Analysis of the 44 MHz rotation scheme in ICOOL for the neutrino factory

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Abstract

The first stage of the CERN rotation and muon cooling 44-88 MHz scenario is studied in the program ICOOL. The aim is to re-evaluate its performance in comparison to the current Neutrino factory baseline.

Some programs are written in ROOT to analyze the result of the particle propagation and beam parameters are determined for the channel in the transverse plane.

1 Introduction

1.1 Neutrino factory

In a Neutrino factory[1] the decay of stored muons is used to produce the final neutrino beam. The short muon lifetime (μs) demands sophisticated bunching, phase rotation and cooling of the beam. In the Neutrino Factory baseline scheme, a proton linac strikes a mercury jet expelling pions that decay to muons over a 12 m decay stretch. At the end of the decay stretch rotation and bunching is performed then a cooling channel cools the muons transversely by alternating absorbers, to cool the beam in all directions, and RF cavities to restore the longitudinal momentum. In the baseline scheme, bunching and subsequent phase rotation is achieved by a system of RF cavities with decreasing frequencies (335 - 201 MHz) for the bunching and 201 MHz cavities for the rotation [2].

1.2 44-88 MHz Scenario

Another scheme developed at CERN and investigated by A. Lombardi[3] uses 44 and 88 MHz RF-cavities to perform the collection, phase rotation and cooling of muons. The general layout is a 2 GeV superconducting linac[4] striking a mercury target in a 20 T magnetic field. The decay stretch in this scheme is 30 m. After the decay stretch the muons are rotated over 30 m using 44 MHz cavities. Then follows a cooling section and an acceleration section with the same frequency cavities and another cooling/accelerating section with 88

MHz. Through the entire channel a focusing magnetic field is present, its magnitude is 1.8 T for the decay and rotation section and 2.0 T for the cooling and acceleration section.

This scenario permitted to provide bunch to bucket capture that keep the longitudinal structure of the beam.

In this note the 30 m rotation channel is studied using ICOOL[5]. The magnetic field is adjusted to better match the design value 1.8 T, the beam file used by A. Lombardi is converted to ICOOL input format. Finally three programs are written in ROOT to read the ICOOL output file and evaluate the evolution of the beam throughout the channel.

2 Methods

2.1 ICOOL

ICOOL is a program developed at Brookhaven National Laboratory and is typically used to analyze ionization cooling channels using solenoid fields, RF-cavities and absorbers. ICOOL requires as input several files named forXXX.dat. The for001 file contains the general geometric setup divided into cells of drift sections, RF-cavities and absorbers. The for003 file describes the particle input with initial for example time, position, momentum. Finally two files, for030 and for031, describing the magnetic field is required. These describe the field using a finite number of coils with a given current.

Running ICOOL it creates a magnetic field map and propagates the particles through the different components of the channel. The output is a file showing each particle's properties at each cell intersection as well as the electric and magnetic field at that point.

2.2 Written code

2.2.1 ParticleConverter.C

The original investigation by A. Lombardi was not done in ICOOL but using Travel/PATH Manager, a windows based program developed at CERN. To be able to duplicate this investigation the same particle input is required. The file containing the particle properties for Travel is in a different format and must be converted into a file with ICOOL input format. For this purpose a program, ParticleConverter.C was written in ROOT that reads a selected number of lines from the original file and converts them to ICOOL format printing into an ICOOL particle input file named for003.dat. The program is called ParticleConverter.C and reads n lines corresponding to n particles. The value n needs to be input in the code.

2.2.2 EllipseParameters.C

ICOOL does not contain any routines for analyzing beam parameters such as the twiss parameters: alpha, beta gamma. For this purpose a program, EllipseParameters.C, was written in ROOT that reads the ICOOL output file, chooses two particles from which the change in x and $x' = \frac{px}{pz}$ is used to calculate the change in beam parameters. The program uses ROOT output graphics to plot the particles positions and the corresponding beam ellipses as well as the beam ellipse parameters $\alpha,\ \beta,\ \gamma$ and ϵ as a function of distance.

The equation used to describe an ellipse is

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \epsilon \tag{1}$$

where ϵ is the beam emittance. The area of the ellipse $A = \pi\epsilon$ and remains under certain conditions constant.

Knowing how the $x,\ x'$ values transform through the channel the beam parameters can be determined using the equations[6]

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \begin{pmatrix} a^2 & -2ab & b^2 \\ -ac & ad+bc & -bd \\ c^2 & -2cd & d^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix} \tag{3}$$

Using the same definitions for a,b,c,d one can define a beam matrix sigma with sigma12=sigma21 where the matrix elements are described by the following equations:

$$\begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix}_0 = \epsilon_0 \begin{pmatrix} \beta_0 \\ -\alpha_0 \\ \gamma_0 \end{pmatrix} \tag{4}$$

$$\begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix} = \begin{pmatrix} a^2 & 2ab & b^2 \\ ac & ad+bc & bd \\ c^2 & 2cd & d^2 \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix}_0 \tag{5}$$

$$\epsilon = \sqrt{\sigma_{11} \cdot \sigma_{22} - \sigma_{12}^2} \tag{6}$$

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \frac{1}{\epsilon} \begin{pmatrix} \sigma_{11} \\ -\sigma_{12} \\ \sigma_{22} \end{pmatrix} \tag{7}$$

The program input parameters are number of particles, number of cells studied, plotting range and which particles to use for determining ellipse parameters.

2.2.3 RemainingParticles.C

Another important property of the channel is how big range of initial space and momentum particles can be contained in the transverse and longitudinal plane. For this purpose a simple code, RemainingParticles.C is written in which the number of particles, the amount of cells to be studied as well as a factor of how many cells to skip for plotting are input. The program computes the number of surviving particles at each selected cell and plots the remaining particles.

2.3 Implementation

Two different sets of particles are run in the simulations. Either a start up ellipse is chosen more or less at random to be a tilted ellipse with a given area and its beam parameters are fed into the program as a initial ellipse. A few particles with x, x' values inside the ellipse are chosen to be fed into ICOOL, or a short part of the particles from A. Lombardi's particle file are chosen and an ellipse is matched by hand to the particles and used as initial ellipse. ICOOL then propagates the particles through the channel either with no B-field or RF cavities, only B-field or both. The program then analyzes the output file to print the particles and the corresponding ellipses.

Also a set of 10000 particles from file are sent through and RemainingParticles.C is used to plot how many particles come to the end of the channel.

3 Results

3.1 Magnetic field map

In the 44-88 MHz scheme a 1.8 T magnetic field is applied throughout the entire 30 m rotation section. The magnetic field is created in ICOOL through a magnetic field map input file named for030.dat. The existing field map was adjusted to better match the design value 1.8 T. By changing values in the filed map file the deviation from 1.8 T was reduced to 0.05%. The resulting magnetic fields are shown in figure 1.

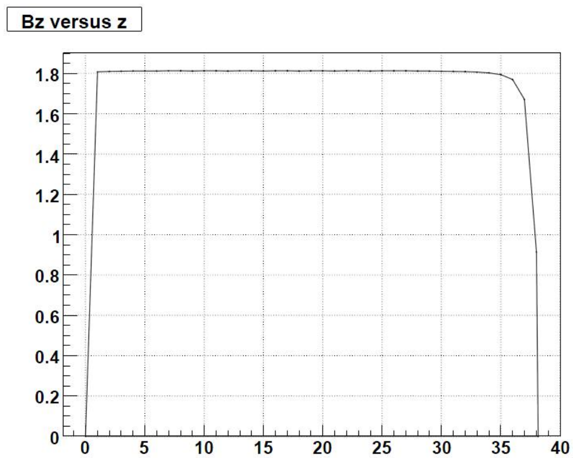
3.2 Converting particle file from Travel to ICOOL

100 particles and 10000 particles are converted using the program.

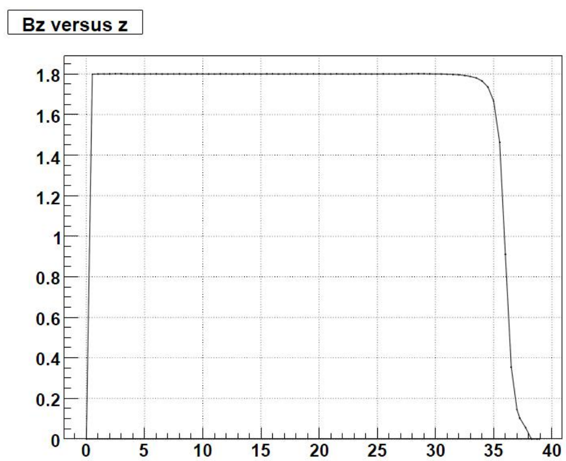
3.3 Calculating ellipse parameters from ICOOL particles

3.3.1 No B-field, no RF-cavities

The code is run without anything to confirm that it is working as it should. As there is no magnetic field the particles drift in x while their x' stays constant and the ellipse stretches out as can be seen in figure 2a. The ellipse parameters also behave as expected as can be seen in figure 2b. β increases as the beam dimension increases and α increases in the negative direction as the tilt of the



(a) Original magnetic field map



(b) Adjusted magnetic field map, file name: "Field map 1.8 T.dat"

Figure 1: Resulting magnetic field from magnetic field map input files

ellipse increases. Both γ and ϵ stay constant as the x' extension and total area stay constant.

3.3.2 Only B-field

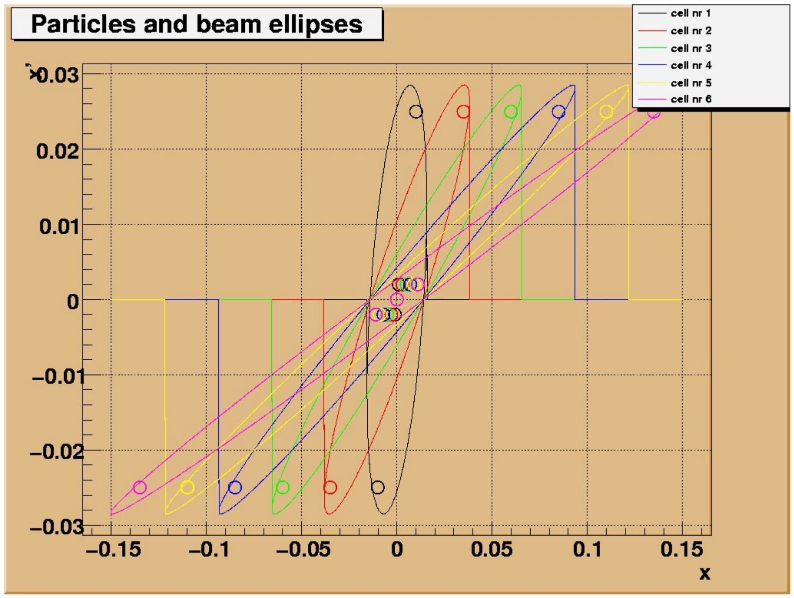
Turning on the B-field and propagating the four test particles through the channel they start rotating in the x, x' plane as in figure 3a. In figure 3b one can see how the ellipse parameters start oscillating with a period of 5 m. Also the solenoid provides magnet provides some periodic focusing/defocusing.

3.3.3 B-field and RF-cavities

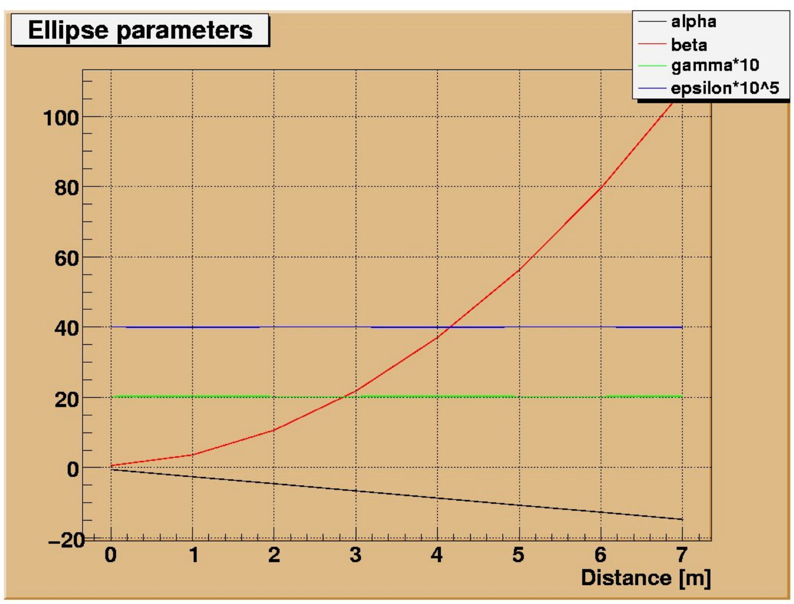
Finally turning on the RF-cavities the particles keep their rotation in the x, x' plane. We expect the longitudinal momentum to increase and thus $x' = px/pz$ to decrease. We do indeed note in figure 4a that the particles have a lower x'value in cell 6 than in cell 1. The effect is approximately of the order 5 % over 5 m.

3.4 Determining remaining particles

The 10000 first particles of the particle file are converted to ICOOL format and propagated through the channel with B-field and RF-cavities. The particles still within acceptance are plotted in figure 5 at 10 m intervals. In the first 10 m almost 3300 particles are lost while for the last 20 m only about 50 are lost. It seems that the particles within a certain acceptance will stay in the channel for a long time. If they are outside this acceptance, they will be lost more or less immediately.

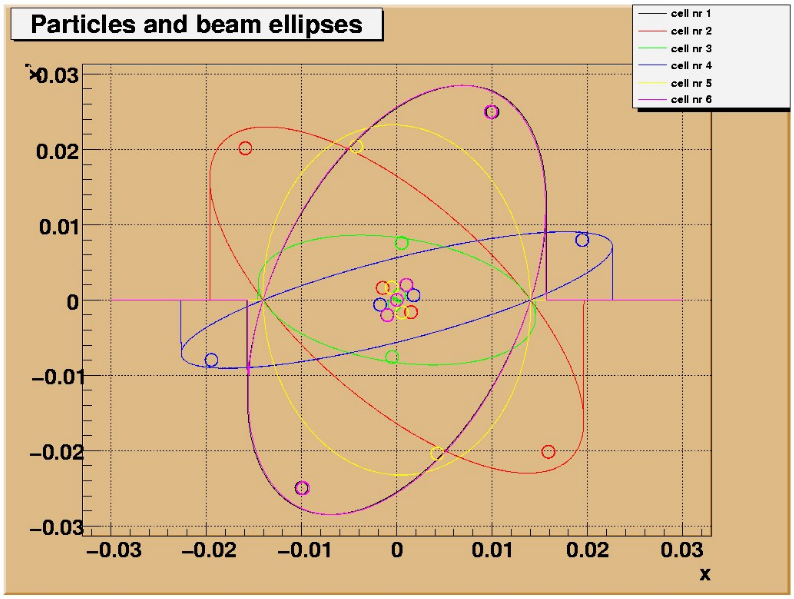


(a) The particles and corresponding beam ellipses plotted for the first 6 m

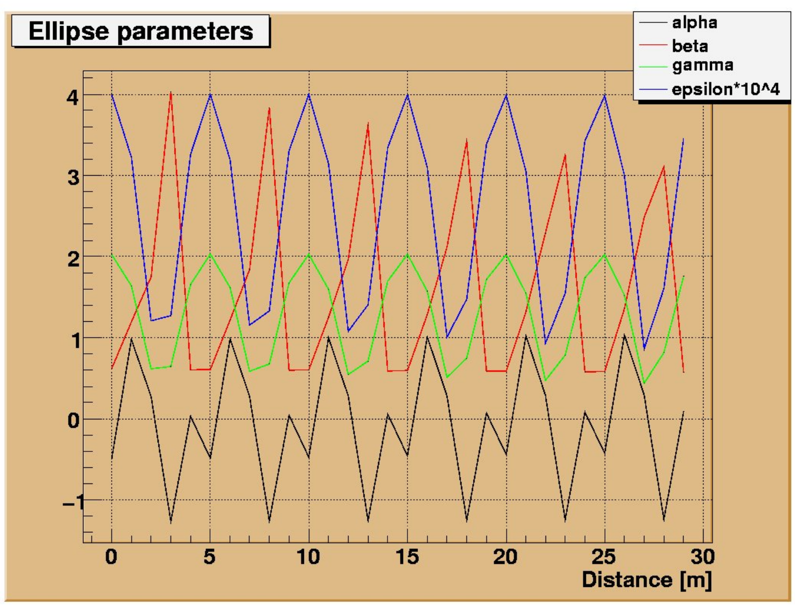


(b) The ellipse parameters plotted for the first 7 m

Figure 2: Beam evolution without B-field or RF-cavities of four particles

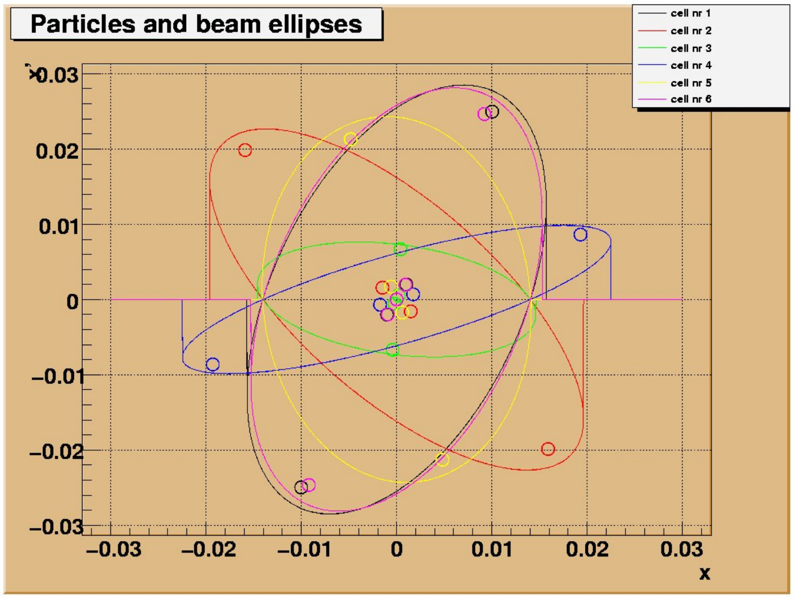


(a) The particles and corresponding beam ellipses plotted for the first six cells

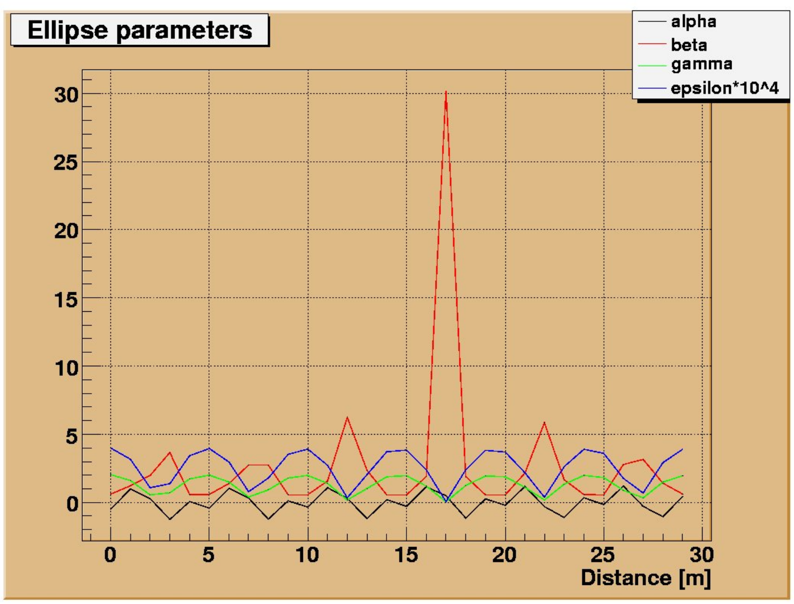


(b) The ellipse parameters plotted for the first 30 m

Figure 3: Beam evolution with B-field without RF-cavities of four particles

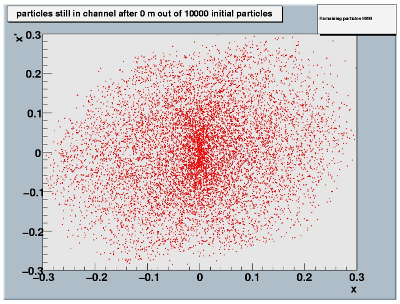


(a) The particles and corresponding beam ellipses plotted for the first six cells

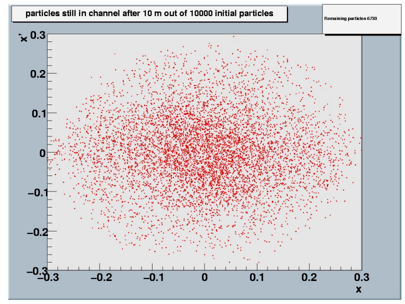


(b) The ellipse parameters plotted for the first 30 m

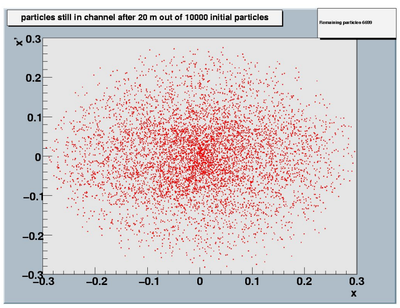
Figure 4: Beam evolution with B-field and RF-cavities of four particles



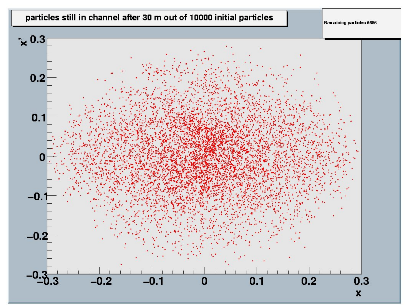
(a) Initial 1000 particles



(b) 6733 particles remain after 10 m



(c) 6699 particles remain after 20 m



(d) 6685 particles remain after 30 m

Figure 5: 10000 first particles from file propagated through channel with B-field and RF-cavities

4 Conclusions

The program to calculate ellipse parameters works well for two test particles which can be propagated through the channel.

The fact that particles that are not lost within the first part of the lattice stay throughout the whole lattice is consistent with a specific acceptance of the lattice yet to be determined.

The note is a step on the way to further studies of the optics and muon acceptance of the 44-88 MHz scheme. Comparison with the previous results will be done to verify that the channel performance is not dependent of the choice of the simulation tool. Final comparison with the current baseline will be performed when the full lattice including acceleration and cooling sections has been simulated both in the transverse and longitudinal plane.

References

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