A 4-MW TARGET STATION FOR A MUON COLLIDER OR NEUTRINO FACTORY

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Abstract

We outline a program of engineering design and simulation for a target station and pion production/capture system for a 4-MW proton beam at the front end of a Muon Collider or a Neutrino Factory. The target system consists of a free liquid-metal (nominally mercury) jet immersed in a high-field solenoid magnet capture system that also incorporates the proton beam dump. Topics to be studied include optimization of proton beam and jet target parameters, of the magnetic configuration for capture and subsequent transport of pions and muons, of the beam dump, of the radiation/thermal shielding of the capture magnets, and of the beam windows.

INTRODUCTION

Attractive physics opportunities will accompany the production of intense muon beams. In particular, electroweak physics at the energy frontier can be explored at a Muon Collider [1], and detailed studies of neutrino mixing, including CP violation can be pursued at a Neutrino Factory based on muon storage rings [2]. A key issue for these machines is the production and capture of copious pions that decay into the desired muons. The requirements for the target station/pion capture system for these machines are similar and are listed in Table 1. Noteworthy among these parameters is the requirement for a pulsed 4-MW proton beam. No existing target system would survive in the extreme conditions of such a powerful beam. The target system will have to dissipate most of the 4-MW beam power, survive the strong pressure waves induced by the short beam pulses, and also survive long-term effects of radiation damage.

A concept that potentially meets all these requirements is a free liquid-jet target [3, 4] that is replaced every beam pulse, as sketched in Fig. 1. For operation at 50 Hz, replacement of two-interaction lengths of mercury (28 cm) every pulse requires a jet velocity of 20 m/s. The mercury is not contained in a pipe in the region of interaction with the proton beam, because the intense pressure waves induced by the proton beam, and consequent cavitation of the mercury, could eventually rupture such a pipe.

Table 1: Baseline parameters for the target station/pion capture system at a Muon Collider or Neutrino Factory.

Item	Value
Beam power	4 MW
E_p	8 GeV
Rep. rate	50 Hz
Bunches/pulse	3
Bunch spacing	$\approx 100\ \mu$s
Bunch width	≈ 3 ns
π Capture system	20-T solenoid
π Capture energy	$40 < T_\pi < 300$ MeV
Target geometry	Free liquid jet
Target material	Mercury
Target velocity	20 m/s
Target radius	4 mm
Jet angle	≈ 100 mrad
Beam angle	≈ 70 mrad
Beam radius	≈ 1.2 mm
Beam dump	< 5 m from target
Dump material	Mercury

The novel concept of a free mercury jet target has led to an R&D program designed to validate its key features. In 2001-2002, experiments with mercury jets in proton beams, without magnetic field, indicated that the disruption of the mercury jet is not severe, and is confined to the region of interaction between the jet and the proton beam [5]. Additional studies of a narrow mercury jet in a 20-T solenoid, without proton beam, indicated favorable stabilization of hydrodynamic instabilities by the high magnetic field [6].

These encouraging results led to a proposal [7] for a proof-of-principle demonstration of a mercury jet in a solenoid magnet in a proton beam whose single pulse intensity would be equivalent to that at a 4-MW Muon Collider or Neutrino Factory. That proposal was approved in 2004 as CERN experiment nToF11, also known as the MERIT experiment [8]. This experiment has successfully demonstrated that the core of the proposed target system can deliver the required functionality to produce intense muon

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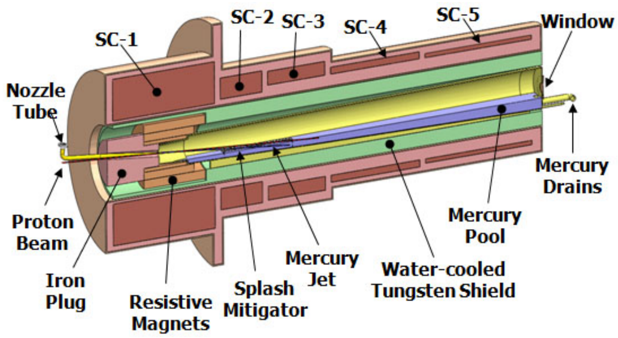

Figure 1: Concept of a 4-MW target station based on a free-mercury jet inside at 20-T solenoid. Both the proton beam and the mercury jet are tilted with respect to the magnet axis to maximize collection of low-energy pions. The mercury is collected in a pool that serves as the proton beam dump.

beams in a high-power environment.

In this paper we outline a program of engineering design and simulation for a target station and pion production/capture system for a 4-MW proton beam at the front end of a Muon Collider or Neutrino Factory. This program will be pursued over the next few years in the context of a Design Feasibility Study for a Muon Collider, and the International Design Study for a Neutrino Factory [9].

BEAM AND TARGET PARAMETERS

The choice of proton beam energy will be made on the basis of issues outside the scope of the target system itself. The present baseline energy is 8 GeV, but ongoing studies explore options from 4 to 16 GeV

The geometry of the proton-beam/mercury-jet interaction has been optimized by simulations using the MARS15 code [10], and results of this optimization are reported in these proceedings [11].

For an incoming proton beam of 8 GeV kinetic energy, the pion yield is maximized for a mercury jet radius of 4 mm, assuming the proton-beam radius has $\sigma_r = 0.3 R_{\rm jet}$. Soft pions emerge from the sides, rather than the end, of the target, so a small radius is favored. Furthermore, the pion yield is maximized when both the proton beam and the mercury jet have small angles with respect to the capture-solenoid axis. This capture geometry reduces re-absorption of the pions on subsequent turns of their helical trajectories.

The tilt of the proton beam directs it to a beam dump a few meters downstream of the target. This beam dump is inside shielding for the superconducting solenoids which generate the required 20-T capture field. The proton beam dump will consist of a pool of mercury fed by the target, and drained appropriately to complete the mercury-flow loop.

Variations on this baseline are under consideration, including options to use multiple jets, and in which the beam-jet crossing is not necessarily in the vertical plane.

LIQUID-METAL JET

The baseline liquid metal for the jet target is mercury. An alternative that is being explored is the Pb-Bi eutectic alloy, with a melting temperature of 124° C. This alloy might be preferred for easier containment than mercury in case of an accident, although it leads to greater abundance of activated byproducts.

The mercury jet in the baseline design has a velocity of 20 m/s. Design issues under study include magnetohydrodynamic aspects of the mercury nozzle, its mechanical structure as part of the iron plug (see Figs. 1-2) that shapes the upstream magnetic field, and the mechanical seal between the nozzle and the mercury chamber/beam dump.

Other target alternatives are also under consideration, such as flowing tungsten powder [12].

MAGNETIC CONFIGURATION

Throughout the front end of a Muon Collider and/or Neutrino Factory the π's and μ's are confined and transported in a solenoidal magnet channel. While the pions are produced in a target with very small radius, and consequently have a small transverse emittance, once they are captured in the downstream solenoid channel we characterize their emittance by its rms value, which is much larger than the "true" emittance. To inject the muons from pion decay into later accelerators and storage rings its is favorable if their emittance (both transverse and longitudinal) is reduced by ionization cooling, which can lower both the rms emittance and the true emittance.

The magnetic configuration in the vicinity of the target can modify the rms emittance of the pions, but not their true emittance. In particular, it is favorable that the target be located in a much higher magnetic field than that of the downstream solenoid channel. While this effect has been known for at least 15 years, no extensive studies have been made to optimize the magnetic configuration near the target so as to minimize the rms emittance of the π/μ beam. We plan to remedy this situation in the near future.

The baseline magnetic configuration includes one very high field magnet, a 20-T hybrid with a 6-T copper insert and a 14-T Nb_3Sn superconducting outsert. The option for a 20-T high-temperature superconducting magnet is also under consideration. In any option, the high thermal load implies there must be substantial cryogenic cooling channels in the magnets, which complicates their design.

PROTON BEAM DUMP

The liquid metal of the target jet must be collected in a suitable pool, in the hollow interior of the superconducting-magnet cryostat, and the liquid metal recirculated. In the baseline design this collection pool also serves as the proton beam dump.

Both the liquid metal jet and the proton beam will perturb the surface of the collection pool, possibly leading to fluid impacting the downstream beam window. Simulation and experimental studies will be needed to validate a viable design for the pool/beam dump/beam windows.

The baseline design is evolving to include the drain at the upstream end of the pool, with the liquid metal exiting between the copper insert and the superconducting outsert of the 20-T magnet as shown in Fig. 2.

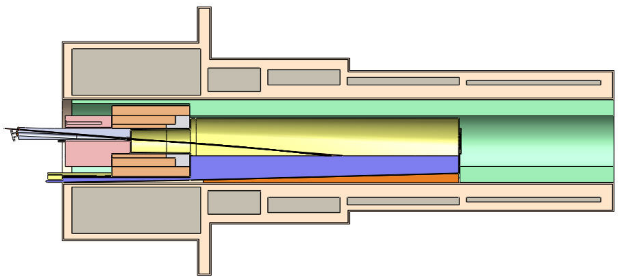

Figure 2: Concept of the mercury collection pool/beam dump with the drain at the upstream end.

RADIATION/THERMAL SHIELDING

The baseline target-system concept includes five superconducting magnets housed in a common cryostat to minimize cryogenic heat leaks and to simplify the mechanical structures that stabilize the large intermagnet forces. A cylindrical shield located inside the bore of the cryostat protect the magnets from the radiation dose and the thermal load from the secondary particles produced in the target. Energy-deposition studies indicate that 40-60% of the proton beam power (*i.e.*, 2.4 out of 4 MW) will be deposited in this shield.

The baseline design is for a cylindrical shield filled with tungsten-carbide spheres cooled by water flow. As this concept is not a standard heat-exchanger design, simulation and experimental efforts are needed to determine optimum sphere size and packing factor, heat transfer coefficients, flow and pressure drop parameters.

Also under study is the alternative that the cylindrical shield be filled with the same liquid metal as the jet target.

BEAM WINDOWS

Beam windows will be required both upstream and downstream of the beam/jet interaction location. The proton beam will pass through the upstream window and secondaries through the downstream window, so their operational lifetimes may be different, but they are expected to share a common design. The baseline concept is a double-walled vacuum containment with an inflatable seal that interfaces with adjacent upstream and downstream beamline components. As these windows will have to be regularly replaced due to radiation damage, their location and configuration must be designed with remote handling as an important consideration.

The beam/jet interaction region will be operated with atmospheric pressure helium, and it would simplify the design of the downstream beam window if the following magnetic channel were also operated at atmospheric pressure, at least for several tens of meters.

CONCLUSIONS

While the principle of a liquid-metal jet target inside a 20-T solenoid has been validated by the MERIT experiment for beam pulses equivalent to 4-MW beam power at 50 Hz, substantial effort is still required to turn this concept into a viable engineering design. We are embarking on a several-year program of simulation and technical design for a 4-MW target station in preparation for the Muon Collider Design Feasibility Study and the International Design Study for a Neutrino Factory.

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