Target R&D for high power proton beam applications

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Abstract. High power targets are one of the major issues in an accelerator complex for future HEP physic studies. The paper will review status of studies worldwide. It will focus on the status of the MERIT mercury-jet target experiment at CERN.

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INTRODUCTION

High power proton beam concepts are demanded in order to produce beams of unstable particles, like high intensity neutrino beams as in the case for a neutrino superbeam or a neutrino factory.

On interaction of the primary particles with a target, it is possible to produce secondary beams of elementary particles like pions, kaons, neutrons and gammas. As the secondary particle yield is often low, but still high secondary particle flux is desired, primary particles beams of highest intensities are developed.

Considering a particle accelerator complex, where the primary particle beam is converted (e.g. through a target) into a secondary particle beam, which itself also turns into another family of particles, it is obvious that the production of high intensities of such third generation particles is even more demanding.

There exists a worldwide interest in the development of new high-power proton machines which are capable of delivering beam powers of 1MW and greater. These machines are foreseen to provide a variety of applications including the transmutation of nuclear wastes, the operation of sub-critical power reactors, the production of nuclear materials such as tritium and other isotopes useful for medical applications. However, the application which most interest the international physics community is the prospects for the production of intense secondary beams which will provide the basis for the discovery of new physics. These secondary beams include neutrons which are particularly useful in understanding solid state phenomena, kaons for the search for rare physics processes, muons for solid state and particle physics studies, and neutrinos for a clearer understanding of the recently confirmed oscillations and the possibility of CP violation in the lepton sector. These applications have in common the need to develop solutions for beam targets which can survive these intense MW class beams.

The evolution of the average proton beam power in the recent decades and projections for future facilities including upgrades is shown in Figure 1. Existing accelerator facilities can typically deliver proton beams with an average beam power of up to 100 kW. Already in the 80s, the LANSCE facility provided 800 kW with a very high proton intensity provided by its linac at 800 MeV. These days facilities like JPARC in Japan and CNGS using the SPS at CERN are going into operation with similar average beam power. On the mid-term future upgrades are discussed for existing facilities like FNAL and BNL exceeding the 1MW border. In order to serve neutrino super-beams and neutrino facilities one envisages newly constructed accelerator complexes delivering an average beam power of at least 4 MW.

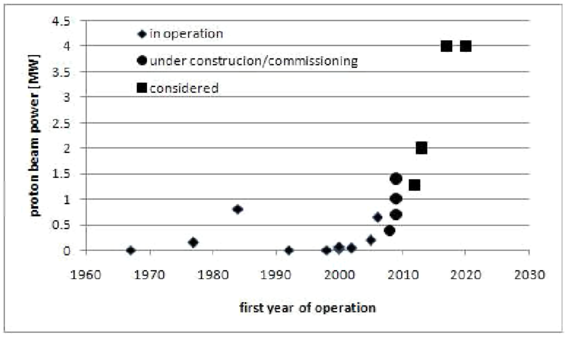

FIGURE 1. The evolution of the average proton beam power in the recent decades and projections for future accelerator facilities.

The high power primary proton beams have typically a beam power of a few MW. Present designs of secondary particle production targets will not withstand the power deposition which comes along with the passage of such primary beams. This is at the same time caused by the fact, that in cases, where the secondary flux of charged particles is of interest, the target is kept small in order to minimize the re-absorption, and the deposited energy density is highest. The principle concept of a moving target, which provides a new target section for each proton pulse would distribute the power dissipation over

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a larger volume keeping the effective target small.

TECHNICAL CHALLENGES

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
    - Radiation damage
    - Radioactivity inventory
    - Remote handling
- Thermal shock
    - Beam induced pressure waves
    - Cavitation

A core activity in order to address the above items is to study the solid material properties in the exposure to proton beams on long-term:

- Yield strength
- Thermal expansion
- Resistance to irradiation damage
- Thermal conductivity

One is confronted with conflicting demands, namely a target material and geometry capable of producing copious pions while minimizing their absorption once they are produced. Modelling studies point to high-Z materials being more efficient at producing pions of both signs, whereas low-Z materials are better in avoiding the absorption of the produced pions. Carbon has the advantage of permitting larger target cross-sections and therefore larger beam spot sizes with a corresponding decrease in shock heating due to high peak energy depositions. The muon collider collaboration is considering another approach, however, which is to retain the pion production advantage from high-Z materials by utilizing a free liquid mercury jet. In this case, the jet can be conveniently replaced so that target integrity after exposure to the proton beam is not an issue. Different to concepts, where the mercury flow is contained, the jet version provides a solution without any beam window, which is also a exposed critically to the beam energy deposition.

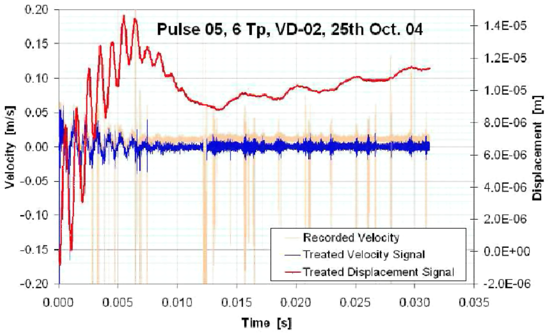

FIGURE 2. Recording of a Laser-Doppler-Vibrometer: Surface vibrations of a CNGS target mock-up exposed to 400 GeV protons.

An important parameter to consider in target design is the energy deposition density, U (usually expressed as J/g) resulting from the interaction of particles in the target media. Until recently, values of U in excess of 100 J/g where considered aggressive but as we shall see this is routinely exceeded in high-power applications. With $Stress = Y \alpha_T U / C_V$,where Y is the bulk modules, α_T is the coefficient of thermal expansion, and C_V is the thermal heat capacity, one sees that several properties of the target material affect the stresses in the target. Clearly a target would benefit for low values of the bulk modulus and the coefficient of thermal expansion and high values of the heat capacity. Additional material property considerations are a high tensile strength (particularly important for pulsed beams) and thermal conductivity. Finally, the susceptibility of material properties to be modified as a result of exposure to radiation is an important consideration.

Especially the charged ion production with small targets and proton beams with smallest duty cycles pose an ultimate challenge.

STUDIES OF SOLID TARGET MATERIALS

Consequently, efforts are underway worldwide to determine the most suitable materials for various target applications. For example, targets for pulsed beams benefit from having a low coefficient of thermal expansion, α_T. This was clearly shown in the BNL AGS experiment E951 [1] in which two grades of graphite were exposed to identical proton beams. The carbon-carbon composite, which possesses an extremely low coefficient of thermal expansion, showed significantly reduced strain waves after the impact of the primary proton beam. Further testing of materials with low coefficient of expansions (super-invar and a carbon-carbon composite) showed that this property is very sensitive to irradiation.

The stress measuring device of choice in E951 were strain gauges glued onto the target. Not exceeding the temperature limits of the glue this method is highly suitable and convenient to apply. For CNGS target stud-

FIGURE 3. The MERIT setup located in the TT2A tunnel of the PS complex at CERN. The picture shows the 15T-solenoid with its bus bars and cryogenic connections. The solenoid bore is occupied by the containment for the mercury jet, which is driven by the piston pump located downstream in the gray box. The direction of the proton beam is into the picture and is stopped by the beam dump seen in the background.

ies this method has been excluded as the strain gauges would have not stick to the carbon surface at temperatures exceeding 500 ^{0}C. A laser vibrometer based on the Doppler wavelength shift caused by the vibrating surface was used instead. It also allowed to place any sensitive electronic equipment as much as 50 m away from the target minimizing exposure to radiation. Figure 2 shows the target response to a 400 GeV proton beam ($6*10^{12}$ protons/pulse). After noise filtering the velocity signal is converted to a displacement signal.

THE MERIT TARGET EXPERIMENT

The Neutrino Factory baseline calls for a 4MW proton beam impinging on a high-Z target with narrow radial dimensions in order to mitigate re-absorption of the generated soft pions. The 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.

MERIT is a proof-of-principle test for a 4MW target station based on the target concept of a fluid metal jet. The mercury jet is driven by a piston pump, which provides a 1 cm diameter jet with a flat top of 2s length at 20 m/s maximum [2]. The mercury jet is placed in the bore of a solenoid (see Figure 3), which provides a maximum field of 15 T for a 1 second flat-top. Primary diagnostics consist of two systems: high-speed cameras for the optical observation of the mercury jet and particle detectors for the measurement of the secondary particle yield.

The experimental key parameters with its maximum values for the MERIT experiment are:

- proton beam: 24 GeV/c, $3*10^{13}$ protons per pulse, up to 1 ms pulse length
- target: mercury jet, 1 cm diameter, 20 m/s velocity, total mercury inventory: 13 liter
- B-field: 15 T peak field during 1 second flat top, 7200 A supply at 740 Volts

The aim of the MERIT experiment is:

- Optical observation of the mercury jet and its splashes in a high magnetic field (magneto-fluid dynamics, Figure 4)
- Measurement of the secondary particle yield (see section below)
- study the behavior of the mercury jet target
  - at nominal beam parameters of studyIIa [3] for a neutrino factory
  - as a scan of the full parameter space given by the proton beam and the magnetic solenoid field to benchmark simulation codes for proton-induced shock waves and magneto-fluid dynamics

At the time of this writing, the MERIT experiment was conducted successfully from 22nd October to 11th November 2007. The MERIT collaboration is currently analyzing the data. In any case, the parameter space has been fully exploited with up to $3*10^{13}$ protons per pulse at 24 GeV/c (corresponding to 115 kJ/pulse), which is a new PS record for proton pulses extracted from the PS. The solenoid provided peak fields of 15 T, running at 7200 A. The maximum pulse length studied was almost $700\mu s$.

Cavitation studies

Early studies on the jet target concept [4] conducted in the ISOLDE target area at the CERN PS booster showed mercury splashes with reduced velocity for extended pulse length. The PS booster allows to extract its bunches (up to four bunches operating in harmonic 1) individually separated by delays being multiples of the beam revolution time. An extended pulse length was substituted by increasing the bunch-to-bunch distances.

Such an effect is primarily explained by superpositioning of the pressure waves induced by the individual bunches. In the case of a short pulse, the induced pressure waves are superimposed constructively and the resulting mercury splash is more violent. However, the effect on the secondary particle yield was not observed directly at that time, even so the experiment

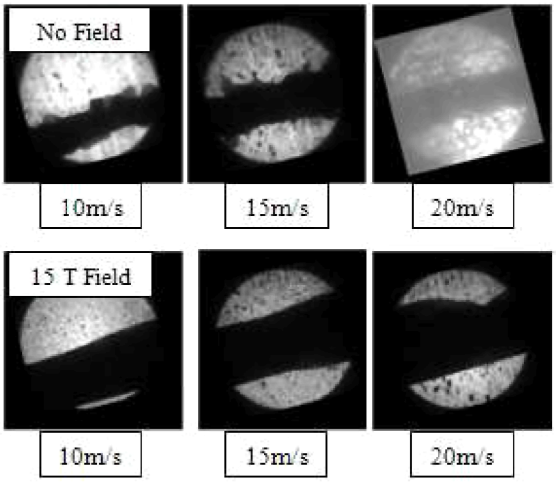

FIGURE 4. Optical observation with shadow photography of the mercury jet at different velocities and each with and without a magnetic field of B=15T. Clearly recognizable is the smoothing effect of the magnetic field on the surface stability of the jet.

E951 showed no splashes before a delay of about 40 μs after proton pulse impact.

For the MERIT experiment it was proposed to have a particle detection system installed, which allows to study the change of the secondary particle yield. This would provide the important information, whether the pulse length has significant impact on the particle production. It would allow to investigate, if the formation of cavitation in the liquid target reduces the total interaction of the primary beam in the target.

Previous to the MERIT experiment cavitation was studied by the means of a water jet and laser induced cavitation [5]. The experimental results described therein show the general behavior of a cavitation bubble growth and collapse inside a liquid jet. It was shown that the mercury jet target disruption observed after exposition to a proton pulse can be explained by the creation and subsequent collapse of vapor cavities within the jet already observed in E951 [6].

The MERIT experiment will have detectors placed in eight different locations distributed over the downstream half-sphere around the target about five meter from the nominal interaction point. The detectors itself cover about one 1 cm^2 aiming at measuring the relative change of the secondary particle yield mainly as a function of the pulse length. Even though it is possible to extend the pulse length up to almost a 1 milli-second, it is very unlikely to see a significant reduction of the particle production. Cavitation does occur on the milli-second time-scale. However, the radial expansion of the mercury jet occurs on a larger time scale, which finally contributes to the total reduction of the average density over the inscribed volume covered by mercury spray.

PS proton beam configuration(s)

A short introduction to the PS beam configurations should provide an overview of the capabilities of the PS machine in view of the MERIT experiment. The PS accelerator can deliver a proton beam with a momentum of up to 26 GeV/c, where the beam line to the experiment limits to 24 GeV/c.

The number of buckets in the PS machine (harmonic number) is limited by RF to 21, where for the MERIT experiment harmonic 8 and 16 are the favored choices. The aim of the MERIT experiment to work with highest intensities suggested to choose harmonic numbers, where machine operation is well experienced and flexibility is given for other beam parameters (e.g. pulse length). However, in harmonic 8 (h8) the PS machine can be filled with any number of bunches (up to 8) distributed over the 8 PS buckets at the full discretion of the experiment. In harmonic 16 (h16) the situation is almost the same, where the maximum number of bunches is limited to 16 and bunches are occurring in pairs only (given by the bunch splitting in the PS).

The extraction at 24 GeV/c occurs within one PS revolution of the proton beam and only within one turn. The kicker systems are not capable of firing twice for a 24 GeV/c beam within delays smaller than 100 ms.

In order to have the possibility extending the pulse length beyond one PS revolution period (about 2.2 μ s) similar to the PS booster method described above, the beam momentum has to be reduced to 14 GeV/c. This allows to use only half the capacitors banks driving the kicker system, and allowing to do so twice within any time delay given by the flat top of the septum (about 700 μs). Beyond 700 μs one could operate beam extraction on the ramp-up and ramp-down of the septum cycle, which requires exploitation. The technical possibility is given and could be used if time constraints during the MERIT physics run allow time for machine development.

The bunch length is sligthly smaller than 50 ns (full base) and bucket-to-bucket distance are multiples of 131.1 ns (h16), respectively 262.2 ns (h8) at 24 GeV/c. The PS revolution time of the 24 GeV/c proton beam is 2.1 μs.

CONCLUSIONS

The need for high-power targets has been well established and a worldwide program working toward there development is underway. The diversity of approaches is a hopeful sign that the issues associated with these target systems can be solved. A major impediment is the lack of suitable test beams, which would be very instrumental in speeding the development of targets. More major experiments, such as the MERIT experiment at CERN, will be required before these target systems can be fully developed and implemented.

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