

# 40-80 MHz MUON FRONT-END FOR THE NEUTRINO FACTORY DESIGN STUDY\*

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## Abstract

To understand better the neutrino properties, machines able to produce an order of  $10^{21}$  neutrinos per year have to be built. One of the proposed machines is called a neutrino factory. In this scenario, muons produced by the decay of pions coming from the interaction of a proton beam onto a target are accelerated to energies of several GeV and injected in a storage ring where they will decay in neutrinos. The so-called front-end section of the neutrino factory is conceived to reduce the transverse divergence of the muon beam and to adapt its temporal structure to the acceptance of the downstream accelerator to minimize losses. We present a re-evaluation of the muon front-end scenario which used 40-80 MHz radio-frequency cavities capturing one sign at a time in a single-bunch to bucket mode. The standard software environment of the International Design Study for the Neutrino Factory (IDS-NF) has been used, for comparison of its performance with the IDS-NF baseline front-end design which operates with higher frequency (330-200 MHz) capturing in a train of alternated sign, the muons bunches.

## INTRODUCTION

The 40-80 MHz front-end has been studied in the past [1], [2], [3]. In this scenario the front-end was simulated by a 30 m long decay channel in 1.8 T solenoid field, followed by a 30 m long phase rotation channel. In the rotator part the focusing was also performed by 1.8 T solenoids integrated in thirty 44 MHz cavities, each 1 m long. Cavities were set with a phase equal to  $-90^\circ$  and a gradient of 2 MV/m. The rotator was followed by a first cooling section with 44 MHz cavities and hydrogen absorbers, then an accelerating section with 44 MHz cavities, and finally another cooling section with radio-frequency (RF) cavities at 88 MHz. The particles beam was simulated with FLUKA [4], using a 2 GeV proton beam impinging on a 26 mm thick Hg target immersed in 20 T solenoid field. The particles tracking and front-end optimization work was performed using PATH [5]. In this paper we present the performance study of the rotator part, with a different input beam. The tracking and rotator performance study has been done with ICOOL [6] version 3.20 and ROOT [7] has been used as graphical interface. The beam was simulated using MARS [8] version m1507 and a 8 GeV proton beam

impinging on a Hg-jet target in the IDS-NF [9] ST2a configuration (20 T solenoid field tapering down to 1.75 T, over 12.2 m). The output negative pions, muons and kaons were taken 12.2 m downstream of the target and served as input to ICOOL.

## SOLENOID FIELD ON AXIS

In ICOOL, solenoid fields can be computed using a coil geometry configuration and current sheets on a z-R grid. The code produces a field map of the radial and axial solenoid field for each grid point. In the simulation we used one (or several depending on the drift length) 10 m long coil followed by a series of 0.5 m long coils, all with 60 cm radius and 10 cm thickness. A current setting of  $14.26 \text{ A/mm}^2$  on each coils provides a field on axis of about 1.78 T. A plot of the field on axis for a 10 m drift and a 30 m long rotator is given in Fig. 1. This coil configuration does not

Magnetic field on axis – 10 m drift + rotator

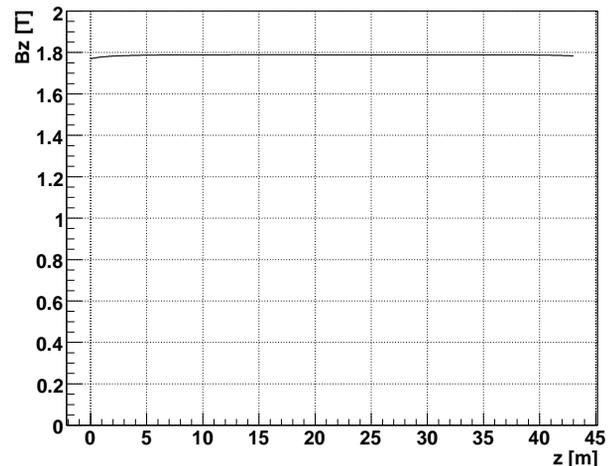


Figure 1: Magnetic field on axis for a 10 m drift and a 30 m long rotator

correspond to the requirement for a realistic coil geometry, and the space between coils and the coils thickness and radius need a full engineering design but this fits the purpose of the simulation.

## DRIFT LENGTH OPTIMIZATION

For the purpose of this study, we used 1 m long cell containing each 1 m long cavity. The rotator was made of nine cells triplets, followed by one cell and finally seven cells. The cavities have all a frequency of 44 MHz, a phase of

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180° and a gradient of 2 MV/m. The ICOOL convention for calculating the electrical field in the RF cavity is described in Eq. 1.

$$E_z = E_0 \cdot J_0(kr) \cdot \cos(2\pi ft + \phi) \quad (1)$$

where  $E_z$  is the electrical field along  $z$ ,  $J_0(kr)$  is the Bessel function of order zero,  $f$  the cavity frequency,  $t$  the particle time, and  $\phi$  is given in Eq. 2.

$$\phi = -\frac{\pi}{2} - 2\pi ft_{ref}^{min} + d\phi \quad (2)$$

where  $t_{ref}^{min}$  is the time of the reference particle when it enters the cavity.

$d\phi$  is the phase shift we apply (180° in this case).

According to the description above, ICOOL uses an additional phase shift of 90° in comparison with PATH.

Drift length of 10 m, 20 m and 30 m before the rotator were used in order to see if the pions remaining after the initial 12.2 m drift and field tapering section from the MARS simulation would produce useful muons.

In our input beam we selected the 1000 first beam entries corresponding to 1989  $\mu^-$  and 1760  $\pi^-$  (MARS uses for each entry a statistical weight, corresponding to the average number of particles having the phase-space coordinates of the entry). The beam mean time  $\langle t \rangle$  was computed and corresponds to 50.7 ns. This value was used to set the reference particle time in ICOOL to the center of the beam, as the ICOOL RF model we use, computes the difference between the reference particle time and the particle time at the center of the cavity in order to calculate the RF electrical field value. The number of muons as a function of  $z$  for different momentum and acceptance cuts was computed for the three cases. Table 1 summarizes the cuts used and the corresponding muon yields. The longitudinal and

Table 1: Summary of the momentum and acceptance cuts used in the simulation, Y (cut used) and N (cut not used).

Cuts	n	n <sub>0</sub>	n <sub>1</sub>	n <sub>2</sub>
$100 < p_z < 300$ MeV/c	N	Y	Y	Y
$A_L = 150$ mm	N	N	Y	Y
$A_T = 15$ mm	N	N	Y	N
$A_T = 30$ mm	N	N	N	Y

acceptance cuts are requirements from the downstream acceleration systems. The reference particle longitudinal momentum has been set to 250 MeV/c. The longitudinal momentum cut upper bound could be slightly relaxed, whereas particles with momentum below 100 MeV/c are not useful muons. In Fig. 2,  $n$  and  $n_0$  are given as a function of the  $z$  position, for the three drift length options. In Fig. 3, the number of muons  $n_1$  and  $n_2$  are given as a function of the  $z$  position, for the three drift length options. As we can see, an increase of the drift from 10 m to 20 m, will not increase much the number of muons falling in the acceptance

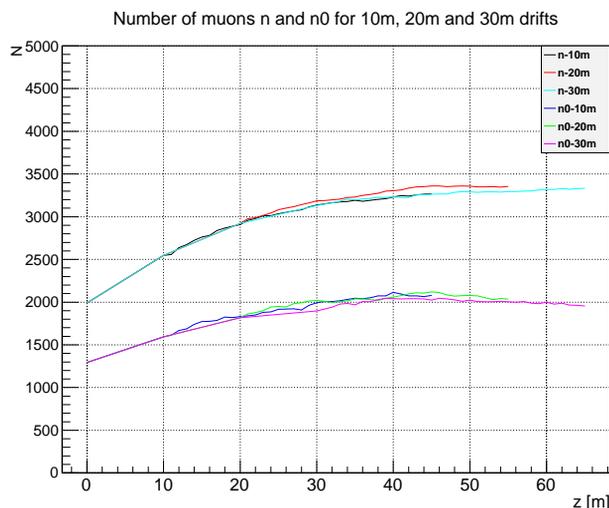


Figure 2: Total number of muons  $n$  and  $n_0$  as function of  $z$  for three drift lengths.

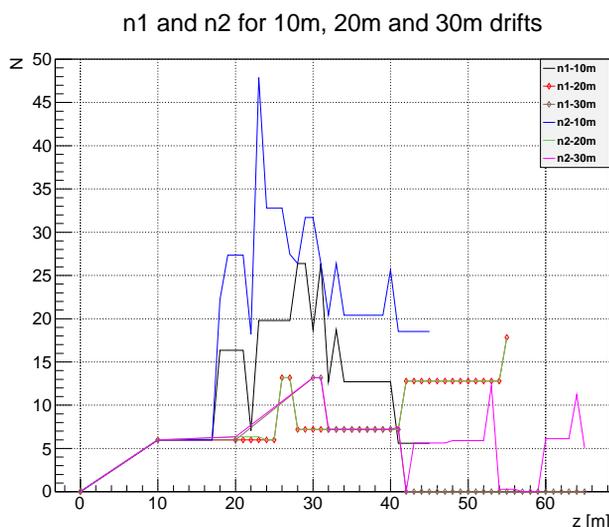


Figure 3: Total number of muons  $n_1$  and  $n_2$  as function of  $z$  for three drift lengths.

cuts of  $n_1$  and  $n_2$ . Whereas for a 30 m long drift before the rotator the number of muons falling in the acceptance cuts of  $n_1$  and  $n_2$  is doubled. The performance of the rotator is very low with approximately 1/100 muons accepted where the IDS-NF baseline lattice rotator section capture 1/6 muons in the  $n_2$  acceptance cuts. For the 20 m drift case, the number of muons falling in the  $n_1$  and  $n_2$  acceptance is multiplied by 3 at the end of the rotator section, whereas for the 10 m the number of muons falling in the  $n_1$  and  $n_2$  acceptance is bigger but falls rapidly passed 20 m of rotator. Finally for the 30 m drift case, the number of muons in the  $n_1$  and  $n_2$  acceptance is decreasing when entering the rotator section, making this configuration completely inefficient, unless we adjust the rotator to a different RF phase.

The muon momentum spread at start (before the drift),

$\frac{|p-p_{ref}|}{p_{ref}}$  is 11% and at the end of the rotator, it has been reduced down to 2-3% (factor 5 reduction).

The performance shown here do not seem to match the results from past studies, but very different initial beams and simulation codes were used at that time. It is planned in the future to send the beam that was used in past studies in the ICOOL lattice and study the capture performance as a cross-check.

## RF CAVITY SPACING STUDY

In the previous configuration, there is no space between the cavities. A rotator configuration of 7 cells 3 m long each has been studied. A cell is made of 0.5 m drift, plus 1 m cavity, plus 0.5 m drift and 1 m cavity. The frequency, phase and gradient were the same as in the study of the drift length. In Fig. 4 and 5 the number of muons  $n$ ,  $n_0$ ,  $n_1$  and  $n_2$  are given for the 10 m drift case. As we can see, the

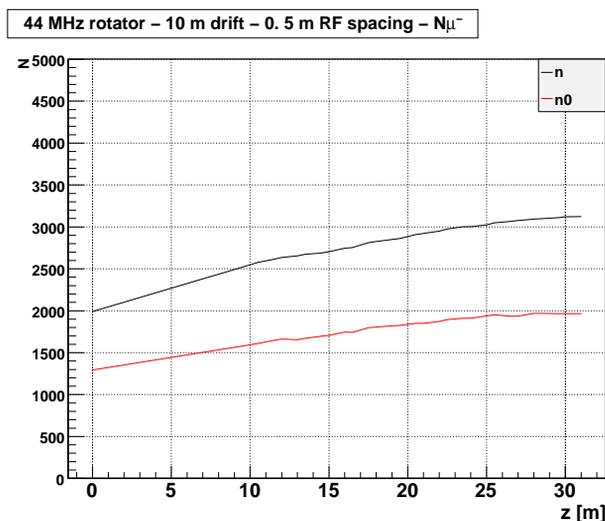


Figure 4: Total number of muons  $n$  and  $n_0$  as function of  $z$  for a configuration with 0.5 m spacing between cavities

number of muons in the  $n_2$  acceptance cuts is now 1/50. The momentum spread has been reduced at the end of the lattice to 1%. The total number of RF is only 14, a gain compared the previous study which has 30 cavities.

## CONCLUSION

The 44-88 MHz lattice configuration has been studied for the rotator section using the IDS-NF baseline beam and ICOOL code. Different drift lengths (without change of the lattice configuration in comparison with previous studies) have been studied showing a very low performance in the IDS-NF acceptance and in comparison with past studies. By increasing the space between the RF cavities, a gain in the number of the muons captured in the performance was shown. Future optimization studies with an increased RF bucket height, different RF cavities spacing, re-adjustment of the phase and reference particle time, will be done.

44 MHz rotator – 10 m drift – 0.5 m RF spacing –  $N_{\mu^-}$  in acceptance

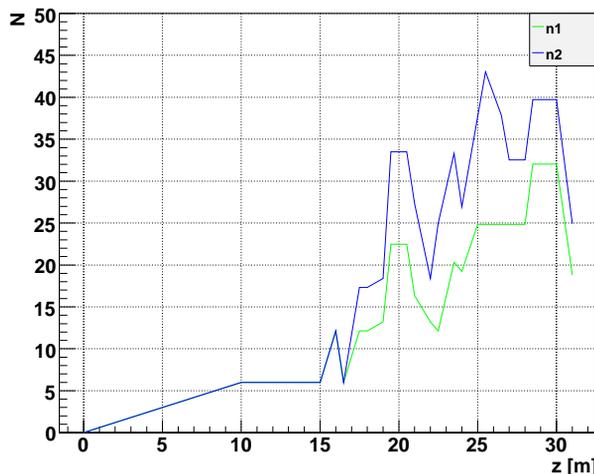


Figure 5: Total number of muons  $n_1$  and  $n_2$  as function of  $z$  for a configuration with 0.5 m spacing between cavities

## ACKNOWLEDGEMENT

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