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High Power Targetry R&D and support for future generation accelerator

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ABSTRACT: A high-power target system is a key beam element to complete future High Energy Physics (HEP) experiments. The target endures high power pulsed beam, leading to high cycle thermal stresses/pressures and thermal shocks. The increased beam power will also create significant challenges such as corrosion and radiation damage that can cause harmful effects on the material and degrade their mechanical and thermal properties during irradiation. This can eventually lead to the failure of the material and drastically reduce the lifetime of targets and beam intercepting devices.

Designing a reliable target is already a challenge for MW class facilities today and has led several major accelerator facilities to operate at lower power due to target concerns. With present plans to increase beam power for next generation accelerator facilities in the next decade and the multi-year time-scale to acquire the knowledge on material behavior under such extreme environment, timely R&D of robust high-power targets is critical to fully secure the physics benefits of ambitious accelerator power upgrades.

The next generation of high-power targets for future accelerators will use more complex geometries, novel materials, and new concepts allowing better high heat flux cooling methods. Advanced numerical simulations need to be developed to satisfy the physical design requirements of reliable beam-intercepting devices. In parallel, radiation hardened beam instrumentation irradiation methods for high-power targets must be further developed. Additional irradiation facilities are needed since only a few facilities worldwide offer beams for target testing, and the beam provided may not be appropriate for the specific facility or project.

Thus, a comprehensive research and development program must be implemented to address the challenges that multi-MW targets face.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Accelerator Subsystems and Technologies; Radiation damage evaluation methods; Targets (spallation source targets, radioisotope production, neutrino and muon sources)

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1 Introduction and context

In the recent past, several accelerator facilities have had to limit their beam powers, not as a result of limitations of the accelerators themselves, but due to the target and/or window and their survivability. The Neutrinos at the Main Injector (NuMI) beamline at Fermilab [1], the Materials and Life Science Experimental Facility (MLF) at J-PARC [2] and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [3] have operated at reduced power for extended periods due to target failure concerns. Recent beam power upgrades at various accelerator facilities are now pushing conventional materials to their limits, and future facilities will present even greater challenges in meeting the physics goals of these experiments.

With present plans to upgrade accelerator facilities at Fermi National Accelerator Laboratory (FNAL) to higher beam powers (1.2+ MW) in the next decade and the multi-year time-scale to acquire the knowledge on material behavior under such extreme environment, timely R&D of robust high-power targets is essential to fully secure the physics benefits of ambitious accelerator power upgrades.

Exposure of material to particles leads to a displacement of a significant number of atoms from their preferential lattice (quantified as displacements per atom, DPA, a reference used to express radiation damage level in material), transmutation and gas production. Irradiation-induced defects such as dislocation loops, point defect clusters, fine-scale precipitates and voids that accumulate at the microstructural level ultimately disrupt the lattice structure of the material and affect the mechanical, electrical, and other physical properties of irradiated materials. Typical bulk material effects include embrittlement, hardening, swelling, reduction of thermal conductivity, and an increase in diffusion-dependent phenomena such as segregation of impurities, and phase transformation [4], all of which are detrimental to the thermo-mechanical health and physics performance of the material.

Thermal shock phenomena arise in beam-intercepting materials as a result of localized energy deposition caused by very short pulsed-beams (1–10 μs). The typical peak temperature increase in a 1-MW neutrino target at Fermilab is approximately 250 K in 10 μs (2.5×10^7 K/s). The rapidly heated core volume of the material in the beam spot region expands but is constrained by the surrounding cooler target material. This condition creates a sudden localized region of compressive stress that propagates as stress waves through the material at sonic velocities. If the initial dynamic stress exceeds the yield strength of the material, it will permanently deform and eventually fail. In addition, the cyclic loading environment from the pulsed beam progressively damages the materials' microstructure such that it ultimately fails at stress levels that are lower than its failure strength (fatigue failure).

The pulsed beam structure and small beam spot size (~1 mm) in accelerators also induce more severe thermal shock effects. As a result, material radiation damage data that cover the accelerator irradiation parameter space are lacking in the literature. It is therefore imperative to understand the behaviour of materials under irradiation conditions analogous to future accelerator target facilities.

Beam-intercepting materials that are resilient and capable of withstanding an order of magnitude increase in particle beam intensities are essential for enabling next-generation multi-MW target accelerator facilities. It is now critical to explore novel targets and advanced materials beyond the current state-of-the-art to improve resistance to beam-induced radiation damage and thermal shock — the leading cross-cutting challenges facing high-power target facilities [5] for current and next-generation accelerators. Conventional materials for key accelerator components, such as beam

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windows and secondary particle production targets, are already limiting the scope of experiments. Novel target materials will enable multi-MW beam operation to fully satisfy design requirements and maximize the physics benefits of future High Energy Physics (HEP) experiments.

The development of novel materials and concepts [6] for future accelerators is mainly supported by simulations at different levels: prediction of beam-matter interactions, thermo-mechanical response induced by beam heating, evaluation of radiation damage with time that enhances degradation of material physical properties. As the next generation of high-power targets will use more complex geometries, novel materials and concepts, the current numerical approaches will not be sufficient and advanced modeling needs to be developed [7]. In order to obtain more confidence in the numerical results to develop more reliable target systems, better validation must be performed in parallel to the simulation development by using prototypes tested under relevant beam conditions. Although some data are available in the literature, more experimental data with controlled beam parameters are needed for targets operating under extreme conditions where the boundary conditions are not fully controlled. Fully instrumented targets with simple geometry are usually difficult to insert online during accelerator operations as they are not dedicated to materials research.

Beam and target monitors are also essential to control accelerator operation and target health to diagnose any failures and to predict their operational lifetime. However, the beam instrumentation performance is often constrained by a prompt radiation dose, integrated radiation dose, operation (ambient) temperature and humidity, available space, and strength of embedded electromagnetic fields at the monitor. These constraints will limit the dynamic range of operational beam parameters, like the maximum achievable beam power. Therefore, a seamless R&D effort to develop the radiation-hardened beam instrumentations is crucial for making future multi-MW beam facilities.

Irradiation facilities and alternative methods are critical to provide a full support of R&D described above and better address these critical challenges. Existing test facilities that can reproduce similar beam conditions that accelerator operation parameters are very limited or don't exist.

2 Novel material and concepts for next-generation High Power Targetry

The current and novel targetry materials, concepts and technologies will need to be explored and developed over the next several years to address the challenges facing high-power beam-intercepting devices. Significant coordinated R&D efforts in these areas will be necessary to enable the safe and reliable operation of future multi-MW accelerator target facilities.

2.1 Novel materials

Below are some promising candidate novel materials that need to be explored and developed for specific beam-intercepting devices, capable of sustaining increased beam power and intensity. Most of the R&D efforts are coordinated within the RaDIATE Collaboration [8]

2.1.1 High-Entropy Alloys

High-Entropy Alloys (HEAs) are fundamentally different from conventional alloys, and typically consist of several principal elements near equimolar quantities. The result is a material with a structure and properties that are not dictated primarily by a single element, but rather behave as an average of each primary constituent. Research into HEAs over the last decade has shown that this

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class of material exhibit a broad range of promising properties for both structural and functional materials, including high yield strengths, fracture toughness and oxidation resistance, even at elevated temperatures. The most relevant and intriguing properties of HEAs for accelerator target applications is their microstructural response to radiation damage. Many studies have shown that certain HEA compositions outperform their less compositionally complex counterparts under irradiation [9–16], especially when comparing void swelling behavior. HEAs therefore offer a unique opportunity to explore a broader range of novel radiation-damage resistant alloy systems with functional properties specific to accelerator beam-intercepting devices.

2.1.2 Electrospun nanofiber materials

Nanofiber materials are promising for future multi-MW targets as they are intrinsically tolerant to both thermal shock and radiation damage. Since the continuum is physically discretized at the microscale, issues such as thermal shock, thermal stress cycles and local heat accumulation can be mitigated. Owing to the nanopolycrystalline grains of individual nanofibers, it is hypothesized that they would also offer better resistance to radiation damage. The large number of grain boundaries and free surfaces would act as sinks to irradiation-induced defects. Initial work on ceramic nanofibers has revealed evidence of radiation damage resistance upon low-energy heavy ion irradiation [17]. However, more systematic studies are needed to qualify potential metallic nanofiber materials for targetry applications.

2.1.3 SiC-coated graphite and SiC-SiC composites

Graphite shows extremely high performance when used in proton beam target applications due to its thermal and mechanical properties, and chemical stability. However, graphite also oxidizes easily at high temperatures, and oxidation contaminants can complicate the recovery procedures and downtimes in accelerator target facilities. Work is currently ongoing to study Silicon Carbide (SiC) coated graphite to improve oxidation resistance. Nano-powder Infiltration and Transient Eutectoid (NITE) SiC/SiC composite is another promising candidate for target material as it is significantly denser and can thus provide higher efficiency of secondary-particles transport. It also exhibits high oxidation resistance and pseudo-ductile behavior which enables it to withstand higher stresses [18–21].

2.1.4 Advanced graphitic materials

Advanced graphitic materials such as 2D carbon/carbon and 3D carbon/carbon and different novel grades also need to be explored as these materials have high temperature resistance, low density, low coefficient of thermal expansion and more importantly excellent performance under radiation due to its crystal lattice configuration and good annealing capabilities. Some of these materials have already been employed in accelerator facilities and also tested at CERN's HiRadMat facility to demonstrate their capabilities to withstand extreme operational conditions [22].

2.1.5 Toughened, Fine-Grained, Recrystallized (TFGR) tungsten

Tungsten (W) is a principal candidate target material because of its high density and extremely high melting point, and can provide 10 times higher brightness of muon/neutron than that of current target materials [23]. However, W is brittle at room temperature and exhibits significant embrittlement due to recrystallization that occurs when W is heated at or above the recrystallization temperature (almost one third of the melting point). In addition, significant embrittlement is observed from proton irradiation damage [24]. TFGR (Toughened, Fine Grained, Recrystallized) tungsten alloy, originally developed at Tohoku University and now taken over by KEK, has been shown to overcome the embrittlement issue due to grain boundary reinforced nanostructures [25, 26] and further R&D work is ongoing.

2.1.6 Dual-phase titanium alloys

Titanium alloys, specifically Ti-6Al-4V, are commonly used for accelerator beam windows due to their low density and high strength [27]. This alloy has a superior balance between strength and ductility due to its two-phase structure in addition to elemental additions and thermomechanical treatments. It can be used in temperatures up to 300°C and has excellent corrosion resistance. However, under irradiation, the alloy hardens significantly and loses almost all of its ductility after only 0.1 DPA [28–30]. Therefore, there is a need for significant R&D to improve the performance of specific Ti-alloys for accelerator target applications. Such R&D areas include control of the microstructure for improved radiation damage resistance (including via 3D printing technology), exploring other single-phase Ti-alloys that show enhance radiation damage resistance [30], developing optimal heat treatments for improved performance at elevated temperatures and ways to further enhance the alloy's corrosion resistance (e.g., through coating treatment of TiN and TiAlN by Physical Vapor Deposition).

2.2 Novel targetry concepts and technology

Key novel targetry concepts and technologies are being developed and optimized via R&D to enable and support future higher beam power accelerator target facilities. Some of these innovative concepts and technologies for targetry are briefly described below.

2.2.1 Rotating, flowing and circulating targets

As beam power continues to increase in future accelerator facilities, rotating targets have been developed and being optimized in order to reduce the power density of the primary beam onto the target. For example, a rotating solid carbon disk is the baseline target at the Facility for Rare Isotope Beams (FRIB) at Michigan State University [31] and the rotating spallation target at the European Spallation Source [32]. With a rotating target, the beam pulse is swept across the target area and spreads the heat deposition and radiation damage in the target material. Associated challenges of a reliable rotation target include the drive system (bearings and lubricants) and the ability to operate in a high-radiation and high-temperature environment. Flowing liquid metals have also been successfully used as high-power neutron-production targets [33–35] after significant R&D to mitigate issues such as cavitation-induced erosion damage [36–42]. Other novel targetry concepts being explored include a fixed granular target design, a conveyor target (being developed at Fermilab to support the Mu2e-II experiment) and a flowing granular target (possible Muon collider target) [43–50]. Significant R&D work will be needed to further develop and optimize the aforementioned novel targetry concepts to support the requirements of future experiments that are well beyond the limit of any existing target technology.

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2.2.2 Advanced cladding materials and technologies

Refractory metals are widely employed in laboratories worldwide for secondary particle production, such as for neutron production [51] or for proposed beam dump experiments [52], owing to their reduced nuclear interaction length and relatively low neutron inelastic cross-section. However, direct cooling with water is not possible due to the high hydrogen embrittlement. Usually tungsten (W) is cladded via Hot Isostatic Pressing (HIP) with pure Tatalum (Ta), with good results [53]. Advanced techniques to clad pure W and other refractory metals with Ta and Ta2.5W are being developed [54–56]. For high power facilities, decay heat on Ta and Ta-alloys may pose safety concerns, and therefore other cladding materials such as Zircalloy or other Nb-alloys are being studied. Furthermore, efforts to study and improve cladding technologies (e.g. Hot Isostatic Pressing and diffusion bonding) are ongoing in order to mitigate cladding breach, corrosion and erosion issues. R&D in the area of advanced cladding materials and technologies will be beneficial to enable and optimize future experiments [51, 52]. It will be fundamental in designing robust beam-intercepting devices for planned upgrades and future intensity and energy frontier facilities.

2.2.3 High heat flux cooling

Alternative advanced cooling technologies need to be explored in order to address the challenges of heat removal as beam power on target increases. Unconventional heat transfer technologies, such as controlled boiling or flowing (liquid or granular) targets, where heat-flux cooling capacity can be significantly increased, is an area that needs to be explored and developed. High heat flux cooling techniques have been investigated in the past and continue to be researched within the fusion/fission communities, as well as in some accelerator target facilities. Optimized radiative cooling is another technique that can be used (eg. Mu2e tungsten target). Exploring other alternatives to forced convection cooling techniques is thus an area of research that should be addressed and will be critical in enabling future multi-MW target facilities.

3 Modeling needs for High Power Targetry

Modeling the physics in a high-power target is complex and requires different expertise. First, a beam interaction calculation needs to be performed to estimate the performance of the target and to provide the heat load for the thermo-mechanical simulations. Structural analysis to estimate the thermal stresses, fatigue, and response to a pulse (if the beam is pulsed) are then performed to validate the mechanical integrity of the target. If the target is cooled by a fluid, computation fluid dynamics analysis may also be performed. This method has led to successful and reliable target designs but is showing its limitation for MW-accelerator. As the beam power increases, the target will face several challenges, such as high energy densities, high power densities per pulse, high averaged deposited power. The first main difficulty is cooling the target adequately. As described above, one solution is to make the target of a fluid such as liquid metal or a fluidized material (granular or pellets) such that the heat load can be transported away from the beam. Another solution is to rotate the target to spread the heat load over a larger volume. Both these solutions are more challenging in modeling due to their geometry which is generally more complex, and to the additional physics introduced (like cavitation for liquid metal target).

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As the beam power increases, radiation damages will limit the target life span. However, there is no numerical engineering tool available to model the material degradation (radiation hardening, embrittlement, swelling, change in material properties). Empirical data are often used, but can be very limited for some materials and do not allow exploration of novel materials. To ensure that target (and beam intercepting devices) operational cost remains reasonnable in the future MW facilities, progresses in the modeling must be made and are described in the following two sections.

3.1 Better and smarter codes

As mentioned earlier, target simulations are interdisciplinary and require data exchange between experts. Unfortunately, the handshake is often done manually and makes design exploration across all the physics very limited. Better interfaces with the different codes could allow leveraging HPC potentially opening the doors to Machine Learning that includes all the physics in the target and Bayesian optimization. A deep investigation on target reliability versus performance could then be done, allowing accelerator facilities to choose the target that fits their operational goals.

In multi-MW accelerator facilities, targets will need to be replaced regularly due to radiation damage. However, the operational cost associated with it (remote handling, disposal, hardware) may become prohibitive. Thus, there will be a strong desire to operate the target longer and accept some radiation damages. Therefore, transient simulations that will take into account the material degradation with time will be needed and will require the codes to run efficiently on clusters. Reduced-Order Modeling (ROM) should also be leveraged for this type of simulation. ROM can also be used to develop digital twin, a virtual prototype of the target system, that could monitor the target health and performance as it is operated.

Finally, the target community must keep up with the ongoing advanced concepts and future computing in the broader computing community. Engineering codes will need to be ready for exascale supercomputers and leverage extreme parallelism. Quantum computing is also another opportunity to explore as they are capable of solving certain problems that cannot be done on classical computers.

3.2 Target geometry and composition optimization

Target systems are optimized with various iterations to maximize the physics output for the experiment and to minimize the operational risks. Usually, a Monte Carlo numerical simulation and a Finite Element Analysis are used to evaluate the physics performance and thermomechanical response of the target systems via several iterations. The number of iterations exponentially grows as the number of variances increases. To simplify this optimization process, the designed target shape is usually monolithic consisting of a single material. However, fine dimensional tuning of the target shape and material composition can further increase the performance efficiency of multi-MW target systems. As a result, the use of Machine Learning based on the Bayesian optimization can help to optimize future target systems. The Bayesian optimization will evaluate the previous result via the Gaussian process recurrence and set a new variance. This method is widely used in the material science field to find new materials/alloys. Combining additional simulator to design the new target material at the atomic level may also be possible. This method should be employed to further help explore and develop target systems for future MW-class target facilities.

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3.3 Modeling radiation damage

When a material is irradiated with energetic particles such as electrons, heavy ions and protons, atoms in the material are getting displaced from their lattice sites. These displacements cause microstructural defects and nuclear transmutations that alter the material composition and properties. More precisely, it can affect dimensions due to swelling, structural stability, hardening and embrittlement, thermal, electrical and optical properties. The current standard to estimate radiation damage is to use particle codes with variables such as DPA (Displacement Per Atom). However, it does not predict the changes in the material's mechanical properties, and the target designers must use empirical data to understand how the material will be impacted by irradiation. Thus, numerical tools that could predict the effect of irradiation on any beam for any material are highly desired. At the atomic or nanoscale level, quantum mechanical or molecular dynamics simulations can be used but will be too computationally demanding at the needed length (cm) and time scale (days). Thus, new modeling tools that leverage these small-scale simulations need to be developed to simulate radiation damage on the macroscale. Such numerical tools would be game-changing for not only the target, but any beam intercepting devices. Novel materials could potentially be explored numerically before being tested in irradiation facilities. Synergy with other communities that are facing similar challenges, such as nuclear and fusion communities, should be leveraged to develop such numerical tools.

4 Radiation hardened beam instrumentations for multi-MW beam facilities

Developing a radiation hardened beam instrumentation is a crucial path to successfully operate a multi-MW accelerator facility. A reliable beam instrumentation is needed to control operating beam conditions and diagnose beam components including a target.

4.1 Beam monitor

A beam monitor is used to characterize the beam by measuring a spatial distribution of charged particles (e.g., a beam centroid position, orientation, and their profile), an integrated charge of particles passing through the monitor (e.g., a total beam intensity per spill), and a time structure of charged particles (e.g., a differentiated beam intensity or a bunch structure) along the beam line. An Optical Transition Radiation (OTR) monitor and Beam Induced Fluorescence (BIF) monitor have been developed at various beam facilities. Those are promising technology to apply for a multi-MW beam because those detectors have a very sensitive light detector that needs only a small intercept of the beam to measure the beam profile. Finding a light yield and acceptable thermal stress on a radiator are a key R&D. Because a small amount of light transmits with the beam related information, maintaining high light transmission efficiency is a key element for the system performance.

Secondary Electron emission Monitor (SEM) is another potential candidate for intense beam facilities. R&D is required to investigate the aging effect on the Secondary Emission Yield (SEY) and to challenge making a thin wire or film to minimize the interruption of beam. A new SEY material, like Ni, carbon graphite, and Carbon Nano Tube (CNT), are considered for multi-MW accelerators. A new radiation hardened Beam Loss Monitor (BLM) system has been developed at CERN for HL-LHC.

Secondary and tertiary beam profile monitors have been developed for high energy beam applications. Those characterize the fragments from the target. The phase space evolution of fragments in the transport line needs to be understood. The signal is sensitive to the health of the target system and the primary beam condition. SEM and gas-RF monitor [57] are considered for a hadron monitor. Electron Multiplier Tube (EMT) [58] and Current Transformer (CT) are new candidates and are demonstrated at J-PARC for a muon monitor. They appear to have a good stability with respect to the beam intensity. Nevertheless, additional R&D is needed for multi-MW beam applications.

4.2 In-situ target health sensor

In-situ target health sensor is widely used to diagnose the target condition and to predict the operational lifetime of the target for medium energy nuclear facilities. Fiber-optic strain sensors are used to measure mega-hertz dynamic strains on the target vessel induced by individual proton pulses. Acoustic sensor and Laser Doppler Vibrometer (LDV) are used to measure a specific vibration mode in the target system which is generated by the beam impact on the target system. Thermocouple sensor and Infra-Red (IR) detector are used to measure the thermal distribution in the target system. Luminescence light from a Chromium doped Alumina is also widely used to measure the beam profile and intensity on the target. The biggest advantage is that it can cover a large area for a large spot size beam and measure the 2D profile accurately even at the beam tail. Mitigating the aging and radiation effect is a key R&D for those. Because the LDV, IR detector, and luminescence monitors measure an optical signal, the radiation hardened light optics is crucial to improve the in-situ target health monitors.

4.3 Radiation hardened light optics and light sensor

The common critical element in the radiation hardened beam instrumentation is a light guide (e.g., an optical fiber) and an optical element (e.g., a lens and mirror) which are widely used for various optical measurements as beam and target health monitors as presented in the previous section. These light optics are used to inject a probe light or extract an optical measurement light from a beam line or a target. It is challenging to mitigate the radiation-induced attenuation (RIA) which indicates a lifetime of an optical material as a function of an integrated radiation dose. Because the optical measurement light transmits the beam-related information, a refractive index profile (e vs l) of the fiber as a function of the integrated radiation dose should be crucial. A high purity silica and Fluoride doped optical material appear to have higher radiation tolerance than a standard silica optics [59].

It is also crucial to develop a radiation hardened image sensor. Several groups report that they have stopped using a CCD camera. J-PARC neutrino group continues to develop a CID camera for the Optical Transition Radiation system. The collider detector group has demonstrated a radiation hardened CMOS which performs in the interaction region. The spatial resolution and data acquisition speed of the CMOS camera are extremely higher than the CCD, while the radiation tolerance on the CCD is an order of magnitude higher than the CMOS. Continuous efforts for developing the radiation robust CMOS are required. Based on the experimental results at the SNS injection area, the major hurdle seems to be the signal processing electronics rather than the sensor itself.

4.4 Radiation hardened ASICs

Detectors and readout electronics are unit structures which are exposed to extremely high radiation dose. CERN and Fermilab collider groups show the advanced technology for the radiation resistive Application-Specific Integrated Circuit (ASIC) to readout and manipulate a signal from a high-granularity fast detector in an extreme environment for the HL-LHC collider detectors and future

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collider detectors [60]. As an example of the radiation hardened ASIC, a beam halo detector has been demonstrated in LHC. These technologies will be adopted to develop a new type of fast beam monitor system.

5 Irradiation stations and alternative beams for High Power Targetry

5.1 Alternative beams for radiation damage

Directly studying material properties of targets exposed to high energy proton accelerators is an expensive and time-consuming method due to the high level of activation and the low radiation damage rate. The high activation of samples requires characterization in hot cells equipped with advanced test machines, and a high user costs/restrictive beam time availability associated with these facilities.

Radiation damage with neutrons to compare with high energy protons might be investigated as a large amount of experimental data are published for several materials of interest for target systems. Handling highly activated materials will still need Post-Irradiation Examination features such as hot cells with limited thermo-mechanical tests.

Using Low Energy (LE) ion irradiations could possibly address the limitations from high energy proton beam irradiation, providing an effective and fast way to produce radiation damage in materials without activating the specimens. It also enables effective exploration of candidate materials for future high intensity target facilities.

Instrumentation performance and its lifetime is often constrained by a prompt radiation dose, and an integrated radiation dose. Having irradiation without activation is an advantage when implementing sensitive or complex instrumentation during on-line and in-situ data acquisition to investigate radiation damage evolution with beam parameters.

Differing from protons or other heavy particles [61], electrons (with energy of few MeV) tend to generate isolated defects more than cascade/cluster and their larger penetration in matter allows the irradiation of larger volumes. Electron irradiations performed at different energies (of the order of the MeV) represent a great tool of investigation to reconstruct NIEL curves or to identify the threshold energies of defect formation.

A characteristic feature of radiation damage by high-intensity proton beams is the formation of helium and hydrogen by nuclear transmutation in the material.

Irradiation with neutrons, heavy ions and electrons cannot well simulate that of high energy protons, because of far less or no transmutant production. Helium effects become pronounced when its concentration is above 500 appm. Solid transmutants may also form high-density nano-clusters and segregation at grain boundaries, although the effects of the clusters and grain boundary segregation are still not understood.

When alternative irradiations such as neutron irradiation or low energy heavy ion irradiation, don't provide a similar amount of gas, the alternative is to use ion beam facilities with combined beamlines (dual or triple beams) to implant He and H ions. Then, it is possible to investigate the synergistic effects of damage and reproduce transmutation gas production in the material. One drawback is the shallow and non-homogeneous implantation (between 1 to a few micrometers depending on ion energy and material) from low energy ions. Several implantation beam energies are necessary to obtain a homogenous distribution of gas in few microns, significantly increasing the irradiation/implantation time.

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Existing facilities with adjustments can provide environments close to displacement rate and gas production created by high-energy, high-intensity proton beams. Future developments are obviously needed to validate that radiation damage creation and associated changes in physical properties are similar despite the radiation sources.

5.2 Alternative beams to simulate thermal shock

Testing materials' response to localized thermal shock at this level in a prototypical manner is only possible using an intense particle beam. Alternatives are currently being explored to use intense proton sources, electron sources or laser sources to test thermal shock response more effectively and enable high cycle fatigue studies ($> 1 \times 10^7$ loading cycles). The advantage of using electron or laser beams is that testing using prototypical beam loading parameters leads to no activation of the specimens.

5.3 Alternative beams to validate design concept and modeling

Testing novel concept design in a prototypical manner is also only possible using an intense beam. Some alternatives are explored with proton and electron high intensity beam.

Electron beams of few MeV have the advantage of simulating the heat deposition in material by adjusting the beam energy in material with reduced risk of activating the tested material. It can be easily used to validate engineering modeling and validate novel concept design.

A non-exhaustive list of existing facilities that provide beams available for material studies can be found in the reference [62].

Nevertheless, each facility has limited access to users and Post-Irradiation Examination may not meet the need for specific test related to accelerator targetry development. Some PIE capabilities are limited or are not existing near some irradiation stations, leading to transport activated materials to other capable facilities, increasing cost and time of the R&D cycle.

Other facilities are only dedicated to operation but could be developed at lower cost to offer testing capabilities or propose an irradiation station as a parasite mode to limit interference with operation.

6 Conclusion

Simulations and modeling, novel material and concept development, as well as target monitoring develpments are critical to better support High Power Targetry R&D needs.

Few facilities exist to support the R&D program to ensure reliable operation of future target facilities, but several aspects need to be developed:

- multiply irradiation under controlled parameters for better understanding of radiation damage behavior in selected material for beam intercepting devices
- Develop alternative methods to high energy proton beam to reduce cost and time of R&D cycle
- Collect experimental data on irradiated material to support advanced modeling on material development
- Test prototypes under similar operational conditions in a safer environment (without activating material) and validate engineering modeling for novel concept design

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The High Power Targetery community has been collaborating and working on several R&D projects to address the target challenges through the High Power Targetry Workshop since 2003 and through the RaDIATE collaboration, led by Fermilab, since 2013. Such international collaborations will be essential in the next 10 years to expand our knowledge on high power targetry.

Accelerator facilities and GARD (DOE HEP General Accelerator R&D) will need to invest more in the target R&D to develop irradiation capabilities and get a better understanding beam effect in material (i.e. radiation damage, thermal shock and fatigue), validate the target modeling, advanced novel concept, and instrumentation/monitoring to the needed level for high power accelerators.

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