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Pion Production and Targetry at $\mu^+\mu^-$ Colliders

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Abstract

Results of simulations of pion production and power dissipation by 8 to 30 GeV proton beams in co-axial and tilted targets of liquid gallium and platinum oxide, placed in a 20 T solenoid, are reported. Pion and muon distributions are followed through the matching solenoid and decay channel.

Introduction

The proposed $\mu^+\mu^-$collider complex [1] includes a rapid cycling (15 Hz) synchrotron which produces protons—up to 10^{14} per pulse—in the 8–30 GeV range. These protons are focused on a production target from which pions are collected and steered down a decay pipe where they produce the desired muons. 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, 3]. Targets of varying composition ($6< Z <82$), radii (0.4–3 cm) and thicknesses (0.5–3 nuclear interaction lengths (λ_I)) have been explored. This paper presents a sample of new results on pion production and target behavior with particular attention to the dependence of these results on tilt angle of the target with respect to the solenoid axis.

Target and Solenoid

The aperture of the 20 T solenoid is assumed to be 7.5 cm which results in transverse momentum acceptance ($p_\perp^{max} = |q|Ba/2$, with B the magnetic field, q the particle charge, and a the solenoid radius) of 0.22 GeV/c. The normalized phase space acceptance ($ap_\perp^{max}/\ m_\pi c = |q|Ba^2/2m_\pi c$) of this solenoid for pions is 0.12 m·rad.

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The MARS code [4], is used to simulate particle production and transport in thick targets within the solenoid field as well as to study energy deposition in the target and surrounding solenoid. The current version includes a newly developed phenomenological model for pion production in hadron-nucleus interactions [5], that exhibits superior description of the pion production for 6 to 120 GeV/c protons compared to previous studies using ARC, MARS, DPMJET, FRITIOF and GEANT codes. In excess of 90% of all accepted muons are found to be the progeny of pions in the momentum range 0.05 - 0.8 GeV/c for 8 to 30 GeV protons. Ref. [6] suggests that tilting the incident proton beam and target with respect to the solenoid axis can increase pion yield. This idea is examined in some detail here. The tilted target geometry is shown in Fig. 1(a). Fig. 1(b) shows the dependence of energy deposition in the target and in the 2-cm innermost region of the solenoid coils, for three different targets $1.5\lambda_I$ long: (i) gallium (R=3.2 cm, beam $\sigma_{x,y}$=1 cm, $\sigma_{x',y'}$=0), (ii) Ga (R=1 cm, $\sigma_{x,y}$=0.4 cm) and (iii) Platinum oxide (R=1 cm, $\sigma_{x,y}$=0.4 cm). All three targets are co-axial with the solenoid. Power dissipation in the targets grows almost linearly with beam energy, being smallest in the 1-cm radius Ga target. Power dissipation in the inner layer of the solenoid coil also grows monotonically with energy, though at a much slower rate, and is roughly the same for the three cases. Total power deposited in the entire solenoid section around the target—and of equal length—is about 2.5 times that shown in Fig. 1(b).

π/μ Production and Collection

The energy spectrum of the produced pions peaks at about 0.05 GeV after which it declines rapidly with energy. Most $\pi(\mu)$ producing/cooling scenarios therefore concentrate on rather low energies, typically $E_\pi < 0.5$ GeV. Tilting the target

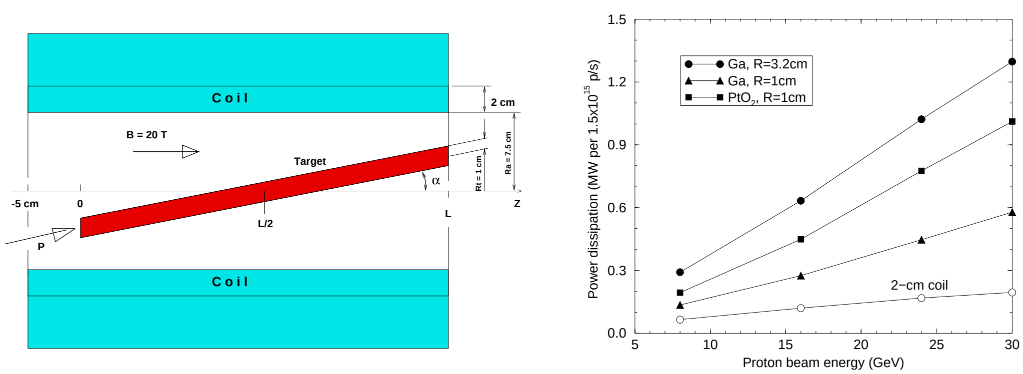

Figure 1: (a) Schematic view of a tilted target in solenoid; (b) Power dissipation in various targets and surrounding solenoid *vs* proton energy.

with respect to the solenoid axis helps low energy pions escape the target through their Larmor motion, with reduced secondary interactions, energy loss, and multiple scattering—but has little effect on higher energy pions. A tilted target also offers a convenient way to dispose of the remnant proton beam after target traversal. The effect on yield is demonstrated in Fig. 2(a) which shows ratios of π^+ produced by a 16 GeV proton beam ($\sigma_{x,y}$=1 cm) in tilted versus untilted liquid Ga targets (L=33 cm, R=3.2 cm) as a function of pion momentum at target exit for pions traveling within 500 mrad with respect to the solenoid axis. Targets tilted up to 150 mrad show mostly increasing yields at low pion energies but with little or no effect for pions above 0.4 GeV/c. The effect is more pronounced for the thinner platinum oxide target (open jet of L=35.8 cm, R=1 cm) as illustrated in Fig. 2(b) which shows yield ratios of π^- versus pion momentum for a 16 GeV proton beam ($\sigma_{x,y}$=0.4 cm). The improved yield for PtO_2 vis-a-vis Ga most likely results because of (i) increased multiplicity and lower average energy of the pions in the heavier target and (ii) smaller target radius (1 *vs* 3.2 cm) which is beneficial via the spiraling-out mechanism. Fig. 3(a) presents yields integrated over momentum between 0.05 and 0.8 GeV/c for a set of $1.5\lambda_I$ long targets (R=1 cm, beam $\sigma_{x,y}$=0.4 cm) ranging across the periodic table and for three different proton energies. The increase in yield with mass number is quite pronounced at 30 GeV while hardly noticeable at 8 GeV. Yield is higher for larger solenoid aperture. For the 150 mrad tilted PtO_2 target and for 0.05$< p_\pi <$0.8 GeV/c yield grows from 0.58 to 0.75 for π^+ (and very nearly the same for π^-) as the aperture increases from 7.5 to 15 cm radius. Fig. 3(b) shows yields (0.05$< p_\pi <$0.8 GeV/c) for the 200 mrad tilted PtO_2 target (R=1 cm, $\sigma_{x,y}$=0.4 cm) and co-axial Ga target (R=3.2 cm, $\sigma_{x,y}$=1 cm) irradiated with a 16 GeV proton beam as a function of target thickness.

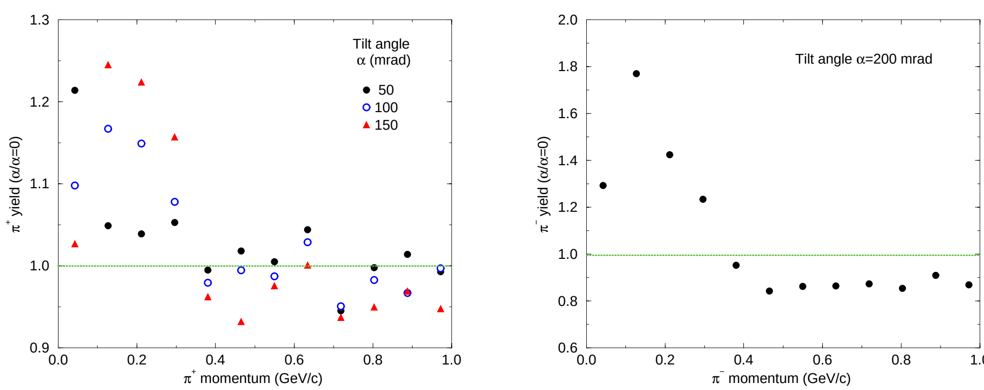

Figure 2: (a) Ratio of π^+ yield from Ga target tilted by 50, 100 and 150 mrad to that for untilted target *vs* p_π for 16 GeV protons; (b) same for π^- from PtO_2 target at α=200 mrad.

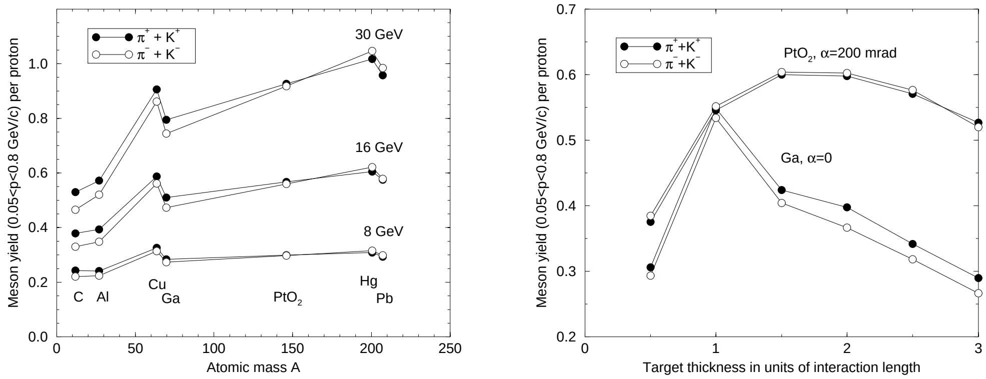

Figure 3: (a) Yield from $1.5\lambda_I$ 1-cm radius target irradiated with 8, 16 and 30 GeV proton beam as a function of target material; (b) Yield from 200 mrad tilted PtO_2 target (λ_I=17.9 cm) and co-axial Ga target (λ_I=24.2 cm) irradiated with a 16 GeV proton beam *vs* target thickness.

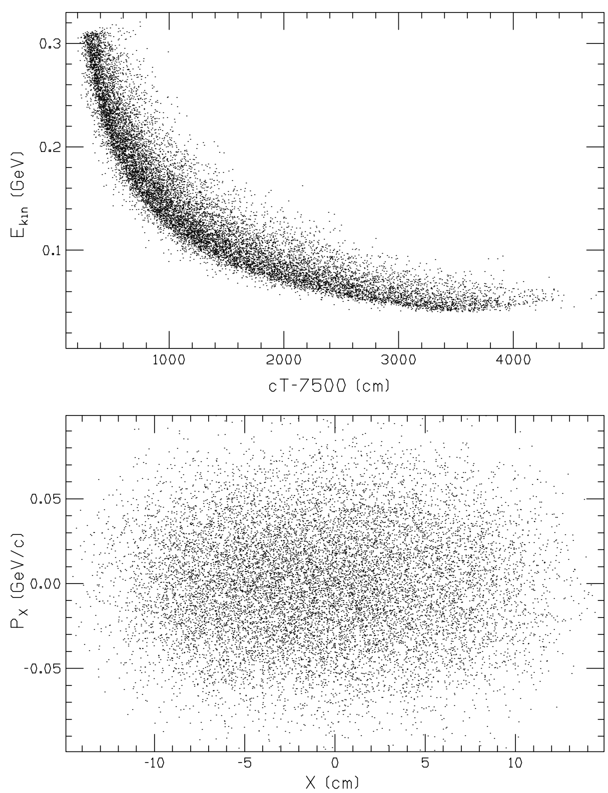

Figure 4: Longitudinal (top) and transverse (bottom) phase space plots of $\mu^{\pm}$ within 0.1$< p_z <$0.4 GeV/c cut 75 m downstream of a 200 mrad tilted PtO_2 target.

Following the target is a solenoid with decreasing field and increasing aperture. After a distance of 1–2 m both field and aperture are once again held constant at 5 T and 15 cm radius in the present simulations. The decay channel may be equipped with RF cavities to rotate the phase space prior to cooling. For results reported here no cavities are present. Pions and muons are propagated through the decay channel as in ref. [2] with decay of π and μ as well as aperture restriction taken into account. Table 1 shows the maximum yield of muons after 75 m in the decay pipe for all surviving muons as well those within a 0.1$< p_z <$0.4 GeV/c cut, i. e., those assumed to be most amenable to cooling. The gains from tilting the Ga target are considerably less here than for pions immediately after the target. Perhaps lower field/larger aperture solenoids in the target region might better accommodate the tilted targets. Fig. 4 shows longitudinal and transverse phase space plots of muons of both signs within the (0.1$< p_z <$0.4)-cut 75 m downstream of a 200 mrad tilted PtO_2 target. Phase space plots of the other cases discussed here have quite similar appearance.

Table 1: Muons in Decay Pipe after 75 m

Target, tilt(mrad)		0.1$< p_z <$0.4		Total	
		μ^+	μ^-	μ^+	μ^-
Ga	0	0.222	0.214	0.420	0.382
Ga	200	0.230	0.232	0.394	0.373
PtO_2	200	0.266	0.273	0.438	0.432

Conclusions

For low beam energy ($\leq$ 8 GeV) any target material with A $\geq$ 50 offers roughly the same pion yield. Power dissipation appears low enough to accommodate many target choices. At 16 GeV higher-A targets yield more pions but power absorption becomes the primary concern. Either liquid Ga inside a pipe or an open PtO_2 jet is a good choice. Yields are optimum for target about 1.5λ_I long and with radius of about 2.5 times $\sigma_{x,y}$ of the beam. Tilting the target at 150–200 mrad increases yields and allows ready disposal of the spent proton beam. The present study shows that smaller target radius, larger solenoid aperture, and higher solenoid field all help increase yield.

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