Fermilab FERMILAB-Conf-00/208 September 2000

Particle Production for a Muon Storage Ring: I. Targetry and π/μ Yield [⋆]

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Abstract

Efficient production and collection of a large number of muons is needed to make a neutrino factory based on a muon storage ring viable. Results of extensive MARS simulations are reported for 2 to 30 GeV protons on various targets in a 20 T hybrid solenoid, followed by a matching section and decay channel. Part I describes pion and muon yields, targetry issues, and beam energy and power considerations. Part II describes radiation loads on targets, the capturing system and shielding.

Key words: Neutrino factory, targets, beam capturing, pion and muon yield
PACS: 41.75.-i, 85.25.Ly, 87.18.Bb, 87.53.Wz

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1 Introduction

To achieve adequate parameters of a neutrino factory based on a muon storage ring [1] it is necessary to produce and collect large numbers of muons. The system starts with a proton beam impinging on a thick target sitting in a high-field solenoid (20 T, 1-m long, aperture radius R_a=7.5 cm), followed by a 3-m long matching section and a solenoidal decay channel (1.25 T, 50-100 m in length, R_a=30 cm) which collects muons resulting from pion decay [2,3]. Optimization of beam, target and solenoid parameters were done over the years with the MARS code [4,5] for a $\mu^+\mu^-$collider project [2,3,6–9]. This paper focuses on parameters needed for a muon storage ring and briefly describes the results of extensive MARS simulations of π/μ-yield (Part I) and radiation fields in the target station and capturing system (Part II) for 2 to 30 GeV proton beams. Preliminary results were given in Ref. [1,9].

[⋆] Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH00300 with the U. S. Department of Energy.

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Preprint submitted to Elsevier Preprint *24 August 2000*

2 Captured π/μ beam *vs* target and beam parameters

Realistic 3-D geometry together with material and magnetic field distributions based on the solenoid magnet design optimization have been implemented into MARS. Graphite (C) and mercury (Hg) tilted targets were studied. A two interaction length target (80 cm for C of radius R_T=7.5 mm and 30 cm for Hg of R_T=5 mm) is found to be optimal in most cases, keeping $R_T \geq 2.5\ \sigma_{x,y}$, where $\sigma_{x,y}$ are the beam RMS spot sizes. The calculation model (Fig. 1), keeping the main features of the baseline design [8,9], has been significantly refined in the course of the study [1]. A deviation of B_z and B_r (Fig. 1 (right)) from the ideal field [8,9], results in the reduction of the π/μ-yield in the decay channel by about 7% for C and by 10-14% for Hg targets.

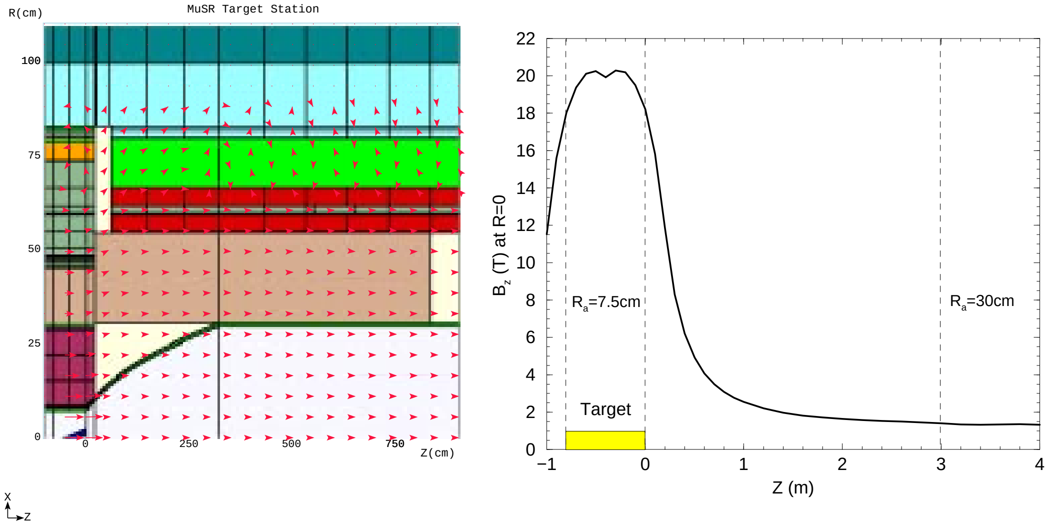

Fig. 1. MARS model of the target/solenoid system (left) and B_z field profile (right).

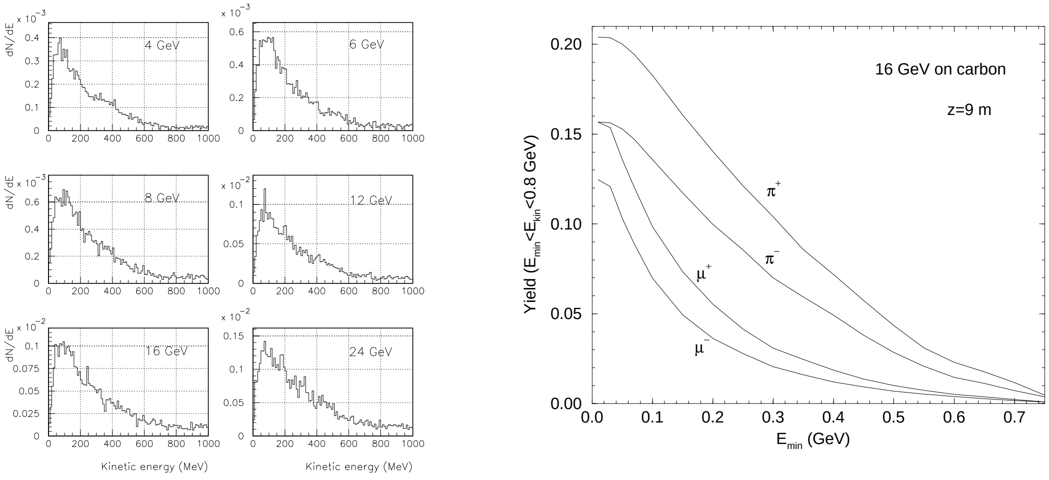

Fig. 2. Energy spectra of $\pi^+ + \mu^+$ for 4 to 24 GeV protons (left) and numbers of particles in the (E_{min}–0.8 GeV) interval *vs* E_{min} for 16 GeV protons (right) at z=9 m for a 80-cm C target (R_T=7.5 mm, α=50 mrad).

Results of a detailed optimization of the particle yield Y are presented below, in most cases for a sum of the numbers of π and μ of a given sign and energy interval at a fixed distance z=9 m from the target. It turns out, that for proton energies E_p from a few GeV to about 30 GeV, the shape of the low energy spectrum of such a sum is energy-independent and peaks around E=130 MeV, where E is π/μ kinetic energy (Fig. 2). Moreover, the sum is practically independent of z at $z \geq 9$ m—confirming a good matching and capturing—with a growing number of muons and proportionally decreasing number of pions along the decay channel. For the given parameters the interval of 30 MeV<E<230 MeV around the spectrum maximum is considered as the one to be captured by a phase rotation system.

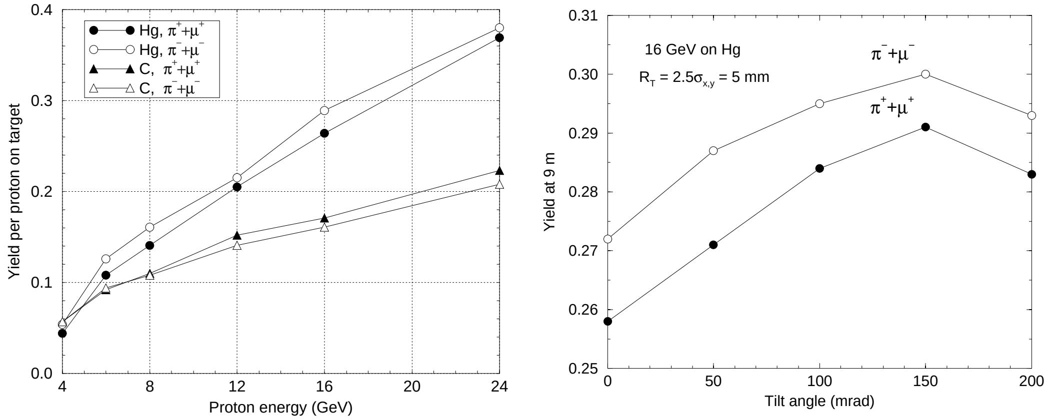

Fig. 3. Yield from Hg and C targets *vs* E_p (left) and yield from a Hg target at E_p=16 GeV *vs* tilt angle (right).

The yield Y grows with the proton energy E_p, is almost material-independent at low energies and grows with target A at high energies, being almost a factor of two higher for Hg than for C at E_p=16-30 GeV (Fig. 3). To avoid absorption of spiraling pions by target material, the target and beam are tilted by an angle α with respect to the solenoid axis. The yield is higher by 10-30% for the tilted target. For a short Hg target, α=150 mrad seems to be the optimum (Fig. 3), while α=50 mrad is chosen in Ref. [1] for a long C target to locate a primary beam dump at ~6 m from the target. Fig. 4 shows the dependence of the yield on Hg and C target radii under the baseline $R_T = 2.5\sigma_{x,y}$ condition. Figs. 4 and 5 show that maximum yield occurs at target radius R_T=7.5 mm for C and R_T=5 mm for Hg targets with $R_T = 3.5\sigma_{x,y}$ and $R_T = 4\sigma_{x,y}$ conditions for the beam spot size, respectively. The baseline criterion $R_T = 2.5\sigma_{x,y}$ reduces the yield by about 10% for the graphite target, but is more optimal from the energy deposition point of view (Fig. 5).

The ratio of Hg to C yields varies with the beam energy, as well as with other beam/target parameters. At 16 GeV it is in the range of 1.5-1.7 for positives and 1.7-2.2 for negatives. Optimizing beam/target parameters, it is found that the best results for the particle yield in the decay channel at 16 GeV with the given cut are: $Y_{\pi^+ + \mu^+} = 0.182$ and $Y_{\pi^- + \mu^-} = 0.153$ for the 80-cm C target and

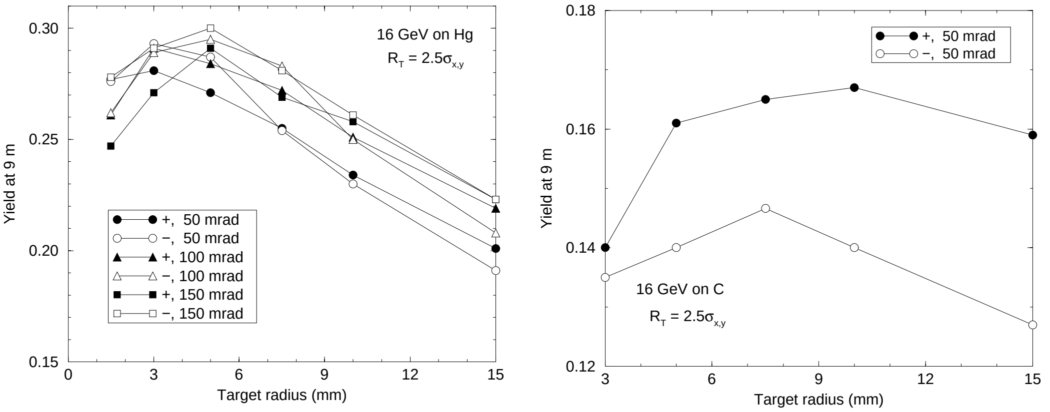

Fig. 4. Yield as a function of a target radius, Hg (left) and C (right), for a 16-GeV proton beam and several tilt angles.

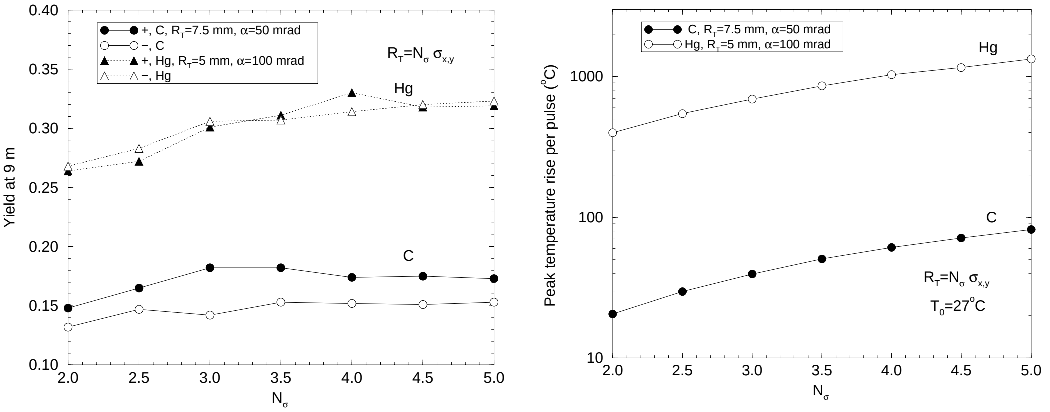

Fig. 5. Yield (left) and maximum instantaneous temperature rise (right) as a function of a target to a RMS beam spot size ratio (right).

$Y_{\pi^++\mu^+} = 0.309$ and $Y_{\pi^-+\mu^-} = 0.315$ for the 30-cm Hg target, i.e., at 16 GeV (best Hg)/(best C) = 1.7 (+) and 2.06 (-).

3 Beam power considerations

The yield per beam power is almost independent of E_p for high-Z targets at $6< E_p <24$ GeV and drops by 30% at 16 GeV from a 6-GeV peak for graphite (Fig. 6 (left)). The higher E_p reduces the number of protons on target. To provide $\mathcal{N}_\mu=2\times10^{20}$ muon decays per year in the straight section at 15 Hz, one needs to have 6×10^{12} muons per pulse in the decay channel, assuming a factor of 3 total loss on the way from the decay channel to the ring. With that, needed are 3.30×10^{13} and 3.92×10^{13} protons per pulse at 16 GeV on the optimal C target for positives and negatives, respectively. This corresponds to 1.27 and 1.51 MW beams. For a Hg target, these numbers are 1.7 and 2.06 times lower. Fig. 6 (right) shows the required number of protons $\mathcal{N}_p$ and beam power as a function of E_p for the C target, while Fig. 7 presents power dissipation and peak heating in the C target to provide $\mathcal{N}_\mu$=2×10^{20} muon decays per year. At 16 GeV, the peak instantaneous temperature rise is 60-70°C and power dissipation is 34.3 and 40.7 kW for the μ^+ and μ^- modes, respectively. For Hg targets, the required beam power is lower, 0.73-0.75 MW; however, the peak temperature rise per pulse is 750°C, because of higher energy deposition density.

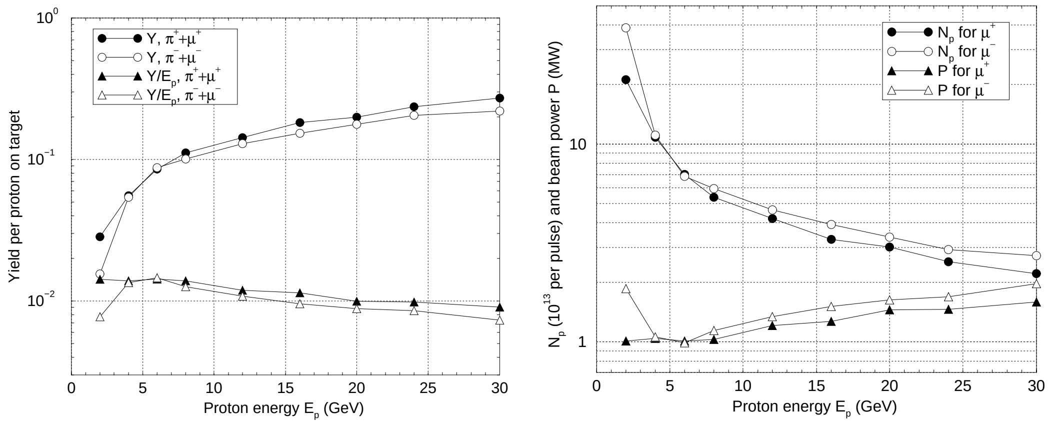

Fig. 6. Y and Y/E_p (left) and $\mathcal{N}_p$ and beam power (right) for C target.

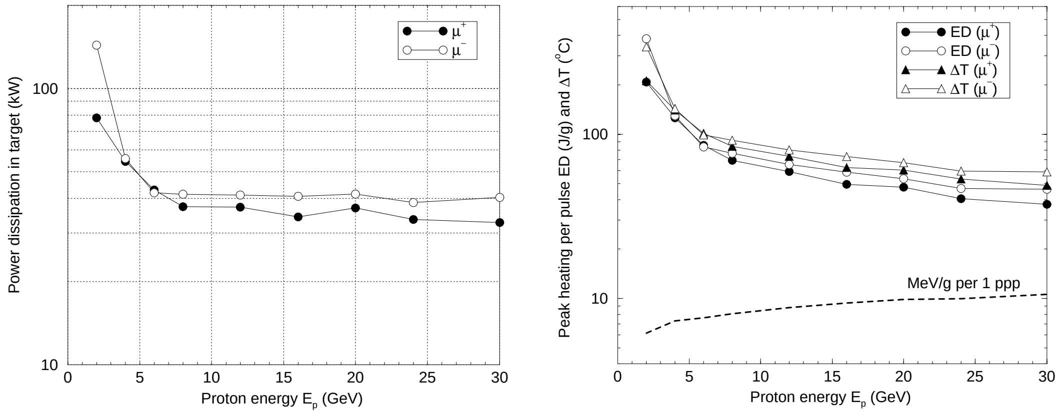

Fig. 7. Power dissipation in C target (left) and peak energy deposition and temperature rise in C target (right), providing $\mathcal{N}_\mu$=2×10^{20} muon decays per year. A dashed line shows a peak energy deposition density per 1 proton on target.

4 Conclusions

The number of muons required for a neutrino factory can be provided in the decay channel for further capturing by a phase rotation system with graphite and mercury targets impinged by intense 15-Hz proton beams in the energy range of 2 to 30 GeV. Depending on proton energy, the required beam power is 1 to 2 MW with a graphite target, and 0.7-1 MW with a mercury target. The results obtained in the course of thorough MARS simulations provide a basis for further optimization of the target/capture system.

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