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# THE IRRAD PROTON IRRADIATION FACILITY CONTROL, DATA MANAGEMENT AND BEAM DIAGNOSTIC SYSTEMS: AN OUTLOOK OF THE MAJOR UPGRADES BEYOND THE CERN LONG SHUTDOWN 2*

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*Abstract*

The IRRAD proton irradiation facility at CERN was built during the Long Shutdown 1 (LS1) to address the irradiation experiment needs of the community working for the High-Luminosity (HL) upgrade of the LHC. The present IRRAD is an upgrade of a historical service at CERN that, since the 90's, exploits the high-intensity 24 GeV/c PS proton beam for radiation-hardness studies of detector, accelerator and semiconductor components and materials. During its first run (2015-2018), IRRAD provided a key service to the CERN community, with more than 2500 samples irradiated. IRRAD is operated via custom-made irradiation systems, beam diagnostics and data management tools. During the Long Shutdown 2 (LS2), IRRAD will undergo several upgrades in order to cope also with new requirements arising for projects beyond the HL-LHC. In this paper, we (1) describe the various hardware and software equipment developed for IRRAD, and (2) present the main challenges encountered during the first years of operation, which have driven most of the improvements planned for LS2 such as applying machine-learning techniques in the processing and real-time analysis of beam profile data.

## INTRODUCTION

The proton IRRADiation facility at CERN (IRRAD), located in the East Area of the Proton Synchrotron (PS) accelerator, is an experimental infrastructure tailored for the qualification of material, electronics and detector components for High-Energy Physics (HEP) experiments. The IRRAD facility was originally built in 1999 [1] on the T7 beam line of the PS East Area and underwent a major upgrade in 2014 during the CERN Long Shutdown 1 (LS1). In the 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 LHC [2].

The PS delivers to IRRAD a Gaussian proton beam of momentum 24 GeV/c, in ~400 ms spills (of about $5 \times 10^{11}$ p) every 10 s on average, and with a typical beam spot of $12 \times 12$ mm$^2$ FWHM. In this beam, objects (also called "samples") up to $10 \times 10$ cm$^2$ in size can be exposed to a particle fluence of up to several $10^{15}$ p/cm$^2$. Smaller objects can be irradiated up to a fluence beyond $10^{17}$ p/cm$^2$. Irradiation experiments with a defocused proton beam or with larger objects are also possible. Furthermore, irradiation experiments at low temperature (−25 °C) or in cryogenic conditions (1.9 K) can be also performed at IRRAD.

The samples to be irradiated are placed on remotely controlled stages (irradiation tables) that can be moved along three axis (x,y,$\theta$) as shown in Fig. 1. The irradiation tables, nine in total, 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 installing them. In addition, a conveyor (shuttle) system is available for the irradiation of smaller samples with maximum dimensions of $5 \times 5$ cm$^2$. This irradiation system can be moved from the outside area to the irradiation position, without the need to interrupt the proton beam operation. In order to precisely align the proton beam over T8, a dedicated beam instrument is used to provide a real-time display of the beam profile [3]. Moreover, dedicated software interfaces are used to control and monitor the IRRAD facility operations [4].


Figure 1: Irradiation tables (front) and shuttle system (back) in IRRAD.

Every year in IRRAD hundreds of samples are exposed to the proton beam (see Fig. 2). As a result, the registration, planning and follow-up of these experiments require the management of a considerable amount of data. In the early days, a dedicated software application was used in a

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local computer for the identification and traceability of the samples to be irradiated. Since 2014, in the framework of the EU-funded AIDA-2020 project [5], a new web-based system (the IRRAD Data Manager, or IDM [6]) better tailored to the needs of the new IRRAD facility and the current CERN software infrastructure, and providing a more advanced User Experience, has been developed.

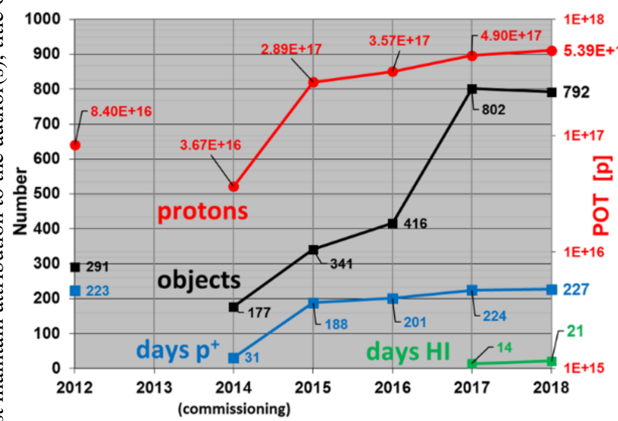


Figure 2: IRRAD statistics after the LS1 (2014). Besides the number of irradiated objects, the days of operation (bottom curves for protons and Heavy Ions) and the total number of protons delivered by the PS to T8 (top curve) are shown.

The overall development of the new IRRAD Data Manager (IDM) web application and its key functionalities are presented in greater detail in a dedicated contribution at this conference [7]. This also includes the planned upgrades being performed during the LS2, as well as possible future works about extending IDM towards other irradiation facilities through the development of a dedicated Irradiation Experiment Data Management ontology (IEDM) [8, 9].

Based on the operational experience accumulated during the first run of IRRAD (2014-2018), in this paper we instead review the major upgrades foreseen during the LS2 for what concerns the facility control system (first section), the beam diagnostic and dosimetry systems (second section) as well as the facility infrastructure (third section).

## CONTROL SYSTEM

The two main components in IRRAD requiring a control system are the irradiation tables and the remotely operated shuttle system. To allow the movement, configuration and monitoring of the IRRAD tables, a dedicated custom-made software developed using Windows Forms and C# is currently used. This application communicates through RS-232 with a M300 microprocessor that is programmed to move the samples to the assigned positions via stepping motors. An equivalent application (running on a touch-screen PC) is in operation also for the shuttle system as shown in Fig. 3. Besides performing the control, these applications monitor a set of Data Acquisition (DAQ) units and store into an Oracle database, every time a proton spill is delivered by the PS, several parameters such as temperatures, axes positions, radiation doses, beam counters, etc. for a total of about 140 acquisition channels. Details about the IRRAD control system architecture are available in Ref. [4].

### *Planned Upgrades to the Control System*

The main upgrade planned during the LS2 consists in introducing additional acquisition channels for the monitoring of the Relative Humidity (RH) in the facility. RH is a challenging parameter to monitor in IRRAD and requires the usage of specific sensing elements (developed to work in harsh radiation environment). The readout of these sensors already used at CERN in other applications will be performed with a PLC-based system [10]. The data acquired through this PLC will need to be integrated in the existing architecture described above, recorded and displayed in real time to the facility users.


Figure 3: User interface to control the IRRAD shuttle system.

Currently, the DAQ of the IRRAD environmental parameters (e.g., temperature, dose rate, etc.) are based on technologies that are becoming by the time obsolete and used by a small user community (e.g., ICP-DAS [11]). Thus, we plan to investigate the possibility of extending the usage of PLCs and integrating them in the whole IRRAD DAQ process and the control systems. Moreover, the user interfaces of the control systems used for the positioning of the IRRAD tables, communicating with the microprocessor, are custom-made applications based on proprietary software that soon will not be supported by CERN. Therefore, another issue that needs to be investigated in detail during the LS2 is to move towards free and open-source software tools such as PyQt [12], which are also platform-independent and functional in multiple operating systems (e.g., Linux or Windows).

## BEAM DIAGNOSTIC AND DOSIMETRY

The beam quality is the most important parameter for the operation of IRRAD. The real-time (on a spill-by-spill basis) knowledge of the position and shape of the irradiation beam

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(to enable its steering) requires the usage of a beam diagnostic that can be permanently exposed to the beam, without excessively contributing to the overall proton interaction length. An ideal device coping with these requirements must thus feature an excellent radiation resistance, and be composed by the least amount of material possible. For these reasons, a dedicated Beam Profile Monitor (BPM) instrument was developed for IRRAD [13].

The BPM detectors are composed of arrays of 4×4 mm$^2$ Cu pads designed on flex-PCB circuits that generate an electrical charge via Secondary Electron Emission when the proton beam impinges on them [3]. These signals are then measured by a DAQ unit outside the radiation zone, which integrates and records them through an Arduino Yún [14]; these data are then sent to a local server for further processing and stored in an Oracle database. These data are finally used to populate real-time on-line displays of the IRRAD beam profile such the one shown as an example in Fig. 4. Four fixed BPMs are located in IRRAD (see subsection "Beam Intensity Measurements") and several others (called "mini-BPMs") are installed directly on the irradiation tables. Besides the IRRAD operation, the BPM information is also used by the CERN Control Center (CCC) to steer the IRRAD beam along the irradiation area. Moreover, this information is stored and available off-line to the IRRAD users, when analysing the results of their irradiation experiment.

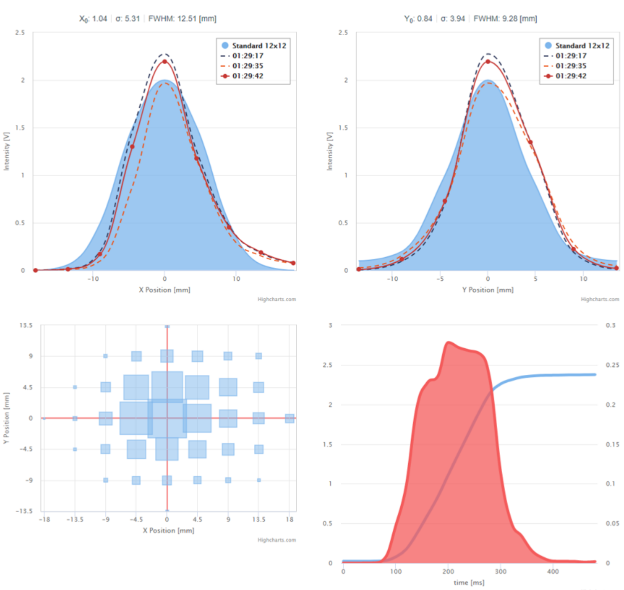


Figure 4: Beam profile display. Upper part: the X-Y Gaussian beam profiles. Bottom part: (left-hand side), pad intensities; (right-hand side), the time structure of the proton beam.

### *Planned Upgrades to the Beam Instrumentation*

The BPM is the main but not the unique beam instrument present in IRRAD [2]. Secondary Emission Monitor (SEC) and Ionization Chamber (XION) devices are also installed for cross-calibration and complementary intensity measurements while operating IRRAD with non-standard beams (e.g., various intensities and/or shapes) or other type of particles such as the Heavy Ions [15]. Since special beam conditions became more and more frequent during the first run of the facility, a series of improvements have been planned on the beam instrumentation side and are detailed in the following sub sections.

**Beam Profile Monitor** Taking into account the detector requirements outlined in the section above and the experience from the first run of IRRAD, indicating that the damage induced by the proton bombardment appeared to be more severe than expected, a completely new technology for the BPM sensors (based on micro-fabricated ultra-thin metal layers) is currently being investigated within an EU-funded ATTRACT project [16] in partnership with the EPFL of Lausanne in Switzerland and the University of Helsinki in Finland. This new development, which has been proven to work in early tests in IRRAD before the LS2 [17], also addresses the issue of striving to continuously decrease the amount of in-beam material in order to achieve a minimum-invasive beam diagnostic. An example of a new BPM monitor (called "micro-BPM") featuring a 50 nm-thick sensitive metal layer over a 9-pad cross-shape array is shown in Fig. 5.

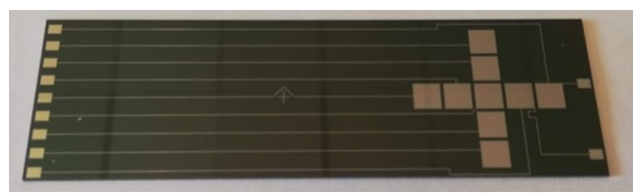

Figure 5: Image of a fabricated micro-BPM.

Today, the transverse beam-profile reconstruction is performed in 2D and the information from the four main BPMs in IRRAD is manually compared, by the IRRAD operators and the CCC operation teams, to "ideal" reference beam profiles (see blue Gaussian shapes in Fig. 4).

To be able to better exploit all features of the new micro-BPM devices after the LS2, the handling and display of the BPM data need to be substantially improved. For instance, the shape of the beam could be compared on-line (on a spill-to-spill basis) to the reference one, by applying Machine Learning-based (ML) techniques. ML classification and evaluation of the beam profile patterns are thus a promising path of investigation for our application and was born by collaborating with MINES ParisTech (PSL University) in Paris, France. Such a process could improve the efficiency of the pattern recognition algorithm (faster data processing), helping to promptly detect deviations of the beam profile w.r.t. the nominal one and thus, in turn, improving the beam quality and the efficiency of the irradiation experiments. This research would be reminiscent of the machine/deep learning applications being also currently investigated at CERN for accelerator control systems, suggesting possible synergies with other groups working on this topic [18]. More specifically, we intend to investigate the possibility of using a Convolutional Neural Network (CNN) on the proton beam

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images in order to provide better prediction of the beam parameters and a classification of the quality of the beam.

In the current version of the BPM system, the local server is a physical PC server hosted in the IRRAD infrastructure and running Windows Server 2012. Today, CERN provides an open platform called OpenStack [19] where images of virtual machines can be hosted. Thus, in view of the changes expected at CERN about the future OS-platforms [20], another upgrade concerning the data acquisition process of BPM is the virtualisation of the BPM server. A virtual machine image running on OpenStack will be deployed to run the BPM server, currently running on a local machine.

**Beam Intensity Measurements** The more and more frequent operation of the facility with low-intensity proton and Heavy Ion beams motivated the need of improving the overall beam diagnostics available for the T8 beam line. In particular, two new devices, a XION and a Fast Beam Current Transformer (BCT), will be added upstream IRRAD, together with the existing SEC, in order to have a common reference location for all types of beam intensity measurements, as depicted in Fig. 6.

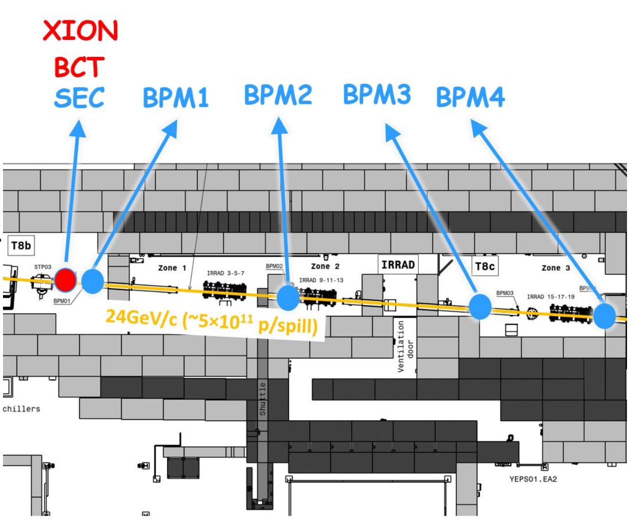


Figure 6: Updated layout of the IRRAD beam instrumentation after the LS2. The devices in red color are the ones newly installed during the LS2.

These new devices, which would need to be inserted in-beam only during the required measurements (because of the constraints about the proton interaction length described above), will be installed on movable stages that would also need to be integrated in the current architecture of the IRRAD control system.

### *Planned Upgrades to the Dosimetry Infrastructure*

The absolute particle fluence measurements in IRRAD are based on nuclear reactions that lead to the formation of radionuclides in thin high-purity aluminum foils. After the foil (or "dosimeter") is exposed to the particles, the amounts of generated radionuclides can be determined by means of gamma spectroscopy analysis, with opportune corrections to take into account the radionuclide decay constant and the thickness of the material foil [21]. With this method, particle fluence can be calculated with an accuracy of a few percentages.

To perform these measurements IRRAD is equipped with a set of HP-Ge gamma spectrometers [22]. To cope with the increasing number of dosimeters to be measured and to simplify their handling within CERN, a new spectrometer station will be added to this existing set during LS2. This project is requiring the upgrade of the software in order to handle a distributed set of detectors, as well as to guarantee the compatibility and the data interchange between this proprietary system and the recently developed IDM. This project will also require the virtualisation of the server in an OpenStack-supported Virtual Machine image, while the client applications will run in to separate locations at CERN.

## FACILITY INFRASTRUCTURE

After irradiation, most of the the radioactive samples removed from IRRAD are manipulated by the users in the technical area around the facility and in the annex storage bunkers. These areas are equipped with proper handling tools and enable the storage of the irradiated (and usually fragile) samples with suitable environmental conditions (e.g., at room temperature or in dedicated freezers below −25 °C in a dry atmosphere). Since these areas are reaching their full capability, during the LS2, an extension has been planned in order to increase the available space.

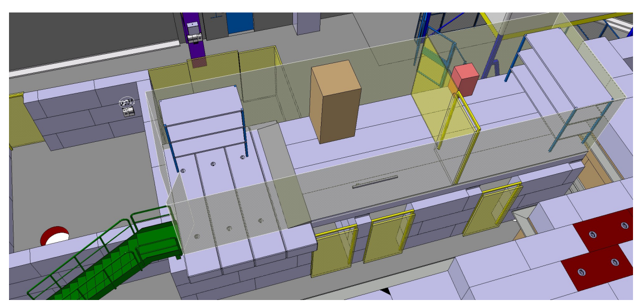

Figure 7: Layout of the IRRAD storage area extension.

### *Planned Upgrades to the Facility Infrastructure*

Post-irradiation measurements are necessary, on average, for more than 50% of the total number of experiments performed in IRRAD. This is to enable the IRRAD users to characterize the irradiated samples, or to record their behaviour for a certain period after the particle exposure ends.

To avoid the transport of irradiated materials around CERN (often in laboratories not designed and classified as CERN radiation areas), whenever possible, the users are encouraged to perform these measurements directly within the IRRAD infrastructure. For this reason, the IRRAD technical area was equipped with dedicated laboratory equipment (inspection microscope, soldering station, etc.). This also includes a new state-of-the-art electrical characterization test-bench composed by a Suss PM8 Probe Station (equipped with 4 Manipulators, a thermos-chuck from 5 °C to 125 °C

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and a vibration isolated table in EM isolated dark box) coupled with a Keithley 4200A Semiconductor Parameter Analyser. Moreover, recently, a 100 liters Temperature and Humidity Test Chamber, from LIB Industries, has been also procured and installed in IRRAD.

The increasing quantity of stored material, the growing number of users requiring the access to the IRRAD technical area and the space occupied by the newly purchased measurement equipment are hitting the limitation imposed by the space initially allocated for these activities within the IRRAD infrastructure (50 $m^2$, in total). Figure 7 details the proposed extension of the IRRAD technical area during the LS2. This new work-space will be located on the first floor, on the top for the existent storage bunkers, at a 2.4 m height from the ground and will act as a new operational storage from the post-LS2 operation period onwards [23].

## CONCLUSION

Only during the year 2018, the IRRAD facility featured 81 performed experiments (by a community of 97 users), 787 samples managed, 405 dosimeters irradiated and 2056 dosimetry measurements analyzed, recorded and supplied to the users. This exceptional performance confirmed a trend that has seen these metrics constantly increasing during the last 5 years.

This paper provided an overview of the major upgrades and modifications planned for the CERN proton irradiation facility (IRRAD) during the CERN Long Shutdown 2 (2019-2021) in order to cope with these performance increases as well as with new arising requirements. Besides the development of a custom-made IRRAD Data Manager (IDM) application (detailed in a separated ICALEPCS 2019 contribution [7]), we focused here on the IRRAD control system and its beam diagnostics, dosimetry and facility infrastructure aspects.

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