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Beam Dynamics Study of a Cooling Experiment based on the 88 MHz CERN Cooling Channel

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Abstract

This note presents a beam dynamics analysis of a possible muon cooling experiment based on 88 MHz cavities. The proposed set-up is a subsection of the cooling channel in the CERN reference scheme for a neutrino factory. We present two different set-ups using 8 and 4 cavities. For each of these set-ups we have carried out a beam dynamics study based on engineering designs for the cavities and solenoids. The study includes a parameter scan which allows to evaluate the performance of the systems for various input beam parameters and settings.

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1 Introduction

The CERN layout for a neutrino factory includes a cooling channel based on 44 and 88 MHz cavities with integrated super conducting solenoids [1].
In order to prove the feasibility of such a cooling channel, a cooling experiment is proposed which is a small subset of the 88 MHz part of the final channel. The first system studied consists of a total of 8 cavities at 88 MHz providing an average effective gradient of 4 MV/m. For an input kinetic energy of 200 MeV, the energy lost in a length of 94 cm of liquid hydrogen (LH) absorber can be replaced by these cavities and the beam energy at the end of the cooling cell is the same as at the entry. The layout of the channel is such that there is an absorber of 47 cm length at the entry of the cooling section, followed by a string of 8 cavities with integrated solenoids (total length 7.2 m) and a second absorber of 47 cm length at the exit of the cooling section. The solenoidal lattice is continued upstream and downstream of the cooling cell where the input and output diagnostics are installed. In the present model, both diagnostic sections have a total length of 3 m which is not necessarily the final design but allows to include the cooling cell properly into a solenoidal lattice.

The second system studied consists of only 4 cavities of the same type (length of the accelerating section 3.6 m). This set-up allows only for a total of 47 cm liquid hydrogen, again split up into a 23.5 cm entry absorber and a 23.5 cm exit absorber. The cooling efficiency then drops down in proportion. Also this cooling cell is matched upstream and downstream to diagnostic sections. Figure 1 shows schematically both systems studied.

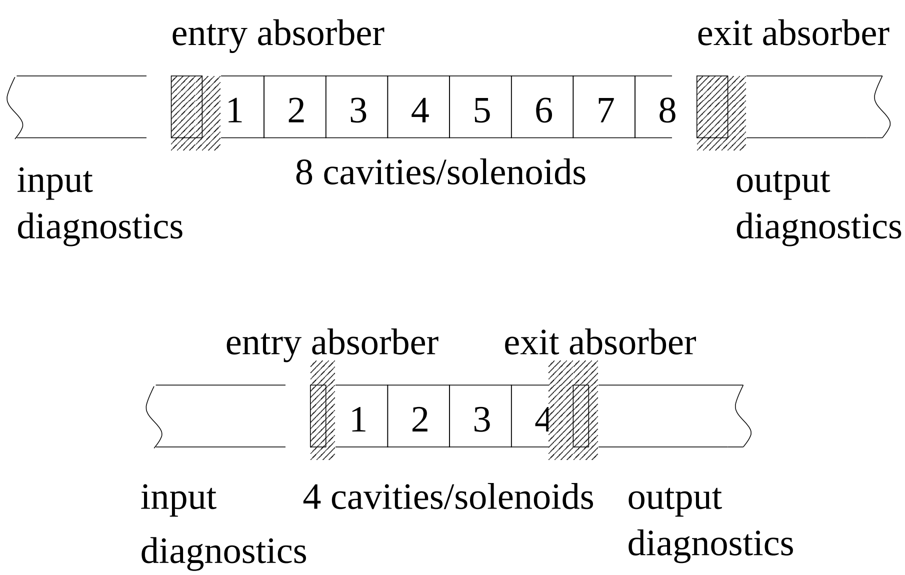

Figure 1: Set-up with 8 cavities (upper sketch) and 4 cavities (lower sketch).

2 Cavity and Solenoid Design

88 MHz cavities for the CERN cooling channel have been designed [2] and the electric field maps obtained using SUPERFISH. They have a bore radius of 15 cm and provide an average effective gradient of 4 MV/m for 2 MW peak power. As the length of one cavity is 90 cm, this corresponds to an energy gain of 3.6 MeV per cavity.
Super conducting solenoids are integrated into the 88 MHz cavities. They have been designed [3] using ROXIE8.1. The solenoid design takes into account engineering constraints, such as space required for the cryogenic system and forces between solenoids. Both the case in which all

solenoids have the same polarity and the case of opposite polarity ('field flip') have been simulated and the corresponding field maps generated. We will in this paper only refer to the case where all solenoids have the same polarity. For this configuration, the maximum field on axis is 4.5 T staying at 60% on the load line and 6 T if going up to 80% on the load line. All the different cases discussed here use settings around 3 T, well below the quench limit.

3 Beam Dynamics of the Channel

A beam dynamics study of the proposed set-ups has been performed, based on the engineering design of cavities and solenoids. The 2D electric and magnetic field maps have been included in the tracking code PATH. The input beam parameters have been chosen close to those in the 88 MHz section of the CERN reference cooling channel: β= 1 m, α=0, E_{kin}=200 MeV, ΔE=$\pm$ 15 MeV. The input beam parameters are of course free parameters and input energy and emittance have been varied as will be seen in the subsequent sections.

For the reference optics discussed here, the solenoids in the cooling cell are set to 3 T and the cavity synchronous phase to 0^o. The transmission is 100% and the transverse emittance at the exit of the cooling channel is reduced by 3.7%. Figure 2 shows the transverse emittance versus z for the set-up with 8 cavities. Using the same optics and input beam parameters, but only 4 cavities, the performance drops down roughly in proportion as expected. Figure 3 shows the transverse emittance versus z for this set-up. The reduction of the transverse emittance is in this case (and for this example optics and input beam) 2%.

A more appropriate way to analyse the results is to count the number of muons that are found inside a given acceptance. In our case, we have chosen the acceptance of the recirculator in the CERN reference scheme, i.e. 15000 π mm mrad (total, normalized) in both transverse and 0.1 eVs in the longitudinal plane[1]. Within this volume, for the example shown in Fig. 2 the number of muons is increased by 9.1 % and for the corresponding case with 4 cavities by 3.5%.

4 Parameter Scan

In order to determine the response of both systems to various input beam parameters and settings, parameter scans were carried out. In particular, the behaviour of the system for various input beam energies was studied. The set-up with 8 cavities was run with kinetic energies of 230, 200, 170 and 140 MeV. For each case, the input emittance was varied and the emittance at the exit of the channel computed. This allows to determine the range of input emittances for which the channel is cooling. It also allows to find out the acceptance of the channel as well as the equilibrium emittance below which the channel starts heating. For the same range of input emittances, the transmission as well as the cooling efficiency, defined as the gain of particles inside a given 6D acceptance in [%] was obtained. The same study was carried out for the set-up with 4 cavities, but here only beam energies of 200 and 140 MeV were considered.

We will in the following sections present the results for the various beam energies and settings, starting with the channel of 8 cavities. Figure 4 shows the output emittance for various values of the input emittance. For an input emittance of about 3500 π mm mrad (r.m.s, normalized), the equilibrium emittance is reached. For values below this threshold, the channel starts heating. For values between 3500 and 6000 π mm mrad, the transmission is 100% and the channel is cooling. For higher values of the input emittance, the acceptance of the channel is reached and the transmission starts to drop down. Figure 5 shows the transmission through the channel for the corresponding range of input r.m.s. emittance. The cooling efficiency, defined as the increase

[1] The choice of this value to analyze the performance of a possible cooling experiment is somewhat arbitrary. One could very well measure the performance using another, possibly smaller value for the acceptance.

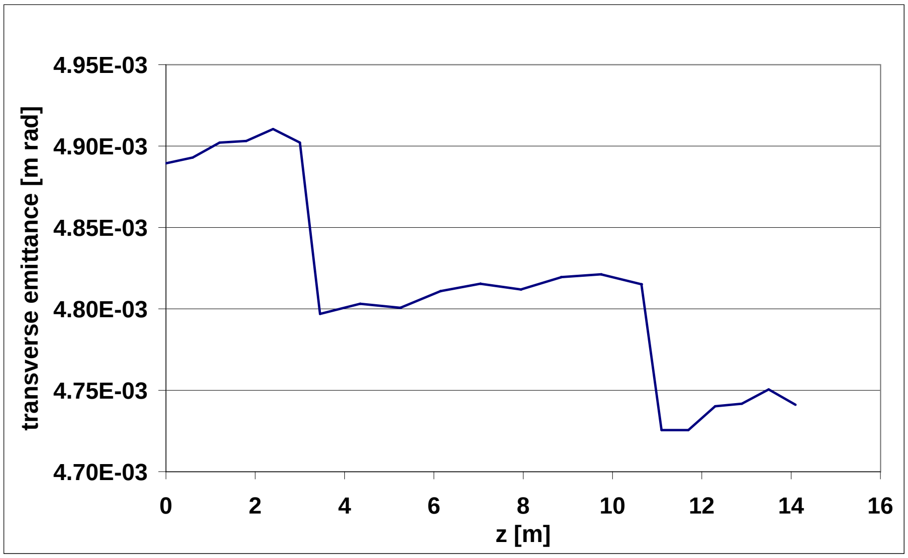

Figure 2: Transverse emittance (r.m.s., normalized) as computed by PATH along the channel for the set-up with 8 cavities. The simulation was done using 50000 particles. The quantity shown is $\sqrt{\varepsilon_x \varepsilon_y}$. It is flat in the entry diagnostic section, drops down in the first absorber, is then again flat in the acceleration section, drops down in the second absorber and is again flat in the exit diagnostic section.

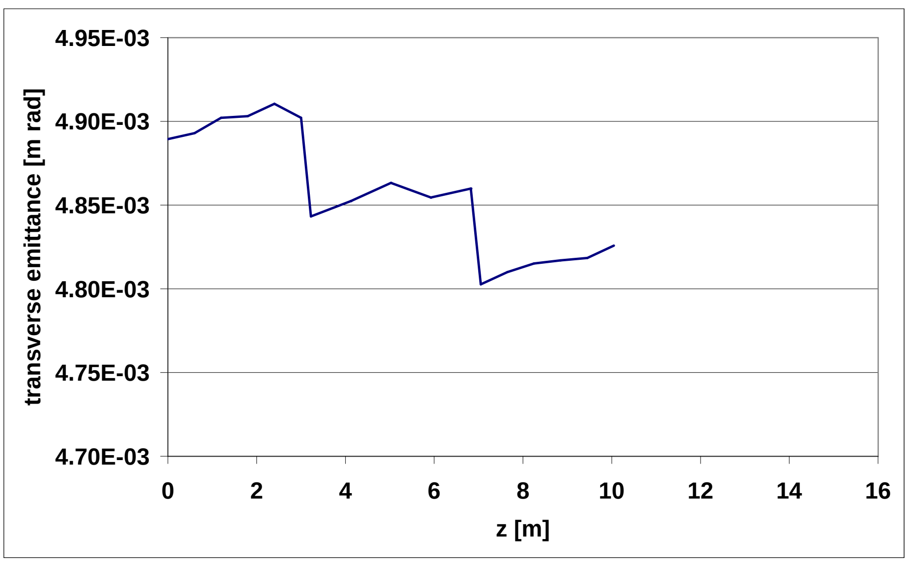

Figure 3: Transverse emittance (r.m.s., normalized) as computed by PATH along the channel for the set-up with 4 cavities. The quantity shown is $\sqrt{\varepsilon_x \varepsilon_y}$. The behaviour along z is the same as for the set-up with 8 cavities, but the length and the cooling performance drops down in proportion.

of the number of particles inside the given acceptance, is shown in Fig. 6. Depending on the input beam emittance, the cooling efficiency goes up to 15%. Note, that good cooling efficiency is still found for emittances larger than the acceptance of the channel, i.e. for values for which the transmission drops below 100% (compare Fig. 5).

We have now changed the input beam energy and we will first look at at case with E_{kin}=140 MeV. Figures 7, 8 and 9 show output versus input emittance, transmission and cooling efficiency for this case. The cooling efficiency is supposed to go up for lower beam energies (however the equilibrium emittance is higher). In fact, it goes up to a maximum value of 19%.
Figure 10, 11 and 12 correspond to an input beam energy of 170 MeV. Also here the cooling efficiency reaches a maximum value of 19%, comparable to the case at 140 MeV.
Figure 13, 14 and 15 correspond to an input beam energy of 230 MeV. Here the cooling efficiency is worse with a maximum value of about 14%.
To summarize the parameter scan for the system with 8 cavities, we consider an input emittance of 5500 mm mrad (r.m.s., normalized), for which the transmission is 100%. The cooling efficiency for this input emittance and the various input beam energies is summarized in Tab. 1. The dependence of transmission and equilibrium emittance on the initial beam energy is negligible. The magnetic field in the cooling cell has a value of 2.7 T.

E_{in} [MeV]	cooling efficiency [%]	solenoid field [T]
230	7.5	2.7
200	10.0	2.7
170	11.5	2.7
140	12.5	2.7

Table 1: Comparison of cooling efficiency for ε_{in}=5500 mm mrad (r.m.s., normalized) and various input beam energies.

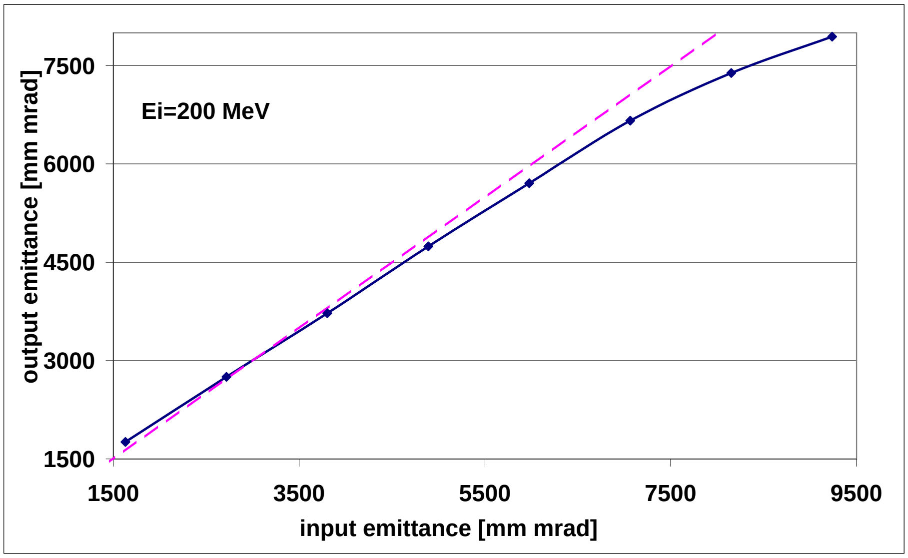

Figure 4: Output emittance versus input emittance (r.m.s., normalized) for an input beam energy of 200 MeV. The dashed line means $\varepsilon_{out} = \varepsilon_{in}$. It can be seen that the channel is cooling for a wide range of input emittances. At about 6000 mm mrad, the acceptance of the channel is reached. At about 3500 mm mrad, the equilibrium emittance is reached.

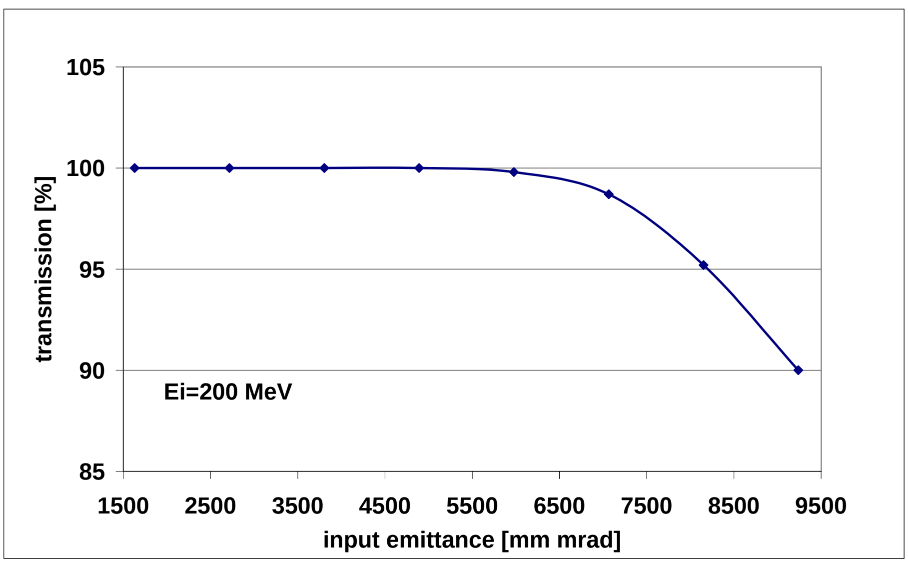

Figure 5: Transmission versus input emittance (r.m.s., normalized) for an input beam energy of 200 MeV. The acceptance is reached at about 6000 mm mrad.

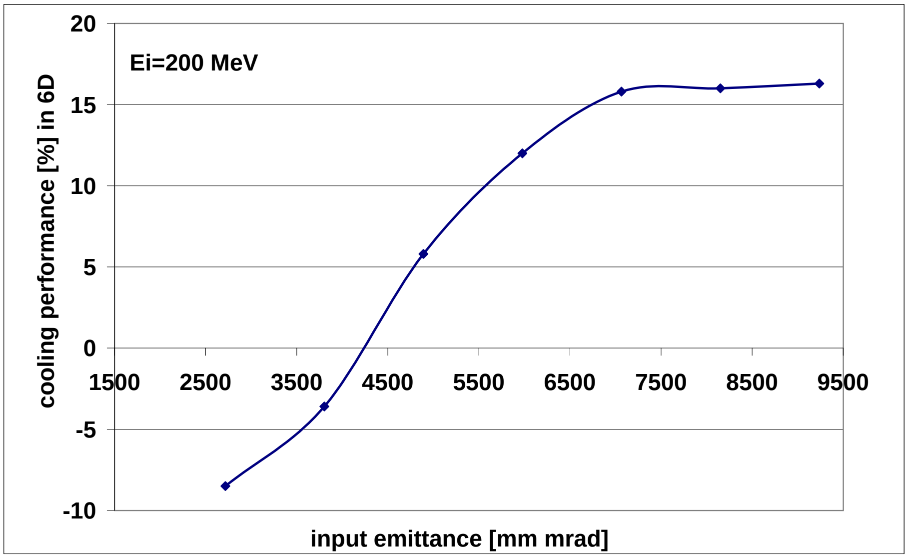

Figure 6: Cooling efficiency versus input emittance (r.m.s., normalized) for an input beam energy of 200 MeV. The cooling efficiency goes up to 15% and stays at this value even beyond the acceptance of the channel. Note, that in this definition heating sets on at $\varepsilon_{in} \approx 4000$mm mrad while Fig. 4 shows an equilibrium emittance of about 3500 mm mrad. This is due to the effect that for a very small beam size the cut is close to the beam size which influences the result. Applying a smaller cut results in a positive cooling efficiency.

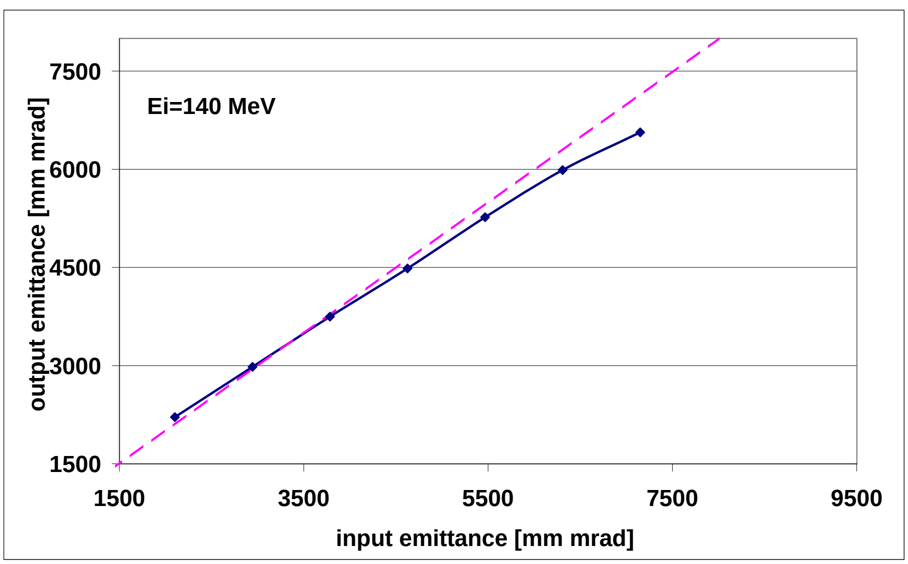

Figure 7: Output emittance versus input emittance (r.m.s., normalized) for an input beam energy of 140 MeV.

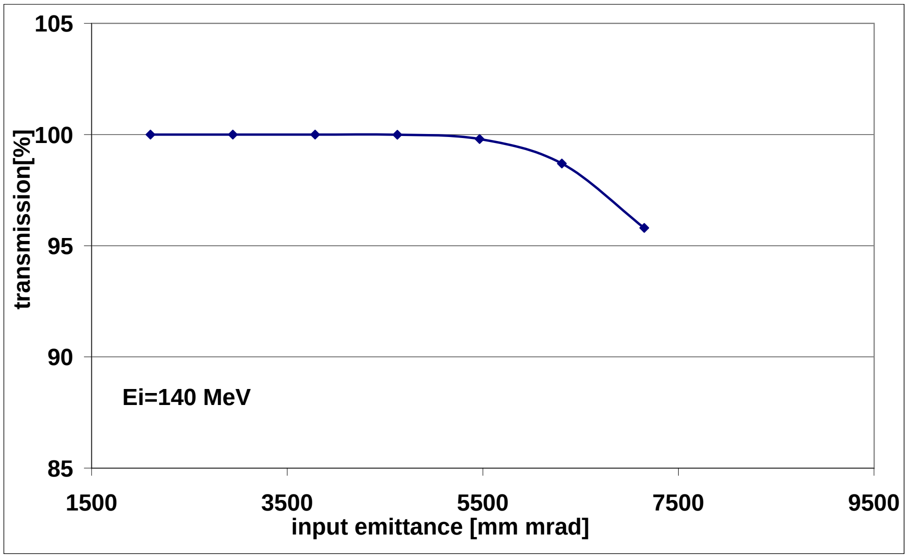

Figure 8: Transmission versus input emittance (r.m.s., normalized) for an input beam energy of 140 MeV.

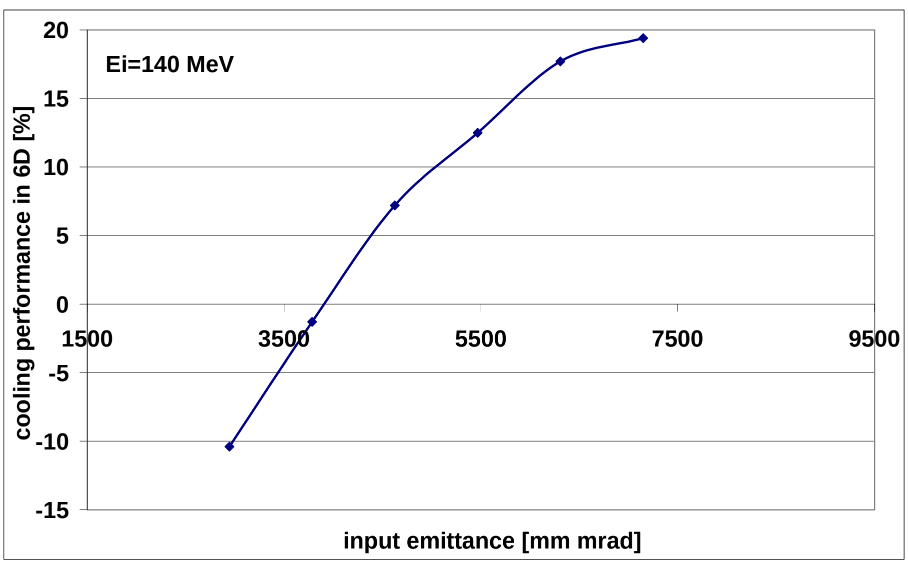

Figure 9: Cooling efficiency versus input emittance (r.m.s., normalized) for an input beam energy of 140 MeV. The cooling efficiency goes up to 19%.

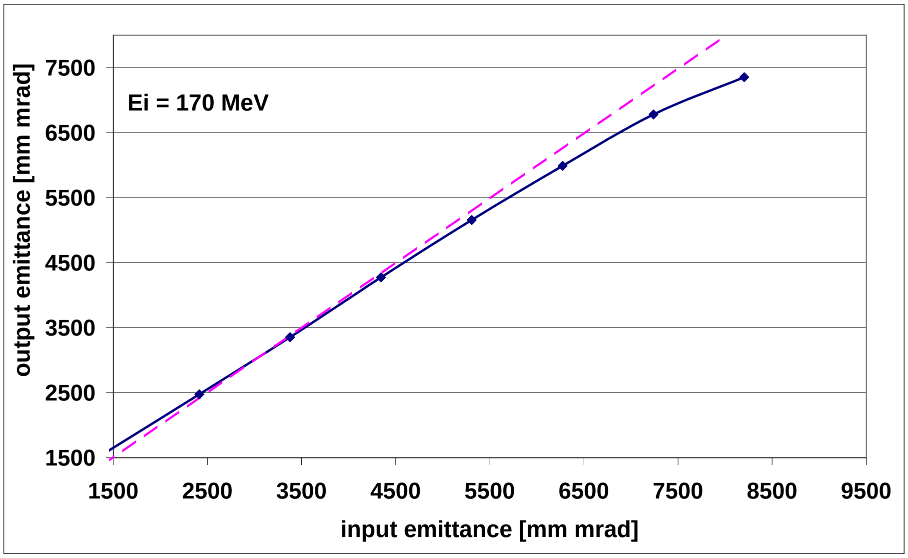

Figure 10: Output emittance versus input emittance (r.m.s., normalized) for an input beam energy of 170 MeV.

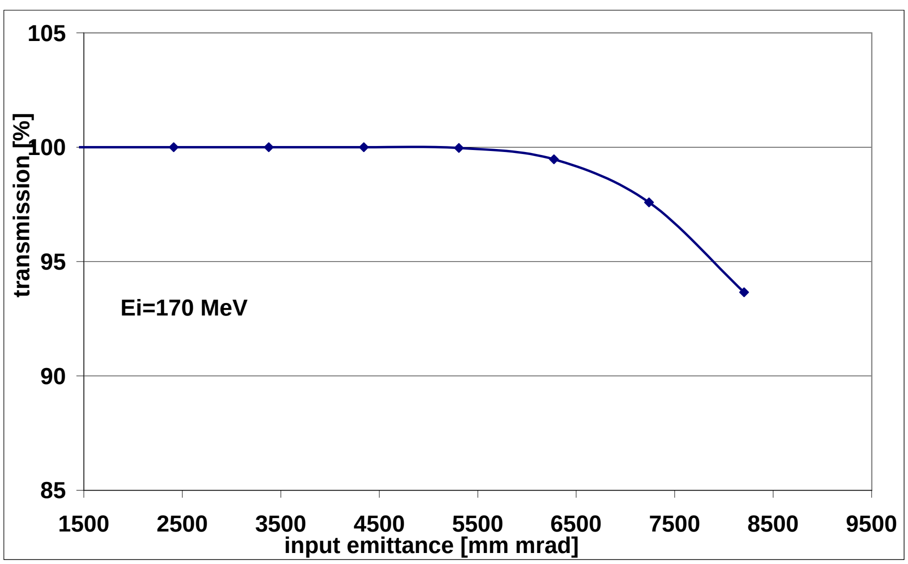

Figure 11: Transmission versus input emittance (r.m.s., normalized) for an input beam energy of 170 MeV.

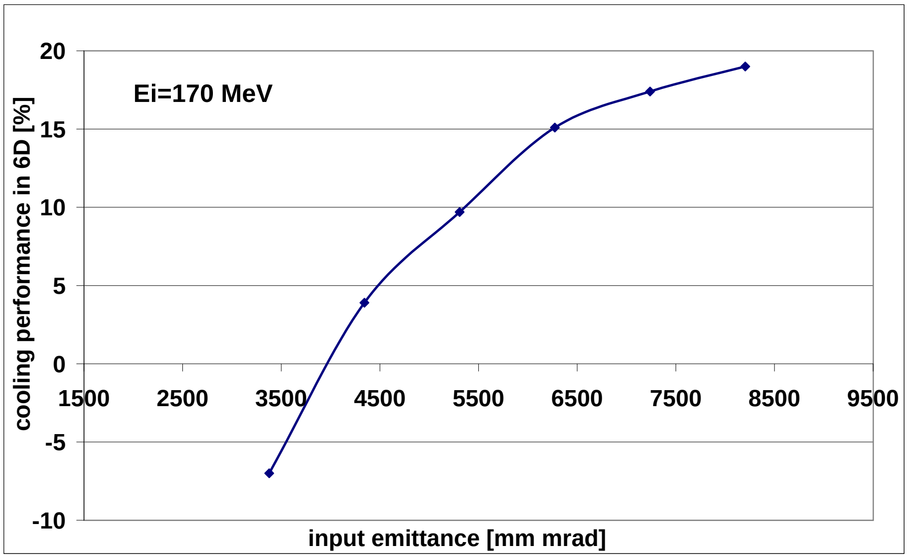

Figure 12: Cooling efficiency versus input emittance (r.m.s., normalized) for an input beam energy of 170 MeV. The cooling efficiency goes up to a maximum of 19%, comparable to the case of 140 MeV.

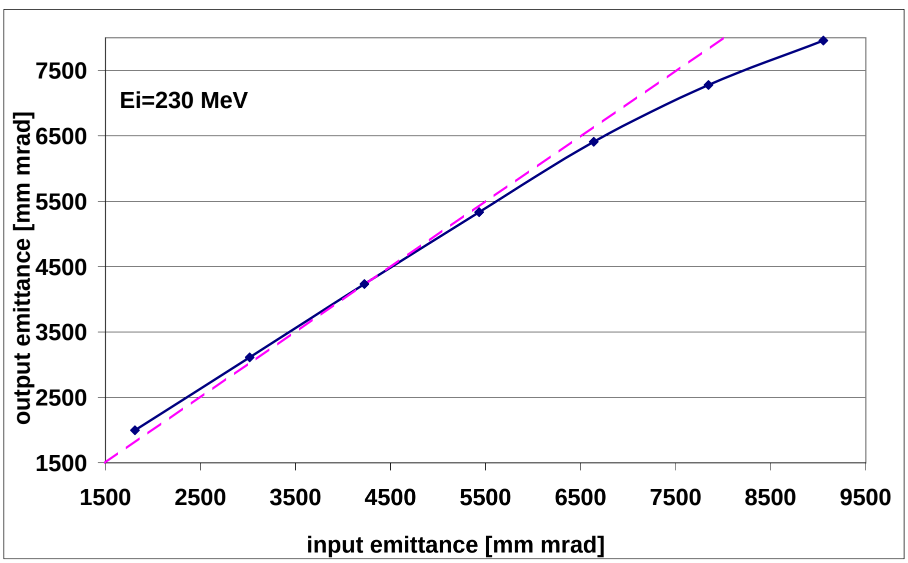

Figure 13: Output emittance versus input emittance (r.m.s., normalized) for an input beam energy of 230 MeV.

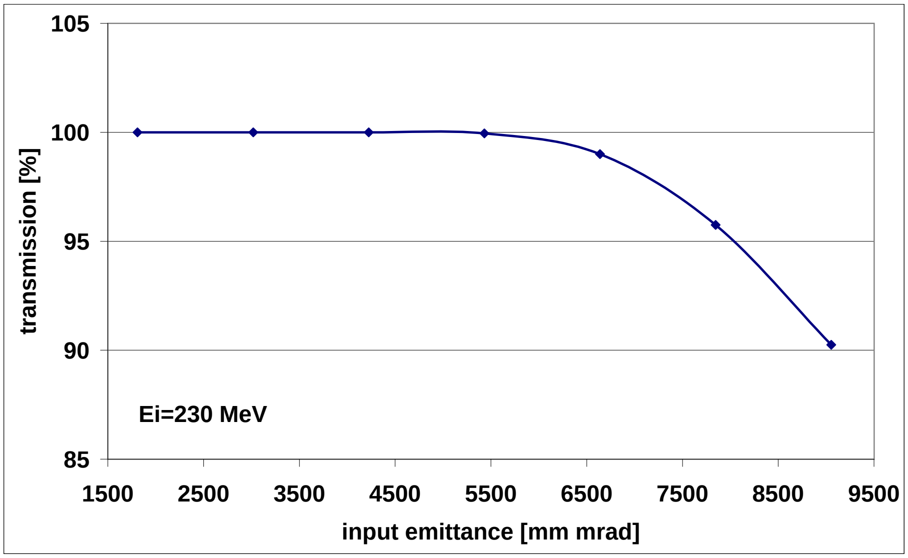

Figure 14: Transmission versus input emittance (r.m.s., normalized) for an input beam energy of 230 MeV.

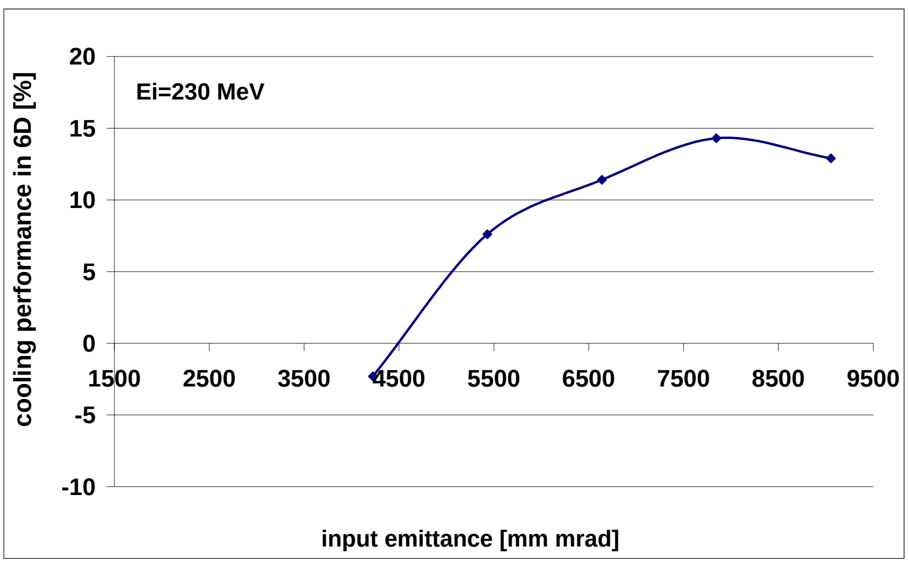

Figure 15: Cooling efficiency versus input emittance (r.m.s., normalized) for an input beam energy of 230 MeV. The cooling efficiency is around 14% and hence slightly worse than for the case with 200 MeV.

We will now consider the channel with only 4 cavities. A priori, the cooling efficiency is worse than for 8 cavities and it will become even worse at higher input energy than 200 MeV. Therefore, the two cases with the nominal input energy of 200 MeV and with a significantly lower input energy of 140 MeV have been studied. Figures 16-18 show output versus input emittance, transmission and cooling efficiency for a range of input emittances and an input beam energy of 200 MeV. The acceptance of the channel is the same as for the case with 8 cavities. The cooling efficiency drops with respect to the case of 8 cavities. The maximum value is about 10%.

Figures 19-21 show the corresponding plots for an input beam energy of 140 MeV. As can be seen from Fig21, the cooling efficiency improves slightly with respect to the case at 200 MeV. The maximum value is still around 10%. The performance of a system with 8 cavities is not reached.

To summarize the cooling performance for a system of 4 cavities, we consider an input emittance of 5000 mm mrad, for which the transmission is 100%. For this input emittance and the two input energies considered, the cooling efficiency is summarized in Tab. 2. The solenoid field in the cooling cell has values of 2.7 T (200 MeV) and 2.5 T (140 MeV). For an input energy of 140 MeV the cooling performance is hence better and lower solenoid fields are required.

E_{in} [MeV]	cooling efficiency [%]	solenoid field [T]
200	4.5	2.7
140	6.5	2.5

Table 2: Comparison of cooling efficiency for ε_{in}=5000 mm mrad (r.m.s., normalized) and various input beam energies.

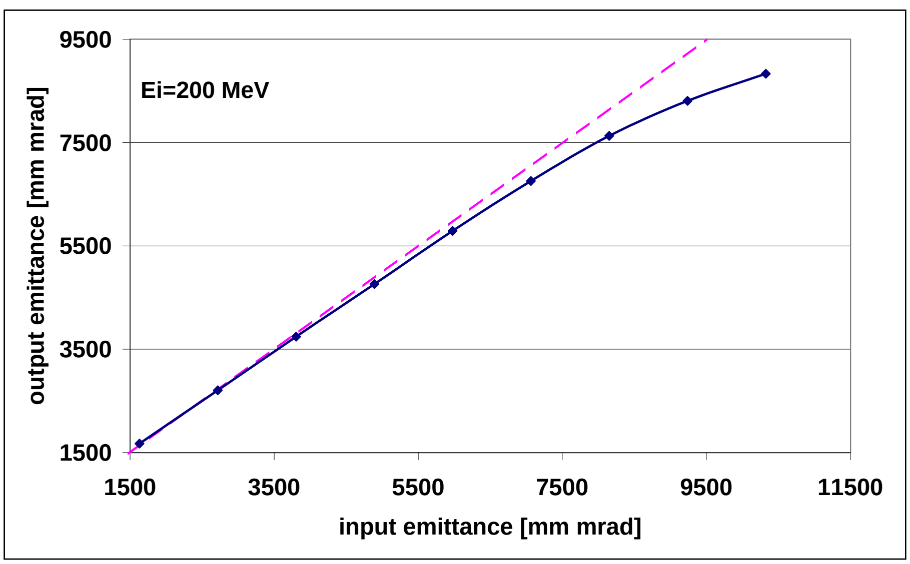

Figure 16: Output emittance versus input emittance (r.m.s., normalized) for a system with 4 cavities and an input beam energy of 200 MeV.

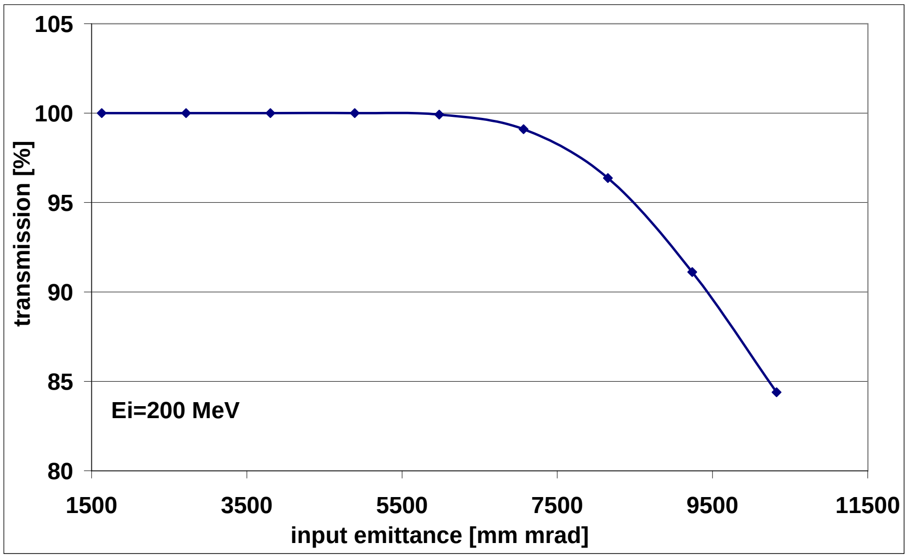

Figure 17: Transmission versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 200 MeV. The acceptance of the channel is comparable to the one of the channel with 8 cavities.

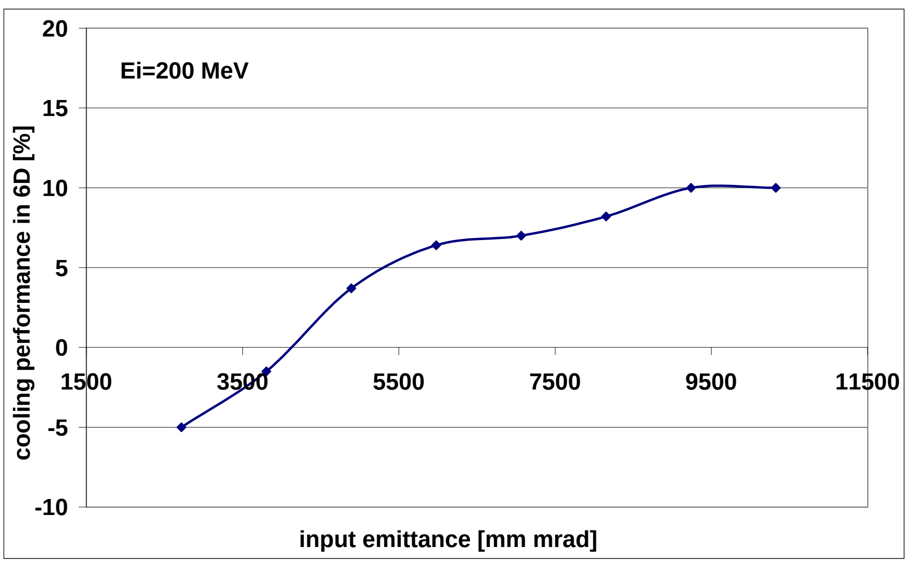

Figure 18: Cooling efficiency versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 200 MeV. The cooling efficiency is obviously worse than for the case with 8 cavities.

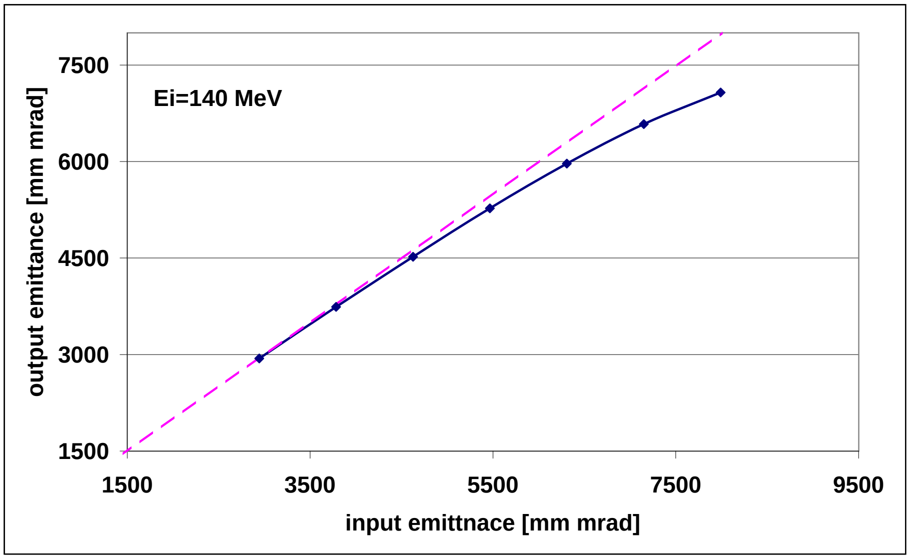

Figure 19: Output emittance versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 140 MeV.

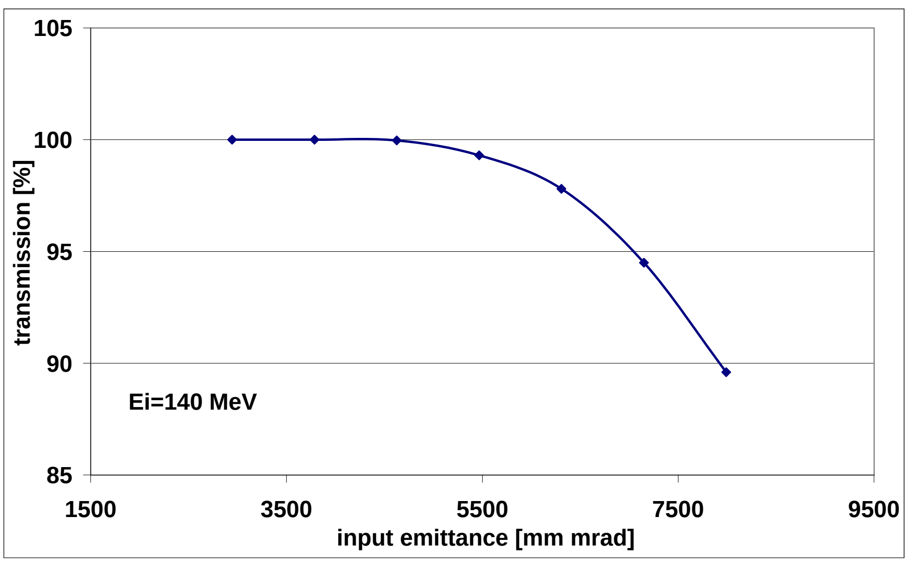

Figure 20: Transmission versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 140 MeV.

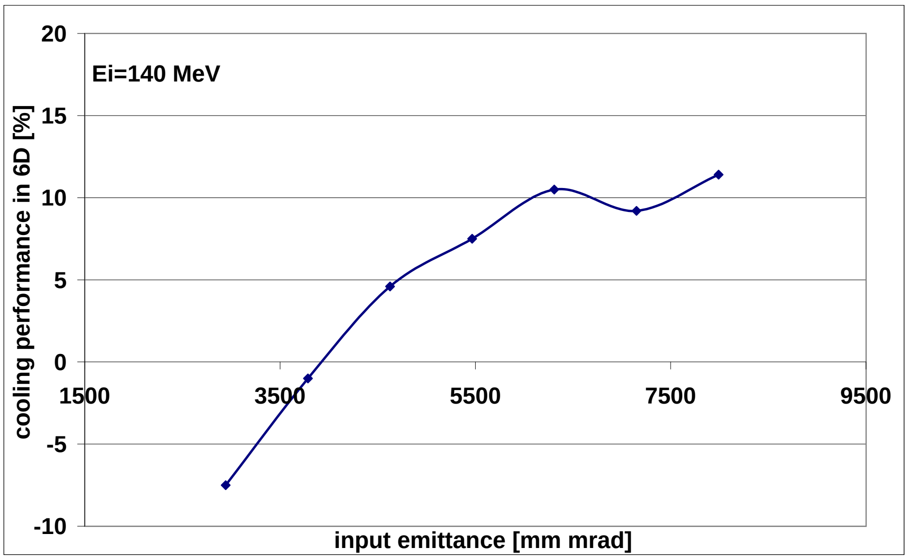

Figure 21: Cooling efficiency versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 140 MeV. There is a slight improvement in cooling efficiency by going to lower beam energy but the performance of a system with 8 cavities cannot be reached. Note, that the results are subject to fluctuations (statistical processes in the absorbers) which can explain the bump around 7500 mm mrad.

5 Conclusion

Two possible options for a cooling experiment based on 88 MHz cavities have been studied. Both set-ups are subsets of the 88 MHz part of the muon cooling channel in the CERN reference scenario for a neutrino factory. The first system studied uses 8 cavities and two liquid hydrogen absorbers of 47 cm length each, the second case studied uses only 4 cavities and two liquid hydrogen absorbers of 23.5 cm length each. For each of these systems, the cooling efficiency has been explored for a range of input beam energies and input beam emittance. It has been shown that, depending on the beam energy, a system with 8 cavities can reach a cooling efficiencies between 14 and 19%. For a channel which uses only 4 cavities, the performance drops roughly down in proportion.

The study shows that a cooling experiment based on 88 MHz cavities can provide the emittance reduction required to do a single-particle measurement of the phase space distribution as proposed by [4].

6 Acknowledgements

The authors would like to thank A. Perrin for help with the code PATH and A. Lombardi for helpful discussions.

References

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[3] S. Russenschuck, M. Aleksa, private communication.

[4] P. Janot, private communication.