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Nuclear Instruments and Methods in Physics Research A 472 (2001) 546–551
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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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 for 2–30 GeV protons on various targets in a 20 T hybrid solenoid followed by a matching section and decay channel are reported. 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. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 41.75.–i; 85.25.Ly; 87.18.Bb; 87.53.Wz

Keywords: Neutrino factory; Targets; Beam capturing; Pion and muon yield

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 kept 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 2–30 GeV proton beams. Preliminary results were given in Refs. [1,9].

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 $R_T \geqslant 2.5\sigma_{x,y}$, where $\sigma_{x,y}$ are the beam RMS spot sizes. The calculation model (Fig. 1), keeping the

☆ Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH00300 with the US Department of Energy.

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PII: S0168-9002(01)01307-9

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.

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 $z \geqslant$

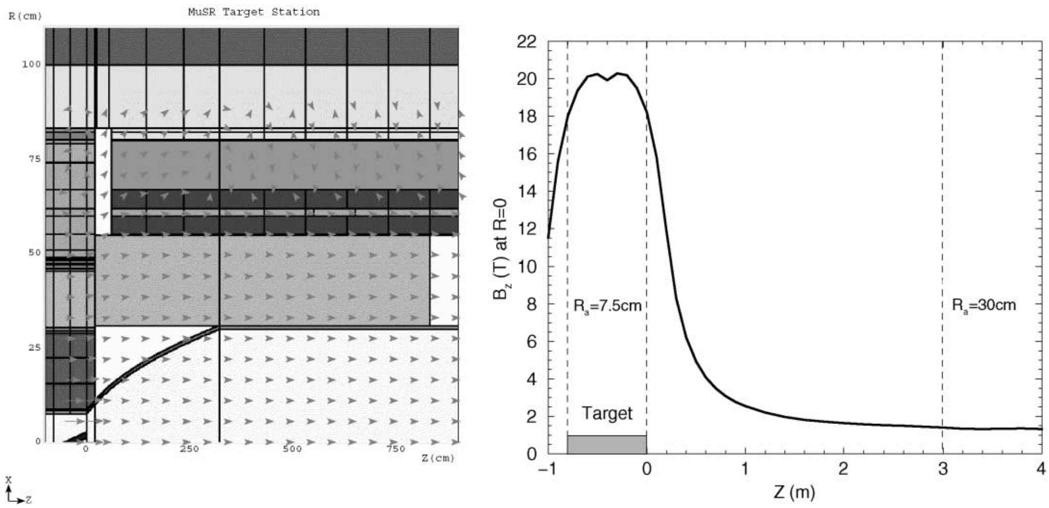

Fig. 1. MARS model of the target/solenoid system (left) and B_z field profile (right).

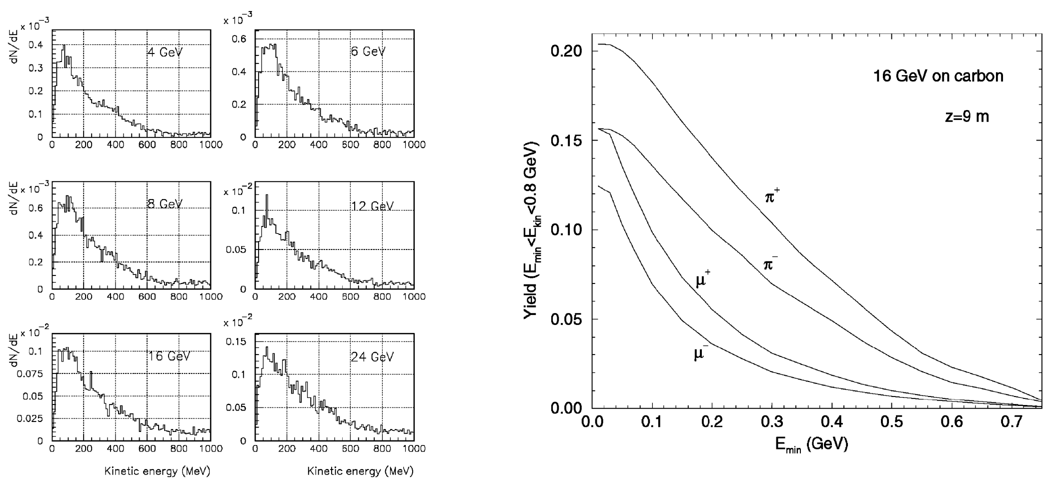

Fig. 2. Energy spectra of $\pi^+ + \mu^+$ for 4–24 GeV protons (left) and numbers of particles in the ($E_{min}-0.8$ GeV) interval vs. E_{min} for 16 GeV protons (right) at $z = 9$ m for a 80-cm C target ($R_T = 7.5$ mm, $\alpha = 50$ mrad).

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 $30\,\mathrm{MeV} < E < 230\,\mathrm{MeV}$ around the spectrum maximum is considered as the one to be captured by a phase rotation system.

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, $\alpha = 150$ mrad seems to be the optimum (Fig. 3), while $\alpha = 50$ 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 tar gets with $R_T = 3.5\sigma_{x,y}$ and $4\sigma_{x,y}$ 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

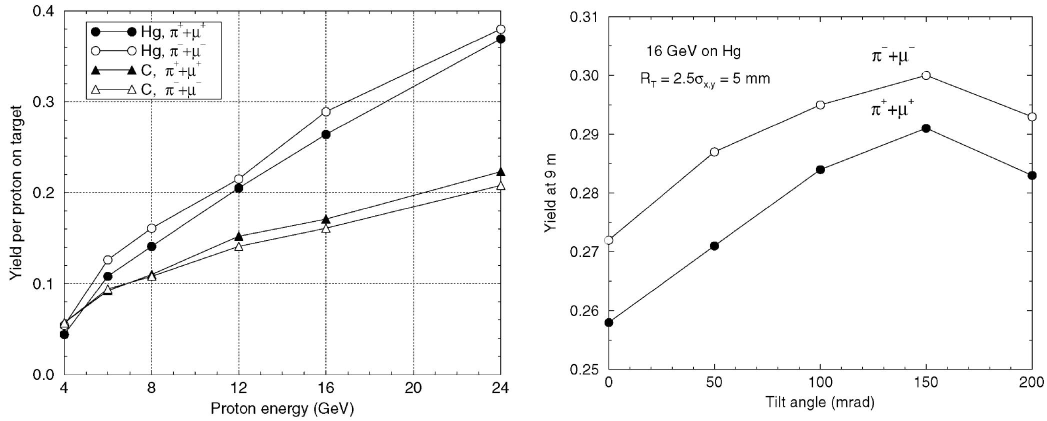

Fig. 3. Yield from Hg and C targets vs. E_p (left) and yield from a Hg target at $E_p = 16$ GeV vs. tilt angle (right).

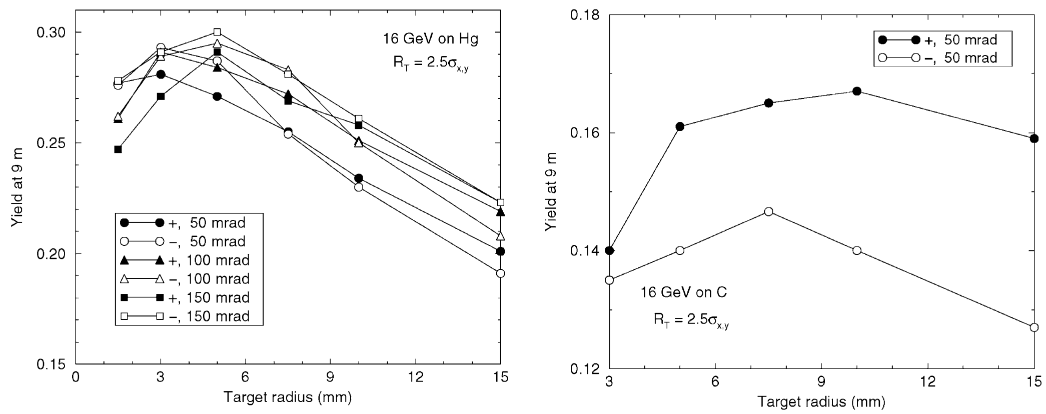

Fig. 4. Yield as a function of a target radius, Hg (left) and C (right), for a 16-GeV proton beam and several tilt angles.

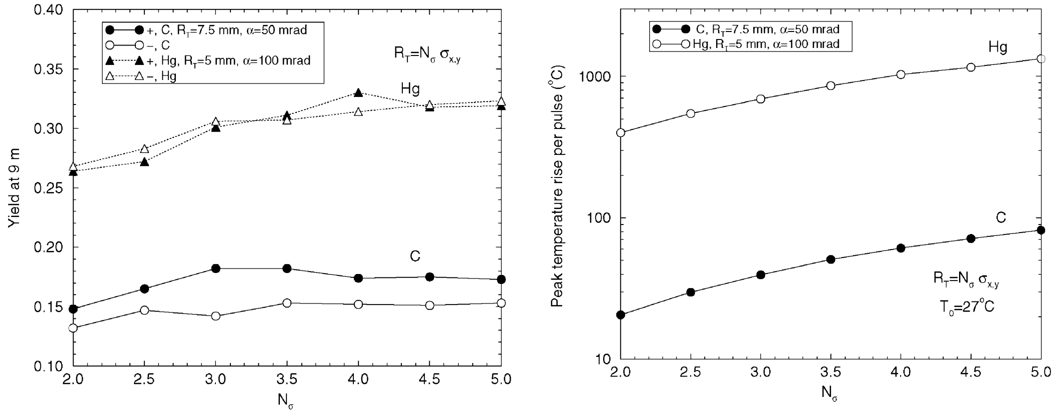

Fig. 5. Yield (left) and maximum instantaneous temperature rise (right) as a function of a target to a RMS beam spot size ratio (right).

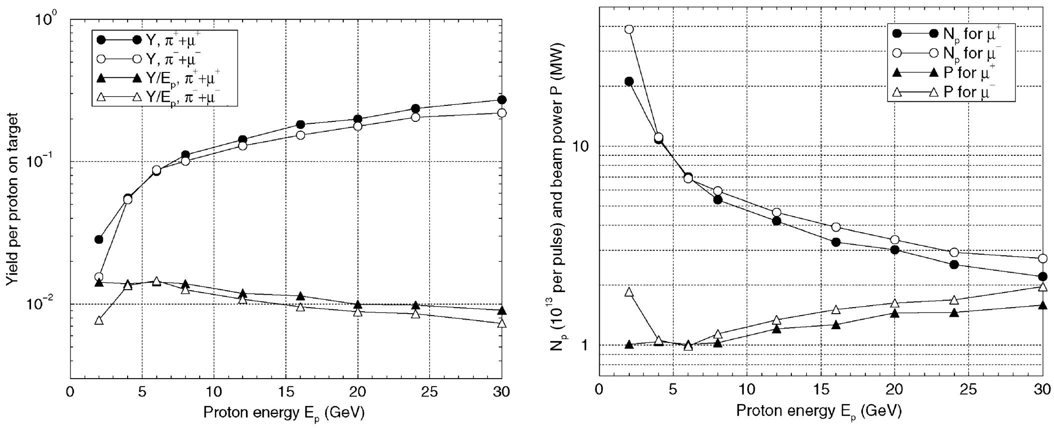

Fig. 6. Y and Y/E_p (left) and N_p and beam power (right) for C target.

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 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 $Y_{\pi^+ + \mu^+} = 0.309$ 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 the target, but results in more severe energy deposition in the target. To provide $N_\mu = 2 \times 10^{20}$ 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 three total loss on the way from the decay channel to the ring. With that,

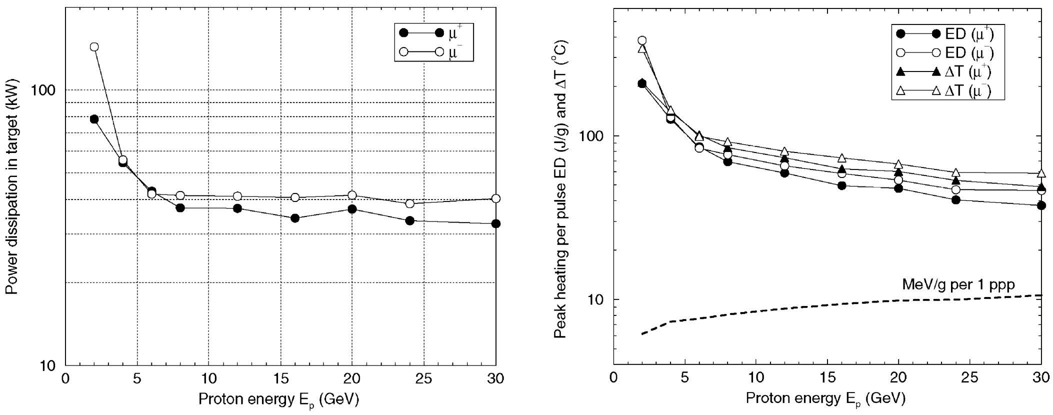

Fig. 7. Power dissipation in C target (left) and peak energy deposition and temperature rise in C target (right), providing $N_\mu = 2\times10^{20}$ muon decays per year. A dashed line shows a peak energy deposition density per proton on target.

3.30×10^{13} and 3.92×10^{13} protons per pulse at 16 GeV on the optimal C target are needed 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 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 $N_\mu = 2\times10^{20}$ 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, in the range 0.73–0.75 MW; however, the peak temperature rise per pulse is 750°C, because of higher energy deposition density.

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 2–30 GeV. Depending on proton energy, the required beam power is 1–2 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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