

Studies on pion/muon capture at MOMENT*

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Abstract

MOMENT (a muon-decay medium-baseline neutrino beam facility) in China is proposed to provide a low energy neutrino beam with $\langle E_\nu \rangle > 240$ MeV induced by muons in order to explore the leptonic CP-violation. In order to provide those neutrinos a continuous working CW linac will provide protons with 1.5 GeV of kinetic energy and 15 MW of power. A Hg-jet which interacts with the proton beam is placed inside a superconductive solenoid which captures the produced charged pions. In this article, an optimization study is presented for the capture solenoid system concerning the proton beam, the Hg-jet target and the applied adiabatic magnetic fields parameters in order to maximize the collection of pions and therefore intensify the neutrino beam.

SIMULATION REPRESENTATION

In this study, optimizations are performed on the pion capture system of the MOMENT project [1–3] with the aim to maximize the yields of the pions and muons along their transport line. The proton beam, Hg-jet and their interactions, and the solenoids are simulated with FLUKA Monte Carlo [4, 5]. The main capture solenoid MCS and the following adiabatic section are represented only by the magnetic field applied inside their empty volume. The shields and the magnets are simulated as a common area where the particles are stopped.

The configuration of the primary proton beam and the Hg-jet target should be engineered in a manner that the two collide at a very small angle such as the interactions to happen for at least two nuclear interaction lengths, because of the helical trajectory of the beam protons albeit with very low curvatures and also any engineering constraints. That system has also to be tilted at a small angle with respect to the solenoid axis in order to avoid the absorption of the pions from the target due to their helical trajectories [6, 7]. In this simulation, the proton beam has a Gaussian profile and interacts fully over the target symmetry axis.

Different tilting-angles, radii and lengths for the target, and different sizes for the beam are studied in order to find the optimum parameters or to understand their range where the pion and muon yields are maximized in the case of different technical criteria in the future. Particles are recorded at the end of the adiabatic taper section. Similar studies have been performed at the Neutrino Factory project [8, 9].

TABLE I: Parameters simulated, the baseline ones are highlighted in bold numbers.

| Proton Beam | | |
|------------------------------------|---------------------------------|---|
| E_{kin} (GeV) | σ (cm) | <i>divergence</i> (mrad) |
| 1.5 , 2, 2.5 | 0, 0.05, 0.1 , 0.15, 0.2 | 0 |
| Hg-jet | | |
| θ_{tilt} (mrad) | L (cm) | r (cm) |
| 0, 40, 80, 100, 120, 140, 180, 220 | 15, 20, 25, 30 , 35, 40 | 0.3, 0.4, 0.5 , 0.6, 0.8, 1, 1.2 |

TABLE II: Particles exiting the Hg-jet per p.o.t., produced by FLUKA with 10^6 p.o.t.

| $E_{kin} = 1.5$ GeV, $L = 30$ cm, $r = 0.5$ cm | | | | | | | |
|--|---------------------|---------------------|-------|-------------------|---------------------|------|-----|
| π^+ | π^- | K^+ | K^- | μ^+ | μ^- | n | p |
| 0.12 | $7.4 \cdot 10^{-2}$ | $7.8 \cdot 10^{-5}$ | 0 | $2 \cdot 10^{-4}$ | $4.3 \cdot 10^{-5}$ | 12.4 | 1.4 |

SYSTEM PARAMETERS, SELECTION AND ADIABATIC MAGNETIC FIELDS

The baseline proton beam and target parameters used in these studies are presented in Table I while the pion, muon, neutron and proton yields for two interaction lengths of Hg (30 cm) are presented in Table II. The latter shows that low pion yields are produced due to the low energy of the proton beam.

The aim of the capture system is to have a peak magnetic field inside the main capture solenoid MCS of $B_0 = 14$ T and the following adiabatic taper section to vary from 14 T to 3 T in order to capture pions that will eventually decay to muons with an $\langle E_\mu \rangle$ of $300 \text{ MeV} \pm 50\%$ [1]. Fig. 1 shows the transverse momentum of the π^+ versus their momentum and the band of pions that will give that muon beam. It also shows the different bands of pions for different MCS-radii. It is clear that the higher the radius the higher the yield and the momentum of the pions [10]. The MCS-radius of 20 cm is chosen for these studies.

The figure of merit for the optimizations are the yields of selected pions with momenta between $0.228 < P(\text{GeV}/c) < 0.776$ and selected muons with momenta between $0.107 < P(\text{GeV}/c) < 0.438$ at the end of the taper. The muons and the neutrinos have an average energy of 57% and 43% respectively of the pion when their directions are the same.

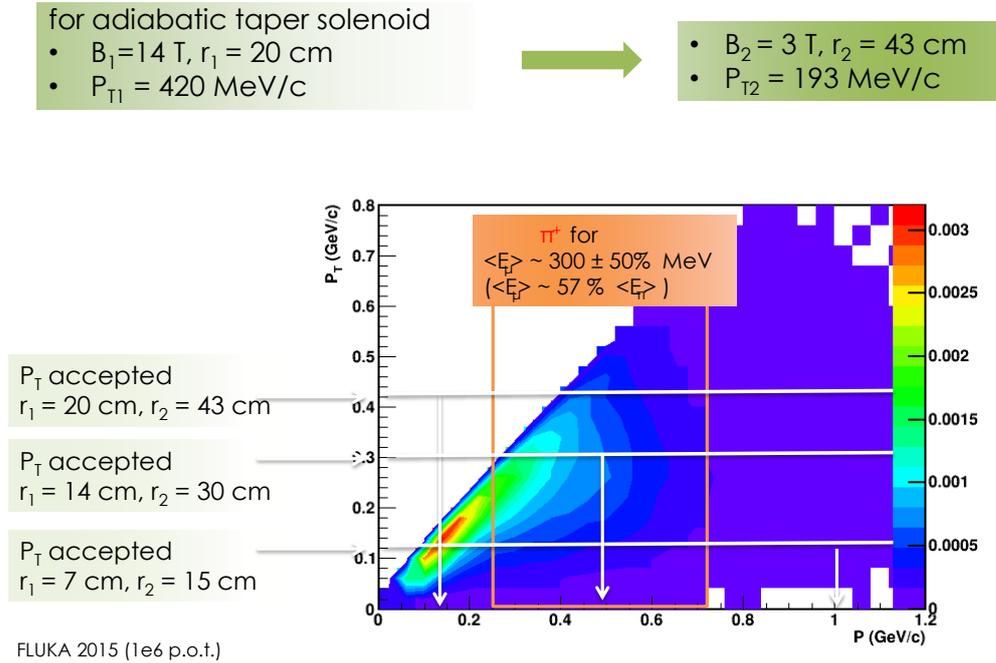


FIG. 1: P_T of π^+ s versus their momentum for a proton beam with $E_{kin} = 1.5$ GeV. The pions which produce the muon beam with an average energy $\langle E_\mu \rangle$ of $300 \text{ MeV} \pm 50\%$ are being located within the orange borders. Arrows indicate the selected P_T for different MCS-radii of $r_1 = 7, 14$ and 20 cm. The final radius r_2 of the taper from 14 T to 3 T is also written.

Adiabatic fields

In the initial studies a constant field of 14 T was applied all over the MCS then substituted by a Gaussian which gives a more realistic field simulation at the edges of the MCS shown in Fig. 3. The field peak of 14 T is applied at the centre of target (at $z_0 = -16$ cm in FLUKA's geometry) and is reduced by 7% after $\pm\lambda_I$ as the response of a field proposed for the Neutrino Factory studies [6] or by 1% as one proposed for MOMENT [11]. Moving the target by $\pm\lambda_I/4$ does not alter the particle yields [10].

The MCS is matched with an adiabatic taper at $z = z_1 = 0$ cm in the geometry. The matching is done between the Gaussian field and an adiabatic field represented by a polynomial function as described in [6, 7]. Then the field is reduced to 3 T along the length of

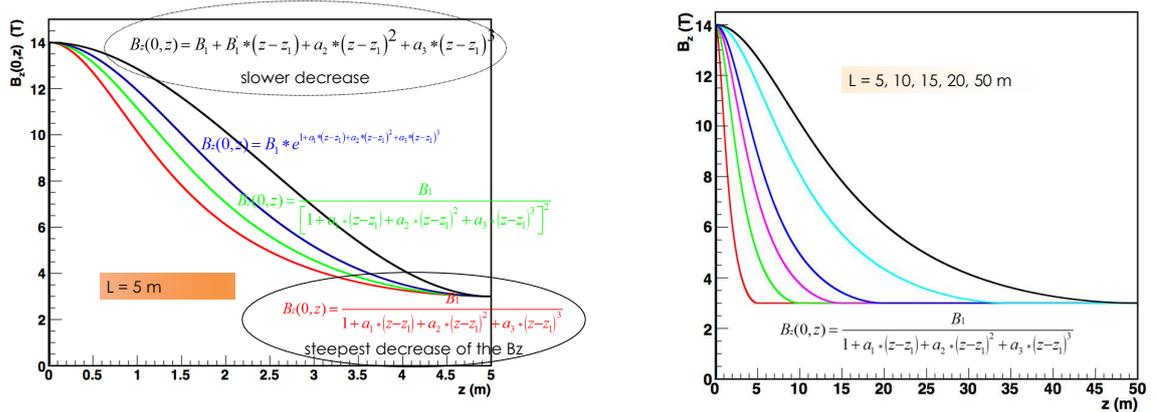


FIG. 2: Functions of adiabatic solenoidal fields for a 5 m taper solenoid (left-plot). The inverse polynomial is chosen and is plotted for different taper lengths (right-plot).

the taper. Therefore the transverse momentum is reduced at the expense of an increased helical radius for the transported charged particles. In Fig. 2, different fields with different responses are presented for a 5 m long adiabatic taper. In these studies, the first degree inverse polynomial function with the fastest decrease response is used:

$$B_z(r = 0, z) = \frac{B_1}{1 + a_1(z - z_1) + a_2(z - z_1)^2 + a_3(z - z_1)^3} \quad (1)$$

This field when matched with the Gaussian is decreasing monotonically as shown in Fig. 3.

The magnetic field in FLUKA implemented for the axial and radial components by the first order terms as shown in the following equations:

$$B_z(r, z) \approx B_z(0, z), \quad B_r(r, z) \approx -\frac{r}{2} \frac{\partial B_z(0, z)}{\partial z} \quad (2)$$

The particle yields have been studied for several adiabatic taper lengths [10] but in this proceeding only the results of the 5 m and the 50 m are shown. The 5 m section is a realistic representation of the solenoids where the particles are mostly pions (75%) at the end, while the 50 m one is considered as an idealistic where the particles are almost muons (90%). The adiabatic tapers are approximated by 5 cones with their radii following the conservation of the magnetic flux ($\Phi = B\pi r^2$). Their representation in FLUKA is shown in Fig. 4.

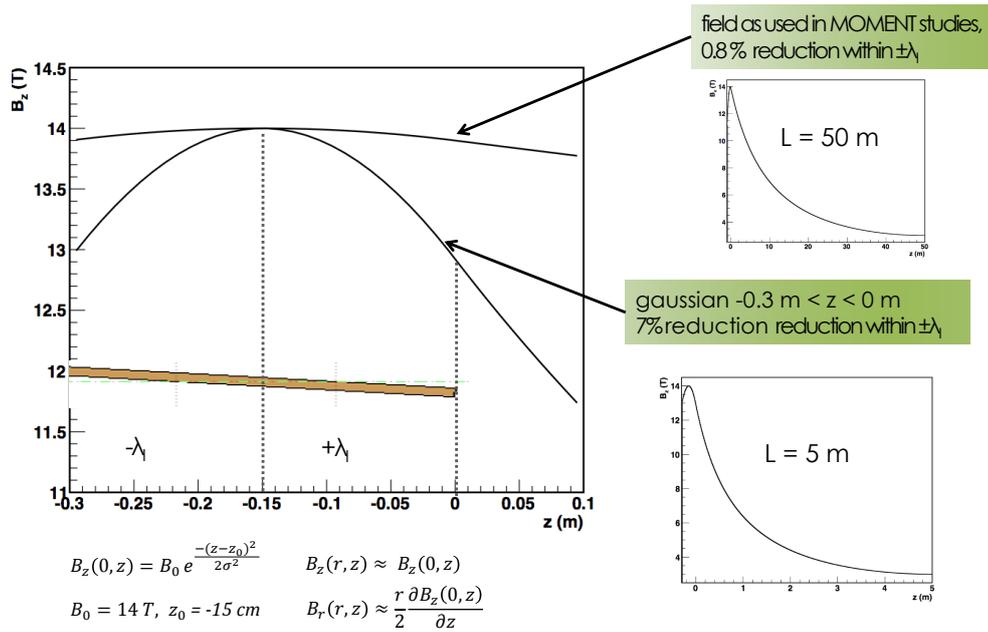


FIG. 3: Representations in FLUKA of the Gaussian field for the main capture solenoid and the studied tapers of 5 m and 50 m lengths.

TARGET TILTING

Different tilts of the target axis with respect to the main capture solenoid symmetry axis are studied by keeping the rest beam and target parameters the same. This is done in order to determine the best angle where the absorption of the captured pions is kept at minimum. In Fig. 5, the yields as function of the tilting-angle are shown for the pions (plus the muons) and only for the muons for the 5 m and 50 m tapers respectively. The tilting-angle pattern is similar with an optimum value seen at 100 mrad. In Fig. 6, the same is shown, now for the separated π^+ , π^- and μ^+ , μ^- . The comparison between the Fig. 5 and the Table II for the 5 m taper indicates that the capture efficiency of the pions is almost 50%.

Protons

Protons have also helical trajectories in the solenoids. The ones with high momenta ($> 1.5 \text{ GeV}/c$) have trajectories with large helical wavelengths and could be separated from

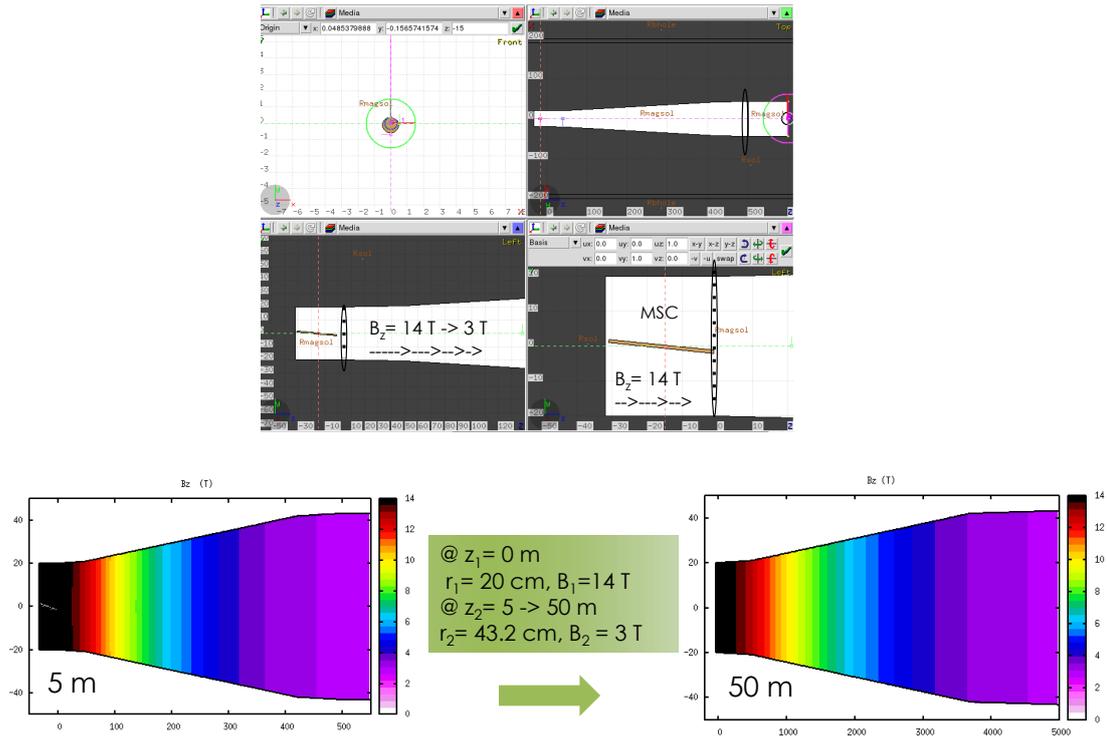


FIG. 4: Geometry representation in FLUKA for the Main Capture Solenoid and the adiabatic tapers of 5 m and 50 m lengths. The intensity of their field is also shown.

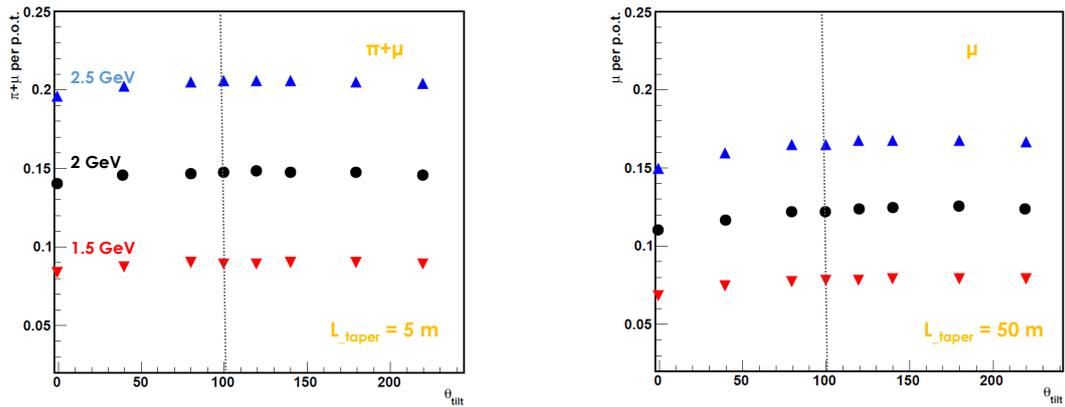


FIG. 5: Particle yields at the end of the 5 m (left-plot) and 50 m (right-plot) as function of the target tilting-angle (in mrad) for proton beams with $E_{\text{kin}} = 1.5, 2$ and 2.5 GeV/c.

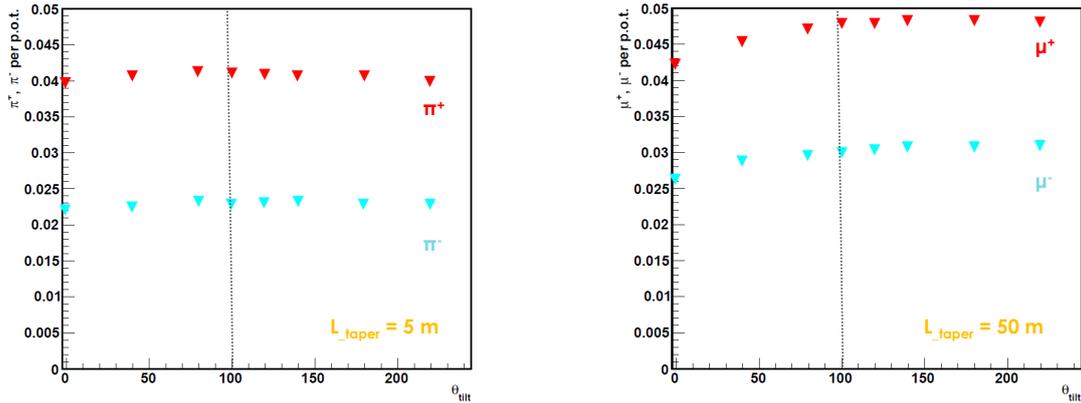


FIG. 6: π^+ , π^- and μ^+ , μ^- yields for the 5 m (left-plot) and 50 m (right-plot) taper solenoids respectively as function of the target tilting-angle (in mrad) for proton beam with $E_{kin} = 1.5$ GeV/c.

the selected pions as shown in these proceedings [12]. In the opposite way, protons with momenta similar to the selected pions are transported along with them. The yield for the former is reduced while for the latter remains similar as function of the tilting-angle [10].

TARGET RADIUS AND LENGTH

Different target radii and lengths are studied by having the target tilt fixed at 100 mrad and by keeping the rest baseline parameters the same. As result, the target thickness could be increased by few millimetres while its length could be decreased or increased by a few centimetres depending on the Hg-jet configuration without decreasing the yields of the particles. This is shown in Fig. 7 and Fig. 8.

Beam size

Variations of Beam sizes between $\sigma = 0$ mm to 2 mm have shown that the particle yields are decreasing for values higher than 1 mm while the rest parameters are kept at their baseline values [11]. This effect is similar to the variation of the target radius where the yield is decreasing for lower values due to the smaller interaction region.

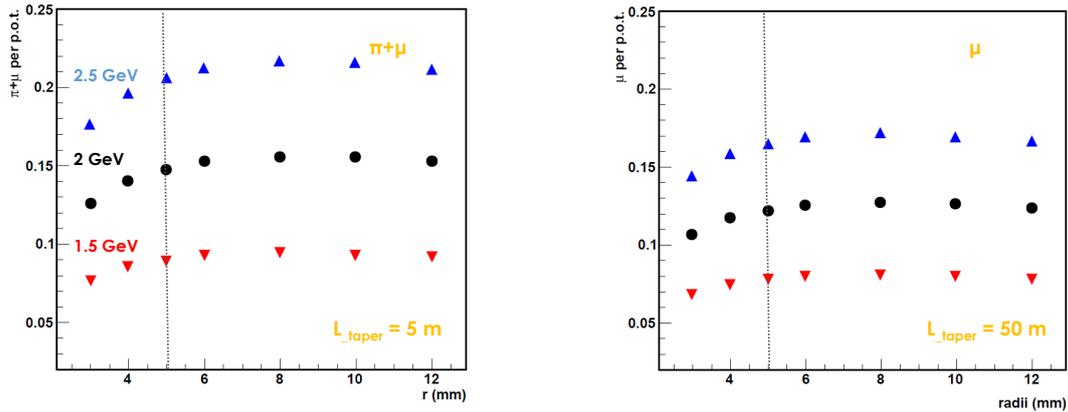


FIG. 7: Particle yields for the 5 m (left-plot) and 50 m (right-plot) taper solenoids respectively as function of the target radii for proton beams with $E_{kin} = 1.5, 2$ and 2.5 GeV/c.

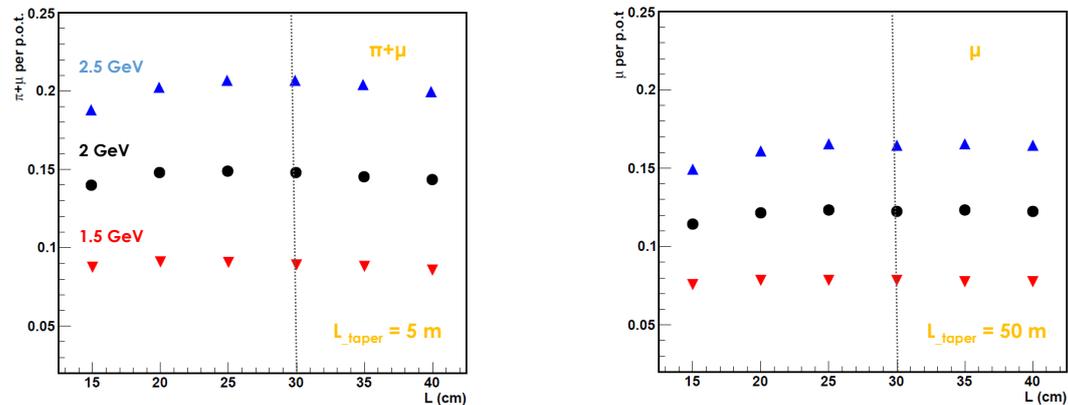


FIG. 8: Particle yields for the 5 m (left-plot) and 50 m (right-plot) taper solenoids respectively as function of the target lengths for proton beams with $E_{kin} = 1.5, 2$ and 2.5 GeV/c.

CONCLUSION

In this study the yields of selected pions and muons at the end of the adiabatic taper are used as a figure of merit in order to find the right values or ranges for the beam and the target parameters. These first results show that a tilting-angle of 100 mrad, a radius greater than 0.5 cm, and a length greater than 25 cm for the Hg-jet target could be used. The thickness of the target is relevant to the beam size, and for the baseline radius of 0.5 cm it should not be greater than about $\sigma = 0.1$ cm.

Further studies are being performed in order to cross-check the results with different

Monte Carlos, to study in detail the configuration of the capture system as the relevant angle between the beam and the target, the shielding, and finally to look for alternative targets [11], to be presented in the future.

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