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Targetry Challenges & HiRadMat

Fiona HARDEN[1], Aymeric BOUVARD, Nikolaos CHARITONIDIS and Yacine KADI
(on behalf of the HiRadMat experiments and facility support teams)

CERN, 1211 Geneva 23, Switzerland

E-mail: [1]*f.harden@cern.ch*

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HiRadMat is a unique user facility providing a controlled test environment for accelerator experiments investigating the effects of high energy, high intensity proton beam. HiRadMat uses a 440 GeV/c proton beam fastly-extracted from the CERN SPS and can currently provide a maximum pulse intensity of 3.5×10^{13} protons. Initially designed to explore the damage thresholds of accelerator components which experienced thermal shocks induced by high-brightness beams, HiRadMat has continued to advance into new areas of research. This contribution will focus on the significant role that HiRadMat plays in Targetry R&D where previous experiments will be discussed and future ideas presented. Due to the extensive CERN support available experiments at HiRadMat have evolved from new target concepts (like powder target and prototype material sample experiments) to validation studies for full-scale prototypes, including absorber jaws for LHC and HL-LHC, collimator's and spallation targets, and more recently cryogenic and pre-irradiated sample experiments. Similarly, diagnostics (e.g. strain gauges, LDVs, temperature sensors) as well as visual inspection and beam monitoring devices (e.g. radiation hard cameras, lighting systems, microphones) have continued to develop providing users with in-situ beam-time statistics and beam profile information resulting in more accurate measurements of the prompt-beam effects. The future upgrade of HiRadMat will be discussed with details on multiple stages of development from improved functionality of the laboratory to optimisation of the experimental area regarding beam potential.

KEYWORDS: HiRadMat, Targetry, High Energy Physics, Experimental Test Facility

1. Introduction

Due to continuing development of accelerators, and thus increased power target goal requirements for these accelerators, it is of utmost importance to investigate the many complex behaviours required for the necessary facility and accelerator upgrades. Subsequently focusing on high power target designs for new physics discoveries (e.g. for neutrino factories, muon colliders and spallation sources), there are several factors that require consideration including: Thermal behaviour and beam induced thermal shock waves; Cyclic fatigue; Radiation damage to material properties; Remote handling requirements post irradiation (e.g. health and safety measures, relating to radiation protection, due to handling of irradiated material which is often dependent on the experiment and therefore must be considered case by case). Due to a limit of high power beam testing facilities the standard practices for investigating new high power targets and complimentary equipment is:

(a) To rely on simulations and numerical codes (e.g. Monte-Carlo, FLUKA [1, 2], ANSYS [3]).

(b) Ad-hoc in-beam installations in order to try to validate prototypes with beam.

However there are drawbacks with these current methods. Relying solely on simulations, which often hypothesises real data results, leads to assumptions on how materials (in particular new or novel materials) or full-scale devices could behave in such harsh environments. Simulations are extremely useful to anticipate how new installations may behave (e.g. new/novel materials, new devices, upgraded equipment) but it is crucial to corroborate the speculative results with real beam experimental data. Yet, in-beam tests are often performed in an ad-hoc beam installation which raises several uncontrollable issues, e.g. logistics (no control over beam-time), safety (cessation of beam unlikely if problems arise within the experiment), experimental requirements (beam parameter(s), beam size(s) tend to be unchangeable parameters when installed within a beam line, the experiment is considered a secondary priority compared to the accelerator projects).

It is evident that controlled experimental testing facilities are required which are designed solely for in-beam assessment under equivalent accelerator beam conditions. Fortunately HiRadMat was designed for such real case scenarios.

2. HiRadMat facility overview

CERN's HiRadMat (High Radiation to Materials) facility is globally unique enabling in-beam tests with high energy, high intensity, proton and ion beams in a controlled experimental environment. The facility originated from the LHC Collimation Project [4] where there was a need to test accelerator equipment under beam shock impacts using equivalent LHC type beam conditions. HiRadMat was designed for these R&D purposes and has successfully completed several experiments in this category [5–9]. However, the facility has also developed into a world renowned high energy testing facility with users from many global institutes performing experiments outside its design remit including tests on superconducting magnetic components [10], developments of beam monitoring equipment [11, 12] and validation of numerical simulations hypothesising the effects of high energy beam pulses [13]. Figure 1 illustrates the location of HiRadMat within the CERN accelerator complex. HiRadMat uses beam directly extracted from the CERN Super Proton Synchrotron (SPS).

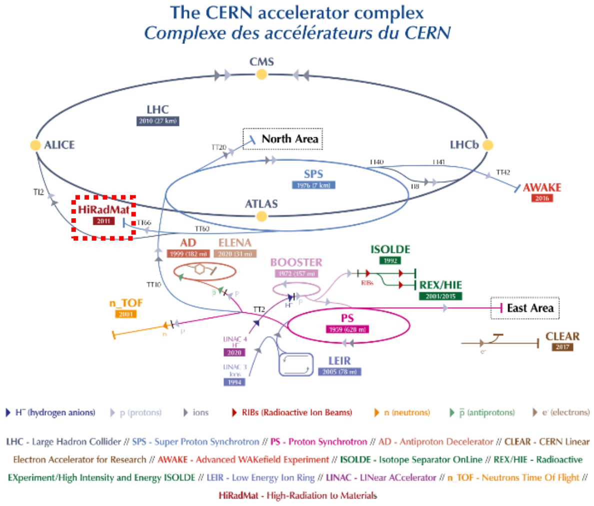

Fig. 1. Illustration of the CERN Accelerator Complex. The location of HiRadMat is highlighted in red [14].

Due to the benefit of HiRadMat being located at a parallel point to the TI2 injection line but completely independent to the injector beam parameters, the delivered beam is adjustable. Beam, equivalent to that injected into the TI2 injection line for the clockwise fill of the LHC is obtainable (e.g. beam energy, beam intensity, etc.), but with the advantage of the parameters being adjustable to fit user requirements (e.g. customisation to the beam spot size, protons per bunch and per pulse, beam position, beam emittance). Table I highlights the key beam paramaters available at HiRadMat.

Table I. HiRadMat beam information

HiRadMat Proton Beam		Additional Information
Beam energy	440 GeV	
Energy per pulse	2.436 MJ	
Bunch intensity	$5 \times 10^9 – 1.2 \times 10^{11}$ protons	
Number of bunches	1 – 288	
Minimum pulse intensity	5×10^9 protons	1b* of 5×10^9 protons
Maximum pulse intensity	3.46×10^{13} protons	288b* at 1.2×10^{11} ppb**
Pulse length (max)	7.95 μs	
Current during pulse	696.4 mA	averaged over maximum 7.95 μs pulse
Power during pulse	3.1×10^5 MW	
1σ r.m.s beam radium	0.5 – 2.0 mm (standard)	0.25 – 4.0 mm achieved in 2018
Protons/year allocation	1×10^6 protons	approx. 10 experiments per year

*bunch(es) **protons per bunch

Note that due to the facility location beam cannot be delivered while the LHC is being filled (see Figure 1). Therefore beam-time must remain flexible due to the operational constraints caused by unanticipated beam dumps from the LHC. Comprehensive details of HiRadMat, the facility layout and infrastructure improvements can be found elsewhere [15, 16].

2.1 Beam-time procedures

HiRadMat holds Scientific Boards (SBs), when necessary, to review requested proposals for beam-time. The SBs goal is to review the scientific merit of the experiment with focus on the significant contribution towards the advancement to the state-of-the-art knowledge on materials, components and systems associated with particle accelerators and the physical sciences. Upon SB approval, Technical Boards (TBs) are held regularly in order to critique the technical aspects of the experiments, e.g. safety, design, pulse requests. As host facility support is provided by the HiRadMat team to all experimental users. The project begins with design and cross-checks of integration models prior to any experiment entering the facility. During the installation phase, support is available from expert teams at CERN, including transport, survey, measurement techniques, beam diagnostics and radiation protection. During beam-time the HiRadMat team facilitates the operation where support is also provided by the beam operators from the SPS as well as measurement equipment experts at CERN.

2.2 Surface laboratory

The surface laboratory is equipped with fixed tables (equivalent to those in the experimental area) to enable pre-commissioning tests on experiments before installation. These include checks of the diagnostics (e.g. cameras, sensors, electronic readouts), complete survey of the experimental tank and specimens (if required) and cross-checks of moving mounts (including in and out of beam positions).

2.3 Control room

During beam-time experimental teams are located in the CERN Control Centre (working with the operators and SPS experts to deliver the optimised beam required) and the HiRadMat control room containing data acquisition systems (DAQs) and offline monitoring systems, which are often specific to each experiment.

2.4 Experimental area

The HiRadMat experimental area is approximately 35 m underground and is equipped with a dedicated beam instrumentation table (which enables in-situ beam information to be collected including beam position, beam spot size, beam bunch structure) and two experimental tables for users. Full details of the experimental area and beam diagnostic equipment has been reported elsewhere [15]. Figure 2 provides a schematic of the layout of the HiRadMat experimental area illustrating the nomenclature of the key sections.

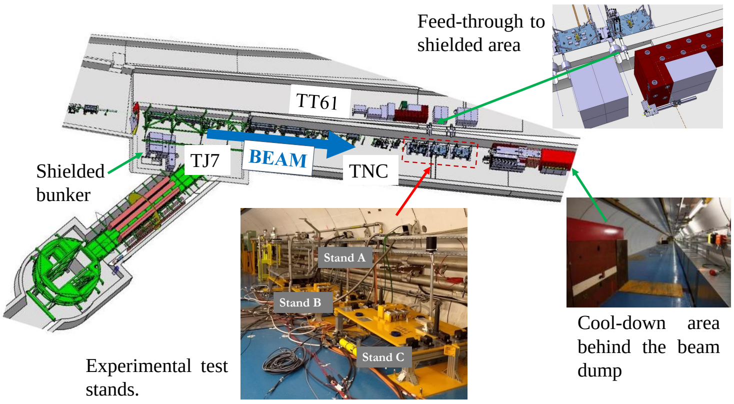

Fig. 2. 3D illustration of HiRadMat underground experimental area. Key points highlighted include the beam direction, the feed-through and the test area; where Stand A is the dedicated beam instrumentation table which includes the HiRadMat BTV, BPKG and diamond detector [15] and Stand B & C are dedicated to the experiments.

2.5 Shielded area (TT61)

HiRadMat has a dedicated feed-through into the adjacent tunnel (TT61). Due to optimised shielding, sensitive equipment is added here to provide protection from prompt radiation effects. Additional equipment can be installed in this area including camera electronics and beam monitoring systems, radiation sensitive cameras and Laser Doppler Vibrometer (LDV) devices.

2.6 Cool-Down area

Approximately 2 weeks after irradiation experiments are moved to the cool-down area located behind the HiRadMat beam dump. The experiment remains in this area until activation of the experimental chamber is low enough to be transported to the users chosen laboratory for post irradiation examination. This coordination is supported by the HiRadMat team and CERN's Radiation Protection Group.

3. HiRadMat and Targetry challenges

HiRadMat has provided high intensity, high energy, proton beams to aid in the investigation of thermomechanical behaviours, structural integrity of novel materials and full-scale prototypes, pulsed beam effects and radiation damage effects. The experimental setups can vary from material samples to complex prototypes enabling benchmark simulation validation, materials selection and design qualification. Table I highlights the array of beam parameters enabling an abundant of test conditions for different experiments. With this variability of beam conditions available, as well as a completely independent experimental area, HiRadMat has housed many Targetry experiments increasing experts knowledge in areas which were once extremely difficult to corroborate under real beam conditions. Since 2012 HiRadMat has completed over 40 experiments in a range of different topic areas. Those relating to Targetry challenges will be discussed.

3.1 Pulsed beam effects on powder targets

Two complimentary experiments HRMT-10 and HRMT-22 were performed in 2012 and 2015 respectively. The experiments investigated a new target technology for high power facilities, an alternative for a liquid mercury target which was a proposed solution for Neutrino Factories [17, 18]. The alternative chosen for investigation was a tungsten powder due to its high melting point, good flowability properties and high impedance. The experiments examined the effect of a single pulse, 440 GeV/c beam, to the powder under different atmospheres. It was hypothesised that the tungsten powder would withstand the high energies deposited after beam interaction while maintaining its operating temperature along with minimal stress effects. HiRadMat was chosen for this investigation due to the flexibility of the beam parameters. The experiments could tune the beam parameters to equivalent energy deposition observed in a single pulse at a Neutrino Factory, maximum of 200 J/g (e.g. 6.25×10^{13} protons at 8 GeV at 1.5 mm beam sigma was equivalent to 3.7×10^{12} protons at 440 GeV at 1.5 mm beam sigma delivered at HiRadMat). HRMT-10 investigated the single pulsed effects on the static tungsten powder in a helium atmosphere. It was observed that the tungsten powder was perturbed when impacted by the 440 GeV proton beam [19]. A continuation of the study was performed in 2015 with HRMT-22 investigating the behaviour of granular tungsten powder in both helium and vacuum atmospheres. Non-aerodynamic lift mechanisms were observed in both atmospheres when the powder was impinged by the proton beam, although slower in the helium atmosphere. Full details of the results are reported elsewhere [20].

HRMT-10 and HRMT-22 highlighted the potential of HiRadMat being used to investigate pulsed beam effects in a controlled environment. Similarly, with complimentary experiments it provided an example of the developments of such a user facility over a few years. For example, during HRMT-10 beam instrumentation was minimal with all equipment being placed within the beam line and within the bunker (in TJ7, see Figure 2) approximately 20 metres upstream of the experiment. This created some disturbance of measurements from the LDVs due to the optical path distance. Key improvements in 2015 included the feed-through to the TT61 area resulting in shielding for the LDVs and camera set-up which minimised the electronic effects to the instrumentation as well as improved any disturbance of the optical path due to a reduced distance (less than 10 metres). Also enhancements to the in-situ beam monitoring characteristics were made with the SPS Beam Position Monitors (BPMs) used in HRMT-10 upgraded to include a beam pick up monitor (BPKG) to measure the bunch to bunch information of each pulse and a Beam Observation TV (BTV) to measure the beam spot profile of the pulses.

3.2 Damage investigations of superconducting strands

The first experiment in cryogenic conditions was completed in 2018. HRMT-37 investigated the damage induced by high energy proton beams and the possible limitations of the superconducting strands of superconducting magnetic components under High-Luminosity LHC (HL-LHC) type beam conditions. The investigation of the limitations of the superconducting magnet material under real beam conditions was vital in case of accidental beam impact due to injection failure resulting in particle showers infringing the magnets. A modified aluminium vacuum vessel (cryostat) was used along with a two-stage cryocooler unit; consisting of a cold head, compressor unit and compressed helium flexlines and motor cables. Due to the flexibility of HiRadMat to the users needs the experimental area could be adapted to very specific requirements. Extra shielding was placed upstream of the beamline for the compressor unit, a separate water supply was provided to the compressor unit for cooling, instrumentation including connection boxes, electronic boards, temperature readouts and power supplies were installed in the TT61 shielded area and during the beam-time beam based alignment was performed using the HiRadMat BTV complimenting the diamond Beam Loss Monitors (BLMs) placed outside the vessel ensuring accurate beam pulse positions for each pulse.

3.3 Prototypes validation & materials investigation

HiRadMat has extreme adaptability to the needs of experiments from small to large scale prototypes and novel materials investigation.

3.3.1 Full-scale rotatable collimator

A rotatable collimator designed at the SLAC National Accelerator Laboratory was investigated at HiRadMat as part of the US-LARP collaboration, the experiment identified as HRMT-21 [21]. The collimator was designed to have up to 20 surfaces and could rotate in case of surface damage caused by 7 TeV failure beams. The experiment aimed to demonstrate the rotation functionality of the collimator rotation mechanism after high intensity, high energy, beam pulses were directed onto the collimator surfaces; to determine the surface damage caused by an iterative number of beam pulses; to determine the integrity of the control systems and cooling pipes after beam impact and jaw rotation; and to determine any hindrance of functionality due to surface effects caused by the beam (in case of ejecta after beam impact). Pulsed beam was delivered to the experiment up to a maximum of 288 bunches for the maximum pulsed intensity available (1.2×10^{11} protons per bunch). After delivery of all beam pulses to the experiment the collimator jaw rotation remained functional (i.e. the high intensity beam pulses had not cased a malfunction in the electronics of the jaw rotation), the cooling pipes received no damage (i.e. the shielding put in place to protect the cooling pipes from beam damage and secondary beam effects like particle showers safely protected the pipes) and any material debris caused by the beam caused no impairment to the functioning of the jaw (i.e. any material that was ejected from the surface of the jaws due to beam impact did not create any surface adhesion of the jaws - the collimator jaws could still be separated fully and rotated as required). HRMT-21 investigated several failure scenarios due to the adaptability of the beam delivered. For example, the design failure anticipated at 7 TeV was measurable at a proton pulse of 1.5×10^{13} protons, with an upper limit achieved with the HiRadMat beam parameters using 72 bunches and 144 bunches at maximum intensity (8.6×10^{12} and 1.7×10^{13} protons per pulse respectively). Similarly, the anticipated beam pulse at HL-LHC injection error could be investigated with the maximum pulse delivered in HiRadMat using 288 bunches at maximum proton intensity (3.5×10^{13} protons per pulse). Also, with use of the dedicated HiRadMat BTV the beam position for each pulse was monitored (to check beam stability) and to cross-check the experimental jaws alignment. Similarly, thermal probes measured the temperature of the jaws and static sensors monitored the cooling water within the collimator tank. Also with the rad-hard camera set-up during the experiment it was possible to observe the direct beam impact as well as monitor the rotation of the jaws and the damage created due to the beam.

3.3.2 Antiproton production target prototypes & materials validation

HRMT-48 investigated future Antiproton Decelerator (AD) production target prototypes, including novel materials and different design configurations. This study was complimentary to previous experiments performed at HiRadMat [22]. This experiment was incorporated into a multi-purpose experimental tank which had the capability to house four experiments during a single installation. HRMT-48 highlighted the development of experimental tanks from the first experiments in 2012 and emphasised the user adaptability possible. This experiment used a copper composite mask to perform beam based alignment, cross-checking with the HiRadMat BTV for beam position confirmation during beam-time. Similarly, the stability of the beam for each individual pulse could be observed via the HiRadMat BTV. The compressed air line available in HiRadMat was used for pressurised air cooling of the targets and high acquisition rate strain gauges were attached to the downstream window of the targets with the DAQs positioned in TT61 (for extra shielding) to monitor any dynamic stresses induced by the propagating wave.

3.4 Materials (non-irradiated and irradiated) investigations

Beryllium has been used extensively for particle accelerator components and targets. Thus investigations into the thermal shock response of beryllium materials under high intensity, high energy proton beams is of critical importance for the operation of such research facilities. Two such investigations into the thermal shock effects of beryllium samples have been performed at HiRadMat, HRMT-24 (in 2015) and HRMT-43 (in 2018). HRMT-24 investigated beryllium discs and slugs of different grades and thickness to determine the temperature, strain and displacement effects created by pulsed high energy beam. Comprehensive details of the study has been published by Ammigan *et al* [23]. HRMT-43 was a subsequent investigation complimenting the studies of HRMT-24 but also investigating new novel material specimens as well as pre-irradiated specimens for comparison. HiRadMat was identified as the user facility for these studies due to its range of beam parameter adaptability in order to induce the necessary thermal responses at the solid threshold temperature of the beryllium samples. Similarly, with the on-line beam instrumentation available in-situ including BTV (improved for the HRMT-43 experiment with the dedicated HiRadMat BTV available), LDVs for radial displacement measurement, strain gauges and temperature gauges to measure any deformation or temperature induced behaviours; a wealth of sample information was available during beam-time. This improved decisions made throughout the experiment optimising the selected beam pulses and also confirming the benchmark numerical simulations for the materials. Due to the uniqueness of HiRadMat uncharted areas of thermal shock investigations could be explored.

With such a facility open for global users, and with improvements being made for future experimental needs, HiRadMat will continue to profit from unique user experiments studying areas of physics which have been impossible to study previously.

4. Future vision

Since commissioning in 2012 HiRadMat has continued to develop to the ever changing needs of accelerator facilities. With the upgrade of the LHC injectors to high luminosity beam [24] improvements are regularly identified. The first International HiRadMat Workshop took place from 10th – 12th July 2019 to determine the necessary modifications desired (addressing future experimental needs) as well as establishing the scientific interest in the future operation of the facility. A total of 81 participants from CERN and non-CERN facilities attended, with 37 presentations from 12 different topic areas including HiRadMat Facility; Remote Sensing & Beam Instrumentation; Materials Science & Beam Induced Damage Research; Future Accelerator Projects; Rare Isotope Beams; Fusion Materials R&D; Advanced Light Sources; Spallation Neutron Sources; Neutrino & Muon Facilities; Theoretical Modelling; Laser Driven Shock Waves; Letters of Interest for future operation. Details can be found on the workshop web page [25]. With future experimental needs being outlined facility upgrades have been identified.

4.1 Low-Level upgrade

Upgrade of the current surface laboratory increasing the area for improved logistical and experimental use. For example, the expansion would accommodate two experiments in the area for pre-commissioning tests (currently only one experiment can be commissioned in a single instance) prior to installation in the experimental area. Similarly, the tables would be fixed independently to the surface laboratory flooring resulting in improvements to the survey procedures (minimising any secondary effects due to movements outside of the table's surrounding area). Also the increased space will improve the storage capabilities and tooling available in the area for a higher number of users at one time.

4.2 Mid-Level upgrade

Construction of a brand new surface laboratory with improved location, layout design and control. The new laboratory would better accommodate the array of different experiments entering HiRadMat and would also provide improved adaptability for non straight forward experiments; for example the radiation protection classification could be adapted (temporarily) to handle pre-irradiated materials. Similarly, with the improved laboratory location better accessibility to the experimental area for all experiments would be achieved.

4.3 High-Level upgrade

In order to accommodated HL-LHC type beams [24] the HiRadMat experimental area requires an upgrade. Initially this would include improvements to the current beam windows and beam dump.

5. Conclusions

HiRadMat has been described as a strategic asset for the investigation of novel materials, prototypes and thermomechanical principles for Targetry challenges. These investigations include: pulsed beam effects (which provide theoretical simulation validations, investigations of material effects to the beam and damage thresholds of new and novel materials being considered for future targets); Thermomechanical behaviours (including thermal shock effects to materials and prototypes); Structural integrity of novel materials and prototypes (especially for proof of concept investigations, design verifications and damage controls in case of accidental beam strikes); Material effects (including pre-irradiated materials investigations). With such an adaptable experimental facility open to global users it remains at the forefront of Targetry challenges research. A visionary plan for the future operation of the facility is already under discussion and due to the ever expanding target needs of the high energy research community, HiRadMat remains a crucial resource for investigations into advanced Targetry challenges.

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