MUON POLARIMETER IN A NEUTRINO FACTORY DECAY RING

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Abstract

Monitoring the muon beam properties in the final stage of the Neutrino Factory (the Decay Ring) is important for the understanding of the beam itself and a crucial piece of information for the downstream physics. The main topics to be assessed are: knowledge of the muon beam energy and polarization, divergence of the beam and beam current. In the framework of the International Design Study for the Neutrino Factory (IDS-NF) a racetrack model Decay Ring based on G4Beamline has been produced to simulate electrons from muon decays and the measurement of the beam energy distribution via the spin precession technique. The use of other codes, like Zgoubi, to generate a realistic beam including effects like spin polarization, are considered. A general discussion on future work is presented.

INTRODUCTION

The racetrack configuration for the Neutrino Factory Decay Rings has been chosen as the baseline case in the framework of the IDS-NF [1]. Its machine properties (dynamic aperture and working point) have been investigated in [2], where details of the ring structure and optical functions can be found. The lattice is characterized by high betas in the long straight sections ($\langle\beta_{x,y}\rangle \simeq 130$ m) and a squeezed beam in the arcs ($\langle\beta_{x,y}\rangle \simeq 8$ m). Straights and arcs are interfaced by four matching sections constituted by three dipoles and four quadrupoles. Here emphasis is put on the issue of beam monitoring, discussing methods and a possible location of devices. The total length of this machine is 1608.8 m (600.2 m for each of the straight sections) with a central momentum of 25 GeV/c.

MUON BEAM MONITORING

The Method of Spin Precession

Following pion decays muons are produced with a longitudinal polarization of -100% in the decay rest frame (*i.e.* the spin vector and velocity are antiparallel). In the laboratory frame this number is expected to become -18% for pions between 200 and 300 MeV/c [3]. The drift and phase rotation sections and subsequent collection in RF buckets create bunches with different specific polarizations, while the overall average value is preserved. It has been shown that a residual polarization in the muon beam can be used to determine its central energy [4]. The precession of the spin associated with each muon in a magnetic field is governed by the Thomas-BMT equation. At every turn this precession is given by the spin tune defined as:

$$\nu = \gamma_\mu a_\mu = \frac{E_\mu}{m_\mu} \cdot \frac{g_\mu - 2}{2} = \frac{E_\mu(\text{GeV})}{90.6223(6)} \qquad (1)$$

which is a function of the muon energy. With no energy spread all the spins precess in unison and every turn produces a modulation of the average polarization $\mathcal{P}$ between a maximum and a minimum value. In a realistic beam, where $\delta = \frac{\Delta E}{E} \neq 0$, polarization oscillations vanish after a certain number of turns (this effect can be counterbalanced by means of RF cavities, a case not considered here). In fact the rate of polarization damping allows the measurement of δ [5]. A way to monitor polarization (and beam energy) is given by the measurement of the energy spectra of the electrons from muon decays, since these are correlated to the initial polarization of the parent particles, as can be seen in the formula (in the muon rest frame):

$$\frac{d^2N}{dx\,dcos\theta} = N_0[(3-2x)x^2 - \mathcal{P}(1-2x)x^2 cos\theta] \qquad (2)$$

where $x = 2E_e/m_\mu$. $\mathcal{P}$ represents the product of the muon charge and the polarization component along the muon direction. After the Lorentz boost we get an expression for the total energy of the electrons in the laboratory frame as a function of the number of turns:

$$E(t) = N_0 e^{(-\alpha t)} \left[\frac{7}{20} E_\mu \left(1 + \frac{\beta}{7}\mathcal{P} cos(\omega t + \phi)\right)\right] \qquad (3)$$

where N_0 is the number of muon decays at turn 0, $\alpha = T_{period}/\gamma\tau_\mu$ represents the turn by turn decay constant, $\beta = P/E$ is the muon velocity , $\mathcal{P}$ is the polarization of the beam, $\omega = 2\pi\nu$ is the angular spin tune (related to beam energy by Eq. 1) and ϕ an arbitrary initial phase.

Application to the NF Decay Ring case

It has been suggested that electrons from muon decays can be collected at the end of the straight section, exploiting the bending power of the dipoles (*e.g.* in the matching sections or in the arcs) and channelling the spectral components to counting devices [5]. However not all the spectrum can be sampled, for example the electrons at very high energy travel parallel to the nominal orbit where a detector would intercept the muon beam. This imposes a selection in the range of the energy spectrum we may want to consider and consequently the signal, given by Eq. 3 , will be modified. In order to understand what sort of distribution we expect when binning the electron energy spectrum we developed a model which describes the polarization of the beam and parametrizes the energy resolution in

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a calorimetric device [4]. A sample of 10^6 muons is generated with a defined polarization (-18%), a beam energy of 25 GeV with a 5% gaussian spread (FWHM), and tracked around a 1608.8 m long ring. Muons decay producing electrons whose energy spectrum has been modeled according to Eq. 2 and Lorentz boosted. Every muon spin precesses with its own spin tune. As expected with no RF and an energy spread in the beam, the initial polarization decoheres after a certain number of turns. To check the validity of the model used, we ran a simulation of the racetrack lattice with the code Zgoubi [7] and compared the results. The tracking of spin in Zgoubi through various types of magnet has already been shown to compare well with theory [8]. The evolution of polarization as a function of the number of turns is displayed in Fig. 1 showing a good agreement between the model and Zgoubi. Fig. 2 shows the electron spectra for two opposite polarizations (±18%) and their asymmetry, a figure of merit used to describe the polarization analysing power. The total energy from electrons belonging to a specific energy bin of the decay spectrum is reminiscent of Eq. 2 and can be expressed as:

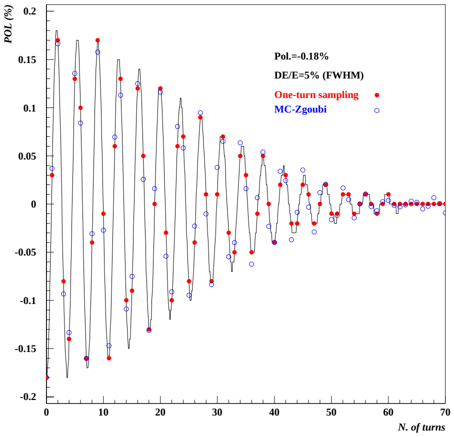

Figure 1: Polarization as a function of the number of turns. (Solid line) model with continuously evolving spin tune. Sampling at every turn from the model described in the text (red dots) and a Zgoubi simulation of the lattice (blue dots).

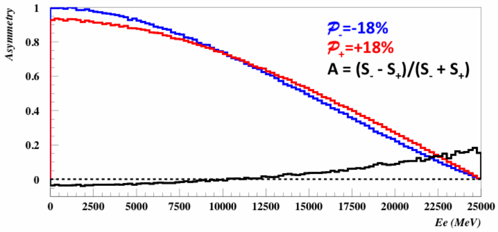

Figure 2: Electron energy spectra for $\mathcal{P}$=+18% (red) and $\mathcal{P}$=-18% (blue). Asymmetry (black histogram) should be as higher as possible to maximize the signal.

$$f(t) = f_0 e^{-\alpha t}\left[1+\frac{\beta}{7}e^{-\frac{1}{2}(\omega\frac{\Delta E}{E}t)^2}\cdot\mathcal{P}cos(\phi+\omega t)\right] \quad (4)$$

f_0 is the total energy of the electrons at turn 0 and the gaussian term parametrises the beam energy spread. $\mathcal{P}$ is the polarization of the beam assuming we can collect all the electrons from muon decays, otherwise it is a free parameter whose relation to polarization needs further study. A fit to this curve, allows a straightforward determination of the beam energy and its relative spread. An example of it is illustrated in Fig. 3 for two energy bins, [0,5] GeV and [15,18] GeV, whose choice is suggested by the properties of the asymmetry curve discussed before and dictated by the practical location of the polarimeter (as described in the following paragraph). The precision with which E_μ and $\Delta E/E$ are measurable is a function of the number of captured electrons and of the number of sampled turns. With about $3 \cdot 10^5$ electrons per turn falling in the device and 50 sample turns we expect a precision 0.2% and 4% on the aforementioned quantities. These are very preliminary numbers and deserve a more realistic simulation, however they give an initial idea of the limits of the method. The relation between the oscillation excursions in the total recorded energy and the polarization provides a measure of the latter.

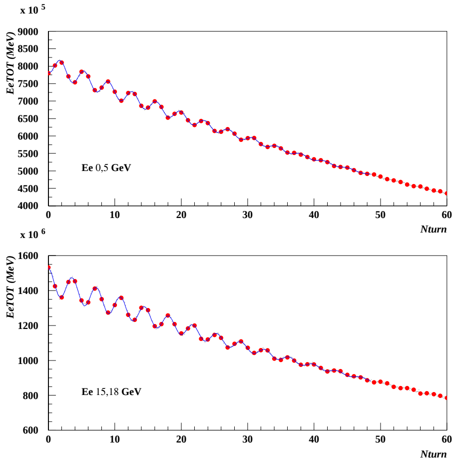

Figure 3: Total energy from electrons belonging to the [0,5] (top) and [15,18] (bottom) GeV bins of the spectrum as a function of the number of turns. The red dots are samples taken at every turn, the superimposed curve is a fit to function defined in Eq. 4.

Location for the device

Once a realistic lattice has been designed, one of the practical issues is finding a location for a device to measure the energy of electrons. Fig. 4 summarizes some of the possible locations for electron monitors together with the

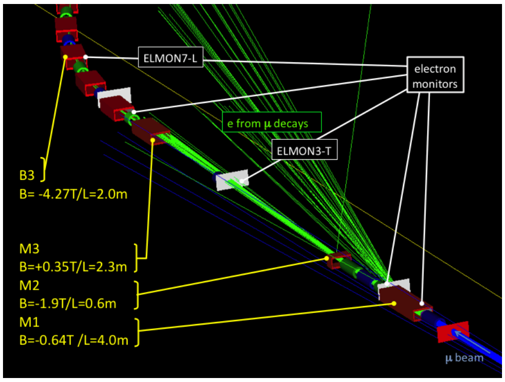

Figure 4: G4Beamline rendering of the region at the end of a straight section and beginning of the arc-section. In the middle the magnets of a matching section are visible. Locations for electron monitors are suggested which exploit the bending power of dipole magnets whose main charateristics are summarized (left bottom side). Blue tracks represent muons, green tracks the electrons from decays.

main features of the dipole magnets used as spectrometers to separate electrons of different energies. When choosing a particular location one should consider both spectral power and the purity of the signal. Ideally the device should collect electrons produced in the proximity of the spectrometer in order to avoid spurious effects from other magnets. With this in mind we focused on two main cases:

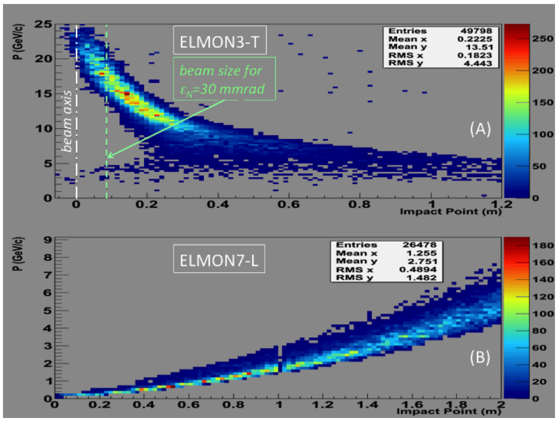

Figure 5: Momentum as a function of the impact point position for: (A) a monitor placed transversally with respect to the beam after a drift of 13 m past a dipole in the matching section. (B) a monitor parallel to the beam trajectory. In case (A) the position of the beam and its maximum width (for a normalised emittance of 30 mm rad) are shown.

- (A) a monitor placed downstream of the second bending magnet in the matching section, just before a quadrupole and orthogonal to the direction of the beam,
- (B) a monitor placed in the third bending element of the arc section, parallel to the beam direction.

In case (A) the device sits transversally with respect to the nominal beam orbit at a distance of about 13 m from a bending dipole (B=1.9 T, L_{eff}=0.6 m) with the long drift allowing a good spectral power despite the relatively low magnetic field. The advantage of this location is that no special magnet is needed which simplifies the engineering. Fig. 5 (A) shows that at this location a device placed at $>$10 cm from the beam axis can intercept a fraction of the spectrum between 0 and 18 GeV without disrupting the muon beam. In this case we simulated muon decays along the whole 13 m of drift to check the uniformity of the signal.

Case (B) is similar to the idea for this device as originally proposed in [5]. The advantage here is the good spectral power of the bending magnet due to its effective length and high field (B=4.3 T, L_{eff}=2 m). However, the requirement to modify the shape of the magnet, introducing apertures through the superconducting element could pose engineering challenges. The graph shown in Fig. 5 is a superposition of decays happening in the 2.4 m path between dipole B2 and dipole B3 (where the electron monitor is located). As in case (A), a good signal uniformity is found.

CONCLUSIONS AND FUTURE WORK

Monitoring the energy and the polarization of the muon beam of the Neutrino Factory is a central aspect of the study of beam properties which are needed for the physics programme. We developed the simulation of the measurement of the muon beam energy distribution by spin precession. We studied possible realistic locations for the polarimeter by means of a 3D tracking code (G4Beamline). In future we plan to use Zgoubi to completely describe a polarized beam, for which some extension in the routine describing decays is advocated.

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