Targets and Magnetic Elements for Pion Collection in Muon Collider Drivers

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Abstract. We review quasi-achromatic magnetic focussing elements which collect pions produced in a target for transport into a π->μ decay channel, with features appropriate to the development of high energy muon colliders. We discuss how the collection and target requirements of a muon collider are different from and similar to existing secondary particle collection systems. We briefly discuss target technology issues.

Introduction

A muon collider at an energy of 2-4 TeV in the center of mass needs to collect of order a few million or more times as many muons per second as the present antiproton source at FNAL collects antiprotons, before the cooling process, in order to produce a large enough luminosity to discover the physics of interest at these energies ($L{\sim}10^{34}$ cm^{-2}sec^{-1}, and beyond). This large increase in secondary particle collection is feasible with: (i) an increase in the source driver intensity (targetted protons/sec to produce π->μ) and a lower proton driver energy, (ii) the intrinsically higher yield of pions per proton compared with antiproton yields, and (iii) higher efficiency collection of the secondaries. In this note, we discuss possible magnetic secondary particle collection elements which directly follow a target, which collect pions for transport into a muon decay channel (FODO and/or solenoid strong focussing). We discuss features appropriate to the development of high energy muon colliders, and how the requirements of a muon collider are different from and similar to existing situations.

The formation of high intensity, large momentum bite beams of secondary particles using magnetic elements has been widely developed at accelerator laboratories, especially for neutrino and muon beams, and for antiproton collection and cooling. The ideal collection system would have achromatic focussing at all production angles, for all momenta, azimuthal symmetry, and have a large depth of focus. To first order, the system of elements focusses point to parallel, from the target into the decay channel.

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The magnetic element will have an outer radius r_{max} sufficient to accept the pion beam divergence anticipated from the target. The accepted divergence is in general a target-energy dependent quantity, which may even include backward pions for a proton beam near threshold (E_p-m_p=T_p~750 MeV) and decreases with target proton energy (θ_{max}~30° at E_p~30 GeV). To increase the number of accepted pions, one would therefore like as large an r_{max} as feasible.

On the other hand, one would like to minimize the r_{max} necessary, both for cost (magnetic volume -> stored energy -> mechanical strength-> cost), and for minimizing beam cross-section. Thus one would like to make the distance of the magnetic element to the target proportional to r_{max} as small as possible.

In general, the maximum bend angle to be provided by the lens element is given by:

$$\theta_b \sim \sin\theta_b \sim 0.3 G r_{max} L/p \sim r_{max}/Z, \qquad (1)$$

where G is the effective lens gradient, L is its length, and Z is the distance from the target center to the lens center. To this approximation, θ_{max} does not depend on r_{max}, except when r_{max} is small, the effective focal length is small, and the different acceptance between the ends of the target becomes important. A large r_{max} also results in sensitivity to focussing errors. For a fixed r_{max}, the acceptance is therefore maximized by making the gradient as high as possible, and the lens as short as possible. To avoid focussing errors, it is also desirable for the target to lens distance to exceed the target length. Clearly, for many technologies, r_{max} and G_{max} are not independent. In general, the bend angle, and hence the focussing, is not independent of momentum, as in equation 1 above.

In the case of muon colliders, the targetting time (proton bunch length) is desired to be very short, typically 1 ns or less in order to reach a high luminosity in the collider. Therefore the active time of the lens may be shorter for this application than in many other secondary collectors, potentially lowering the cost of the energy store necessary to erect the focussing field, but raising the technical difficulty of the proton source and the target peak powers. Moreover, the repetition rate is desired to be high, depending on the driver, as high as 10-100 Hz in the case of a fast synchroton or other recirculating proton driver accelerator (say 3-30 GeV), or perhaps as high as CW in the 100's MHz in the case of a ~1 GeV linac, which elevates the average power of the energy-store for the lens fields .

A second feature of muon collider pion collection elements is the very large pion momentum bite needed, as much as ±100% about an average momentum in order to generate a sufficient flux of muons before ionization cooling.

We have therefore considered quadrupole triplets, magnetic horns (2 elements), Li lenses (2 elements), solenoids (tapered), and plasma channels.

Quadrupole Triplets

Quadrupole triplets are the simplest elements to construct with large R_{max}, but do not produce perfect images of the target in all transverse directions. They cannot match the field gradients of the other collection devices, when run DC. We have not considered pulsed triplets at this time.

Magnetic Horn Systems

Magnetic horns were developed to generate neutrino beams with a large density of particles per area at ~ 0.1-1 km from the target. They are excellent for collecting pions in terms of B·dl, but not over a short enough distance to create a beam of small cross-section. For example, the BNL horn system which produces toroidal magnetic fields of about 6 T with 300 kA of pulsed currents, requires nearly 8 m of space (Fig. 1). The resulting pion beam is ~ 30 cm or more in radius, for a modest momentum bite of ~15%. A typical magnetic horn system uses 2 horns, the first of which somewhat overfocusses the large angle particles, and the second of which brings them parallel.

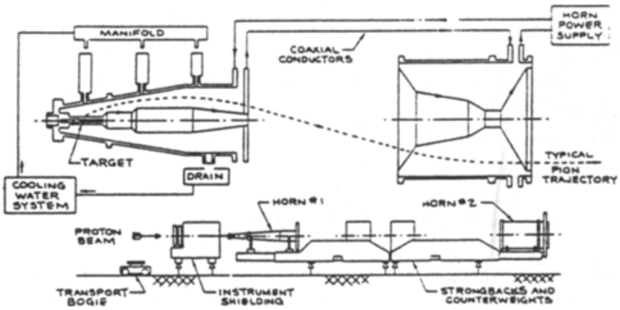


Figure 1. Magnetic horn system at BNL, from reference [2]. Note the large size.

A typical horn has a current distribution shown in Figure 2a and creates an axisymmetric parabolic magnetic field as shown in Figure 2b [1], with a dependence

$$B_{\phi} = \mu_0 I/2\pi r. \quad (2)$$

A particle from the target traversing the horn, diverging at a polar angle θ, receives a deflection:

$$\theta = (1/B_0) \int B_{\phi} ds. \quad (3)$$

Since the path length in a parabolic horn is proportional to r^2, the deflection will be proportional to r, as in a linear focus lense. The current is chosen to so that the deflection cancels the initial divergence θ.

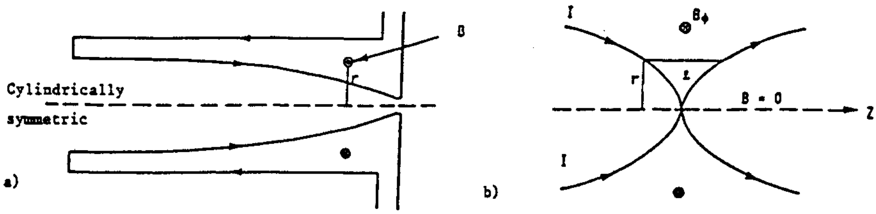


Figure 2a, b: The current profile and parabolic magnetic field shape in a typical parabolic horn, from reference [1].

Magnetic horns cannot be thought of as thin lenses because of their length. A typical horn system is ~ 2.5-3 times worse than an ideal lens [2]. Also, about 30% of the particles are lost in the Al web of the horn. Current magnetic horns have lifetimes of $\sim 10^4$-10^5 pulses before failure because of stress fatigue. Even 10^6 shots would be unacceptable for a muon collider with a 30 Hz driver repetition rate (~ 10 hours of operation). Magnetic horns are proven in general, but cannot match the gradients of a system of Li lenses.

Lithium Lenses

In the most analogous case to that of the muon collider, the antiproton accumulators at Fermilab[3] and CERN[4], the primary collection element of choice is a lithium lens. A Li lens is a cylindrical piece of Li with a large axial current. Lithium is chosen for the obvious advantage of long nuclear absorption and radiation lengths, with relatively good resistivity and skin depth. The field produced by a constant current density J is:

$$B = \mu_0 J r/2 \tag{3}$$

where r is the radius at which the field is sampled by the pions. The field is thus proportional to the radius, which results in focussing, and has an important advantage over A.G. focussing in that the horizontal and vertical (x,y) planes are focussed in the same device. The lens gradient is therefore the constant:

$$G = \mu_0 J/2 \tag{4}$$

Figure 3 shows the field configuration and trajectory of a particle within the lens. A particle diverging with angle $\tan\theta = dx/ds$ will be determined by an equation of motion:

$$\frac{d\sin\theta}{ds} = (e/p)B = [e\mu_0 J_0/2p]\, x \tag{5}$$

Solving for x, x', for small angles, gives:

$$x = x_o + x_o' \sin\sqrt{k}s, \quad x' = x_o \cos\sqrt{k}s, \tag{6}$$

which is the equivalent to a lens of strength:

$$k = 1/2\,(e\mu_o/p)\,J \tag{7}$$

A particle produced at $x = z = 0$ with a production angle θ_x will project to $z = 0$ with an $x = -z\,\theta_x/2$. For a given θ_x, $z < \pm L\theta_x/2$, where L is the target length along z. The critical strength per unit length which removes the depth of focus problem of a normal lensed target which is given by

$$k = (\pi/L)^2, \tag{8}$$

where L is the target length. With this strength, the beta of a subsequent beam transport is matched at

$$\beta = 1/\sqrt{k} \tag{9}$$

The further inclusion of smearing from proton beam size and multiple scattering will demand a short target for efficient use of the lens. The disadvantage compared with quadrupoles is the passage of the particles through lithium and the windows of the device.

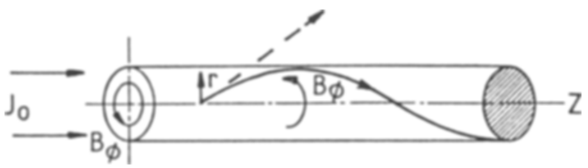
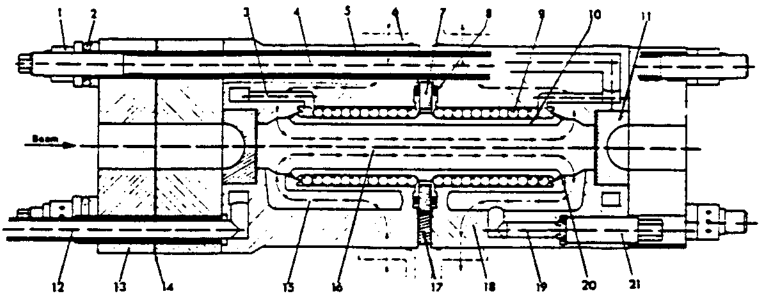


Figure 3: Field configuration and particle trajectories of a Li lense, from reference [1].

At CERN and FNAL, gradients of 800 T/m have been achieved, but in an r_{max} of only 1 cm in a 10 cm length. A prodigious current density of ~ 130 kA/cm^2 is necessary, with a total current of ~400 kA. The time constant must be long enough to allow the fields to penetrate the Li, but not so long as to deposit enough energy by Ohmic losses (~10 kJ/pulse) to exceed the physical limitations of the Li or the electrical leads. This half-sine wave time is ~0.1-0.3 ms minimum and < ~1-3 ms maximum. At FNAL, the magnetic (Jx**B** body forces) and thermal stresses (~150 MPa) produce stresses in the cooling jacket of order 0.5 GPa. These will scale with the lens area ~ r^2. Figure 4 shows a schematic of the CERN Li lense [5].



_. Cross-section of the lens.

1. Titanium nut
2. Silicon nitride spheres (∅=0.35 cm)
3. Cooling inlet channels
4. Titanium tie bolts
5. Alumina insulation
6. Current contact of transformer
7. Silicon nitride ring
8. Metal gaskets
9. Silicon nitride spheres (∅=0.5 cm)
10. Stainless steel container
11. Titanium window
12. Cooling inlet pipe
13. Insulated auxiliary flange
14. Insulating mica disc
15. Lithium channels
16. Central lithium rod
17. Ceramic spacers
18. Steel housing
19. Pressure piston
20. Final weld after assembly
21. Sealing plug

Figure 4. Lithium lense from CERN, from reference [5].

For the muon collider, for 30 GeV protons incident, we are considering lenses with a total current ~8-10 times those currently in use (4 MA), a length 2.5-3 times current technique (25-30 cm) , radius ~8-15 times existing lenses (8-15 cm radius), current density ~0.2-0.1 times current technique (15-4 kA/cm^2), with repetition rates ~20-25 times higher (~10 Hz). Figure 5 shows schematic of a possible target collection system with 2 lenses of 8(15) cm radius and lengths 25(30) cm long. The lenses are preceeded by an 18 cm long Cu target which is itself a lens, by passing 3 MA of axial current through it.

Using this lens system, a Monte Carlo using the Wang formula[6] for pion production for 30 GeV incident protons was run, using a 6 mm radius beam spot. At 30 GeV, about 1.2 π/proton are collected. The maximum angle of collected pions was about 500 mrad, with an average (maximum) p_T of about 0.3 (0.8) GeV, and an average pion momentum of 2.4 GeV. Reducing the energy by a factor of 3 reduces the pion capture by about a factor of 2. (The 6T pole-tip quadrupole FODO channel with a 40 cm periodicity for pion decay will be described elewhere. With 30 GeV protons incident, the number of muons collected per proton after the decay channel may be as large as $N_{\mu/p} = 0.25$. This implies that ~1 MW of 30 GeV protons is sufficient to generate ~ 5 x 10^{13} collected muons/sec.)

Substantial development work is necessary to prove the feasibility of this extrapolation of Li lens technologies. However, we note that:

(1) The resistance of the Li will be ~25-75 times lower than that of the FNAL lens, and the I^2R losses per pulse in the Li will be similar to or lower than the FNAL case, over a volume of Li hundreds of times larger than existing lenses, despite the larger current. With the repetition rates expected, the specific Power/Volume lost in the Li would be an order of magnitude lower than existing lenses;

(2) Much larger volumes of Li and liquid Li have been investigated experimentally for reactor cooling and fusion reaction heat exchange; and

(3) A gradient of 125 T/m would be achieved in the first lens, well-below the gradient used at FNAL of ~800 T/m. At FNAL, a surface field on the Li of ~8 T is used, similar to the 10 T is used in the muon collider design.

If lower production energies are chosen (<30 GeV E_p), then the peak current parameters of the Li lens may be relaxed.

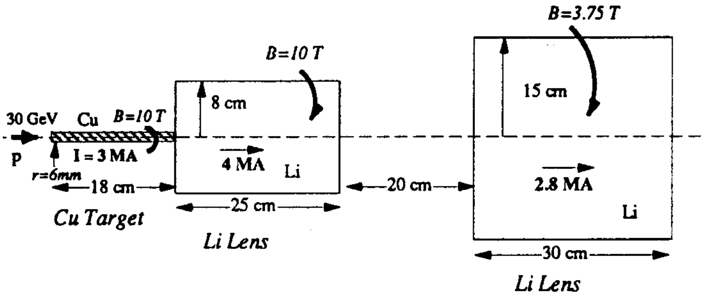


Figure 5. Example of a Li lens schematic system proposed for a muon collider pion collection element.

Solenoids

Solenoidal focussing becomes promising at low particle momenta where eLβcBsinθ is significant compared with p_T or at large angles where the bending force is effective, where L is the length along z of a solenoid of field $B=B_z$. Modern solenoids may achieve very large axial fields, and for pions (as compared with heavier particles), the solenoid becomes attractive an attractive lens compared with quadrupole triplets, especially because of the symmetric focussing and long depth of focus.

Particles enter the lens first through radial magnetic fields and then an axial field. The radial field gives an azimuthal force $ev_z \times B_r$ and the resulting v_ϕ leads to a radial force when crossed with B_z inside the solenoid, leading to a lens condition of net deflection towards the axis independent of the sign of the charge or transit direction. As it leaves the lens, the conservative force cancels out this radial velocity, but leaves a fixed rotation. For constant B_z, the rotation in the lens from the conserved azimuthal forces $\Delta\phi$ is approximately [7]:

$$\Delta\phi = \phi-\phi_o = (qB_z/2p)\Delta z \quad (10)$$

The longitudinal derivative of a track in the uniform solenoid is proportional to:

$$v_r/v_z \sim \int dz\, (qB/p)^2 r/4 \quad (11)$$

from which a focal length f is derived as:

$$f^{-1} = \int dz\, (qB_z/p)^2/4 \tag{12}$$

with

$$\theta = v_r L/v_z r \tag{13}$$

and with lens strength

$$k = eB_z/2p \tag{14}$$

The focal length is inversely proportional to the square of the gyroradius and the field must increase proportionally to the momentum. The lens gives a real focus, independently of the direction of the magnetic field. The focussing is second order, resulting from a small azimuthal velocity crossed into the axial field, with strength $\propto B_z^2$. The lens is said to be "weak" if $eB_zL/p = 2kL << \pi$. The effective gradient is $G \sim B\sin\theta_{max}/r_{max} \sim B(r_{max}/L)/r_{max} \sim B/L$, for small r/L. Figures 6a, 6b show the geometry of the the transverse motion of a charged particle in a uniform solenoidal field(6a), and the radial fields and forces (6b) of a end of a solenoid[8].

While solenoidal lensing is most effective on electrons because of the mass effect, the pion is light enough that solenoidal focussing for pion collection can be competitive at momenta characteristic of pion production kinematics at lower proton energies, from threshold to roughly 10 GeV. Moreover, the target can be immersed in the lens.

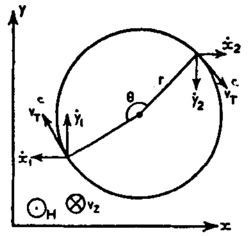


Figure 6a: Geometry of the the transverse motion of a charged particle in the uniform field of a solenoid , from reference [8] .

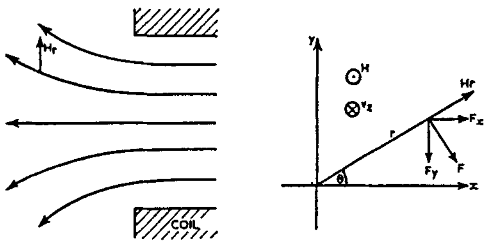
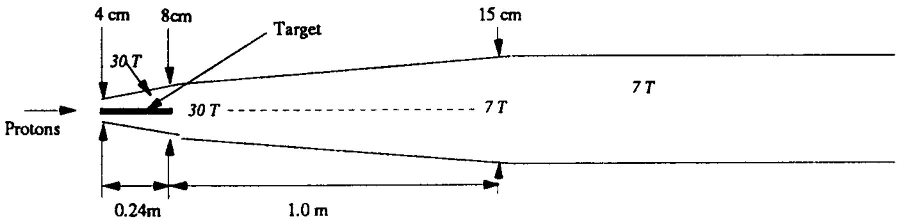


Figure 6b: Geometry of the the fields and forces on a charged particle at the end of a solenoid (axial view), from reference [8] .

High field, large volume solenoids are now possible. DC superconducting solenoids with large bores ~50 cm - 2m radius achieve ~8-4 T with lengths up to ~5-10 meters possible (as used in several varieties of plasma or fusion experiments and in high energy colliding beam detectors). With warm bores, a ~1.5 cm radius, 40 T field is possible over a 10 cm axial length [9].

We considered a solenoid system which starts at 30 T, 8 cm radius, 24 cm long, with an immersed 24 cm Al target, and tapers from 30 T to 7 T over a 1 m length, tapering up to an exit bore of 30 cm in diameter (Fig. 7). The final solenoid is 7T with a 30 cm diameter bore, of arbitrary length. A Monte Carlo of the collection efficiency at E_p=10 GeV gives the same number of pions captured per proton as in the Li lens case described above, $N_{\pi/p}$ = 0.67 at 10 GeV. (After a solenoidal decay channel, to be described elsewhere, the N_μ per proton roughly matches or slightly exceeds that of the Li Lens system described above for targetted protons between 30-100 GeV. For incident protons of 10 GeV and below, the collection efficiency $N_{\mu/p}$ ~0.23 (10 GeV) exceeds that of a Li lens by factors of 2 or more.)



Tapered Solenoid Lens

Figure 7. Schematic of a tapered solenoid pion collection system.

The non-pulsed nature of a superconducting or superferric solenoid is extremely attractive, but at present, it is unkown whether such a system can operate in the radiation field and loss conditions downstream of a target which is accepting 1-2 MW of average beam power, and peak powers of ~10^{14} W. However, it seems feasible to make large diameter conductors which are heavily shielded, with warm bores. Alternatively, pulsed solenoids (example: Bitter-type) of non-superconducting materials may be contemplated.

Plasma Lenses

A plasma channel conducting large axial currents produces a toroidal magnetic field similar to that of a lithium lens, but with a much lower mass density than Li, and the potential for larger currents over large axial lengths [10]. An example which might be applicable is the spark- or Z- channel, as sketched in Fig. 8. Examples conducted ~200 kA over 50 cm, and 75 kA over 5 m at a gas pressure of ~1-10 Torr. It consists of annular plates serving as cathode and anode for the discharge, inside a vacuum chamber filled with a light or heavy gas (Argon + others). A laser preionizes and heats a conducting channel to strike the arc. The channel radii are typically 1 cm and larger, up to ~10 cm, well-matched to typical target conditions where a Li lens would be used.

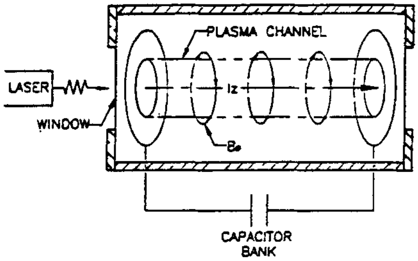


Figure 8. Schematic of a plasma channel (spark- or Z- channel) which may be adaptable as a lens for a muon collider [10].

A Z-pinch has conducted 2.8(10) MA over 20(3) cm with pulses 10's of ns long in milliTorr pressures, but in very small radii (~ well-less than 1 mm in the pinch), and could only be used very near the target, in the later stages of ionization cooling, or possibly for the muon storage ring insertion section focussing. (This has some similarities to the plasma lens final focus concept at electron linac colliders).

These speculative examples may even offer the possibility of "electron cooling" pions or muons when the velocity of the plasma conduction electrons matches that of the muons or pions[10], in the case of the Z-channel. Recent estimates require 3 km at 10 MA to bring a muon into equilibrium with the plasma.

Target Issues

The shortest possible target maximizes the phase space density of pions, and thus targets of heavy nuclei are desired. Unfortunately this also maximizes the specific energy density deposited in a target which may lead to failure. In Cu, a typical number is of order 1.5 MeV per cm of target per GeV per proton, for proton energies above ~10 GeV[11]. The energy deposition scales as $\sim Z^2$ (mainly because of electromagnetic processes); in W, this number rises by a factor of ~9.

In one example, a 10 Hz, 30 GeV, 3 x 10^{13}/pulse, 1 ns long bunch proton beam has been proposed for the muon collider driver. In 7 cm of Cu, 16 kW would be dissipated, which is feasible but difficult (13 times that of the CERN antiproton source). However, the specific energy density may easily exceed the local ability to extract heat. Using a large beam spot of σ=1 mm, about 7 times larger than the beam spot at FNAL, about ~0.06 GeV/g/proton is deposited in Cu, ~ 300 kJ/g per pulse at 3 x 10^{13} protons per pulse. Using:

$$\Delta E \sim C_v \Delta T \sim C_v(T\text{-}300°K), \qquad (15)$$

one finds T ~ 1,100 K°, approaching the melting limit in Cu but quite tolerable.

The short deposition time (~ 1 ns) compared with the sound velocity (scales as thermal conduction) prevents cooling from affecting this conclusion. Indeed, the short deposition time leads to thermal shock, and a resulting overpressure. The target maximum pressure P from an energy deposition E in a material with density ρ is estimated from Gruneison's equation[12] and Gruneison's constant γ as:

$$P = \rho\gamma E \tag{16}$$

In the FNAL target for the antiproton collider, this pressure reaches 7 GPa, under beam conditions which are ~35x less in total deposition than might be envisaged for a muon collider at 1 mm spot radius. It may be required to use a rotating or replaceable target. A beam spot of 1 mm may be at the limits of tolerability for most efficient imaging for pion collection, although in Monte Carlo, 6 mm spot-sizes seem to be tolerable, and reduce the instantaneous energy density to tolerable limits. To reduce aberration in the collection system, a shorter W-Rh target with interspersed graphite disc shock dampers as used at CERN may be contemplated[13].

Another target technology to increase pion collection is to pulse a conducting target (Cu) with a large axial current (3 MA), creating a toroidal lens-target, as shown schematically in Fig.5, and studied in the Monte Carlo of pion collection. This type of combined lens-target has been successfully tested at CERN at 100 kA, using W, Cu, Al and related alloys, in lengths of about 10 cm[14]. Prestressing and cooling proved essential. The extra Ohmic losses and radiative enhancement of target dissipation from captured electrons have not been been included in our target design at this time.

Conclusion and Experimental Plans

A pion collection system using Li lenses is attractive for proton energies on the production target above ~20-30 GeV. Between threshold and 10-20 GeV for the proton driver energy, solenoid collectors may offer some advantages over Li lenses, provided that the radiation hardness of superconducting systems can be demonstrated. The hardware proposed is a reasonable extrapolation from existing technologies.

For the future, we will consider proposals to:

(a) Design and construct a large Li lens, at least 20 cm in diameter and 25 cm long, with at least 1 MA current.

(b) Design and construct a 20-30 T solenoid, >10 cm diameter x >1 m long (stored energy ~1 MJ), with sufficient radiation shielding, thermal protection and thermal reservoir to accept pulses on a 5 cm Cu target directly in front of the solenoid.

(c) Design and construct pulsed Cu or other targets in lengths between 7 cm and 18 cm, with at least 1 MA of axial current.

(d) Conduct beam tests with the targets, lenses and solenoids at proton energies between 0.8-30 GeV to measure the pion collection optics, stability and reliability.

A by-product of tests could be a measurement of the pion yields at energies and angles appropriate to muon collider cooling channels, at each proton driver energy, and for several targets. Surprisingly, a comprehensive set of directly comparable data on pion yields (both charges, similar target materials and lengths, similar phase space) over a kinetic energy range of 0.8-30 GeV incident protons apparently is not available in the literature.

Acknowledgements

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