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THE IRRAD PROTON IRRADIATION FACILITY DATA MANAGEMENT, ANALYTICS, CONTROL AND BEAM DIAGNOSTIC SYSTEMS: CURRENT PERFORMANCE AND OUTLOOK BEYOND THE CERN LS3*

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Abstract

The recent Proton IRRADIATION Facility (IRRAD) at the CERN East Area was built in 2014 during the Long Shutdown 1 (LS1), and later improved during LS2 (2019), to address the needs of the HL-LHC accelerator and detector upgrade projects. IRRAD, together with the CHARM facility on the same beamline, exploits the 24 GeV/c proton beam of the Proton Synchrotron (PS), providing an essential service at CERN while showcasing more than 4400 samples irradiated during the last decade. IRRAD is operated with precise custom-made irradiation systems, instrumentation for beam monitoring (IRRAD-BPM), monitoring GUIs (OPWT) and a dedicated data management tool (IDM) for experiments follow-up and sample traceability. Moreover, performance tracking generated by custom-made analytics tools (Jupyter, etc.) guarantees operational feedback, thus maximizing beam availability for IRRAD. While the HL-LHC components qualification is coming to an end with LS3 (2026-2028), new challenges arise for future detector, electronics components and material irradiations: reaching extremely high fluence levels, operating low-momenta or heavy-ion beams, being some of those. In this context, we first describe the last improvements implemented at IRRAD after LS2 and then present the challenges ahead that will drive future upgrades such as, for example, applying ML techniques to the beam data, aiming to achieve real-time automatic beam steering and control.

INTRODUCTION

The Proton IRRADIATION Facility at CERN (IRRAD), located in the East Area of the Proton Synchrotron (PS) accelerator, is an experimental area primary tailored for the qualification of inner-detector components for High-Energy Physics (HEP) experiments. The IRRAD facility was first built in 1999 [1], originally on the T7 beam line, and underwent major upgrades in 2014 and 2019 during the CERN Long Shutdown 1 (LS1) and 2 (LS2) respectively.

During LS1, IRRAD was extended and moved to the T8 beam line, to cope with the increasing demand of irradiation experiments of the HEP community working for the High-Luminosity Large Hadron Collider (HL-LHC) [2].

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Downstream IRRAD on T8, a twin experimental area named CERN High-energy Accelerator Mixed field facility (CHARM) and equipped with a massive 50cm-long cylindrical target was also built during LS1. The secondary radiation field from the protons on target (e.g., the portion of beam that did not interact with the upstream material in IRRAD) reproduce accurately a broad mixed field (hadrons, photons, electrons, etc.) up to GeV energies, as expected in the CERN accelerator infrastructure, in the service areas of the HEP experiments but also mimicking ground- and atmospheric-neutron spectra as well as space environments [3].

From the very beginning of IRRAD operation post LS1 (see Fig. 1), several hundred samples are exposed yearly to the proton beam, serving today an enlarged community extending to electronics and material testing, accelerator components qualification and R&D users. As a result, the registration, planning and follow-up of these experiments require the management of a considerable amount of data. Therefore, during LS2, beside the commissioning of a custom-made IRRAD Data Manager (IDM) application, several upgrades were also made to the IRRAD control system, beam diagnostics, dosimetry and facility infrastructure required by the users to safely handle, store and perform post-irradiation measurements [4].

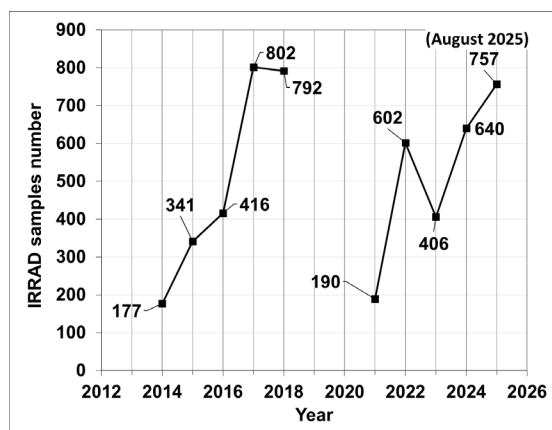


Figure 1: IRRAD statistics towards the end of the second run of operation after LS1 (2014). Data for the 2025 run (ending mid-November) refer to the month of August.

Looking beyond HL-LHC, CERN has now completed the FCC Feasibility Study [5], showing the technical feasibility of a future hadron collider (FCC-hh) with a centre-of-mass energy of approximately 100 TeV. This accelerator

would be preceded by an electron–positron Higgs factory as a possible first stage (FCC-ee). The FCC project imposes very stringent demands on future detector design (complex machine–detector interface, high luminosity, extreme radiation hardness, etc.) that pushed forward the formation of large, coordinated R&D efforts in need of radiation testing to achieve the expected readiness in several detector (DRDs) and accelerator technology domains.

Finally, since post-LS2, IRRAD is also being used as a test-bench for a specific project (HEARTS) aiming to develop a high-energy heavy-ion beam that can reproduce the effects of galactic cosmic rays at ground level for shielding, radiobiology, and microelectronics testing [6].

To cope and satisfy in the best possible way these new user and testing requirements, and in view of the upcoming LS3, this paper first reviews the main characteristics of IRRAD (first section), describes the improvements implemented after the LS2 (second section) and then reviews the remaining challenges ahead that will drive future hardware and software upgrades at IRRAD (third section).

FACILITY OVERVIEW

The CERN Proton Synchrotron (PS) delivers to IRRAD, on the T8 beamline of the East Area, a proton beam with a momentum of 24 GeV/c, extracted in ~ 500 ms spills of about 8×10^{11} p/spill every 10 s on average, and with a typical Gaussian beam spot of the order of 10 mm \times 10 mm (FWHM). In this beam, objects (also called “samples”) up to several tens of squared cm in size can be weekly exposed to particle-fluence levels of up to several 10^{16} p/cm². Smaller objects, typically within 5 \times 5 mm², can be irradiated up to a fluence beyond 2×10^{17} p/cm², corresponding to more than 60 MGy in silicon. Irradiation experiments with a defocused proton beam, with larger objects or specific environmental conditions are also possible.

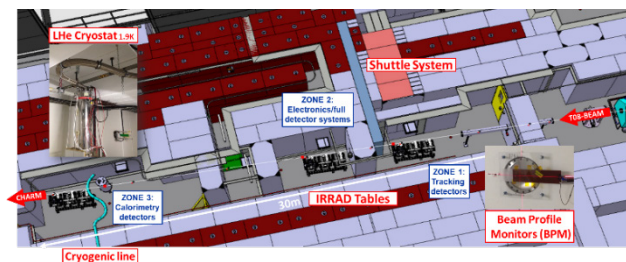


Figure 2: Three-dimensional layout of the IRRAD facility. The grey and brown elements in the drawing are concrete and iron shielding blocks. The T8 beam is coming from the right-hand side of the picture.

The samples to be irradiated, together with their associated dosimetry samples (thin metal activation- foils [7]) are placed on custom-made remotely controlled stages, the “irradiation tables”, that can be moved along three axes with a control system described in [4]. As shown in Fig. 2, nine irradiation tables are grouped in three consecutive zones along the proton-beam trajectory and require the users to access the irradiation area, during weekly technical stops, for samples installation. As shown in Fig. 3, depicting

Zone 2 of IRRAD, some tables are equipped with dedicated cold-boxes or cryostats allowing the execution of irradiation experiments at low temperature (-25 °C), in cryogenic conditions (1.9-4.2 K) or in inert-gas atmosphere.



Figure 3: The three tables of IRRAD Zone 2 loaded with samples. The central table hosts a cold box.

In addition, a conveyor (shuttle) system is available for the irradiation of smaller samples with maximum dimensions of 5 \times 5 cm². This irradiation system can be moved from the outside area to the irradiation position without the need to interrupt the beam operation on T8.

To precisely steer, quantify the intensity and measure the transversal/longitudinal beam profiles on T8, a dedicated instrumentation is installed and used at IRRAD. After the last upgrade during LS2, this consists nowadays of secondary-emission (XSEC), ionization (XION) and multi-wire proportional (MWPC) chamber [3]. In particular, a custom-made Beam Profile Monitor (IRRAD-BPM) device, capable of operating under constant beam irradiation, was developed, and it is used to provide real-time information regarding the beam profile, as shown in Fig. 4 [8].

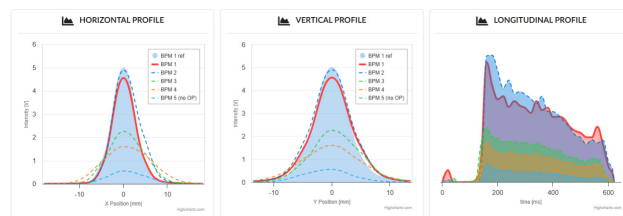


Figure 4: Horizontal and vertical Gaussian transversal (left-hand side) and longitudinal profiles (right-hand side) of the typical proton beam in IRRAD.

FACILITY IMPROVEMENTS AND OPTIMIZATIONS

Dedicated software tools, based on open-source or CERN standard software stacks, are used to operate and monitor in real time the systems and beam parameters described in the previous section, to manage the user’s experiment and samples as well as to track the facility performance. The subsections below highlight the most significant improvements implemented at IRRAD after LS2:

- Operation, control and information GUIs
- Data management system
- Data analytics for facility performance
- Beam monitoring.

Operational Control and Information GUIs

A dedicated web application, hosted within the CERN OPWT web application portal (grouping the main web tools used by the CERN Beam Operation group), is the main interface used for the daily operation of IRRAD [9]. An updated version of the application has been released to comply with the CERN IT infrastructure requirements and to include additional information relevant for the monitoring and control of the IRRAD experiments. Data are acquired in real time on a spill-by-spill basis, stored on the ORACLE database and are combined with data from the timing system to timestamp each data point and correctly tag the correct spill number. Information from other services, like the access system, are fetched using dedicated APIs. This set-up allows real-time monitoring of a wide range of irradiation parameters: beam profiles and intensity, position of the IRRAD tables and shuttle, cooling systems, etc. Moreover, the last update enabled a more detailed monitoring of the status of the beam area and access system (access doors, radiation veto, areas patrol, etc.) as well as of the equipment present in the storage and measurement areas (fluid levels, temperatures, alarms, etc.). A screenshot of some of the new information available from the *IRRAD Status Panel* page¹ is available in Fig. 5.

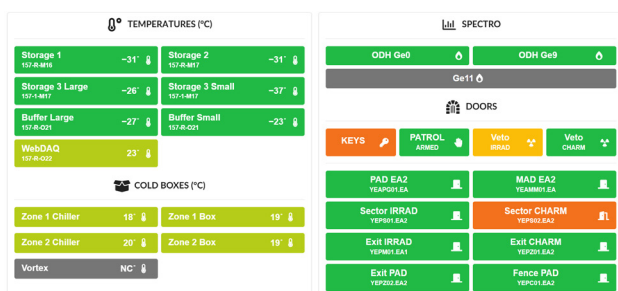


Figure 5: Some new Status Panel information in OPWT.

Data Management System

Developed in the Django framework using Python, the IRRAD Data Manager (IDM) [10] handles the considerable amount of data stemming from users' experiments. This tool stores relevant details about the submission, the life cycle of the IRRAD experiments and the traceability of the samples, dosimeters, and users (see Fig. 6) [11]. Several key features have been improved since the IDM's first version in addition to implementing a handier web application. Today, IDM integrates modules to connect to the dedicated CERN platform for sample traceability (TREC) [12] and transfers to it data relevant for sample transport, storage and logistics such as their material composition, dimensions and location through an EAM-API model. Some functionalities have been recently also added to send and print

user's requests as well as generate IRRAD-customized labels that include a QR code identifier with information about the specific tested items.

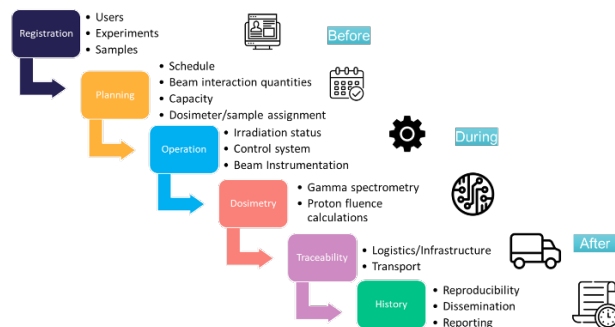


Figure 6: Irradiation-experiment lifecycle implemented in IDM.

After an irradiation has taken place, IDM automatically generates the report of the integrated proton fluence cumulated by accessing the result database of the gamma-spectrometry laboratory where the sample's dosimetry data are stored. The IDM model retrieves the necessary information and performs the dosimetry calculations using several parameters measured or provided as input by the users or the facility operators (weight, duration, end date of the irradiation experiment, nuclide, activity measurements, etc.).

IDM is also used as a test-bench, within the EU-funded AIDAInnova project. The aims of this project are twofold: on one hand, it helps at exploring the usage of RFIDs as a replacement of the QR-code labels currently used to tag irradiated samples, and, on the other, it intends to test and integrate in IDM commercial tools for samples tagging and radiation measurements (such as the CAEN DigiWaste platform [13]). The integration of this new IDM functionality with the CAEN RadHAND tool was recently successfully performed and tested in the IDM instances used at CERN but also deployed outside CERN, i.e., at the partner ITA at Fermilab, USA [14].

Data Analytics for Facility Performance

The CERN injector complex delivers protons to multiple facilities simultaneously over a certain operational period during the year. The Proton Synchrotron Booster (PSB) delivers beams to the PS and to the ISOLDE facility, while the PS further distributes beams to the SPS (to serve, in turn, multiple users) and other facilities, including IRRAD. Additionally, Machine Development (MD) studies are regularly conducted either during dedicated periods or in parallel to standard beam operations. Proton sharing among these facilities, achieved using supercycles², is therefore a challenge and requires regular feedback to the accelerator operation centre to maintain the agreed-upon beam sharing, thus maximizing its availability for IRRAD.

For this reason, a regular follow-up of several Key Performance Indicators (KPIs) became thus an integral part of

¹<https://op-webtools.web.cern.ch/irrad/#/status>

²a supercycle is a pre-defined sequence of cycles that is repeated continuously, with each cycle delivering beams to a specific facility.

the daily facility operation. Measuring and reporting KPIs is expected to gain even more importance after LS3, when new experimental facilities will become operational (SHiP, etc.), introducing additional constraints on the beam-sharing capabilities of the CERN injector complex.

Figure 7 shows the intensity KPI as reported weekly to the PS/SPS Physics coordination, obtained by a set of Jupyter Notebooks developed for IRRAD and based on the accelerator logging system NXCALs. Beside proton intensity, the IRRAD KPIs include, for instance, the beam alignment performance, the beam transmission, the frequency of the EAST_T8 cycle within the PS supercycle, etc.

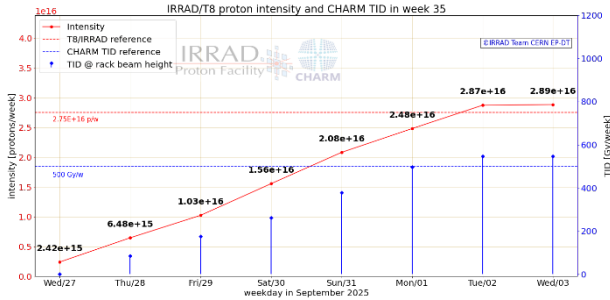


Figure 7: Weekly proton intensity KPI for T8 (red curve). On the same plot, the Total Ionizing Dose (TID) simultaneously generated by the CHARM target is also visible.

To promptly send this information to the beam-operation team and allow them to balance the beam sharing to achieve the agreed physics performance, some of this KPI data (such as the one in Fig. 7) are also available quasi-real-time on the CERN Beam Performance Tracking portal [15].

The analyses of the evolution of the IRRAD KPIs on an annual basis (see Fig. 8), beside contributing to improving the quality of the T8 beam (better alignment, reduced transmission losses, etc.) brought also to the decision of increasing, from the run 2024 of IRRAD, the number of proton per spill accelerated and delivered to T8 (from 6 to 8×10^{11} p/spill). All these improvements resulted in an increase of more than a factor 3 on the average daily beam intensity delivered to T8 during the last decade as shown in Fig. 9.

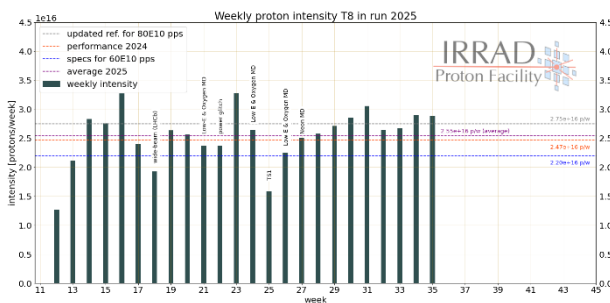


Figure 8: Annual view of the weekly proton intensity delivered to T8 (until week 35 in 2025). The coloured dotted lines represent the reference KPIs.

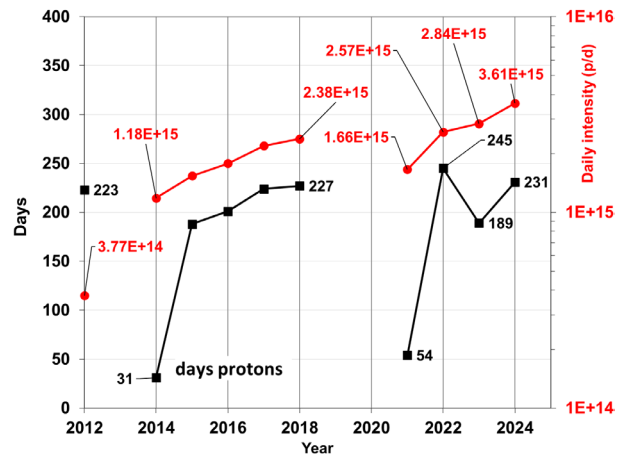


Figure 9: Annual view of the average daily proton intensity delivered to T8 (red curve). The black curve represents the number of days of IRRAD operation in one year.

Beam Monitoring

As mentioned in the first section, beside the regular beamline instrumentation, specific Beam Profile Monitor (BPM) devices are located along the IRRAD beam trajectory to supply a direct and on-line measurement of the profile and position of the irradiation beam as well as to facilitate the alignment of the user's samples relative to it. The IRRAD-BPMs are pixelated sensors that generate an electrical charge from a Secondary Electron Emission (SEE) process when intercepted by the proton beam. The integrated charge is thus proportional to the number of particles crossing each pad, and the beam profile (shape, position) can be subsequently reconstructed when measuring the intensity of the charges generated by every pad during beam delivery [16]. A custom-made Data Acquisition system (DAQ) records the intensity data and stores them in the ORACLE database for further processing and display, as shown in the sections above.

Limitations observed in the first run of IRRAD, and the need to support the development of a rich experimental program on T8, pushed forward the R&D on new BPM devices featuring more radiation tolerance, less invasive materials, increased particle sensitivity [8] as well as a new and fast DAQ system [17]. Beside the standard proton operation, the IRRAD-BPM should now also be able to cope with the use of low-intensity (down to 10^9 p/spill) or variable spill-length (100's ms, fast ns pulses) proton beams and possibly also low-intensity heavy-ion beams.

The new IRRAD-BPM DAQ readout electronics, planned to be fully deployed during LS3, enables the measurement of currents in the 1-100's nA range, better matching the dynamic range of the newly developed IRRAD-BPM sensors. The sampling rate of this new DAQ improved from a 20-ms to a 1-ms range, allowing to acquire and process signals from four BPMs in parallel, each one consisting of a set of 40 channels, for a total of 160 channels per DAQ unit.

The DAQ architecture is scalable, including a large motherboard that serves as the central hub, five smaller interposer boards that are placed as shields, and a panel board

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that functions as the user interface. Each interposer board is equipped with a 20-bit, 32-channel, current-input ADC from TI (DDC232), which provides analog-to-digital conversion and signal conditioning for the BPM sensor. In case of malfunction, each interposer can be replaced independently without the need to dismount the entire motherboard or perform complex soldering operations. Such an approach also simplifies the maintenance and reduces the cost and time for repairing the system in case of failure during operation [17]. During the run 2024, this new system allowed acquiring time-resolved beam-profile measurements of the proton spills during the delivery of 500-ms spills [3].

The IRRAD-BPM system architecture provides a constant data volume during operation resulting in a data flow of raw measurements reaching about 160 MB/day. These data can be exploited to conduct research towards AI-based analysis of IRRAD beam profiles and define new metrics for beam characterization. By exploiting both novel and established ML models and algorithms, a R&D project began after the LSs aiming to improve efficiency and precision of beam-pattern recognition. Neural network architectures such as Convolutional Neural Networks (CNN) [18] or attention-based Visual Transformers (ViT) [19] are especially promising for the tasks related to image processing and pattern recognition, which are crucial when analyzing the beam profiles as shown in Fig. 10.

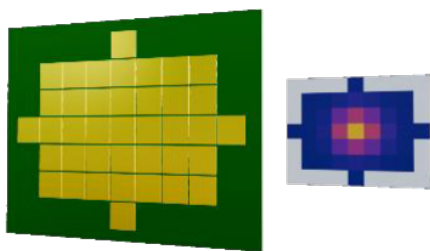


Figure 10: BPM pads schema confronted with a data representation of the space distribution of a proton spill.

Upon this groundwork, further applications can be built for the automatic classification of the IRRAD-BPM profiles [20] and anomaly detection [21]. This solution, when coupled with feedback mechanisms and control systems, aims to improve the operation of the facility and ease the continuous quality monitoring of beam properties, thus increasing its stability and consequently the quality of the performed irradiation experiment.

CHALLENGES BEYOND LS3

Among the future requirements related to the operation of the IRRAD facility outlined in the first section, the one concerning ultra-high fluence-level irradiation remains the most difficult to fulfil. This becomes even more challenging when long irradiation experiments need to be performed at low or even cryogenic temperatures.

As an example, to qualify organic insulation systems for use in superconducting magnets of future particle accelerators, irradiation beyond doses of 80 MGy at cryogenic

temperatures need to be performed [22]. Previous irradiations of this type were carried out at IRRAD using a liquid helium (LHe) cryostat available in the facility. This cryostat needs to be refilled daily with LHe and several weeks of decay are required prior opening it to access the samples. These constraints limit, at present, LHe irradiations to a few weeks and towards the end of the irradiation run only.

To overcome the limitations of the current LHe irradiation set-up, a cryocooler cooled set-up is being designed (see Fig. 11), and it is planned to be installed at IRRAD during LS3 on a future new dedicated irradiation system. This will enable cryogenic proton irradiations lasting several months per year in IRRAD without LHe consumption. The goal is to achieve irradiations at a sample temperature less than 20 K to the highest possible doses beyond LS3.

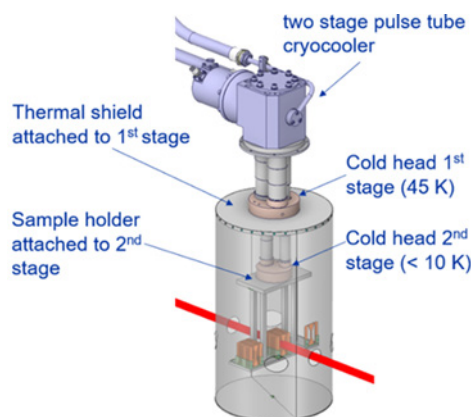


Figure 11: New Cryocooler design (Courtesy L. Wolf).

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