BE Department Annual Report 2015

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Abstract

The Beams Department hosts the Groups responsible for the beam generation, acceleration, diagnostics, controls and performance optimization for the whole CERN accelerator complex. This Report describes the 2015 highlights for the BE Department.
LHC:

**BE-ABP Group**

The 2015 LHC optics commissioning was faced with hardware improvements in the AC dipole and the BPMs for longer data acquisitions and with new algorithms with higher accuracy (N-BPM method). The initial proton optics commissioning took 20 shifts carried out by the OMC team. Measurements at injection suffered from poor BPM performance and AC dipole issues. At top energy the main limitation was the orbit drifts due to quadrupole movements in IR8. The initial goal of commissioning all optics between $\beta^*$ of 80 cm and 40 cm had to be finalized during dedicated MDs as part of the $\beta^*$-reach MD campaign. Figure 1 shows how global corrections deteriorate when used at a different $\beta^*$ than the measured one.

![Figure 1. Measure and expected rms beta-beating when applying corrections at a different $\beta^*$ than the measured one. The horizontal axis shows the ratio of these 2 $\beta^*$ values.](image)

The $\beta^*$-reach MD campaign resulted in the choice of $\beta^* = 40$ cm for 2016. This campaign also included studies of the non-linear errors in the IRs. Combined ramp and squeeze was demonstrated in MDs during 2015 leading to its operational use already in 2015. Transverse coupling demonstrated to be a key parameter for the machine performance, yet its measurement and control should be more efficient to follow the coupling drifts over time. First tests on a new coupling measurement based on DOROS BPM readings were performed in 2015, which could lead to automatic coupling corrections and feedback.

The last month of the 2015 run was devoted to the heavy-ion programme. During the first week, proton-proton reference data were taken at a beam energy of 2.51 TeV, to achieve the same centre-of-mass energy per colliding nucleon pair, 5.02 TeV, as in the 2013 p-Pb collision run. The remainder of the time was devoted to Pb-Pb collisions at a beam energy of 6.37 Z TeV, producing the 5.02 TeV nucleon-nucleon energy in the third species combination requested by the experiments.

This first run close to maximum LHC energy brought a number of long-predicted Pb-Pb performance limits into play for the first time. In particular, the bound-free pair production (BFPP) process led to powerful secondary beams of modified Pb ions emerging from the interaction points.
and impinging on the beam screens in the dispersion suppressors. The strategy of displacing the losses from cryo-magnets into the connection cryostats was implemented and allowed the LHC to operate at up to 3 times its design luminosity without being continually interrupted by magnet quenches. This mechanism was also used to achieve the first controlled quench test of an LHC cryo-dipole with beam, finally quantifying the steady-state quench level. The need for new collimators and associated 11 T Nb$_3$Sn magnets in IR2 and IR7 for BFPP and heavy-ion collimation losses (another anticipated performance limit) was also convincingly demonstrated. Figure 2 shows the luminosity and total beam intensities during the 18 days devoted to colliding Pb beams at the end of 2015, showing the evolution of the number of bunches and other events interspersed with production data-taking. The final luminosity in ATLAS and CMS exceeded the design value (shown as a red line) by a factor 3 while the ALICE experiment was levelled at the design (saturation) value.

![Figure 2. LHC luminosity and beam intensity during the 2015 Pb run.](image)

**BE-BI Group**

**Orbit and tune feedback software renovation**

During the LHC restart the refurbished software servers for the beam-based feedbacks were successfully commissioned for LHC Run 2. Changes include the hardware upgrade to modern application servers, porting of the controller code from 32 to 64-bits, the standardization of the controller’s logging mechanism and reengineering the orbit trigger mechanism. Various system configuration sources were reverse engineered and updated to meet new machine specifications and documented. A schematics overview of the system can be seen in Figure 3:
The stability problems which affected the system during LHC Run 1, were addressed by fixing, simplifying and removing code. Issue tracking tools were used to keep records of all changes and problems and wiki pages used for documentation purposes. In order to assist in the system validation prior to deployment, a collaboration between BE-CO, BE-OP and BE-BI was established with the goal of providing an infrastructure for running thorough acceptance tests. As a result, a realistic testbed infrastructure was put in place and a JAVA-based domain-specific language was developed to ease the process of writing tests. The usefulness of this setup goes beyond system validation as it is now also routinely used for reproducing and understanding operational events.

**Upgrade of the Synchrotron Light Monitor system**

The LHC Synchrotron Radiation Telescopes (BSRT) are used to determine the beam size through imaging the synchrotron light generated in dedicated superconducting undulators and the D3 dipoles of IR4.

During Run 1 the performance of the BSRTs was limited by heating of the in-vacuum extraction mirror. This heating, induced by electromagnetic coupling with the beam was so severe that the mirrors were damaged and had to be removed from the machine. New mirrors and holders featuring smoother transitions in the beam pipe were designed and installed for Run 2. In 2015 the temperature of the new extraction mirrors was closely monitored using thermocouples integrated into the vacuum assembly. No significant heating was observed, with temperature variations limited to a few degrees in contrast to the several hundred degrees Centigrade reached in 2012.

The resolution and accuracy of the BSRT was further improved by installing a calibration line that includes most of the BSRT optical components. At injection energy the radiation emitted by the undulators is in the visible range while at top energy the radiation from the D3 dipole is broadband and extends into the UV. As the ultimate resolution of the telescope is limited by diffraction, which decreases with the observation wavelength, it was also decided to install a second optical system optimized for the UV range for use at top energy.

The FESA server, controlling the acquisition and the automatic bunch scan, was completely rewritten at the beginning of 2015. All these modifications result in a much more reliable and accurate instrument, with the BSRT now relied upon during LHC operation for on-line emittance measurements. The BSRT system was also crucial for several studies (beam-beam, instabilities...
and electron-cloud). Crosschecks with independent emittance measurements such as luminosity scans, confirmed that the accuracy of the BSRT beam size measurement is of the order of 5%.

**LHC Schottky diagnostics:**

After a complete overhaul of the 4 Schottky monitors during LS1, their electronics was further improved during the 2015 run. Their use during proton operation was still proving to be problematic due to the large coherent content of the beam spectrum even at the 4.8GHz operation frequency of the detectors, but the improved system gave excellent signals with lead ion beams. An example of the evolution of Schottky signals from a heavy ion fill is shown in Figure 4. The area of Schottky lobes shrink as the beam sizes decreases with increased energy, with the jump from injection to collision tune at the end of the ramp clearly visible. The measurement of tune and chromaticity were compared with other beam diagnostics and showed good agreement.

![Figure 4: Evolution of Schottky signals through the ramp during an ion run (fill #4712).](image)

**Detecting Beam Instability in the LHC:**

Diagnostics to characterise beam instabilities are important, both for experimentally qualifying the LHC impedance model and for making adjustments to machine settings if instabilities occur during operation. Since Long Shutdown 1, a new beam instability trigger network was put in operation which continuously analyses the transverse beam oscillations measured by the base band tune (BBQ) monitor, using different algorithms to detect larger signal amplitudes as beam instability occurs. It then provides a signal to trigger other monitors, such as the head-tail monitor capable of measuring intra-bunch motion over several turns. Examples of signals observed with the LHC beam can be seen in Figure 5.
Figure 5: Turn by turn oscillation amplitude as measured by the tune measurement system during an instability with two nominal bunches, with the markers indicating the instability triggers generated. The inset plots show the related head-tail measurement for the indicated triggers.

Wall current Transformer:

A prototype of a new Wall Current Transformer (BCTW) was installed in the LHC during LS1 and commissioned successfully with beam in 2015. This monitor demonstrated a very good time response for measuring the bunch-by-bunch beam intensity. Unlike the current, operational LHC Fast Beam Current Transformer (FBCT), this new design is insensitive to beam position and bunch length variations. It was therefore decided to replace the operational FBCT detectors for both beams by the BCTW for the 2016 LHC run.

Figure 6: Prototype of the new Wall Current Transformer installed on Beam 2 in LHC LSS4

BE-CO Group

Changes to the Sequencer for faster LHC turn-around

In order to reduce LHC turn-around time, operators had implemented complex logic to work around limitations of the sequencer framework. This logic implied manual and error-prone maintenance of dozens of device groups in the LSA settings database. Recognizing the obvious gain in time for LHC operations, the sequencer responsible in BE-CO-APS did a better
implementation inside the sequencer framework. It allows to save up to 20-30 minutes per LHC ramp down. It was ready at the end of 2015, and tested and deployed into operations for the LHC start up in 2016.

**Accelerator Fault Tracking**

The Accelerator Fault Tracking (AFT) project delivered a production system for the restart of LHC in 2015. The system aims to facilitate answering questions like: “Why are we not doing physics when we should be?” and “What can we do to increase machine availability?” The AFT system was heavily used throughout 2015, and regularly developed based on user feedback. The now famous “LHC Cardiogram” (shown below) frequently featured in beam commissioning and operation meetings.

![Figure 7: LHC Cardiogram example usage](image)

Thanks to the tools put in place to help streamline the fault capture and review process, more than 1700 faults were recorded during the year, and for the first time ever there was consensus between operations teams and equipment groups about causes of lost LHC availability when the results were presented in the 2015 Evian workshop.

**Beam Loss Threshold Calculations**

The new approach for LHC Beam Loss Monitor settings management (calculating and managing beam loss thresholds directly inside the database) was deployed and used successfully in operation throughout the year. The BE-CO provided BLM experts also extended infrastructure to facilitate the process of registration and management of new BLM families.

**Fixed Displays**

In order to help address operational issues a new Fixed Display for LHC temperature monitoring was developed. Its functionality is integrated with the Logging Service GUI called TIMBER allowing experts to configure lists of temperature signals to monitor at runtime. Data from the Logging System is also used to display historical temperature values whereas the most recent values are shown online from the corresponding FESA devices.
2015 was another busy year for operations as can be seen from the schedule shown below. The LHC was re-commissioned following the major activities of LS1.
The year 2015 marked the restart of LHC operation with beam after its first Long Shutdown (LS1). Operation with beam started relatively late, as the first three months were still devoted to hardware commissioning. The Copper Stabilizer Continuity Measurement required the extension of the LS1 by one month, the dipole training campaign to 6.5 TeV took longer than expected, and a worrisome earth fault appeared in the dipole circuit in sector 34. The machine checkout interwove with the end of the hardware commissioning, and the first bunches were circulated on Easter Day (5 April). Beam commissioning, including recommissioning all machine protection systems, lasted 8 weeks and culminated with the first “Stable Beams” declared in the morning of 3 June. During this period, and despite the low intensity beams, issues were found at the location 15R8: first fast losses, with signature similar to the Unidentified Falling Objects (UFOs), then, after a thermal cycle of the beam screen to 80 K, an aperture restriction, now dubbed the ULO (Unidentified Lying Object).

The summer was devoted to a step-wise scrubbing run and intensity ramp-up: first with 50 ns, then with 25 ns beams. A total of 3 weeks were dedicated to electron cloud scrubbing at 450 GeV. In September and October, the intensity ramp-up with 25 ns beams continued, mostly limited by the heat load induced on the cryogenic system. The month of August was particularly difficult as the machine availability was impaired by Single Event Effects on the Quench Protection Systems and...
by high UFO rates, most of the luminosity production happened only in the months of September and October.

The last month of beam operation was dedicated to physics with lead ion beams. It is also worth recalling that proton-proton physics operation was interrupted throughout the year to accommodate special physics runs (e.g. the low pile-up LHCf run, the 90 m run for TOTEM and ALFA, the proton-proton reference run at 2.51 TeV/beam), 3 scheduled stops for hardware maintenance (Technical Stops, TS), and three 5-day long Machine Developments (MDs).

At the end of the proton physics running period the instantaneous luminosity reached $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$ with 2244 bunches per ring, laying a good foundation for the 2016 run. The luminosity integrated by ATLAS and CMS over the course of the 2015 proton physics run is just above 4 fb$^{-1}$, while LHCb and ALICE integrated 360 pb$^{-1}$ and 9 pb$^{-1}$ respectively. The integrated luminosity ran short of the initial projection due to the delayed start and the difficulties encountered in August, in addition to the time allocated for the special physics runs and for scrubbing. The production rates reached 250 pb$^{-1}$/day and 1 fb$^{-1}$/week at the end of the run, which make good foundations for the 2016 physics production.

![Graph showing number of bunches per beam, peak luminosity, and integrated luminosity in 2015.](image)

Figure 9: Number of bunches per beam (top), peak (middle) and integrated luminosity in 2015.
BE-RF Group

The year 2015 was exceptional for the LHC also from the RF point of view. After a quick and smooth restart, the machine was running close to its nominal parameters by the end of the year (2244 bunches vs. design value of 2808, 25 ns bunch spacing in batches of 144 bunches, $1.2 \cdot 10^{11}$ protons per bunch, 6.5 TeV top energy for each beam). This success was of course the result of a true team effort, but several details deserve to be highlighted here:

1) The LHC klystron DC settings were increased to 58 kV (from 54 kV used through run1), which allowed running the klystrons at saturated powers between 250 kW and 300 kW. These settings became necessary to compensate transient beam loading with the increased beam current, but they of course also required conditioning of the entire system up to the resulting larger power and voltage levels for reliable operation (2015 settings: 6 MV at injection 10 MV at flat top) – but on the other hand these settings also required the cavities to run at larger voltage and power levels, which in turn require longer conditioning.

2) In this context it is noteworthy that cavity B in the cryomodule M1.B2 “America”, which limited performance in run1 and led to the module swap between “America” and “Europa” in 2014, could be completely recovered in SM18 applying pushed conditioning as is illustrated in Figure 10.

3) Careful analysis of RF trips during run1 had led to an improvement program during LS1 (described in the 2014 Annual Report), which clearly paid off during 2015 with significantly improved fault statistics. These improvements concerned in particular the high voltage system of the 400 MHz klystrons (replacing obsolete tetrodes in the modulation anode voltage divider and improved welds of HV connectors), the fast protection system and the arc detectors.

Figure 10: Recovery of cavity B in module “America”, showing the onset of field emission with increasing accelerating field before (blue diamonds) and after (red squares) conditioning. To be noted that also cavities A and C improved performance during this commissioning.
4) RF specific beam diagnostics were implemented and deployed during 2015, notably the so-called “ObsBox” (short for “observation box”), which allows recording of both stable phases and bunch oscillations in all three planes, bunch by bunch, for many turns, and has proven an excellent tool for electron cloud diagnostics and to precisely measure stability limits. The ObsBox system is being complemented by a trigger mechanism using the White Rabbit Network linking different instruments from RF and BI to make synchronous and time stamped acquisitions.

It was clear that with increased bunch intensity and beam current we were getting closer to stability limits, both single bunch and coupled bunch, some of them maybe unobserved as yet. One example is illustrated in Fig. 11: during a long physics fill at 6.5 TeV (here: fill 4538, the longest fill of the year), synchrotron radiation damping leads to bunch shortening (stronger than the emittance growth caused by intra-beam scattering) and when the estimated single-bunch stability threshold is reached (the limit was predicted from a combination of theory and observations made in previous MDs), Landau damping is lost and more and more bunches turn unstable. This observation of course improves significantly our understanding of the machine, relevant for future performance improvements.

![Figure 11: Loss of Landau damping in B2 at 6.5 TeV and 10 MV RF voltage in the longest fill of the year (Fill 4538). The single-bunch threshold (black) was obtained in MDs [J. F. Esteban Müller et al., “LHC longitudinal single-bunch stability threshold,” CERN-ACC-NOTE-2016-0001, 2016]. The number of unstable bunches was determined through observations of undamped oscillations in the bunch-by-bunch stable phase.](image)

**High Luminosity LHC (HL-LHC) – LHC Upgrade**

**BE-ABP Group**

During 2015, the impact of the decision to decrease the nominal gradient of the triplet quadrupoles from 140 to 132.6 T/m has been studied and a new version of layout and optics of the high luminosity interaction regions IR1 and IR5 (HL-LHCv1.2) has been released. The experience of LHC Run I has been used in the definition of the aperture requirements to finalize the requirements on the aperture of the magnets and in particular for the revision of the aperture of the Q4 magnet in occasion of a review of its design. The powering schemes for the triplet and the other new circuits have been revised and the characteristics of the power converters have been specified (e.g. maximum currents, ramp and acceleration rates, noise levels, reproducibility and accuracy) after analysis of the magnetic cycles of the impact of ripple on machine performance.
The work towards the specification of the field quality and the mechanical tolerances of the new magnets has continued taking into account the latest techniques developed for the measurement and correction of the linear and non-linear optics and by additional simulation work to evaluate the effect of the field error for the injection and squeezed optics. The sensitivity to other machine parameters like chromaticity and powering of the Landau Octupoles has been included.

Significant progress has been done in the estimate and optimization of the impedance of new components (e.g. RF fingers for the triplet beam screens, crab cavities,..) in collaboration with the equipment groups. The requirements in terms of beam stability have been reviewed indicating the possibility to limit the upgrade of the collimation system with low impedance collimators to the secondary collimators in LSS7 and the need to reduce the impedance of one remaining High Order Mode (at 920 MHz) of the DQW crab cavities.

The operation with 25 ns beam for HL-LHC relies on beam-induced scrubbing for suppressing multipacting in the arcs to keep the heat load on the beam screen within the cooling capacity provided by the cryoplants. The beam-induced heat load in the beam screens of the triplets (both the present and the new ones) and of the magnets of the high luminosity insertion regions has been estimated showing the need for coating the beams screens of these elements. The corresponding analysis for all the other elements in all the sectors has been started together with the study of the beam stability in these conditions. This requires a significant effort to improve the existing simulation codes (parallelization). As a result of the recent electron cloud studies, an alternative scenario based on a new bunch pattern (so called 8b+4e) has been devised and successfully tested in the LHC demonstrating the possibility to suppress electron cloud with a limited reduction of the integrated luminosity as compared to the alternative 50 ns scheme.

The study of the beam-beam effects has been extended to include the effects of the lower luminosity points IP2 and IP8 allowing to specify the required values of the crossing angles. Preliminary studies for the operation of IP8 to higher luminosity (in the range of 1-2x10^{34} cm^{-2}s^{-1}) have also been launched, although this option is not included in the baseline yet.

A review of the heavy-ion operational requirements and beam parameter specifications for Pb-Pb operation from post LS2 to LS4 in order to provide the luminosity requested by the experiments has been made and the beam parameters required at injection have been provided to identify the required upgrade actions in the injectors.

The possible impact of the HL-LHC civil engineering work close to IR1 and IR5 on LHC operation during Run III and in particular the effect of the vibrations induced on the magnetic elements in the IRs have been estimated showing that the resulting orbit oscillation could seriously affect luminosity production. As a result of that study, the planning for the civil engineering work has been revised.

All the above studies have been summarized in the version 0 of the HL-LHC Technical Design Report published at the end of 2015.

**BE-BI Group**

**HL-LHC**

**Beam Gas Vertex Detector Demonstrator**

Most elements of the Beam Gas Vertex (BGV) system were successfully produced and installed in LSS4 of the LHC during 2015.
Two planes of fibre scintillator detectors were installed and accurately aligned and all front-end electronics were installed and connected to the back-end electronics situated in the service gallery. Based on the LHCb control system, dedicated software was developed for monitoring relevant environmental parameters (including radiation levels) and to read-out the complete trigger and DAQ chain, which allowed the first beam-gas interaction data to be acquired. First commissioning steps were taken and a preliminary analysis of this data shows promising results. In order for the silicon photomultipliers to work under optimal conditions, a light-tight aluminium tent was installed around the detector. The cooling system, which will be required in the future for reducing the silicon photomultipliers dark current when the radiation dose increases, is under construction and will be installed in 2016.

**Halo Measurement**

For the HL-LHC project, monitoring the beam halo is a critical aspect, as an overpopulation of the halo could lead to damage of machine components under some fast loss scenarios following a failure of the crab cavities. A halo monitor is also an essential tool to understand halo formation and study the efficiency of an eventual hollow electron lens or long-range beam-beam compensator. Observation of synchrotron radiation using a ‘Lyot’ coronagraph was therefore proposed to provide such a measurement. The system is being developed in collaboration with the KEK institute in Japan and uses many of the components of the coronagraph designed by T. Mitsuhashi for the KEK Photon Factory. The coronagraph was originally developed for solar imaging and is an optical telescope system that allows the bright core of the Sun to be masked-out while reducing the diffraction background to allow observation of the Sun’s corona. In the LHC the coronagraph will be used in a similar way to observe the tails of proton beams (Figure 13). A first R&D system was prepared and characterized in the laboratory (Figure 14) during 2015 and is expected to be installed ready for the 2016 run. This test system aims at achieving a contrast of between $10^3$ and $10^4$ between the core and the halo and will be used as proof of principle for the final HL-LHC system which aims at a contrast of $10^6$. 

![Figure 12: The complete BGV setup as installed in LSS4 of the LHC](image)
Figure 13: Sketch of the Lyot coronagraph adapted to measure the halo of LHC beams.

Figure 14: The coronagraphs test stand in BAF3 including the 30 m long line from the source to the telescope (left). Images of an artificially produced halo from the light source used in the test for different exposure times (right).

BE-RF Group

After the successful testing of the Proof of principle (PoP) prototypes in 2014-15, an intense simulation campaign was launched within US-LARP and EuCARD programmes to develop the LHC type cavities with the required higher order mode (HOM) damping scheme for both cavity topologies, the “double quarter-wave” (DQW) selected for vertical beam crossing and the “RF Dipole” (RFD), selected for horizontal crossing. The result was a further optimization of the cavity geometry with strong HOM damping. Machine architecture and integration studies for the LHC led to an optimum choice of housing a two-cavity string in one stand-alone cryomodule. Each cavity is individually connected to the high power RF and a common cryogenic distribution. This nominal configuration of a two-cavity cryomodule was adopted for both the initial beam tests in SPS and for later implementation in the LHC as a basic unit. This approach maximizes flexibility and will ease spares policy.

The fundamental power coupler parts were assembled, solving some minor issues on the ceramic brazing in the process. The helium vessel prototypes were completed (with EN-MME) to check both mechanical and vacuum tests. First pieces of the HOM couplers were machined from bulk Niobium showing dimensions well below the allowed tolerances. The cold magnetic shields were fabricated in the UK and sent to CERN for their eventual cavity assemblies for SPS tests. A tuner mock-up test on the PoP cavity was prepared to validate the tuning range and precision. Several mechanical and thermal calculations of the cryomodule, structural support and alignment systems have led to an initial conceptual designs for both cryomodules (see Fig. 15).
Progress was equally significant in understanding what influence the crab cavity systems will have on the beam, both wanted and unwanted. The “wanted” effect of course is the correction of the geometrical effect of a finite crossing angle on the bunch overlap in collision; the transverse force by the crab cavity fields creates different orbit bumps for head and tail of each bunch, these bumps are closed around the IP. “Unwanted” – and for this reason well studied – are potentially detrimental effects of the impedance spectrum of the crab cavities and a possible transverse emittance increase by noise entering through the crab cavity system.

The study of RF noise effects, undertaken in collaboration with CalPoly University in California, is now complete: Theoretical studies, using a statistical signals approach, considering the complex interplay of the beams, the crab cavity systems with their amplifiers and LLRF systems and the transverse damper, and simulations using the PyHeadTail tracking code were performed. The results have been summarized in a paper (“Transverse emittance growth due to RF noise in the high-luminosity LHC crab cavities”, PRST-AB 18, 101001, 2015). Work has started on the reduction of the crab cavity noise using a feedback acting on the crab cavity demanded voltage, and on the cleaning of the transverse bunch tails using spectrally shaped phase noise in the crab cavity, to selectively excite the tail population.

LHC Injector Upgrade

BE-ABP Group

The main goal of the LHC Injectors Upgrade (LIU) project is to enable the accelerators of the LHC injector chain to produce LHC beams matching the requirements of the future High Luminosity LHC (HL-LHC) run. Throughout 2015, important machine and simulation studies for the different accelerators of the injection chain (for both protons and ions) were carried out in order to define, steer and/or validate the upgrade baseline program. The highlights of the ABP contributions to LIU in 2015 are described in the following paragraphs.

The brightness of the LHC beams is defined at the PSB injection, in particular it is determined by the space-charge effects occurring in the low-energy part of the ramp (and by the multi-turn injection process itself). By a careful choice of injection working point to move the space-charge tune footprint away from the integer lines, followed by a re-optimization of the injection steering, the LHC-25ns beam emittances could be brought down from > 2.6 µm (at the start-up) to ~2 µm, in line with the best performances obtained before LS1. A similar gain was achieved for the LHC-50ns and for the high intensity LHC-Scrubbing beams, as shown in Figure 16.

Figure 15: Conceptual Design of the 2-cavity cryomodules for the DQW cavities (left) and the RFD cavities (right).
Figure 16. Emittance vs. intensity at extraction in the PSB. In blue the reference “PSB brightness curve” measured by B. Mikulec in 2012 after a careful optimization, on R3 only. In red the points before/after the change of working-point, averaged over the 4 Ring.

In the PS, progress was done in understanding the potential and the limit of the new longitudinal damper, in improving the machine impedance model and using it to deepen the understanding of the transition instabilities, in the studies to mitigate the space charge limitation considering flat/hollow bunches and alternative integer tunes.

At the SPS, two full weeks of the 2015 run were devoted to the so-called “beam induced scrubbing”, i.e. running the machine with beams able to produce enough electron cloud in the vacuum chamber to lower the Secondary Emission Yield (SEY) of the chamber walls and eventually permit stable operation with LHC beams. The main focus of the 2015 scrubbing runs was to acquire experience with beams having intensities close to those expected after the LIU upgrades. LHC beams with about $2 \times 10^{11}$ protons per bunch can be produced nowadays at the exit of the PS with much larger transverse emittances and larger longitudinal emittance than the future target values. Besides, they cannot be accelerated in the SPS due to the insufficient RF power. However, these beams can be stores at injection energy in the SPS and the effects of the electron cloud in this high intensity regime can be assessed by:

- Monitoring the speed of scrubbing through the evolution of the pressure in the arcs, of the electron cloud signal in the strip monitors and of the beam quality indicators, like losses and emittance growth at flat bottom;
- Exploring and determining the machine settings needed to keep the high intensity beams stable.

The information collected during the scrubbing periods was presented to a panel of internal and external experts at a formal review, which took place on 8-9 September, 2015. As a result, the final recommendation was to continue relying on scrubbing also for future operation. The coating of the inner wall of the beam chambers with amorphous carbon will be applied to only one full arc of the SPS during Long Shutdown 2 (LS2) in order to test the logistics, while the option to extend it to the rest of the machine will be kept in store for the following long shutdown (LS3), if the experience with beams during Run 3 will prove it to be necessary.

Concerning ions, at Linac3 an intense study of the low energy beam was made, including a more detailed source extraction model that showed a serious aperture bottleneck after the source, for which preparation was made to modify the region at the end of the year. Additionally, as the oven delivering the lead vapour inside the source is not well understood, an oven test stand was developed and constructed, with the aim is to study the thermal properties of the oven and the lead evaporation evolution during a run.

[17]
The LEIR ring demonstrated an intensity limitation, and once lead beams returned, ABP performed a series of studies focused on the understanding and mitigation of this issue at LEIR. In particular at the end of the year, an intense effort was put into machine development. The studies showed that space charge is the mechanism leading to beam losses in LEIR during the RF capture process. The losses could be significantly reduced with respect to previous years by mitigation measures such as reducing the space charge tune spread by maximizing the longitudinal emittance and flattening the longitudinal bunch profile at RF capture, as well as resonance compensation.

Like in previous years, also in 2015 the ABP group has contributed to the LIU project through a strong support in general management activities, beam parameter definition and Machine Development (MD) coordination. The project has now a clear baseline defined for both protons and ions and is proceeding at the expected speed towards the hardware implementation in LS2.

**BE-BI Group**

**Fast wire scanner development and testing**

A new generation of fast wire scanners (FWS) is under development and expected to replace all existing scanners in the PSB, PS and SPS during LS2. The first prototype of this new system was installed in the SPS during LS1 (Fig 17).

![Figure 17: SPS test setup of the new fast wire-scanner prototype](image)

Before its installation, the scanner was mounted in the laboratory and extensively tested to verify its motion dynamics, compatibility with a UHV vacuum environment, contribution to longitudinal and transverse beam impedance and mechanical reliability with more than 60000 cycles performed. On the electronics side, 2015 was used to develop and test a whole set of highly specialised systems for controlling, powering and acquiring signals. This included advanced control techniques implemented into an FPGA, the motor powering unit and the DAQ to digitize the detector signals in an ionizing radiation environment. The system architecture is shown in Fig. 18.
Figure 18: System architecture of the new fast wire scanner control and acquisition electronics. The plot in the lower right corner shows the speed of the shaft as simulated and measured.

First beam tests were performed at the end of the 2015 run. Multiple measurement cycles were performed with ion beams at injection and top energy allowing beam profiles to be reconstructed. A detailed data analysis of these results and more tests with this and future prototypes will be required to conclude on the performance of the new system. The diamond detector performance was, however, already compared to standard scintillator-PMT detectors (Fig. 19).

Figure 19: Read-out architecture (left) and beam profiles obtained for 1 proton bunch of $1 \times 10^{11}$ at 450 GeV.

The diamond detectors showed promising results for high intensity beams at flat-top, but at low intensity or energy were dominated by statistical noise linked to the number of particles crossing the diamond detector surface ($1 \, \text{cm}^2$). These results suggest that further research is required on alternative detectors to achieve the high dynamic range required.

LIU-PSB

Beam and foil observation system at the stripping foil for PSB H⁻ injection

The new PSB injection region required for LINAC4 connection requires a system for monitoring the stripping foil integrity and observing the beam at the stripping foil location during the injection process. The design of this system was particularly complicated due to the limited space available and the required robustness and radiation tolerance. Production and assembly of these monitors was completed in 2015 with a total of 6 systems ready for vacuum acceptance testing.
**H0/H- Beam Current Monitors**

The H0/H- dump to be installed downstream of the PSB injection stripping foils to absorb unstripped particles, will be equipped with a set of measurement plates that will allow the relative amount of H0 and H- to be quantified. The design of this new detector was completed in 2015 with a first mechanical assembly and first version of the new acquisition electronics foreseen to be tested at the end of 2016 during the LINAC4 Half Sector Test.

![Figure 20. 3D drawing of the H0/H- dump with the measurement plates (red) and signal cabling (blue).](image)

**BE-RF Group**

As part of the upgrade of the LHC injector chain, the individual beam control and feedback systems of PSB, LEIR, PS and SPS are being completely redesigned using modern FPGA based digital systems. During 2015, the hardware upgrades of the PSB LLRF system and in the SPS 800 MHz LLRF system were completed. For the SPS damper, commissioning with ions has started and will be completed in 2016 with the addition of fibre delays to cope with the FSK modulated clock for alignment of beam signals and kicks in BA2. MD work on the 800 MHz cavities has shown the flexibility of the new LLRF system with commissioning of both cavities on the new LLRF foreseen for 2016. Noteworthy also the contributions to the feedback systems of the Finemet® cavities for tests using the new digital LLRF system of PSB.

The LEIR LLRF is planned to be fitted with the PSB-style LLRF suite of hardware in early 2016. Studies have started in the PS and SPS for the 200 MHz LLRF to decide on the technology to be used for the future upgrade under LIU, which is planned to be rolled out in LS2. In the SPS this comprises adapted feedback systems for the shortened RF cavities as well as independent control of cavities for slip-stacking of ions.

For the PS systems new 1-TFB (“single-turn feedback”) on the 10 MHz cavities now also include the AVC loop control of the voltage. All hardware using the same VME board for the higher frequency PS cavity feedbacks and the transverse dampers in PSB and PS were produced, tested and deployed in the machines. Dedicated firmware and software is now being developed to provide impedance reduction using feedback for the 20 MHz, 40 MHz and 80 MHz cavities as well as for the PSB and PS transverse dampers. The development of new, solid state power amplifiers in the kW range and covering the frequency range up to 30 MHz for the PSB and PS transverse dampers is also part of the LIU project.

The new distribution of the frequency program and B-train using White Rabbit technology is now considered mature so that full operation using the new system is planned for 2016.
SPS Power upgrade

After a careful, months-long analysis, the Final Amplifiers was granted to TCS (Thales Communications & Security) for the construction of a SSPA solution. This was unexpected and is remarkable, since it is a paradigm change for CERN. The design of the demonstrator has started and the schedule was agreed as follows: one demonstrator autumn 2016, 16 amplifiers autumn 2017, 16 remaining amplifiers Summer 2018. The design is based on RF blocks providing 2 kW, 80 of which will be combined in a cavity combiner instead of the usual 3 dB combiners. This proposal is still protected by a non-disclosure agreement, since it contains delicate choices that allowed the solid-state solution to be the lowest compliant offer.

![Image](image_url)

**Figure 21:** Far left: the proposed architecture of the new SSPA Final amplifier for the SPS, centre: concept of the cavity combiner in the centre of the tower, far right: the finished BAF3 building, which will house 32 of these towers.

Fig. 21 shows on the left a possible architecture of a 150 kW tower combining eighty 2-kW-blocks with a central cavity combiner, in the centre a cut-open view of the cavity combiner itself and on the right a photograph of the new BAF3 building close to the entrance to the CERN Prévessin site, which will house 32 towers of 150 kW each.

A detailed study of the coaxial line integration continued in order to find the best path from the surface building to the cavities. A huge number of lines will have to be added, with an additional total length of almost 500 m.

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

BE-ABP Group

Linac2 had a good year. Despite the fact that the source failed two times with a broken cathode the beam availability was in total 97%. At the end of the year some tests were done to quantify some parameters of the proton source for a better understanding of the operational behaviour.

A record intensity of $1.0 \times 10^{13}$ protons on the PSB Ring2 for TOF was achieved three weeks after the restart, mainly thanks to the successful alignment campaign done during the Christmas stop and the reduction to $<2\text{mm}$ rms orbit excursion in all the rings. The limitation in the production of high intensity beams in 2014 was indeed the physical aperture of the machine in the low energy part, and the orbit correction helped to make better use of it. ABP contributed by the choices of the minimum set of magnet displacements and of the optimum set of orbit correctors and by participating to the exploitation of the YASP application in the PSB.
On the theoretical side, progresses on the optics modelling and on the understanding of space-charge effects, thanks to several Machine Development sessions. In particular studies took place on the effect of chromaticity in combination with space charge, of tail repopulation time scale after scraping, beam profiles at low energy and optics with AC dipole excitation.

At the PS an intense measurement and simulation campaign was put in place to prepare the Multi-Turn-Extraction (MTE) beam for the 2015 operation. Thanks to these efforts the source of the limited reproducibility of the magnetic splitting could be pinned down. This allowed commissioning the MTE shadowing with the dummy septum together with the new extraction schemes for all others PS beams. The MTE beam was put in production for the North Area Fixed Target Physics in September and the MTE shadowing became operational in November.

At the SPS, the commissioning of the fixed target beam with the MTE from the PS was studied and optimized in detail. After a series of machine development studies in close collaboration with colleagues working on the PS side, this optimized beam transfer could be put in operation. Equivalent transmission compared to the traditional continuous transfer procedure could be reached in the SPS.

The performance limits of LHC beams in the SPS were explored through a series of machine developments and simulation studies, covering high brightness single bunch beams up to high intensity 25 ns beams. Two full weeks of the 2015 run were devoted to so-called scrubbing runs with 25 ns beams of up to 2x10^{11} protons per bunch stored at injection energy in order to study electron cloud effects. The data collected during these special runs provided invaluable input for defining the strategy for future high intensity operation of LHC beams in the SPS, i.e. relying also in the future on scrubbing as e-cloud mitigation strategy. In addition to the scrubbing runs in the SPS, ABP also made essential contributions to the studies and preparation of the special doublet beam for scrubbing studies in the LHC.

For the ion beams, at the beginning of the year Linac3 delivered pulses of 6x10^9 Ar^{11+}, for the fixed target experiment NA61 in the SPS North Area. The argon operation was demanding especially in the respect of source life time. Due to preventive maintenance and permanent survey no problems occurred during the run.

After this run the source was converted to be able to deliver the lead beam for the heavy ion run at the LHC at the end of the year. This included also the completion of the source control system, as the oven controls were only integrated at that moment.

At LEIR, after the argon run a strong study programme with lead was started, which helped deliver unprecedented ion beam intensities to LHC, such that the peak luminosity exceeded more than three times its nominal value for Pb-ion beams.

**BE-BI Group**

**AD:**

**First results with the Cryogenic Current Comparator**

A new current monitor was installed and commissioned in the AD for the 2015 run. This device, known as a superconducting Cryogenic Current Comparator (CCC), uses a SQUID-sensor to measure the tiny magnetic fields induced by the beam in a ferromagnetic core, to give nA current resolution. The instrument was also constructed to have a very low thermal in-leak, allowing the cooling power to be provided by a commercial liquefier unit (~1W @ 4.2K) for 24/7 operation.
The system enabled a stable and continuous measurement of anti-proton (pbar) beam currents along the AD cycle (see example in Figure 23), both during the bunched-beam deceleration phases, and the de-bunched beam cooling phases. A current resolution of 30nA was obtained after filtering out excess of noise showing up at 50Hz and odd harmonics. The beam intensity resolution achieved was $0.48 \times 10^5$ pbars (at injection) and $4.3 \times 10^5$ pbars (at extraction).

Limitations in the liquefier unit cooling power and cryostat heat in-leak in excess of the design value did not allow the cryostat to be operated continuously, while the 30nA resolution is still some way from the 10nA specification. Both of these issues will be addressed during the 2015-2016 shutdown, aiming at providing nominal performance for the 2016 run.
The CCC system was developed in collaboration with GSI and University of Jena in Germany with the cryogenic and cryostat system developed, manufactured and assembled at CERN in collaboration with TE-CRG, EN-MME, TE-ICE and TE-VSC.

New Orbit acquisition system

The BI group is renovating the obsolete electronics and software for the AD orbit system. The detectors are based on electrostatic beam position monitors (BPMs) fitted with low noise front-end amplifiers in the tunnel. In the new measurement system, the BPM signals are down-mixed to baseband, decimated and filtered before a beam position is computed. The digital acquisition part of the orbit measurement system (developed by the BE-RF group), is based on VME Switched Serial (VXS) and will allow orbit measurements to be made on the ramps, a major improvement over the existing system.

A vertical orbit was measured using a Python script on the 10th November 2015, with a beam of $3.4 \times 10^7$ antiprotons at injection. A comparison of the orbit measurement from both the new (blue) and old system (green) can be seen in Fig 24. Full commissioning if the system is foreseen in 2016.

![Figure 24: Vertical orbit measurement comparing new and old systems](image)

**SPS**

**HiRadMat:**

For the HIRADMAT experimental facility, the BI group was requested to equip each experimental station with diagnostics to be installed in front of the target station at atmospheric pressure capable of determining the target alignment with respect to the proton beam. Based on very good experience from the CNGS facility, it was decided to use stripline Beam Position Monitors (BPM) of the BPKG type. Even after a very accurate mechanical alignment the residual offset between the mechanical and electrical centre of the BPKG is often difficult to determine. It was therefore decided to install a BTV (a 2D beam imaging device based on screen) just downstream of the BPKG to determine such offsets with beam. Figure 25 shows the layout of the BPKG and BTV on a common girder. Experiments HRM23, HRM24 and HRM27 were successfully operated with the BPKG and BTV.
SPS North Area
Scintillating fibre detector development

In the SPS experimental areas, the extracted proton beam is made to collide with primary, secondary and sometimes tertiary targets, producing beams of particles that are selected and sent to experimental users in the North Area. These beams can be composed of hadrons (protons, kaons, pions, antiprotons...), leptons (electrons, positrons, muons...) and lead ions. Their momenta vary greatly, from 1 to 400 GeV/Z/c, with intensities from $10^3$ to $10^8$ particles per second.

The profile and position of these beams are typically measured using wire chambers or scintillator finger scanners (FISC). The maintenance and repair of these monitors is becoming problematic and a new monitor based on scintillating plastic fibres (SciFi) is therefore being developed to replace the ageing detectors installed in the zones. Scintillating fibres have a core made of polystyrene cladded with one or two layers of lower refractive index material. This gradient of refractive index allows a fraction of the light created inside the fibre to be trapped by total internal reflection. Light production typically reaches up to 8000 photons per MeV of energy deposited while the trapping efficiency of square fibres varies between 4.2% and 7.3%.

The fibres are read-out with silicon photomultipliers (SiPM) which have a very good photodetection efficiency in the wavelength at which the fibres operate (435 – 450 nm). Apart from their compact size and insensitivity to magnetic fields, SiPMs have a high gain (>10$^6$) and provide fast pulses with sub-nanosecond rise time and a fall time of 50 – 100 ns.

A prototype of such a detector was built and tested in the H8 beam line of the SPS North Experimental Area. It was installed close to two other profile monitors: a delay wire chamber (DWC) placed upstream and a FISC downstream allowing direct comparison between them. A scintillator counter placed upstream provided accurate intensity measurements.

Hadrons and leptons with momenta between 20 GeV/c and 180 GeV/c and intensities from $10^3$ to $10^6$ particles/spill were measured and the profiles compared to the other monitors. The SciFi monitor worked satisfactorily in all situations, whilst the DWC had troubles with high intensities, showing distorted profiles or artificial tails. The FISC on the other hand was unable to work at intensities lower than $10^4$ particles/s. In addition to that, the intensity measured by the fibres agreed with the intensity from the scintillation counter.
**BE-CO Group**

**Data Concentrators**

A new data concentrator instance was developed and deployed for the PS Beam Loss Monitors. This involved the complex task of adapting the software used in the LHC to work at the data frequency relevant to the PS (i.e. every basic period of 1.2s).

**Fixed Displays**

As shown in the screenshot, a new dedicated Fixed Display was developed and deployed to monitor the PS Complex Beam Loss Monitor activity.

![CPS BLM FIXDISPLAY](image)

**Figure 26: The newly developed Fixed Display for PS Complex BLMs**

**Beam Quality Check for the SPS**

BE-CO tries to port solutions that were developed for the LHC into the rest of the accelerator complex. A recent example is the new SPS Beam Quality Check system, which is based on the LHC Injection Quality Check. BE-CO-APS collaborated with three other teams: BE-BI for the analysis data, TE-MPE for data storage infrastructure, and BE-OP for the requirements, implementation of analysis logic and a GUI (c.f. image below).

The SPS BQC collects, displays characteristics of the SPS beams. It saves the data in long-term storage, so that beam characteristics at different times can be compared, and trends can be established on how certain characteristics evolve over time. The characteristics important for OP are summarized in a new GUI (c.f. below). Previously the operators had to open a dozen different GUIs to gather the same information.
Improvements in CESAR

In 2015, members of the CESAR team worked on long-standing feature requests and on reduction of technical debt. Amongst others, the configuration of the beam lines was simplified, to reduce the support load on the CESAR team. GUI tools were developed to handle common re-configuration requests (e.g. changing the main user of a beamline, c.f. image below), and stored procedures were written in the database to reliably handle less frequent requests (e.g. changing the safety matrix). Now that the EA liaison physicists are able to configure many things on their own, the support load on the CESAR team went down considerably. Other new features include a display of the beamlines, and a status panel (c.f. image below) that was embedded into CESAR GUI. The latter provides the SPS operators and EA liaison physicists with a list of possible reasons preventing the beam from arriving to experimental areas, which greatly facilitates their diagnostics.

Figure 27: GUI to display Beam Quality of an SPS beam for LHC

Figure 28: New GUI to configure rights of terminals located in the Experimental Area barracks
New timing diagnostics applications

The timing system is a fundamental and complex component of the accelerator controls system. It is important that the operations teams can diagnose timing problems around the clock, without having to call a timing expert. Similarly, the timing team need good tools to detect malfunctions before they affect operations. For this purpose, two new timing applications have been developed, one to show the external conditions of the timing system which might inhibit the beam (first image below) and one to inspect the static and dynamic configuration of the central timing events (second image below). These tools have been put into operations at the end of 2015. They are expected to increase accelerator availability, and reduce the support load on the CO timing experts.
The CO group undertook in 2015 a major reverse engineering of all existing PSB cabling databases (Gesmar and CO) used for the control of core systems such as OASIS, General Machine Timing (GMT) system and Power converters. This effort conducted on the field with our colleagues from the Field Support Unit (FSU) allowed the deconnection of obsolete cables, the renovation of about 1000 operational signals and the operational recommissioning of all systems concerned. All obsolete cables will be dismantled during the EYETS 2016-17.

BE-OP Group

2015 was a full year of injector operations. See schedule below.
Booster

The start-up of the PS Booster after the 2014/15 year-end technical stop (YETS) was smooth and rapid. Throughout the year the machine was running with high up-time and delivered beams to its direct user, the ISOLDE facility, and to the downstream synchrotrons.
Besides beams for the physics users, the PSB delivered also a variety of special beams for machine studies with the goal of pushing the performance, reducing beam loss and preparing the LHC injectors upgrade (LIU). One of the important items to study in the PSB was the new wideband RF system, for which a test cavity had been installed in Ring 4. After having undergone numerous tests, the new cavity was used in a reliability run delivering ISOLDE beams with nominal performance and availability.

Preparation work has also been ongoing for the future upgrade of the Booster to 2 GeV beam energy. The most visible item has been the construction of a new building 245 for the 2 GeV main power supply, which took shape during 2015.
PS

The Year 2015 saw an early start after a very short year end technical stop (YETS). The PS closed already on January 19th and the first Argon ion beam was delivered to the SPS on Tuesday January 27th. After the initial setting up period the Argon ion beam was deliver to the SPS for the 6 week physics run in the NA that was completed on April 8th.

In parallel different proton beams were setup with as first deliverable the LHCPROBE and LHCINDIV beam for the LHC sector test scheduled on March 6th.

Prior to the delivery of the various proton beams for fixed target physics in the PS and SPS, a period of beam development was devoted to the so-called doublet beam to be used for scrubbing with enhance electron cloud production in the SPS. The aim was to setup the beam also for tests in the LHC later in the year. For the PS this meant producing the nominal LHC beam with higher bunch intensity, but instead of shortening the bunch prior to extraction it was kept long and the synchronisation was changed such that the PS bunch would cover two SPS buckets, producing 2 bunches (doublet) spaced by 5 μs spaced by 20 ns, resulting in 144 bunches at low energy in the SPS.

On April 7th the nTOF beam was send on the target heralding the start of the 2015 nTOF physics run for which 1.7x10¹⁹ protons on target were forecasted. Until the end of May the new 2nd experimental area was successfully commissioned. When the nTOF physics run finished on Monday November 16th 1.88x10¹⁹ pot were accumulated, which is 11% more than initially anticipated. This was achieved thanks to the continuous optimisation of the beam intensity and the super cycles’ configuration to maximise the proton flux, but also in large part thanks to the more efficient switch-over of the nTOF experiment in October.
The SPS Fixed target proton beam (SFTPRO) was send to the SPS for setting up on April 17th and for physics as of April 27th. The extraction system used in the PS was the continuous transfer (CT) until September 21st when after full commissioning the Multi-turn Extraction was used operationally until the end of the proton run. It was then also decided to restart with MTE immediately at start up in 2016 and leave the CT extraction available as back-up.

The setting up and beam commissioning for the new IRRAD and CHARM facility in the East Area started on April 20th. Several beam optics with different beam sizes at the irradiation tables were adjusted, tested and validated. The physics in both, the East Area North branch (T9, T10 and T11) and South Branch (T8: Irrad and CHARM) started on May 4th. The East Area beam in the PS is produced, using low intensity (~4x10^{11} ppb) from one PS Booster ring, leaving room to inject a 2nd (parasitic) higher intensity bunch (~3.5x10^{12} ppb) that is extracted at 20 GeV/c to nTOF. The low intensity bunch is further accelerated to 24 GeV/c where the beam is slow extracted during ~400 ms to the East Area users.

In the meantime, the LHC started the commissioning with beam followed by the intensity ramp up, using the standard 72 bunch LHC beam with 25 ns bunch spacing. The quality of this production beam was followed closely in the PS by making longitudinal and transverse beam quality measurements every shift.

On June 10th the PS delivered successfully and timely the next beam for the AD on target.

In the meantime, the busy parallel and dedicated MD program in the PS and SPS had started for which many different beams have been setup. The OP teams provided a high level of support to the teams performing these MDs, ensuring beam delivery and quality, but also training to those less experienced with PS operation.

The proton runs ended on Monday November 16th. However, due to a delayed start of AD physics the AD beam production continued together with the LHC proton beams until November 23rd.

During the protons run the ion chain was switch from Argon to Lead again with first beam in the PS towards the end of August. The PS then delivered the lead ion beam to the SPS towards the end of September, for setting up followed by a North Area and LHC lead ion physics run.

Thanks to the excellent support from the equipment and support groups and the efficient troubleshooting by the operations teams the PS enjoyed an excellent beam availability, which is summarised in the table below. This availability is the accumulated availability of LINAC2, PSB and PS for the protons and the LINAC3, LEIR and PS for the Argons and Lead ions.
Beams | start | 2015 Availability |
--- | --- | --- |
LHC | 25/03 | 95% |
EAST | 04/05 | 94% |
SFTPRO (CT/MTE) | 27/04 | 93% / 95% |
TOF | 07/04 | 94% |
AD | 06/07 | 94% |
Pb Ions | 16/11 | 98% |

SPS

2015 operation with beam in the SPS started on 26th of January, when Ar ions were sent down TT10 first time after the shutdown - ready to be injected into the SPS. Only two days later Ar ions were successfully slow extracted to the North Area. The first 6 weeks of physics were dedicated to ion operation in the North Area at 6 different energies with up to 5e+10 charges extracted per spill. The programmed Ar beam momenta were 333.3 ZGeV/c, 28.9 ZGeV/c, 42.2 ZGeV/c, 66.7 ZGeV/c, 88.9 ZGeV/c and 166.7 ZGeV/c. In parallel with this complicated operation the LHC pilot cycle was commissioned for the LHC sector test and ready for the start of LHC commissioning at Easter.

After Easter the SPS switched to proton operation in the North Area and a series of dedicated SPS scrubbing runs started with the goal to evaluate the possible secondary electron emission yield reduction attainable with scrubbing only. For the purpose of scrubbing the SPS injectors were pushed to the edge of their performance possible before the LIU upgrades. They provided bunch intensities of up to 2e+11 protons per bunch in 25 ns trains, albeit with twice the normal transverse emittance. The transmission for these very high intensities was rather poor in the SPS, with losses of up to 25 % seen just on the flat bottom. And with the fourth and final scrubbing run in June it was evident that further scrubbing did not improve the situation, reinforcing the need to continue the development of the amorphous carbon vacuum chamber coating for electron cloud suppression.

The record bunch intensity accelerated for 25 ns LHC beams was achieved during the HiRadMat experiment “Collimator jaws” in July 2015. It amounted to 1.37e+11 protons per bunch extracted at 440 GeV (the injected intensity was 1.49e+11 protons per bunch). A total of 6 different HiRadMat experiments took place in 2015 with a total of 3.7e+15 protons extracted, with beam time on this unique facility in high demand.

A large variety of proton beams were prepared for the LHC: 50 ns beams, 25 ns beams, doublet beams, single bunches, 8b+4e, etc. For the typical physics fills the LHC was filled with 25 ns standard beams with maximum 144 bunches extracted from the SPS, 1.2e+11 protons per bunch in about 2.5 um transverse emittance. The main limitation for increasing the bunch intensity further is beam loading and capture losses, to be addressed by the major LIU upgrade of the 200 MHz RF system in LS2. Uncaptured beam that is partly re-captured during the first part of the SPS acceleration was also one of the main sources of injection losses at LHC injection during 2015.

Fixed target operation changed significantly in 2015. The spill is no longer controlled with the localized servo quadrupole feedback system, but with a feedforward correction distributed on the main quadrupoles. In this way the trajectory in TT20 remains stable despite changes in the spill. The feedforward algorithm was commissioned with the fixed target ions and put into operation on the first day of proton fixed target physics.

At the end of September the SPS switched to injecting MTE beam from the PS as the standard fixed target beam, in an attempt to reduce losses in the PS from the CT extraction. Similar overall transmission was finally achieved with MTE beams despite its larger emittance in the vertical plane, although losses in the
SPS were slightly higher, balancing the gains in the PS. The total number of protons slow extracted to the North Area in 2015 was very high, at 1.65e+19. This already had a negative impact on the activation in the extraction region in LSS2 and at the NA splitters that distribute the beams to the different targets, made worse by the fact that the losses per proton in LSS2 were roughly 20 to 30% higher than in previous years. To combat this, more surveillance and more stringent interlocking was put in place for the 2016 run. Inadequate alignment of the ZS with respect to the orbit was found to be the main culprit, due at least in part to an overall lack of machine stability.

In October ions returned to the SPS, in the shape of fully stripped Pb\(^{82+}\). The last 4 weeks of the run were dedicated to Pb operation for the LHC and the North Area. The momentum of the extracted Pb ions to the North area was 76.1 ZGeV/c.

An effective way of increasing the number of ion bunches in the LHC was put in place in the last weeks of the ion run. The trick was to inject batches in the SPS spaced by only 150 ns using a (faster) subset of the injection kickers, and to make the transverse damper operational for ion cycles to damp the resulting injection oscillations of the partially kicked bunches. Compared to using the nominal injection kicker rise time of 225 ns, about 20% more bunches and hence luminosity could be obtained in the LHC. The transverse damper was also beneficial for the notoriously short ion beam life time at the flat bottom of the SPS cycle.

Overall it was a complicated, varied and challenging year, but one in which the SPS again demonstrated its versatility and capacity to deliver, both as a key element in the LHC injector chain and as a provider of beams to its own community.

![Fig 36: Intensity through the cycle for all shots during HiRadMat experiment HRMT23 Collimator jaws where the record bunch intensity extracted was achieved.](image)

**BE-RF Group**

The year 2015 again is characterized by a high availability of the RF systems of the LHC injector chain. This high availability leaves no “highlight” to write about, but it is nonetheless remarkable, since some systems are very old, kept modern and functional with much care by a team of committed experts (many of who are younger than the equipment they care for). They anticipate potential shortcomings, suggest and implement improvements and intervene quickly and effectively when troubleshooting becomes necessary.

**ELENA**

**BE-ABP Group**

The Extra Low Energy Antiproton ring (ELENA) project aims at constructing an small synchrotron further decelerating antiprotons injected with 5.3 MeV, which is the lowest energy
safely achieved in the six times longer Antiproton Decelerator AD, down to 100 keV. The machine will be equipped with an electron cooler to limit losses during deceleration and provide dense bunches for the users. The aim is to improve the efficiency of experiments typical capturing the antiprotons in a trap and to make new types of experiments on gravitation of antihydrogen possible.

At the beginning of the year, kicker generators for the AD and in the future ELENA, which had been located inside the AD hall at the location needed for ELENA, have been re-installed in the new annex building. Then, finally, preparations for installations have started. Most of the infrastructure required as a false floor, a modified area for electronics racks with a second floor to increase the available space, electrical distribution, cooling water distribution have been installed and a first cabling campaign has taken place. Only a few machine components could be installed.

In particular preparations for the installation of the part inside the AD tunnel of the transfer line from the AD to ELENA were well advanced to complete the installation before the AD restart 2016. Construction of components is well advanced with all contracts for large equipment as magnets and power converters placed or manufacture started at CERN as for all complex vacuum chambers.

The aim for the future is to complete the installation of the ELENA ring and the transfer lines required for the commissioning of the ring until early summer 2016 followed by commissioning until the end of the year. From 2017 on, 100 keV antiprotons will be available at least in the new experimental zone housing the GBAR experiment.

**BE-BI Group**

**Beam profile measurements**

A new BTV system was developed to be capable of measuring the transverse beam position and size just upstream of the injection kicker and on the first turn in the ring. The setup consists of two distinct systems each incorporating a 6x4 cm Al₂O₃ scintillating screen, a CCD camera, filter wheel, optical elements and a pneumatic in/out movement in a common vacuum tank.

The BTV for the circulating beam will be part of the access interlock system. The design was completed and based on a ‘bellow-less’ in vacuum magnetic push-pull actuator (Fig. 37).
Beam Position Measurement System

The ELENA closed-orbit measurement will be using 20 circular BPMs mounted inside quadrupoles and dipoles. After amplification, the difference and sum signals will be transported by ~50m cables, digitized and processed using digital normalization for position calculations. Prototypes of both the mechanics and electronics have been successfully tested and series production is not underway.

Special BPMs are also under construction to measure both the circulating beam and electron beam trajectories in the electron cooler.

Tune Measurement System

The ELENA tune measurement system is based on the direct diode detection principle already deployed on many accelerators of the CERN complex (Base-Band Tune or BBQ). Two dedicated strip-line pick-ups were constructed (Fig. X), one for the detection and one for use as an exciter.

Figure 38: ELENA stripline monitor for the tune measurement system.

BE-CO Group

Accelerator Timing and Sequencing

ELENA central timing

A first version of ELENA central timing was released and made available to the clients to allow early tests using ELENA timing events, as well as integration with the central timing itself. The central timing reuses existing components and is based on the same principles as the new AD central timing, the so called dynamic beam negotiation (DBN). The new approach to scheduling beams is well suited not only to precisely defined short cycles, but also long ones that may be even paused for a (theoretically) unlimited time.
ELENA Controls Infrastructure

2015 was a very intense year for the BE-CO to put in place the completely new control system infrastructure for the ELENA machine.

After collecting all operational requirements and equipment groups specific requests, the BE-CO group deployed a brand new central timing distribution network and OASIS system covering about 28 electronic racks in ELENA and AD.

Figure 39: Systems involved in defining and scheduling for the ELENA central timing (CT).
BE-RF Group

The stochastic cooling system has worked reliably during 2015 thanks to the consolidation of the LLRF and its control using modern PLCs. Forty-eight power amplifiers, meticulously maintained in the shutdown, which is essential for correct operation of the system that cools the beam in all three planes, horizontal, vertical and longitudinal. It is known that the system does not presently achieve the theoretically possible cooling rate; there is a potential gain in cooling efficiency by improving the electronics which can help reduce the cycle time (presently 100 s); this would increase the number of anti-protons provided to the experiments and to ELENA. Primary aim of present investments in the system however is the consolidation at present performance.

The next items that were started in 2015 are the power amplifiers and the notch filters of the longitudinal system. Collaborations with experts at GSI and Cosy in Jülich are being explored for help and expertise. Alternatively a digital solution was also considered and will further be followed-up with external experts.

For ELENA, the development and production of the ferrite loaded cavity pick-ups continued. Optimised high impedance amplifiers were developed and the system is now ready for production with installation of the first pick-ups in ELENA foreseen for 2016. The LLRF system using the PSB-style suite of electronics has been produced and tested, including a series production to be used by BE-BI for beam instrumentation purposes.

LINAC4

BE-ABP Group

In November 2015 the Linac4 reached an important milestone: the beam was commissioned up to the energy of 50MeV, matching the energy of Linac2. The beam was accelerated through the DTL to the final energy without losses. This milestone validated the design and construction of the Drift Tube Linac components, of the Permanent Magnet Quadrupoles and of the RF regulation system. The transverse emittance and the phase energy spread measured on a temporary bench located after the 3rd tank matched perfectly the expectation from the simulation. Beam based
measurements were used to cross check RF settings allowing a perfect tune of the RF parameters. The chopping was verified.

Installation of the Cell Coupled Drift Tube Linac and the PI-Mode Structure continued through the year with about 80% of the accelerator installed by the end of 2015.

The Linac4 source demonstrated to have the potential to provide 50 mA of H-. During 2015 only a fraction (30 mA) of the total available current could be transported through the RFQ due to the too large emittance. The operation of the source during the 50MeV commissioning was stable, reliable and dependable. The caesiation was mastered and done remotely. In parallel the Linac4 source test stand was run to investigate how to improve source performance.

![Figure 33. Beam output energy as a function of RF phase and amplitude, measurement (dots) and simulation (lines) shown. Right: Simulated and measured emittance at 50MeV.](image)

**BE-BI Group**

During 2015 the LINAC4 H- beam energy was increased to 50 MeV. The 3 and 12 MeV measurement bench was therefore dismantled, with all its beam instrumentation recuperated for later use elsewhere in the machine, and a new measurement line installed (Fig. 35). At 50 MeV the spectrometer installed at lower energies can no longer be used because of insufficient field strength in the magnet, while the slit-and-grid emittance meter also had to be abandoned because the energy deposition in the slit would have been too high.

![Figure 35: 3D drawing of the 50 MeV test bench, with beam diagnostics highlighted](image)
As a consequence, a new emittance measurement system consisting of 3 profile measurement stations was installed. While it was foreseen to use wire-grids for these measurements, there was sufficient space in the wire-grid tank to additionally install wire-scanners, allowing a direct comparison between wire-scanner and wire-grid measurements. This showed that the coupling of signals between wires in the wire-grids, caused by stripped electrons created when the H- ions hit a wire, was negligible.

The standard method for emittance determination using the three profile method does not work in the case of LINAC4 due to space charge effects. A new method, known as the “forward” method was therefore developed in the BE-ABP group to take these effects into account. The results obtained using this method very nicely fit the Twiss parameter values expected by simulations.

The existing bunch shape monitor (BSM) was recuperated from the 3 MeV measurement line and re-installed on the new 50 MeV measurement bench. At the end of the 50 MeV commissioning the BSM was successfully running on a new VME control platform.

**Adjusting the RF cavities using beam position monitors as phase probes**

The Beam Position Monitor (BPM) system installed on the 50MeV measurement line can measure position, relative intensity and phase. During commissioning of the DTL RF cavities, the RF amplitude and phase must be adjusted and modifying these parameters results in a change of particle energy at the output of the cavity. This can be measured using a time-of-flight method comparing the phase measurement at 2 BPMs. The energy curve obtained when scanning the RF phase for a fixed RF amplitude has a characteristic shape such that the measurement result can be easily assigned to a specific RF amplitude. All three DTL cavities were adjusted in this way (see example in Fig. 36).

![Figure 36: Beam energy as measured after the DTL1 tank by the time-of-flight method (round markers), compared to beam dynamic simulations (solid lines).](image)

**The laser wire profile meter**

A new laser wire emittance meter was successfully tested at 3 and 12MeV. However, since the 50 MeV test bench did not include a spectrometer such a direct emittance measurement was not possible as the neutralised H\(^0\) particles created through laser stripping could not be separated from the primary H\(^+\) beam. It was however possible to extract the electrons created by laser stripping and detect them with a diamond detector. This allowed a measurement of the beam profile by scanning the laser through the beam while detecting the number of electrons generated. The profile measured in this way was compared to profiles measured with neighbouring wire-scanners and wire-grids, with the results agreeing to within a few percent (Fig. 37).
In 2015, the third and the second Drift Tube Linac (DTL) tanks have been assembled in this order, subsequently tuned and tested, and finally installed in April and August 2015, respectively. On the left of Fig. 5 is a view of the new DTL installed inside the Linac4 tunnel. This brought the number of installed cavities to about half of the total. Also three out of twelve Pi-Modes Structure (PIMS) modules were completed and placed in the Linac4 tunnel for installation in 2016.

On the surface, the last klystrons were received, installed and connected – the Linac4 klystron gallery now houses 9 former LEP klystrons and 8 new, state-of-the art 2.8 MW klystrons. The first two of these new klystrons were put in service and started successful operation, powering the DTL cavities. A view of the Linac4 klystron gallery is shown on the right of Fig. 5. To cope with the operational mode of Linac4, profound retuning of the LEP klystrons was necessary: the high voltage tank had to be replaced to minimize the stored energy in the high voltage cabling. In addition, the klystron cavities were retuned and the operating voltage increased by 10% to achieve sufficient stability of the RF output signal over the range of (70% ... 100%) of maximum saturation power. However, the associated impact on the klystron performance is important and the efficiency loss is large; the impact on the life time is not yet known.

Development and commissioning continued on the new Linac4 LLRF system, which is an evolution of the system developed for the LHC, more compact and using more recent components. For each cavity we have one VME crate with CPU, timing receiver card, a clock generation card using the Reference Line signal, an interlock card and two cards respectively responsible for tuning and field control.

Linac4 was subsequently (23rd November 2015) commissioned with beam to 50 MeV – the RFQ, buncher, chopper, DTL1, DTL2 and DTL3 are now operational – an important milestone since now Linac4 would be ready to replace Linac2 in case of unrecoverable failure.

Figure 37. Vertical beam profile at 50 MeV as measured by the laser wire system and compared to two adjacent SEM grids.

**BE-RF Group**

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Figure 37: Left: the Drift Tube Linac (DTL) installed in the Linac4 tunnel, right: a view inside the Linac4 klystron gallery.

COLLIMATION PROJECT:

BE-ABP Group
In LS1, the LHC collimation system underwent important upgrade and consolidation plans. New passive protection of the warm magnets of the momentum cleaning insertion (IR3) were installed; the collimation of collision products (physics debris) was improved by adding 8 new collimators around the high-luminosity experiments; 18 collimators were replaced by a devices with a new design that integrates beam position pickups at either side of each jaw. These new systems were successfully commissioned in 2015, producing important benefits for the first operation at beam energies up to 6.5 TeV, in particular, in terms of a faster alignment. Within BE, the responsibility of this system lays in the ABP and BI groups that work in close synergy with EN/STI.

Overall, the beam cleaning performance has been outstanding. In 2015 the LHC stored beam energy reached about 250 MJ. Operations were ensured without quench from circulating beam losses, thanks to a betatron cleaning inefficiency of a few $10^{-4}$. The system maintained this performance throughout the year, with a single alignment in IR3/6/7, providing also an excellent availability.

The collimation hierarchy determines the protected aperture and therefore the minimum $\mu$ in the high-luminosity experiments. Through a series of machine studies that addressed tighter hierarchies, impedance of the system triplet aperture and alignment tolerance, the collimation team collected the information needed for pushing the LHC performance and prepared a solid proposal for an operation at 40 cm $\mu$ in 2016.

Collimation activities in ABP also covered studies for the HL-LHC project (WP5). In 2015, the first technical design report of the collimation upgrade has been completed. Upgrade activities also cover machine studies to understand limitations for HL-LHC and propose new collimation solutions. For example, for the first time hadron beam channelling at 6.5 TeV was observed in a dedicate crystal collimation setup installed in IR7 to study the possible usage of bent crystals for beam collimation. Lead ion channelling was observed at 450 Z GeV. These are world records that lay the foundation for possible usage of this novel technique for beam collimation in the future.
An example of crystal measurements, showing the onset of channelling from the reduction of beam losses downstream of the crystal, is shown in Figure 5.

Figure 38. Dependence on crystal angle of the beam losses observed downstream (curve 1) for the LHC coasting beam of 6500 GeV/c protons. Curves 2 (solid line) and 3 (dotted line) show the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by different simulations tools (From Phys.Lett. B758 (2016) 129-133).

**BE-BI Group**

In 2015, the first Beam Position Monitors embedded in collimator jaws were put into operation in LHC. They are now used routinely to centre the 16 TCTs and 2 TCSPs collimators in few seconds with a sub-micron resolution as shown on Fig. 39.

Figure 39: Example of a BPM-based alignment of the TCSP.A4R6.B1, showing the left-up (LU), left-down (LD), right-up (RU) and right-down (RD) electrode (top left) and jaw positions (right), as well as the upstream (UP) and downstream (DW) measured beam positions.
REX/ISOLDE/HIE-ISOLDE:

**BE-ABP Group**

During the year the low-energy part of the REX-ISOLDE post accelerator delivered stable beams for the commissioning of the HIE-ISOLDE superconducting linac. By the end of the year also a few neutron-rich radioactive Zn isotopes was delivered for physics. For REXEBIS new timing and function generation systems were also introduced. With these the last legacy of non-standard controls for REX-ISOLDE were suppressed.

As part of our strive to characterize the beam delivered to the post accelerator a campaign aiming to measure the transverse emittance of REXEBIS was initialised. Performance optimization of an emittance meter using a pepper-pot combined with MCP detector was carried out. The pulsed, very low-intensity beam places extra challenges on the device, but great progress was achieved concerning the measurement method.

At TwinEBIS a new IrCe cathode type was tested. An activation procedure as well as additional data points for the cathode work function could be established. It was found that IrCe does not suffer from poisoning, however the mechanical mounting of the cathode was insufficient so a heat bridge developed at high heating power.

**MEDeGUN development**

The CERN Knowledge Transfer fund decided to support the development of a high-compression electron gun, capable of producing C6+ ions with a high repetition rate. The electron gun is a derivative of the HEC2 gun developed in collaboration with BNL. Throughout the year the basic concept was revised, and 2D symmetric and 3D asymmetric simulations of the electron beam inside the electron gun and collector regions were performed. Special attention was given to the phase-space acceptance in the magnetic gradient of the main solenoid to assure that the electron beam losses are low. Based on the simulations mechanical tolerances for the individual electron gun elements could be established, and a first version of the design was produced.

**BE-BI Group**

**HIE ISOLDE**

During the early part of 2015 all the diagnostic boxes of HIE-ISOLDE were installed (Fig. 40). Two types of boxes were developed in order to optimize the accuracy of the measurements and accommodate the tight space constraints in the inter-cryo module regions. In total 5 diagnostic boxes of the short type were installed and 8 of the long type. Each box includes: a Faraday cup for the measurement of beam current, a moveable blade with two V shaped slits for the measurement of transverse beam profiles and a collimating blade with apertures of different shapes and sizes. In a few special boxes, additional measurement devices are installed such as silicon detectors for the measurement of particle-energy and mobile stripping foils for changing the charge state of ions.
During the second part of the year the devices were commissioned with beam and used for setting up and operating this new machine (see example in Fig. 41 (left)). All devices performed as expected and were extensively used. In particular, the compact Faraday cup designed for the short diagnostic boxes proved to be as accurate as the standard version used in the longer boxes. In both cases an excellent pulse-by-pulse readout resolution of 5 fC was achieved.

Silicon detectors installed inside two diagnostic boxes, upstream and downstream of the cryo-module were extensively used to measure the beam energy as a function of RF parameters inside the buncher and normal and superconducting accelerating cavities. This type of measurement is crucial for the setup of the RF system and Fig. 41 (right) shows a clear correlation between the RF phase and the beam energy measured using these detectors.

**Figure 41:** (Left) Transverse beam profiles as function of quadrupole current for a total beam current of only 19 pA. (Right) Beam energy as measured by a silicon detector inside a diagnostic box installed downstream of the cryo-module as function of the RF phase in the first superconducting cavity.

**BE-CO Group**

**Renovation of the REX-EBIS control system**

Prior to 2015, REX-EBIS was controlled via a FESA2-based control system which had become obsolete and difficult to maintain, especially since the person implementing it had left CERN.

The system was given a complete overhaul, essentially replacing it with a system based on the latest CO standard components, which brings with it two major advantages: 1) it guarantees that a number of different CO experts can readily intervene in case of problems, i.e. there is no single
point of failure and 2) the system no longer contains any application logic, which now resides at
the Java application level. This makes the REX-EBIS control system flexible and maintainable for
the years to come. The new REX-EBIS control system was made operational during 2015.

![Figure 42: REX-EBIS timing dependencies](image1)

**REX central timing**

The REX central timing was renovated. The front-end crate has been redesigned and renovated, as
well as the software has been rewritten using new FESA3 components. In parallel to the new
implementation, an extensive automated test-suite was developed to guarantee smooth release and
easy re-testing in case of future upgrades.

![Figure 43. The new simplified design of the REX central timing crate.](image2)
2015 was a particularly important year for the ISOLDE facility. In addition to a rich low-energy experimental campaign, phase 1A of the HIE-ISOLDE project was completed and the first high-energy experiment was conducted.

Activities at the facility started right after the Christmas break. Maintenance of the different systems was completed during the technical stop between January and March. The separators and the low-energy experimental transfer lines were re-commissioned using stable beam during the first two weeks of April.

The physics campaign started with the first Radioactive Ion Beam (RIB) in mid-April and continued until mid-November. Dozens of experiments were successfully carried out during those eight months covering multiple research areas in nuclear physics, solid state physics, biophysics and medical physics.

The HIE-ISOLDE project made a lot of progress during the year and reached an important milestone in May when the first cryomodule was moved from the SM18 building where it was assembled to the linac bunker. The installation of the rest of the linac and the first two HEBT lines had started at the beginning of the year and continued until June when the first tests of the hardware commissioning phase took place. In addition to HIE-ISOLDE, many systems of the REX linac were renovated or refurbished during 2015. Among others: new water cooling circuits for magnets and RF cavities were installed, the power converters of the quadrupoles were replaced, two fast Penning gauges and a fast acting valve to protect the SRF cavities were installed and the RF systems were connected to a new reference line.

The beam commissioning of the combined REX/HIE post-accelerator started in June 2015 after the refurbishment of the REX linac was completed. Different pilot beams produced in the REX-EBIS charge breeder were used during this time. The physics campaign started with the delivery of stable $^{22}\text{Ne}^{7+}$ with an energy of 2.85 MeV/u to the Miniball experimental station on October 19th. The first 4 MeV/u radioactive beam was delivered a few days later on October 22nd. Over the following weeks, different charge states of two zinc isotopes ($^{74}\text{Zn}^{25+}$, $^{76}\text{Zn}^{22+}$ and $^{74}\text{Zn}^{21+}$) and energies of 2.85 and 4 MeV/u were sent to the experimental station. In addition to the radioactive Zn, several stable beams were delivered to the scattering chamber and to the SPEDE detector for commissioning purposes.

The bunker was opened after the physics campaign concluded at the end of November. The cryomodule was disconnected from its ancillary equipment and prepared to be moved to the SM18 building to address a problem with its couplers found during the hardware commissioning.

The linac and the rest of the facility were prepared for the technical stop after a two-weeks training course for the users was completed at the beginning of December. The year closed with the traditional ISOLDE Workshop and Users Meeting.
BE-RF Group

2015 was an eventful year for HIE-ISOLDE: 1) The first cryomodule (CM1) was completely assembled in the special clean room (see Fig. 45 top left), transported to and installed in HIE-ISOLDE (see Fig. 45 top right). 2) The industrial production of Cu substrates had serious issues that led to reduced cavity performance after Nb sputtering – ultimately identified as a problem with the electron beam weld joining the inner and outer parts of the cavity. 2) The LLRF system of HIE-ISOLDE (see Fig. 45 bottom centre) was completed and a first cavity module commissioned, but the events described below required reprogramming and adaptation of the system several times to overcome issues. 3) The main issue was a malfunction of the new FPCs of the five cavities: the antenna tip overheated (see Fig. 45 bottom left). This problem was completely solved only in 2016, but as an intermediate mitigation, the power through the coupler had to be limited, leading to a larger external $Q$ and a substantially reduced bandwidth – difficult to cope with for the LLRF system. 4) In spite of these severe set-backs, cryomodule 1 was successfully put in operation and made available for a first physics run in 2015 (see Fig. 45 bottom right). First physics data were taken immediately afterwards – a first radioactive $^{74}$Zn$^{25+}$ beam was measured at 4 MeV/u in the Miniball experiment.

Figure 45: HIE-ISOLDE 2015. Clockwise from top left: A view inside the cryomodule during clean room assembly in SM18, CM1 installed in HIE-ISOLDE, Measurement of the increase of beam energy switching individual cavities on in CM1, front view of the new HIE-ISOLDE LLRF system, view of the overheated power coupler, which caused difficulties for the LLRF setup and limited the RF power in 2015.
Superconducting RF R&D

BE-RF Group

Jointly with EN-MME and TE-VSC, BE-RF are re-establishing their capabilities in superconducting RF, essential to be able to intervene on the LHC superconducting cavities and HIE-ISOLDE, but also to prepare the future with the HL-LHC crab cavities and in the frame of the FCC study. Within this coordinated R&D effort, a remarkable result could be obtained in 2015 with the successful test of a superconducting 5-cell cavity operated at 704 MHz (relevant for ESS). As illustrated in Fig. 7, this cavity reached an accelerating gradient of 23 MV/m, limited by field emission. This result is a record for CERN and is a proof that the recent investments done to improve the infrastructures in SM18 (clean rooms, high pressure rinsing, tooling) are paying off.

![Graph showing accelerating gradient and field emission](image)

Figure 46: A record (for CERN) accelerating gradient of 23 MV/m could be measured for the first time in a superconducting, bulk Nb, 5-cell cavity at 704 MHz.

CTF3/CLIC:

BE-ABP Group

The beam loading experiment in the CTF3 dog-leg beam line was one of the highlights of the year. RF conditioning to a sufficient level was rapidly achieved, and first results were obtained showing that beam loading does not worsen the structure breakdown rate and pointing to a possible optimization of the structure design to increase its performance. The Two Beam Module (TBM) – see Figure 6 – has been installed in summer 2014 as planned, in spite of the very aggressive schedule, and successfully commissioned during the autumn run. Several issues with its RF network were identify through beam measurements and successive tests, and have been corrected. Progresses in CTF3 during 2014 included improvements in the bunch train recombination (factor 8), with better repeatability and a current stability enhanced from a few percent to a few 10^-3.
Further progress in availability was obtained by qualifying a new supplier of RF sources for the sub-harmonic bunchers and refurbishing and consolidating the old ones. A realignment campaign was also initiated, to be completed in 2015. The drive beam phase feed-forward system was commissioned with limited power - it will then be upgraded to nominal in two steps. The kick response and the bump closure was verified and a first test has demonstrated a feed-forward gain of the order of 2 and identified the main limitation, uncorrelated phase noise growth between the end of linac and CLEX. All CLIC diagnostics tests planned were successfully carried out, in particular the performance of the main and drive beam BPMs in CLEX were as expected and the Electro-Optical bunch length monitor run successfully showed sub-ps resolution, after the hardware modifications implemented during the 2013-2014 shutdown. Studies on OTR emission started as planned in the second run of 2014, with initial encouraging results. The characterization of the wake-field monitors in the TBTS was also carried out demonstrating a resolution in the few microns range, well within the CLIC requirements.

The CLIC parameters optimization for cost and power (re-baselining) reached a milestone in 2014, with the choice of the energy and luminosity targets for the initial stage, and the definition of the upgrade path strategy towards the final 3 TeV c.m. energy. Optimum parameters for beam and structure have been identified as well. Collaborative studies on the potential use of CLIC high gradient technology for compact X-FELs continued and a consortium was formed to bid for an EU co-financed design study. In spite of the good marks, the proposal was not granted funding; however the collaborating institutes agreed to proceed according to plans using internal funding. Dedicated studies on potential for X-band technology use in medical and industrial applications, jointly with key industrial partners, also intensified. The CLIC-ATF2 collaboration has been considerably strengthened in 2014. The two new octupoles for ATF2 are under fabrication, as well as their alignment system. ATF2 ground motion studies were very successful, among other things leading to the identification of a vibration source that could be removed via a hardware intervention. The CLIC collaboration continues to strongly support ATF2 activities and ultra-low β*, ground motion and wakefield free studies were a priority in the 2014 December run. Other advancements in the beam delivery system area includes finalization of an alternative “traditional” final focus design with considerably easier tuning and progress with two beam FFS simulations and with the analysis of ATF2 data. The collaboration with the Australian synchrotron on low emittance tuning and new measurement techniques continued and results were documented. The agreement between CLIC and Spanish institutes including experimental tests for Damping Ring stripling kicker prototype and pulser in ALBA was signed. Additional experiments work in the DR area includes experimental program at CESRTA on instrumentation (new proposal for halo monitoring), e-cloud, and measurements for ion effects. Wakefield Free Steering was tested in FACET with very good results. A measure of transverse long-range wakefields in a CLIC accelerating structure was also performed at FACET. The experiment was fully successful, showing unprecedented precision and accuracy. The measurement verified that the strict requirements for CLIC are indeed met and measured data were also remarkably close to 3d simulations results obtained with GDFIDL, validating the design procedure. Tests of beam based alignment were performed at both Fermi at ELETTRA, and at ATF2, in both cases proving that dispersion-free and wakefield-free orbits can be obtained.
In 2015, an emittance measurement station, developed for future linear colliders was built and installed on the extraction line of the Advanced Test Facility 2 at KEK. This device, as shown in Fig. X includes a sub-micron Optical Transition Radiation (OTR) imaging system combined with a non-interceptive monitor based on Optical Diffraction Radiation (ODR). The commissioning of this device will start in 2016.

Figure 48: (Left) Newly developed small beam size measurement station using OTR and ODR installed on the ATF2 extraction line at KEK/JAPAN. (Right) Chemically etched Si targets with different slits widths (200, 105, 80, 56 microns) for ODR and no slit for OTR.
BE-RF Group

The CLIC Study has continued to make excellent progress during 2015 on many fronts. Since however the time scope of the CLIC study is now limited to 2019 and CTF scheduled to run until the end of 2016, the study is preparing for a review to be held in early 2016 to focus on the highest priority themes that will have to be covered optimally. Looking back on 2015, the CLIC Study can be proud of its successes which comprise 1) A deep understanding of break-down physics, its causes and possible cures, the dependency of the breakdown rate on pulse length, surface fields, power flow and material properties, 2) The successful demonstration of acceleration with a sustainable accelerating gradient in excess of 100 MV/m including beam loading and with an acceptable breakdown rate, 3) The conception, design, construction and now operation of dedicated stand-alone X-band testing facilities, which are valuable assets not only for CLIC but for X-band structure tests in general (see Fig. 49 showing (left to right) Xbox-1, Xbox-2 and Xbox-3). 4) The successful technology transfer of the developed technology for possible other applications including light sources and medical accelerators. 5) Initiation of an in-depth study of klystrons reaching significantly higher energy conversion efficiency than existing klystrons. First results are very promising (PIC simulations indicate the possibility to reach 90% efficiency) and the study is now extended due to its relevance for the entire accelerator community, not limited to CLIC.

![Image](image.jpg)

In spite of problems incurred with the electron gun, CTF3 had a very successful run during 2015. Highlights were the operation of the CLIC module with full power, two beam acceleration with measured acceleration above 100 MV/m and the confirmed resolution of 5 µm for the wake field monitors incorporated into the CLIC prototype accelerating structures. Phase feed-forward studies showed a correction of the beam phase in CLEX of the order of 0.3° at 12 GHz (very close to 0.3° required CLIC).

![Image](image.jpg)

**Figure 49:** The stand-alone X-band test facilities (left to right) Xbox-1, Xbox-2 and Xbox-3.

<table>
<thead>
<tr>
<th>Xbox-1: operational</th>
<th>Xbox-2: operational</th>
<th>Xbox-3: Commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI 50 MW klystron, Scandinova modulator, 1.5 µs, 50 Hz</td>
<td>CPI 50 MW klystron, Scandinova modulator, 1.5 µs, 50 Hz</td>
<td>4x Toshiba 6 MW klystrons, 4x Scandinova modulators, 5 µs, 400 Hz, pulse compressors</td>
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Neutrino Facilities Studies

BE-ABP Group

The 14 Hz, $10^{15}$ particles per pulse, 5 MW European Spallation Source (ESS) linac, presently under construction in Lund, Sweden, has the possibility to produce extra pulses that can be used for production of a neutrino beam in addition to the neutron beam, giving a total beam power of
10 MW at 28 Hz. These extra pulses would be sent to a dedicated target that can only focus the secondary particles for a few microseconds due to otherwise excessive osmic heating. This makes it necessary to collect the 2.86 ms long linac beam in an accumulator, and extract shorter, but more intense, pulses to the production target. Charge exchange injection is used to inject the beam efficiently into the accumulator which implies acceleration of H- in the ESS linac. This will require upgrades of the linac equipment, which has been shown feasible, CERN-ACC-NOTE-2016-0050.

A first design of the accumulator and beam-lines is made within a collaboration between CERN and Uppsala University, and during 2016 the firsts results of the simulations of the injected beam, using different codes, for comparison, have shown that foil temperatures and emittance growth are within acceptable values (MOPR021, HB2016). From these results, the injection painting will be optimized and beam dynamics analysed to consolidate the design.

**Future machines and EuCARD**

**BE-ABP Group**

**FCC**

Consistent designs of hadron and lepton colliders (FCC-hh and FCC-ee) were developed, with identical footprints for more than 90% of the circumference. The only difference is found in the interaction regions, where an asymmetric optics reduces synchrotron radiation for the lepton collider, while providing a bypass path around the detector for its top-up-injector booster (the latter following the path of the hadron collider). A new parameter baseline was defined for FCC-ee. The dynamic aperture of the FCC-ee optics, obtained by optimizing the strengths of 100’s of sextupole pairs using the SAD code, is adequate, even for pushed IP beta functions, equal to half the nominal value in both transverse planes. The possibility of a monochromatization scheme for direct Higgs production was explored, which required the analytical derivation of self-consistent effect of beamstrahlung on longitudinal and transverse beam parameters, including the effect of IP dispersion. Studies of FCC-ee alignment tolerances, optics correction and emittance tuning advanced. For FCC-hh the optics for arcs and interaction-region straights are complete and well performing.

About 340 participants from around the world attended the first annual conference of the Future Circular collider study at Washington DC in March 2015. By the end of the year, the FCC collaboration has grown to about 75 institutes and five topical reviews with international experts were organized during the year 2015, addressing the tunnel footprint, the FCC-ee crab waist scheme, the FCC-ee optics and beam dynamics, the choice of the FCC-hh injection energy, and the FCC-hh optics and beam dynamics, respectively.
A common footprint for FCC-hh, FCC-ee, and he FCC-ee top-up injector (or “booster”), with a zoomed view of the FCC-ee interaction region.

**EuCARD**

In 2015 EuCARD-2 Work Package 5 “Exterme Beams” organized or co-organized the following networking workshops, and made great strides towards its four intermediate-deliverable strategy reports.

1. The WP5 workshop on “Advanced Optics Control” (“AOC”) was organized at CERN, 05.-06.02.2015.
3. The LHeC Workshop, CERN & Chavannes-de-Bogis, 24-26 June 2015.
6. “Beam Dynamics meets Diagnostics” (“BeDi2015”) workshop in Firenze, Italy, 4-6 November 2015.

**BE-RF Group**

**FCC**

The superconducting radiofrequency (SRF) accelerating cavity technology is key for future colliders at the energy frontier, for which the wall-plug efficiency will be one of the biggest challenges. The FCC SRF R&D has well advanced through 2015 and several collaborations have been established. This work package addresses technological challenges to design the RF systems required for a 100 TeV hadron and a high-luminosity lepton collider. One of its main goals is to identify the ultimate limits and potential showstoppers as well as to define the R&D topics that need to be addressed in order to optimize the SRF technology for large superconducting RF system.
AWAKE

The electron source and injector for AWAKE has been fully designed and fabrication of missing parts has started. Necessary work package descriptions and safety documents have been produced and approved.

The AWAKE experiment requires a proton bunch synchronously extracted from the SPS with respect to a Laser pulse and electron beam generated in point 4 of the SPS. All three beams (proton bunch from SPS, laser beam and electron beam) must be aligned in space and time in the plasma chamber installed close to the former CNGS target area in the SPS. The LLRF must achieve the synchronisation of these 3 beams, the transport and generation of all timing and synchronisation signals over more than 1 km used for synchronisation, in the experimental set-up as a reference and for beam instrumentation.

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.

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, the CERN contract review board, and the Standing Concertation sub-group dealing with modifications of the Staff Rules & Regulations, Administrative Circulars and Operational Circulars. The indispensable strong relationships with all units in the HR Department go together with the role of departmental Human Resources Officer (HRO).

In order to overview, plan and control all departmental resources within the medium term period, the ASR group leader has also the role of Departmental Planning Officer (DPO).

The BE Newsletter

Yet another three issues of the BE Newsletter, introduced in 2011, were published in 2015, reaching a total of fifteen. The content varies widely from scientific and technical to practical, social and safety information, provided by each group via its correspondent. The management, compilation of all contributions and final editorial work is in the hands of BE-ASR. A dedicated column on “life in BE” is devoted to contributions of newcomers reporting on more lightweight subjects and personal impressions.

Administration & Secretariats – BE-ASR-AS

The Administration and Secretariats team is tasked with ensuring an effective and high quality administrative assistance for Group Leaders and Section Leaders, as well as providing an administrative support for all categories of personnel for a wide range of activities. The team of eight group secretaries and departmental support in the Central Secretariat (DAO, DDAO) is geographically split between the Meyrin and Prévessin parts of the CERN site and located in different buildings. The recurring activities of the assistants start from the welcoming of new arrivals (262 in 2015), ensuring that they all are allocated an appropriate work space. The management and follow-up of staff contract extensions, transfers, secondments, contract
terminations and departure formalities (225 in 2015) is voluminous due to the increasing number of associate members of personnel. Since 2014, the follow-up of special paid leave for doctoral students and payment of travel expenses for their university supervisors, requires an extra workload and careful attention.

Of particular importance also is the coordination of selection committees for Fellows as well as Doctoral, Technical and Summer Students. The central secretariat is also involved in the follow-up of induction interviews, mid- and end-probation reports, the coordination of the MARS exercise as well as all actions related to advancement, promotion and awards of staff members, treatment and monthly control of overtime, shift work and stand-by duty. In the groups the secretaries assist the CERN personnel with arranging official travel and calculation of reimbursements, treatment of reimbursements of education fees, management of subsistence fees, control of absences and third party claims. The secretaries also provide assistance with the administrative organization of some 12 off-site events and international conferences, the creation and update of group websites and documentation systems and the coordination of visits onsite, especially in the CCC.

The Departmental Administrative Officer (DAO) collaborates proactively and continuously with the HR department and the Legal Service to streamline and improve the administrative procedures, making sure to implement correctly and efficiently the revisions of administrative circulars and contributing to the pragmatic documentation of the CERN Admin e-guide.

Since the introduction in 2013 of new statutes such as Cooperation Associates (COAS) and Visiting Scientists (VISC), the related administration has been substantial. The search for existing agreements, creation and verification of new agreements with the Legal Service, the Procurement Service and supervisors are time consuming activities. The management and the follow-up of payment of subsistence for these categories of personnel is also an important monthly activity. For the year 2015, 72 COAS and 22 VISC were registered.

Resources & Logistics – BE-ASR-RL

The main tasks of the Resources and Logistics team are to provide assistance to the Departmental Planning Officer (DPO) on budgetary and financial matters, and to the Departmental Space Manager (DSM) for space and storage management, follow-up of small works and related logistics. The financial and budget related activities concern primarily monitoring and reporting on material budgets for all BE Groups and projects, monitoring and follow-up of the invoices and yearly accruals, maintenance of budget codes and signature rights. This includes externally funded budgets such as EU projects and the collaboration for the HIE-ISOLDE project.

The activities of space management continued to be challenging. The strategic and operational activities are intertwined, due to a minimalist coordination team of 1.2 FTE: the Departmental Space Manager (DSM) from BE-ABP, his deputy (BE-ASR GL) and the DSM Assistant. As from July, the DSM Assistant was replaced and the activity outsourced. The DSM, as member of the Groupe de Travail sur le Partage de l’Espace (GTPE) actively contributes to the CERN-wide space management.

The move of the BE Head Office and the complete BE-CO group new Prévessin main building 774 took place early 2015. The space in the existing office buildings 864, 865 and 866 was redistributed between BE, EN and TE, rationalised and optimised. Both on the Prévessin site and the Meyrin site, large offices were refurbished and converted to burotel type offices, which can be managed and reserved for defined-length periods. Towards the end of 2015, fourteen months after the fire in building 6, the PS auditorium is again fully operational.

The departmental logistics includes the management of keys and cylinders (472 requests, still in paper format), management of the departmental car fleet (66 vehicles), the departmental inventory of equipment, the monitoring of the use of telephones, management of photocopiers and office and workshop furniture. With the installation of the tracking devices on the new vehicles, the BE
The Departmental Training Officer (DTO) – actually in BE-RF, his deputy being in BE-ASR – monitors a rigorous departmental strategy, in line with the Learning & Development Policy, on communication (news and reporting), training request authorisations and budget follow-up. Target levels for language courses, justified by the staff member’s supervisor, are now imperative before acceptance by the DTO.

The fifth edition of the annual BE Workshop was again a success with several ideas and proposals being followed up and implemented, e.g. BE welcome brochure and guided visits for newcomers, BE seminars given by fellows, intra-departmental secondments.

Safety Unit – BE-ASR-SU

The BE Safety Unit comprised seven members representing a total of 5.3 FTE (compared to 5.6 FTE in 2014). The BE Safety Unit was composed of the DSO, DDSO, RSO, DRSO, LSO for the A&T Sector, the PSO for the LIU project and one fellow. The contract of the part-time administrative assistant was not renewed, hence the administrative tasks have been redistributed.

The DDSO is still an organizing member of the CERN Crisis Coordination Team. The goal is to set up a crisis organization to react and manage a crisis, should it happen at CERN.

All members of our unit are committed in the three Complex Safety Advisory Panels, “CSAP” (LHC, SPS and PS), for which we also provide two scientific secretaries. These panels are composed of members from all technical departments, report to the IEFC & LMC, and make recommendations in matters of safe operation of CERN Accelerator Complexes. The BE DDSO acts also as scientific secretary for the DSO Committee.

Safety of Personnel

The statistics on accidents implying BE personnel or occurring in BE premises revealed low numbers in 2015 (of the order of only 6-7% of the CERN accidents). No severe professional or commuting accidents were to be deplored in our Department.

The number of reported commuting accidents and incivilities on the roads continued to increase in 2015. Again, this remains a concern, in particular the commuting accidents with bicycles. The higher number of reports reflects an improvement in the safety awareness and culture.

A procedure for accident investigation in BE has been edited on EDMS 1489978 and is followed by the Safety Unit. The BE Safety Unit investigated accidents and dangerous situations reported on the Meyrin site. The implementation of the remedial actions were followed-up.

Similarly, a procedure for the management of post-accidental situations has been edited on EDMS 1513662. This procedure targets tertiary surface buildings or installations impacted by events such as fires, pollutions, floods, etc.

The standardized panels designed by the BE Safety Unit to inform people about the Personal Protection Equipment (PPE) to be worn upon access have now been installed at the entrance of primary beam areas.

Two evacuation exercises took place: one in the ISOLDE Hall and one in building 774. The feedback was positive. Such exercises are beneficial to raise awareness and promote good behaviour when faced with an emergency situation.

Safety Communication

The effort to improve Safety communication in the department was pursued. The departmental Safety web site has been rearranged and now contains Safety news and tips. The Safety Unit
communicates regularly in the BE Newsletter. In 2015, the articles focussed on the risks related to seasonal specifics: the summer heat wave and preparation for the bad winter conditions.

The Safety officers continue to maintain frequent and constructive communication with our TSOs: meetings are organised regularly in order to share experiences and provide them with information that could make their tasks easier. As an example, the Radiation Protection group was invited as an external speaker to present the new procedure for industrial radiography.

**Radiation Safety**

Previsions of radioactive waste to be generated from BE activities in the accelerators up to LS2 have been compiled and transmitted to HSE-RP.

Together with the BE Radiation Safety Support Officers, the BE RSO has reviewed all DIMR (Dossier d’Intervention en Milieu Radioactif) generated by BE during the LS1. The aim was to see if improvements could be made in order to better prepare for upcoming LS2 activities.

In the framework of the shielding installations management, the project of a database managed by EN with input from the Departments and from HSE-RP has progressed, but is still not operational.

The TREC (Traceability of Radioactive Equipment at CERN), of which the BE DSO was the project owner, has been almost completed in 2015. Some 50 Buffer Zones are now equipped with TREC stations, mostly at the entrances of beam facilities, but also close to radioactive storage and workshops (such as in bldg. 867).

**Safety of Installations**

Implementation of a quality assurance plan concerning EIS (Equipment Important for Safety) has progressed well, and some management documents have been finalized. Also, more equipment groups have now procedures available to manage interventions on their EIS.

The system allowing the reporting of deviations in matters of Safety (EDMS 1161842) is still maintained by the BE Safety Unit. In 2015, a dozens of deviations were analysed.

The lessons learned from the restart after LS1 led to a decision to review the Beam Permit process, and possibly to introduce Hardware Permits for injectors as already existing for the LHC. This reviewing process has started under the leadership of the BE DSO.

The Safety Unit is still a driving force in encouraging the creation of Safety Files for Beam Facilities. In particular concentrating on safety files linked to the LIU project: Linac4, PS, PSB, and LEIR. Furthermore, The LIU PSO defined the process to manage the safety documentation for the LIU project. The “Safety Folders’ Editors Club” set up by the BE DDSO continues to be a useful forum to share experience and homogenize the approach.

The BE DDSO defined the regulatory requirements and controls applicable to the LIGHT facility so that the RF commissioning and future beam commissioning activities conform to CERN standards. In the North Hall, the final installation of requested safety equipment on GIF allowed the Safety Unit to remove the compensatory measures put in place during commissioning.

The new safety-training scheme, proposed in 2013 to avoid repetitions from one course to another (and avoid discrepancies), has now made its way. More training courses related to access rights in Beam Facilities were released in 2015. The editing of the course material is always supervised and reviewed both by HSE and the BE Safety Unit. In particular, the LHC and SPS Machine safety courses were authored by the BE Safety Unit and received positive feedback.
BE-ABP

Code development

In 2015, MAD-X was extended on few aspects including new physics capabilities, new commands, and an improved user’s guide published in PDF format on the website. For the first time, MAD-X training has been provided and is part of the CERN technical training. The MAD team also started to port a new version of the PTC/FPP library from E. Forest in MAD-X. In parallel to MAD-X improvements, a demonstrator of the MAD Next Generation was developed to validate the concepts and technologies selected after two years of R&D, and presented to the CERN community.

SixTrack had been further consolidated in its two main parts, i.e., the version used for single-particle tracking and for collimation studies with the long-term goal is to merge the two versions into a single one.

BE-BI Group

A general purpose FPGA-based electronic board (Fig. 50) was designed in the BE-BI group for several projects including the renovation of the SPS beam position electronic read-out system. This GBT-based Expandable Front-End (GEFE), which includes ASICs developed by EP-ESE, should withstand a Total Ionizing Dose (TID) up to 750 Gy. The qualification of the components for radiation environments was performed in 2015 and a test of the full board is foreseen for middle 2016.

BE-CO Group

Accelerator Performance Statistics

In 2015 the LHC Performance and Statistics Web application was extended to integrate dedicated statistics data for the PS Complex and SPS. The team worked closely with operators and other users to deliver a single application aiming to cover the needs of the accelerator complex. For the LHC, new calculations and displays were implemented to support various analyses that were made and presented at the 2015 Evian workshop.
The application is visible from outside CERN, and is increasingly used by people from around the globe to get an insight into the performance of CERN’s accelerators. So far there have been more than 30K visits from 100 different countries.

**Phoenix – a new Console for the Alarms system**

Since 2011, members of BE-CO and GS-ASE have been collaborating on C2MON, a software project for monitoring the whole accelerator controls infrastructure. In 2015, members of BE-CO have implemented a new Alarms console called Phoenix, which is a GUI on top of C2MON that implements the Alarms functionality used mainly by TI-OP. Phoenix is the first GUI in BE-CO developed with JavaFX, the new GUI technology for Java. The outside of the Phoenix GUI (image below) is very similar to the old LASER console, but the internals are completely different.

The combination of Phoenix and C2MON shall be deployed operationally in 2016, to replace the old LASER system that was developed in the early 2000s. Replacing LASER will enable CO to get rid of really outdated technology (the OC4J application server and the SonicMQ broker), which in turn will mitigate a considerably risk of failure and reduce maintenance work.
Figure 52: New Phoenix Alarm Console

**Tracing system for diagnostics and smooth upgrades**

The proof of concept version of the Tracing system built in 2014 was turned into a stable service in 2015. The Tracing system is not developed in-house, but based on popular open source products (ElasticSearch, Kibana and Grafana). This setup enables anyone involved with controls to easily send information into the Tracing system and to display their data in dashboards tailored to their needs. Since 2014, Tracing already collects the log files from all the 2000 front-ends, and helps diagnosing problems. In 2015, new sources of information were added. One example are notifications when new versions of software (e.g. FESA classes) are actually deployed operationally. Another example is data to discover run-time dependencies between different parts of the controls system (c.f. image below), e.g. keeping track of which applications access which devices (which is important for smooth upgrades from RDA2 to RDA3). A further example is TiDE, the new timing distribution system, which is being continuously monitored using the Tracing system.
Java applications running with obsolete libraries

For Smooth Upgrades of Java applications

Connections from applications to RDA2 classes

For Smooth Upgrades from FESA2 to FESA3
Controls Configuration Service

The main focus for 2015 in the Controls Configuration Service (CCS) was consolidation efforts to reduce the significant technical debt, in turn helping limit support, reduce complexity, and give a platform upon which to improve usability and integration with other parts of the Control System. Major progress was made throughout the year, including dropping more than 20 production database accounts, 380 database tables, not mentioning details significant re-factoring efforts. Thanks to thorough analysis and careful planning such potentially high-impact actions happened fully behind the scenes with no disruptions to the large and diverse user community. To facilitate this work a proper production-grade testing environment was established and database schemas were synchronized between development, test, integration and production databases. The data management facilities for OASIS and Power converter Controls were consolidated, and the integration with other systems such as LanDB, Naming, and user Accounts was rationalised, as was the configuration of LASER and DiaMon systems. As expected there was a notable reduction in support as a result, however the consolidation efforts are foreseen to continue until LS2 in order to reach the desired state.

In addition, a large number of improvements and extensions were also delivered to directly serve the end users including: extensions to RBAC with support for E-groups, and a new user interface to replace the obsolete Oracle ADF technology; A new user-friendly CCS application portal with long-awaited CERN Single Sign-On integration; A completely new device migration framework and user interface to facilitate migrations from GM and FESA2 to FESA3; A new and streamlined device responsibility model to allow proper semi-automated workflows and follow-up of important changes in the Control System.

The Layout Service in the A&T Sector

With reinforcements to the BE-CO Layout team, the development of the new Layout database accelerated in 2015. The first version of the complete core was implemented with a full hourly data synchronisation between the current production database and the newly modelled database. This was a major achievement. Significant progress was also made on investigating and prototyping with appropriate Web technologies in order to develop the graphical user interfaces that will be used by the A&T community to visualise and maintain their data. In summary development of the new Layout database and tools is on schedule to be delivered ahead of LS2.

In the context of clarifying and redefining the scope of the Layout database, millions of cryogenic controls parameters were transferred from the Layout Database schema to a dedicated Cryogenics UNICOS (controls) configuration database. This development allowed TE-CRG to gain a lot more autonomy when managing their data.

The Logging Service across CERN

The Logging team deployed the new data extraction API (developed during 2014), removed the obsolete old APIs and helped clients in the transition process. The powerful new functionality of Advanced Filtering was developed and deployed in the API and TIMBER – allowing for complex filtering predicates based on any Logging Variable. This feature aimed to allow users to filter any data by occurrences of any other data including value filtering e.g. "show me the beam losses over the last 2 months when the energy was above 6 TeV". Other enhancements to TIMBER included the introduction of data distribution histograms and the possibility to display textual data in a table. Behind the scenes, parts of the application were refactored and solidified with the introduction of many manual test scenarios.

Data acquisition and logging processes were refactored to allow for better handling of error situations and prevent data loss scenarios in the event of database unavailability. Introduction of rolling update procedures allowed for smoother and transparent upgrades, also avoiding data loss
during the frequently required process restarts required to support upgrades of devices from FESA2/RDA2 to FESA3/RDA3.

A new data transfer mechanism was developed and deployed to allow for more optimized and efficient transfers between the WinCCOA or Measurement databases towards the long-term storage in LDB. The Logging databases were reviewed and consolidated by removal of legacy objects and business logic. Additional database environments were prepared and unified to allow for better testing of new features in Continuous Integration automatized process. The Logging Service continued to experience dramatic increases of data rates both stored and extracted that are visible on the chart below.

![Figure 53 Logging Service Daily Storage in GB / day](image)

As a result of this fact and in order to reply to the growing requirements put on the current system, the decision was taken to begin investigations in early 2016 into possible new solutions for a future Logging system.

**Towards automatic propagation of new FESA configurations to LSA**

FESA developers regularly have to change the properties and fields of their classes, to implement new functionality or to accommodate new types of hardware. To make these changes visible in the CCC, they need to be propagated from the Controls Configuration Database (CCDB) where FESA stores them, to the LSA configuration database (LSA DB). This is a straightforward procedure for backward compatible modifications, e.g. when new properties have been added. However, it is not trivial for non-backward compatible changes, e.g. when existing FESA properties are removed or changed. The reason is that the LSA DB already has settings for these device properties. In around 90% of the cases such settings can be deleted, but sometimes they should be preserved and transformed (migrated) according to some device-specific logic.

Currently, non-backward compatible changes have to be analysed and handled manually. This process puts a considerable support load on the LSA team, the FESA developers and OP. Therefore, it was decided to streamline this process, and to automate it as far as possible.

In 2015, the LSA team did a first part of this work, mainly development inside the LSA database, to properly deal with multiple, possibly incompatible, versions of the same FESA class and react accordingly on settings stored in the LSA DB.
CMW - Controls Middleware

The RDA3 framework was smoothly introduced to many equipment systems, mainly FESA3 classes, during several upgrade campaigns, namely Technical Stops and YETS. RDA3 is used operationally for many critical systems in Injectors & LHC. It is also the default middleware used in FESA3, FGCD, LabVIEW and WinCCOA frameworks. The graph below shows the status of migration of RDA servers from RDA2 to RDA3 framework, for the period January-September 2016.

Figure 54. Migration of RDA servers from RDA2 to RDA3 framework, Jan-Sep 2016.

The RBAC authentication service was extended in order to support authentication based on CERN SSO (Single-Sign-On) tokens. Thanks to this extension, CO web applications (e.g. AFT) may fully profit from integration with the CERN SSO infrastructure and avoid any additional user authentication.

In 2015 CMW team developed and deployed a new service responsible for gathering snapshots of all RDA-based communication in the CERN accelerator control system. The retrieved data helps to get an overview of the RDA infrastructure, i.e. active client/server connections, and allows to generate graphs showing the current use of released versions of RDA libraries as displayed of the following figure.

Figure 55. Use of released RDA versions as retrieved from running RDA servers.

Once a RDA snapshot is completed, the resulting data, namely active client/server connections, is sent to the CO Tracing service, where it can be later browsed via a user friendly web interface (i.e. Kibana
Many CO and equipment experts confirmed that this report was very useful for retrieving information about connected client applications, especially when planning migrations of RDA servers (e.g. FESA3) from RDA2 to RDA3.

Figure 56. New Kibana dashboard allowing to browse RDA client/server connections.

Accelerator Timing and Sequencing

TiDE replaces DTM

An essential activity of CO is providing timing and sequencing for the accelerators – at the FrontEnd level as well as at the Java application level. Prior to 2015, timing events were delivered to Java applications via the DTM (Data Table Management) system. Over the years, DTM has become increasingly unreliable and hard to maintain. Consequently, a new system, TiDE (Timing Distribution over Ethernet), was developed using standard CO components. As a transport layer the new RDA3 library has been used. It helps to guarantee handling of hundreds of clients within the tight timing thresholds. TiDE has been deployed in operation for all CERN’s accelerators during the EYETS. Being more reliable and performant than the previous system, it has reduced greatly the time and effort spent on support.

Figure 57: Operational installation of TiDE.

Timing testbed

With the move to the building 774, a new Timing testbed has been established in the lab. It is housed in four racks and integrates a copy of all the operational central timings: LHC, LIC (SPS, PS, PSB, LEIR, LN2, LN3), REX, AD, ELENA, and CTF3; as well as all crucial timing services (logging, archives, clock survey). It also allows to test the timing client side stack (hardware and software responsible for timing reception) in all flavors supported by BE-CO: 32/64 bit machines; SLC5/SLC6 OSes; CTRV, CTRP, CTRI timing cards.
Timing clock survey
The Clock Survey system was redesigned, updated, and integrated in LASER. Its core functionality is to survey synchronization of clocks driving central timings of LHC, SPS and AD. In case of anomalies, depending on configuration, it may raise an alarm or act on external conditions which may block central timings from playing new beams.

Security
In collaboration with the IT Network and Security teams, an analysis of network traffic and dependencies between the General Purpose and Technical Networks was performed, then firewall rules implemented to protect critical accelerator services. As part of this activity, a poster was presented at ICALEPCS 2015, which won the best poster prize and an initial investigation of two-factor authentication was performed.

Following the above-mentioned work during 2015, the collaboration between BE-CO and the Security Team continues to review how the security of the control system can be improved.

A computing security course for newcomers to the accelerator sector was also organized to highlight security issues for the control system.

Virtualization Infrastructure 2015
All terminal servers transformed in virtual openstack cluster, for a total of 56 servers, granting a non-stop 24h service even during upgrade/reboot to the control infrastructure. BE-CO Terminal Servers provides the expert application access (even from home) for more than 400 experts in beam instrumentation, transfer lines, cryogenics, cooling, ventilation, vacuum, radio-frequency, wall screens... for each expert group we have a dedicated cluster.
Virtual PC: 450 Machines migrated to Openstack, with the help of the 240 developers that have moved to the new infrastructure. Lot of work has been done to prepare the next generation infrastructure for 2016, that will have CC7 virtual machine and a new application to connect to them called VNCManager we develop to satisfy all the needs of the 270 VPC users, including easy access from home, connect from win, mac and Linux, session recovery and graphical access to all the machines of the control system.

GIS Portal Racks

As a follow-up of the work already make for the PS complex, the GIS portal team fostered efforts in 2015 on the full integration of the SPS and LHC surface and underground electronic racks into the GIS portal, as well as the electrical distribution boxes. The next phase will consist in the final allocation of rack responsibilities between all groups concerned.
BE-RF Group

Very high efficiency klystrons

Since 2013, HEIKA (High Efficiency International Klystron Activity), an initiative from the CLIC study for a collaboration between laboratories and industry has been working on modelling and producing higher efficiency klystrons and has already produced some exciting results this year.

Klystron amplifiers with RF power production efficiency above 80% are crucial for the future generation of large accelerators. Together with high efficiency, operating voltages below 60 kV are of great interest. Lower voltages significantly reduce the length and weight of klystrons and eliminate the need of an oil tank for the modulator pulse transformer. Multi-beam technology is one of the key components in achieving such an improvement. Another important advancement is the application of a periodical permanent magnets (PPM) focusing system which can replace the standard focusing solenoid. This allows for reduced power consumption, weight and cost of the entire RF power source.

In 2015, the coordinated effort by international experts connected by the HEIKA collaboration came up with an interesting novel concept referred to as “core oscillation method”, which may revolutionize the way klystrons are built. While in classical bunching many electrons (so-called “outliers”) are actually accelerated in the output cavity of the klystron and thus decrease the efficiency, the “core oscillation method” allows the electron beam repeatedly to bunch and debunch longitudinally, which allows the outliers to slowly migrate into the core and contribute to the RF power generation in the output cavity. Fig. 59 illustrates this mechanism, details can be found in [http://ieeexplore.ieee.org/document/7194781/].

![Figure 59: Explaining the “bunch core oscillation” method to obtain large efficiency in a klystron, comparing the distribution of electrons in longitudinal phase-space versus the axial location of the classical bunching method (top) with the “bunch core oscillation” method (bottom). The bright part is the “core” of the bunch while the grey part characterizes the “outliers”.

[70]