TARGET SYSTEM CONCEPT FOR A MUON COLLIDER/NEUTRINO FACTORY*

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Abstract

A concept is presented for a Target System in a staged scenario for a Neutrino Factory and eventual Muon Collider, with emphasis on initial operation with a 6.75-GeV proton beam of 1-MW power, and 50 Hz of pulses 3-ns long. A radiation-cooled graphite target will be used in the initial configuration, with an option to replace this with a free-liquid-metal-jet target should 4-MW beam power become available at a later stage.

INTRODUCTION

The basic concept for the Target System for a Muon Collider as a solid or liquid-metal target that intercepts the proton beam inside a high-field solenoid magnet to capture both signs of secondary particles emerged already in 1995 [1]. The present concept is for a graphite (or carbon-carbon composite) target and proton beam dump inside a 20-T solenoid field, which field tapers down to 2 T, used throughout the rest of the Muon Collider/Neutrino Factory Front End [2], over 5 m [3]. The yield of muons from the target is maximal at low kinetic energies, roughly $40 < \mathrm{KE} < 180$ MeV, which particles emerge at large angles to the proton beam, favoring a cylindrical target of small radius, and tilted slightly with respect to the magnetic axis to minimize reabsorption of particles if their helical trajectory passes through the target a second time [4].

The solenoid field is to be provided by superconducting coils (with cable-in-conduit conductor as used in the ITER project [5]), except for a 5-T resistive coil insert (with Mg)/spinel insulation as used at J-PARC [6]) near the target [7]. Radiation damage (particularly to organic insulators) limits the dose on the superconducting coils to about 10 MGy [8], which translates to a peak power deposition of about 0.1 mW/g for a 10-year operations lifetime of 10^7 s/year. To achieve this performance, superconducting coils must have internal shields, here taken to be tungsten beads cooled by He gas flow. The required shielding is substantial [9, 10], and leads to an inner radius of the superconducting coils of 1.2 m near the target; consequently the energy stored in the 20-T coils is about 3 GJ.

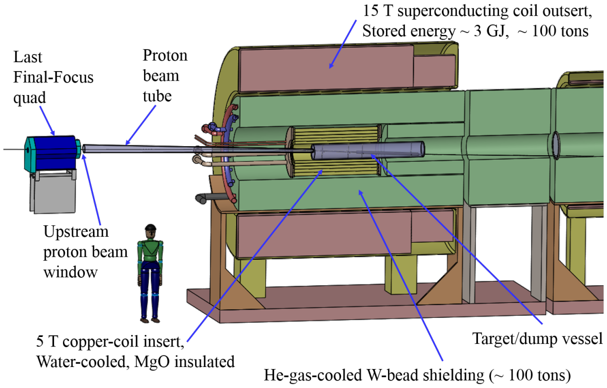

Figure 1: Sketch of the Target System concept.

The target will also suffer radiation damage and must be replaced periodically. Operation at high temperature provides annealing of radiation damage and substantially longer target lifetime (as demonstrated at the CERN CNGS neutrino target [11]). The target will be radiation cooled, operating at about 1700° C for a carbon-based target at 1-MW beam power. It is encased in a double-walled stainless-steel vessel with intramural He-gas flow for cooling, shown in Fig. 2. The upstream proton beam window (Fig. 1) will be of Ti or Al, and the downstream (double) window will be of Be to minimize degradation of the secondary-particle beam. This vessel will be replaced along with the target (and could be replaced with a different vessel for possible use of a liquid-metal-jet target at eventual higher beam powers [12]).

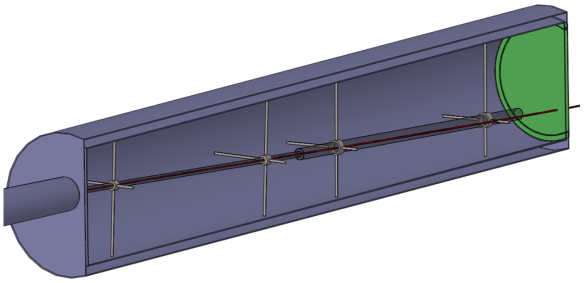

Figure 2: Target vessel with graphite target and proton beam dump. The downstream beam window (green) is of Be.

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The use of short proton pulses (3 ns rms) leads to severe stress (thermal shock) on a solid target, which is mitigated by use of materials with high strength, high heat capacity and low thermal-expansion coefficient. A carbon-carbon composite can have thermal-expansion coefficient 1/5 that of graphite and may be favored for operation at beam power higher than 1 MW or at repletion rates less than the nominal 60 Hz.

Summaries of the proton beam parameters and of key Target System parameters are given in Tables 1 and 2.

Table 1: Parameters of the incident proton beam.

Parameter	Value
Proton beam kinetic energy	6.75 GeV
Proton beam rep. rate	60 Hz
	15 Hz (Muon Collider)
Proton pulse rms length	3 ns
Proton spot rms radius	2 mm
Proton beam β^*	80 cm
Rms geometric emittance, $\epsilon_\perp$	5 μm

Table 2: Parameters of the Target System.

Parameter	Value
Solenoid field on target	20 T at $z = 0$
Final solenoid field	2 T at $z = 5$ m
Stored magnetic energy	3 GJ
Final radius of secondary beam	23 cm
Target density	1.8 g/cm^3
Target length	80 cm
Target radius	8 mm
Target (and beam) tilt angle	65 mrad
Dump length	120 cm
Dump radius	2.4 cm

TARGET SYSTEM OPTIMIZATION

Optimization of the graphite target and dump was performed via MARS15(2014) simulations [13], as reported also in [4]. In an iterative procedure the best values of the target length, radius and tilt angle were determined, assuming that the proton beam is along the target axis at its center, $z = 0$ and that the rms beam radius is 1/4 the target radius. The figure of merit in the optimization was the number of muons at $z = 50$ m with kinetic energy in the range $40 <$ KE < 180 MeV. The reuslts are illustrated in Figs. 3-5.

A comparison of the yield from a graphite target with that from gallium and mercury free-liquid-jet targets is shown in Fig. 3, which indicates that higher-Z targets are favored. While the optimum graphite target radius is near 0.7 cm, as shown in Fig. 4, there is little decrease in muon yield with a target of larger radius, which latter leads to a lower operating temperature of the radiatively cooled target. Hence a radius of 0.8 cm has been adopted for operation at 1 MW, and a radius as large as 1.2 cm might be favored for use at 4 MW.

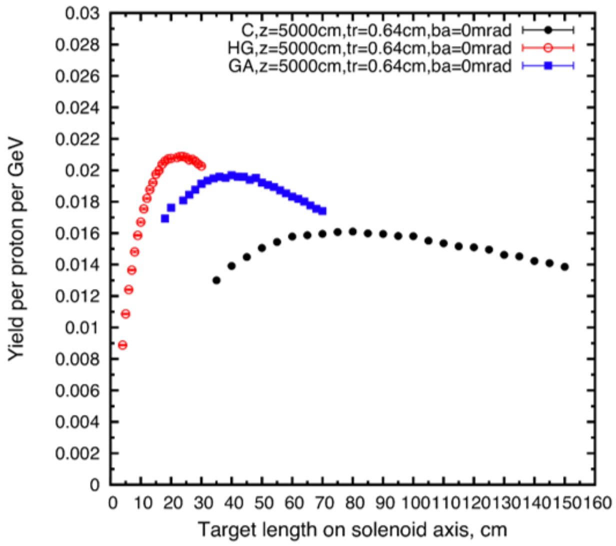

Figure 3: Muon yield at z = 50 m as a function of target length for carbon, gallium and mercury targets.

While a beam/target tilt angle of 65 mrad is optimal, as shown in Fig. 5, it would be simpler for the Final Focus system of the Proton Driver [14] if the tilt angle were zero. This would imply a decrease of $\approx 15\%$ in the muon yield.

Another aspect of the Target System optimization concerned the length of the "taper" of the solenoid field from 20 down to 2 T. For this, simulations using the ICOOL code [15] were used, with input of the secondary-particle spectrum at the end of the target from a MARS15 simulation. It turns out the a longer, more adiabatic taper improves the transverse emittance of the muons, but increases the longitudinal emittance. The latter increase is unfavorable for capture of the muon beam into rf bunches, such that the optimum taper length is about 5 m [16], as shown in Fig. 6.

ISSUES FOR FURTHER STUDY

Numerous issues related to the Target System concept presented here deserved further study

- Thermal shock of the short proton pulse on the graphite target.
- Cooling of target, and the W beads.
- Lifetime of target against radiation damage.
- Beam windows, and the related issue of air activation.
- Assembly (and possible repair via remote handling) of the massive solenoid/shield modules.
- Infrastructure that must be in place at "day 1" to preserve an upgrade option to a liquid-metal-jet target.

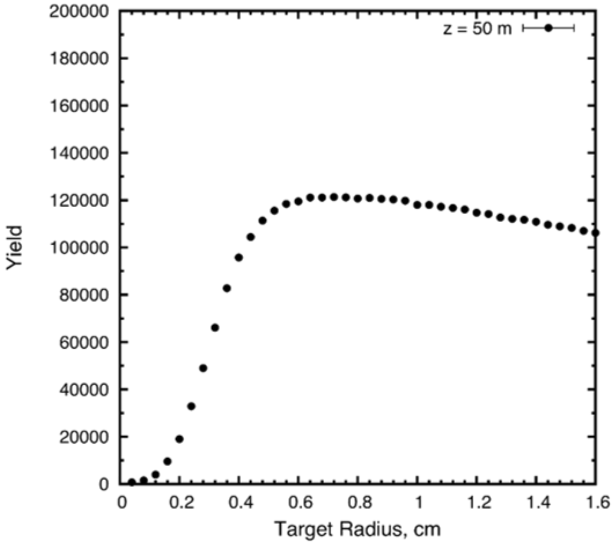

Figure 4: Muon yield at z = 50 m as a function of graphite target radius.

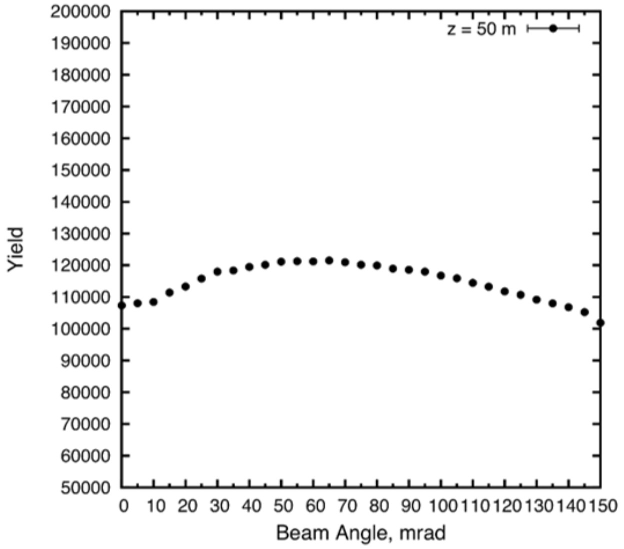

Figure 5: Muon yield at z = 50 m as a function of beam angle.

- The beam emittance $\epsilon_\perp$, and $\beta^\star$ at the target.
- Effect of the 20-T solenoid fringe field, and of radiation from the target on the Final Focus quadrupoles.

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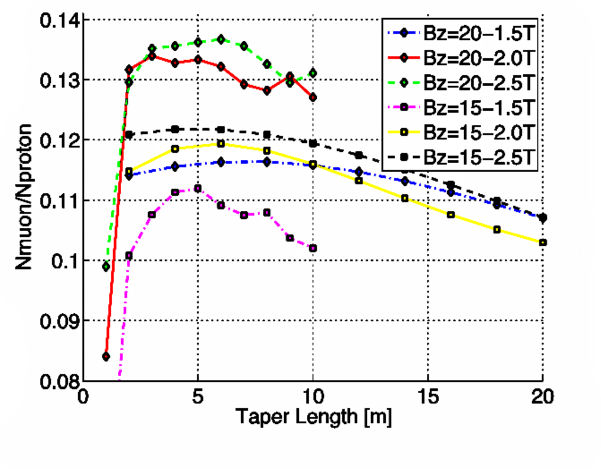

Figure 6: Muon yield at the end of the Buncher and Phase Rotator of the Front End [2] as a function of taper length, for various combinations of initial and final solenoid fields.

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