Beam Dynamics Study of a Muon Cooling Experiment with 200 MHz Cavities in the Framework of the CERN Cooling Study

M. Migliorati, L. Palumbo, Università di Roma "La Sapienza", and INFN - LNF, Frascati, Italy,
F. Tazzioli, C. Vaccarezza, INFN-LNF, Frascati, Italy
K. Hanke, E. B. Holzer, A. Lombardi, CERN, Geneva, Switzerland

Abstract

Muon cooling is one of the building blocks for a Neutrino Factory. It has the potential to increase the muon flux at the detector by an order of magnitude. Different set-ups for the experimental observation of cooling are proposed and discussed by an international collaboration [MICE]. In this paper we present the results of the tracking studies for a cooling experiment based on 200 MHz cavities with superconducting solenoids and liquid hydrogen absorbers. For 200 MeV muons passing through a system of 4 cavities at 7.6 MV/m, the number of muons in a given acceptance increases by a factor of about 10 %. This is believed to be well within capability of the measurement apparatus and sufficient to gather important information for the final design of a full-scale cooling channel.

1 INTRODUCTION

A Neutrino Factory (NF) based on a muon storage ring is an important tool for studies of neutrino oscillations. Ionization cooling of muons is fundamental for a NF, but has never been realized in practice. In the CERN layout for the NF, the cooling channel is based on 44 and 88 MHz cavities with integrated superconducting solenoids [1].

An international collaboration on a muon ionization cooling experiment (MICE) has been set up in order to study the feasibility of a section of cooling channel that would be able to give the performances required for a NF. For the CERN case, a cooling experiment has been proposed which is a small subset of the 88 MHz part of the final channel[2].

As an alternative to the cooling experiment based on 88 MHz cavities, we present a system at 200 MHz as proposed in the US study II design for a NF [3]. The aim is to verify the possibility of using cavities at 200 MHz with the same beam characteristics as in the 88 MHz case, and to compare the cooling performances in the two cases. Even with a completely different beam optics, the beam dynamics shows a similar cooling efficiency.

2 LAYOUT

The use of pill-box cavities with conductive irises resonating at 200 MHz prevents the possibility of integrating the solenoids into the cavities as in the case of 88 MHz [4].

Since a design of a cooling channel with 200 MHz cavities has already been presented in the US study II proposal [3], we have simulated a system based essentially on the same engineering constraints, but with differences due to the different beam dynamics, that in our case has characteristics similar to the 88 MHz cooling channel. In the US proposal there are two possible schemes: SFOFO lattice 1 and 2. Preliminary simulations [5] showed that, for our beam dynamics, the second scheme, with groups of two cells separated by solenoids, gives a more uniform magnetic field and better performances. We have therefore based our simulations on this set-up with the difference that we use a scheme with equal solenoid polarity. This cheap solution is not the one proposed for the full-scale cooling channel, but it can give a clear demonstration of muon cooling.

The solenoid configuration is illustrated in Fig. 1 where the magnetic field lines as computed with the POISSON code [6] are shown. In the input and output diagnostic sections there are two continuous solenoids with a radius of 33 cm and length of 2 m. At the entry of the cooling channel there is a 47 cm long liquid hydrogen absorber inserted inside a solenoid of 21 cm inner radius. The absorber is followed by a system of two cavity cells resonating at 200 MHz with an average effective gradient of about 11.8 MV/m. In the middle of the cells and outside of them there is a short solenoid (18 cm) with a large radius of 61.5 cm. After the two cells, there is another 40 cm long solenoid with an aperture of 21 cm that contributes to maintain the magnetic field as uniform as possible. The second part of the cooling channel is identical to the first, with two more cavity cells followed by the exit absorber. The total length, including diagnostics, is 8.6 m, and we have assumed a physical aperture of 20 cm. The total energy lost in the absorbers at a kinetic energy of 200 MeV corresponds to the energy gained in the cavity system.

3 BEAM DYNAMICS

The coil arrangement shown in Fig. 1 results in a longitudinal magnetic field on axis of Fig. 2 from which the PATH simulation code gives the emittance diagram of Fig. 3.

For a kinetic energy of 200 MeV and $\Delta E = \pm 30$ MeV, the final normalized rms emittance is 4630 π mm mrad, which, compared to the input emittance of 4900 π mm mrad, gives a reduction of about 5.6 % with

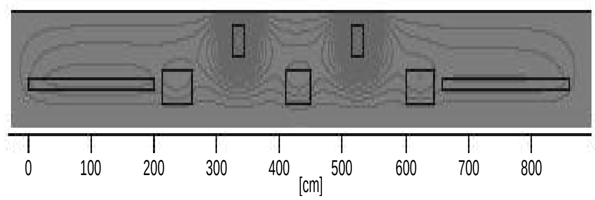

Figure 1: Solenoid layout and magnetic field lines computed with POISSON. The system has a cylindrical symmetry with respect to the horizontal axis.

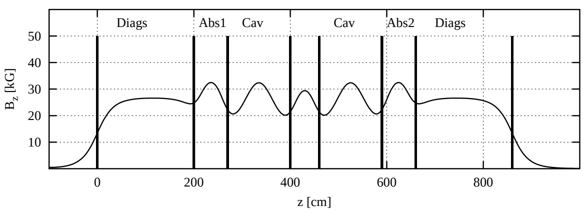

Figure 2: Longitudinal magnetic field on axis.

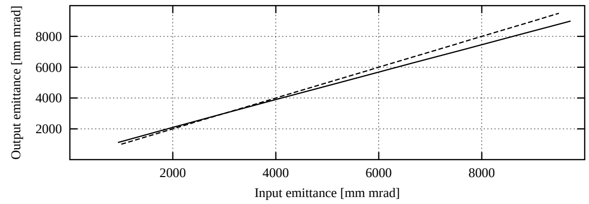

Figure 4: Output emittance vs input emittance (r.m.s., normalized) at 200 MeV.

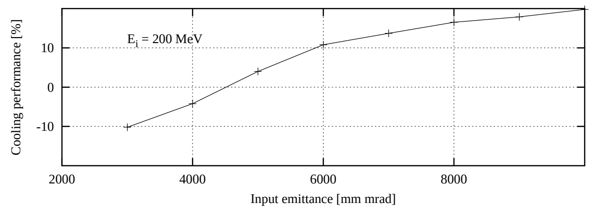

Figure 5: Cooling efficiency vs input emittance (r.m.s., normalized) for an input beam of 200 MeV.

a particle transmission of 100 %. The initial beam parameters are $\beta_{x,y} = 1$ m, $\alpha_{x,y} = 0$, and the number of particles is $N = 50000$. The cavity system is set to work on crest. If we define the cooling efficiency as the increase of the number of particles inside a given acceptance, and use as acceptance 15000 π mm mrad (normalized) in both transverse dimensions, we get an efficiency of 8.8 %.

In Fig. 4 we show the output versus input emittance. For an input emittance of about 3000 π mm mrad (r.m.s. normalized) the equilibrium emittance is reached. Below this threshold the beam is heated. The transmission remains 100 % up to the maximum emittance that we have simulated, 10000 π mm mrad. In Fig. 5 we show the cooling efficiency, as defined above, for a range of input r.m.s. emittance. It is negative for small input emittances (heating) and goes up to about 20 % for the largest input emittance.

We have run the same set-up at input beam energies of 140 MeV and 230 MeV, adjusting slightly the solenoid field, and also in these two cases the transmission is about 100 % up to the largest input emittance.

With the scheme of the cooling channel that we have illustrated, it is possible to change the solenoid currents and work with other values of the magnetic field. For example, with the magnetic field shown in Fig. 6 (on axis), which is about a factor of 1.5 higher than the previous case, the same cooling performance is achieved even if the emittance along the channel (Fig. 7), is higher. This demonstrates the flexibility of the proposed scheme.

4 FIGURE OF MERIT OF THE COOLING EXPERIMENT

In the cooling channel of the NF, the relevant figure of merit is the increase of the number of muons in the acceptance of the downstream accelerators. This acceptance is defined independently in the three planes (x, y and longitudinal). To increase the figure of merit, correlations between the planes have to be minimized at the point of transition from solenoidal focusing to quadrupole focusing.

In the cooling experiment, the emittances are measured inside the solenoid field. If the beam dynamics of the experiment is not chosen to minimize inter-plane correlations, there is no possibility to compensate for these correlations. In a general solenoidal beam transport, correlations will

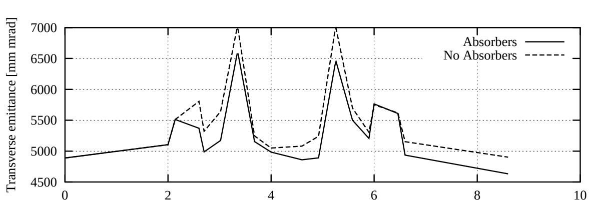

Figure 3: Transverse emittance (r.m.s., normalized) along the channel with and without absorbers.

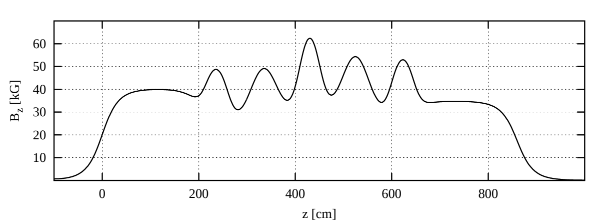

Figure 6: Alternative longitudinal magnetic field.

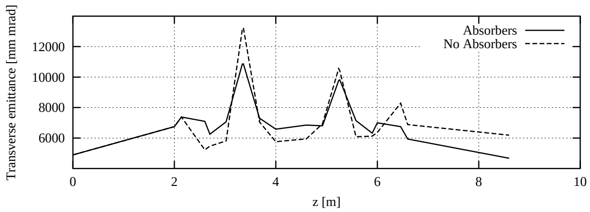

Figure 7: Transverse emittance (r.m.s., normalized) along the channel with and without absorbers for the magnetic field of Fig. 6.

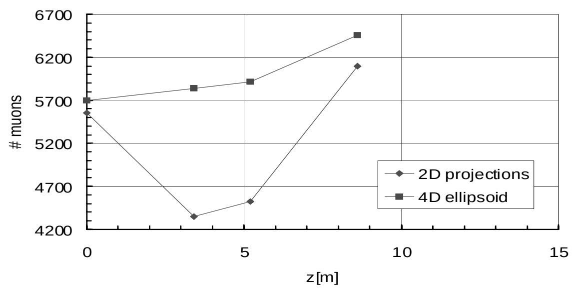

Figure 8: Number of muons inside a 4D volume of $(15000\,\pi\text{ mm mrad})^2$ for a cooling experiment at 200 MHz.

mainly develop between the x and the y plane. Therefore, an algorithm was developed to count particles in 4D or 6D hyper-ellipsoids, to be used as figure of merit for the cooling experiment in the presence of inter-plane correlations [7]. It allows to measure 4D and 6D cooling rather than the 2D projections.

Fig. 8 shows the number of muons inside a normalized 4D volume of $(15000\ \pi$ mm mrad$)^2$ as a function of distance for the 200 MHz cooling experiment. Values are shown at the beginning and the end of the experiment and at two points in the middle, where $\epsilon_x \times \epsilon_y$ peaks (at 3.4 m and 5.2 m, compare to Fig. 3). The inter-plane correlations are 0, 0.7, 0.6 and 0.14 respectively at the 4 analyzed positions. At the points of high correlation, the method of 2D projections does not give a useful result for measuring the cooling performance of the experiment. The figure of merit calculated in the 4D ellipsoid and the 2D projections is 13.3% and 9.9% respectively. Counting the muons in 4D or 6D yields a stable figure of merit in the presence of correlations. The 4D ellipsoid looks at a more central core of the distribution and has therefore a higher density of muons and a slightly higher figure of merit than in the 2D projections.

5 CONCLUSIONS

We have simulated a possible scenario for a muon ionization cooling experiment at 200 MHz with the goal of comparing it from a beam dynamics point of view with the 88 MHz channel proposed at CERN. In particular, we optimized the cooling efficiency, which has to be well in the range of the proposed emittance diagnostics [8]. We find that in terms of cooling efficiency this scheme shows a performance comparable with the 88 MHz case. The set-up at 200 MHz has a naturally higher acceleration gradient which results in a better cooling rate per metre. However, the overall cooling performance of the two systems (8 cavities at 88 MHz versus 4 cavities at 200 MHz) is, as the total absorber length is the same, comparable. The choice of frequency is therefore a technical one, i.e. for a required minimum cooling efficiency one has to consider the total length of the system, number of cavities used, achievable gradient and rf power.

A major difference between the two schemes is the arrangement of the solenoids. The large bore solenoids between and around the 200 MHz cavities result in a magnetic field pattern which is less homogeneous than in the case of the 88 MHz cavities, where the solenoids (all identical) are integrated in the cavity such that they are close to the beam and generate a periodic structure. Consequently, for the 200 MHz system, the coil arrangement and hence the magnetic field along the channel vary much more. This results in strong coupling between the planes, thus giving large transverse emittance oscillations along the channel.

Another technical difference is that the 200 MHz cavities have to be separated by conducting windows in order to achieve the required gradient. This could result in unacceptable high dark current. Also, windows might break during cavity conditioning.

6 ACKNOWLEDGMENTS

This paper includes important contributions by Arnaud Perrin who passed away in a tragic accident.

7 REFERENCES

[1] A. Lombardi, 'A 40-80 MHz System for Phase Rotation and Cooling', CERN Neutrino Factory Note 37 (2000).

[2] M. Aleksa, et al., 'Beam Dynamics Study of a Muon Ionization Cooling Experiment', CERN-Nufact-Note-108 (2002).

[3] S. Ozaki, R. Palmer, M. Zisman, J. Gallardo (ed.), 'Feasibility Study-II of a Muon-Based Neutrino Source', BNL-52623 (2001).

[4] F. Tazzioli, private communication.

[5] M. Migliorati et al., 'Preliminary Study of the Cooling Channel based on the 200 MHz Cavities', presented at the Workshop on a Muon Ionization Cooling Experiment, October 25-27, 2001, CERN.

[6] J. H. Billen, L. M. Young, 'Poisson Superfish', Los Alamos National Lab report LA-UR-1834.

[7] E. B. Holzer, CERN Neutrino Factory Note 111, in preparation.

[8] P. Janot, private communication.