A SOLENOID CAPTURE SYSTEM FOR A MUON COLLIDER

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Abstract

The concept for a muon-production system for a muon collider or neutrino factory calls for an intense 4-MW-class proton beam impinging upon a free-flowing mercury jet immersed in a 20-T solenoid field. This system is challenging in many aspects, including magnetohydrodynamics of the mercury jet subject to disruption by the proton beam, strong intermagnetic forces, and the intense thermal loads and substantial radiation damage to the magnet coils due to secondary particles from the target. Studies of these issues are ongoing, with a sketch of their present status given here.

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.

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Table 1: Baseline Parameters for the Target Station/Pion Capture System at a Muon Collider.

Item	Value
Beam power	4 MW
E_p	8 GeV
Rep. rate	15 Hz
Bunches/pulse	3
Bunch spacing	$\approx 120\ \mu$s
Bunch width	2 ± 1 ns
π Capture system	20-T solenoid
Stored magnetic energy	≈ 4 GJ
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
Beam angle	≈ 70 mrad
Beam-jet angle	≈ 27 mrad
Beam radius	≈ 1.2 mm
Beam dump	< 5 m from target
Dump material	Mercury
Shield material	W-C beads + H_2O
Thermal load @ 4K	≈ 1 kW

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 demon-

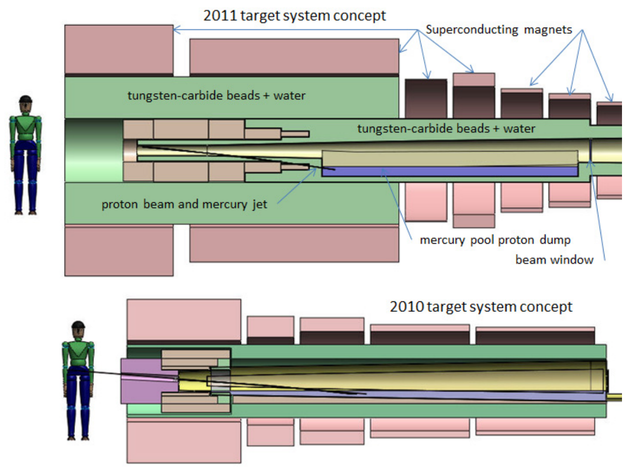

Figure 1: Concept of a 4-MW target station based on a free-mercury jet inside at 20-T solenoid. Both the proton beam and the mercury jet are tilted with respect to the magnet axis to maximize collection of low-energy pions. The mercury is collected in a pool that serves as the proton beam dump. The W-C shielding needed to provide a 10-year lifetime of the superconducting magnets has led to a substantial increase in the mass of the system compared to earlier concepts.

strated that the core of the proposed target system can deliver the required functionality to produce intense muon 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], with results reported in [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 $\sigma_r = 0.3R_{\rm jet}$. 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 [12] 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 [12]. 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 suppression of turbulent jet breakup, magnetohydrodynamic aspects of jet flow in the 20-t 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 [13].

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 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.

To insure at least a 10-year operational lifetime of the superconducting magnets against radiation damage, we hade adopted the ITER criterion of a maximum energy deposition in them of 0.1 mW/g [14]. As discussed further below, and in [15], this leads to a requirement of an inner radius of $\approx$ 120 cm for the superconducting coils around the target, such that the stored magnetic energy of the target magnet string is ≈ 4 GJ. The thermal load in these coils is roughly 1 kW at 4K, which requires use of cable-in-conduit conductor with internal He flow.

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.

RADIATION/THERMAL SHIELDING

The baseline target-system concept includes 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, filled with tungsten-carbide spheres cooled by water flow, is located inside the bore of the cryostat to protect the magnets from the radiation dose and the thermal load from the secondary particles produced in the target. Energy-deposition studies [15] indicate that 60% of the proton beam power (*i.e.*, 2.4 out of 4 MW) will be deposited in this shield. Some 20% of the power is transported into the downstream beam elements.

Close to the target a radial thickness of $\approx$ 80 cm of W-C shielding is needed to lower the radiation damage to the superconducting coils enough to permit a 10-year lifetime.

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 may have to be 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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