

AIDA-2020-CONF-2017-007

AIDA-2020

Advanced European Infrastructures for Detectors at Accelerators

Conference/Workshop Paper

Irradiation Facilities at CERN

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04 October 2017



The AIDA-2020 Advanced European Infrastructures for Detectors at Accelerators project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

This work is part of AIDA-2020 Work Package 15: **Upgrade of beam and irradiation test infrastructure.**

The electronic version of this AIDA-2020 Publication is available via the AIDA-2020 web site <http://aida2020.web.cern.ch> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=AIDA-2020-CONF-2017-007>

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Irradiation Facilities at CERN

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Abstract—CERN provides unique irradiation facilities for applications in many scientific fields. This paper summarizes the facilities currently operating for proton, gamma, mixed-field and electron irradiations, including their main usage, characteristics and information about their operation. The new CERN irradiation facilities database is also presented. This includes not only CERN facilities but also irradiation facilities available worldwide.

Index Terms—radiation effects, irradiation facilities, radiation hardening, High Energy Physics, accelerators, space radiation

I. INTRODUCTION

NOWADAYS more and more complex High Energy Physics (HEP) experiments and accelerators are built, pushing back the energy frontier and aiming to answer some of the open questions in the standard model about the electroweak symmetry breaking, such as the existence of dark matter. Therefore, their electronic equipment and components require a more and more comprehensive qualification against various radiation-induced effects [1], [2]. Similarly, several industrial, energy and space applications also need testing materials and components with various radiation sources and at various radiation levels [3]. The primary goal of the CERN Irradiation Facilities is indeed to fulfill the requirements of the HEP community. However, the wide choice of radiation fields and intensities available at CERN, also enable the possibility to respond to the demand for radiation testing in different scientific areas and of different communities.

More in detail, in the CERN facilities users can perform:

- **Radiation damage studies:** on materials used around accelerators/experiments, on semiconductor devices, and various electronic components COTS (Commercial Off-The-Shelf) and ASIC (Application-

The CERN irradiation facilities database development project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 654168 (AIDA-2020).

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Specific Integrated Circuit), as well as on specific accelerator elements exposed to high-intensity pulsed beams;

- **Test and development of prototypes:** final assemblies and/or electronic equipment before installation in their final positions to study their performance degradation after long exposure/ageing due to Total Ionizing Dose (TID), Non Ionizing Energy Loss (NIEL) or their functional degradation: Single Event Upset (SEU), latch-up, etc.;
- **Test and calibration of devices:** dosimeters, radiation monitoring and measurement devices, as well as to provide benchmark data for Monte Carlo particle transport codes.

In the following sections we summarize the main characteristics of the irradiation facilities currently operating at CERN and we introduce the new on-line irradiation facilities database [4], developed at CERN in the framework of the EU-funded AIDA-2020 project [5]. This new database includes not only the CERN facilities but also a collection of other infrastructures available worldwide.

II. IRRAD

The main purpose of the **IRRAD** (Proton **IRRAD**iation Facility), located in the East Area of the Proton Synchrotron (PS) accelerator, upstream of the CHARM facility (see Section IV), is the qualification of components for the HEP experiments [6],[7]. The PS supplies IRRAD with a high-energy proton beam with momentum of 24 GeV/c and typical size of 12×12 mm² in spills of ~400 ms duration, every 10 s on average.

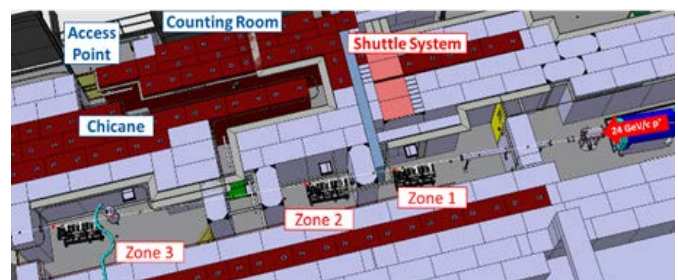


Fig. 1. IRRAD facility irradiation area.

The irradiation area is divided in three irradiation zones. With reference to Fig.1., from right to left: in Zone 1, low-Z samples as thin silicon devices and particle detector test structures are irradiated; in Zone 2, tests of electronic

equipment under power and with an active readout are performed; Zone 3 is used for the highest-Z samples, such as dense materials used in the construction of calorimeter detectors. These samples can be up to $10 \times 10 \text{ cm}^2$ in size and can be exposed to a particle fluence of up to several 10^{15} p/cm^2 . Smaller samples can be irradiated up to a particle fluence of 10^{17} p/cm^2 .

IRRAD is equipped with remotely controlled tables to position the samples in the beam. The IRRAD tables can position the samples with $\pm 0.1 \text{ mm}$ precision in the transversal plane with respect to the beam-axis; they can also rotate over the azimuthal angle aiming to a precise alignment with the beam within $\pm 0.025^\circ$ [8]. In addition, a remotely controlled conveyer (*IRRADI shuttle*) is available for the irradiation of smaller and passive samples with maximum overall dimensions of $5 \times 5 \text{ cm}^2$; this shuttle can be moved from the outside area to the irradiation position without the need of stopping the beam and human access inside the area. The shuttle travels across the radiation shielding blocks for a length of about 10 m through a conduit of $400 \times 400 \text{ mm}^2$; in order to minimize the direct radiation streaming. The path of the conduit follows a chicane located between Zone 1 and Zone 2. As for the IRRAD tables, this system also guarantees a precise transversal plane alignment of $\pm 0.1 \text{ mm}$ with respect to the beam axis. For both types of systems, dedicated user interfaces have been developed allowing the users to remotely control the systems in an easy and user-friendly manner, as well as to monitor the samples positions and the environmental conditions of the IRRAD facility in real-time. All these information are displayed on dedicated IRRAD webpages in IRRAD accessible to the users [9].

In IRRAD, there is also the possibility to perform irradiations at low temperature (cold irradiation experiments down to $-25 \text{ }^\circ\text{C}$). Two cooling systems, located outside the irradiation area, provide the chilled fluid to specially designed cold boxes positioned on two IRRAD tables [8]. The temperature on these tables is continuously monitored and notification alarms are sent in case of temperature variations. Tests on the possibility to permanently monitor the relative humidity during cold irradiation tests are ongoing [10].

Zone 3 is mainly used for high-Z samples, such as the irradiation of calorimeter detectors. In addition, a cryostat filled with liquid Helium (LHe) allows special irradiations with samples exposed at cryogenic temperatures down to 1.9 K [11]. This zone comprises a bigger space which allows the irradiation of larger experimental setups. The beam spot in Zone 3 is also larger than in the previous zones with a typical size of $20 \times 20 \text{ mm}^2$.

In special occasions, a defocused beam can be also used to irradiate large objects (up to $50 \times 70 \text{ mm}^2$ FWHM) or to perform SEU studies.

As far as the dosimetry is concerned, pure Aluminum foils are used for the measurement of the total proton fluence delivered to a sample with a precision of $\pm 7\%$ [12]. This is achieved by gamma spectrometry measurements of the irradiated foils to evaluate the ^{24}Na and ^{22}Na activities. Preliminary measurements of the *hardness factor* (k) from the

24 GeV/c protons in the facility were performed and provide a value of 0.57 ± 0.03 that approaches the theoretical value 0.51 predicted by simulations [13].

To align the beam in the beam line, a dedicated Beam Profile Monitor is used [14], which provides a real-time image of the Gaussian beam profile in a webpage display. The same type of detector is used to align the IRRAD tables w.r.t. the beam [15].

III. GIF⁺⁺

The GIF⁺⁺ (Gamma Irradiation Facility) is mainly used to test muon systems (gas detectors) for HEP experiments [16]. It is located on the H4 beam line of North experimental area of the Super Proton Synchrotron (SPS), and combines a high energy charged particle beam (muons up to 100 GeV) with 0.662 MeV photons from a 14 TBq ^{137}Cs gamma-ray source. The detectors are exposed to photons while being tested with μ which are used to simulate the background conditions experienced in real operation. A picture of the GIF⁺⁺ irradiation bunker is shown in Fig. 2. Two large radiation fields ($\pm 37^\circ$ degrees horizontally and vertically) allow testing detectors with sizes of up to several m^2 , as well as a broad range of smaller prototype detectors, materials and electronic components in a dose-rate of $\sim 0.5 \text{ Gy/h}$ at a distance of 1 m.



Fig. 2. GIF⁺⁺ facility irradiation area.

The photon flux of each irradiation zone is corrected by a specially designed stainless-steel “lens” of variable thickness to give equal counting rates over large planar thin detectors and can be tuned using a set of lead filters with attenuation factors up to about 50'000 [17]. The attenuation factor can be set independently for each irradiation field, allowing to operate a large number of setups with different requirements in parallel. The irradiator is placed inside a concrete bunker equipped with a material access door ($3.2 \times 1.6 \text{ mm}^2$) in order to allow easy installation of large detectors. In addition, the roof can be opened to allow the installation of even bigger experimental setups. GIF⁺⁺ has also a large Preparation Zone for the detectors under test, which is fully equipped with gas lines, electricity, network and where the detectors can already be connected to the final DAQ hosted in the service area. This significantly reduces the preparation time needed inside the irradiator bunker.

GIF⁺⁺ is equipped with two movable dumps (XTDVs),

which allow irradiations from the ^{137}Cs source inside the bunker independently of the access situation in the upstream and downstream beam areas of H4.

Alongside the bunker there is a two floors rack area that hosts the gas service system. This service includes a gas mixing zone with all the necessary gases for the operation of the detectors. Moreover, the gas analysis systems allow the monitoring of the flammability level, the measurement of the oxygen and the vapor content on the supply lines and the returns from the detectors [18].

GIF⁺⁺ is also equipped with a control system which monitors and archives all the operation parameters (irradiator source state, beam conditions, environmental conditions, access status, etc.) and the status of the attenuation filters [19], [20].

While the availability of the muon beam is in few defined periods depending on the SPS users schedule (typical 8-9 weeks per year), the irradiation from the gamma source is available throughout the whole year, except for short maintenance periods.

IV. CHARM

CHARM (CERN High energy AccelERator Mixed field facility) is used to test radiation effects on electronic components/systems and large equipment mainly for accelerators applications [21]. As IRRAD (see Section II), CHARM exploits the PS 24 GeV/c proton beam impinging on moveable targets (copper, aluminum or an aluminum sieve for reduced average density) that can be selected according to the required intensities. This generates a mixed radiation field in a room of $5 \times 6 \text{ m}^2$ that can be used to irradiate an entire standard electronic rack ($0.6 \times 2 \times 1 \text{ m}^3$) weighing up to a ton. According to the environment to which the electronics under qualification will be exposed in operation, the facility can be configured using different targets, movable shielding walls and test positions. In order to move the equipment in the correct position a specific semi-remote conveyer is used. Electrical connections to the tested equipment can be installed using a rail on the ceiling that follows the same track as the conveyer (Fig. 3).

The complex radiation fields at CHARM are simulated using the FLUKA Monte Carlo code [22]–[24] and benchmarked against an extensive set of measurements with the LHC RadMON system [25]. A dedicated software for the calculation of the radiation levels also exists [26]. Though mainly focused on reproducing the radiation field for high-energy accelerator applications [27], other radiation environments such as LEO (Low Earth Orbit) in space or atmospheric can also be achieved depending on the facility configuration [28].

In CHARM, operation periods are divided into weeks, according to the access schedule of the facility. For a given test configuration (i.e. target, shielding and location) the radiation levels scale with the number of accumulated protons on target. The beam delivery, the same as of IRRAD, corresponds to integrated weekly radiation levels of $\sim 350 \text{ Gy}$ and $\sim 10^{12} \text{ HEH}_{\text{eq}}/\text{cm}^2$, typically sufficient to ensure the

equipment lifetime in the accelerator, as well as an SEE failure rate low enough not to negatively impact its performance. In addition to the standard operation with the target, components can be directly exposed to the defocused 24 GeV/c proton beam (see Section II), thus providing a worst-case experimental condition in terms of beam energy for space and accelerator applications. In the near future, the beam line will be also commissioned with Heavy Ions (Xe, Pb), providing highly penetrating xenon and lead beams, depending on the CERN injector physics program.

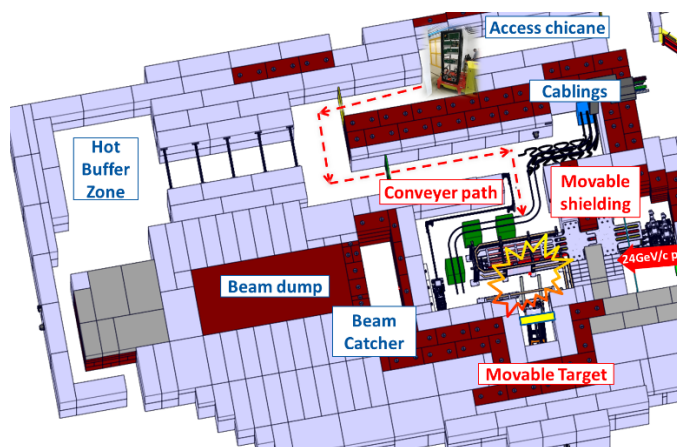


Fig. 3. CHARM facility irradiation area.

V. CERF

Neutron calibrations and tests often need to be performed at energies or spectra very much different from those generated by radioactive sources. The **CERF (CERN-EU high-energy Reference Field)** facility [29]–[31] is a workplace field unique in its kind, which reproduces the mixed radiation field encountered in the vicinity of high-energy particle accelerators and at commercial flight altitudes. CERF, installed in the North Experimental Area, is served by the SPS with a 120 GeV/c positively charged hadron beam (about 2/3 pions and 1/3 protons) impinging on a 50 cm-thick copper target. The target can be placed below either an 80 cm thick concrete, or a 40 cm thick iron roof shield (Fig. 4). Sixteen reference exposure locations ($50 \times 50 \text{ cm}^2$ each) are provided on the top of the two roofs.

The beam is delivered to CERF with a typical intensity in the range 10^6 to 10^8 particles per SPS beam extraction (spill), with two to three beam extractions of about 5 s duration over an SPS cycle (which is repeated every 30-45 s). The beam monitoring, on which the normalization of all measurements relies, is provided by an air-filled, parallel-plate, transmission-type ionization chamber (IC) calibrated with the multi-foil activation technique [32]. Typical values of ambient dose equivalent are 0.2-0.3 nSv per IC-count on the concrete roof and 1-1.5 nSv per IC-count on the iron roof. By assuming an average of three spills per minute and by adjusting the beam intensity on the target, one can obtain ambient $H^*(10)$ dose rates equivalent rates approximately from $5 \mu\text{Sv/h}$ (30 nSv per spill) to $250 \mu\text{Sv/h}$ (1.5 μSv per spill) on the concrete roof, and from $18 \mu\text{Sv/h}$ (100 nSv per spill) to $360 \mu\text{Sv/h}$ (2 μSv per spill) on the iron roof. The uncertainty on the reference values

of ambient dose equivalent rate is about 15%.

CERF is primarily a simulated workplace field for testing radiation protection instrumentation (active monitors and passive dosimeters) used at high-energy accelerators and/or for aircrew dosimetry. In addition, the Linear Energy Transfer (LET) distribution of dose equivalent makes CERF a suitable facility for space dosimetry. Other applications of the CERF radiation field are: radiobiology studies; spallation cross section measurements (in the hadron beam); investigation of activation of accelerator materials (by exposing them next to the target); intercomparison of individual dosimeters and, benchmarking Monte Carlo codes against experimental data. For a more exhaustive list of possible applications in CERF, the reader can refer to [32].

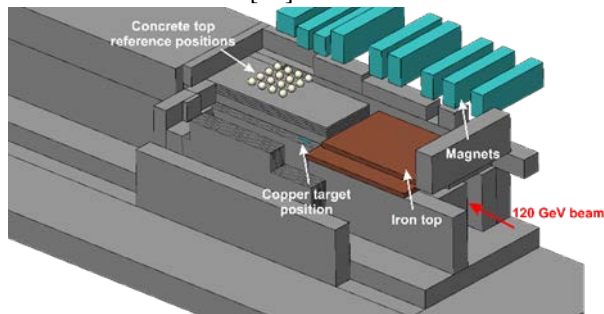


Fig. 4. FLUKA model of the CERF facility irradiation area [22]–[24].

VI. VESPER

VESPER (Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments) is a high-energy electron beamline located in the CTF3 (CERN Linear Collider Test Facility 3) [33].

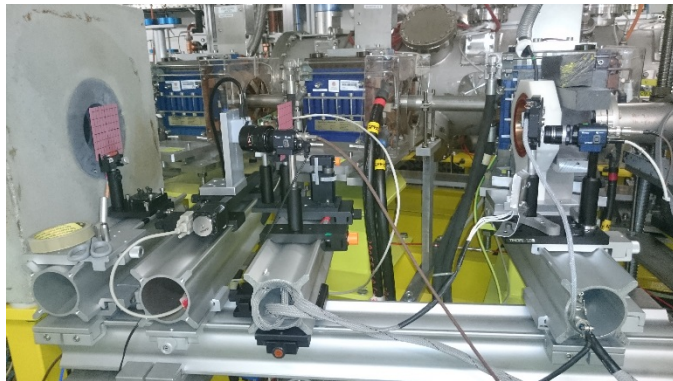


Fig. 5. VESPER test bench.

This facility is used for radiation testing and qualification of electronic components for the operation in the Jovian environment, as well as for the characterization of devices and detectors in a purely electro-magnetic beam for high-energy accelerator applications. VESPER uses a 200 MeV pulsed electron beam with an average flux of 10^8 e/cm²/s. Lower beam energies (down to 20 MeV) and different intensities are being also commissioned. Moreover, copper blocks can be remotely placed in the beamline in order to allow for the progressive conversion of the electron beam into a bremsstrahlung photon beam. Fig. 5 shows a picture of the experimental setup where the irradiated devices are exposed.

A FLUKA Monte Carlo model of the beam line [22]–[24] can be used to determine the contribution of the various particles (electrons, photons, neutrons) to the radiation effects of interest (i.e. SEE, TID and NIEL) [34].

VII. CALLAB

CALLAB (CALibration LABORatory), on the CERN Preveessin site, is a new state-of-the-art calibration facility [30], [35] designed according to the requirements of ISO 17025 standard [36]. CALLAB consists of two irradiation rooms – a main calibration hall (designed to minimize neutron scattering) and a smaller room for CC60 (see later Section VIII) – office space, storage and control rooms. The main calibration hall is a $13 \times 13 \times 13$ m³ concrete vault, half of which is underground to take advantage from the natural shielding provided by the earth. It houses:

- four Am-Be sources, providing ambient dose equivalent $H^*(10)$ rates between tens of nSv/h and 700 μ Sv/h;
- five Cs-137 sources and one Co-60 source ($H^*(10)$ rate between tens of nSv/h and 200 mSv/h);
- two beta sources (1.85 GBq Sr-90 and 4 GBq Kr-85);
- an X-ray tube having a peak voltage of 320 kV



Fig. 6. Gamma irradiator at CALLAB.

CALLAB is typically used for the calibration of personal dosimeters and radiation protection instrumentation. There is also the possibility to perform simultaneous neutron/gamma irradiations in order to investigate the detector response in mixed radiation fields. Typical uncertainties on the reference values are below 5%. All irradiators (Fig. 6) and the available test benches are remotely controlled.

VIII. CC60

The CC60 (Cobalt-60) facility (Fig. 7), which is located to the same building as CALLAB, is used for the qualification of the electronic components against TID effects. CC60 exploits a 10 TBq ⁶⁰Co source that can provide low and high dose rates through position modification or using absorbers. It is also

planned to upgrade the facility with a 100 TBq ⁶⁰Co for high dose rates testing. For large systems the total dose can reach from 1 to 10 kGy whereas for smaller samples it can reach up to 100 kGy. The facility is also equipped with several instruments such as a table to position the devices under test, an ionization chamber, and several cable ducts.

In addition, there is a dedicated control software for monitoring of the test conditions and the dose rate delivered to the samples [24], [33].

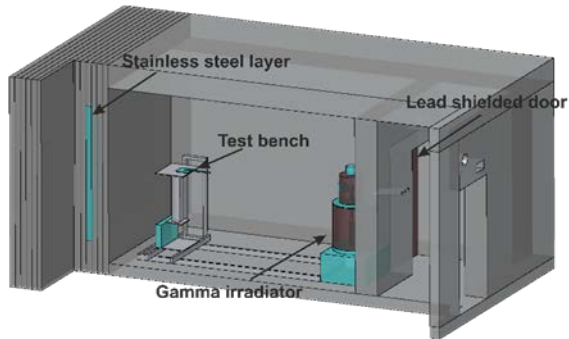


Fig. 7. The CC60 Facility part of CALLAB.

IX. HiRADMAT

HiRadMat (**High-Radiation to Materials**) is a facility where state-of-the art experiments are performed with the purpose of evaluating the effect of high-intensity pulsed beams on material samples or accelerator component assemblies in a controlled environment located underground in an accelerator tunnel as displayed in Fig.8.

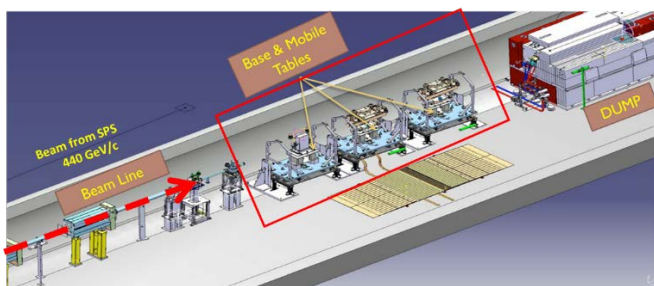


Fig. 8. HiRadMat experimental area.

HiRadMat uses a 440 GeV focused pulsed proton beam (beam spot $\leq 1\text{mm}^2$) extracted from the SPS. In addition to protons which have an intensity up to 3×10^{13} protons/pulse, ion beams with an energy of 137.5 GeV/nucleon and maximum intensity up to 4×10^9 protons/pulse can be used. These beam parameters can be tuned according to the requests of the experiments. In this facility, the experiments are performed underground on three stands that support the remote installation and transport to a dedicated cool-down zone once the experiment is completed. There are also automatic connections for signals, power and water on these stands. However, the users can prepare their installation in a specific laboratory on the surface. Various instruments such as Beam Loss Monitors, Laser-Doppler Vibrometer and high-speed cameras to monitor the experiment are also available [37].

HiRadMat received more than 40 experimental proposals and

experiments in the recent years, with the main focus in the research fields of particle beam collimation, high power targets and detector technology. Experiments on collimation reach from basic material research [38] to the exposure of collimator proto-types [39]. Novel concepts for high-power targets were investigated in a series of experiments [40]. Detector technologies such as diamond detectors, beam screens and RP monitors are tested in this facility [41, 42].

X. IRRADIATION FACILITIES DATABASE

Besides the in-house irradiation facilities, CERN users often need to perform additional irradiation experiments with complementary radiation field or irradiation conditions. The information about these external facilities, collected in static lists on CERN webpages, were often outdated. For this reason, a new Irradiations Facilities Database [4] was recently developed at CERN in the framework of the EU- funded AIDA-2020 project [5]. This database includes information about the irradiation facilities at CERN described in this paper and, currently, of about other 194 facilities, some of which were also retrieved from collections published in occasion of previous RADECS conferences [43].

The users can search irradiation facilities by country, type of source or radiation field. The facility details page (Fig. 9) includes information on the facility itself, the contact person, the institute, the irradiation conditions, safety and accessibility. The facility coordinators can enter and edit their data anytime. However, annual reminders are also sent to them in order to keep the database up to date [44].

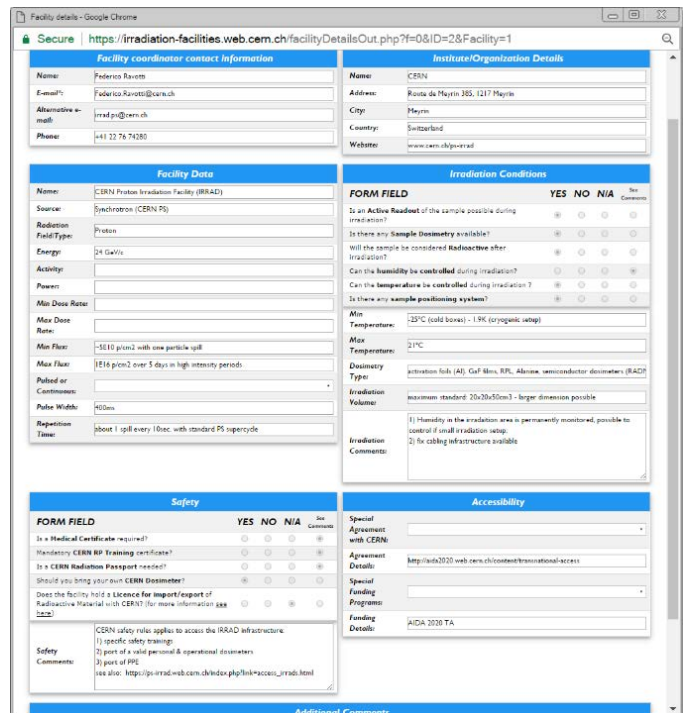


Fig. 9. IRRAD irradiation facility information page.

TABLE I
IRRADIATION FACILITIES AT CERN

Facility	Location	Particle Type	Energy / Momentum	Intensity / Activity	Beam Spot	Beam structure	Availability
IRRAD	PS East Area (T8)	p ⁺	24 GeV/c	~1-3×10 ¹⁰ p/cm ² /s	12×12mm ² (FWHM)	1-3 spill/CPS (30s) spill = 0.4s	May-November (PS operation)
CHARM	PS East Area (T8)	mixed-field (24 GeV/c p ⁺)	n ⁰ (thermal - HE) + HEH >100MeV	Lateral: 10 ⁷ -10 ¹⁰ HEH/cm ² /h Long.: 10 ⁸ -10 ¹² HEH/cm ² /h TID: 0.01-100 Gy/h	secondary environment from target	1-3 spill/CPS (30s) spill = 0.4s	May-November (PS operation)
GIF ⁺	SPS North Area (H4)	γ + μ	0.662 MeV + 100 GeV μ	14TBq (~1Gy/h at 1m.) + 10 ⁴ particles/spill	panoramic (±37°) + 100×100mm ²	Continuous + spills/SPS cycle	all year + 6-8 weeks/year (SPS operation)
CC60	Preveessin Site	γ	1.17 MeV, 1.33 MeV	10TBq (~3Gy/h at 1m.)	standard	continuous	all year
CERF	SPS North Area (H6)	mixed-field (120 GeV/c HEH)	n ⁰ (< 10-100 MeV) + HEH	max: 10 ⁸ particles/spill (on the target)	tertiary environment from target	spills/SPS cycle (few sec. spill)	few weeks/year (SPS operation)
HiRadMat	SPS West Area (TT60)	p ⁺ or HI	max 440 GeV(p ⁺) max 173GeV/u (HI)	3×10 ¹³ (p ⁺) 4×10 ⁹ (Pb ⁸²⁺)	≤~1 mm ²	1 pulse/ SPS cycle pulse = 7.2μs	May-November (SPS operation)
VESPER	CTF3	e ⁻	200MeV	~1×10 ⁸ e/cm ² /s	20×12mm ²	0.8-5Hz frequency/ pulse = ~1μs	CTF3 operation
CALLAB	Preveessin Site	γ, β, n, X-Ray	Several: depending on the source	From 100MBq to 3TBq	Several depending on the source	Continuous	All year

XI. CONCLUSIONS

CERN irradiation facilities play a fundamental role for the study of radiation effects on materials, electronic components and detectors in HEP but also for a range of other applications. This paper describes the various facilities, the available radiation fields and related dosimetry, and their potential for irradiation experiments. The aim of this paper is to provide a reference to the users community for selecting the most suitable CERN facility while planning a specific irradiation experiment but also to guide them to external facilities for additional irradiation tests. For the convenience of the reader, a summary table (Table I) was prepared in order to provide an overview of the CERN facilities.

ACKNOWLEDGMENT

The Irradiation Facilities coordinators would like to thank the CERN beam operation group (BE-OP) for the high quality of the delivered beams, as well as the PS/SPS users coordinator for the continuous support.

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