R&D on High-Power Target System for future HEP experiments

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A high-power target system is a key beam element to complete future High Energy Physics (HEP) experiments. The current target technology tolerates a beam power up to 1 Mega Watt (MW). The goal of the proposed R&D extends its capability beyond 1 MW beams. Future neutrino facilities, like LBNF and J-PARC, propose 1-3 MW proton beams delivered to a neutrino target [1,2]. The beam power range is comparable to a muon collider and neutrino factory, which propose 2-5 MW proton beams [3]. On the other hand, the European Particle Physics community suggests investigating a 100 TeV center-of-mass energy hadron collider (Future Circular Collider, FCC) [4], which requires a radiation harden beam element like a beam collimator, beam damper, beam window, and beam instrumentation that will meet a multi-MW beam power, even though FCC does not have a target system in the complex.

In order to increase the pion yields, the energy of beams delivered to the HEP target is relatively high comparing to a neutron spallation (NS) source [5-7]. The length of HEP targets is a couple of interaction lengths which is much longer than the NS target. The number of hadronic interactions in the HEP target are significantly large. A hot spot appears after one interaction length of the target in every beam cycle. Such high cycle thermal stress and radiation damage make the target lifetime short. High production yield of useful secondary particles in the target is another requirement for the HEP experiments. To this end, a precise hadronic interaction simulation is a vital tool to find out an optimal target dimension and magnetic horn field configuration. The tool is also useful to design a low systematic uncertainty HEP experiment. We propose to R&D a radiation harden beam instrumentation to maintain the multi-MW beam facilities. Detail description is given in following sections.

Material science:

RaDIATE collaboration has been formed to research a radiation tolerate material for the HEP target [8, 9]. Post Irradiation Experiment (PIE) and Displacement Per Atom (DPA) cross-section experiment are proposed at several national facilities like Fermilab, BNL, and CERN to extend the fundamental radiological material science in HEP energy regions. A graphite is currently the most popular material because it restores a mechanical strain because it can be annealed at high temperature by an energy deposition of a beam. State of the art technology in nano science is capable to investigate a radiation damage in an atomic scale. The recent study suggests that a compound material, like Ti-6Al-4V compound [10] and high entropy compound [11] have a radiation resistance by controlling a crystal phase change and an irradiation temperature. A nano-fiber target is other possible technology to mitigate propagating thermal shock [12].

Develop precise simulation tool for HEP target design:

Making a precise hadronic interaction model in simulation is crucial for designing of the target system and reducing a systematic uncertainty in a neutrino experiment [12]. To this end, the experimental data (currently consider NA61 [13] and EMPHATIC [14]) will be implemented into a simulation code (GEANT4, MARS and FLUKA). The present target is a monolithic shape by stacking either a small piece of identical rod or block. An optimal HEP target may vary its cross section and material property along with the target length to have better mechanical strength and secondary particle yield. Artificial Intelligence (AI) will be applied to optimize the design of target system. AI will also be useful to identify an anomaly event by monitoring a signal from beam instrumentations during the beam operation [15]. Utilizing a national High Performance Computing (HPC) facility supported by DOE is considered to gain high statistics in simulation.

Radiation harden beam instrumentation:
Four-layer of pixeled ionization chambers downstream of a decay pipe in the NuMI target system are used for monitoring the target healthiness by observing the profile of secondary and tertiary particles. Recently, the AI has been applied to analyze the pixeled image from the ionization chambers and precisely reconstructed the proton beam position at the target and the horn current with less than 1 % of a systematic error [16]. However, the first ion chamber which is the nearest distance from the target has been heavily damaged by radiation. The monitor lost a function to reconstruct the proton beam intensity at the target and to predict the target deterioration. We propose the R&D to develop a radiation harden beam detector. Electron Multiplier Tube (EMT) [17] and gas-filled RF cavity [18] are a good candidate. Other R&D for a beam position monitor, beam profile monitor, and current transformer are also needed to mitigate the aging and a non-linear gain shift due to the beam intensity. Optical Transition Radiation (OTR) [19], Secondary electron Emission Monitor (SEM) and Beam Induced Fluorescence (BIF) [20] are a good candidate.

Remote handling and Robotics:
Remote handling and robotics technologies must be applied to maintain a multi-MW beam facility. A modern robotic technology is sufficiently matured to apply for an accelerator facility. Typically, a beam enclosure is long, narrow, and curved labyrinth, and sometimes undergrounded. Because the enclosure is sealed by a thick metal plate for a radiation shielding, no Global Positioning System (GPS) is available. WiFi is most likely not available during a beam operation. Therefore, an autonomous robot requires a 3D AI visualization processor to find out a location by itself [21]. A long lifetime battery and/or a special recharging system are needed. Mobility is an important parameter to design the accelerator robot. An Unmanned Aerial Vehicle (UAV) has been developed to quickly take a 3D radiation map from a hot device [22]. A portable compact radiation detector is other key elements for the accelerator robot to monitor radiation and minimize radiation damage on it.

Plan:
RaDIATE has played a core role to investigate the high-power target material. It has been supported by the General Accelerator R&D (GARD). Fermilab will build the Target Systems Integration Building (TSIB) to fabricate and maintain the LBNF target system [23]. It will have a new facility to work out above items. An initiative activity of the R&D has begun by collaborating with several universities supported by the AD operation budget, the US-Japan collaboration budget, and a general university faculty budget. If the additional funding support will be approved, we will support a graduate student and a young engineer and scientist to accomplish above items in a decade.

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