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High-Power Targets

The next stage of discovery in the domain of particle physics is expected to come from the advancements in the both the energy and intensity frontier. Both of these approaches are well served by the world wide drive of accelerator developers of high-intensity and high-power proton machines. The principle objective of these powerful machines is to transform the source of intense protons into prodigious quantities of secondary particles which can then be used for new and innovative applications as well as new discoveries. Examples of useful secondary particles include neutrons, Kaons, muons, and neutrinos. Each of these particle species can be used for applications ranging from driving sub-critical reactors to providing beam to address important questions about our physical universe. Neutrons, for example, are useful as unique projectiles having important applications in the science of condensed matter. An intense source of Kaons will be extremely useful in providing precision measurements of rare decays which can give physicists key insights into the nature of physical processes beyond the standard model. The precision study of neutrino interactions provide physicists with the hope for spectacular breakthroughs into understanding the nature of fundamental building blocks of nature and perhaps provide insights into the creation of the universe as we now know it.

The creation of these particles have a common attribute—they are all produced as secondary particles resulting from the interaction of primary beams of protons with ordinary matter. The need for intense beams of these secondary is the fundamental driving factor in the development of intense proton beams with megawatts of beam power. The conversion of these protons into useful beams of secondaries requires a target interface which in turn leads to the production of these particles. These targets will absorb much of the beam power and the management of this absorbed power is proving to be one of the key challenges for this technology.

A variety of technical issues accompany the development of target systems capable of exploiting high-power primary beams. Among these issues are:

- Thermal management
    - Target melting
    - Target vaporization
    - Heat removal
- Radiation
    - Radiation protection
    - Radioactivity inventory
    - Remote handling
- Thermal shock
    - Beam induced pressure waves
    - Cavitation
- Material properties
    - Yield strengths
    - Thermal conductivity
    - Thermal expansion
    - Resistance to radiation damage

Almost any solid target will suffer mechanical failure due to radiation damage after exposure to a proton beam sufficient to cause several “displacements per atom” (DPA), roughly 10^{22} protons incident per cm^2. This requires ever more frequent changes of the target as the beam power increases, such that it eventually becomes preferable to use a flowing liquid target.

Another issue that limits the use of static solid targets is the temperature rise, and consequent melting/sublimation. Low-Z materials, such as carbon are favored in this respect, because a smaller fraction of the incident beam power is absorbed in the target, compared to the case of high-Z materials. To use the latter, a solid target must feature continuous rotation of a wheel or band.

In the case of intense proton beams with short pulses, peak energy deposition in excess of 100 J/g in the target during one sonic transit time leads to generation of destructive pressure waves. This issue alone makes the use of solid targets not viable in some applications.

Examples of static solid targets include the FNAL NuMI target [1] which consists of an array of segmented carbon blocks and the CERN CNGS target system [2] which is a single rod of carbon. A further advancement of this concept is to utilize moving solid targets such as the FNAL Pbar target [3] and the carbon target wheel [4] at the PSI facility in Switzerland. This technique facilitates heat removal at the expense of added target design complications.

When a pulsed beam is required the structural integrity of the target material becomes an important issue as the beam power increases. Current thinking is that solid targets become less viable as the beam power exceeds 1 MW. The details of where the beam power limitations lie depend on several factors such as proton beam energy and the length of the beam pulses. This limitation is closely related to the physical properties of the material in and surrounding the target. A further complication is that the radiation environment in which the target is situated will result in these physical properties changing as the impact of the radiation becomes more pronounced during the lifetime of the target. Hence, significant R&D in the study of properties of irradiated material is an important requirement for these target systems.

For high-power pulsed beams, attention is shifting toward the used of liquid targets. Examples include the Spallation Neutron Source [5] at Oak Ridge which uses mercury as the target material, and the MegaPie project [6] at PSI which uses a eutectic lead-bismuth alloy. A further example is the target concept which has been developed for a Muon Collider [7] or Neutrino Factory facility [8].

The Neutrino Factory baseline calls for a 4-MW proton beam impinging on a high-*Z* target with small radius to mitigate re-absorption of the generated low-energy pions. This is done within the confines of a high-field solenoid which contains the soft pions and then conducts them down a capture channel to allow for the subsequent collection of the muon-decay products. The chosen target material is liquid mercury, which presents interesting challenges in that this metallic fluid must flow within a 15-20 T solenoid field. The velocity of the Hg jet is determined by the rep rate of the primary proton beam; for a 50-Hz rep, rate the jet must flow at ~20 m/s so that a new target can be formed before arrival of the subsequent proton pulse. Another important consideration is the nature of the beam-induced cavitation process within the Hg jet, which could influence the pion production characteristics depending on the microstructure of the primary beam.

To test these concepts, the MERIT (MERcury Intense Target) experiment [9,10] was performed at CERN in the Fall of 2007. Many favorable aspects of the presence of the high-magnetic field were observed. First, the surface instabilities of the mercury jet were greatly reduced. The extent of the beam induced disruptions as well as the velocities of the dispersed mercury droplets were also reduced. The experiment resulted in the validation of this unique target concept, but much R&D remains to demonstrate that a complete target system capable of sustaining a 4-MW proton beam environment can be achieved.

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