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CERN PROTON IRRADIATION FACILITY (IRRAD) DATA MANAGEMENT, CONTROL AND MONITORING SYSTEM INFRASTRUCTURE FOR POST-LS2 EXPERIMENTS*

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Abstract

Since upgrades of the CERN Large Hadron Collider are planned and design studies for a post-LHC particle accelerator are ongoing, it is key to ensure that the detectors and electronic components used in the CERN experiments and accelerators can withstand the high amount of radiation produced during particle collisions. To comply with this requirement, scientists perform radiation testing experiments, which consist in exposing these components to high levels of particle radiation to simulate the real operational conditions. The CERN Proton Irradiation Facility (IRRAD) is a well-established reference facility for conducting such experiments. Over the years, the IRRAD facility has developed a dedicated software infrastructure to support the control and monitoring systems used to manage these experiments, as well as to handle other important aspects such as dosimetry, spectrometry, and material traceability. In this paper, new developments and upgrades to the IRRAD software infrastructure are presented. These advances are crucial to ensure that the facility remains up-to-date and able to cope with the increasing (and always more complex) user needs. These software upgrades (some of them carried out within the EU-funded project AIDAinnova and EURO-LABS) will help to improve the efficiency and accuracy of the experiments performed at IRRAD and enhance the capabilities of this facility.

INTRODUCTION

The CERN Large Hadron Collider (LHC) upgrades and the post-LHC particle-accelerator design studies make necessary the qualification of various components against radiation. The CERN Proton Irradiation Facility, IRRAD (see Fig. 1), is a reference facility in High-Energy Physics (HEP) community, dedicated to radiation tests of components, materials and irradiation experiments on complex detector or accelerator systems. Detectors, materials and electronic components of different dimensions (from a few mm^2 to several cm^2) are being exposed to the proton beam in order to assess their radiation hardness. The proton beam is delivered from the Proton Synchrotron (PS) accelerator at CERN with a momentum of 24 GeV/c, in spills of 400 ms every 10 s on average, and it has a typical Gaussian shape of 12×12 mm^2 full width at half maximum (FWHM). It impinges on the devices under test positioned along the beam line. The Devices Under Test (DUT), are usually positioned on stages (IRRAD Tables) that can be remotely controlled and moved horizontally, vertically or rotated by a certain angle w.r.t. the beam axis, while providing also in-beam scanning capabilities. The samples can be installed or withdrawn from the irradiation zones only once a week. Therefore, for smaller samples (e.g., 5×5 mm^2) and shorter irradiation experiments, a 9-m long shuttle system is used for moving the samples in and out of the beam line without stopping the beam operation. The IRRAD facility is also equipped with two cold boxes for irradiation experiments down to -25 °C, but also with a LHe cryostat for experiments performed down to 4.2 K. Beam Profile Monitors (BPM) are also installed in IRRAD for the real-time monitoring of the beam profile and quality [1] but also for aligning precisely the IRRAD Tables in the beam. Since 2022, IRRAD is also one of the research infrastructures that provide Transnational Access to users coming from other countries through the European Project EURO-LABS [2].

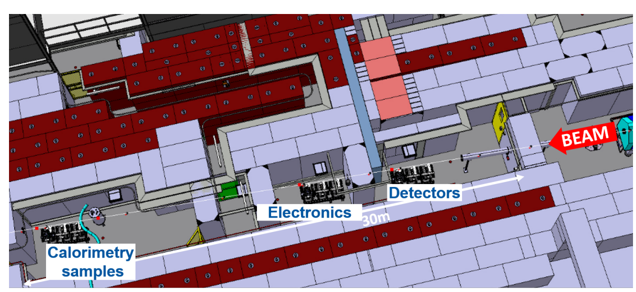

Figure 1: IRRAD Facility.

For the successful operation of the IRRAD facility, a robust hardware and software infrastructure had to be established. This includes data management systems, beam and environmental monitoring/logging tools, and control systems. In order to cope with the continuous demand of experiments, improve and facilitate the operation as well as be compliant with the CERN IT infrastructure updates and security rules, several upgrades have been performed and detailed in the following sections.

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Following this introduction, in the second section, the upgrades for the data management system are described, while in the third section new features related to BPM-data logging is presented. In the fourth section, upgrades related to the virtualization of the servers are described, while in the fifth section, we present the improvements related to the IRRAD control and monitoring system. We conclude this paper by providing a summary of the current IRRAD upgrades and suggestions for future improvements.

DATA MANAGEMENT

Only during this year of 2023, 37 experiments have been requested and 399 samples are being tested in IRRAD. This makes proper data handling, experiments' follow-up, and samples traceability quite challenging for the team operating the facility. For this reason, a software tool named IRRAD Data Manager (IDM) has been developed [3] and put into production since 2018. This tool is used for storing data relevant to the experiments, samples, dosimeters, and users. IDM was built using Django [4], a python framework for web development, and stores the data in an Oracle centrally-managed database. Table 1 provides some statistics for the records registered in IDM since its first launched version for the IRRAD run of 2018.

Since IDM's first version, several improvements and new features have been developed. Based on the usability sessions performed with the IDM users, a new, more user-friendly design was implemented. IDM is also used for reading and transferring data to TREC [5], a software platform provided by CERN Radiation Protection (HSE-RP) to ensure traceability, using the EAM API [6], used for TREC's back end. This part was enhanced with additional features such as displaying in TREC the material composition of the samples, important for the RP classification. Another IDM upgrade was the use of the EAM API for sending printing requests and printing IRRAD-customized labels that include a QR code identifier with information about the specific tested items [7]. Moreover, in order to ensure security but also be compliant with the CERN IT infrastructure, changes in the user model and additional configurations had to be performed for the upgrade of the new CERN authentication and authorization system, Single Sign-On (SSO). Within the framework of the European Project AIDAinnova [8], IDM is also being customized and deployed in other irradiation facilities at CERN such as GIF++ [9] but also ENEA-FNG [10], in Italy, and the ITA facility at Fermilab [11], in the United States.

Table 1: IDM Records Statistics

Category	Number
Experiments	198
Samples	1952
Dosimeters	701
Users	196

The final goal of an irradiation experiment is that the samples reach the integrated particle flux (fluence) requested by the users. To estimate this value, while the irradiation experiments are ongoing, beam instrumentation equipment, such as the Secondary Emission Chamber (SEC), is used. These values are read by the IRRAD hardware display units, and are also stored in a database and accessible through the IDM administrator's view when required for the follow-up of the experiments. Moreover, during the irradiation experiments, activation samples (typically thin aluminum foils also referred as the dosimeters) are usually placed in line with the samples, allowing for the validation and cross-check of the final accumulated fluence w.r.t. the estimated fluence from the beam instrumentation. This is accomplished by performing gamma-spectrometry measurements, where the activity values can be determined, and by using these values to compute the accumulated proton fluence.

Before the new IDM features were implemented, the fluence calculation was done manually using a custom software interface and inputting the necessary information by hand. After the latest upgrades, these data are automatically integrated in IDM. This was achieved by identifying the necessary information in the gamma-spectrometry database and developing the module in IDM able to connect and communicate with the gamma-spectrometry database, read and calculate the fluence-related values. The fluence calculation is determined by several parameters that can be found either in the gamma-spectrometry or the IDM database. These parameters include the weight, material of the dosimeter (usually aluminum), duration and end date of the irradiation experiment, nuclide and activity measurements. Figure 2 illustrates an example of fluence-related results for the dosimeter DOS-004480.

Another work within the AIDAinnova framework and currently in progress is testing RFID sensors provided by the CAEN [12] company to use them for tagging samples exposed in IRRAD. For this purpose, two irradiation campaigns for their characterization were performed. The first one in the IRRAD facility with protons [13] and the second one, in ENEA-FNG with neutrons [14]. These tests actually showed that the selected model of RFIDs could reliably function in a radioactive environment, as long as they are not exposed in a high-energy beam. CAEN also provided a RadHAND device for reading the RFID tags as well as to simultaneously display other samples information (dose-rate, gamma-ray emission spectrum, etc.). An API is also available. New IDM functionalities are currently being developed for using the CAEN API and making possible to have these data also integrated in the system.

BEAM-DATA MONITORING AND LOGGING

The proton beam delivered to IRRAD is steered and aligned by the CERN Control Center (CCC). To facilitate the proper beam alignment, BPMs are placed in IRRAD in fixed positions, which allow for the continuous monitoring

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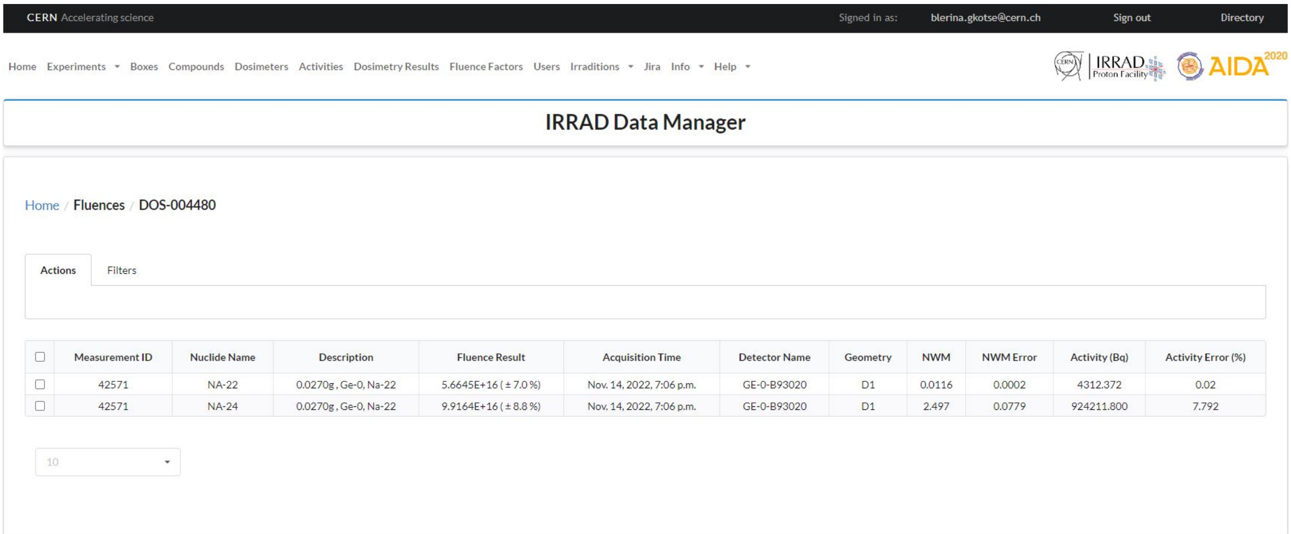

Figure 2: Fluence-related results for the dosimeter DOS-004480 displayed in IDM.

of the beam profile and intensity. These BPM sensors, composed of 39 Cu/FR4 pads of 4x4 mm^2, are called fixed-BPMs. Other smaller BPM sensors, called mini-BPMs (9 pads forming a cross shape) and single-pad BPMs, are installed on the IRRAD tables to enable the correct alignment of the samples w.r.t. the beam line. A dedicated Data Acquisition (DAQ) system had been implemented for the readout of the BPM sensors. All collected data are processed on a BPM server, stored in an Oracle centrally managed database and displayed in almost real time through a website. This system was put in place already since the first run in 2014 [15].

The BPM data are quite important for the IRRAD operators, users but also CCC. For this reason, there was request to log these data also in the CERN Accelerator Logging Service (NXCALS) [16] and make them available in Timber, a CERN internal portal that allows for the visualization and extraction of time-series data from NXCALS (see Fig. 3) [17]. To achieve this goal, first registering the BPMs as virtual devices in the CERN Control Database (CCDB) [18] was needed, and then an additional Control Middle-ware (CMW) server for publishing the BPM data to the CERN Accelerator Logging Service (NXCALS) was required and successfully deployed.

Throughout the years, it was observed that the original BPM sensors used in IRRAD were experiencing beam-induced degradation effects. For this reason, new BPM sensors were developed to be more radiation-hard, less invasive (e.g. thinner material layers) and with an increased particle sensitivity [19, 20]. In addition, the current DAQ electronics have several limitations such as sampling time of 20 ms, limited number of channels, dynamic range and longitudinal profile availability. For these reasons, a new compact DAQ electronics system with sampling time down to 100's μs it has been developed within the framework of EURO-LABS EU-project. A first prototype of it has been already tested and the full system will be deployed in IRRAD in the coming years [21]. Using the new electronic system in production will mean that much more data will be also produced. This data can be used to train machine learning (ML) models and develop tools to be used for the automatic classification of the IRRAD beam profiles aiming to improve its quality and stability. This model will be able to detect if the profile of the beam is according to the beam specifications and this information used to provide feedback to the beam operation team.

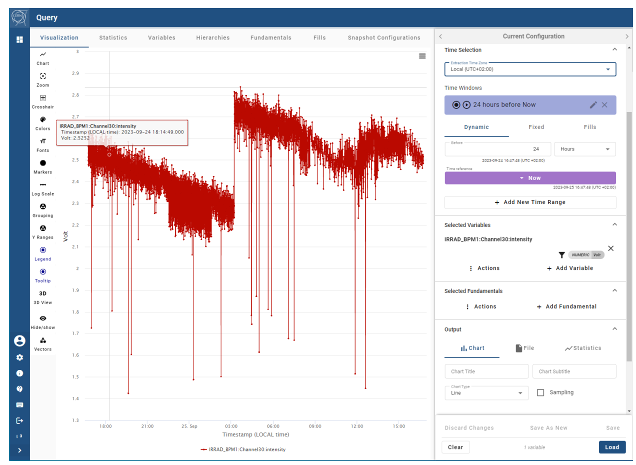

Figure 3: BPM channel data displayed in Timber.

VIRTUALIZATION

During the first IRRAD run, all servers were deployed on locally running computers. To minimize the risks of computer hardware failures or upgrades and enforce resilience, OpenStack [22] virtual machines, provided by the CERN IT infrastructure, were used as servers. This enabled the IRRAD team to increase redundancy and allowed to have two virtual machine instances of the same server. This means that in the case that one server would fail, data traffic could

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be redirected to the second instance of the server. For example, the BPM and CMW server used in daily operation are running on one of the IRRAD virtual machines. Another advantage is that costs from computer purchases are minimized. For the same reasons and security, the gamma-spectrometry server and database are also deployed in two separate virtual machine instances. In this way, the spectrometry system could become more scalable; currently two spectrometry client stations were installed (see Fig. 4).

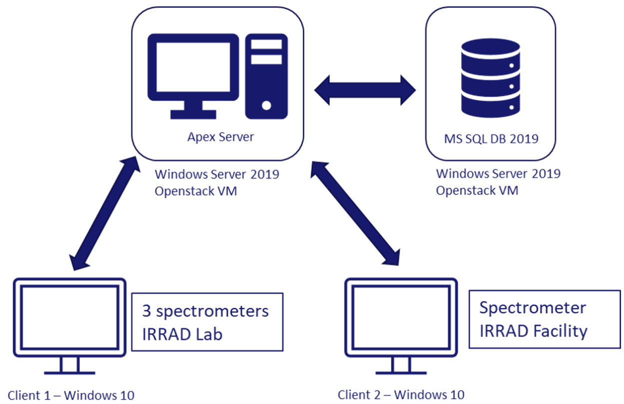

Figure 4: Architecture of the spectrometry system in IRRAD bases on VMs.

CONTROL AND MONITORING SYSTEMS

A dedicated control system for the IRRAD Tables and shuttle system is deployed in the IRRAD facility. This is because most of these equipment are operating in a radiation environment and for this reason they are custom-made to enhance their radiation resistance. The IRRAD Tables are controlled by specific micro-controllers (M300), one per IRRAD Table, allowing for moving the tables horizontally, vertically or rotating them with a certain angle. The shuttle system can be moved along two axes. The first one enables moving the shuttle along the 9 m-long path connecting the external path and the irradiation zone. The second axis is a few mm long, enabling to move the shuttle in and out of the beam while in the irradiation area. The shuttle system is also controlled by one driver AKD [23] and one M300 micro-controller. Throughout the years, Graphical User Interfaces (GUIs) have been developed and adapted to the CERN IT infrastructure, enabling users to control their experiments safely and in a user-friendly manner. The first GUIs were developed using C++ and Visual Studio and had to be upgraded in order to be compatible with the new Operating System versions. Additional amd more lightweight GUIs were also build, using open-source technologies like PyQT [24, 25]. A database is used in the back end to log the defined and custom positions while the calibration parameters of the tables and shuttle are also stored.

Regarding the monitoring system, several DAQ units are used for monitoring the position of the IRRAD Tables and shuttle, the sensors of temperature and humidity, and the dose rate monitors (e.g., AD6). These units are readout in parallel by a DAQ module (Arduino [26]) triggered during the beam delivery, collected and processed in the same server as the data collected from the BPM. These data are also stored in an Oracle database and displayed in an online page, the IRRAD Status Panel (see Fig. 5).

Figure 5: IRRAD Tables' position and temperature sensors display in the IRRAD Status Panel.

Moreover, a dedicated alarms' server was deployed; it is used for the constant checking of the beam conditions and temperature changes. In case the monitored values are reaching out of certain thresholds, e-mail notifications are sent to the IRRAD operators.

SUMMARY AND FUTURE WORK

In summary, IRRAD is a reference facility in HEP for performing proton irradiation experiments. A data management tool called IRRAD Data Manager (IDM) has been built and is in production since 2018. It has gone through several upgrades for improving usability, irradiation-experiment follow-up, and traceability. Gamma-spectrometry data are also integrated in IDM, allowing for the automatic calculation and display of the accumulated fluence received by the samples. IDM is also being currently customized and deployed in other facilities.

Virtual machine instances have been used for the IRRAD servers deployment to minimize computer failures and costs, improve security and increase redundancy. IRRAD includes also customized control and monitoring systems which had to be upgraded in order to be compliant with the current CERN IT infrastructure. Furthermore, the BPM architecture has been upgraded, including a new CMW server for logging data in NXCALS and providing data through Timber, making the BPM data easily accessible by everyone at CERN. New BPM sensors were developed, more radiation-hard, with higher sensitivity and non-invasive. New DAQ system, more scalable and with better sampling rate has been built and is being tested before its deployment during the regular IRRAD operation.

As future work, a system for the beam-quality classification is foreseen taking advantage of the big quantity of data received from the new DAQ system. We also aim to have IDM generalized and used in several irradiation facilities. Moreover, work is in progress for building an integrated system for spectrometry and traceability using possibly the CAEN RFID tags, as well.

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