

EURO-LABS

EUROpean Laboratories for Accelerator Based Science

HORIZON-INFRA-2021-SERV-01-07 Project EURO-LABS

Deliverable Report

WP3- Access to Rerearch Infrastructures for Accelerator R&D

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Abstract

This document reports on the progress of the Transnational Access (TA) activities at the CERN HiRadMat facility, conducted within Work Package 3, Task 1 of the EURO-LABS project. The projects carried out at the facility to date are described, together with their impact on the relevant research domains and selected highlights of the results obtained. In addition, the ongoing and planned projects foreseen up to the end of the project in August 2026 are outlined. Finally, an evaluation of the TA experience within the EURO-LABS framework is presented.



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EURO-LABS Consortium, 2026

For more information on EURO-LABS, its partners and contributors please see:

<https://web.infn.it/EURO-LABS>

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Delivery Slip

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Executive Summary

This report presents the progress and outcomes of Transnational Access (TA) activities conducted at the HiRadMat facility at CERN within Work Package 3, Task 3.1 of the EURO-LABS project. HiRadMat provides a unique experimental platform worldwide, delivering high-brightness 440 GeV/c proton beams from the CERN Super Proton Synchrotron (SPS) for controlled beam–matter interaction studies. HiRadMat is an instrumental facility for accelerator R&D, materials research, machine protection, as well as to wide spectrum of physics research like laboratory astrophysics or fusion. The facility allows experimental conditions that cannot be reproduced elsewhere and is therefore of strategic importance for CERN and Europe.

Objectives and Scope

The objectives of Task 3.1 were to provide transnational access to HiRadMat for advanced accelerator material studies, radiation damage benchmarking, thermomechanical shock investigations, validation of beam diagnostics and protection systems, and exploratory fundamental research into relativistic plasma phenomena. These objectives have been fully achieved and, in quantitative terms, significantly exceeded. Over the reporting period, a total of eleven experimental campaigns were supported, comprising forty-four approved sub-project visits. A total of 6,824 Access Units (AU) have already been delivered, with an additional 2,312 AUs projected to be delivered by August 2026, bringing the total to 9,136 AUs over the four-year duration of EURO-LABS. The originally planned allocation of 4,800 AUs was fully committed by Month 32 of the project, demonstrating demand substantially higher than anticipated. The subsequent budget reallocation enabled a near doubling of access provision, confirming both the sustained scientific demand and the strategic value of the facility.

Access Implementation and Demand

The supported experimental programme delivered high-impact results across multiple domains. In radiation damage physics, the campaign HRMT-63 provided the first benchmark displacement cross-section measurements at 440 GeV/c, addressing a long-standing gap in experimental data and significantly strengthening the validation of Displacement Per Atom (DPA) models used for superconducting magnet and high-power component design. In thermomechanical studies, campaigns such as HRMT-60 and HRMT-67 investigated the dynamic response of beam-intercepting materials under intense proton pulses representative of multi-megawatt accelerator conditions, while HRMT-66 explored the coupling between shock loading and radiation damage in advanced structural materials. These results directly enhance the predictive modeling capabilities for the European next-generation accelerator facilities.

In parallel, detector-physics oriented validation campaigns like HRMT-55 and HRMT-71, have assessed Beam Loss Monitor technologies under realistic high-intensity conditions. These studies provided essential calibration data and operational insights for machine protection systems at CERN and other high-brightness facilities. Beyond accelerator technology, the FIREBALL series of experiments (HRMT-62, HRMT-64, and HRMT-68) successfully reproduced relativistic electron–positron plasma phenomena in the laboratory, generating high-impact publications (in *Nature Communications* and *Physical Review Letters*) and extended HiRadMat’s scientific reach into fundamental plasma astrophysics. This interdisciplinary dimension highlights the broader research

potential unlocked through transnational access to the facility.

Scientific Impact

The Transnational Access (TA) programme proved not merely supportive but a key enabler, providing researchers with access to a unique facility, instrumentation, and expertise necessary to carry out experiments that would otherwise not have been feasible. HiRadMat experiments are technically complex and require extensive preparation, multi-year coordination, strict safety compliance, advanced instrumentation integration, and post-irradiation analysis across international collaborations. Transnational Access funding ensured the participation of external research teams, facilitated repeated technical visits throughout all phases of the campaigns, and enabled full scientific exploitation of the experimental results. The facility remained consistently oversubscribed, and strong engagement from the international user community was maintained throughout the project duration.

Outlook (2025-2026)

Looking ahead, the final experiment under EURO-LABS, HRMT-74, will focus on radiation tolerance and optical performance of novel carbon nanotube foils for beam instrumentation in high-brightness machines. Ongoing post-irradiation analyses from multiple campaigns are expected to continue generating publications and modelling improvements beyond the formal end of the access period.

The outcomes of Task 3.1 clearly demonstrate that transnational access to HiRadMat is essential for sustaining European excellence in accelerator materials research, machine protection technologies, and high-brightness beam science. Continued support through a successor framework, like HORIZON-INFRA-2027-SERV-01-01, is considered critical to maintaining the scientific momentum and strategic impact established under EURO-LABS.

1 Introduction

The EURO-LABS Task Force 3.1 comprises a single facility: HiRadMat, a truly unique research infrastructure worldwide, dedicated to testing materials with the high-brightness beam of the CERN Super Proton Synchrotron (SPS). No other installation globally offers comparable beam characteristics combined with such a high level of technical organization and operational support. Owing to these exceptional beam properties, together with the strong scientific and logistical support provided by CERN and EURO-LABS, **HiRadMat remains in extremely high demand within the international research community** involved with the accelerator technology R&D. This is demonstrated by the impressive deck and diversity of experiments that have taken place in the facility since its inauguration in 2011¹ and as highlighted by the international workshop organized in 2019².

The facility attracts teams from across Europe and beyond, enabling the realization of highly challenging and innovative experiments that are of clear technical & strategic importance to the wider scientific community. The complexity and technical requirements of these experiments require significant preparation, coordination, and financial support. In particular, many participating teams face substantial constraints in covering essential costs, and notably the transport and logistics of experimental equipment, within the strict scheduling framework of the facility, where beam time is limited to a single allocated week per year per experiment. In this context, EURO-LABS support has not been merely beneficial; **it is indispensable. Transnational access support by EURO-LABS provides the essential mechanism that enables broad participation, scientific excellence, and equitable access to this unique infrastructure.** Without transnational access support, the ability of the international community to utilize HiRadMat would be severely compromised, and the facility's full scientific potential could not be realized.

1.1 Purpose and Scope of the Document

The objectives of Task 3.1 have been fully achieved and delivered. The HiRadMat facility provided a unique high-intensity pulsed proton beam test bed for advanced accelerator material studies, enabling experimental campaigns directly targeting beam-intercepting devices such as collimators, beam windows, and high-power targets. Through projects including HRMT-60 (dynamic thermomechanical response of target materials), HRMT-66 (shock and radiation effects in advanced structural materials), HRMT-63 (displacement cross-section measurements at 440 GeV/c), and HRMT-55/71 (validation of beam diagnostic and protection systems), the programme delivered benchmark experimental data under realistic beam conditions that cannot be reproduced elsewhere. The facility successfully supported complex, multi-institutional R&D activities on material performance, radiation damage, and detector behaviour in high-brightness beam environments, fully realising the scope and ambition of the Transnational Access task as defined in the proposal.

¹<https://hiradmat.web.cern.ch/list-publications>

²<https://indico.cern.ch/event/767689/>

1.2 Structure of the Document

This document is organised as follows: Section 1 provides information about the report content whereas Section 2 introduces the TA projects conducted in each facility along with highlights, results and impact to the field. The deliverable is concluded in Section 3.

2 TA Activities

As shown in Table 1, HiRadMat has hosted and supported, under the framework of EURO-LABS, **11 experimental campaigns** (“Projects”). It should be emphasized that, owing to the high level of technical complexity and the demanding nature of HiRadMat experiments, **several visits are typically required for the completion of a single campaign, often extending over multiple years**. A detailed overview of the corresponding individual team visits (“Sub-projects”) is provided in Table 2, which illustrates the distribution and continuity of access associated with these campaigns.

Table 1: Summary of Transnational Access Projects for HiRadMat up to March 9, 2026

Project ID	Project Title	Field of Research	Days	AUs	Users
HRMT-55	BLM	Beam diagnostics	37	296	11
HRMT-58	ATLAS-ITk	Particle detectors	0	0	2
HRMT-60	RaDIATE2022	Materials R&D	78	624	16
HRMT-62	FIREBALL-I	Plasma astrophysics	123	984	44
HRMT-63	DPA	Materials R&D	91	728	18
HRMT-64	FIREBALL-II	Plasma astrophysics	167	1336	31
HRMT-66	SMAUG2	Materials R&D	40	320	1
HRMT-67	RADIATE-II	Materials R&D	48	384	13
HRMT-68	FIREBALL-III	Plasma astrophysics	219	1752	45
HRMT-71	BLM4	Beam diagnostics	13	104	8
HRMT-75	ORNL Target	Targetry R&D	0	0	5
HRMT-76	FIREBALL-IV	Plasma astrophysics	37	296	16
Total			853	6824	210

The initial allocation of Access Units (AUs) within EURO-LABS — based an estima-

tion based on prior experience from ARIES and EUCARD2 — has been substantially exceeded. The originally requested 4800 AUs, agreed at the kick-off Meeting, were fully allocated by the User Selection Panel (USP) within the first three years of the project (by month 32), as illustrated in Figure 1. This clearly reflects the significantly higher-than-anticipated demand for transnational access to HiRadMat.

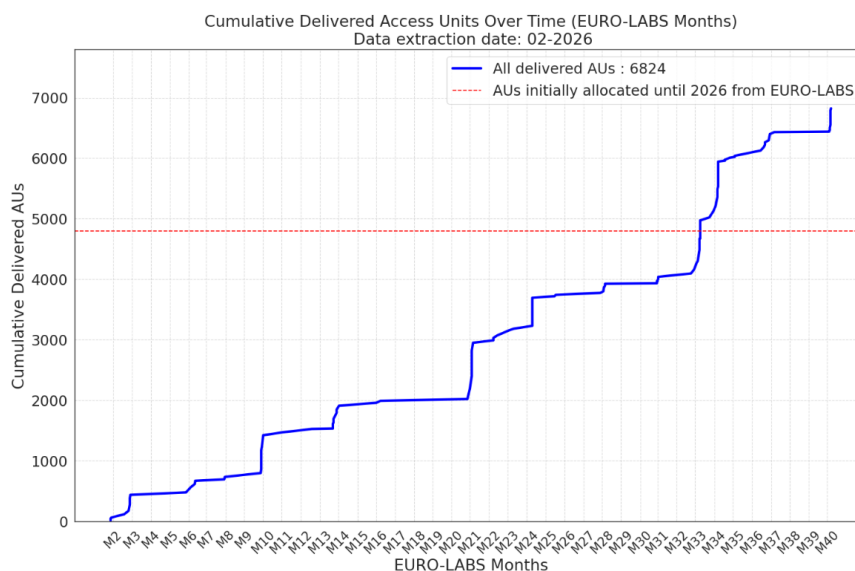


Figure 1: Timeline of Access Units (AUs) delivered at HiRadMat. The initially granted 4,800 AUs were fully allocated by Month 32 of the project duration.

Following the agreed budget reallocation in October 2026, a total of **6824 AUs** have already been delivered. An additional **2312 AUs** are projected to be allocated by 31.08.2026, bringing the total to **9136 AUs** over the four-year duration of EURO-LABS. This represents almost a doubling of the initially foreseen access provision and provides quantitative evidence of the sustained and increasing demand for HiRadMat. This evolution unequivocally demonstrates the essential role of transnational access support in enabling the scientific exploitation of HiRadMat. Without this mechanism, the scale, continuity, and inclusiveness of the supported experimental programme would not be achievable. The current status of AU allocation is shown in Figure 2.

Table 2 provides a detailed overview of the individual team visits supported under EURO-LABS, together with the corresponding Access Units allocated per visit. A total of 44 sub-projects have been requested and approved by the USP. This high number of visits clearly demonstrates that EURO-LABS support is required across all phases of a HiRadMat experimental campaign — including preparation, technical and scientific coordination, beam time and data-taking, decommissioning activities, and post-irradiation analysis.

The structured timeline and justification of each visit are rigorously assessed by the USP, which evaluates both the necessity of personnel involvement and the scientific and technical relevance of the requested access.

HiRadMat EURO-LABS AU Status
Data extraction date: 15-02-2026

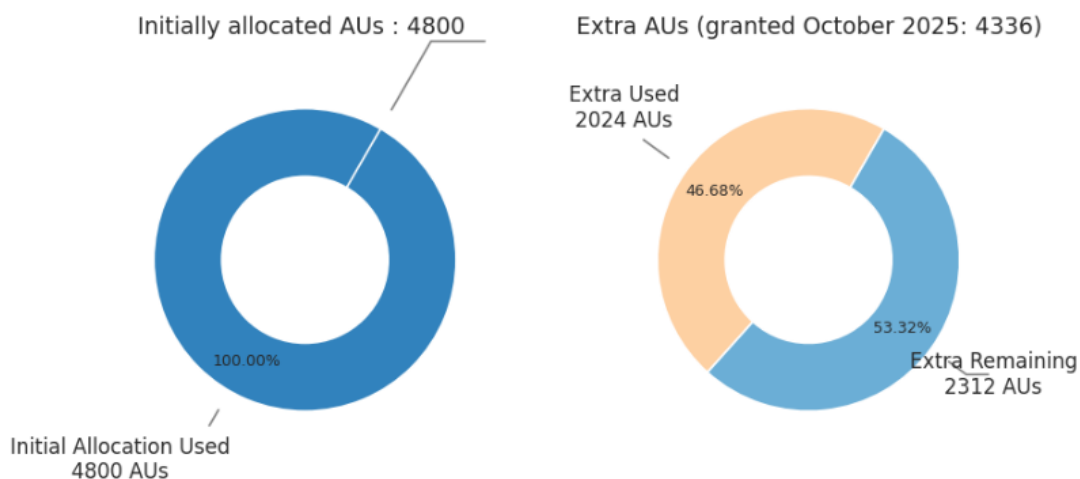


Figure 2: Status of AU allocation for HiRadMat. The initial 4,800 AUs were fully allocated within the first three years of EURO-LABS, and an additional 4,336 AUs were made available following the budget reallocation in October 2026.

Table 2: Summary of Sub-projects

Sub-project Identifier	Total Days Spent in the Facility	Access Units Allocated
HRMT-63-3	46	368
HRMT-63-4	10	80
HRMT-63-5	4	32
HRMT-63-6	0	0
HRMT-67-2	4	32
HRMT-67-3	31	248
HRMT-67-4	4	32
HRMT-67-5	6	48
HRMT-68-2	10	80
HRMT-68-4	68	544
HRMT-68-5	4	32

Continued on next page

Sub-project Identifier	Total Days Spent in the Facility	Access Units Allocated
HRMT-68-6	121	968
HRMT-68-7	4	32
HRMT-68-8	0	0
HRMT-71-1	4	32
HRMT-71-2	3	24
HRMT-71-3	6	48
HRMT-71-4	0	0
HRMT-75-1	0	0
HRMT-76-1	37	296
HRMT-76-2	0	0
HRMT-71-5	0	0
HRMT-60-1	47	376
HRMT-62-1	8	64
HRMT-55-1	6	48
HRMT-55-2	7	56
HRMT-60-2	8	64
HRMT-62-2	16	128
HRMT-62-3	13	104
HRMT-62-4	86	688
HRMT-63-1	7	56
HRMT-64-1	41	328
HRMT-64-2	10	80
HRMT-55-3	15	120
HRMT-55-4	6	48
HRMT-55-5	3	24
HRMT-58-1	0	0
HRMT-60-3	15	120
HRMT-60-4	8	64

Continued on next page

Sub-project Identifier	Total Days Spent in the Facility	Access Units Allocated
HRMT-63-2	24	192
HRMT-64-3	116	928
HRMT-66-1	40	320
HRMT-67-1	3	24
HRMT-68-1	12	96

Table 3: HiRadMat HRMT Sub-projects: Access, Users and Scientific Field

HRMT-ID	Field of Research	Days	AUs	Users
HRMT-62-4	Plasma Astrophysics	86	688	18
HRMT-64-3	Plasma Astrophysics	116	928	16
HRMT-62-1	Plasma Astrophysics	8	64	14
HRMT-64-1	Plasma Astrophysics	41	328	13
HRMT-68-2	Plasma Astrophysics	10	80	13
HRMT-76-2	Plasma Astrophysics	0	0	9
HRMT-60-1	Materials R&D	47	376	9
HRMT-68-4	Plasma Astrophysics	68	544	9
HRMT-63-2	Materials R&D	24	192	8
HRMT-68-6	Plasma Astrophysics	121	968	8
HRMT-76-1	Plasma Astrophysics	37	296	7
HRMT-62-3	Plasma Astrophysics	13	104	7
HRMT-68-8	Plasma Astrophysics	0	0	6
HRMT-67-3	Materials R&D	31	248	6
HRMT-75-1	Targetry R&D	0	0	5
HRMT-68-1	Plasma Astrophysics	12	96	5
HRMT-62-2	Plasma Astrophysics	16	128	5
HRMT-63-3	Materials R&D	46	368	3
HRMT-63-4	Materials R&D	10	80	3

HRMT-ID	Field of Research	Days	AUs	Users
HRMT-71-3	Detector Physics	6	48	3
HRMT-55-3	Detector Physics	15	120	3
HRMT-55-4	Detector Physics	6	48	3
HRMT-60-3	Materials R&D	15	120	3
HRMT-67-4	Materials R&D	4	32	3
HRMT-68-7	Plasma Astrophysics	4	32	3
HRMT-64-2	Plasma Astrophysics	10	80	2
HRMT-67-2	Materials R&D	4	32	2
HRMT-55-1	Detector Physics	6	48	2
HRMT-55-2	Detector Physics	7	56	2
HRMT-60-2	Materials R&D	8	64	2
HRMT-60-4	Materials R&D	8	64	2
HRMT-63-1	Materials R&D	7	56	2
HRMT-71-5	Detector Physics	0	0	2
HRMT-58-1	Detector Physics	0	0	2
HRMT-63-5	Materials R&D	4	32	1
HRMT-63-6	Materials R&D	0	0	1
HRMT-67-5	Materials R&D	6	48	1
HRMT-68-5	Plasma Astrophysics	4	32	1
HRMT-71-1	Detector Physics	4	32	1
HRMT-71-2	Detector Physics	3	24	1
HRMT-71-4	Detector Physics	0	0	1
HRMT-55-5	Detector Physics	3	24	1
HRMT-66-1	Materials R&D	40	320	1
HRMT-67-1	Materials R&D	3	24	1

In general, and as already mentioned in the introduction and detailed in Subsection 2.1, the 11 experimental campaigns supported under EURO-LABS were scientifically unique and addressed questions that cannot be investigated at any other facility worldwide.

For example, HRMT-63 delivered the first experimental displacement cross-section measurements for 440 GeV/c protons, providing benchmark data for the validation of DPA models used in the design of superconducting magnets. HRMT-67 (RaDIATE II) ad-

vanced the understanding of beam-induced damage in materials for high-power targets and beam windows, while HRMT-71 validated beam loss monitor performance under realistic high-intensity conditions. The FIREBALL series (HRMT-62/64/68) demonstrated laboratory reproduction of relativistic pair-plasma phenomena, leading to high-impact publications (including many Physical Review Letters and Nature Communications) articles, while at the same time extending HiRadMat's reach into fundamental astrophysics.

These results were only possible due to the unique combination of the SPS beam energy, pulse intensity, and dedicated experimental infrastructure available at HiRadMat. The technical complexity of the campaigns, the need for repeated visits, and the extensive preparatory work made Transnational Access essential. EURO-LABS support ensured participation of international teams, continuity across multi-year experimental programmes, and the full scientific exploitation of this unique European infrastructure.

2.1 Description of TA projects in HiRadMat

2.1.1 HRMT-55: [BLM-3]

HRMT-55 focused on the experimental evaluation of Beam Loss Monitor (BLM) detector responses under controlled high-intensity proton beam conditions at HiRadMat. Beam loss monitors are critical diagnostic and protection systems in accelerator complexes: they must protect machine components from radiation damage and quench while providing sufficient sensitivity for machine tuning and optimisation studies. Ionization chambers, in particular, are widely used across facilities such as CERN, ESS and GSI, and were a primary detector type evaluated in this campaign. The campaign involved systematic tests of various BLM detector types, including CERN-designed ionization chambers and other detector technologies, to assess their sensitivity to different loss levels and their overall operational response in realistic high-energy loss scenarios. This work contributes directly to improving BLM system design, calibration data, and the interpretation of loss signals in diverse accelerator environments. Because beam loss monitors serve both machine protection and beam diagnostics, experimental validation under high-intensity conditions is essential. HiRadMat's unique capability to deliver high-brightness 440 GeV proton pulses allowed the experiment to expose detectors to loss profiles representative of extreme accelerator scenarios. This provided data that would not be accessible in normal operational machine environments due to safety and operational constraints.

The experimental programme also fostered collaboration between CERN, ESS, and other partners, advancing shared detector development goals. Given the complexity of integrating multiple detector technologies, coordinating beam tests, and analyzing detector signals post-irradiation, EURO-LABS TA support was crucial in enabling participation of the involved teams, ensuring timely preparatory work, and allowing multiple technical visits essential for setup, beam execution, and data interpretation. In Figure 3, a characteristic plot of the discrepancies that need to be better understood is shown.

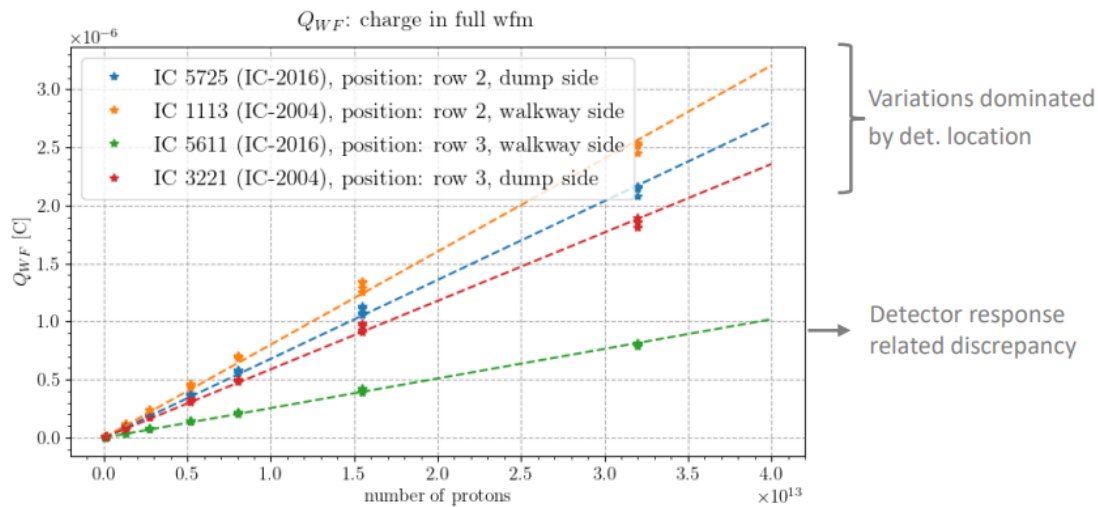


Figure 3: Discrepancies measured in HRMT-55, were critical for the development phase of the BLMs. Two follow-up experiment HRMT-71 and HRMT-76 address these questions during 2025 (already completed) and 2026 campaigns.

2.1.2 HRMT-60: [RADIATE]

HRMT-60 (RaDIATE2022) was a comprehensive beam-impact experiment designed to investigate the dynamic thermomechanical response of beam-intercepting materials under high-intensity SPS proton pulses. Building on the RaDIATE collaboration's earlier HiRadMat campaigns prior to EURO-LABS, the objectives were to improve understanding of single-shot thermal shock effects, compare the behaviour of non-irradiated with pre-irradiated materials, explore novel materials and advanced alloys, and directly measure dynamic responses to validate numerical models used for high-power target design. The experiment exposed a diverse matrix of specimens — including isotropic graphite, multiple grades of beryllium, titanium alloys with varying heat treatments, high-entropy alloys, nanofiber mats, silicon carbide composites, tungsten-based materials and others — to controlled proton beam pulses at HiRadMat. The test assembly featured four instrumented arrays of thin specimens and instrumented cylinders equipped with temperature sensors, strain gages and Laser Doppler Vibrometry (LDV) for real-time measurements of temperature, axial/circumferential strain and radial velocity/displacement during and immediately after beam impact.

The experimental setup incorporated beam-based alignment techniques and carefully interfaced containment systems, underscoring the complexity of coordinated high-intensity tests. HRMT-60 successfully completed its assigned beam time in October 2022, delivering four high-intensity pulses totaling approximately 7×10^{13} protons, creating conditions representative of multi-MW accelerator target environments. Online and post-beam visual inspections, followed by disassembly and careful specimen packaging, prepared the irradiated materials for detailed Post-Irradiation Examination (PIE) at participating laboratories. Preliminary raw dynamic data (strain and velocity profiles) have been compared with finite-element and Monte Carlo simulations, contributing valuable input for model validation and refinement. The extensive material set and instrumentation strategy have broadened the empirical basis for thermal shock and radiation damage

assessment across conventional and emerging target materials. The HRMT-60 campaign exemplified the interdisciplinary, high-complexity nature of HiRadMat experiments: it required detailed coordination among international collaborators, advanced instrumentation integration and iterative preparatory work. EURO-LABS Transnational Access support was essential to enable participation by external teams, facilitate repeated technical visits, and ensure full exploitation of the experimental programme’s scientific potential.

A photo of different phases of the experiment can be shown in Figure 4 below.



Figure 4: Different phases of HRMT-60 experiment, including the first-time challenging irradiation of pre-irradiated samples.

2.1.3 HRMT-62: [FIREBALL-I]

HRMT-62 (FIREBALL), was the first experiment of the series of the FIREBALL campaigns. Aim of the FIREBALL campaigns was to investigate the generation and propagation of relativistic electron–positron pair plasma beams as a laboratory analogue for astrophysical pair jets. The experiment was motivated by the need to reproduce collective plasma phenomena — such as beam–plasma instabilities and magnetic field amplification — under controlled conditions in the laboratory, replicating key aspects of kinetic processes thought to occur in relativistic astrophysical environments. In HRMT-62, high-yield pair plasma beams were produced by directing the 440 GeV/c proton beam from the CERN Super Proton Synchrotron (SPS) onto a high-Z converter target, triggering Bethe–Heitler pair production. Beam profile and energy spectra measurements showed good agreement with simulations using FLUKA, validating the experimental generation of a broad spectrum of relativistic electrons and positrons under realistic conditions. The campaign combined experimental diagnostics with advanced Particle-in-Cell (PIC) simulations to study the impact of finite energy spread and transverse beam divergence on kinetic instability growth. A key observation from simulations and preliminary analysis was that realistic divergence and spectral spread sufficiently suppress unstable modes that would be predicted by idealized theory alone; this highlights the influence of realistic beam quality on plasma instability development. Additionally, scaling of these results enables meaningful comparison with astrophysical scenarios, contributing to the interpretation of high-energy cosmic phenomena. HRMT-62 represented a foundational step in the FIREBALL series, establishing experimental methodologies, beam–matter interaction channels, and diagnostic strategies that were further refined in HRMT-64 and HRMT-68. The unique combination of high beam energy, pair

production yield, and available diagnostics at HiRadMat made this research possible, and the experiment has significantly advanced laboratory plasma astrophysics by providing benchmark data where none existed previously. Given the highly specialized beam parameters, the coordination required to implement advanced detectors and simulations, and the need for repeated expert visits during commissioning, data acquisition, and analysis phases, EURO-LABS Transnational Access support was essential for enabling broad participation and maximizing the scientific output of this programme.

2.1.4 HRMT-63: [DPA]

HRMT-63, conducted in collaboration with J-PARC (JAEA/KEK), focused on the measurement of the displacement cross section for 440 GeV/c protons, with the objective of improving the quantitative understanding of radiation-induced damage in accelerator materials, in particular superconducting (SC) coils. Accurate knowledge of DPA cross sections at SPS energies is essential for reliable lifetime predictions of components exposed to high-intensity proton beams in modern and future accelerator facilities. Existing radiation damage models largely rely on extrapolations and numerical simulations; however, experimental benchmark data at 440 GeV have been scarce. HRMT-63 therefore addressed a critical knowledge gap in high-energy radiation damage physics. The campaign required precise irradiation of dedicated material samples under well-controlled beam conditions at HiRadMat, together with careful control of beam parameters to ensure reliable cross-section measurements. The experimental programme was complemented by detailed post-irradiation analyses and close coordination between CERN and J-PARC, ensuring alignment between experimental design, material selection, and subsequent characterization studies.

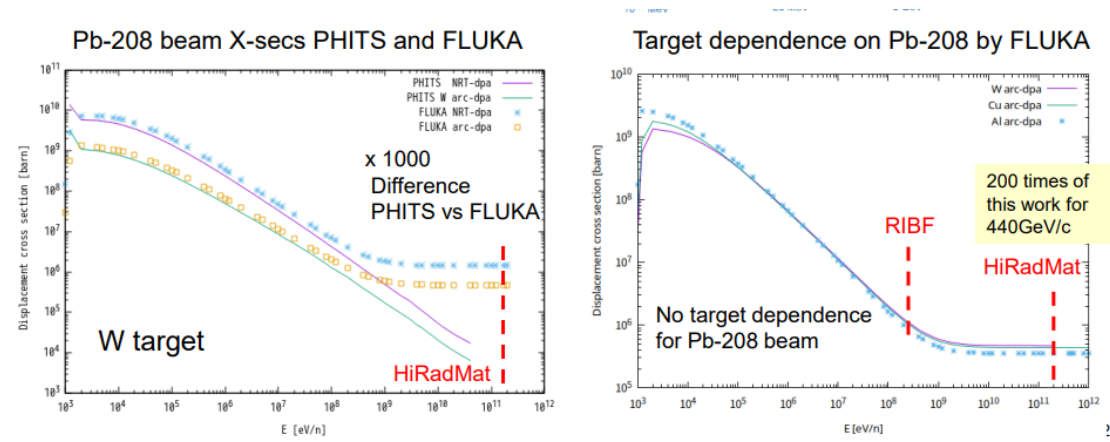


Figure 5: DPA cross section for heavy ion projectiles from two simulation codes: FLUKA and PHITS. The energy range of HiRadMat is depicted with the red dashes line, showing that the data from the HiRadMat experiment could help resolving this discrepancy.

The results, yet to be published, are expected to significantly strengthen the validation of radiation damage models and Monte Carlo simulation tools used worldwide for the design of superconducting magnets and high-power accelerator components. In turn, this contributes directly to improved reliability, safety margins, and performance optimization of high-brightness machines. Given the complexity of the irradiation setup, strict safety constraints associated with high-intensity beam operation, and the need for exten-

sive preparatory discussions and multiple technical visits, EURO-LABS transnational access support was instrumental in enabling the successful execution of this campaign. In Figure 5, the displacement per atom differences between two major Monte-Carlo programs (FLUKA & Particle and Heavy Ion Transport code System (PHITS) [1]) is shown.

2.1.5 HRMT-64: [FIREBALL-II]

HRMT-64 (FIREBALL-II) followed HRMT-62 and aimed at reproducing and investigating the microphysics of extreme astrophysical scenarios using laboratory-generated electron-positron jets. Pair beam generation and its propagation through argon ambient plasma were key elements of this experiment; the plasma was produced via an inductively-coupled radio-frequency discharge and characterized using a Langmuir probe. The growth of magnetic fields associated with plasma instabilities was investigated via improved Faraday rotation diagnostics, based on the properties of a magneto-optic crystal (TGG), with the overall sensitivity limited by intrinsic electrical noise in the setup.

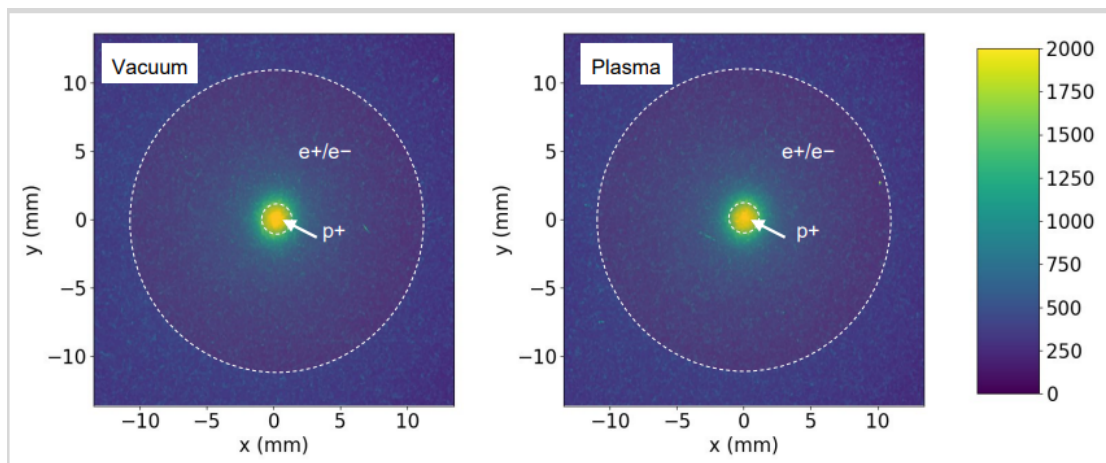


Figure 6: In HRMT-64 (FIREBALL-II), time-integrated post-plasma luminescence screens showed very small differences between plasma-on and plasma-off configurations; together with Particle-in-cell (PIC) simulations, this indicates that finite beam divergence can strongly suppress observable filamentation at the plasma exit under realistic beam conditions.

A key experimental outcome of HRMT-64 was that the post-plasma luminescence screens showed very little difference between shots with the plasma turned on and off. No clear evidence of filamentation was observed at the discharge exit in the time-integrated transverse profiles (all species combined); the collaboration notes that filaments may nevertheless be overlapped in the integrated images. Complementary PIC simulations indicate that filamentation is expected for ideally collimated pair beams, whereas a finite transverse divergence suppresses filament formation at the plasma exit. In particular, the experimentally derived constraint on the filamentation growth rate is consistent with a divergent beam condition of approximately $\Delta\theta \gtrsim 0.02$. In addition, HRMT-64 included a parasitic proof-of-principle study investigating the dynamical response of meteorite samples under SPS beam irradiation. A total of 27 shots were delivered at two different intensity settings, and LDV measurements were performed. The results indicated measurable changes in mechanical response, including evidence of beam-induced

hardening effects, demonstrating the broader interdisciplinary potential of the HiRadMat platform.

2.1.6 HRMT-66: [SMAUG-2]

HRMT-66 (SMAUG II) was designed to investigate the dynamic response of structural materials subjected to simultaneous shock and radiation environments representative of future high-power accelerator conditions. The experiment builds on the first SMAUG campaign by expanding the range of tested materials and instrumentation, with the objective of improving understanding of high-strain-rate deformation and radiation effects in materials critical to beam-intercepting devices. The experimental setup employed HiRadMat's high-brightness proton pulses to induce rapid energy deposition, generating stress waves and lending unique insight into the interplay between shock loading and radiation-induced damage mechanisms. A matrix of specimens, including advanced alloys and composite materials, was instrumented with dynamic diagnostics such as strain gauges and high-speed velocimetry, enabling real-time measurement of velocity and strain during and immediately following beam impact. The initial campaign also integrated optical diagnostics to capture surface motion and shock wave profiles, enabling direct comparison with numerical simulations.



Figure 7: Photo highlights from the post-irradiation analysis of SMAUG-2 from experiment slides presented at the HiRadMat User Day 2024. The unique results are currently being written-up to a publication.

A significant outcome from HRMT-66 was the identification of material-dependent differences in shock response and energy dissipation characteristics under high-intensity proton loading, which are relevant for the structural design of beam windows, targets, and other high-power components. The collected dataset provides valuable empirical validation points for hydrodynamic and finite-element models used in the design and lifetime assessment of critical accelerator infrastructure. HRMT-66 exemplified a highly interdisciplinary and technically complex programme, requiring tight coordination of specimen preparation, instrumentation integration, beam alignment, and post-irradiation data analysis across participating institutions. EURO-LABS Transnational Access support was essential in enabling collaborative participation with a material science expert

from Athens, that played a critical role in performing simulations for the experiment and participating hands-on in the preparation and the post-irradiation analysis of the samples. A slide shown in the HiRadMat User Day³ by the collaborators is shown in Fig. 7.

2.1.7 HRMT-67: [RADIATE]

HRMT-67 (RaDIATE II), conducted in collaboration with Fermilab and international partners within the RaDIATE collaboration, investigated beam-induced damage and thermomechanical response in conventional and novel materials intended for beam windows and high-power targets. The experiment aimed to characterise material behaviour under intense, short-pulse proton irradiation representative of next-generation multi-MW accelerator facilities. The campaign exposed a broad matrix of materials to controlled SPS proton pulses at HiRadMat, enabling direct comparison between different grades, manufacturing routes, and irradiation histories. Instrumented specimens and post-irradiation examination (PIE) campaigns were used to assess dynamic strain response, crack formation, surface degradation, and changes in mechanical properties. The results provide empirical validation data for numerical models used in the design of high-power targets and beam windows, where coupled thermal shock and radiation damage processes govern component lifetime. HRMT-67 builds on earlier RaDIATE campaigns and strengthens the international knowledge base on material degradation mechanisms under extreme beam loading. The experimental data contribute directly to improving predictive capabilities for facilities such as LBNF/DUNE, ESS, and other high-intensity proton machines, where reliability and safety margins are critically dependent on accurate material performance models.

HRMT-67 Assembly and Installation

- Assembly and testing
 - August 4th – 15th
- Installation
 - August 18th – 22nd








17
12/4/2025
Quinn Peterson | HRMT- 67 Experiment Overview


Figure 8: Selected photos from the assembly and installation campaign of HRMT-67, from experiment slides presented at the HiRadMat User Day in 2025.

The experiment required extensive preparation, integration of complex instrumentation, coordination across multiple laboratories, and multi-stage analysis following irradiation.

³<https://indico.cern.ch/event/1419944/>

Given the scale of international collaboration and the technical complexity of specimen preparation, irradiation, and characterisation, EURO-LABS Transnational Access support was essential to enable participation, ensure continuity of the research programme, and maximise the scientific return of the campaign. A slide shown in the HiRadMat 2025 User Day from the assembly and installation campaign of HRMT-67 is shown in Figure 8 and some post irradiation images in Fig. 9.



Figure 9: Preliminary PIE images from HRMT-67. The results will contribute significantly to the knowledge of the international community about the behaviour of these alloys under the effect of the high-energy proton beam.

2.1.8 HRMT-68: [FIREBALL-III]

HRMT-68 (FIREBALL-III), led by the University of Oxford, aimed at performing experimental (laboratory) astrophysics to study the formation and propagation of relativistic electron–positron beams through a plasma medium, reproducing phenomena relevant to intergalactic environments. This experiment represents a unique interdisciplinary application of HiRadMat, extending its impact beyond accelerator physics into fundamental astrophysics. The high-intensity proton beam enabled the generation of plasma conditions that cannot be reproduced elsewhere. The experiment builds upon earlier campaigns (HRMT-62 and HRMT-64) and has already led to high-impact publications (including Nature Communications and Science). Multiple sub-project visits were necessary for setup optimisation, diagnostics development, beamtime execution, and post-irradiation analysis. EURO-LABS support was instrumental in enabling the international collaboration and ensuring continuity across several experimental phases. A photo of the new longer plasma cell used in this experiment, is shown in Figure 10.

Many publications were produced from HRMT-62, HRMT-64 and HRMT-68, all acknowledging EURO-LABS:

- Arrowsmith, C. D., Dyson, A., Gudmundsson, J. T., Bingham, R. & Gregori, G., *Inductively-coupled plasma discharge for use in high-energy-density science ex-*

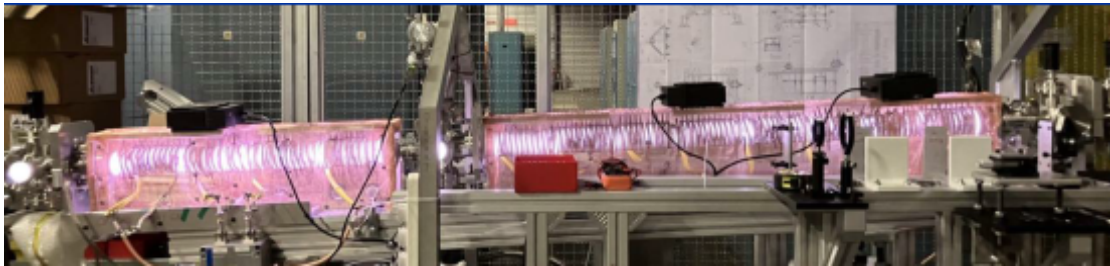


Figure 10: The new longer plasma cell used in HRMT-68 experiment.

periments, Journal of Instrumentation 18 (2023) P04008. DOI: <https://doi.org/10.1088/1748-0221/18/04/P04008>

- Arrowsmith, C. D. et al., *Laboratory realization of relativistic pair-plasma beams*, Nature Communications 15, 5029 (2024). DOI: <https://doi.org/10.1038/s41467-024-49346-2>
- Andersen, E. M., *Radiation Protection and Energy Deposition Studies for FIREBALL-II*, Bachelor Thesis, Bergen University (2024). Available at CERN Repository: <https://repository.cern/records/jzz6a-jkq28>
- Gregori, G., *Extreme Astrophysics with laboratory electron-positron jets*, CERN Presentation, 2 December 2024.
- CERN News, *FIREBALL at HiRadMat – experimenting with high-energy plasmas*, CERN Home News (2024). Available online: <https://home.cern/news/news/experiments/fireball-hiradmat>
- CERN ATS Seminar, *Accelerator experiments to probe beam instabilities in blazars’ pair jets*, Indico Event at CERN (2024). Available online: <https://indico.cern.ch/event/1597706/>
- Arrowsmith, C. D. et al., *Suppression of pair beam instabilities in a laboratory analogue of blazar pair cascades*, Proceedings of the National Academy of Sciences (2025). DOI: <https://doi.org/10.1073/pnas.2513365122>
- Bochmann, M. et al., *Dynamical development of strength and stability of asteroid material under 440 GeV proton beam irradiation*, Nature Communications 16, 11710 (2025). DOI: <https://doi.org/10.1038/s41467-025-66912-4>
Available at CERN CDS: <https://cds.cern.ch/record/2953269>
- CERN News, *Bringing black hole jets down to Earth*, CERN Home News (2025). Available online: <https://home.cern/news/news/physics/bringing-black-hole-jets-down-earth>
- University of Oxford Physics Division, *Pioneering lab-generated plasma fireballs*, University of Oxford Physics News (2025). Available online: <https://www.physics.ox.ac.uk/news/pioneering-lab-generated-plasma-fireballs>
- Rousiadou, P., *Target Optimization Studies for the HRMT-64 Plasma Astrophysics Experiment*, Bachelor Thesis, University of Ioannina (2025). Available at CERN Repository: <https://repository.cern/records/h64h8-5j878>

- Ramm, H., Simon, P., Alexaki, P., Arran, C., Bingham, R., Goillot, A., Gudmundsson, J. T., Halliday, J. W. D., Lloyd, B., Los, E. E., Stergiou, V., Zhang, S., Gregori, G. & Charitonidis, N., *An online data analysis framework for small-scale physics experiments*, Nuclear Instruments and Methods in Physics Research A 1085 (2026) 171269. DOI: <https://doi.org/10.1016/j.nima.2025.171269>

Available at CERN CDS: <https://cds.cern.ch/record/2940908>

2.1.9 HRMT-71: [BLM-4]

HRMT-71 (BLM4), conducted in collaboration with CERN and ESS, focused on the validation of multiple Beam Loss Monitor (BLM) technologies under realistic high-intensity SPS beam conditions at HiRadMat. BLM systems are critical for machine protection and beam diagnostics in modern accelerator complexes, where reliable detection of abnormal beam losses is essential to prevent equipment damage and superconducting magnet quenches. The campaign tested several detector concepts in a controlled irradiation environment, enabling direct comparison of response characteristics, linearity, dynamic range, and robustness under representative loss scenarios. HiRadMat provided a uniquely suitable platform for this validation: the combination of 440 GeV proton energy, well-defined pulse structure, and flexible experimental configuration allowed the exposure of detectors to realistic beam-loss conditions that cannot be reproduced during routine accelerator operation.

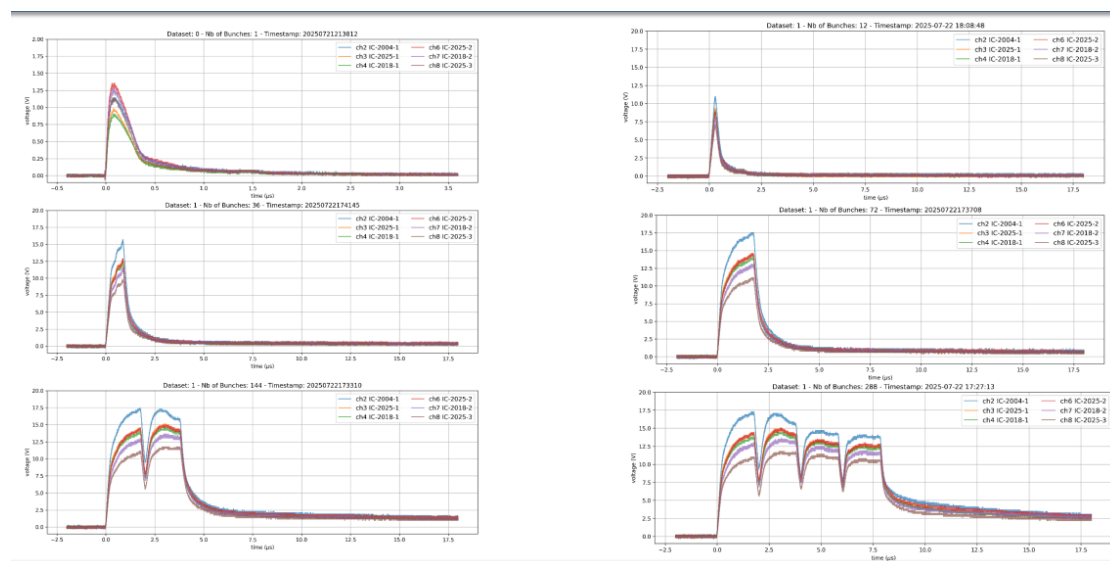


Figure 11: Measured intensity per bunch by the BLMs used in HRMT-71. The results were critical to understand the exact behaviour (or limitations) of those detectors that are machine-protection elements in CERN and other European high-brightness machines.

The results contribute directly to the optimisation of BLM systems not only for HiRadMat itself but also for the broader CERN accelerator complex and future high-brightness facilities, including applications relevant to ESS. The experiment provided empirical benchmark data to support calibration strategies, improve signal interpretation models, and refine detector deployment concepts in high-radiation environments. Given the need

for coordinated installation of multiple detector types, iterative beam-based alignment, and dedicated expert presence during beamtime, EURO-LABS Transnational Access support was instrumental in enabling participation of the expert external teams, ensuring effective technical coordination (that was absolutely necessary to prepare the experiments and optimize the beamtime), and thus maximising the scientific and operational impact of the campaign. A few examples of the measured per-bunch intensity from HRMT-71 can be seen in Figure 11.

2.1.10 HRMT-76: [BTVmat]

HRMT-74 is scheduled to take place in August 2026 and will be the final experiment supported under the EURO-LABS framework. The experiment focuses on the irradiation and performance evaluation of novel carbon nanotube (CNT) foils intended for use as Beam TV (BTV) screens in high-brightness accelerator environments. Preliminary irradiation of two CNT foils has already been performed in preparation for the full experimental campaign. The light yield produced by the irradiated samples is currently under detailed analysis, while scanning electron microscopy (SEM) investigations are planned in the coming months to assess potential structural modifications and radiation-induced damage. This study is of high strategic importance for future high-brightness machines, as threshold knowledge of radiation tolerance, optical response, and material stability is essential for the development of next-generation beam diagnostic systems. Identifying materials capable of withstanding extreme beam conditions while maintaining reliable optical performance is critical for machine protection, beam monitoring, and operational efficiency. As the concluding experiment of the EURO-LABS transnational access programme at HiRadMat, HRMT-74 represents both a scientific milestone and a forward-looking contribution to accelerator instrumentation for future facilities. In Figure 12 the irradiated CNTs can be seen, with the beam impact clearly visible and requiring further understanding.

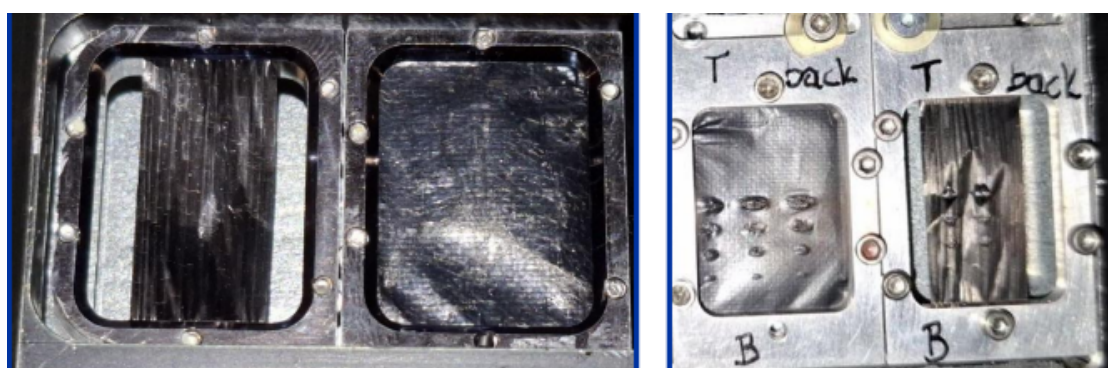


Figure 12: Beam Impact on a carbon nanotubes foil, part of HRMT-74 experiment. This material certainly needs more investigation, and a detailed analysis is ongoing and expected to bring breakthrough results in the field.

3 Conclusions

Task 3.1 has fully achieved and exceeded its objectives. Over the course of the EURO-LABS project, HiRadMat supported **11 experimental campaigns**, covering advanced accelerator materials, thermomechanical shock studies, radiation damage benchmarking, detector validation, and frontier plasma astrophysics. The campaigns delivered results uniquely enabled by the combination of 440 GeV SPS proton energy, high pulse intensity, and flexible beam configuration available at HiRadMat.

The scientific impact spans:

- First benchmark displacement cross-section measurements at SPS energies (HRMT-63);
- Dynamic thermomechanical response studies of beam window and target materials (HRMT-60, HRMT-67);
- Shock and radiation coupling studies in advanced structural materials (HRMT-66);
- Validation of Beam Loss Monitor technologies under realistic loss conditions (HRMT-55, HRMT-71);
- Laboratory reproduction of relativistic pair-plasma phenomena with high-impact publications (HRMT-62/64/68).

These activities significantly strengthened predictive modelling capabilities for high-power accelerators and contributed directly to safer and more reliable machine operation worldwide, offering at the same time unique physics results.

Overall Evaluation of TA Activities

The Transnational Access (TA) programme at HiRadMat proved scientifically essential and strategically impactful. The facility was consistently oversubscribed due to its unique beam parameters and the impossibility of reproducing such beam–matter interaction conditions elsewhere. TA support was not merely logistical but essentially enabling physics. The complexity of the experimental campaigns required multiple preparatory visits, extensive safety coordination, instrumentation integration, and post-irradiation follow-up work across international collaborations. Without EURO-LABS support, many of these campaigns would not have been feasible, particularly for academic institutions and early-career researchers. User engagement has remained strong, as demonstrated by active participation in the annual HiRadMat User Days (2023, 2024 and 2025), where intermediate and final results were presented and discussed. The continued submission of new proposals and sustained participation reflect strong user appreciation of both the facility and the transnational access framework, **that essentially was the only way forward for their scientific research.**

Access Units Delivered vs Planned

At project start, **4,800 Access Units (AUs)** were allocated based on estimates from previous programmes (ARIES, EUCARD and EUCARD2). The demand for physics @

HiRadMat has exploded in the last 4 years, and the AUs were fully allocated within the first three years (by Month 32), significantly earlier than planned, demonstrating strong scientific demand and the need for more experimental data.

Following the agreed budget reallocation (October 2026):

- **6824 AUs have already been delivered;**
- **An additional 2312 AUs are expected to be allocated by 31 August 2026;**
- **Bringing the projected total to 9136 AUs over the four-year duration.**

This represents nearly a doubling of the initially foreseen access provision and confirms the sustained and increasing demand for HiRadMat.

Outlook to August 2026

The final experiment under EURO-LABS support, HRMT-74 (BTVmat), is scheduled for August 2026 and is expected to deliver critical data on radiation tolerance and optical performance of novel beam instrumentation materials for high-brightness machines. In parallel, ongoing post-irradiation analyses from HRMT-60, HRMT-63, HRMT-66, and HRMT-67 are expected to generate further publications and modelling improvements throughout 2025–2026. Dissemination through peer-reviewed journals and international conferences will continue beyond the formal end of the access period. HiRadMat remains a strategic European infrastructure for high-power beam–matter interaction studies. **The outcomes of Task 3.1 demonstrate that transnational access to this facility is critical for sustaining excellence in accelerator materials research, machine protection, and high-brightness beam technologies and essentially cannot operate without a EURO-LABS successor program.**

References

- [1] T. Sato and et al. “Features of Particle and Heavy Ion Transport code System (PHITS)”.
In: *Journal of Nuclear Science and Technology* 55-6 (2018), pp. 684–690.

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List of Abbreviations

AU	Access Units
BLM	Beam Loss Monitor
DPA	Displacement Per Atom
LDV	Laser Doppler Vibrometry
PHITS	Particle and Heavy Ion Transport code System
PIC	Particle-in-cell
PIE	Post-Irradiation Examination
TA	Transnational Access