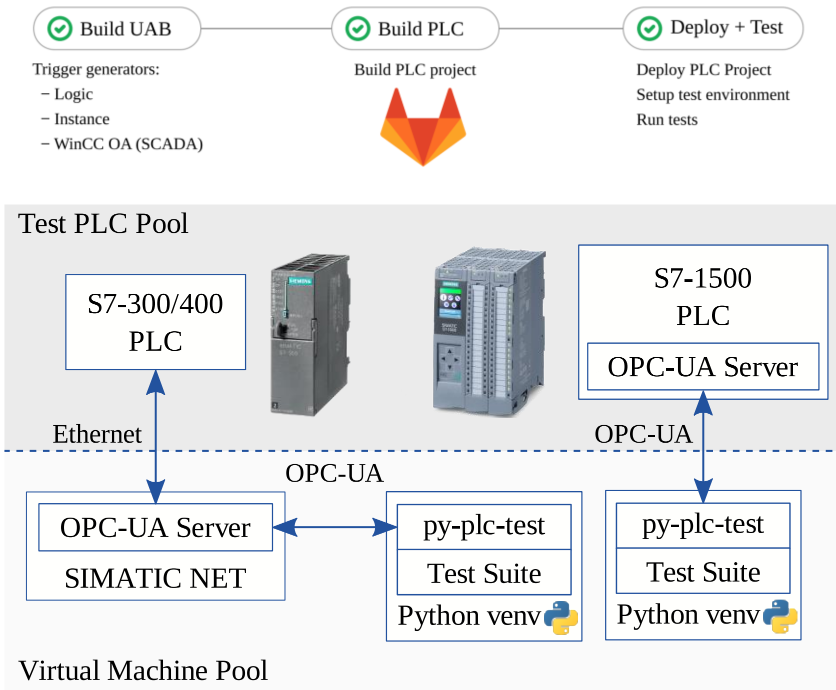


Figure 87. Testing framework.

Simulation and Virtual Commissioning

In 2019 there was a collaboration with EP-DT to link the CORA process simulation implemented in EcosimPro with the control system of the real process. This was successful, and a considerable part of the process model could be controlled by the PLC. It is intended to continue this collaboration and enable the complete simulation to be controlled externally.

Later in 2019 a collaboration began with TE-CRG to renovate their process simulator, used for operator training. The existing solution based on OPC-DA was no longer operational and a migration to a new solution based on OPC-UA was desired. A prototype of the new solution was operational at the end of 2019.

Frameworks and Technology

The CERN industrial controls systems developed by BE-ICS are made out generic and reusable building blocks which build on top of a standard stack of industrial technologies. This building-blocks are the so-called components of the CERN Industrial Controls Frameworks (JCOP and UNICOS). Whereas the UNICOS framework is entirely developed by BE-ICS, the JCOP framework is a collaboration with the LHC experiments. Besides these components, the frameworks also provide a set of guidelines and, in the case of UNICOS-based applications, a strict engineering methodology. Besides the provisioning of the Frameworks, BE-ICS also provides CERN-wide support of all underlying technologies employed by the Frameworks and acts as liaison with the different vendors.

Industrial Control Technology Support

Table 4 shows the main underlying technologies employed by the CERN Industrial Controls Frameworks and that BE-ICS provides CERN-wide support. It is important to mention that BE-

ICS also employs many other technologies provided by other groups at CERN like ORACLE databases from IT-DB or CMW, FESA, CALS and NXCALS from BE-CO.

Table 4. Main technology stack employed in CERN Industrial Control Systems.

Technology Type	Name
SCADA	WinCC Open Architecture
Middleware	OPC Data Access & Unified Architecture, DIM and DIP
Industrial Communication Protocols	Modbus, Siemens S7,
Fieldbuses	Profibus, Profinet, EthernetIP, CANbus
PLC	Schneider and Siemens

Siemens/ETM for WinCC Open Architecture

In 2019, the initial discussions with Siemens/ETM, provider of WinCC OA, took place to renegotiate the current agreement, which comes to an end in 2020. The CERN objectives for this reorganization were compiled with input from the main CERN users of the product and presented to the company. The company also expressed its interest in continuing the partnership with CERN under the same terms and conditions. BE-ICS also continue the technical collaboration with Siemens ETM on the following fronts that will be developed in the following sections:

- openlab collaboration on the Next Generation Archiver.
- Improving the Object-Oriented capabilities of the WinCC OA scripting language

CAEN, Wiener and iSEG for OPC Unified Architecture

Collaboration with the power supplies vendors continued to develop jointly the OPC UA server that are critical for the LS2 upgrades of the powering systems of the experiments as explained below in the section on JCOP. The collaboration agreement includes the provision of a hardware access library by each of the hardware vendors that are being used by BE-ICS to develop the OPC UA servers. Throughout the year, different versions of the OPC servers were produced mainly for Linux and some initial versions of the CAEN OPC UA server also for Microsoft Windows. Major validation steps were also conducted in the ATLAS Muon detector and ALICE, especially for the CAEN and iSEG servers.

Work was also started with the vendors to integrate the CERN CAN Common Module as part of their hardware access libraries. This is especially relevant for Wiener and iSEG as it will enlarge the set of CAN gateways supported by the library and it will allow for multiplatform releases.

Siemens and Procon for Data Analytics

In the first half of 2019, the work focused on the monitoring of various LHC control systems, using two distinct analytics solutions from Siemens: Smart IIoT, a framework used to monitor a multitude of control signals in a distributed manner, and ELVis, a web-based platform for handling multiple streams of time-series data from sensors. In the second half of 2019, focused on optimising the ion-beam source for the Linac3 as well as on deploying the Siemens's Distributed

Complex Event Processing (DCEP) technology to enable advanced data analytics and predictive maintenance for the oxygen-deficiency sensors in the LHC tunnel.

In 2019, initial discussions were also held with Procon for the development of generic algorithms for predictive maintenance applied to industrial systems using cooling and ventilations systems as a study-case. This should reflect in a collaboration agreement with the company to be established in 2020.

CERN Industrial Controls Frameworks

In 2019, the work performed on the CERN Industrial Controls Frameworks focused on the following areas:

- Maintenance of the current systems.
- Foreseen changes to the operational infrastructure.
- New developments.
- Frameworks Consolidation and Redesign Project.
- UNICOS New Project Organisation.
- Frameworks Licensing.

These points are described in the following sections.

Maintenance and continuous improvement of the current systems

The CERN Industrial Controls Frameworks are presently used in 650 mission-critical control systems in the experiments (LHC, NA62 and COMPASS), accelerator complex (e.g. PIC, WIC, QPS, etc.) and technical infrastructure (electrical network, cooling and ventilation, etc.). A continuous investment on the frameworks is required to allow for the evolution of these control systems to respond to the needs from operation and to keep up to date with the latest version of the technology stack. In 2019 several releases were delivered to address the points described in the following sections.

Preparation of the migration to WinCC OA v3.16 during LS2

Due to the large time span foreseen for the upgrades, special attention was put in ensuring the interoperability of WinCC OA applications running versions 3.15 and 3.16 with the corresponding versions of the frameworks. Example where this interoperability of the frameworks is required are the upgrade of the cryogenics controls since different sectors will be upgraded at different times or the upgrade of the different subdetectors in the LHC experiments, which may also be scheduled on different periods depending on the operational constrains. Despite employing different versions of the frameworks while the applications are upgraded, both the cryogenics and the detector control systems must still work coherently to ensure safe operation.

One of the main challenges faced during the porting of the frameworks to WinCC OA v3.16 was the change of from ISO to UTF-8 byte-encoding introduced in the product. This change in the underlying SCADA packaged required the conversion of run-time database of the WinCC OA applications, in many cases with 10+ years of history, from ISO to UTF. In addition, a careful validation and identification of the impact on the existing project constructs and the code was performed. The frameworks were reviewed and adjusted. This activity triggered the need to migrate to the more future-proof and universal XML format for the WinCC OA HMI. Once more, this required careful validation and the development of dedicated tools.

Another important task initiated in 2019 was the production of a catalogue of all database schemas used in production and the review of these schemas together with IT-DB. Several discrepancies between the schemas were identified. All schemas will be reviewed and aligned to the same version during the LS2 upgrades.

Finally, the QA platform of the frameworks also experience a major boost in 2019. The so-called vertical slice, a set up comprising standard hardware and software use to test daily release of the frameworks was largely extended. Moreover, a web visualization of the results of the tests, as well as of the CI/CD pipelines used for the build and release process of the frameworks was implemented and it is permanently displayed in the developer's corridor as shown in Figure 88. The location of this screen allows developers to identify issues in their code immediately and react promptly to these problems.

Figure 88. Report on the execution of the nightly tests of the CERN Industrial Controls Frameworks displayed in building 864 so that it can be consulted by all Framework developers.

UNICOS Integration of the IEC 60870-5-104 communication

Integration of the **IEC 60870-5-104** communication protocol in the UNICOS framework for the TE/EPC power converters. This protocol enables communication between control station and substation via a standard TCP/IP network and it is used to communicate from the UNICOS application to the ABB server of the new static VAR compensators BEQ1 (SPS) y MEQ59 (PS complex) as shown in Figure 89.

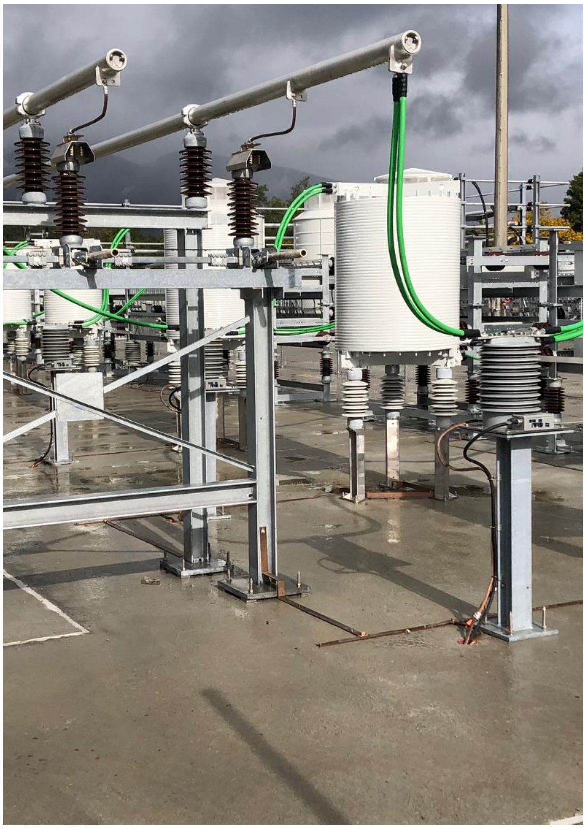


Figure 89. The integration of the IEC-104 protocol in UNICOS is presently used for the communication with the ABB server of the new Static Var Compensators BEQ1 (SPS) y MEQ59 (PS complex).

CAN Common Module

The CAN Common Module is a multi-platform software package developed at CERN that abstracts different hardware CAN gateways and it exposes a single API to the OPC UA servers. An agreement was reached with the ATLAS Collaboration to take over the development of the CAN Common Module and to extend it with the new features required to implement the OPC Unified Architecture Servers needed for the LS2 upgrades. One of the main achievements in 2019 has been the unification of the different forks of the CAN Common Module that were spawned over the recent years.

Further developments

Besides the major developments aforementioned, a long list of improvements and new features were added to the frameworks, like:

- Integration of fast interlocks in UNICOS.
- Study for ergonomics of integration into the TIA portal into the Continuous Process Control (CPC) package.
- First integration of the S7-1500 PLC family.
- Extension of the Schneider PLC baselines to support the M580 PLC family.
- A new Qt-based help mechanism introduced that allows for direct access to the API documentation from the development environment, which represents an important productivity enhancement.

In 2019, a major collaborative effort with Siemens/ETM was carried out to improve the Object-Oriented capabilities of the WinCC OA scripting language. In addition, the company delivered a set of new features for CERN for WinCC OA 3.16 that were evaluated and approved by BE-ICS for wide use in the frameworks. These achievements open the floor for new possibilities in the framework which will play a major role in the Consolidation and Redesign Project of the CERN Industrial Controls Frameworks.

Impact on the Frameworks due to foreseen changes to the operational infrastructure

The following foreseen changes to the operational infrastructure to be implemented during LS2 triggered the need to start work to adapt the frameworks and consequently minimize their impact on the running control systems:

CALS to NXCAL Migration

With the phase-out of CALS in early 2021, the current data transfers from the WinCC OA data archives (based on ORACLE) to CALS (also based on ORACLE) had to be re-engineered. This project triggered a fruitful collaboration between BE-ICS, BE-CO and IT-DB where all parties played a major role in the definition of the new strategy, which consists in the joint development of a Java process and a set of PL/SQL procedures to transfer the data from the SCADA's historical values database to NXCLAS. Moreover, the historical data from the industrial control applications was migrated from CALS to NXCALS by BE-CO. Development efforts on this front are expected to continue in 2020 and will be followed by a long validation process until the discontinuation of CALS.

RDA2 to RDA3 migration

In 2019, BE-ICS extended the collaboration with IHEP, Protvino, Russia, for participation in the migration of the interfaces between WinCC OA and CMW from RDA2 to RDA3. At the same time, these interfaces were completely reengineered to pioneer the use of the Device Server Framework library delivered by BE-CO, proving again a good collaboration between ICS and CO.

Microsoft Alternative (MAlt) Project

The MAlt Project heavily impacts the frameworks in two ways:

- the access to all industrial control's applications at CERN. In 2019, the work carried out included the evaluation of the impact of the changes planned by the IT Department IT to handling of user accounts and egroups and the evaluation of early prototypes to ensure that the integrated authentication from the industrial control's applications using CERN's credentials remained possible.
- A collaboration with IT and BE-CO on the "Linux Terminal Server" as a successor for the WindowsTS used so far (the use of which needs to be reduced due to MAlt) resulted in an interesting solution based on FastX, which would also provide the secure web-access to the UNICOS applications.

Oracle Upgrade to version 19c

In 2019, most of the validations steps for the new ORACLE version 19c to be deployed on the database servers during the LS2 upgrades were carried out. Further steps to validate the client side will be performed in 2020.

New Framework Developments

In 2019, three main projects concentrated the develop efforts for new major features and functions in the frameworks:

WinCC OA Next Generation Archiver

This project focuses on the development of a modular and future-proof system for the storage of historical values and alerts, the so-called Next Generation Archiver (NGA), capable of sustaining the data rates expected from the industrial control systems during the High Luminosity phase of the LHC and that supports different SQL and NOSQL technologies to provide operators with process data and to enable data analytics. The project is jointly developed with Siemens ETM as an openlab collaboration.

Two important milestones for the NGA project were achieved in 2019:

- Release of a version for public distribution as part of WinCC OA.
- Initial production-grade deployment at the ALICE experiment in the context of the ALICE O^2[4] project.

Significant progress was made with all areas of the NGA project, including providing support for redundancy, for complex queries, and for handling signal metadata. Much progress was also achieved in terms of performance and scalability of queries. To ensure reliability of the NGA in large systems with high throughput, several tests were performed at CERN. Existing test automation tools were significantly extended in order to allow for better synchronisation of testing efforts at CERN and ETM.

Moreover, in 2019, BE-ICS decided to take over the implementation of the ORACLE back-end from Siemens/ETM in order to meet the deadlines of the ALICE O^2 project [4] (see section "JCOP" on page 110). This decision together with the strong progress done on the ORACLE back-end places BE-ICS in an advantageous situation for a successful deployment of a first version of the NGA archive in ALICE during the LS2 upgrades.

Initial results from InfluxDB performance tests performed at CERN show that, most likely, the technology will not be able to replace the current Oracle technology used for systems with very large numbers of signals (in the range of hundreds of thousands). However, it could successfully act as a shorter-term storage, improving the performance of certain queries and enabling users to easily create web dashboards using Grafana.

Initial pilot deployments of the NGA took together with the InfluxDB and Grafana were carried out in ATLAS Tilecal and ProtoDUNE as shown in Figure 90.

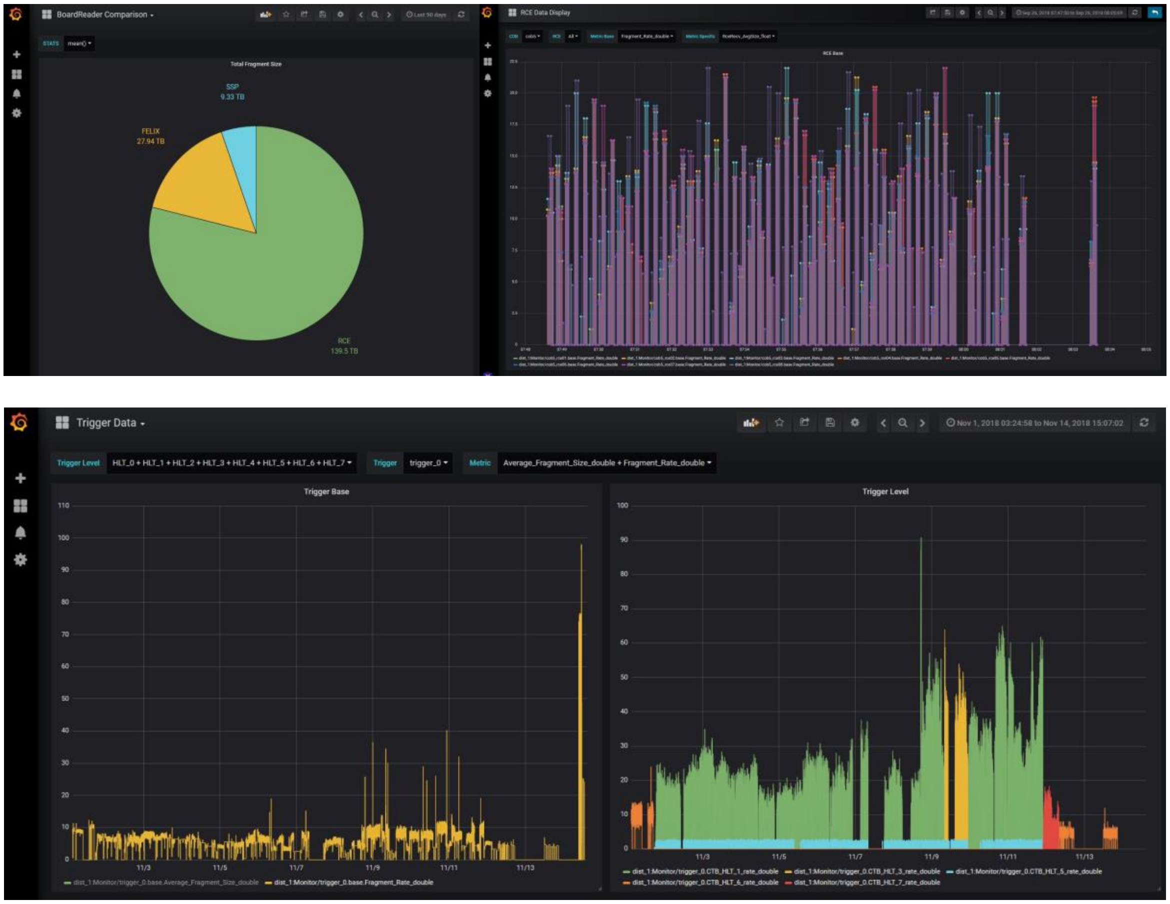


Figure 90. Pilot deployment of the WinCC OA Next Generation Archived allowed for the development of different Grafana dashboards showing properties of the events in ProtoDune.

Next Generation Alarm and Event Screen

Over almost 20 years of usage of WinCC OA at CERN, we have seen a large proliferation of Alarm and Event Screens built on top of WinCC OA that tried to address specific use-cases. Unfortunately, these extensions were built on libraries that contained many shortcomings and did not provide solid grounds for the development, which make all these implementations very difficult to maintain. In 2019, major steps were taken to develop a new highly configurable alarm and event screen, the so-called Next Generation Alarm and Event Screen (NGAES) to be delivered as part of the Frameworks that should replace all these dedicated developments. Moreover, the new alarm screen will provide new functions like handling of metadata associated to alarms (for example for geographical location of the alarms), strong filtering and grouping capabilities as well as improved performance. In 2019, the requirement gathering phase was finalized with the input from many groups in the Accelerator and Technology sector as well as from the experiments. Furthermore, initial prototypes of the NGAES demonstrated in the CCC to the operators as shown in Figure 91, with very positive feedback on the feature set. The development of the NGAES is performed in collaboration with IHPE, Protvino, Russia.

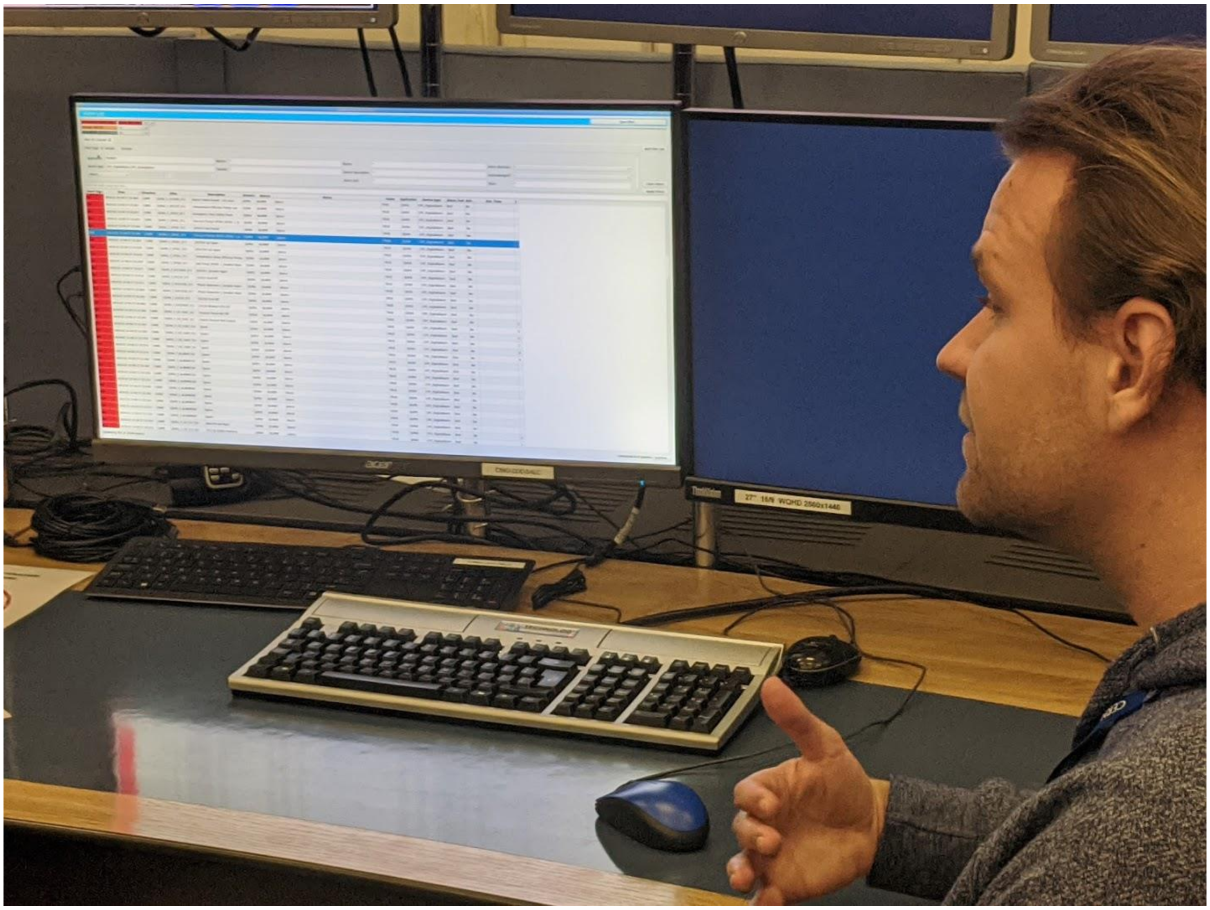


Figure 91. Initial prototype of the Next Generation Alarm and Event Screen being demonstrated to the CCC operators.

New UNICOS HMI

The replacement of the monitor used in the CCC envisaged during the LS2 upgrades, triggered the need to review the functionality of the UNICOS HMI provided for the industrial control applications. The size of the monitors will be increased from 19” to 27”, which enables many possibilities for the display of information and the interaction between operators and the control system. In 2019, the operator requirements for the new UNICOS HMI were laid down and a set of functional prototypes were presented to the operators to confirm the validity of the functionality provided as shown in Figure 92. This development required a strong partnership with Siemens/ETM to provide missing features in WinCC OA that will be required to satisfy the operator’s requests. Some of the main features of the new UNICOS HMI will be:

- Optimal use of screen space by employing layout management which makes the size and aspect-ratio of the application window fully adjustable.
- Direct reuse of thousands of existing fixed-size synoptic panels for applications such as CRYO, CV, power interlocks developed by machine experts over the past decades, with the new layouted HMI, with no need of their adaptation.
- Compensation for the higher density of panels in the new monitors with respect to the old screens. The HMI were optimized for the 19” screens with a much lower pixel density. When opening the panels in the new monitors, symbols and fonts will appear much smaller

due to the higher pixel density. The new HMI allows for a smooth zoom effect that allows to magnify the area of interest or expand to see the entire synoptic view.

- Display multiple synoptic panels at the same time, making optimal use of the screen. The new HMI will be to display side-by-side (in a splitter-view) synoptic views or in scaled-down docked live previews. These previews allow to open up instantly the visualizations into the main view. This allows to operate on one synoptic view while keeping an eye on the state of other parts of control systems and to switch between different views of the process effortlessly.
- Recording of the complete layout of the screen, defining the position of synoptic panels for later usage.

The new HMI is expected to be massively deployed during the upgrades of the industrial control applications in LS2.

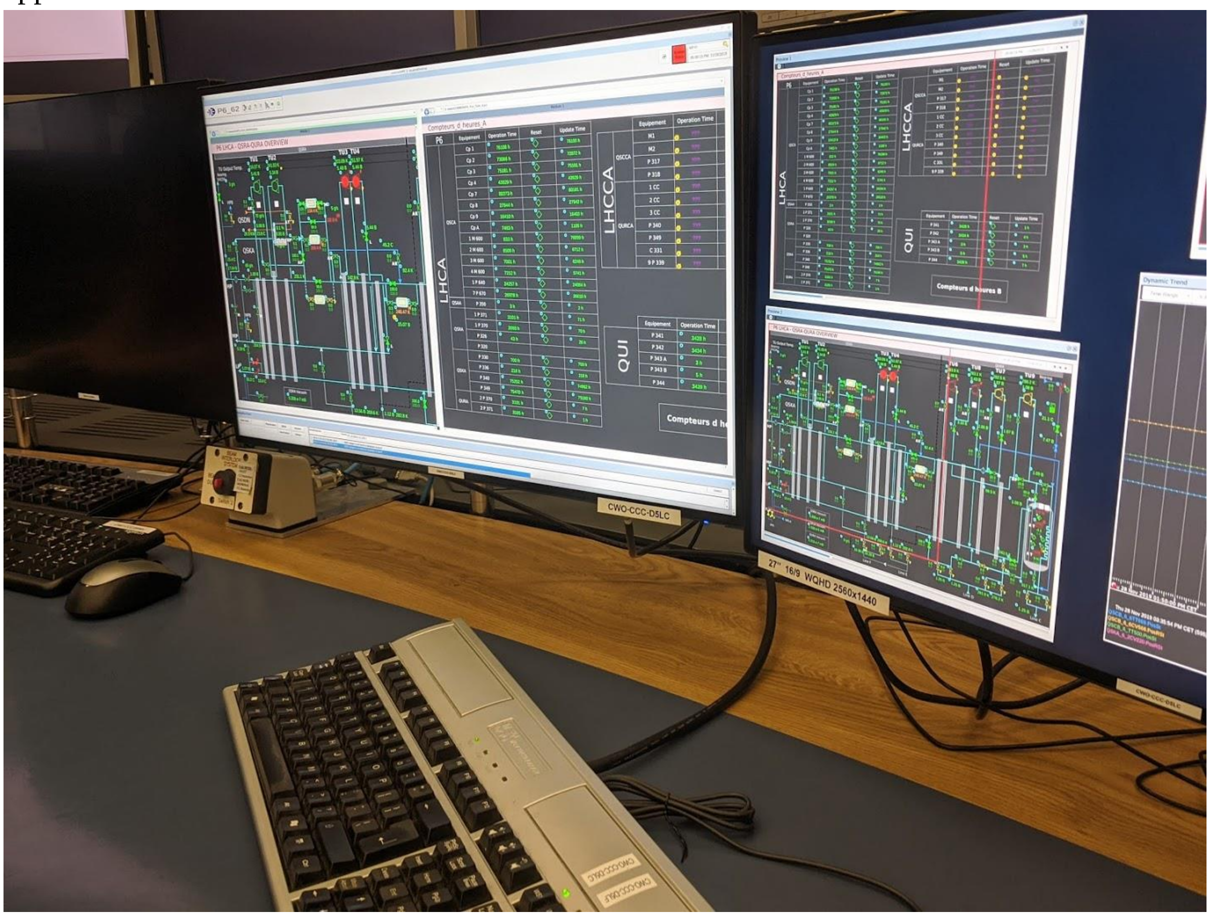


Figure 92. Initial versions of the new UNICOS HMI running on the 27" monitors in the CCC being demonstrated to the operators. The monitor on the left-hand side of the picture shows the new UNICOS HMI whereas the old HMI running on the new screens is displayed on the monitor on the right.

Consolidation and Redesign of the CERN Industrial Controls Frameworks

The development of the CERN Industrial controls frameworks took place over the last 16 years. In 2019, the Frameworks comprised more than 50 components that amount around 2 million lines of code contributed by more than 60 developers with a high turn-over (mostly short-term resources). Until 2019, the provision of the functionality required to implement the control systems was prioritized with respect to consolidation efforts. Only a major review of the JCOP Framework took place in 2003. The Consolidation and Redesign Project of the CERN Industrial Controls Frameworks aims at simplifying their long-term maintenance and prepare the frameworks for new control systems and future operation conditions of the LHC by:

- Reviewing the inventory of existing functionality and its implementation.
- Removing obsolete code and functionality.
- Overcoming existing limitations in the present architectures.
- Extending their functionality by adopting new features of the underlying technologies, e.g., CTRL++ in WinCC OA, and by introducing new technology trends and function, e.g., Data Analytics.
- Reducing the learning curve for newcomers.
- Streamline the integration of the two Frameworks.
- Assuring long-term maintainability of the project by recovering lost knowledge and providing up-to-date technical documentation.

The work is divided into two phases:

- PHASE I: The work in this phase focused to a large extend in reviewing the existing Frameworks, document the short-comings and propose solutions. This suggestions for changes are presented to the stakeholders for approval. Moreover, in this phase, new developments will also take place, e.g. Next Generation Archiving, Alarm and Event Screens.
- PHASE II: In this phase, a major implementation effort of the changes agreed with the stake holders will take place. This work will aim at simplifying the long-term maintenance of the frameworks, provision of new functionality, improve the frameworks quality as well as to achieve a sound integration of JCOP and UNICOS.

In 2019, the initial phase of the Consolidation and Redesign Project was addressed where practically all working groups defined in [2] were active. Given that one of the main aims of this project is to ensure backwards compatibility of the frameworks to minimize the impact on the end-users, shortly after the work started, it was obvious that three major components needed to be developed to face the consolidation and redesign project with guarantees of success:

- A standard build and release platform to remove the reliance on the component developers, to standardize the steps during the build and release process, as well as automate many of the manual steps performed.
- An automatic testing infrastructure, which is largely integrated with the build and release platform.
- A central repository with all SCADA applications in production in the A&T and Research sectors was set up. This repository is key to ensure backwards compatibility since it contains the user-code and allows to check what are the functions of the frameworks that are used and how, as well as the other code dependencies.

In 2019, resources were mainly allocated to these three projects which allowed a major progress in these two projects.

In parallel, a significant part of the code was reviewed enabling the reconstruction of knowledge loss during the years due to the high turn-over. Obsolete code and functionality of the frameworks was systematically deprecated and a number of components underwent deep clean up.

A major consolidation of the backlog was also finalized in 2019, where many open issues were reviewed together with the end-users and closed whenever possible. The effect of this backlog clean-up is shown in Figure 93. Close collaboration with ETM took also place to enrich the WinCC OA object-oriented scripting language as this was considered to be strategic for the second phase of the consolidation and redesign project. The full list of achievements done in the initial phase of the project can be found in [4].

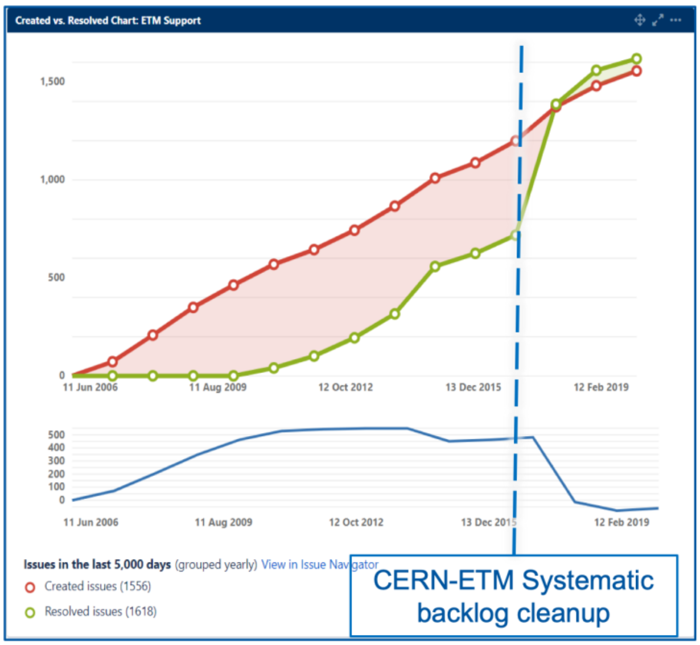


Figure 93. Effect of the consolidation of the backlog of the JCOP Framework during 2019.

Licensing

The licensing the CERN Industrial Controls Frameworks is motivated by two main factors:

- The collaborations established by various groups at CERN and external institutes and labs that envisage the utilization of the frameworks, e.g., TE-CRG and INFN;
- The frameworks are already being used by external companies and labs, like ITER.

This triggered an effort in 2019 to regularize the usage of the Frameworks by third-party institutes or companies by defining, together with the Knowledge Transfer group, a licensing model. The procedure defined with KT relies on the resolution of the intellectual property of the frameworks; a major step that involves several groups at CERN, to resolve the contributions of the different authors to the frameworks over the last 16 years. It is planned that the bulk of this work will be carried out in 2020 leading to the open-sourcing of the frameworks in 2021.

A new UNICOS Project Organisation

In 2019, a completely new structure was put in place for the UNICOS project with the following main objectives:

- Reinforcing the participation of the users in the definition of the priorities and the steering the evolution of the UNICOS project.
- Formalize the flow of requests as well as their prioritization for the project to avoid impacting other projects like JCOP.

The new project organization gave birth to two new governing bodies for the project:

- Technical Committee (TC), which is responsible for the day-to-day decisions in the UNICOS project, prepares the annual plan of work and maintains an up-to-date list of priorities for the project.
- Advisory Board (AC), which is responsible for strategical decisions that may have an impact on the long-term evolution of the project and evaluates the proposal for the UNICOS PoW prepared by the TC and make a recommendation to the project management in BE-ICS.

Both bodies include representatives from BE-ICS and the main UNICOS users at CERN.

The Joint COntrols Project (JCOP)

The Joint COntrols Project (JCOP) is a collaboration between the LHC experiments, the EP-DT Group and BE-ICS to develop the Detector Control Systems (DCS) of the CERN experiments in common. Given the increasing constraints on manpower, as well as the evident similarity in technical requirements for controls amongst the experiments, the project set out in 1998 with the aim of making a more efficient use of resources. Today, JCOP provides, supports and maintains a common Framework of tools and a set of components and it also provides critical turn-key applications for the operation and safety of the experiments, for example: The Gas and Detector Safety Systems. The tools provided by JCOP allow configuration, monitoring and safe operation of the different sub-detectors and also include communication mechanisms with the Data Acquisition/Trigger systems, as well as with external systems such as CERN infrastructure services and the LHC.

JCOP is a good example of collaboration across departments. Since 1998, JCOP has proven to be a very successful project leading to a high degree of coherence of the DCS and the LHC experiments with limited resources. JCOP is responsible, to a large extent, for the selection of a technology stack (e.g., WinCC Open Architecture and OPC) that has changed the landscape of industrial controls at CERN since early 2000's. Today, the tools developed in the frame of the JCOP are used in 250 mission critical applications in the A&T Sector.

As with many other groups, the JCOP efforts in 2019 focused on the LS2 upgrades. In addition, an important number of development tasks also experienced a strong push to guarantee their timely availability for their deployment in LS3. The following lists some of the main actions performed by BE-ICS for the Experiments in the context of the JCOP project in 2019:

- Preparation for migration of the Experiments' DCSs to WinCC OA v3.16. This included validating the full stack of technologies as well as new releases of the JCOP Framework for this version of the SCADA. Validation was carried out in close collaboration with experiment controls teams and this new set of tools is currently being deployed in nearly 600 WinCC OA-based control systems in LHC experiments, NA62, COMPASS and the Neutrino Platform. As a benefit of this preparation, a number of Gas Control System application migrations were already successfully upgraded ahead of schedule in 2019 (previously, all migrations had been foreseen to be carried out only in 2020).

- Migration of the powering systems of the LHC detectors from OPC Data Access (DA) to OPC Unified Architecture (UA): The OPC DA specification relies on DCOM, a now deprecated Microsoft technology. OPC UA enables communication between the WinCC OA SCADA system and the very large powering systems of the experiments, these systems can include several tens of thousands of individually controllable channels, as is the case of the CMS tracker powering system shown in Figure 94. The OPC UA migration effort included:

    - Finalization of the collaboration agreements with commercial power supply vendors (CAEN, Wiener and ISEG) for joint development of the OPC UA servers.
    - Finalization of the implementation of all OPC UA servers.
    - Validation of the servers at the experiment's setups in close collaboration with end-users.
    - Definition and implementation prototypes to migrate the SCADA applications. These tools will be further developed in 2020 such that they can be used by the experiments to handle the migration themselves.

  Although major work is still ongoing, efforts carried out in 2019 sets the OPC UA servers on a good trajectory to handle the massive upgrades envisaged in 2020.

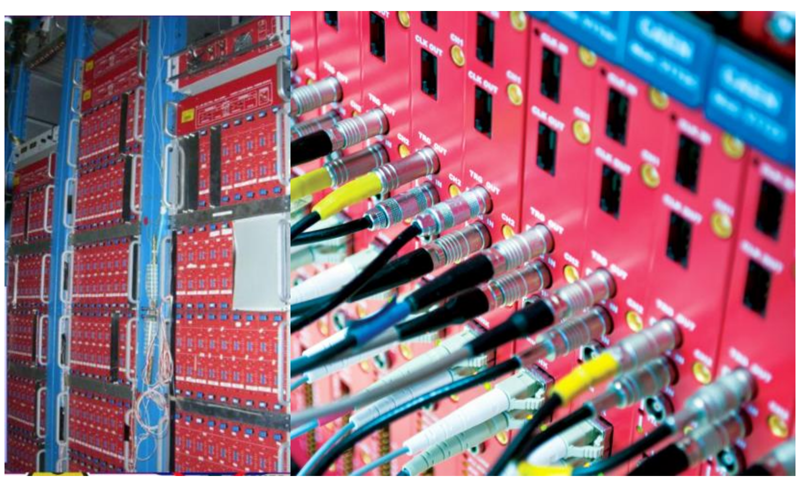


Figure 94. CMS Tracker powering system is based on CAEN power supplies that are controlled via OPC UA servers provided by BE-ICS.

- Contributions to the ALICE O^2 project: This is one of the flagship projects during the LS2 in ALICE, providing a completely new computing system to perform the functions presently performed by the DAQ, HLT and offline systems. This new computing system will acquire and inspect Pb-Pb collisions at 50 kHz, sampling the pp and p-Pb at up to 200 kHz. In the O^2 architecture, controls data (~100 000 conditions parameters) must be injected in the DAQ data stream every 50 ms. To achieve this, ALICE heavily relies on the Next Generation Archiving (NGA) currently developed by BE-ICS as an openlab collaboration with Siemens/ETM. NGA's modular architecture shown in Figure 95, will be exploited by ALICE to develop a dedicated back-end manager (under the supervision of BE-ICS), which will inject the DCS process image on the DAQ data stream as needed for online event reconstruction.

- Contributions to the ATLAS New Small Wheel detector: The ATLAS NSW detector will make use of a new generation of CAEN power supplies. To integrate these power supplies into the ATLAS DCS requires extension and validation of components currently provided by BE-ICS, namely the OPC UA server and the WinCC OA component for CAEN equipment. This integration is expected to be accomplished by Q1 2020.

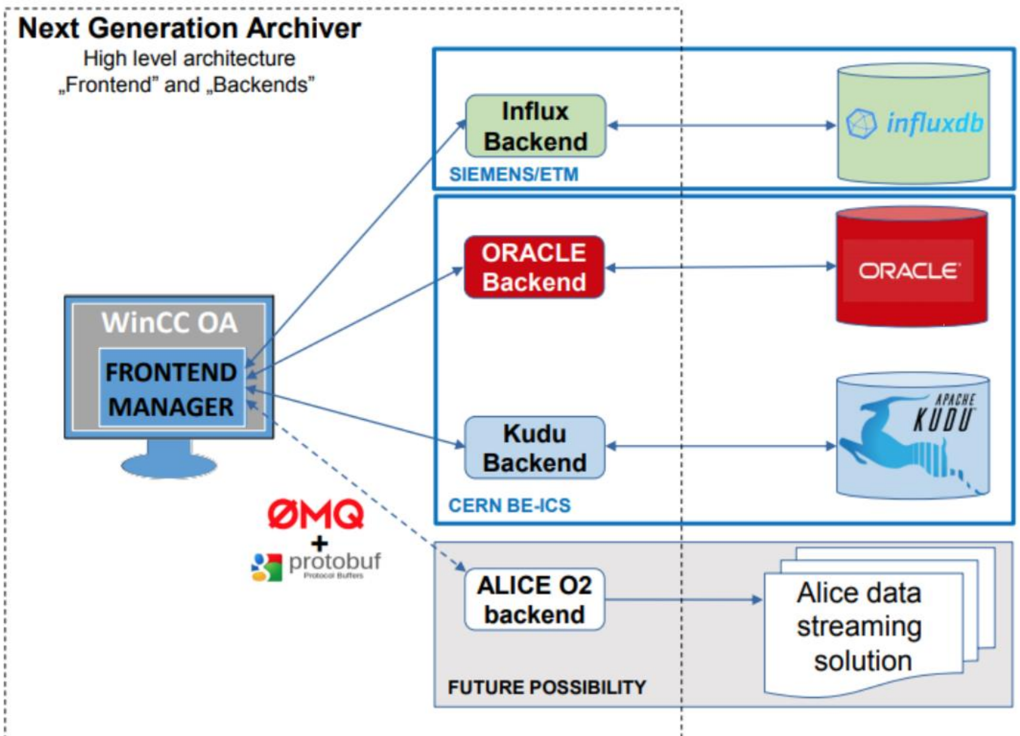


Figure 95. The WinCC Open Architecture Next Generation Archiver (presently developed by BE-ICS is an openlab collaboration with Siemens/ETM) will be a key building block in the ALICE O^2 Infrastructure to inject DCS data into the Physics data-stream every 50 ms as required for online reconstruction of events.

Tools and Infrastructure

The LS2 work also comprised a number of upgrades and development of tools and computing infrastructure such as:

- Windows Terminal Servers upgrade Windows Server 2016
- Jenkins job migration to a Dockerized Jenkins infrastructure allowing to remove server machines and reduce the infrastructure needs
- Setting up an agreement with IT department to provide a self-service SVN solution that we could propose to the CERN PLC developer community
- Revamping the Technical Infrastructure Monitoring data validation procedures with modern techniques allowing a huge reduction in code

ADaMS (Access Distribution and Management System):

A new “role” concept was implemented for those technical services with dozens of persons that require access to hundreds of locations: being in such a role, when the role is approved for access in a permission avoids the creation and subsequent signature of thousands of access requests.

Checklist Web application

A checklist application was developed as a system to easily track year over year the tests needed to prepare an accelerator before its restart, identify issues that appear regularly and eliminate bottlenecks.

A structure of nested nodes is created per each machine, grouping tests by location, responsible groups and/or time scheduled for performing the tests.

Each node can have a list of test and targets against which the tests need to be performed. The result is a table where the user can select one or more cells and apply a result to them (see Figure 96). A comment can be added, if needed, to explain, for example, the reason of a failure to pass the test. Priority can set by sorting each test and target in the table.

Figure 96. Overview about scheduled test and obtained result.

Fire Detection

The internal audit launched in 2018, by the DG, Fabiola Gianotti, on the fire detection systems of CERN surface, was completed. The audit showed that the number of fire detectors tripled since 2008 and that the existing fire detection installation matches the criteria stablished by the CERN Fire Safety Code E. About half of the fire detectors park is obsolete: there is an urgent need to consolidate. There is also a need of additional maintenance budget to meet the maintenance needs. Meeting the consolidation and maintenance criteria requires an additional budget of 10 MCHF over the next 10 years. The DG approved 5 MCHF for the first next 5 years (2020-2024).

The focus in fire detection systems in 2019 was put to consolidate the data quality of the equipment database (INFOR) in a two-year project. In addition, a reliability analysis was launched in collaboration with HSE, in the context for the FIRIA project, to determine the reliability of fire detection installations at CERN.

Many new fire detection installations were deployed in 2019 such as the LHCb and ALICE PC Farms and the Electrical substation M9 in Meyrin. Many others were under preparation like the extension of SX5 (SXA5), the NanoLab (Extension of Medicis), the new TT2 Power Converter building (B269), and the new B937 building for offices and labs. Many new projects were launched like the new Kindergarten, the multi-service buildings for Point 1 and Point 5 to house the primary C02 cooling equipment, the Prevessin Data Center (PCC), and the refurbishing of B38- Hotel to comply with fire safety swiss standards. Several consolidation projects were launched in the PS: LEIR, LINAC3, EAR2 and AD Target, as well as in the North Area: BA82, TDC2-TCC2 and RWTC ISR2. The ticketing system used to trace fire detection requests is now fully operational.

The Science Gateway project was launched. The fire safety concept was defined. An important cabled alarm infrastructure is to be put in place, requiring big consolidations. Cost estimates for such consolidation were approved by the project and started.

Gas Detection

The focus for gas detection systems in 2019 was given to the introduction of the ticketing system to manage flammable gas, toxic gas and oxygen deficiency detection requests.

In order to improve project management, specific forms were developed and integrated in ServiceNow ticketing tool to collect all required information when a new request is made. Behind this entry point, several processes were developed to ease interactions with the stakeholders HSE and contractors and allowing to link all project information in one place in ServiceNow. The team in charge of the automatic gas and fire detection projects is now able to plan the project execution and to represent individual and global workloads in a Gantt chart, which allows to anticipate capacity issues in midterm (next two years) and improve confidence in delivering projects in time.

To ensure a continuous renewal of the park, the renewal effort was put on the EHN1 Saleve Experimental Areas, and on the preparation works for EHN2 and ECN3 Experimental areas. In addition, several small consolidations were done to the automatic ODH detection systems of the LHC underground to be able to wait until the LS3. And an important firmware upgrade was done to the gas detection infrastructure of the North Area.

Manufacturing of spare electronic cards for the SNIFFER systems was launched to cater for the period up until LS3. There is however an upcoming problem of obsolescence of the SNIFFER systems and a first discussion on best contractual approach was done with the Experiments.

Preliminary design and cost estimates for CO_2 and ODH detection in the North Area galleries was done.

Alarm Transmission

A first focus for alarm transmission in 2019 was to support the renovation of the Fire Brigade Control Room. A project that touched deeply the CSAM central system and associated cabled alarm infrastructure.

A second focus was given to launch the main alarm dispatcher consolidation in Meyrin. Installed in the early years of CERN, it concentrates big quantities of alarms and technical faults at the old *TCR – Technical Control Room* in building 212. Its renewal implies the decentralization of cabled alarms to minimize common modes of failure and represents the biggest cabled alarm consolidation of the last 10 years.

The current CSAM system required several software upgrades to ensure its optimum operation: firstly, the CSAM high resolution upgrade was deployed to welcome the changes of the refurbished Fire Brigade Control Room and the Central Synoptics were updated. Secondly, the obsolete CSAM Operational Stations were replaced and the preparation work to replace the obsolete CSAM Local Synoptic started. Thirdly, the OPC communication for SYNTEL gas detection infrastructure was upgraded and the redundant OPC communication for fire detection was validated and will be deployed in 2020.

A new database for alarm cabling traceability, R3Web, was validated and as-built data was collected for Meyrin. The migration of the Red Telephones to the new IT infrastructure was done.

Many urgent corrective interventions were required during HL-LHC works (cable cut between BA7 and SM18) and LS2 (cable cut between SR5 and UL5).

Safety alarm system management tools

The first focus for tools in 2019 was to provide the fire detection auditors with all information needed in terms of detailed maintenance cost estimates for the next 10 years and a deep understanding of the IS37.

The second objective was the consolidation of the data structure in the INFOR equipment database to enable automatic reporting in order to gain park insight overview (i.e., impact of material obsolescence, etc..). An automatic import procedure was also defined to introduce fire detectors in the CERN Geographical Information System (GIS) automatically from the AUTOCAD drawings so all AS equipment can be represented in GIS by the end of 2020.

Several attempts were done to use artificial intelligence to move from preventive maintenance to predictive maintenance for the cleaning of air sampling smoke detectors. Several attempts were also done with Machine Learning to better understand the ODH detector behaviour and identify most adequate cells replacing periods. These ideas were presented in ICALEPS 2019.

A comparison tool between “Inhibited Alarms” and “Detectors in IS37” was developed to avoid leaving sensors inhibited when they need to be put back in operation.