TARGET OPTIONS AND YIELDS FOR A MUON COLLIDER SOURCE

D. Ehst, Argonne National Laboratory, Argonne, Illinois 60439, USA and
N.V. Mokhov, R.J. Noble and A. Van Ginneken,
Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA*

Abstract

Efficient production and collection of a large number of muons is needed to make a muon collider viable. Target options are considered to maximize pion yield and to provide target survivability for 8 and 30 GeV primary beams of approximately 10^{14} protons per pulse at 15 Hz. Realistic Monte-Carlo simulations are performed for targets of different configurations and dimensions in a high-field solenoid. Different materials, including liquid metals and coolants, are studied to optimize heat removal.

1 INTRODUCTION

To achieve adequate luminosity in a muon collider it is necessary to produce and collect large numbers of muons. The basic method starts with a proton beam impinging on a thick target (one to two interaction lengths) immersed in a 20 T solenoid followed by a long 5 T solenoid channel which collects muons resulting mainly from pion decay (Fig. 1). The aperture of the 20 T solenoid is assumed to be 7.5 cm so as to give a large transverse phase space acceptance adequate for a transverse momentum $p_\perp^{max} = qBa/2$, where B is the magnetic field, q the particle charge, and a the solenoid radius. The normalized phase space acceptance of this solenoid for pions is $ap_\perp^{max}/m_\pi c = qBa^2/2m_\pi c$. For a 20 T solenoid the momentum acceptance is 0.22 GeV/c, and the phase space acceptance is 0.12 m·rad.

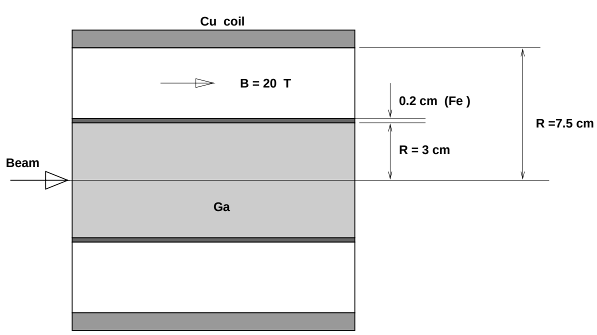

Figure 1: Production target in 20 T solenoid.

Extensive simulations have been performed for pion production from 8 and 30 GeV proton beams on different target materials in a high field solenoid [1, 2]. Solid (carbon, aluminum, copper, tungsten iridium) and liquid (gallium, mercury, lead) targets of different radii (0.4 cm to 3 cm) and thicknesses (0.5 to $3\lambda_I$, where λ_I is nuclear interaction length) have been explored. Values of λ_I are taken from [3].

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2 YIELD AND TARGET HEATING STUDIES

For the collection geometry described in the previous section, target composition, length and radius are varied and pion yield is studied using particle production and transport simulation codes. The MARS code [4], developed over many years at IHEP and Fermilab for particle-matter interaction simulations, is used for simulating particle production and transport in thick targets within the solenoid field. The MARS code is also used to study energy deposition in the target and surrounding solenoid. In excess of 90% of all accepted muons are found to be the progeny of pions in the momentum range 0.05 - 1 GeV/c for both 8 and 30 GeV protons.

Materials investigated as target candidates are carbon, aluminum, copper, gallium, tungsten, iridium, mercury and lead. This set spans the Periodic Table and ranges in density from 1.8 to 22.4 g/cm^3. It is found [1, 2] that the pion yield is higher for high-Z materials, but saturates at $Z \geq 29$. At the same time, power dissipation grows rapidly with Z. Analysis shows that for the required beam parameters the only practical materials are those with $Z \leq 31$ (gallium or lighter). Copper and solid carbon have been studied in detail in [1, 2]. Below we concentrate on carbon/water and liquid gallium since they appear to have a desirable combination of thermal and yield properties in the proton energy range of 8 to 30 GeV. The π+K yield in the kinetic energy range from 0.05 to 2 GeV is studied for the above targets in the 20 T solenoidal field.

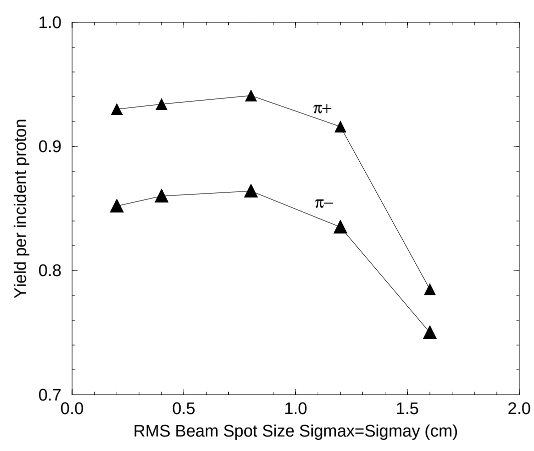

Figure 2: Positive and negative meson yields per 30 GeV proton for gallium target (R=3 cm, L=36 cm) *vs* rms beam spot size σ_x=σ_y.

It is found that pion yields are nearly optimized as long as the target radius R≈2.5σ, where σ is the rms beam spot size, for all target materials and lengths, at both 8 and 30 GeV. For the fixed target radius, the yield is slightly smaller for small beam spot sizes and drops rapidly at $\sigma \geq$ R/3 (Fig. 2).

Figures 3 and 4 show the yield versus target thickness for carbon and gallium targets. The optimal target length is about 1.2 to 1.4 λ_I, but yields vary by no more than 10% over a range of 1 to 2.5 λ_I.

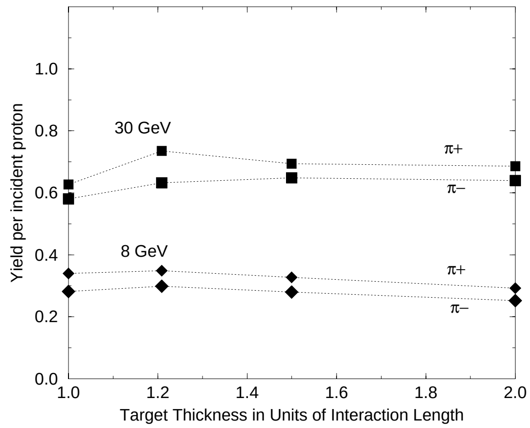

Figure 3: Positive and negative meson yields per one 8 or 30 GeV proton for a target composed of carbon disks (0.704 cm thick) with 0.15 cm water gaps *vs* target assembly thickness. Beam rms σ=0.4 cm. R_C=1 cm, R_{water}=4 cm, λ_C=53 cm, λ_{water}=91 cm.

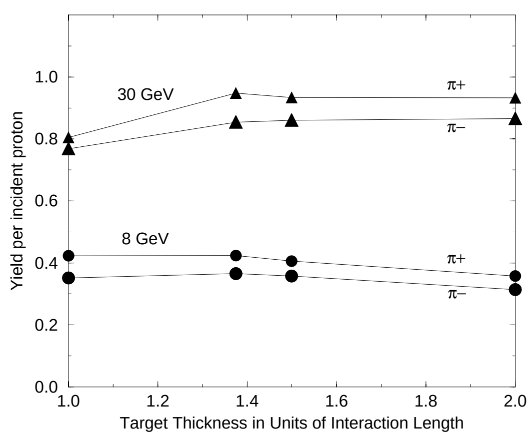

Figure 4: Positive and negative meson yields per one 8 or 30 GeV proton for gallium target (R=3 cm, λ_{Ga}=24 cm) *vs* target thickness. Beam rms σ=0.4 cm.

Beam power deposited in the target varies greatly with composition mainly due to increased electromagnetic shower development in high–Z materials. Because pion yield roughly doubles from 8 to 30 GeV, target heating studies were done using 1.5×10^{15} protons per second at 8 GeV and 7.5×10^{14} protons per second at 30 GeV to produce the same number of muons per second in the collider. This corresponds to beam powers of 1.9 MW at 8 GeV and 3.6 MW at 30 GeV. Due to the relatively short target lengths, only 5 to 15 percent of the beam power is absorbed by the target.

3 TARGET COOLING OPTIONS

The MARS calculations show the target energy deposition per pion produced increases linearly with target length for lengths more than one interaction length, and so, since the yield maximizes at lengths slightly in excess of one λ_I, the remaining calculations were typically performed for targets of length about 1.3 λ_I. A broad set of liquid targets as well as solid targets with forced cooling are considered. The best coolants include water and low-melting point alloys of gallium. Carbon is the best option for a surface-cooled, solid-cylinder geometry due to its relatively low heating power density. However, a large radius graphite cylinder is needed at these powers in order to have enough surface area for heat transfer to the cooling water which flows through the solenoid bore at 10m/s. There is a film drop ΔT_f =46°C across the target-coolant interface, so for an inlet temperature of 40°C the water temperature will approach 86°C at some locations.

A core-cooled bar with narrow water channels improves heat transfer for any solid target by increasing the heat transfer surface area. In this geometry, coolant channels may be drilled through the bar. The selected core-cooled design has the target sliced into disks (7 mm thick with a 1.5 mm coolant channel between adjacent slices), and the proton beam passes through the whole stack of these disks. This results in a smaller target radius (2.5 cm for carbon) with a water tank of only 4 cm radius at these beam powers. Water supplied at a flow rate of 19 liter/s is adequate to provide 3 m/s flow across the carbon disks, resulting in a maximum water temperature of about 75°C as shown in Fig. 5. The steady-state maximum disk temperature is about 110°C for both 8 and 30 GeV beams.

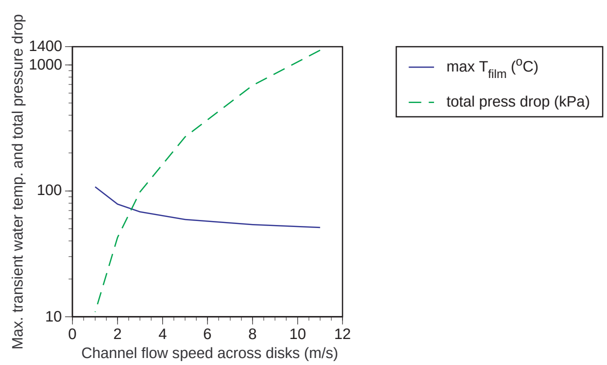

Figure 5: Maximum water temperature and pressure drop in 2.5 cm radius, 69 cm long carbon target for 8 and 30 GeV protons.

A liquid target circumvents the fatigue life limits associated with solid targets at high beam powers. A cylindrical tank of stagnant gallium could be inserted into the solenoid bore and cooled by concentric loops of flowing water, immersed in the liquid metal. This approach eliminates all MHD pressure drops, since the liquid metal is not flowing through the magnetic field. The preferred liquid target option however, is the simplest system: the Ga serves as the coolant as well as the target. In this target geometry, inlet and outlet headers flow the liquid gallium parallel to the solenoid's magnetic field in order to minimize the MHD pressure drops. Within the niobium alloy tank (3 cm radius), the gallium flows a short distance across the magnetic field at a slow speed (less than 0.1 m/s). A volumetric flow rate of 1.2 liter/s is adequate to keep the outlet temperature at 248°C (for the higher power, 30 GeV beam) with a total pressure drop of 176 kPa (see Fig. 6). Extensive experimental work at Argonne has shown that a thin ceramic coating (*e.g.*, 10 μm Al_2O_3) inside the tank will essentially eliminate the MHD portion of the pressure drop (Fig. 6). Alternatively, flow control and MHD pressure reductions are possible by tank geometry modifications and/or electric biasing [5].

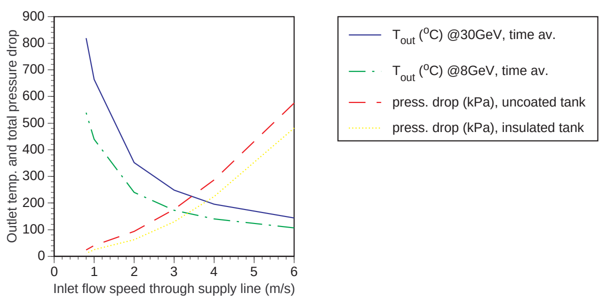

Figure 6: Outlet temperature and pressure drop in a 3 cm radius, 33 cm long liquid gallium target in a metal tank irradiated by 8 and 30 GeV beams.

4 CONCLUSIONS

For a 30 GeV proton driver with 12.5×10^{12} protons/bunch, gallium yields 10.6×10^{12} pions/bunch while graphite yields only 7.7×10^{12} pions/bunch. At 8 GeV, these yields are about a factor of two lower. Using a large beam and target radius (2.5 - 3 cm) reduces the maximum pulsed energy density to 10 J/g in graphite and 20 J/g in gallium, minimizing shock damage. A gallium target is about half the length of a graphite assembly, possibly reducing costs of the high field solenoid. It is desirable to operate coolants at pressures less than 400 kPa to reduce the likelihood of leaks and loss of flow accidents (LOFA). The graphite performance here assumed unirradiated properties, but thermal conductivity, shock and fatigue resistance may deteriorate with beam fluence.

For solid targets water cooling is simplest, but operation near boiling can result in possible overpressure failure with LOFA and water leaks will introduce high vapor pressure (V. P.) coolant to the vacuum. Tritium production and removal must also be considered in water cooled systems. Liquid gallium has several useful properties for high power targetry including a very large temperature margin to boiling (less sensitive to LOFA), extremely low V. P. and low reactivity in air and water. It is also safe to handle. To minimize corrosion, gallium should be kept below 350°C. We have not performed detailed calculations for pressure and flow behavior in high magnetic fields or activation of gallium at high proton fluence. In summary, either water cooled, solid carbon disks or liquid gallium can probably be used as targets in a muon collider source.

5 REFERENCES

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