MAGNET MISALIGNMENT STUDIES FOR THE FRONT-END OF THE NEUTRINO FACTORY*

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Abstract

In the Neutrino Factory front-end the muon beam coming from the interaction of a high-power (4 MW) proton beam on a mercury jet target is transformed through a buncher, a phase rotator and an ionization cooling channel before entering the downstream acceleration system. The muon front-end channel is densely packed with solenoid magnets, normal conducting radio-frequency cavities and absorber windows for the cooling section. The tolerance to the misalignment of the different components has to be determined in order on one hand to set the limits beyond which the performance of the front-end channel would be degraded; on the other hand to optimize the design and assembly of the front-end cells such that the component alignment can be checked and corrected for where crucial for the performance of the channel. In this paper we show the results of some of the simulations of the front-end channel performance where the magnetic field direction has been altered compared to the baseline.

THE NEUTRINO FACTORY FRONT-END

In the International Design Study for the Neutrino Factory (IDS-NF) [1], a proton beam of kinetic energy 5-15 GeV impinges on a Hg jet target, producing pions that will be captured and decay into muons over a 79.6 m-long drift channel. The muon beam is then bunched, rotated and cooled in the so-called $\sim$ 211 m-long front-end channel in order to reduce the transverse emittance and adapt its longitudinal profile to the downstream acceleration systems. The target sits in a solenoid field tapering from 20 T down to 1.5 T over 18.9 m, permitting an optimized capture of the pions that will produce useful muons for the machine. The 1.5 T magnetic field then remains constant in the 60.7 m-long remaining drift section, the 33 m-long buncher and the 42 m-long rotator. A small matching section of 6 m length and the $\sim$ 130 m-long cooling section then follow, both sitting in an alternating field of $\pm$ 3 T. In Fig. 1, the value of the magnetic field on-axis as function of z is shown.

SIMULATION FRAMEWORK

For the purpose of this study, the G4BeamLine (G4BL) version 2.0 of the front-end lattice [2] has been used. The simulations have been performed using G4BL version 2.06 [3]. In order to estimate the number of good muons at the end of the front-end, the following acceptance criteria have been applied:

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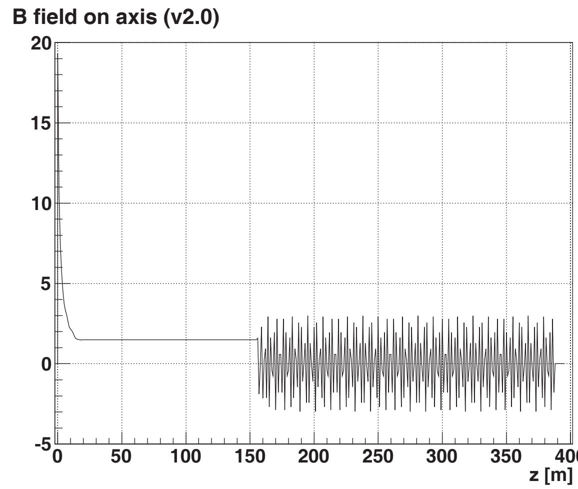

Figure 1: Magnetic field on-axis as a function of z.

- $100 \leq p_z \leq 300$ MeV/c
- $A_T < 30$ mm
- $A_L < 150$ mm

where p_z stands for the muon longitudinal momentum, A_T for the transverse acceptance and A_L for the longitudinal acceptance. The ICOOL version 3.20 [4] of the ECALC9F [5] routine has been used in order to select the muons that passed the acceptance criteria and compare the performance of the different setups.

Beam

The beam used in this study [2] comes from a MARS15 [6] simulation of $4{\times}10^5$ protons with 8 GeV kinetic energy on the Hg-jet target using the IDS-NF setup. The beam is handed off at z= 0 m corresponding to a length of target crossed of about twice the mercury interaction length λ_{Hg}. Only the negative pions, kaons and muons are kept for further tracking of the beam. The particle time is then smeared by applying a random time shift taken from a Gaussian of σ = 2-3 ns to account for the proton bunch spread coming from the proton driver. Due to the small drift distance already traversed by the beam in the MARS15 setup, the mean time of the beam is not centered around zero where it is handed off, thus causing a mismatch of the radio-frequency (RF) phasing compared to the reference particle time. In order to correct for this mismatch the beam distribution center time is calculated then used to apply a time shift to all the particles in order to re-center the

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beam around zero. Particles with time bigger than 5σ of the distribution are not taken into account in the calculation of the distribution center [7]. In order to speed up the simulations, a limited statistics is used with the first 50000 beam particles only sent through the front-end. This corresponds to half the statistics of the beam file. Each simulation takes about 2-3 hours.

Front-end Magnets and Fields

The field in the target and front-end regions is generated by solenoid coils. For the target system the magnet geometry has been defined (see [1] Table VIII page 64). However, the magnet configuration is being revised in order to determine an acceptable level of radiation in the target system [8]. For this reason no magnet misalignment study has been performed for the target system yet.
The G4BL lattice uses field maps generated by ICOOL for the capture (where the field goes from 20 T down to 1.5 T) as well as for the matcher and cooler sections. For the drift, buncher and rotator sections, where the field is constant, it is defined as a volume with magnetic field. Therefore no magnet geometry is defined in the code, a great advantage for speeding up the simulation but a difficulty for the magnet misalignment study. For the regions where the field is not constant, a study will be performed in the future using altered field maps produced with randomly shifted/rotated magnets. For the purpose of this paper, only the regions where the field is constant have been studied.

SIMULATION RESULTS

For the buncher and rotator, the magnets are described in [1] as a series of 0.5 m-long coils with 0.25 m space between the coils. It is almost certain that this description will have to be revised to accommodate the RF services without losing quality in the field (by both increasing the magnet length and the space between magnets). So as a conservative approach it has been chosen to perform a displacement of the field over a 1 m length in z, according to equation 1 with B_{sol} = 1.5 T.

$$\begin{aligned} B_x &= B_{sol} \times sin\phi \\ B_y &= 0 \\ B_z &= B_{sol} \times cos\phi \end{aligned} \qquad (1)$$

Two tilt angles ϕ have been studied, 10 mrad and 1 mrad, corresponding respectively to a shift in the transverse plane of 1 cm and 1 mm.
Figure 2 gives the total number of muons as a function of z from the target to the end of the cooling section. The cooling section itself is about 227 m long in this simulation as extra cooling was added to study the performance of the lattice on longer sections [7]. Figure 3 gives the number of muons that passed the acceptance criteria as a function of z. As we can see from Fig. 2 and 3, the performance of the v2.0 lattice is worse (∼20% less accepted muons) in comparison with the IDR version. The IDR lattice does not contain the proper Be windows and the RF space was very

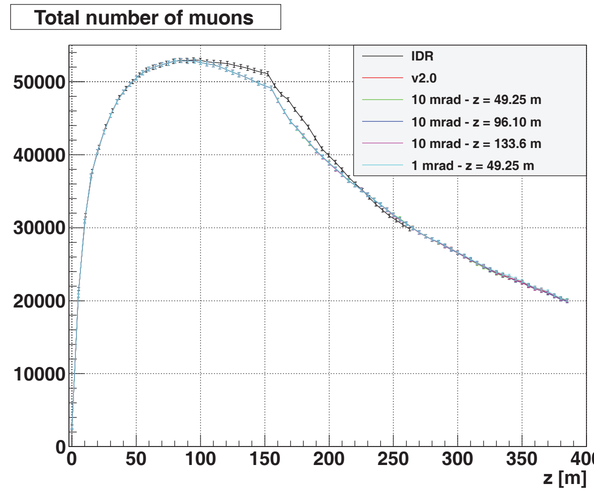

Figure 2: Total number of muons as function of z.

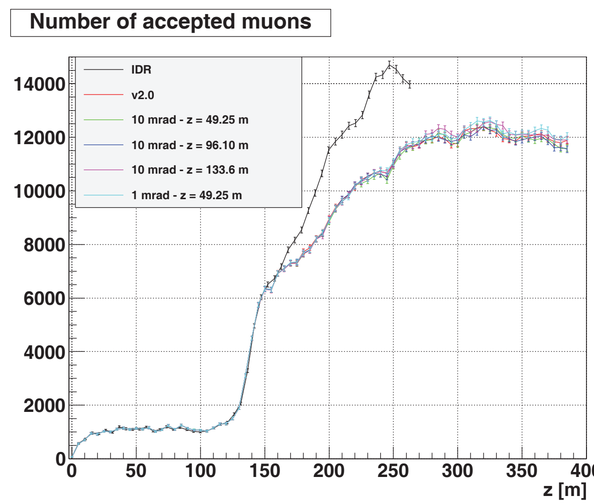

Figure 3: Number of accepted muons as function of z.

tight. The v2.0 lattice contains a more realistic design from the engineering point of view for the RF length, spacing and windows to the detriment of a worse performance.
Figure 4 and 5 show the relative difference (compared to the reference lattice v2.0) of the total and accepted number of muons when the field is misaligned.

To calculate the error bars for the number of total and accepted muons, the definition of the variance of equation 2 has been used (see [9]) where w_i stands for the statistical weight of particle i.

$$\begin{aligned} Var(\sum_{i=1}^{N} w_i) &= \frac{S_0 \cdot S_2 - S_1^2}{S_0 - 1} \\ S_j &= \sum_{i=1}^{N} w_i^j \end{aligned} \qquad (2)$$

To calculate the errors bars for the relative difference between two setups, the general formula for the variance of a

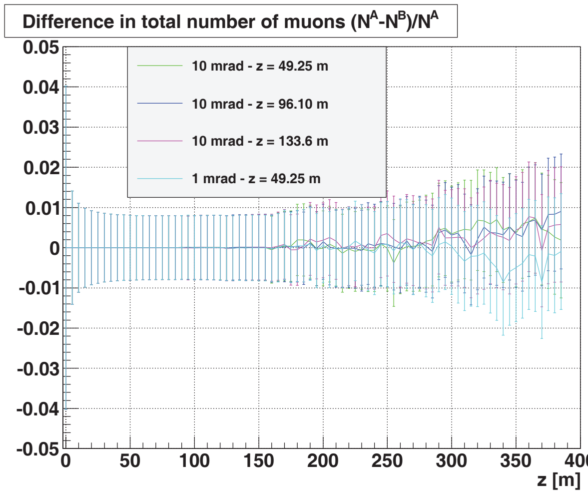

Figure 4: Comparison in the total number of muons with the reference baseline (v2.0).

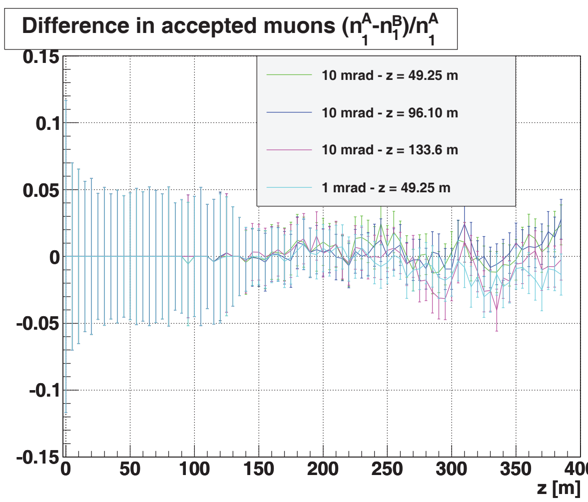

Figure 5: Comparison in the number of accepted muons with the reference baseline (v2.0).

function of two variables has been used (see equation 3).

$$\begin{aligned} w &= f(x,y) \\ Var(w) &= \frac{df}{dx}^2 \cdot Var(x) + \frac{df}{dy}^2 \cdot Var(y) \\ &+ \frac{df}{dx} \cdot \frac{df}{dy} \cdot Cov(x,y) \end{aligned} \tag{3}$$

According to Fig. 4 and 5 the difference in the lattice performance is independent of where the misalignment happens, z = 49.25 m corresponds to the middle of the drift section, z = 96.1 m the middle of the buncher and z = 133.6 m the middle of the rotator.

The difference in the total number of muons is below 1% (3% with the errors bars).

The difference in the number of accepted muons is below 5% within the error bars.

We observe that an angle of 10 mrad or 1 mrad (as tested for the middle of the drift), for the statistics we use, does not change the relative difference variation. As we can also see, we are statistically limited and thus to observe differences in the lattice performance at the percent level a much higher statistics will have to be studied.

CONCLUSION

A preliminary study of the effect of the magnets misalignment has been performed for the drift, buncher and rotator section of the IDS-NF front-end. The change in the performance of the lattice is within 5% for the number of accepted muons and a tilt angle of 10 mrad of the magnetic field over a length of 1 m in the longitudinal direction. Further studies will have to be performed with increased statistics to observe effects down to the percent level. The other sections of the front-end (matcher and cooler) will be studied as well. Finally a study of the RF field misalignment has also to be performed. This will enable a determination of the sensitivity of the full lattice performance to all the components misalignment.

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