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EURO-LABS

EUROpean Laboratories for Accelerator Based Science

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DELIVERABLE REPORT

REPORT ON THE USAGE OF ACCESS UNITS FOR IRRADIATION

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Abstract:

WP4 provides Transnational Access for detector R&D at eleven research infrastructures (RIs): three providing test beam access, two detector characterization and six for irradiations. The overall Access Units (AU) for the overall activities of WP4 is discussed in Deliverable 4.1. Here only those related to irradiation facilities are presented (taken for D4.1).

For more information on EURO-LABS, its partners and contributors please see https://web.infn.it/EURO-LABS/

The EUROpean Laboratories for Accelerator Based Science (EURO-LABS) project has received funding from the Horizon Europe programme dedicated to Research Infrastructure (RI) services advancing frontier knowledge under Grant Agreement no. 101057511. EURO-LABS began in September 2022 and will run for 4 years.

Delivery Slip

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Executive summary

WP4 provides Transnational Access for detector R&D at eleven research infrastructures (RIs): three providing test beam access, two detector characterization and six for irradiations. The overall Access Units (AU) for the overall activities of WP4 is discussed in Deliverable 4.1. Here only those related to irradiation facilities are presented (taken for D4.1).

1. INTRODUCTION

WP4 of EURO-LABS is devoted to support detector R&D via Transnational Access (TA) carried out at 11 RIs in Europe. The typical detector R&D cycle consists of constructing a series of prototypes, testing them in high-energy particle beams, irradiating them, re-analyzing in test-beams, and possibly evaluating their performance in special characterization facilities. This is followed up by the division of WP4 into tasks: WP4.1 supplies the test beams in 3 RIs, WP4.2 offers detector characterization in 2 RIs and WP4.3 irradiation opportunities in 6 RIs.

The six RIs offering irradiations in WP4.3 are:

- 4.3.1: CERN IRRAD, Switzerland
- 4.3.2: CERN GIF++, Switzerland
- 4.3.3: JSI TRIGA reactor, Slovenia
- 4.3.4: IFJ PAN AIC-144 cyclotron, Poland
- 4.3.5: UCLouvain CRC, Belgium
- 4.3.6: UoB MC40 Cyclotron, United Kingdom

2. ASSESSMENT OF AU USAGE

The usage of AUs at the eleven RIs of WP4 the project (Sep 22 – Aug 26) is summarized in Table 1. While for most of RIs the figures can be considered final, for some of them they contain estimates for the last month of the project. The final figures will be provided in the Final Report in October.

WP4	Research Infrastr.	AU M48 estimate	AU pledged	% of pledge
WP 4.3.1	CERN-IRRAD	4567	4000	114.2%
WP 4.3.2	CERN-GIF++	6792	4060	167.3%
WP 4.3.3	JSI	700	700	100.0%
WP 4.3.4	IFJ-PAN	792	800	99.0%
WP 4.3.5	UCL	65	100	65.0%
WP 4.3.6	UoB	101	300	33.7%

Table 1: Usage of AUs at the eleven RIs of WP4. The AUs estimated to be delivered by end of the project, the AUs pledged for the duration of the project and the accomplished percentage of the pledge are provided by RI and for all RIs of WP4.

3. REPORTS FROM RI'S

Following are the reports from individual RIs highlighting major achievements of user projects at the respective facilities. Note that the Figure and Reference labels are internal to the (sub-)chapters.

3.1. CERN IRRAD

The proton irradiation facility (IRRAD) at the Proton Synchrotron (PS) East Area (EA) at CERN was built during the Long Shutdown 1 (LS1, 2013-2014) and improved during LS2 (2019-2021) to cope with the increasing needs for radiation tests of the experimental community working for the HL-LHC upgrade and beyond. The facility is operated by Detector Technologies (DT) group in the Experimental Physics department (EP-DT) and part of a more complex infrastructure in the CERN East Area serving radiation tests. The IRRAD facility exploits the 24 GeV/c PS proton beam for irradiation experiments and was for the last four years heavily loaded with irradiation experiments serving the qualification and testing of materials and components for the upcoming HL-LHC upgrade.

Next to this rich and demanding program, part of the available beam time could be made accessible through the EURO-LABS transnational access program to more generic radiation testing experiments and users outside the HL-LHC community. Two highlights of such experiments are given below that would have been difficult to implement without EURO-LABS but are of high scientific value to the HEP detector development community. The first one is targeting very high fluences in perspective of detectors for future hadron accelerators and as such required a significant number of access units. The second one is targeting a comparison of various radiation sources and facilities and, as such, not only profited from the access to the IRRAD facility but also from the access to other facilities within the EURO-LABS TA program.

Characterization of thick LGAD sensors after irradiation to very high particle fluences

The aim of the project is to measure the properties of Silicon sensors after exposure to hadron fluences above 10^{16} n_{eq}/cm^2 with the ultimate goal to design sensors capable of operating in extreme fluence regimes at 10^{17} n_{eq}/cm^2 and above. Within the irradiation project at CERN 24 sensors of different thickness and 6 test structures have been irradiated to 3 different fluences with 24 GeV/c protons. The fluences, expressed in terms of 1 MeV equivalent neutrons (n_{eq}), are 10^{16}, $5x10^{16}$ and $10^{17}n_{eq}/cm^2$.The irradiated sensors are from the EXFLU1 (EXtreme FLUence) production made by FBK [1] and comprise thin sensors, with an active thickness ranging from 15 to 45 µm, as well as compensated LGAD (Low Gain Avalanche Diodes), a new design of the gain implant that exploits the compensation of p-type (Boron) and n-type (Phosphorus) atoms to enhance the radiation tolerance of LGAD sensors. The concept of this design is shown in Figure 1. In the given example, the boron and phosphorous concentrations have a ratio of 5 to 4 and are thus resulting in an active doping level that corresponds to 1/5 of the implanted boron. The idea is to preserve an active doping level after irradiation even if large fractions of the initial implant have been rendered non-active by radiation damage.

The irradiation campaign at CERN is part of a larger campaign that aims to compare the results from different radiation sources with a similar level of equivalent fluence. In particular, results with protons will be compared with those already presented in [2] and shown in *Figure 2*. It is observed that in thin LGAD sensors with a standard gain-implant design, charge multiplication is strongly suppressed at fluences above $5x10^{15}$ n_{eq}/cm^2. The irradiation campaign at CERN IRRAD has enabled further data collection to optimise the compensated LGAD design. This study is still ongoing within the framework of working group 3 – Radiation Damage Characterization – of the DRD3 collaboration, and the results will be part of the DRD3 project CERN-DRD3-PROJECT- 2024-005 [3], aiming among others to perform post- irradiation electrical and structural characterisation, modelling, and parametrisation of very highly irradiated silicon sensors.

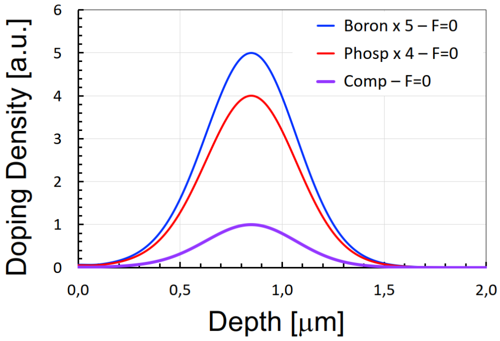

Figure 1: Sketch of the gain implant profile of the deep gain layer of a compensated LGAD.

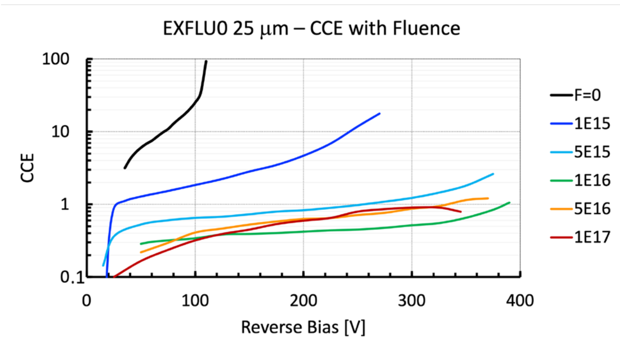

Figure 2: Charge amplification of 25 µm thick LGAD sensors before and after irradiation up to the extreme fluence of 10^{17} n_{eq}/cm^2.

HADES - HArdness factor and DEfect studies in Silicon

The HADES project (HArdness factor and DEfect studies in Silicon) aims to provide a comprehensive dataset on particle-dependent radiation damage in silicon detectors across a broad range of particles and energies, spanning from the keV to the multi-GeV regime, including neutron, electron, proton, and gamma radiation. By combining results obtained on irradiations performed at multiple facilities, employing silicon diodes of identical design, and applying standardized characterization procedures, the project ensures methodological consistency and enables cross-comparison of results. A wide range of complementary measurement techniques (including current–voltage (IV), capacitance–voltage (CV), deep-level transient spectroscopy (DLTS), and thermally stimulated current (TSC)) provides access to both macroscopic device properties and microscopic defect characteristics. By correlating defect-level information with detector performance, the project addresses known limitations of the Non-Ionizing Energy Loss (NIE) hypothesis, in particular improving the understanding of the distinct effects of point defects and defect clusters. Another central objective is the consolidation and extension of hardness factors within the NIEL scaling framework. Using leakage current as a robust damage indicator, HADES aims to reduce existing uncertainties and improve the reliability of radiation damage predictions relevant for environments such as the LHC. Overall, HADES seeks to develop an improved modelling approach beyond traditional NIEL scaling by incorporating the nature of radiation-induced defects. In combination with detailed simulations, this approach enhances the predictive power for silicon detector performance in complex radiation environments.

Irradiations for this project have been performed at several irradiation facilities, including facilities participating in EURO-LABS. In particular 24 GeV/c and 12 GeV/c proton irradiations at CERN IRRAD, 11, 16 and 24 MeV proton irradiations at the MC40 Cyclotron in Birmingham, 18, 40 and 60 MeV proton irradiations at AIC-144 IFJ PAN, Krakow and 41 and 62 MeV proton irradiations at UCLouvain-CRC as well as neutron irradiations at the JSI TRIGA reactor and in a neutron field with a spectrum around 20 MeV at the UCLouvain. A full list of the used facilities, including facilities not participating in EURO-LABS, is given in [5]. Figure 3 shows exemplary a comparison of the majority carrier traps in p-type silicon diodes after exposure to 24 GeV/c protons and reactor neutrons and Figure 4 gives an overview of existing hardness factors for monoenergetic proton sources (see [4] for details and references) including the newly obtained results for 12 GeV/c protons at the IRRAD facility. In this case the hardness factor is obtained from comparing the radiation induced leakage current per particle versus the leakage resulting from 1 MeV neutrons (see [4] for details). The samples for other facilities mentioned above are still under investigation. The point at 12 GeV/c is of particular interest, as it is a new beam setting to the IRRAD infrastructure that required a particular machine tuning and has so far not been measured in this way before.

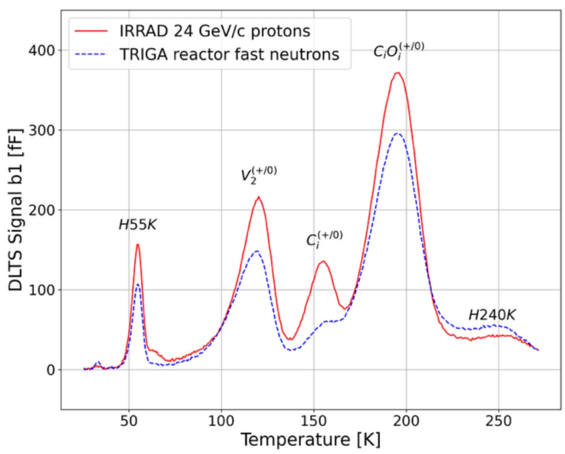

Figure 3: Deep-level transient spectroscopy (DLTS) spectra of proton and neutron irradiated silicon diodes after exposure to the same neutron equivalent particle fluence (2x10^11 n_{eq}/cm^2). DLTS settings: T_W = 20 ms, U_R=10 V, U_P=0.6 V, t_p=100 ms.

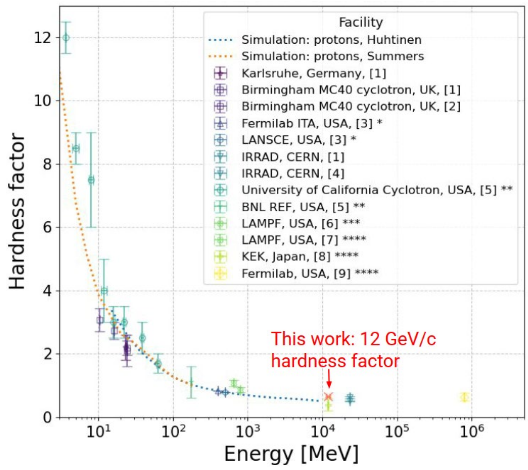

Figure 4: Hardness factors for various monoenergetic proton sources. The data are obtained from the measurement of the radiation induced increase of leakage current in silicon diodes.

3.2. CERN GIF++

The CERN Gamma Irradiation Facility (GIF++) is a joint BE & EP Department facility located on the H4 beamline (SPS, Zone PPE-154) in EHN1 (North Area, Prevéssin site).
It is a unique place for detector R&D, where a strong gamma source and a muon/pion particle beam are simultaneously available. Together with the IRRAD in the East Area (Meyrin site), the GIF++ delivers essential services to the HEP community, with the focus on validating and optimizing detector technologies, mainly in view of the High-Luminosity upgrade of LHC and accelerator projects beyond.
The irradiator (^{137}Cs, 14 TBq as of 2014) is operated throughout the year, independently of the SPS and offers two adjustable gamma irradiation zones, with a total floor space of more than 100 m^2. The two gamma fields (<= 2Gy/h) enable ageing studies and provide radiation background similar to the future working conditions inside the LHC large experiments.
In 2025 the facility underwent a major upgrade, with the extension of the bunker (Fig. 1).

OLD LAYOUT **NEW LAYOUT**

Figure 1: GIF++layout before and after the 2025 upgrade

The muon (or pion) beam, available during dedicated time slots (typically 3 x 2 weeks/year, 2 x 2 in 2026 due to the shorter running period of the SPS, before LS3) is used to investigate and validate the detectors performance and behavior under these expected conditions.
The new layout allows for a better exploitation of the beam, in particular the complete scan of large (> 1m^2) detector.
The facility is equipped with excellent gas and electronics infrastructures, a unified control/monitoring system, setups for beam and cosmic trigger as well as radiation and environmental conditions monitoring.
The gas area has also been extended in order to host and support the still increasing number of users.
The facility is intensively exploited by a large collaboration, mainly composed by users belonging to the LHC experiments. On average, more than 7 setups run continuously in parallel during the year, with a peak of 15 in July 2026, during the last test beam before the Long Shutdown 3 (LS3).
During LS3, the North Area will undergo a major renovation and consolidation campaign and beam is expected to be back only mid-2029, but GIF++ will continue to run in irradiation mode-only.
The main detector R&D programme remains the upcoming upgrade of the LHC experiments in view of the High Luminosity LHC phase (HI-LUMI LHC), including long term ageing studies for various gas mixtures. Over the last years the search for environmentally friendly gas mixtures gained momentum and became a driving element of the scientific programme of the facility via the ECOGAS collaboration.
Projects running in the facility requires, with few exceptions, long-term, even years, irradiation and scientists involved spend a large fraction (> 50%) of their working time at CERN or are permanently

based at CERN. Shown in figure 2 is an experiment setup at GIF++, taken in July 2026, just before the start of the test beam period.

Figure 2: Pictures of an experiment at GIF++, taken in July 2026, just before the start of the test beam period

3.3. JSI

Radiation damage remains a major challenge for the use of silicon detectors in charged-particle tracking at high-energy physics experiments. A key performance-degrading mechanism is the displacement of silicon atoms by neutrons, protons, or other high-energy particles. This displacement damage scales with particle fluence and is typically expressed in terms of the equivalent fluence (Φ_{eq}) of 1 MeV neutrons that would produce the same effect as the irradiating particles. Silicon detectors in the innermost layers of experiments at the High Luminosity Large Hadron Collider (HL-LHC) will need to withstand fluences of up to $\Phi_{eq} = 2\times10^{16}$ cm^{-2}. Achieving such radiation hardness has required decades of research, including extensive irradiation campaigns using various particle sources. Neutrons play a particularly important role in displacement damage in silicon in particle physics environments. The Ljubljana TRIGA reactor is a key facility for studying radiation effects in particle detectors.

EURO-LABS is providing Transnational Access (TA) for irradiations under WP4. Up to now 63 irradiation projects have been approved by the user selection panel and most of them already carried out.

EURO-LABS has contributed significantly to the final stages of development of tracking detectors currently in production for the HL-LHC. Particular emphasis has been placed on improving of radiation hardness of Low Gain Avalanche Diodes (LGADs), which provide precise timing information in addition to spatial tracking. These devices will significantly extend the scientific reach of HL-LHC experiments by improving vertex reconstruction and tracking performance in high-pileup

environments. Good timing resolution will also be one of basic requirements in experiments at future colliders [1,2].
Several projects have also focused on radiation testing of photon detectors being developed for upgrades of the LHCb experiment, where radiation damage is expected to become relevant even in previously unaffected detector regions [3,4].
Large irradiation campaigns within EURO-LABS have enabled continued studies of silicon detector properties at fluences approaching and exceeding HL-LHC levels. Despite decades of research, important open questions remain, driven in part by ever-increasing radiation levels. In particular, understanding the acceptor removal phenomenon is crucial, as many modern detector concepts rely on controlled internal gain to achieve high timing resolution.
A significant fraction of the projects has focused on the development of detectors for future experiments. Emphasis has been placed on resistive sheet AC coupled LGADs (AC-LGAD) technology, which aims to eliminate the dead regions present in standard LGADs due to inter-pad insulation structures [5,6].
Variants of detectors with gain such as nLGADs are being developed for the detection of low-penetrating protons, soft X-rays, and UV photons, with growing interest in imaging applications at synchrotron light sources. In applications involving low-energy protons, displacement damage remains an important consideration and must be carefully studied. [7]
Several projects have also addressed the irradiation of various monolithic CMOS detectors including projects following a broader trend toward fully monolithic designs with sensing elements with gain. EURO-LABS has played an important role in supporting these developments through TA to irradiations in the reactor [8].
In addition, several studies have investigated wide-bandgap materials, particularly silicon carbide (SiC), which is widely used in high-power electronics and has seen significant improvements in material quality. Recently, SiC-based devices with gain (LGAD-like structures) have been demonstrated. However, radiation studies, including those supported by EURO-LABS, indicate that radiation hardness in terms of Charge Collection Efficiency (CCE) remains inferior to that of silicon. Nevertheless, the inherent advantages of wide-bandgap materials—such as higher breakdown fields and lower leakage currents—may outweigh the reduced CCE in certain applications, justifying continued research [9].
The TRIGA reactor offers a unique capability for neutron irradiations over a wide range of fluences spanning many orders of magnitude. Electronic circuits containing commercial off-the-shelf (COTS) components have been tested at fluences as low as $\Phi_{eq} = 10^{12}$ cm^{-2}. Silicon devices were irradiated with only e $\Phi_{eq} = 10^{8}$ cm^{-2} in a specialized study. At the other extreme, irradiations up to $\Phi_{eq} = 10^{18}$ cm^{-2} have been carried out [10].
In collaboration with DRD3, EURO-LABS organized two irradiation campaigns at extreme fluences to accelerate the development of detectors for operation in harsh radiation environments, such as those expected at future hadron colliders or in fusion reactors. Such irradiations would not have been possible without EURO-LABS support.
The highest neutron flux at the JSI reactor reaches $\Phi_{eq} = 6.7\times10^{12}$ cm^{-2} s^{-1} in the core centre. Achieving $\Phi_{eq} = 1\times10^{18}$ cm^{-2} requires at least 40 hours of irradiation, corresponding to approximately five full shifts of continuous reactor operation for a single container. Due to the reactor's tight schedule, such long irradiations must be carefully planned and cannot be performed frequently.
For the 2024 campaign, samples were provided by 12 groups, and for 2025 by 10 groups, involving collaborations with institutions across Europe, the USA, and China. The samples included structures made of Si, SiC, ZnTe, GaN, and diamond. Only small, bare sensor samples were accepted to fit into the irradiation containers and to minimize activation. Nevertheless, the long irradiation times resulted

in significant activation, requiring special handling and extended cooling periods. Most samples, however, were distributed to testing sites within three months after irradiation. These campaigns provided valuable experience in both irradiation procedures and post-irradiation handling at extreme fluences.

Results from irradiated samples have been presented at several conferences, with some already published in peer-reviewed journals. Notable studies at extreme fluences include measurements of carrier recombination lifetime and diffusion coefficients in GaN as a function of fluence up to $\Phi\_eq = 10^{18}$ cm^{-2}, as well as measurements of low-field mobility in silicon at similar fluences. Data on fundamental semiconductor parameters at such extreme radiation levels remain scarce but are essential for realistic detector modelling in future high-radiation environments in hadron colliders.

Among the irradiated silicon devices were trench 3D detectors, in which electrodes are formed within columns etched through the silicon bulk. Unlike planar detectors, 3D architectures allow the electrode spacing to be decoupled from the wafer thickness, which is advantageous under high radiation damage conditions where charge carrier trapping times are very short. As shown in Figure 1, the charge collection distributions measured before and after irradiation to $\Phi\_eq = 1\times10^{17}$ cm^{-2} are nearly identical—a remarkable result. Test-beam measurements further confirm high minimum-ionizing-particle (MIP) detection efficiency even after irradiation to extreme fluences.

Transient Current Technique (TCT) measurements of trench 3D detectors have demonstrated measurable responses even after irradiation to $\Phi\_eq = 5\times10^{17}$ cm^{-2} and 1×10^{18} cm^{-2}. These results represent promising initial steps toward the development of detectors suitable for future hadron collider environments.

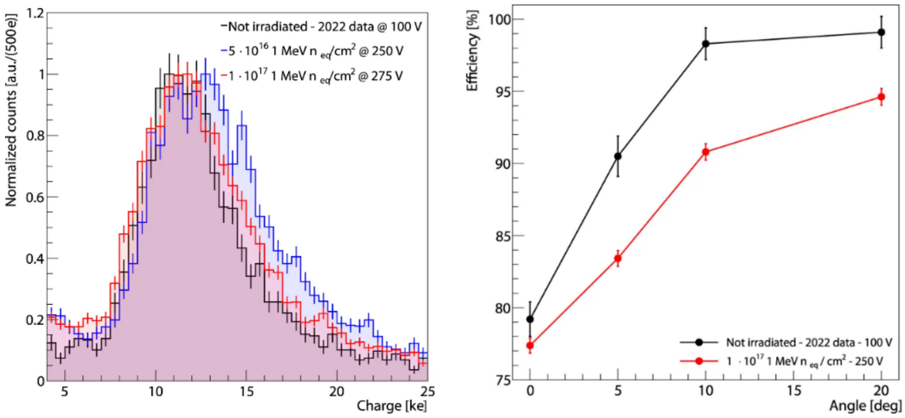

Fig. 1: Distribution of collected charge from MIP passage (left) and efficiency vs. tilt angle (right) measured in test beam with trench 3D detector irradiated up to 1×10^{17} *n/cm2 from [1].*

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3.4. IFJ-PAN

The AIC-144 cyclotron facility provides 60 MeV proton beams with intensities of up to 100 nA in two experimental areas: (a) a former proton therapy eye-treatment room, equipped for precise positioning and clinical-quality irradiation with beam diameters of up to 40 mm; and (b) an experimental hall featuring an irradiation line with a 2D scanner (EURO-LABS service improvement), enabling the exposure of larger samples up to 400 mm × 400 mm. The facility operates as a user-oriented platform, supporting experiments in detector physics, medical physics, the space and aerospace industries, and radiobiology. The irradiation stations are equipped with a comprehensive range of dosimetry instruments and are metrologically linked to the Secondary Standard Dosimetry Laboratory in Warsaw.

Testing Commercial Off-The-Shelf *(COTS) electronics - the susceptibility of the central router to radiation faults*

This work was to radiation test of a Network On Chip (NoC) with star topology with the purpose of evaluating the susceptibility of the central router to radiation faults. The work was jointly performed by the Interdisciplinary Centre for Security Reliability and Trust (SnT), University of Luxembourg and the Department of Radiation Research and Proton Radiotherapy Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland.

Systems deployed in space must operate reliably in a radiation-rich environment. Traditionally, this has been addressed through shielding and the use of expensive space-grade Application-Specific Integrated Circuits (ASICs). However, to reduce costs and leverage the performance and energy efficiency of modern semiconductor technologies, COTS computing systems—particularly FPGA-based platforms—are increasingly being considered as alternatives. One such development is the Self-protecting Hybrid ARChitectureS (SHARCS) framework—a hardware-software approach designed to provide fault tolerance in distributed computing clusters, with a particular focus on radiation-induced faults. It was designed at the Interdisciplinary Centre for Security, Reliability and Trust (SnT) at the University of Luxembourg.

The aim of this experiment performed at the AIC-144 cyclotron using 58 MeV proton beam was to assess the robustness and fault tolerance of a computing cluster built from commercially available off-the-shelf (COTS) processors intended for operation in space. In particular, the study evaluates the system's ability to withstand faults, errors, and crashes caused by radiation-induced Single Event Upsets (SEUs) and Single Event Functional Interrupts (SEFIs). The experiment utilized a custom-designed computing cluster composed of Compute Modules arranged in a planar configuration, enabling uniform irradiation of all system components. The selected modules were COTS devices originally designed for industrial and automotive applications. Prior testing at the IFJ facility demonstrated that these components exhibit suitable semiconductor properties for Low Earth Orbit (LEO), specifically showing no latch-up events under proton irradiation up to 58 MeV.

To evaluate SHARCS in practice, selected compute modules were deployed in a clustered configuration, allowing observation of system-wide behaviour, fault mitigation strategies, and the implications of architectural design decisions. A dedicated test platform, the SHARCS Compute Cluster MVP (SHARCS-CC-MVP), was developed for this purpose. The objectives of the irradiation campaign were to observe cluster behaviour under radiation exposure, evaluate the effectiveness of fault-tolerance mechanisms, ensure consistency across distributed nodes, assess the system's ability to continue operation despite random faults and finally evaluate the system's ability to recover faulty compute modules at runtime.

The cluster was irradiated with proton flux at the level of 5.0×10^5 p/cm²/s, with gradual increase up to approximately 1.0×10^7 p/cm²/s. In order to irradiate of all four compute modules and the voting integrated circuits a wide 12 cm diameter beam was used. The irradiations were performed in two sessions of between 18 and 20 minutes, keeping the beam energy constant during that particular session. Starting with 20 MeV, the beam energy were gradually increased to 30, 40, and 50 MeV, and the maximum of 58 MeV. Whenever a failure was detected during a session that the system could not work through, we stopped the beam, rebooted the entire system, and resumed the test.

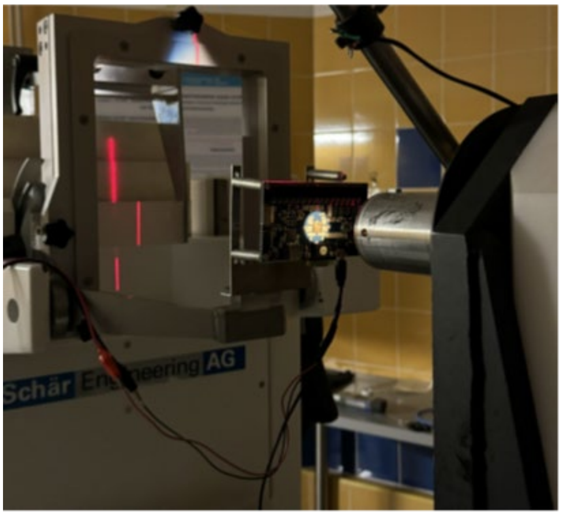

Fig. 1: Experimental setup under proton beam at the irradiation station of AIC-144

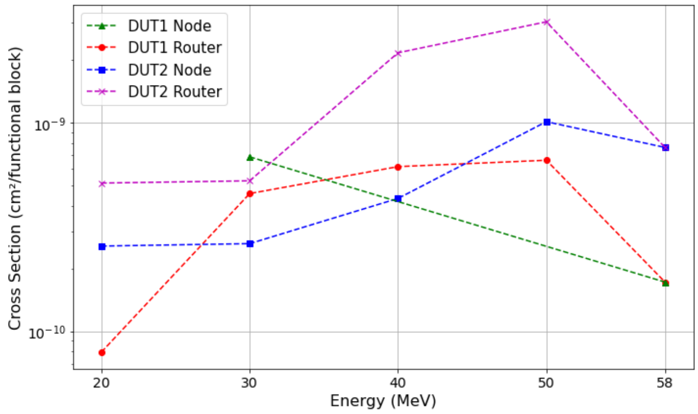

Fig. 2: Cross section of functional block over different proton energy levels

Proton beam radiation test was performed on a FPGA board: the Basys-3 with its Arty-7 FPGA chip. A soft core and soft NoC implementation in two variants with four nodes connected in a star topology. In the first, no additional protection was applied at the node level, while in the second, proactive rejuvenation and consensus on the node to rejuvenate were introduced to counter node-level radiation faults and, in particular, to remove resident radiation effects from nodes. While periodic proactive rejuvenation proved effective in allowing more messages to be delivered successfully, the unprotected router and a single point of failure were identified. From all failures observed 77% of them contributed to situations where the router delivered wrong messages to incorrect destinations or caused the system to crash, which required a total reset of the FPGA. To guide the research towards more resilient networks on a chip, we highlight possible directions for future research and discuss the implications of some of these solutions. The results of the work were published in: 2024 24^{th} European Conference on Radiation and Its Effects on Components and Systems (RADECS) [1].

Testing SiPM readout system for X- and gamma-ray detectors in POLAR-2 mission

This experiment was performed by international collaboration under the leadership of Xin Wu from the Department of Particle Physics, University Geneva. [2].

Gamma-Ray Bursts are one of the biggest mysteries of modern astrophysics. These are the most energetic astrophysical events in the Universe known to man, emitting energies up to 10^{51} J. This emission is studied within the POLAR experiment by means of by polarization measurements performed by dedicated polarimeters POLAR (50-500 keV) and GAP (50-300 keV) installed on a satellite. The new version of the polarimeter will be installed on the China Space Station for a mission of at least 2 years. Since the polarimeter will be exposed to galactic cosmic-rays, solar cosmic-rays and trapped charged particles it has to be tested in adequate radiation field. POLAR 2 consists of 100 modules facing deep space with a half -sky filed of views. Each detector module consists of a target of 64 plastic scintillators which are read out by silicon photomultipliers (SiPM). These SiPMs are using the module of front electronics which was designed using commercial off-the-shelf (COTS) components. One of the main concerns when using these components is their radiation resilience.

Among all components used, only the Citiroc 1A ASICs are at TRL 8, indicating a high level of radiation tolerance. The radiation tolerance of the IGLOO FPGA, the DC/DC converter used to power the SiPMs, and the ADCs has not been established. Of particular concern was the DC/DC converter: initially, the C11204-01 model by Hamamatsu, specifically designed for powering SiPMs, was considered. However, it failed a basic proton irradiation test, leading to its replacement with the T3482 DC/DC converter in the current design.

The objective of the experiment was to test performance of the front-end electronics (FEL) of the polarimeter to doses equating to 2-10 years of exposure in space. Theses doses, delivered incrementally to different elements of the FEL should allow for testing components for failures and operational performance. To assess the radiation tolerance of the complete system, it was subjected to wide-beam proton irradiation tests at the Instytut Fizyki Jądrowej (IFJ) in Kraków, Poland, using a 58 MeV proton beam. A brass collimator was used to shape a 40 mm diameter beam into a 25 mm square field, allowing irradiation of the central rigid part of the readout in six steps. Six regions were irradiated sequentially to cover the full sensitive area (see Figure 2).

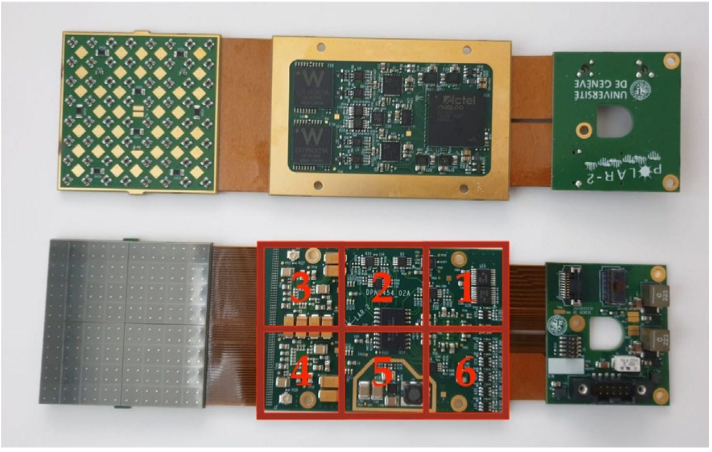

Figure 3: Top and bottom view of the electronics showing the 6 irradiated areas.

The system was exposed to three doses of 0.17 Gy and a fourth dose of 0.25 Gy. Based on simulations of the POLAR-2 detector, this corresponds to approximately 11 years in low Earth orbit. Data acquisition runs performed between irradiation steps showed no degradation in performance or increase in power consumption. The estimate of 11 years in space is based on POLAR-2 simulations and cannot be directly generalized to other missions. In POLAR-2, the electronics are shielded by several millimetres of aluminium. Nevertheless, the results indicate that all components in the readout are tolerant to radiation levels equivalent to several years in low Earth orbit. The results of the experiment were published in [2].

[1] G. L. Da Costa et al., "Assessment of Router Failures Under Proton Beam Radiation," 2024 24th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Maspalomas, Spain, 2024, pp. 1-7, doi: 10.1109/RADECS61970.2024.11298585.
[2] M. Kole et al Nuclear Instruments and Methods in Physics Research A 1080 (2025) 170782, https://doi.org/10.1016/j.nima.2025.170782

3.5. UCLOUVAIN

UCLouvain offers a series of facilities at the Centre de Ressources du Cyclotron (CRC) .
It consists of 4 facilities:

- Heavy Ion Facility (HIF).
- Light Ion Facility (LIF)
- Neutron Iradiation Facility (NIF)
- Gamma Irradiation (GIF)

The first three are set around the CYCLONE, a research cyclotron in which the first radioactive beam was accelerated. They are used mainly for the study of Single Event Effects (SEE) in electronic

components, HIF and LIF, but also for TID studies, LIF and NIF. Most of the EURO-LABS projects have used HIF (four projects) and two projects ask for irradiation at LIF.
The 4th one is a high intensity Co60 source is also proposed for long TID studies. EURO-LABS has not used this facility.
The start of the project was quite disappointing: during almost two years, just one proposal was received, as if the EURO-LABS community was not interested in this kind of tests, despite the efforts of the CRC and the WP manager to target audiences. After the second year, a larger community was targeted, and we started to get proposals at a reasonable rate. It's quite striking because the facility is highly demanded in the SEE test in Europe.
In the following, two scientific projects, one at HIF and one at LIF, are presented. The beam was delivered to these projects quite late (less than one year) and there is, to our knowledge, still no results communicated.

Ion Beam Radiation Testing of the FastRICH ASIC
User Group Leader: Dr. Florin Maciuc, IFIN-HH / LHCb Collaboration
The FastRICH chip is a new front-end readout ASIC developed jointly by CERN's Microelectronics section and the University of Barcelona, designed to meet the demanding requirements of the Ring Imaging Cherenkov (RICH) detectors in the LHCb experiment at CERN. Fabricated in 65 nm CMOS technology and conceived to operate well into the 2040s under the harsh radiation conditions of the High-Luminosity LHC, the chip must demonstrate robust radiation tolerance before it can be approved for large-scale deployment during the LHC Long Shutdown 3.
The first major scientific highlight of this project is the systematic mapping of Single Event Effect (SEE) cross-sections in the FastRICH chip as a function of Linear Energy Transfer (LET). By exploiting the wide ion cocktail available at the CRC Heavy Ion Facility — covering species from Carbon to Xenon and extending the effective LET range through sample tilting — the team was able to trace for the first time the full Weibull-curve behaviour of Single Event Upsets and Single Event Latchups in this device. This quantitative characterisation had never been carried out on this chip before and provides the LHCb community with the data needed to validate the radiation-hardness design choices made at the 65 nm node.
A second highlight relates to the operational realism of the test conditions. The chip was kept fully active throughout irradiation, running at parameters representative of its future LHCb deployment: realistic data-stream rates, live reconfiguration, and power cycling between irradiation steps. This approach revealed the interplay between configuration-register upsets and transient effects in the data stream — information that purely passive or low-rate tests would have missed. The group was also able to check in real time whether chip resets or power cycles could recover radiation-induced errors, directly informing the fault-recovery strategies that will be implemented in the LHCb readout firmware. The results of both test sessions are being prepared for publication and will be presented within the LHCb collaboration and at international detector instrumentation conferences.

Radiation Damage Studies of Silicon Detectors
User Group Leader: Michael Moll / Marie Muehlnikel, CERN Solid State Detector Lab
Silicon particle detectors operating in high-radiation environments such as the LHC experiments degrade over time as energetic particles displace atoms in the crystal lattice. These displacement defects alter the leakage current, the effective doping concentration, and the charge collection efficiency of the device, ultimately limiting its useful lifetime. A widely used framework to compare radiation damage induced by different particle types and energies is the Non-Ionizing Energy Loss (NIEL) scaling hypothesis, which predicts that damage scales with a single hardness factor regardless of the particle species. Recent experimental evidence, however, suggests that this hypothesis breaks

down for materials with varying resistivity or impurity concentrations, pointing to a gap in the current understanding of microscopic damage mechanisms.
The first scientific highlight of this project is a comprehensive, cross-facility calibration of hardness factors for proton and neutron irradiation of silicon PIN diodes. By irradiating samples with protons at two distinct energies at the CRC and combining these with neutron irradiation data obtained at a complementary facility, the team is assembling a coherent, internally consistent dataset that spans a broad range of damage levels. The deliberate choice of well-controlled silicon PIN diodes as a common reference material is key: it allows the group to isolate genuine deviations from NIEL scaling from artefacts arising from differences in sensor geometry or processing, laying the groundwork for more reliable damage prediction models for future detector generations.
A second highlight is the depth of post-irradiation characterisation planned at CERN. Beyond standard electrical measurements, the irradiated diodes will be analysed using Transient Current Technique (TCT), Deep Level Transient Spectroscopy (DLTS), and Thermally Stimulated Current (TSC) measurements. This combination of techniques gives access to the identity, concentration, and annealing kinetics of individual radiation-induced defects, connecting macroscopic performance degradation back to specific microscopic damage centres. Understanding which defects are responsible for the observed deviations from NIEL scaling is a prerequisite for defect engineering strategies — deliberate introduction of impurities during crystal growth — that could substantially improve the radiation tolerance of future silicon detectors, with applications ranging from LHC tracking detectors to CMOS imaging sensors and dark matter detection experiments.

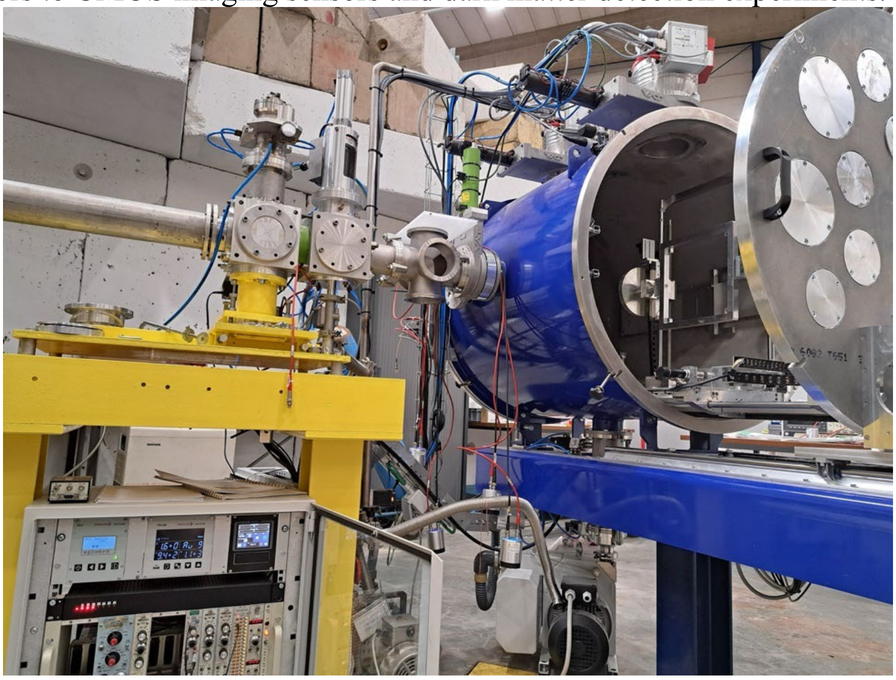

Figure 1:The end of the HIF beam line with the newly installed test chamber

3.6. UOB

The following includes a brief summary of some of the more noteworthy TA projects conducted at the UoB MC40 cyclotron facility:

Annealing studies of proton-irradiated silicon diodes for the CMS HGCAL project (EURO-LABS-2024-UOB-002)

From previous studies using 6” n-type silicon wafers it is well known that protons and neutrons cause different radiation damage. In the context of the CMS HGCAL project, recent studies with neutron-irradiated samples of 8” p-type silicon wafers resulted in significant deviations from the annealing behaviour expectations for neutron damage. This study aimed to investigated whether similar deviations also occur after proton irradiation. The aim of the project is to compare the proton and neutron irradiated samples to investigate the differences in annealing behaviour in terms of the types of defects that are predominantly created during irradiation of the substrate. The measurements were conducted in the same setup using the same production of sensors to keep the comparability as high as possible, as outlined in *JINST* 21 (2026) 03, P03034. The samples were proton irradiated at the UoB MC40 cyclotron to the target fluences successfully and initial comparisons between proton and neutron irradiated samples, before annealing, have been undertaken. The project is now undertaking a comprehensive study of the long-term annealing behaviour, the results of which will be prepared for publication once the study has concluded.

Studying the temperature stability of Silicon Photonics devices during proton irradiation (EURO-LABS-2025-UOB-001)

Silicon photonics (SiPh) ring modulators are highly sensitive to temperature variations, affecting both their basic operation and their response to radiation damage. Therefore, temperature control and stability are crucial for successful irradiation tests. The UoB proton facility can provide high proton fluxes, allowing the limits of SiPh radiation tolerance to be investigated. However, this high flux also causes significant energy deposition into the samples and substrates. This project studied approaches to optimise sample preparation, test board design, and cooling methods in order to maintain temperature stability of SiPh samples during irradiation. A dedicated test board with eight sample locations and 20 temperature sensors was developed and used to monitor temperature stability during irradiation, as shown in Figure 1. The findings, an example of which is shown in Figure 2, will provide valuable insights into achieving sufficient temperature stability in future radiation tests of SiPh components at UoB and other proton irradiation facilities.

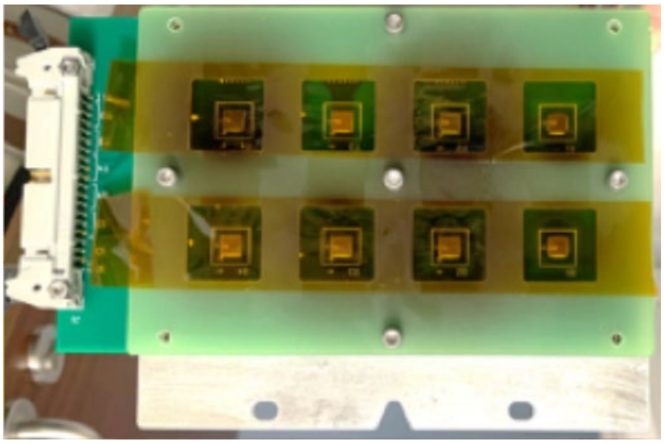

Figure 1: *Dedicated test frame developed for assessment of temperature stability of SiPh devices during proton irradiation.*

Figure 2: *Time evolution of temperature measured on the test frame during irradiation.*

Measurement of proton hardness factors in silicon at MeV-scale beam energies (EURO-LABS-2025-UOB-002)

Silicon detectors used in high-radiation environments such as the LHC experiments suffer from performance degradation due to radiation-induced displacement damage in the silicon crystal lattice. This damage affects key detector properties including leakage current, charge collection, and depletion voltage. To compare and quantify these effects across different radiation environments, the Non-Ionizing Energy Loss (NIEL) scaling hypothesis is commonly used. However, recent studies have shown that NIEL scaling does not fully capture all damage mechanisms, particularly for materials with varying resistivity or impurity levels. This project aimed to refine the understanding of radiation damage in silicon detectors by consolidating and expanding the available experimental data on *hardness factors* which quantify the relationship between radiation type and induced damage, across multiple radiation facilities. A key outcome will be the development of standardized silicon dosimeters for consistent hardness factor evaluations. Ultimately, the findings may lead to improved damage prediction models and inspire new strategies for radiation hardness, such as defect engineering, with broader applications including CMOS electronics and dark matter detection. This TA project was notable in that it made use of two of the facility's key auxiliary capabilities, namely the ability to vary the beam energy and provide high precision dosimetry. Samples were irradiated at three beam energies: 27 MeV, 20 MeV and 15 MeV and a detailed understanding of the beam energy at the samples, based on Geant4 simulates (described in *JINST* 20 (2025) 01, P01024) was shared with the team, as shown in Figure 3. Furthermore, high precision dosimetry was delivered at a level of around 5-10%, based on careful analysis of activation foils and technical information on its associated systematic uncertainties was shared with the team to facilitate their data analysis on the measurement of the hardness factors.

Figure 3: *A simulation of the energy profile of the UoB MC40 proton beam as it passes through the irradiation setup. Given the low beam energy, significant energy loss is experienced and the beam energy incident on the dosimetry foil and samples are notably lower than that of the primary beam. Image from* JINST *20 (2025) 01, P01024.*

Post-irradiation characterisation of detector modules from the ATLAS High Granularity Timing Detector upgrade (EURO-LABS-2026-UOB-002)

The High Granularity Timing Detector (HGTD) is a critical component of the ATLAS Phase-II upgrade, designed to mitigate the effects of extreme pile-up by providing a time resolution of approximately 30-50 ps per track. To ensure the operational stability of the detector throughout the High Luminosity LHC (HL-LHC) lifetime, it is imperative to validate the integrated performance of the final sensor-ASIC assembly under realistic end-of-life radiation conditions. An irradiation campaign at the UoB MC40 cyclotron was planned to evaluate the radiation hardness and operational stability of the HGTD modules. These modules, comprising Low Gain Avalanche Detectors (LGAD) bump-bonded to the ALTIROC front-end ASIC, are designed to provide high-precision timing (<70 ps) necessary to mitigate pile-up effects at the HL-LHC. A total of three modules were irradiated to neutron-equivalent fluences of 2.5x1015 neq/cm2 to simulate the most extreme conditions expected, and one module will be irradiated to an intermediate fluence of 1x1015neq/cm2. The post-irradiation characterisation will focus on the hit efficiency and time resolution despite radiation-induced gain degradation in the LGADs and potential noise increases in the ALTIROC electronics. These results will be compared against pre-irradiation benchmarks to validate the final module design. This project is particularly notable in that it was the first to make use of the facility's service improvement involving an upgrade to the sample scanning system, allowing the large area samples, around 2 cm x 4 cm, as shown in Figure 4, to be each irradiated in one day of operations. This had a significant advantage over the previous system in that it mitigated potential difficulties associated with sample handing and environmental exposure inherent in irradiations which span multiple runs.

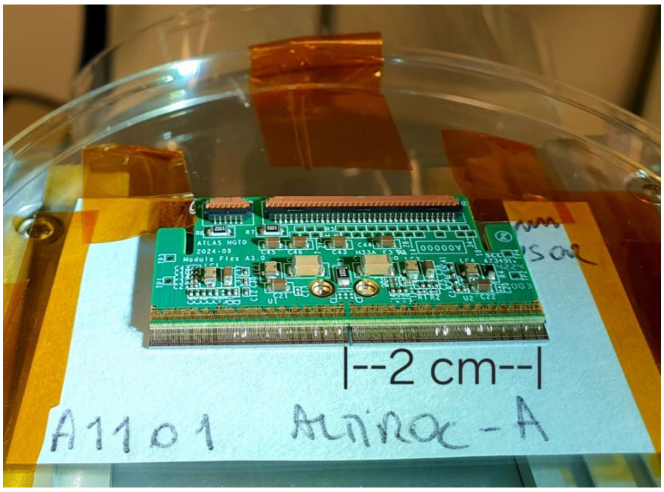

Figure 4: A photograph of one of the ATLAS HGTD modules irradiated at the UoB MC40 cyclotron, labelled for scale.

4. ANALYSIS

In the four years of EURO-LABS 131 projects with nearly 435 users were carried out for irradiation activities for Detector R&D, benefiting from the TA provided. While the number of projects is indicative of the TA usage, the number of users should be evaluated with care. The TA was namely provided in two modalities: *physical* and *remote* access. With *physical* access, users visited the RI to carry out their experiments, and user support was available. For *remote* access, typical for irradiations, samples were sent to the RIs, irradiated and sent back to the users after checking the activity and allowing for the appropriate cool-off period. Naturally, users' incentive to register was more pronounced for the physical access; applications for remote access had a reduced number of users, in some cases only the PI of the project. Table 1 lists the number of projects and number of users in the 6 irradiation RIs of WP4.

WP4	Research Infrastructure	Projects	Users
WP 4.3.1	CERN-IRRAD	18	57
WP 4.3.2	CERN-GIF++	12	72
WP 4.3.3	JSI	65	197
WP 4.3.4	IFJ-PAN	19	64
WP 4.3.5	UCL	6	18
WP 4.3.6	UoB	11	27

Table 1: Number of projects and number of users in irradiation Ris (WP4) during the 4 years of TA in EURO-LABS

ANNEX: GLOSSARY

Acronym	Definition
RI	Research Infrastructure
TA	Transnational Access
AU	Access Unit, usually equal to a beam hour
SERI	Swiss State Secretariat for Education, Research and Innovation
CHRISP	Swiss Research Infrastructure for Particle Physics
PSI	Paul Scherer Institut
DESY	Deutsches Elektronen Synchrotron
ECR	Early Career Researcher
IRRAD	CERN Proton Irradiation facility
CHARM	Cern High energy AcceleratoR Mixed-field facility
GIF++	CERN Gamma Irradiation Facility
JSI	Jožef Stefan Institute
IFJ-PAN	Nuclear Physics Institute of the Polish Academy of Sciences
UCL	Catholic University of Louvain
UoB	University of Birmingham
DRD	Detector Research and Development
HL-LHC	High Luminosity Large Hadron Collider