# IRRAD: THE NEW 24GeV/c PROTON IRRADIATION FACILITY AT CERN

**Blerina Gkotse, Maurice Glaser, Michael Moll, Federico Ravotti***
Detector Technologies Group, Experimental Physics Department
European Organization for Nuclear Research (CERN)
CH-1211, Geneva 23, Switzerland
blerina.gkotse@cern.ch; maurice.glaser@cern.ch; michael.moll@cern.ch;
federico.ravotti@cern.ch

**ABSTRACT**

The proton and mixed-field irradiation facilities at the CERN PS East Area (known as IRRAD1 and IRRAD2), have been heavily exploited for irradiation of particle detectors, electronic components and materials since 1992. With the increasing demand of irradiation experiments, and in view of the High-Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC), these facilities suffered of a number of unpleasant restrictions such as the space availability, the maximum achievable particle flux and several access constraints. In the framework of the AIDA project, an upgrade of these facilities was carried out during the Long Shutdown 1 (LS1) of the CERN accelerator complex. The new combined East Area IRRADiation facility (EA-IRRAD) started the commissioning in October 2014. While the new proton facility (IRRAD) continue to be mainly devoted to the radiation hardness studies for the High Energy Physics community, the new mixed-field facility (CHARM) mainly hosts irradiation experiments for the validation of electronic systems used in CERN accelerators. In this paper, we describe the new IRRAD proton facility in terms of layout, area equipment and potential for new irradiation experiments.

**KEYWORDS**
High Energy Physics, IRRAD, LHC, Proton Irradiation Facility, Radiation Hardness

## 1. INTRODUCTION

The former East Area proton and mixed-field irradiation facilities, based on the 24GeV/c proton beam extracted from the Proton Synchrotron (PS) accelerator, have been extensively exploited during the LHC construction [1]. These old facilities suffered however from a number of unpleasant restrictions:

- The available space was very limited and allowed only the irradiation of small and stand-alone objects (limited services for cooling and/or electrical power);
- The proton flux was limited on the one hand by the weakness of the shielding (due to lack of space for more) and on the other hand by the competition for proton spills with the DIRAC experiment sitting in the same experimental area in the T8 beam-line.
- The access to the proton facility required long cool-down time and the stop of the whole East Area for the full duration of the access, as this facility was located inside the common primary zone.

Within the framework of the EU-funded AIDA project [2], an upgrade of these facilities was performed during LS1 (2013-2014). This upgrade relied on the completion of the scientific program of the DIRAC

* Corresponding author. Tel.: +41 22 767 4280

experiment by the end of 2012. The DIRAC experimental apparatus was thus dismounted and replaced by the new irradiation facility. The new proton irradiation area (IRRAD) is now located on T8 more or less at the former location of the DIRAC target and detectors and the new mixed-field area (CHARM) was upgraded downstream IRRAD. In CHARM, the protons that have traversed the proton irradiation area impinge on a target and generate an intense radiation field optimized to reproduce the one encountered in the LHC underground areas. A schematic overall layout of the new Irradiation Facility in the East Area (EA-IRRAD) is shown in Fig. 1 [3]. The concept of this new combined infrastructure brings indeed several advantages:

- The access to the facility is independent of the rest of the East Area;
- The new layout is optimized for exploitation as an irradiation facility, with appropriate shielding, ventilation, infrastructure and sufficient space for proper installation and easy accessibility of equipment;
- The same protons can be used for the proton and mixed-field facilities at the same time, thus leading to a strongly improved proton and PS cycle economy and optimal use of available protons;
- The beam requirements for the new proton facility correspond to the beam conditions previously used for DIRAC on the T8 beam line (apart from the intensity, which was lower for DIRAC on their request). Therefore, the beam optics for the DIRAC beam can be reused for the new EA-IRRAD with a minor change in the vacuum layout downstream of the last quadrupole.

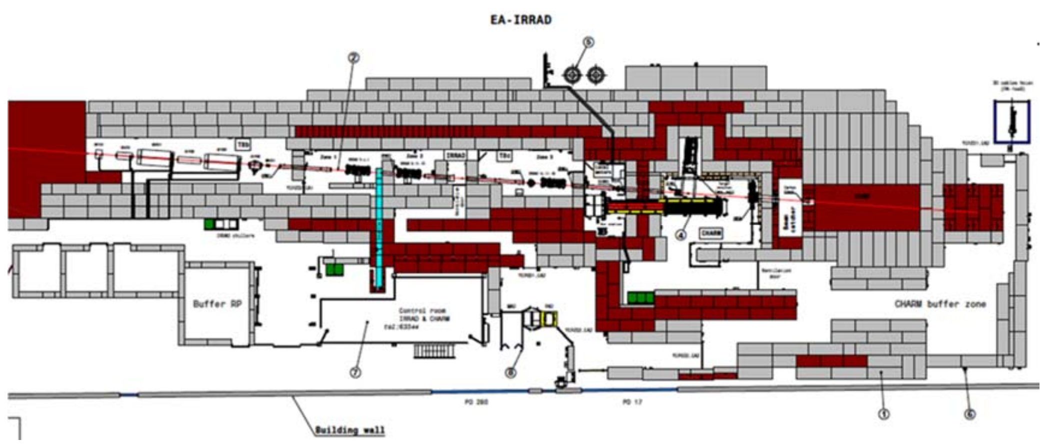


**Figure 1. Layout of the new EA-IRRAD facility.**

The T8 beam itself is a slowly extracted primary proton beam of momentum 24GeV/c delivered in spills with a maximum intensity of $5\times10^{11}$ppp and about 400ms duration. Different focusing options are possible on T8 in order to provide variable Gaussian beam dimensions ranging from about $5\times5$mm$^2$ to $20\times20$mm$^2$ (FWHM). Due to sharing of protons with other users of the PS complex, the typical proton flux achievable during standard operation is of $\sim1\times10^{14}$ p/h on average, leading to about 5days to integrate a fluence of $1\times10^{16}$ p/cm$^2$ over a surface of $12\times12$mm$^2$ [4]. The intensity and the beam dimensions can variate from the standard one upon request to the PS users' coordinator and in agreement with the other users of the experimental area. The design of the shielding (made of 4.5k tons of cast iron and 11.5k tons of concrete) and the ventilation systems allow a theoretical maximum intensity of $1\times10^{17}$ p/cm$^2$/4d over a surface of $12\times12$mm$^2$.

The effectiveness of the shielding has been studied and optimized extensively by the radiation protection experts, as well as validated by measurements during the commissioning phase. The exposure of intervening personnel due to activated air is reduced by the new ventilation system. The air inside the irradiation rooms is re-circulated and filtered. Some air extraction ensures a small under pressure so that air goes preferentially from the outside into the facility. The extracted air is liberated outside at height.

The IRRAD and CHARM facilities share a unique access point giving access to a common entrance area. From there, two sector doors give ultimately access to the IRRAD and CHARM irradiation rooms. Finally, as shown on Fig. 1, IRRAD has a new control room on the ground floor next to the access point as well it is equipped with three storage areas for the safe handling of the activated equipment after irradiation (Fig 1 on the left-hand side corner) [5].

In the following sections of this paper, we focus on the characteristics of the equipment used for proton irradiation, as well as on the results of preliminary beam quality and radiation background measurements performed during commissioning.

## 2. IRRAD PROTON FACILITY EQUIPMENT

The detailed layout of the IRRAD proton irradiation facility is shown in Fig. 2.

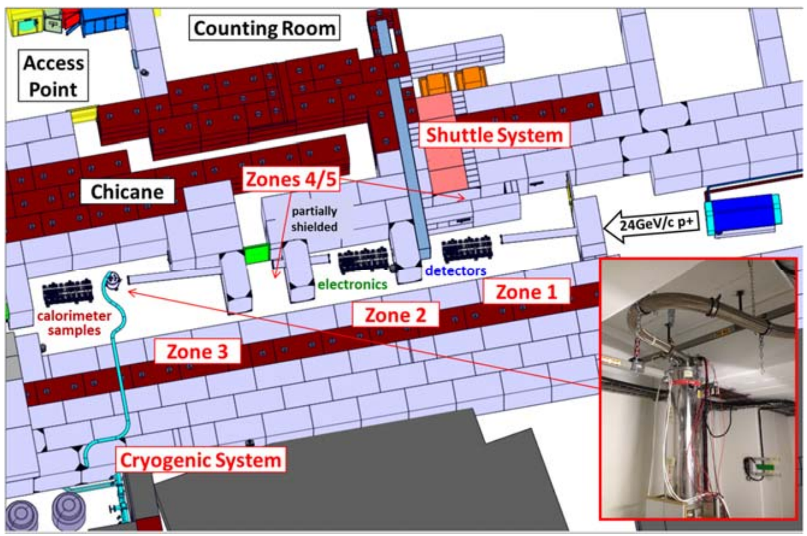


**Figure 2. Layout of the new IRRAD proton facility.**

With reference to Fig. 2, from right to left, three groups of remote-controlled tables installed along the protons path allow the positioning of samples on the beam line or close to it. The access to these tables requires access to the facility and thus stopping the T8 beam. The low-Z samples as thin silicon devices are irradiated on the upstream tables (Zone 1), while the highest-Z samples, such as dense calorimetry material, downstream (Zone 3). The intermediate group of tables (Zone 2) is typically used for the irradiation of electronics equipment. Small objects can instead be positioned directly from the outside area to the irradiation position via a dedicated shuttle system. All is automatic and no access to the IRRAD zone is required. In the irradiation room, two additional areas partially shielded from the primary proton beam (Zone 4 and 5), have been equipped to accommodate the front-end readout electronics which need to sit close to the samples being irradiated. Every IRRAD zone is equipped with a patch-panel to provide the IRRAD users with the possibility to perform on-line measurements during the irradiation experiments. The patch-panels host a set of pre-defined connections over cables with length ranging from 13m to 20m. Finally, in the downstream Zone 3, one table is reserved for a cryostat filled with liquid Helium (LHe). This allow special irradiation runs with samples exposed at cryogenic temperatures down to 1.8K The cryogenic liquid is provided from a Dewar located outside the irradiation zone, in a freely accessible area downstream of the T9 beam line (see left-hand bottom corner of Fig. 2). The cryogenic transfer line connecting the Dewar to the cryostat is permanently installed in the IRRAD lateral shielding.

## 2.1. Irradiation Tables

The tables are remote-controlled stages providing the possibility to position the samples with ±0.1mm precision in the transversal plane (X-Y) with respect to the beam-axis. The tables also rotate over the azimuthal angle (θ) in order to achieve a precise alignment with the beam within ±0.025º [6]. Three independent groups of tables, separated by a concrete shielding wall, are installed in IRRAD as shown in Fig. 3. A maximum of three tables per group (e.g. nine in the whole facility) can be installed and operated in parallel. This allows the irradiation of several materials at the same time with a "clean" proton beam and minimum background induced by scattered secondary particles.

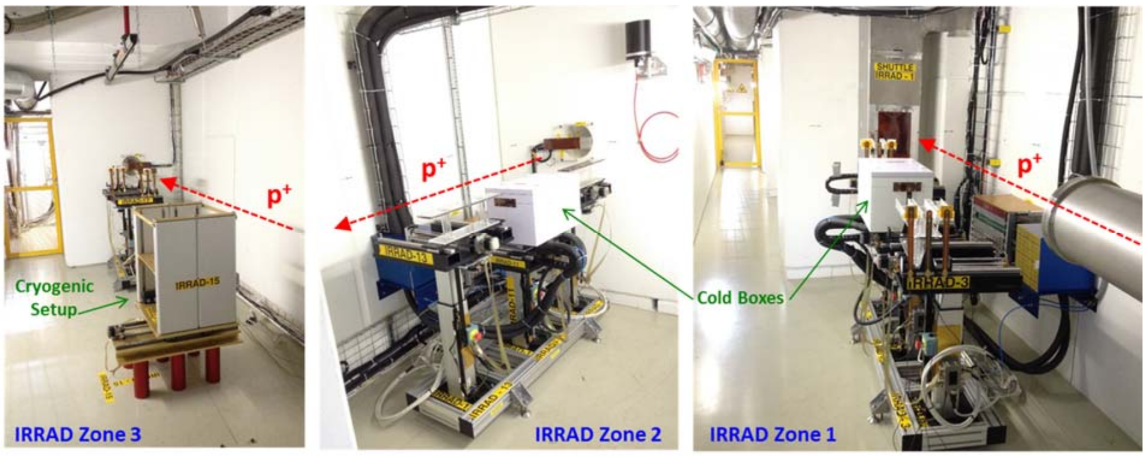


**Figure 3. Irradiation Tables installed in the proton facility.**

The tables are numbered from Zone 1 to Zone 3 using odd numbers (*IRRAD3* to *IRRAD19*). With exception done for *IRRAD15*, reserved for the cryogenic system, the maximum volume available for irradiation on each table is of 200×200×500mm$^3$ while the maximum samples weight is 50Kg. The tables can automatically move (e.g. "scan") the samples during irradiation in order to provide a uniform irradiation spot over the 200×200mm$^2$ surface (or a smaller portion of it, depending on the user request). On these tables, the test of equipment "in operation" (e.g. powered and connected to a DAQ system) is possible as well as irradiation of detector components at low temperature, down to -25ºC. Two cooling systems, located in the technical area outside the facility, provide the chilled fluid to specially designed cold boxes installed on the *IRRAD5* and *IRRAD11* tables [3]. Moreover, additional cold boxes equipped with a VORTEX cooling can be installed and connected to the compressed air network supplying the IRRAD room. With the VORTEX system, a temperature of -15ºC can be reached during irradiation.

## 2.2 Shuttle System

The *IRRAD1* Shuttle is a remote-controlled conveyor travelling on a rail system that allows the positioning of "small" objects in the IRRAD beam, without the need for human access into the area. This system guarantees a precise X-Y alignment of ±0.1mm with respect to the beam axis and it is manly dedicated to the irradiation of passive samples at RT (typically silicon detector test-samples). The shuttle for the new proton irradiation facility is a clone of the previous IRRAD1 and IRRAD2 shuttles already installed and operational in the former IRRAD facilities in the East Area since 1998 [1]. Fig. 4 shows the detail of the shuttle with its samples holder (left-hand side), together with the samples loading station located next to the IRRAD counting room outside the irradiation area (right-hand-side).


**Figure 4. IRRAD1 Shuttle. Samples holder (left-hand side). Loading station (right-hand side).**

On the shuttle, the maximum volume available for irradiation is of 50×50×150mm$^3$ for a maximum weight of about 1Kg. The shuttle travels across the shielding blocks for a length of about 10m inside a conduit of 400×400mm$^2$. To minimize the direct radiation steaming, the path of the conduit follows a chicane located in between Zone 1 and Zone 2 (see Fig.2 and Fig. 3). The standard size of the beam spot on this system is of ~5-7mm ($\sigma_{RMS}$) but it can vary according to the different beam focusing options (see Sec. 1). In particular, focusing on the shuttle system, the spot size can be reduced further during high-intensity irradiation periods.

## 3. BEAM INSTRUMENTATION AND DOSIMETRY

At the upstream end of the irradiation area an experiment-specific SEC monitor (secondary emission counter) measures the proton flux while a TV screen located downstream allows monitoring the beam position and size. Moreover, at four locations along IRRAD, dedicated Beam Profile Monitors (BPM) based on the metal-foil detector technology are installed. The BPM devices are described in a dedicated contribution presented at this conference [7]. The information from the BPMs is made available to the CERN Control Center for the steering of the IRRAD proton beam.

The basic measurement performed on the 24GeV/c proton beam is the determination of the proton fluence by evaluating the $^{24}Na$ and $^{22}Na$ activity of Aluminum (Al) foils produced via the nuclear reactions $^{27}Al(p,3pn)^{24}Na$ and $^{27}Al(p,3p3n)^{22}Na$ respectively [8]. With the activation technique, it is possible to obtain fluence measurements with an accuracy of ±7%. The size of the aluminum foils with a thickness of 100µm varies from 5 to 50mm$^2$ according to the size of the samples that have to be irradiated. The half-lives of $^{24}Na$ and $^{22}Na$ are 15h and 2.6y respectively. According to the time elapsed after irradiation and the irradiation time itself one of the two isotopes is chosen to be measured for the fluence calculation.

A preliminary measurement of the *hardness factor* ($k$) for the 24GeV/c protons in the new IRRAD facility was also performed by evaluating the *current related damage rate* ($\alpha$) of irradiated high-resistivity silicon PAD detectors as explained in Ref. [9]. The $k$ value for the 24GeV/c protons was determined to be 0.57 ± 0.01 which is in good agreement with the theoretical value 0.51 predicted by simulations.

## 4. RADIATION BACKGROUND

Secondary particles including neutrons ranging from thermal to high-energies, photons >100keV and charged hadrons on the GeV energy-range [3], are generated by the interaction of the primary protons with the samples being irradiated, as well as with the air and the materials surrounding the target samples on the tables. Extensive simulation studies with the FLUKA Monte Carlo tool [5] enabled the evaluation of the background inside the IRRAD room and, in particular, around the partially shielded locations named Zone 4 and 5 shown in Fig. 2. Table I details some of the results of the simulations performed for Zone 4 compared with the experimental radiation measurements performed with Gafchromic films (KERMA) and p-i-n silicon diodes (particle fluence) [8] in similar exposure conditions. The simulations assumed a standard beam-spot size and material samples loading on the irradiation tables of Zone 1 and 2 as well as on the *IRRAD1* shuttle. The total equivalent material thickness in beam simulated was less than one nuclear radiation length in silicon. Data were normalized to 1h of irradiation that, with standard beam conditions, delivers a 24GeV/c proton fluence of $4\times10^{13}$p/cm$^2$ to the samples under test.

**Table I. Radiation background in Zone 4. Data normalized to $4\times10^{13}$ p/cm$^2$/h hitting the samples.**

| Quantity | FLUKA | Measurements |
|---|---|---|
| **air KERMA rate** | 0.13-0.15 Gy/h | 0.10 Gy/h |
| **neutrons (> 20MeV)** | $3\times10^8$ n/cm$^2$/h | - |
| **neutrons (1MeV eq.)** | - | $3.8\times10^8$ n/cm$^2$/h |

The data measured and simulated for Zone 4 are in good agreement, proving that in standard irradiation conditions the background in this shielded area is dominated by the interaction of the high-energy protons with the surround materials of the IRRAD room. Air KERMA and particle fluence obtained for Zone 5 bring to similar conclusions and are about ×2 lower because of the most favourable geometrical position of Zone 5 (upstream IRRAD) with respect to the proton beam path.

## ACKNOWLEDGMENTS

The authors would like to thank R. Froeschl (HSE-RP) and I. M. Suau (EP-DT) from CERN for their assistance with the FLUKA simulations and the radiation measurements respectively. This project has received funding from the European Commission project AIDA, as well as from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

## REFERENCES

1. M. Glaser, L. Durieu, C. Leroy, M. Tavlet, P. Roy and F. Lemeilleur, "New irradiation zones at the CERN-PS," *Nucl. Instr. and Methods*, **A426**, pp. 72-77 (1999).
2. "AIDA Project," http://aida2020.web.cern.ch/content/aida.
3. F. Ravotti, M. Glaser, M. Moll, "Upgrade scenarios for irradiation lines: Upgrade of the Proton Irradiation Facility in the CERN PS East Area," AIDA Deliverable Report D8.4, http://cds.cern.ch/record/1951308/files/AIDA-D8_4.4.pdf (2014).
4. L. Gatignon, "Beam properties for the East Area irradiation facility in the T8 beam-line," CERN EDMS 1270807 (2013).
5. F. Ravotti et al., "IRRAD Safety File - Descriptive Part," CERN EDMS 1353928 (2014).
6. M. Glaser, M. Moll and F. Ravotti, "AIDA Milestone Report MS31 - Movable Irradiation Tables Operational," https://cds.cern.ch/record/1594787/files/AIDA-MS31.pdf (2013).
7. M. Glaser, "The Beam Profile Monitoring System for the IRRAD Proton Facility at the CERN PS East Area," *Proceedings of Twelfth International Topical Meeting on Nuclear Applications of Accelerators (AccApp'15)*, Washington, DC, Nov. 10-13, 2015.
8. F. Ravotti, M. Glaser, M. Moll, "Dosimetry Assessments in the Irradiation Facilities at the CERN-PS Accelerator," *IEEE Trans. Nucl. Sci.*, **53**(4), pp. 2016-2022 (2006).
9. M. Moll, *Radiation Damage in Silicon Particle Detectors - Microscopic Defects and Macroscopic Properties*, PhD thesis, DESY-THESIS-1999-040, ISSN 1435-8085 (1999).