Optimizing the neutrino factory capture section

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Abstract. The *capture section* is studied using the simulation tools `FLUKA` and `G4beamline`. Protons hit a Hg-target producing charged secondary particles in a region with a high magnetic field. The pions and muons are focused by a tapered magnetic field produced by a series of solenoids. The goal of the study is to improve the capture efficiency, by using alternative magnetic field tapering, solenoid geometry and solenoid shielding.

Keywords: Neutrino factory, capture section, solenoid, magnetic field, taper
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INTRODUCTION

The Neutrino Factory (NF) will provide intense, high energy neutrino beams from the decay of muons [1]. The majority of the muons will be created from the decay of pions, produced by a proton beam impinging on a Hg-target. It will be important to capture a large fraction of the produced pions, then let them decay to muons and transport them through the NF *front-end* to maximize the particle flux into the accelerator. The NF front-end consists of the target and capture section, a longitudinal drift, a buncher, a rotator and finally a muon cooling section.

In the baseline design the capture section consists of a series of high magnetic field solenoids (see figure 1), making a magnetic field tapered from 20 T to 1.75 T over a distance of 12 m [2]. Charged particles from the target are captured in the 20 T magnetic field to form a beam. The beam's divergence is then gradually decreased by the tapered magnetic field, before it enters the constant 1.75 T field in the drift section. Here pions decay and the particles develop a position and energy correlation. The longitudinal phase space is then manipulated in the buncher and phase rotation section to reduce the beam momentum spread. Finally the transverse phase space is reduced in the cooling section.

The number of pions captured depends on the magnetic field strength, the shape of the tapering and the geometry of the shielding. To maximize the muons flux into the accelerator an optimization study is performed for these key concepts and the results are presented here.

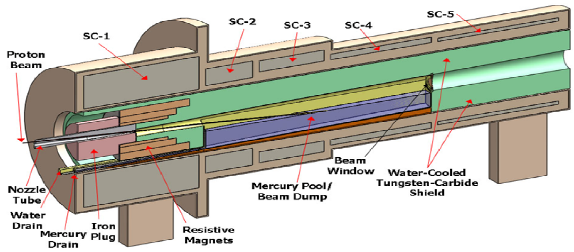

FIGURE 1. Baseline layout of the target and capture section of the NF. The proton beam is focused on the Hg-target to produce pions in a 20 T magnetic field made by superconducting solenoid magnets. The pions are then transported downstream towards the frond-end [2].

OPTIMIZATION METHOD

The results presented are produced using G4beamline, a particle tracking program based on Geant4 [3]. A Hg-target is used with length $l = 30$ cm and radius $r = 0.5$ cm. The target center is placed at $z = -37.5$ cm and tilted an angle $\theta_T = 96.68$ mrad with respect to the z-axis. The impinging 8 GeV kinetic energy proton beam has an angle $\theta_{BT} = 30$ mrad with respect to the target axis at the center of the target ($z = -37.5$ cm). All these parameters are held constant for each setup.

The accelerator can only accelerate a fraction of the muons arriving from the front-end. To find this fraction a setup of the full front-end for G4beamline is used. The muon flux is counted at $z = 50$ m and at the end of the front-end (at $z = 271.1$ m). Then the emmitance calculation tool *ecalc9f* [4] is applied at the end of the frond-end to find the muons accepted for the accelerator, defined as *good muons*. G4beamline labels each of the particles in such a way that the momentum, position and time distribution can be traced back and found at 50 m for these good muons within the *acceptance cuts*. See table 1. This makes it possible to compare different capture systems by the particle flux at 50 m while being confident that the particles within the cuts have a high probability of being good muons. The results are compared with the capture section from Study 2A (ST2a) [2].

TABLE 1. Acceptance cuts at 50 m and the input parameter for the ecalc9f routine at 271.1 m. The acceptance cuts were found by using the survivors from the ecalc9f routine and finding their momentum, time and position distributions at 50 m.

Position (m)	p_z **(MeV/c)**	p_T **(MeV/c)**	t **(ns)**	r **(mm)**
50	100-300	< 50	160-240	< 200
Position (m)	p_z **(MeV/c)**	A_T **(m rad)**	A_L **(m rad)**	**Input for ecalc9f**
271.1	100-300	< 0.030	< 0.150	

Optimization without magnet shielding

First the magnetic field tapering for 5 different setups is studied, all without any magnet shielding. There is one variant of *13sol*, three variants of the *3sol* setup that is compared with the *ST2a* setup. The 3sol layout, figure 2, has 3 superconducting (SC)solenoid magnets. The large SC1 magnet will generate the high 20 T field with help from the normal resistive inner solenoids and SC3 generates a 1.5 T field. The SC2 generate fields that can be read from figure 3. The *13sol* setup has 13 SC

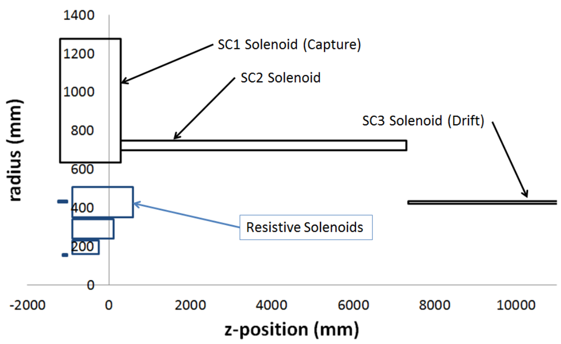

FIGURE 2. The 3sol solenoid magnet setup. The picture shows the upper half of a vertical cut of the solenoids. The black boxes are the superconducting solenoids and the blue boxes are the resistive solenoids. Here we have no magnet shielding.

solenoids and a long field tapering. The magnetic fields on axis can be seen in figure 3. The simulation stoped tracking any particle that hits the solenoids.

The results can be seen in figure 4. The 3sol_1 setup (28513 $\mu^{\pm}$) has the highest muon flux, an increase of 9% compared with the ST2a (26262 $\mu^{\pm}$).

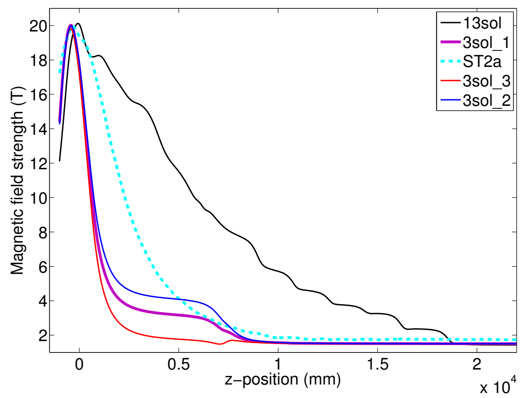

FIGURE 3. Magnetic field tapering for all the setups. The 3sol_1 setup is the thick purple line and the ST2a setup is the thick cyan dashed line.

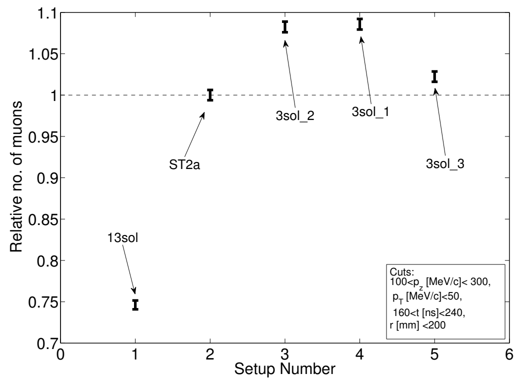

FIGURE 4. Relatice muon flux at 50 m, see figure 3. The 3sol_1 setup give the highest muon flux.

Optimization with magnet shielding

Shielding is needed to protect the magnets from radiation, the radius of the shielding is found as follows. The inner radius of the magnet shielding is calculated assuming an adiabatic tapering and conservation of magnetic flux $\Phi = \pi B R^2$. Where B and R are the magnetic field strength and the inner shielding radius, respectively. From flux conservation

$$\pi B_1 R_1^2 = \pi B_2 R_2^2, \tag{1}$$

where the subscrips refer to different points along the tapering where the flux is conserved. This helps to calculate the inner shielding radius as a function of position along the z-axis, taking account of the field taper. The inner shielding radius in the ST2a setup is 7.5 cm in the 20 T field region around the target. Using equation 1, with $B_1 = 20T$, $R_1 = 7.5$ cm, $B_2^{ST2a} = 1.75$ T and

$B_2^{3sol} = 1.5$ T, the radii are found to be $R_2^{ST2a} = 25.4$ cm and $R_2^{3sol} = 27.4$ cm. In figure 5 there is the two different

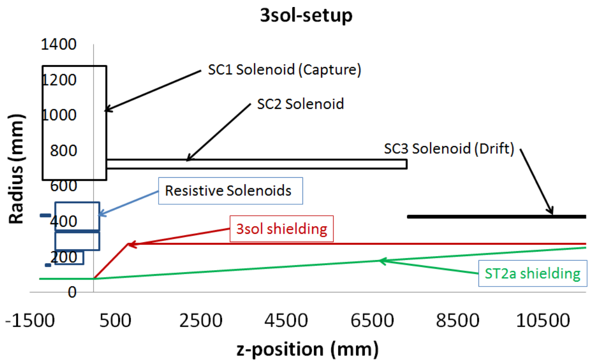

FIGURE 5. The 3sol solenoid magnet setup. The picture shows the upper half of a vertical cut of the solenoids. The black boxes are the superconducting solenoids and the blue boxes are the resistive solenoids. The shielding used in the ST2a is showed in green and the 3sol shielding is in red.

magnet shieldings, naming the new shielding made for the 3sol setup for *shielding3*. The shielding for SC1 is not changed, but for SC2 a quickly expanding shielding cone is prefered since the field tapering is shorter. With less shielding the magnet will be more exposed to radiation. Assuming that a low field SC2 magnet can have an increased inner radius the radiation exposure can be decreased.

Varying the SC1 magnet strength

The optimisation of the SC1 magnet strength was studied by varying the trength of the SC1 magnet from 10 T to 40 T while observing the muon flux. During this study the SC2 and SC3 magnetic field strengths are held constant at 1.5 T and the 3sol setup and shielding are used. The ST2a muon flux is used as normalization and the relative number of muons is shown in figure 6. Errorbars are statistical only, calculated as the square-root of the muon flux.

The muon flux graph flatens out around 25 T. We choose to set a maximum for SC1 at 20 T, taking into account the technical challenges of making a magnet producing a field higher than 20 T and the increased cost. The relative difference in muon flux between 20 and 25 T is 13%.

Varying the SC3 magnet strength

The magnet strength of SC2 is set equal to SC3, the magnet strength of SC3 (and therefore SC2) is then varied from 1 to 2.5 T. SC1 is at 20 T. Again we use

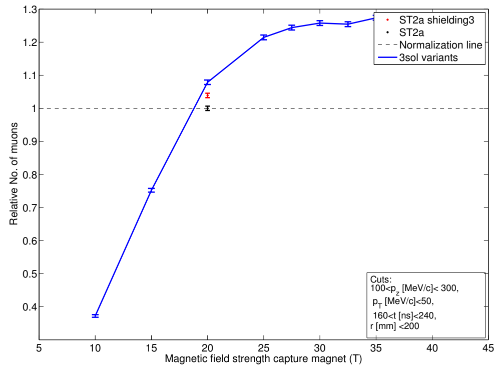

FIGURE 6. Relative muon flux at 50 m when varying the SC1 magnet strength from 10 to 40 T are shown in blue, normalized with the muon flux from the ST2a (shown in black). The red point is the ST2a setup with the 3sol shielding. All points include errorbars.

the ST2a muon flux as the normalization(see figure 7). The SC3 magnet should create a field of 1.5 T.

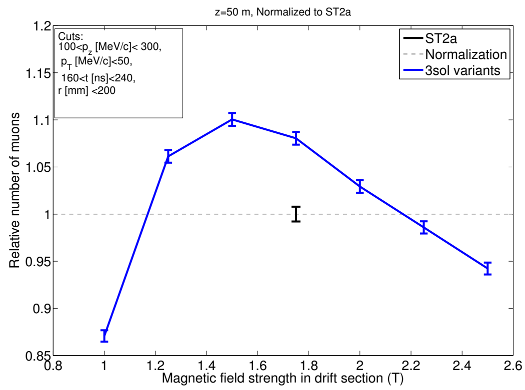

FIGURE 7. Relative muon fluxes when varying the SC3 magnet strength from 1 to 2.5 T are shown in blue, normalized with the muon flux from the ST2a (shown in black). Errorbars are statistical.

Varying the SC2 magnet strength

SC1 is set to 20 T and SC3 to 1.5 T and the magnet strength of SC2 is varied from 1.75 to 9 T. In figure 8, the results are normalized with the ST2a muon flux. The maximum is found when SC2 is at 4.8 T with an increase in particle flux of about 10 %. Going down to an even lower field is possible without a huge particle loss.

The momentum distributions for the ST2a and the 3sol, both with shielding3, are compared in figure 9. They are similar, with the 3sol having a slight advantange over the ST2a.

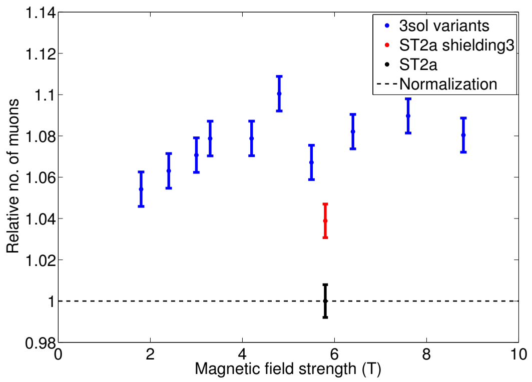

FIGURE 8. Relative muon flux when varying the SC2 magnet strength from 1.75-9 T are shown in blue, normalized with the muon flux from the ST2a (shown in black). The ST2a with shielding3 shown in red. Errorbars are statistical only.

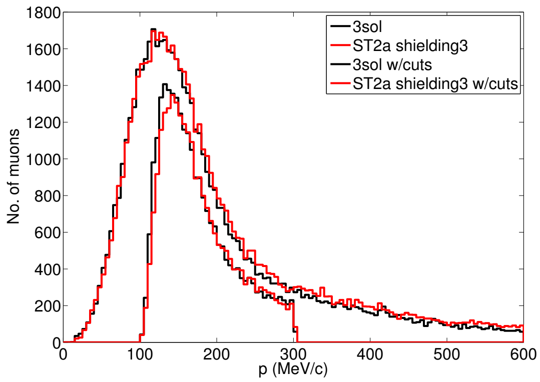

FIGURE 9. Muon momentum distribution for the ST2a and the 3sol setups shown in red and black, respectively. We can see that the distributions are similar and the 3sol captures a higher number of muons. The two upper lines show the momentum distribution without any cuts applied while the two lower lines show the distribtion with the acceptance cuts.

A study with FLUKA is done in order to compare the results with G4beamline. Table 2 shows some comparisons between the two monte-carlo simulation tools.

TABLE 2. Relative no. of total muons and the relative no. of muons within the acceptance cuts for the ST2a and the 3sol. Both have shielding3.

	No cuts		w/cuts	
Setup	G4BL	FLUKA	G4BL	FLUKA
ST2a shielding3	1.09	1.57	1.04	1.24
3sol	1.05	1.38	1.10	1.14

According to the G4beamline simulations, the 3sol setup is better than both the ST2a and the ST2a-shielding3. The results from FLUKA suggests that the 3sol is better than the ST2a and the ST2a-shielding3 is even better than the 3sol. However, reducing the shielding thinkness for the ST2a magnet layout may cause an increase in the radiation exposure to the magnets. For the 3sol the increased inner magnet radius means there can be more shielding between the beampipe and the magnets. FLUKA seems to be more sensitive to a change in shielding layout than G4beamline, increasing the muon flux with 24 % for the ST2a-shielding3.

Summary and outlook

The magnetic field tapering and the shielding layout for the Neutrino factory was studied. The study of the magnetic field tapering without any shielding, showed that a faster magnetic field tapering is a good alternative to the longer adiabatic tapering. The lower current in SC2 may allow this solenoid, expected to receive the peak of the radiation from the target, to have a larger radius thereby exposing it to less radiation.

When the magnetic field in SC3 is decreased, an increased shielding radius is needed to conserve the magnetic flux. A shortening of the magnetic field tapering, an increase of the shielding inner radius and a shortening of the cone length was done. Then the field strength was optimized in each of the three SC magnets, but varying the field in 1 magnet at a time. This altenative 3sol setup gives a higher yield compared to the ST2a setup, for both FLUKA and G4beamline.

A study of the energy deposition in the magnets to check if the magnets are properly shielded with the new shielding3 is needed. A study with the 30 cm mercury target replaced by, the baseline, full liquid mercury jet target included is needed.

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