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Book of Abstracts

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HiRadMat Facility: Facility Overview, Technical Details & Future Plans

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Due to the ongoing R&D projects within the accelerator physics community HiRadMat has established itself as a unique user facility enabling scientists to perform pulsed high energy, high intensity proton (and ion) beam experiments to investigate a range of concepts from materials examination to prototype design. HiRadMat uses a 440 GeV/c proton beam extracted directly from the CERN SPS, where a maximum intensity of 3.5×10^13 protons/pulse is achievable. Through collaborative efforts, HiRadMat has developed its facilities with improvements to in situ measurement routines, beam diagnostic systems and data acquisition techniques, which are available to all users. This contribution will provide an overview of the HiRadMat facility, information on technical aspects, experimental procedures and beam specifications, as well as highlighting potential future improvements and upgrades.

Rare Isotope Beams / 42

Present and future pulsed proton beams at ISOLDE : Impact on target design and facility performance

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While Isotope Separation OnLine (ISOL) facilities operate with cw primary beams, ISOLDE is the only ISOL facility that receives a pulsed proton beam. It is delivered by the PSBooster injector, on average 3kW with □s, Hz time structure, induces peak energy deposition in the target material in the range of 500J/cm3 -per-pulse. Past experiences show that proton beam window ruptures, liquid metal splashing and corrosion pitting, early target unit failures and accelerated isotope production

target material sintering are as many adverse aging effects that can ultimately reduce the overall performance of the facility. It was also shown that the pulsed beam can enhance the release of exotic isotopes and be used to deduce physico-chemical isotope release characteristics [1].
Considering the present LHC injector upgrades (LIU) at CERN, the PSBooster is expected to deliver more than 6.1013 ppp 2GeV proton beams. These beam characteristics, if delivered to ISOLDE, could lead to an important improvement of the facility performance, provided the present target unit designs including oxides, carbides, molten and refractory metals and the target stations become compatible.
In this context, we present test experiments that were undertaken at HiRadMat on a new class of ISOL targets with unidirectional porosity and compared with beam irradiation at ISOLDE [2].
We also introduce a new spallation neutron source in the form of a segmented tungsten cylinder directly embedded in the uranium fission target, operated at high temperature under pulsed beam conditions. The tested prototype showed significantly improved fission isotope yields with respect to previous designs, and provide good isotope release characteristics for alkalis [3].
We finally provide prospects for tests at HiRadMat that could help qualify the ISOLDE target designs, should the LIU beam characteristics become available.

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Materials Science & Beam Induced Damage Research / 40

Irradiation and Structural Analysis Capabilities at Brookhaven National Laboratory

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The unique suite of tools available at Brookhaven National Laboratory (BNL), which provides irradiations capabilities at the Brookhaven Linac Isotope Producer (BLIP) along with on-site structural analysis capabilities at the National Synchrotron Light Source II (NSLS-II), provides a complementary materials evaluation capability to the High-radiation to Materials Facility (HiRadMat) at CERN. The breadth of materials testing and analysis capabilities available at BNL will be discussed along with some recent results obtained at these facilities. In particular, the range of irradiation options at BLIP, which can provide fluences of ~10^21 protons/cm^2 as well as irradiation with secondary spallation neutrons, and analysis options at the NSLS-II using beam lines such as the X-Ray Powder Diffraction (XPD) line will be described.

HiRadMat Facility / 41

Overview of the Physics Programme at HiRadMat Experimental Facility (2012-2018) and its Future Outlook and Integration with the broader field of radiation and matter

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HiRadMat a dedicated irradiation experimental area at CERN SPS facilitating pulsed high energy, high-intensity proton and ion beams has enabled the study of an array of materials and other particle accelerator components since its commissioning in 2011 serving both the Large Hadron Collider and other accelerator initiatives around the world. The deliverance of a 440 GeV/c proton beam pulses of ~3.5 x 1013 intensity has offered a unique perspective on the response of materials (novel and otherwise), electronic devices, detector and optical systems relying on the fast rate and energy density characteristics of the delivered pulses. These characteristics, intensity and fast rate, enabling the study of shock in matter form a strong foundation where the utilization of the potential of such experimental facility can serve a broader research community.

In this presentation the highlights of unique experiments facilitated by HiRadMat in support of several particle accelerator initiatives including the Large Hadron Collider, Long Baseline Neutrino Facility Experiment the Facility of Rare Isotope Beams, etc. will be summarized setting the stage for the envisioned next phase of this important experimental facility which aims to expand the scientific base by bringing together a range of scientific communities of ongoing and future projects including and not limited to accelerator physics, condensed matter physics, materials science, plasma physics and engineering.

The potential synergy of the research space offered by HiRadMat with the capabilities of other experimental facilities around the world which can provide either the long-term component of particle/matter interaction (i.e. irradiation damage) or the characterization of the fast rate/intense effects induced by the pulses at HiRadMat at the microstructure level (electron microscopy, synchrotrons) will also be discussed.

LoI / 39

The HiRadMat capabilities for ESSνSB future target tests

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The ESSνSB project, financed by the EU H2020 programme as a 4-year design study (Grant Agreement No 777419), proposes to use the protons produced by the LINAC of the European Spallation Sources (ESS), currently under construction at Lund (Sweden), to deliver a neutrino superbeam. A very challenging component of this project is the enormous target heat load generated by a 5 MW proton beam. As a baseline, a granular (pebble-bed) target is being considered. In order to reduce the heat load, four targets are going to be used, which will be hit in sequence by the compressed proton pulses, about 1 μs long. The hadron collection will be performed by four hadron collectors (magnetic horns), one for each target.
With its very high proton pulse energy and a short pulse length of 7.2 μs, the HiRadMat facility offers very interesting possibilities of testing the properties of the ESSνSB target, when the project enters the R&D phase. These capabilities are being considered now, parallel to the design of the target.

Materials Science & Beam Induced Damage Research / 36

Beam impact response of irradiated and functionally graded materials

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The HiRadMat beamline at SPS, CERN, made possible materials science experiments at high energy densities driven by high intensity proton beam pulses with short duration. Although for light materials at some of the future facilities, the deposited power density in the beam intercepting devices is much higher than what can be achieved at HiRadMat, this facility offers an unprecedented test bench of innovative materials solutions for components for the future high–power accelerator facilities like FAIR, Hi-Lumi LHC, FRIB, neutrino factories, ESS, ITER and for ESA missions. In the past years comparison of the response of different materials and design to beam induced transient thermal stresses, validation of calculated figure of merits and FEM simulations and failure thresholds were performed within numerous experiments. Some of the important unsolved issues for the application of these materials at future accelerator facilities are: how the accumulated radiation dose will impact on the lifetime of the components, which are the failure scenarios of irradiated materials in comparison to pristine materials and how to mitigate premature failure of components due to radiation-induced thermo-mechanical properties degradation. An intense campaign at GSI tries to tackle this complex puzzle by quantitative measurements of thermo-mechanical properties of irradiated materials, deriving scaling laws for extrapolation to operational conditions and using a broad spectrum of impact techniques on irradiated materials to understand the dynamic response as a function of accumulated dose. This work will present planned beam impact experiments at HiRadMat on irradiated and functionally graded materials. Such experiments are extrapolating the current knowledge acquired at GSI from microscale impact techniques using nanoindentation and short pulse, intense swift heavy ions impact experiments using online monitoring techniques. Possible pump-probe experiments using laser-based diagnostic, enabling online structural degradation studies during ion-beam driven shock experiments will be discussed.

Neutrino & Muon Facilities / 38

Technical challenges for higher intensity operation at J-PARC neutrino facility

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The J-PARC neutrino facility is producing the high intensity muon neutrino beam for the long baseline neutrino oscillation experiment with the conventional method using the 30GeV proton beam from the J-PARC MR accelerator. The neutrino beam-line is originally designed for the proton beam power of 750kW, and the stable neutrino beam production with the 500kW beam power is acieved. The beam power upgrade of the J-PARC MR accelerator and neutrino beam-line has been started aiming to achieve ~1.3MW beam power for the CP violation search in lepton sector.

Because the beam required for the long base-line neutrino experiment is the low-duty pulsed beam, the J-PARC neutrino beam-line utilizes the fast-extraction proton beam. Therefore there are several technical challenges for the beamline equipment design due to the high instantaneous proton intensity. The neutrino oscillation measurement is long-term experiment extend over 5-10 years, the

robustness of the beam-line equipment is also very important to keep stable experimental conditions.

In this presentaion, the technical challenges for the high-power neutrino beam facility, the needs and desireds for the related studies on the material propaties will be discussed.

Materials Science & Beam Induced Damage Research / 37

CERN's Beam Intercepting Devices development and integral testing at the HiRadMat facility

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HiRadMat proved in the last few years to be an essential part of the design, testing and validation of CERN's beam intercepting devices applications, managed by the CERN's EN-STI Group. This includes studies on high power (density) targetry, testing and validation of collimators materials, integral testing of new equipment, validation of absorbers materials and studies on material R&D for future applications.

The contribution will highlight the main findings from the different tests executed in the HiRadMat phase 1 between 2012 and 2018, including online measurements, comparison with simulations and modelling and post irradiation examination on critical parts.

The potential future use of the facility until LS3 for approved and proposed projects and will be discussed as well.

Neutrino & Muon Facilities / 35

Interaction of intense proton beam pulses with granular and powdered materials

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Two experiments conducted at HiRadMat have revealed the disruption of granular and powdered materials by intense proton beam pulses, and that the results are consistent with an electrostatic mechanism. While the initial purpose was to investigate practical issues of concern for granular target technology, these experiments have opened a window onto the behaviour of granular media that we believe has not previously been observed and is of more general interest. Furthermore, it is believed that future experiments at HiRadMat have the potential to probe more fundamental aspects of physics, and may even offer tantalising insights into some astrophysical phenomena.

Theoretical Modelling / 34

Simulation of energy deposition and radiation damage effects for HiRadMat experiments using Monte Carlo tools

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Monte Carlo shower codes like FLUKA are essential for simulating beam-matter interactions for HiRadMat irradiation experiments. FLUKA has been extensively used for the preparation and analysis of LIU- and and HL-LHC-related HiRadMat tests, including tests for the HL-LHC collimators, the new HL-LHC injection protection absorber, and the new SPS-to-LHC transfer line collimators. The shower studies were crucial for determining impact conditions which generate similar energy densities and stresses as in the HL-LHC era despite the lower beam intensity available from the injector complex before LS2. Using past HiRadMat experiments as example, this talk will show how FLUKA Monte Carlo simulations were used for selecting beam parameters and for analyzing the outcome of these tests by generating energy deposition maps for thermo-mechanical studies. Monte Carlo simulations are also essential for possible future HiRadMat tests using materials which have been pre-irradiated at other facilities where higher levels of radiation damage can be achieved than in HiRadMat. Testing the thermo-mechanical response of materials which have suffered radiation damage (displacement damage) is important for harsh radiation environments as in the HL-LHC, where beam-intercepting devices must retain their protective functionality even after exposure to high radiation fluences. Monte Carlo shower simulations are the only way to establish a relationship between the displacement damage achieved in irradiation tests and the damage expected in real accelerator environments like the HL-LHC betatron cleaning insertion. This talk will demonstrate how relevant quantities like DPA (Displacement Per Atom) can be calculated using FLUKA and how these calculations are used to establish an equivalence between irradiation tests and operational conditions in accelerators.

Materials Science & Beam Induced Damage Research / 33

An introduction to the mechanics of materials interacting with energetic particle beams and their testing

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The rapid interaction of highly energetic particle beams with matter induces dynamic responses in the impacted body. If the beam pulse is sufficiently intense, extreme conditions can be reached such as very high pressures, changes of material density, phase transitions, intense stress waves, material fragmentation and explosions. Even at lower intensities and on longer time scales, significant effects may be induced such as vibrations, large oscillations and permanent deformations on the impacted components.

Advanced simulation codes permit to analyse extremely complex thermo-mechanical phenomena; however, to provide reliable results, they require constitutive models sufficiently accurate for all the conditions that materials may reach during such events.

Unfortunately, the constitutive material models, in particular at the extreme conditions generated by high-energy beam impacts and for unconventional materials, are far from being readily available and experimentally validated. Besides, numerical simulations cannot easily predict consequences of beam accidents on nearby elements, on UHV performance, on electronics, etc.

Only in-beam material tests in dedicated facilities such as HiRadMat can qualify critical equipment and provide the correct inputs for numerical analyses, allowing to benchmark and validate simulations on simple specimens as well as on full-scale, complex structures.

This presentation provides an introduction to the mechanisms governing the thermo-mechanical phenomena induced by the interaction between particle beams and solids and to the analytical and numerical methods that are available to assess the response of the impacted components.
An overview of the experimental tests required to validate materials and devices exposed to the interaction with energetic particle beams is also provided.

Fusion Materials R&D / 32

Fusion research at CCFE including investments in new facilities

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Magnetic fusion research in the UK is centred on UKAEA's Culham Centre for Fusion Energy (CCFE). UKAEA operates the JET facility for a collective R&D programme by the EUROfusion consortium and also conducts UK research (much of which is also part of the EUROfusion programme). An overview will be given of recent developments, including a major upgrade of the MAST tokamak and new investments in facilities for R&D on remote handling, fusion technology and the tritium fuel cycle. Fusion materials research will be summarised including the capabilities of the new £20M Materials Research Facility for processing and analysis of radioactive material; this is for fission and fusion researchers in UKAEA, universities and industry, and also has wider applications including materials for accelerator facilities

Fusion research at CCFE is funded by the Euratom research and training programme 2014-2018 and 2019-2020 under Grant Agreement No. 633053, and by RCUK grant number EP/P012450/1.

Remote Sensing & Beam Instrumentation / 31

Lessons learned about mechanical instrumentation in HiRadMat facility and possible future developments

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This talk will describe lessons learned of advanced instrumentation's used in the HiRadMat facility over the last years. After a description of techniques used to measure shock waves (as electrical and optical strain devices, ultrasound devices, laser Doppler devices), future tests to validate new instrumentation will be developed.

Rare Isotope Beams / 30

Pushing the frontier of accelerator targets at TRIUMF

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With over five decades of experience in accelerator-based targetry, TRIUMF also ensures that Canada remains on the leading edge of research and development of high-intensity radiation damage in materials. TRIUMF operates a variety of target systems from 13-500 MeV, kW-class proton targets for medical isotope production to higher power proton and electron beam targets for muon, neutron and rare isotope beam production.
As an example, ISAC-TRIUMF is the only ISOL facility worldwide that is routinely operating targets under particle irradiation in the high-power regime in excess of 10 kW. TRIUMF's current flagship project ARIEL, Advanced Rare IsotopE Laboratory, will add two new target stations providing isotopes to the existing experimental stations in ISAC I and ISAC II at keV and MeV energies, respectively. In addition to the operating 500 MeV, 50 kW proton driver from TRIUMF's main cyclotron, ARIEL will make use of a 35 MeV, 100 kW electron beam from a newly installed superconducting linear accelerator, adding the first high-power pulsed beam driver to the suite of accelerator target systems at TRIUMF. This calls for dedicated studies of the combined temperature shock and radiation aging effects in target, structural and functional materials.

Remote Sensing & Beam Instrumentation / 29

High radiation beam instrumentation use and needs at SNS

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At SNS several instrument systems are used in high radiation environments to measure the parameters or the impact of the 1 GeV proton beam at up to 1.4 MW. To measure the beam location and width, we use a luminescent coating on the target that produces light where the proton beam hits. An optical system consisting of mirrors, lenses, and an optical fiber bundle, transports the light to a camera in a low radiation environment for analysis. A tungsten-wire harp also continuously monitors the beam profile but at an upstream location and therefore only indirectly predicts the beam position at the target. The impact of the beam on the mercury filled stainless steel target is measured by in-house developed radiation-hard optical strain sensors. The strain sensors can handle 10's of GRads of radiation and have a bandwidth of over 400 kHz. These sensors have documented the mercury response at different beam power levels and demonstrated the reduction of strain, and therefore reduction in damage, to the target due to helium bubble injection in the mercury flow to the target.

This presentation will detail the above mentioned diagnostics and also the needs for research of radiation damage to the materials used in these diagnostics, For example, research into the glue used for attaching the optical sensors could lead to longer lifetime of strain measuring system. Research of the mirrors surface damage due to the combination of radiation and chemical agents could lead to a longer lifetime of the imaging system while research into the radiation damage of the different luminescent coatings could lead to a better performing target imaging system.

Rare Isotope Beams / 28

Material Testing Demands by Heavy-Ion Pulsed Beams

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For many applications especially in combination with storage rings pulsed high energy beams of heavy ions are needed.
The energy deposition of heavy ions is dominated by their high electronic stopping power (dE/dx), leading to high energy densities even for lower numbers per pulse. We will give examples of energy deposition profiles.
The FAIR facility under construction is planned to operate with 5x1011 Uranium ions per pulse of less than 100ns. With millimeter spots energy densities of 40 kJ/g can be reached, which is beyond any limit for solid materials. The HIAF facility (China) is based on similar beams. Not only targets but also beam dumps and collimators are affected.
Only with a careful choice of beam parameters an operation close to material limits will be possible. The best material choice is given by low thermal expansion, low mass number of material (resulting in low dE/dx), good yield strength and high temperature before phase transition. Here polycrystalline graphite is a favored choice. Examples of dynamic stress calculations for a FAIR beam catcher will be shown.
Simulations of the resulting pressure waves are possible and several criteria for stability exist. But tests with similar beam conditions on the actual materials remain most import. They must be done at a dedicated facility to also provide the proper diagnostics in beam. While the first choice is to avoid plastic deformation, this regime must be investigated for failure tolerance and as some creep will occur.
Few tests have been done in last years with the existing GSI beam of up to 1010 U/pulse reaching up to 2 kJ/g. But downscaling is not easily possible because the pulse structure cannot be reduced enough correspondingly and critical stresses by pressure waves are washed out and not peak pressures are important but tensile forces at critical boundaries.
HiRadMat also with proton beams offers energy densities in this range. The more complicated pulse structure requires improved simulation. In a facility like HiRadMat no long term irradiation is possible, but pre-irradiated samples can be used. Damage creation and material modifications are much stronger for same dose at lower projectile velocities and can be done at other facilities for high dose.

LoI / **27**

Study of beam induced damages to the ATLAS ITK pixel and strip detectors

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The HiRadMat facility offers a unique possibility to study the effect of possible HL-LHC beam failure scenarios on the ATLAS detector. The requirement of detector safety is of primary importance for an accelerator, specially at HL-LHC where the increase of the TAS aperture will potentially increase the exposure of detectors to machine induced background.

By mean of complex Monte Carlo simulation, it is possible to estimate the energy deposited in the ATLAS detectors in case of accidental HL-LHC proton beam failures. The risk to produce a irremediable damages to the detector is established by comparing the energy deposition with the damage threshold.

In 2017 and 2018, for the first time, it was possible to estimate the damage threshold of ATLAS pixel and strip detector modules thanks to fast extracted and intense proton beam irradiation provided at the HiRadMat facility.

Post irradiation analysis showed that the mechanism for the protection of sensor and electronics in case of large deposit of charges in the bulk material is not yet completely understood.

We propose new test beam campaigns to evaluate the damage threshold of the latest ATLAS ITk pixel and strip detector prototypes which will be used at HL-LHC and possibly the performance of alternative solutions to protect sensor and electronics.

Seminar: Laser Driven Shock Waves / 26

Characterization of matter in the Megabar regime using laser shock compression: applications to planetology

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The high power lasers are today an important tool for studying matter under extreme conditions, characterized by density greater than the solid density, moderate temperatures (T ≈ a few eV) and pressures in 1-10 Mbar range. The behavior and physical properties of this matter are still poorly understood, both theoretically and experimentally, and far from trivial to be simulated numerically. We will present a brief introduction on the different experimental methods used to generate this matter, on its characterization and its fundamental role in the planetology. The talk will be focused on a review of last results on equation of state using optical diagnostics and studies to investigate phase transitions, structure changes and test approximations used in calculations using X-ray diagnostics. The materials investigated are between the main components of planetary interiors: water, mixtures, silicates and iron. The experiments have been performed on LULI 2000 at Ecole Polytechnique, on GEKKO at ILE (Osaka) and on MEC at LCLS (Stanford).

Advanced Light Sources / 14

Simulation and Experimental Efforts to Develop Whole Beam Dump Collimators for the APS-U Storage-Ring

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We describe numerical and experimental efforts to assess the suitability of various materials for the Advanced Photon Source Upgrade (APS-U) storage ring (SR) horizontal collimators. These collimators will act as beam dumps in the event that the stored charge is lost. Of particular concern is the

ultra-low emittance of the APS-U 6-GeV electron beam which, at 42-pm, is 70-fold smaller relative to the present-day APS SR. Simulations include the use of the electron-beam dynamics code ELEGANT to both model beam in the APS-U as well as generate APS-U-relevant conditions to prepare for collimator tests in the present APS. Simulations under these conditions with the particle-matter interaction code MARS, as well as simple estimates based on the stopping power, suggest that aluminum and titanium are the best candidates for the horizontal collimators. They also predict the relative importance of melting point and thermal diffusivity in the choice of material. In order to guide and verify our numerical studies thus far, an experiment was conducted in the present APS to compare the effects of beam dumps on both materials. In addition to the usual suite of diagnostics including BPMs and current monitors, the experiment employed fast loss monitors for turn by turn tracking and a visible-light camera for online imaging of the collimator surfaces. A postmortem microscopic examination of the surfaces was also conducted. The results of both numerical and experimental studies will be presented.

Remote Sensing & Beam Instrumentation / **25**

Challenges for the beam instrumentation of the ESS target and the role of the HiRadMat facility

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Materials degradation due to radiation damage is the limiting factor for the lifetime and efficiency of high power spallation targets, as well as of their beam instrumentation. In this presentation, firstly, the beam instrumentation devices for the European Spallation Source (ESS) target monolith will be described, namely:
- The target imaging system for measuring the 2D current density distribution, based on optical components and luminescent coating which is exposed to challenging current densities and surface temperatures;
- The aperture monitors, including thermocouple assemblies and secondary emission blades, severely affected by the exposure to mixed irradiation fields;
- The multiwire grids, meant to measure two orthogonal 1D projected profiles of the beam in the vicinity of the ESS target.
Secondly, the results of MCNP simulations and tests of components performance (with protons of 7 MeV at DTU and of 400 MeV at J-PARC) will be summarized.
It is foreseen that further tests at HiRadMat would allow to investigate the impact of thermal shock loads and consequently improve cooling systems. In addition, online density measurements techniques, relevant for MPS, could be investigated so that the detection of errant beam conditions would suppress the beam production on a sufficiently fast time scale to minimize component damage.

Rare Isotope Beams / **24**

Charge strippers and target for Radioactive Ion Beam Factory (RIBF)

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The Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility that is used for nuclear science studies. RIBF can produce the most intense RI beams using fragmentation or fission of high speed heavy ion beams. Charge strippers for the accelerator system and a target with a beam dump for RI beam production were successfully developed although they have risk to be a bottle neck to increase the beam intensity. A helium gas stripper and rotating graphene foil from are used for the 1st and 2nd stripper in acceleration of high power uranium beam. Rotating target and beam dump made of tilted cupper plate with swirled pipes are used to accept the high power beam up to 10~kW.

Theoretical Modelling / **22**

Shock-wave and high strain-rate phenomena in high energy particle beam impacts

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The understanding of the material response in the case of high strain-rate, impact or shock loading is fundamental in several applications, including also high particle beam impacts. In order to be able to predict dynamic events it is necessary to adopt accurate and reliable numerical methods. To do this, first of all it was necessary to understand which are the involved variables. To reach this goal, a general study of the wave and shock-wave propagation in solids should be performed. In general, in case of shock loading conditions, producing the propagation of waves, the material is allowed to deform only in the impact direction, while in the orthogonal direction the deformation is prevented (or limited) by the inertia. This implies that a uniaxial strain state is generated to which also a great level of pressure is associated. The results obtained from simple numerical models, in case of purely hydrodynamic material, demonstrated that no signals move ahead the shock front: the shock front is supersonic relative to the undisturbed material. Otherwise, in case of shocked material, the sound speed is higher than the signal speed: the shock front is subsonic with respect to the shocked material. This means that any disturbance can catch the shock front from behind and explains why a shock front is spontaneously generated starting from a quite smooth pressure signal. Another important point is that, after the end of the planar shock, the shocked material returns in the undisturbed condition. This is not true in case of cylindrical wave propagation, for which, due to the axisymmetric constraint, the shock is always followed by a negative pressure wave. After that, the case of solid material was considered, for which also the material strength had to be taken into account. For low pressure wave that material remains elastic and a single elastic front is generated, which propagates at the solid sound speed. For medium intensity pressure wave, the material enters the plastic domain: two different pressure fronts are generated (elastic and plastic), which moves at different velocity (the plastic wave moves with a lower velocity). Depending on the intensity of the shock, the material could yield also during the unloading phase. The last case implies that a very strong shock is generated with a single plastic supersonic front.
The results of the studies of the wave propagation regimes in solids were very useful in the prediction of the evolution in high energy deposition scenarios: by looking the results in terms of path on the EOS surface allowed to observe that in the part close to the maximum energy absorption, during the deposition phase, there is a sudden increase in the internal energy with a negligible variation in the material density (isochoric transformation), but when the rarefaction process starts, the material could be expanded (reaching lower values of pressure and density). For the part of the target, in which low values of energy are deposited, the deposition phase leaves this quite undisturbed: the consequent growth in pressure is limited and no significant changes in density occur. On the other hand, when the shock-wave reaches these elements, they are strongly compressed, reaching high values both in density and pressure.
An improvement in the numerical models, is a soft coupling between FLUKA code and FE codes. The

method was applied to simulate the beam impact against a 3D tungsten target. The FLUKA model was built using the voxel geometry and the FE one using 3D solid elements. Comparing the results obtained for coupled and non-coupled simulations it was possible to make some important considerations. The material, in which a great amount of energy is deposited, is subjected to a significant density reduction during the shock-wave propagation. This implies that the material becomes more transparent to the next proton bunches, and consequently the probability of interaction decreases. This provokes the so called tunnelling effect. The consequences of this are that the proton beam penetrates more in depth in the material in the beam axis direction and the energy is more diluted over the target. The density distribution emphasizes the tunnelling: the density modification involves much higher longitudinal coordinates increasing the number of bunches. The results in terms of pressure showed that the maximum of pressure remains more or less in the same longitudinal position with respect of the first bunch, but the pressure wave starts to travel in the transversal directions. The fact that the energy deposited by the following bunches is lower and more widespread implies that the pressure increment, consequent to the next bunches, is reduced in the zone in which the first bunch deposited a greater amount of energy. On the other hand, it should increase in the part of the target, where there is an increment in density. The results obtained showed also that until 8-10 bunches (~200 ns), the differences between the two simulations are negligible. Thanks to this, it was possible to conclude that the results obtained from the uncoupled analysis could be considered reliable if few bunches are impacted. By increasing the number of bunches, however, the change in density becomes relevant, because the shock-waves has the time to travel away from the impacted zone, producing a great rarefaction in the middle. The consequence is the coupled and uncoupled simulations give more and more different results increasing the number of bunches. In particular two situations could be developed, depending on the position on the target. For the target part situated in the neighbourhood of that in which the maximum energy was deposited by the first bunch, the uncoupled simulation overestimates the pressure. This could be easily explained since those elements are subjected to the greatest density variation. Consequently, they become more transparent to the proton beam and the successive bunches deposit on them lower energy, which implies lower growth in pressure. Otherwise, elements that are situated along the beam direction at higher longitudinal coordinates (far from the maximum energy region), are subjected to higher energy deposition during the successive bunches due to the tunnelling effect with respect to the first bunch. Obviously, this provokes an underestimation of the pressure level in case of uncoupled analysis.

LoI / **23**

Beam steering performance of bent silicon crystals irradiated with high-intensity and high-energy protons

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Beam steering performance of bent silicon crystals irradiated with high-intensity and high-energy protons have been studied. In particular, crystals of the type used for collimation purposes at the CERN Large Hadron Collider have been irradiated at the HiRadMat CERN facility with 2.5 x 10^13 440 GeV protons, with a pulse length of 7.2 µs, to study possible changes in bending angle and channeling efficiency due to thermo-mechanical stresses in case of accidental irradiation during accelerator operation. A comparison between measurements performed before and after the irradiation shows negligible differences concerning the angle and the efficiency in both crystals.

LoI / **21**

Experiments for machine protection: from consequences of beyond-design failures to damage limits of sc. magnets

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HiRadMat is an unique facility to experimentally verify the consequences of beam impact on accelerator equipment. These experiments are essential for machine protection to validate simulation results and confirm the consequences of beam failure cases in the LHC and future accelerators. In the early years of HiRadMat, a dedicated experiment could prove the existence of the so-called hydrodynamic tunnelling effect, which leads to a significantly increased penetration depth of the beam in accelerator equipment in case of a direct impact of the LHC beam. During Run 2, the damage limits of superconducting magnet components have been studied in HiRadMat at room temperature and at 4.2 K.
This presentation reviews the major results achieved through the different HiRadMat experiments performed in the scope of LHC machine protection and gives an outlook on outstanding topics and future follow-up experiments.

LoI / 20

Expression of Interests on the future HiRadMat experiments from J-PARC

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J-PARC, Japan Proton Accelerator Research Complex, consists of a series of the world's most intense accelerators and experimental facilities producing and utilizing high-intensity proton beams. Future experiments at HiRadMat facility will provide great opportunities to J-PARC for undergoing research and developments. In this talk following three LoIs submitted from J-PARC are overviewed:

1. Thermal shock experiments of advanced target/window/dump materials with high energy proton beam at HiRadMat Facility
2. Displacement cross section of target and beam window materials for 440 GeV/c protons
3. Development of the Next Generation High Radiation Tolerant Detector with the High Intensity Proton Beam at HiRadMat Facility

with emphasis on the topics which will not be covered by later presentations.

Fusion Materials R&D / 19

A neutron source for fusion: The DONES Project

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It has been clearly stated that the development of low activation and radiation resistant materials is a key issue for future fusion reactors success. Temperature and radiation conditions are far more

extreme than in present applications, including fission reactors. Therefore the need of a high intensity fusion-like neutron source for the qualification of these materials in an environment similar to the one in a fusion reactor has been identified in the European Fusion Roadmap as a key step for the design and licensing of the Demonstration Reactor (DEMO). This need has pushed, at European level, the development of a neutron source based on the Li(d,nx) stripping reaction called DONES (DEMO Oriented Neutron Source). The facility has also been included in the 2018 ESFRI Roadmap and recently Granada has been identified as the European reference site in case the facility is finally built in Europe.
This talk will present the project justification, status of development and the expected near future, including its possible use for other scientific and technological research fields. Conversely, similarities and differences with HiRadMat radiation damage studies will be briefly reviewed.

Spallation Neutron Sources / 18

Target development activities in J-PARC and related expectation in HiRadMat irradiation facility

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In J-PARC various targets are used to produce the secondary particles: the stationary solid targets, rotated targets, liquid metals targets. Technical issues accompany the development of target systems capable of exploiting high-power primary beams: thermal loading conditions, high strain rate effects, yielding effects, irradiation damage, effective methods of target cooling, lifetime, remotely handling, safety, etc. In particular, heat dissipation rate and thermo-mechanical stress are both limiting factors for a high power target concept. Through a review of target development activities in the J-PARC, the expectation to the HiRadMat facility will be discussed.

Neutrino & Muon Facilities / 17

Theoretical modeling for the thermal stability of solid targets in LEMMA muon collider

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This work, in the context of the LEMMA project, is aimed at assessing thermal stability and heat dissipation problems of crystalline solids used as targets for the purpose of producing muons. Monitoring the increase in temperature on the target due to the passage of positrons and the consequent energy loss is fundamental in order to keep the target operational and avoid fractures or damage. This study deals with solid targets made of beryllium and carbon due to the low Z value of these materials which allows greater efficiency in muon production. First of all, simulations have been carried out in Fluka environment aimed at estimating the energy loss of a single positron crossing the target, and in this way it has been possible to evaluate the energy density deposited on the target by a single bunch of positrons. Both temperature rise and thermal shock are related to the beam size on target. For a given material the lower limit on the beam size is obtained when there is no pile-up of bunches on the same target position. For this reason both the target and the positron beam have to be movable. The target has to be therefore sliced in many thin targets to facilitate the power removal. Be and C composites/structures are in use and under study for low Z target and collimators in accelerators for high energy physics also because of the stringent vacuum requirements in such complexes that are not easy to fulfil with liquid targets. Recently developed C based materials with

excellent thermo-mechanical properties are under study for the LHC upgrade collimators. The spatial and temporal distribution of the thermal field has been calculated using the Fourier heat transfer from the heat density deposited taking into account the dependence on temperature of the thermal parameters of the material. A Finite difference time-domain method (FDTD) code has been developed for the evaluation of the temperature gradient on the target and the timing of heat diffusion on the latter. This procedure has been first applied to the case of a single bunch and allowed to identify three temporal regions for the temperature field. In the first temporal region, during the interaction between the e+ and the target, there is a rapid temperature increase (t< 10ps). After the pulse (second temporal region) the heat initially does not diffuse and remains confined to the area of interaction (order of μs); after a third phase begins where heat diffuses radially to the colder regions of the disk. The evaluation of the spatial and temporal temperature gradients produced on the target is very useful for estimating the thermo-mechanical stress induced by a single bunch or a sequence of bunches. In order to obtain the working temperature of the target in steady state and the trend of the residual temperature, we used a simple model based on the energy balance between the energy deposited by the sequences of the positron pulses and the energy dissipated by radiation only.

Neutrino & Muon Facilities / 16

Challenges of Neutrino Targets and the Role of the HiRadMat Facility

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Following from the Particle Physics Project Prioritization Panel (P5) 2014 report, Fermilab is hosting a new Long-Baseline Neutrino Facility (LBNF) with greater than one megawatt of proton beam power on target and upgrade potential to greater than two megawatts. As future accelerator neutrino sources, such as LBNF, become increasingly powerful and intense, there is a pressing need to address the technical challenges presented by this high power on target. Energy deposition from high intensity primary beam induces sudden heating (thermal shock) as well as micro-structural changes (radiation damage) in the target material. As higher intensities are desired for future neutrino sources, these effects have neared the limits of the currently utilized materials. The HiRadMat facility offers the unique opportunity to evaluate candidate targetry materials in extremely high beam intensity and thermal shock environments. Recently neutrino targetry candidate materials have been tested at HiRadMat in the non-irradiated and previously irradiated condition. This was the first in-beam high intensity thermal shock test conducted upon previously irradiated material and brought together the research areas of radiation damage and thermal shock effects in targetry materials. Future experiments, building upon this first experiment are critical to understanding how the effects of radiation damage and thermal shock from high intensity beam can be mitigated, ensuring the success of high intensity neutrino beamlines such as LBNF. This presentation will review the material challenges of neutrino targetry, describe the role of HiRadMat in neutrino targetry research, and discuss possible benefits of HiRadMat facility upgrades and improvements.

Neutrino & Muon Facilities / 15

Demands for Thermal Shock Experiments of Pulsed-Muon-Production Target Materials

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Muons are widely used for the various fields in condensed matter physics and fundamental nuclear physics. Muons or parent particles, pions are produced by collision of high energy protons against a target material. A pulsed muon beam and a continuous DC muon beam are selectively used for the purpose of the experiments. In particular, the pulsed muon beam is useful for Muon-Spin-Spectroscopy technique investigating rapid time transient phenomena, detection of rare events with a large background, and studies using devices synchronizing with the proton beam, e.g. high-power pulsed laser to stimulate specimens and so forth. A typical pulsed muon beam is produced by a pulsed proton beam with a time-width of around 100 ns and with a frequency of 20-50 Hz. Then, highly-cyclic and volumetric heating with extremely short-time width is induced by high-energy and pulsed proton beam. Consequently, the compressive-to-tensile stress causes the propagation of the displacement. The wave propagation could severely damage the target material. The HiRadMat Facility at CERN is a unique facility to study the impact of intense pulsed beams on the target materials for the muons and pions production.
Polycrystalline graphite is the principal candidate for production of pions and muons with high-intense proton beam irradiation in different facilities all over the world, because graphite shows an extremely high performance for these applications due to its thermal, mechanical, and other properties. However, graphite is easily oxidized at high temperature. If air is unexpectedly introduced into the primary beamline in vacuum during the high-power beam operation, the rapid oxidation of the graphite target and the consequent mass loss could be detrimental to safe operation. Target materials denser than graphite would be preferable to have a point wise source for secondary beam transport. Therefore, to replace the graphite, it is important to develop the material that is denser while keeping excellent mechanical and thermal properties as well as more resistant to oxidation. Recently, we have been working on investigation of a variety of new materials, such as SiC-coated graphite as an oxidation resistant material, SiC/SiC composite material as a denser and oxidation resistant material, and TFGR (Toughened, Fine Grained, Recrystallized) W-1.1%TiC as an extremely denser material for next-generation pulsed-pions/muons-production targets and other spallation targets. The fabricated specimens of each material were supplied and were successfully irradiated at CERN-HiRadMat Facility. This presentation will address our motivation, the present status, and the prospective outcomes of the thermal shock experiments at CERN-HiRadMat Facility.

Future Accelerator Projects / 13

Positron Sources and Beam Dumps for the International Linear Collider-ILC

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A short introduction to the ILC project will be given, with emphasis on the various types of positron sources which are at present being studied for this facility. Moreover, some considerations will be made of the required beam dumps for the e-,e+ and photon beams of the ILC. The question will be raised as how predictions and tests, made with proton beams at the HiRadMat facility at CERN can replace or validate the effects of electrons and photons in target, window and dump materials

LoI / 11

HiRadMat tests on collimator elements

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Proton impact tests in the HiRadMat facilitiy, performed during the LHC Run 1 and Run 2, were of key importance for the Collimation project. They followed up similar tests on collimator elements done in 2004 and 2006 in the TT40 area, and provided outstanding inputs on the choice of collimator materials, as well as on the validation of the design proposed for critical sub-assemblies (e.g. the jaw) and for the integral device. Although the existing design of the HL-LHC halo cleaning collimators was successfully tested under peak energy densities equivalent or higher than the accidental design scenarios, it was not possible so far to reach the same integral energy on the jaw, because of the limitation in intensity in the facility . Also, new and unconventional designs are being exploited for the collimators in the region between the TAXN and the D2, and have not been validated so far under beam impact. Finally, tests on material samples at higher intensity may shed light on unexplored regions of the material models, providing important results that can be scientifically exploited also outside the domain of particle physics.
The present talk will give an overview of the main results achieved in the past tests on collimator elements, and will present the proposals and goals of future tests in the HiRadMat facility.

Spallation Neutron Sources / 10

Fast Transient Beam-Matter Interactions at the European Spallation Source

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The beam intercepting devices in the linac at the European Spallation Source (ESS) include the spallation target, proton beam window, tuning dump, beam stoppers, and a number of beam instrumentation devices such as faraday cups, wire scanners, grid monitors, and halo monitors. These devices interact with intense proton beam, intercepting protons with kinetic energies up to 2 GeV and transient beam currents up to 62.5 mA, and they suffer from beam loads of transient nature due to beam pulses, beam trips and beam raster. In order to improve the functionality and reliability of beam intercepting devices, it is important to understand the physics of fast-transient responses of the constituent materials to the proton beam of dynamic character. The HiRadMat facility provides a unique opportunity to perform experiments on fast-transient beam-matter interactions, which is crucial for engineering of beam intercepting devices at high power spallation sources. The physical phenomena that can be studied using HiRadMat include, for example, beam induced thermo-mechanical response, change of lattice structure, beam collision driven release of recoil particles, solid transmutation, and gas production. In this talk, after a brief introduction of beam intercepting devices at ESS, the potential future research areas where HiRadMat facility could be utilized for the upgrade of these systems are presented.

Spallation Neutron Sources / 9

Why In-Beam Testing and Development Is Important – The SNS Target Example

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Challenges for accelerator targets and beam intercepting devices show no sign of easing in the coming decades. Unprecedented beam energies and intensities will be put to bear for producing new collider physics and leaps in secondary particle production. Engineers and scientists are being called upon to design, build and operate these vital components to reliably perform as expected. In many cases, new technologies and engineering techniques need to be developed and validated. For pulsed-beam applications the transient effects can be difficult to confidently simulate, particularly when innovative designs or novel materials are necessary to meet design goals, or when protective components are expected to experience permanent damage or phase change. In-beam testing is vital for these situations.

The Spallation Neutron Source mercury target is a first-of-a-kind design: MW-class, liquid metal and short-pulse. In-beam testing was conducted to characterize several aspects of pulse response behavior from the R&D project phase and well into facility operation. The target vessel's response from a μs beam pulse needed to be understood to validate the design for the desired giga-cycle fatigue life. The pressure wave induced by the pulsing was determined to cause mercury cavitation which complicates modeling of the fluid-structure interaction. For that, real vessel response data was essential to coming up with a credible simulation method. The pressure wave cavitation also leads to erosion damage of the vessel. As SNS power on target increased, development of techniques to mitigate the erosion and fatigue stress also required in-beam testing.

Suitable facilities for in-beam target testing are uncommon. It was fortunate for the SNS that the Los Alamos National Laboratory offered suitable pulsed beams to experimental areas where mercury target tests could be conducted. A review of SNS target experiments will be presented with parallels to HiRadMat capabilities noted. Key areas of envisioned future needs for the broader target / BID community that HRM will be discussed.

Materials Science & Beam Induced Damage Research / 6

Displacement cross section measurement at HiRaDMat

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As the increase of beam power of hadron accelerators, the damage to target material is essential. For estimation of damage such as target material used at the facility, displacement per atom (DPA), calculated by the particle flux multiplied displacement cross section, is widely employed as an index of the damage. Although the DPA is employed as the damage index of the materials, the experimental data of displacement cross-section are scarce for a proton in the energy region above 20 MeV. A recent study reports that the displacement cross section of tungsten has 8 times difference among the calculation models. Therefore, experimental data of the DPA cross-section is crucial.
The DPA cross-section can be obtained by observing the change of resistivity of the sample cooled by GM cooler to sustain the damage. The sample is placed in the vacuum chamber placed at upstream of the beam dump for 3-GeV and 30-GeV synchrotrons in J-PARC for the proton energy range between 0.4 and 30 GeV. Already, we obtained budget to carry out the same experiment for 120-GeV protons at FNAL. In order to expand the proton energy region up to 450 GeV, we are planning to perform the experiment at the HiRaDMat.

Remote Sensing & Beam Instrumentation / 4

Beam instrumentation developments on Hiradmat

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The contribution will briefly review the past beam instrumentation development performed on Hiradmat during the last run. We will also present our plans for testing and developing beam instrumentation on Hiradmat during the next run.

LoI / 2

Study of the signal linearity and response, calibration, saturation, and comparison of different types of beam loss detectors

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Continuation of study of the signal linearity and response, calibration, saturation, comparison of different types of BLM detectors. The LHC type of Ionization Chambers, IC08 and IC17, were tested in 2017-2018 and will need to continue to be tested in 2020-2022 to check the aging of IC and comparison with Run 2 data. This is highly important for evaluating the requirement of beyond 20 years of operation in the LHC and HL-LHC environment as well as evaluating the ceramics used in the production of the IC17 batch. The LIC (Little ionization chamber) type with IC ceramics was tested for the first time in 2017-2018. Based on the very promising results of this test we are following with a second pre-series production of these type of detectors. Those make use of different ceramics than the LICs currently installed at LHC. To support the investigations of the 16L2 limitation and anticipate other possible similar future problems, we have produced a new type proportional chambers, which would be preferable to be tested first at HRM together with the standard detectors. This new type of detectors has the same outside geometry but the sensitivity is 10-100 times higher in comparison to the existing detectors.

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Speech

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Speech

5

Laser Driven Shock Waves