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Summary of Simulation Results for a Muon Cooling Experiment based on the 88 MHz CERN Cooling Channel

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Abstract

We present a summary of simulation results on a muon cooling experiment based on 88 MHz cavities. The systems studied are subsections 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 channels we have carried out a beam dynamics study based on engineering designs for the cavities and solenoids. The study comprises a scan of input beam parameters, various optics with and without alternating solenoid polarity as well as a cross-check with an independent simulation code.

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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 solenoid Al lattice is continued upstream and downstream of the cooling cell where the input and output diagnostics are installed.

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.

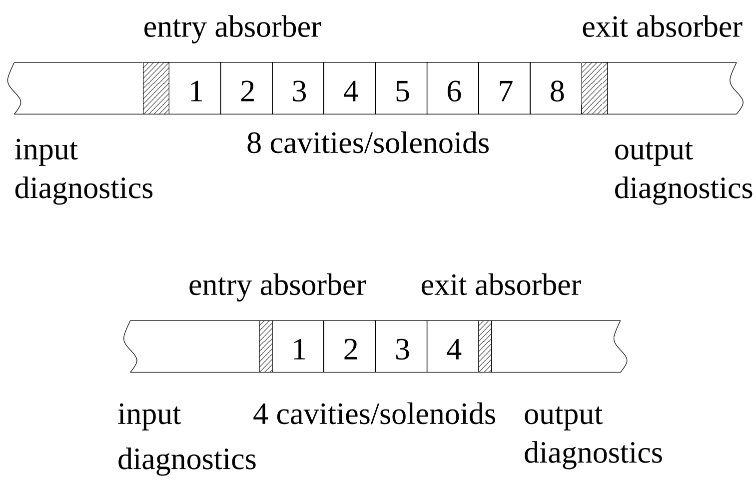

Figure 1: Set-up with 8 cavities (upper sketch) and 4 cavities (lower sketch).

2 88 MHz Cavities for the Cooling Lattice

The large phase space of the muon beam requires low frequencies (88 MHz), large bore radii (0.15 m) and a high magnetic field produced by super conducting solenoids. The present approach [2] to match these demands is to incorporate the solenoids into the cavity design in order to avoid the huge dimensions of solenoids surrounding the cooling channel. Using an asymmetric cavity design (Fig. 2) enables the construction of units which consist of solenoid plus cavity and which can then be assembled to a continuous lattice.

A higher mechanical filling factor of solenoid over unit length can be obtained by increasing the length of the solenoids by a few centimetres for the price of higher RF power consumption and bigger amplifiers delivering higher peak power (details in [2]).

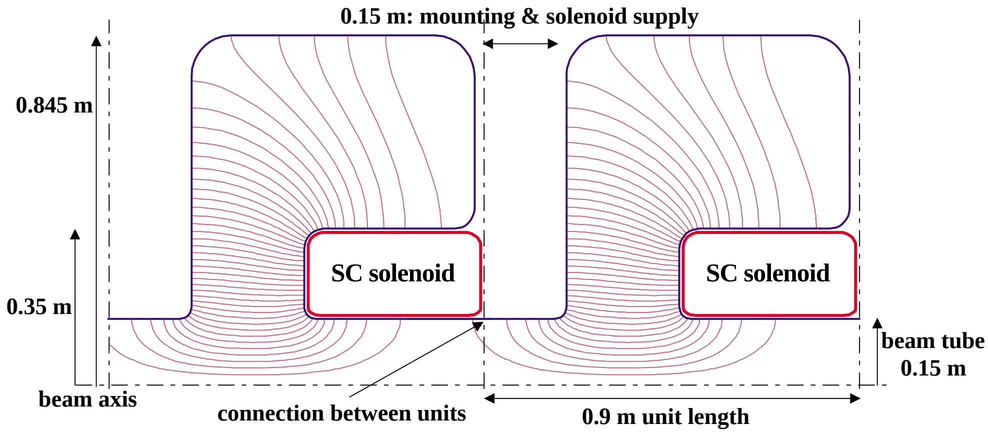

Figure 2: Scheme of assembling 88 MHz cavities with solenoids.

Table 1: Parameters for the 88 MHz cavities (calculated by SUPERFISH)

f_{rep} [Hz]	E_0T [MV/m]	Q	R/Q [Ω]	t_{pulse} [ms]	$P_{amp.}$ [MW]	P_{mean} [kW/m]	Kilp.	$R_{cav.}$ [m]	$l_{sol.}$ [m]
50	4	44000	144	0.48	2.04	54	2.3	0.845	0.4

3 Solenoid Design

In the present design, 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 with all solenoids of the same polarity and the case of opposite polarity ('field flip') have been simulated and the corresponding field maps generated. Fig. 3 shows the configuration for same polarity. The field strength on axis is limited by the current density and the field strength in the coil. At 4.5 K, $NbTi$ quenches at about 9 T for the given current density. If one wants to stay below 60% on the load line, a field in the coil of 5.2 T resulting in 4.5 T on axis is the limit. Gaining field strength is possible by increasing the percentage on the load line, i.e. having a smaller quench margin. This is important to maintain a sufficient thermal margin

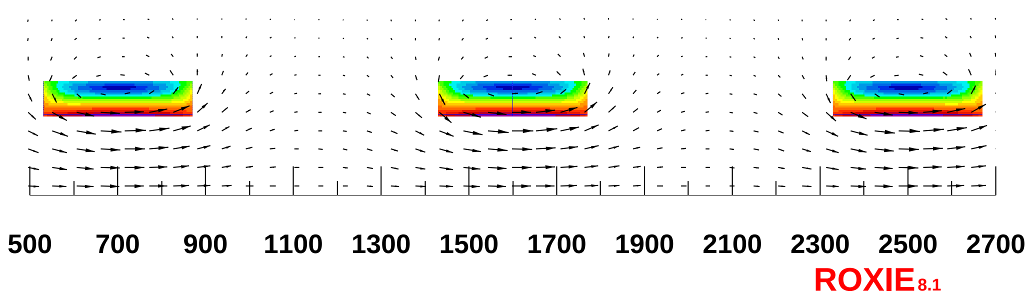

Figure 3: Solenoid design for the case of same polarity.

in view of the beam energy deposited in the super conductors. Here further simulations have to be done. In case the losses can be kept small by appropriate shielding a maximum of 80% on the load line could be envisaged. In any case an appropriate quench protection has to be designed. One should also investigate working at lower temperature or using other super conductors, e.g. Nb_3Sn, in order to achieve the desired field strength of about 6 T. Fig. 4 shows the B_z and B_r

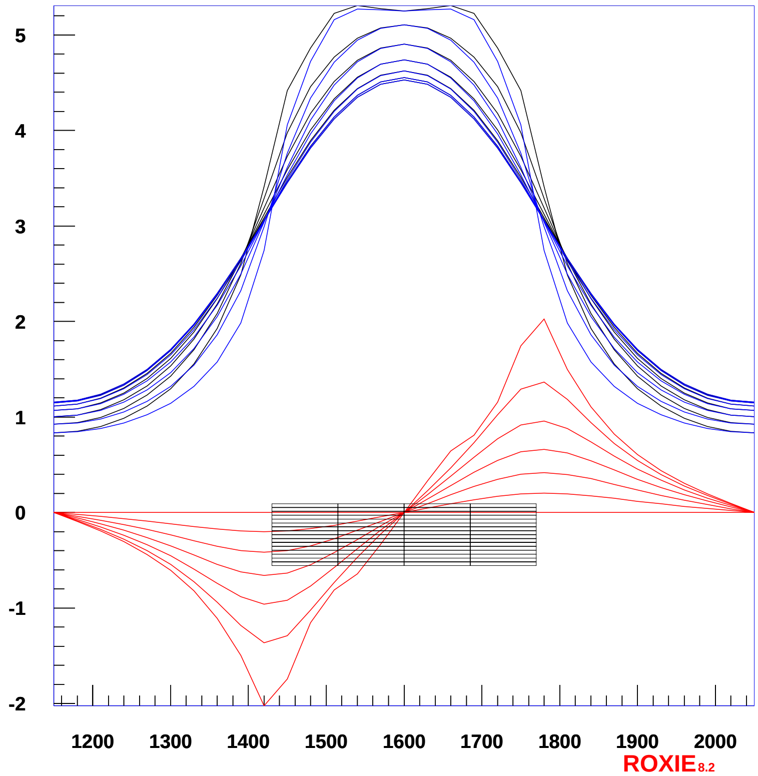

Figure 4: B_z (upper plot) in [T] and B_r (lower plot) in [T] versus z [mm] for maximum field strength of $NbTi$ solenoids at 4.5 K and staying below 60% on the load line.

versus z for the maximum field achievable with $NbTi$ at 4.5 K and staying below 60% on the load line. For the assumed currents (1920 kA $\times$ turns) the force between the first and second solenoid are 78 kN. Inside the cooling channel (all solenoids apart from the first and the last one) the force cancels.

4 Beam Dynamics of a Channel with 8 Cavities

4.1 Reference Optics

A beam dynamics study of the proposed cooling channel has been performed, based on the engineering design of cavities and solenoids. The solenoid field maps have been included in the tracking code PATH. The input beam parameters have been chosen similar 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. For this example case, the solenoids in the cooling cell have settings around 3 T and the cavity synchronous phase is set on crest. For this optics and appropriate input beam emittance the transmission is 100% and the transverse emittance at the exit of the cooling channel is reduced by about 3.7%. Figure 5 shows the transverse emittance versus z computed for 50000 muons.

4.2 Scan of Input Emittance

In order to determine the response of the system to various input beam parameters, parameter scans were carried out [4]. The input emittance was varied and the emittance at the exit of the channel computed. Figure 6 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.

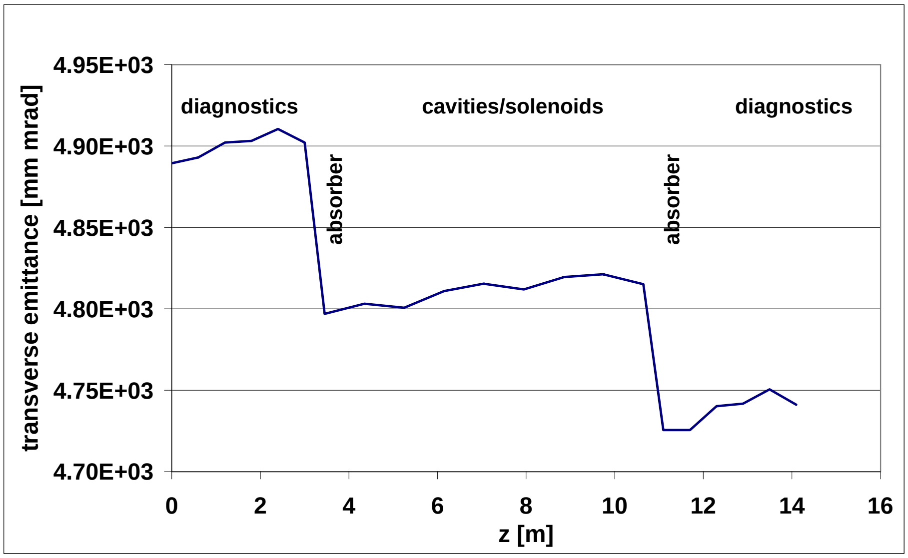

Figure 5: Transverse emittance (r.m.s., normalized) computed with PATH along the channel of 8 cavities.

For values between 3500 and 6000 π mm mrad, the transmission is 100% and the channel is cooling. For larger values of the input emittance, the acceptance of the channel is reached and the transmission starts to drop down. Figure 7 shows the transmission through the channel for the corresponding range of input r.m.s. emittance.

Another 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 (normalized) in both transverse and 0.1 eVs in the longitudinal plane. Within this volume, for the example case discussed in Section 4.1 the number of muons is increased by 9.1 %.

The cooling efficiency, defined as the increase of the number of particles inside the given acceptance, is shown in Fig. 8 for a range of input r.m.s. emittance. Depending on the input beam emittance, the cooling efficiency goes up to 15%. Note, that positive cooling efficiency is still found for emittances larger than the acceptance of the channel, i.e. for values for which the transmission is no longer 100% (compare Fig. 7).

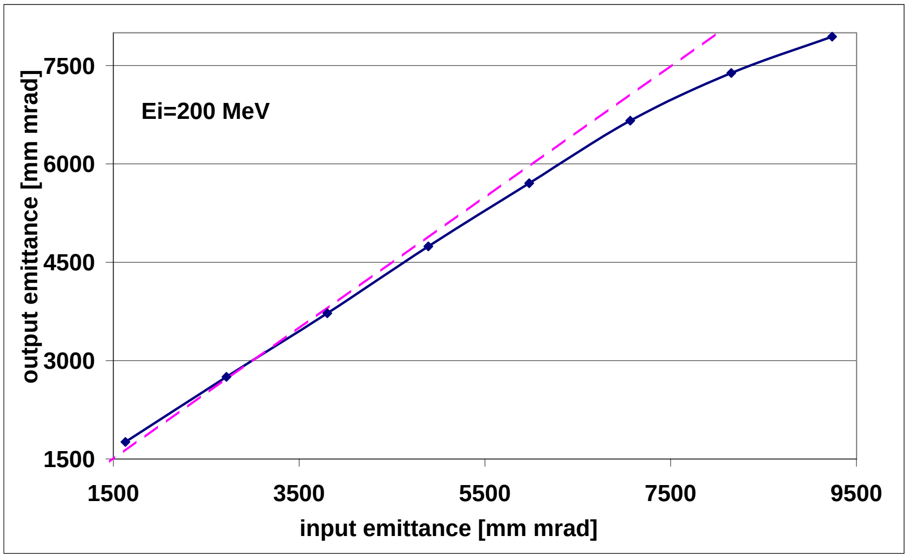

Figure 6: Output emittance versus input emittance (r.m.s., normalized) for a channel of 8 cavities and an input beam energy of 200 MeV. The dashed line means $\varepsilon_{out} = \varepsilon_{in}$. It can be seen that the channel is cooling for a wide range of input emittances. At about 6000 mm mrad, the acceptance of the channel is reached. At about 3500 mm mrad, the equilibrium emittance is reached. The solenoid and cavity settings are kept constant during the scan.

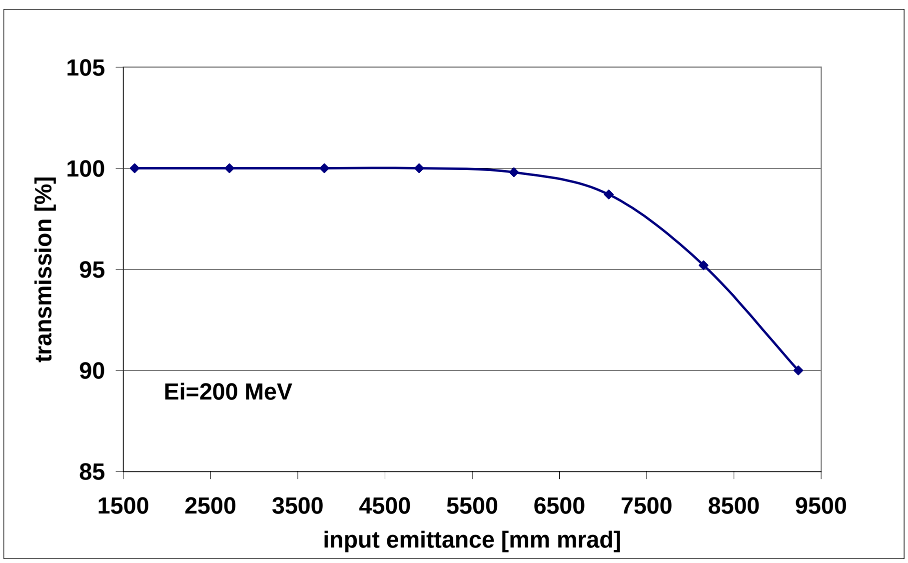

Figure 7: Transmission versus input emittance (r.m.s., normalized) for a channel of 8 cavities and an input beam energy of 200 MeV. The acceptance is reached at about 6000 mm mrad.

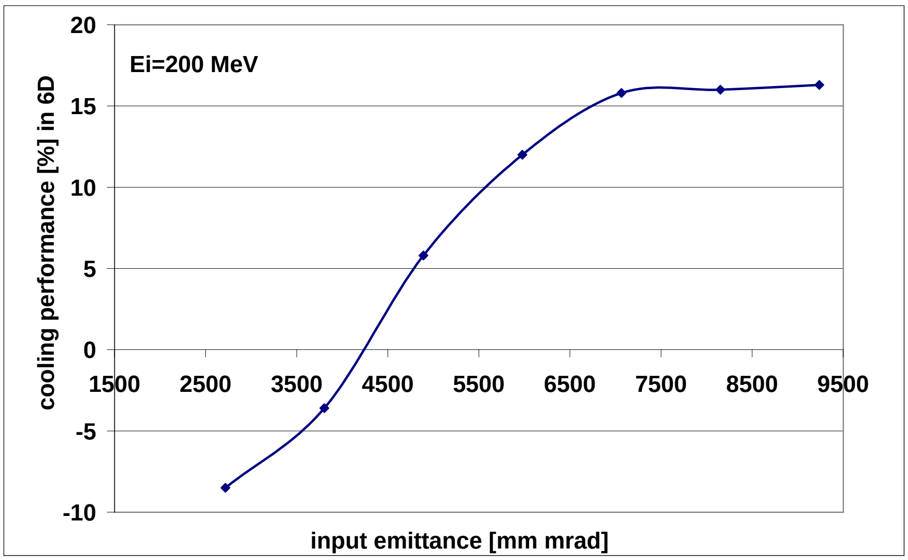

Figure 8: Cooling efficiency versus input emittance (r.m.s., normalized) for a channel of 8 cavities and an input beam energy of 200 MeV. The cooling efficiency goes up to 15% and stays at this value even beyond the acceptance of the channel. Note, that in this definition heating sets on at $\varepsilon_{in} \approx 4000$mm mrad while Fig. 6 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.

4.3 Influence of Beam Energy

We have run the setup with 8 cavities for various input beam energies: 230 MeV, 200 MeV, 170 MeV and 140 MeV. Detailed results are reported in [4]. Figure 9 shows the cooling efficiency for the four different input beams. To summarize the parameter scan for the system with

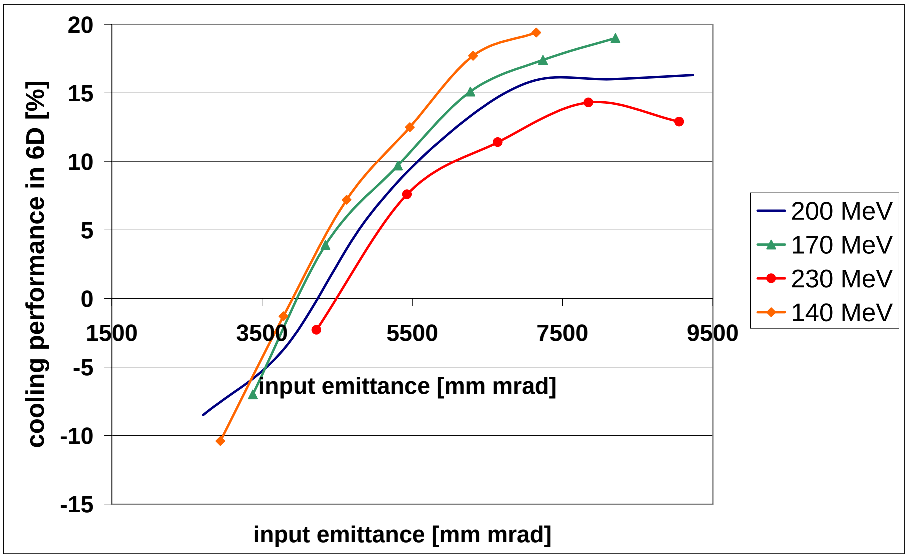

Figure 9: Cooling efficiency versus input beam emittance (r.m.s., normalized) for a system of 8 cavities and various input beam energies.

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. 2. The dependence of transmission and equilibrium emittance on the 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 2: Comparison of cooling efficiency for ε_{in}=5500 mm mrad (r.m.s., normalized) and various input beam energies. The results illustrate that the 88 MHz cooling channel is broadband.

4.4 Simulations with alternating Solenoid Polarity

Running the cooling experiment in a configuration with alternating solenoid polarity (*'field flip'*) is not advantageous in terms of cooling efficiency. However, it is of importance for the final cooling channel and hence one may want to set up also the experimental channel in this configuration. The channel with 8 cavities and the example optics discussed in Section 4.1 was therefore simulated with alternating solenoid field in the cooling section. The emittance reduction is the same as in the case where all solenoids have the same polarity (Fig. 5). Figure 10 shows the transverse emittance along the channel.

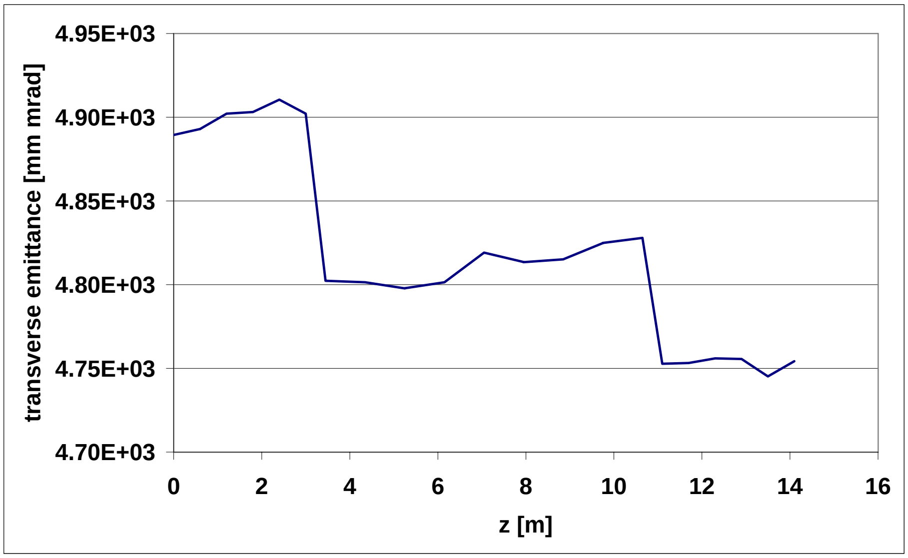

Figure 10: Transverse emittance (r.m.s., normalized) along the channel for a channel of 8 cavities and an input beam energy of 200 MeV. The polarity of the solenoids in the cooling section is alternating (*'field flip'*). The cooling performance is the same as in the case of same polarity (Fig. 5). Simulation with PATH and 50000 muons.

4.5 Absorber Walls

We have re-run the configuration with 8 cavities and the reference optics and added absorber walls of 150 μm thickness. The cooling performance is affected only slightly. Figure 11 shows the transverse emittance along the channel taking into account the absorber walls.

5 Electric Field Map

While in the simulations reported in the previous sections the cavities were represented by a stepwise energy increase, we have for the reference case (8 cavities, input beam and optics as in 4.1) performed a simulation which includes both the magnetic field map and the electric field map. These have been obtained from a SUPERFISH simulation of the cavities described in Section 2. The emittance evolution along the channel is shown in Fig. 12. The result is consistent with the one shown in Fig. 5.

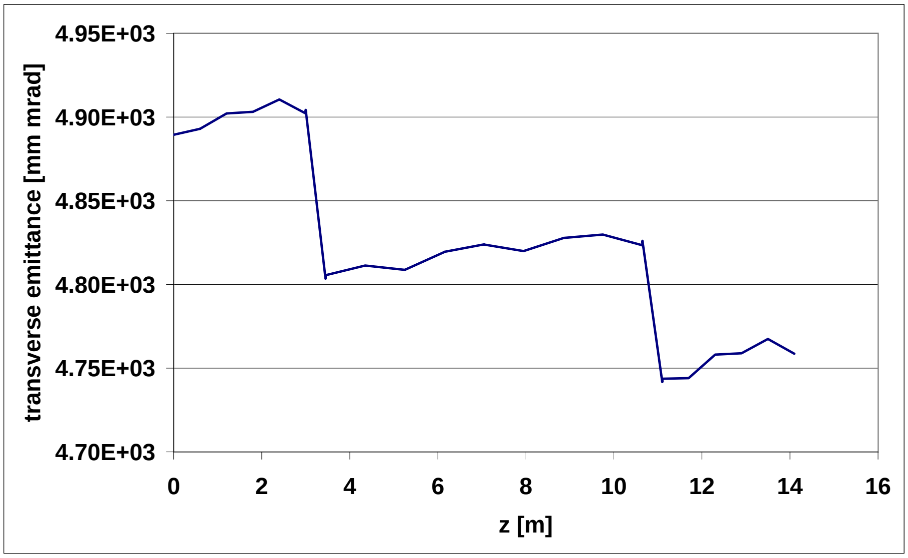

Figure 11: Transverse emittance (r.m.s., normalized) along the channel with 8 cavities at 200 MeV taking into account the absorber walls. Simulation with PATH and 50000 muons.

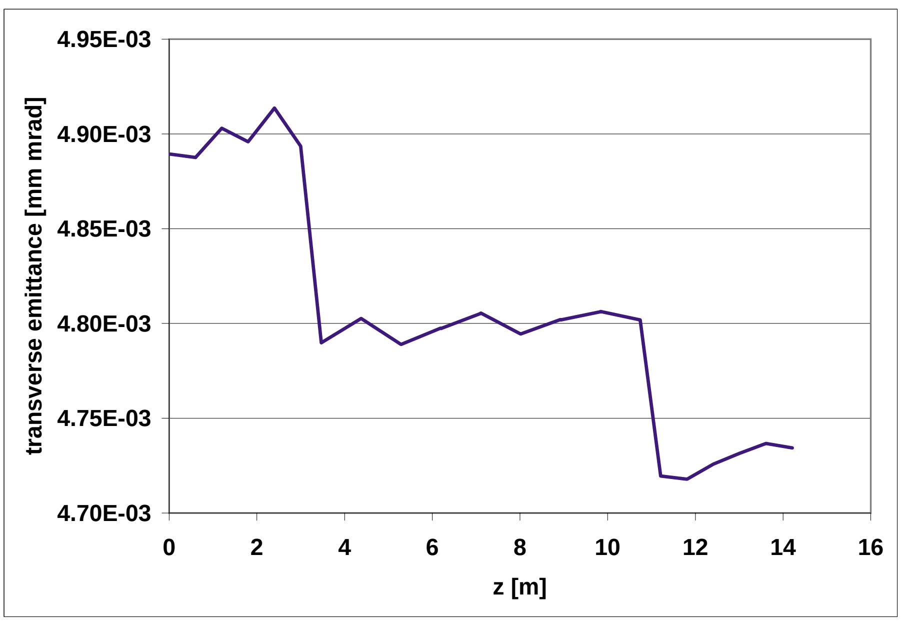

Figure 12: Transverse emittance along the channel with 8 cavities at 200 MeV taking into account both the magnetic and electric field map.

6 Beam Dynamics of a Channel with 4 Cavities

6.1 Reference Optics

Using the same optics and input beam parameters, but only 4 cavities and half the absorber length, the cooling performance of the channel drops down roughly in proportion. Figure 13 shows the transverse emittance versus z for this set-up. The reduction of the transverse emittance is in this case 2% and the number of muons inside the acceptance is increased by 3.5%.

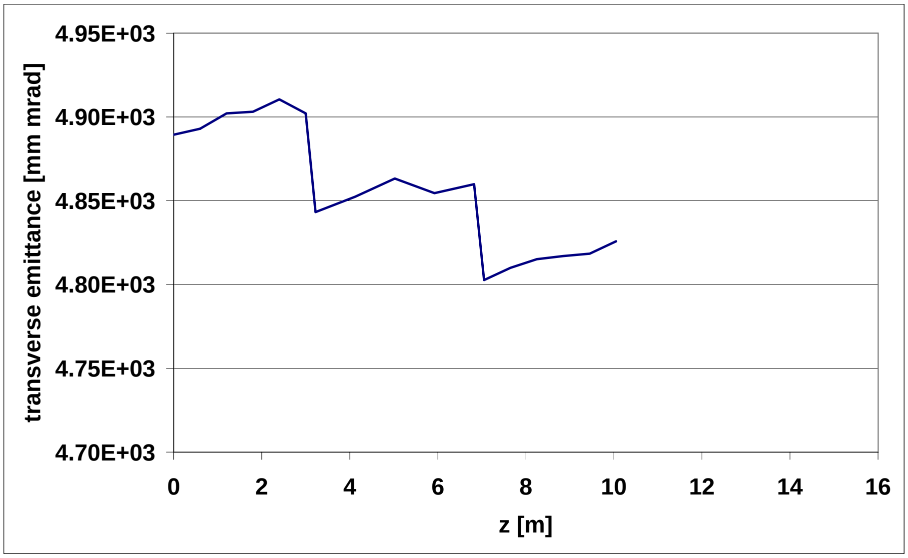

Figure 13: Transverse emittance (r.m.s., normalized) as computed by PATH along the channel for the set-up with 4 cavities. The emittance evolution along the channel is similar to the case of 8 cavities (see Fig. 5), but the length and the cooling performance drops down in proportion. Simulation with 50000 muons.

6.2 Scan of Input Emittance

Figures 14-16 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%.

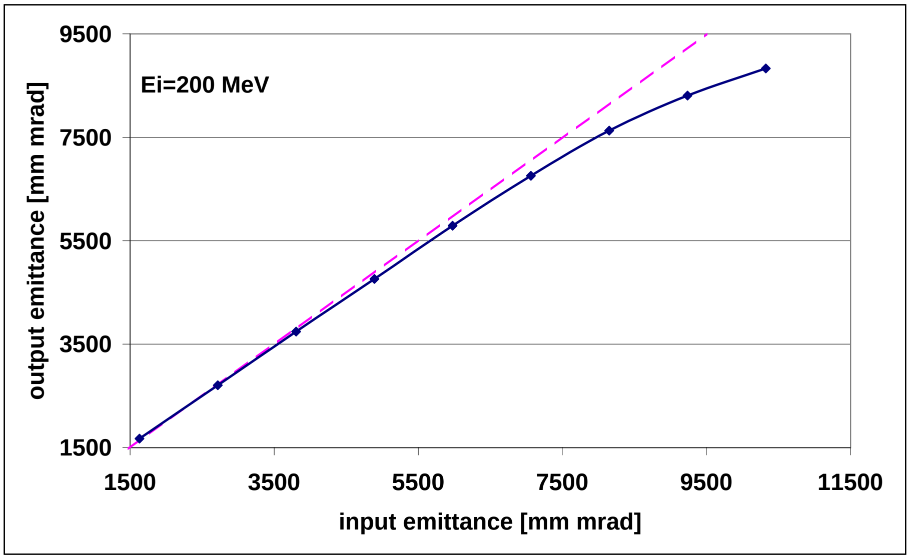

Figure 14: Output emittance versus input emittance (r.m.s., normalized) for a channel of 4 cavities and an input beam energy of 200 MeV. The dashed line represents $\varepsilon_{out} = \varepsilon_{in}$.

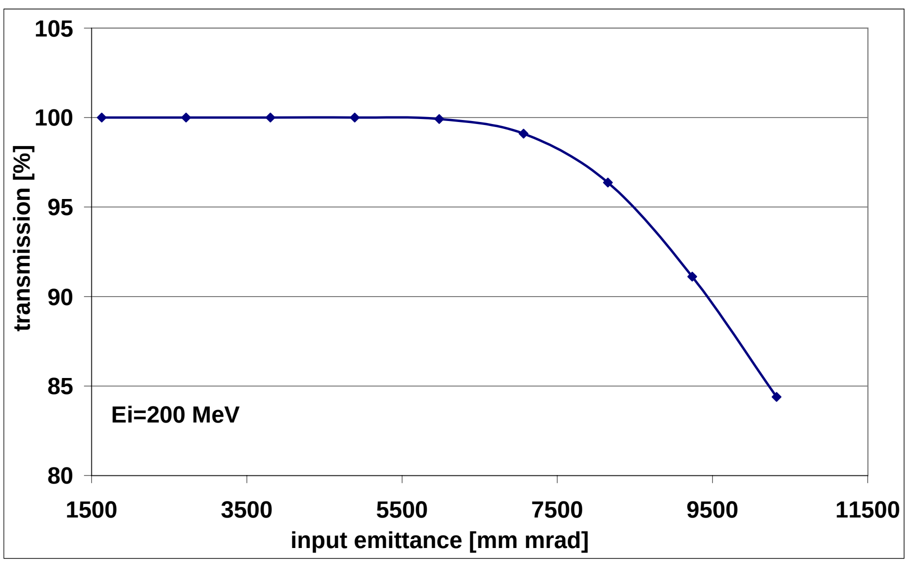

Figure 15: Transmission versus input emittance (r.m.s., normalized) for a channel of 4 cavities and an input beam energy of 200 MeV.

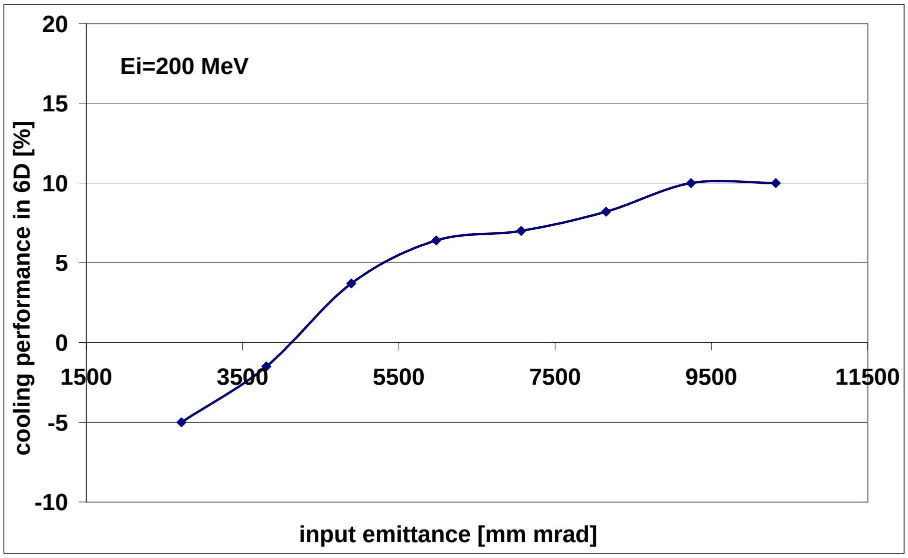

Figure 16: Cooling efficiency versus input emittance (r.m.s., normalized) for a channel of 4 cavities and an input beam energy of 200 MeV.

6.3 Influence of Beam Energy

As the cooling efficiency is worse than in the case of 8 cavities and it will become even worse at higher input energy than 200 MeV, we have studied a case with a significantly lower input energy of 140 MeV. As can be seen from Fig. 17, the cooling efficiency improves slightly with respect to the case of 200 MeV. The maximum value is still around 10%. The performance of a system with 8 cavities cannot be reached.

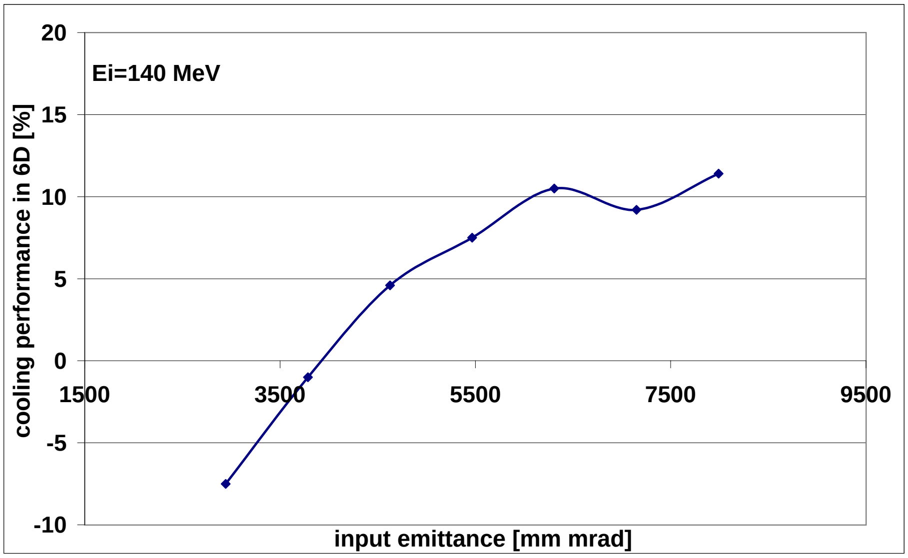

Figure 17: Cooling efficiency versus input emittance (r.m.s., normalized) for a system of 4 cavities and an input beam energy of 140 MeV. There is a slight improvement in cooling efficiency by going to lower beam energy but the performance of a system with 8 cavities cannot be reached. Note, that the results are subject to fluctuations (statistical processes in the absorbers) which can explain the bump around 7500 mm mrad.

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. 3. 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 3: Comparison of cooling efficiency for ε_{in}=5000 mm mrad (r.m.s., normalized) and various input beam energies.

7 Cross Check of PATH and ICOOL Simulations

The results obtained from PATH have been reproduced using the code ICOOL. The same input beam distribution and the same channel optics were used. The simulations were done with a total of 50000 particles. Figure 18 shows the transverse emittance versus z as computed with ICOOL. Excellent agreement with the corresponding plot for PATH (Fig. 5) is found. The cooling performance for the example case studied is summarized in Tab. 4.
Figures 19 and 20 show the horizontal and vertical r.m.s. emittance (normalized) as computed by the two codes along the channel.

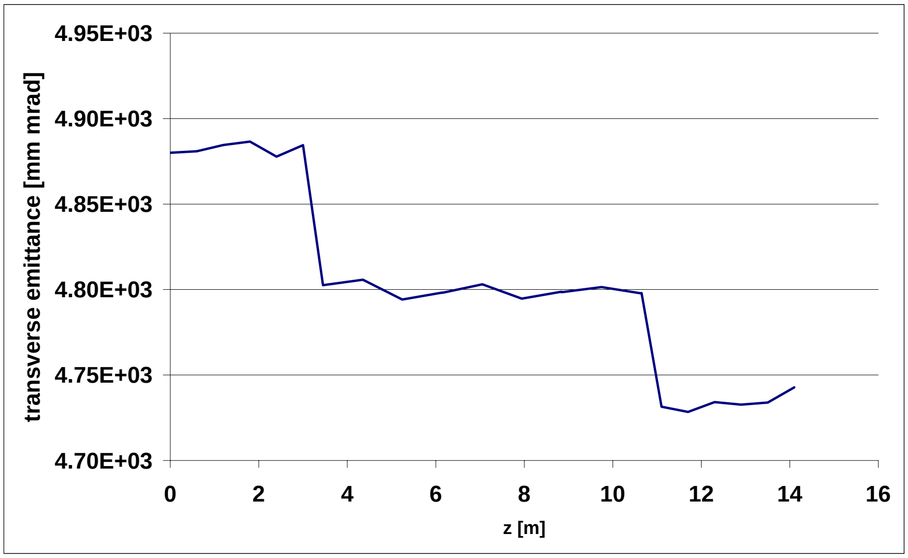

Figure 18: Transverse emittance (r.m.s., normalized) along the cooling channel as computed by ICOOL.

	PATH	ICOOL
transmission	100%	100%
transv. emittance reduction	3.7%	3.2%
particle gain in 6D volume	9.1%	7.6%

Table 4: Comparison of PATH and ICOOL results for one example case.

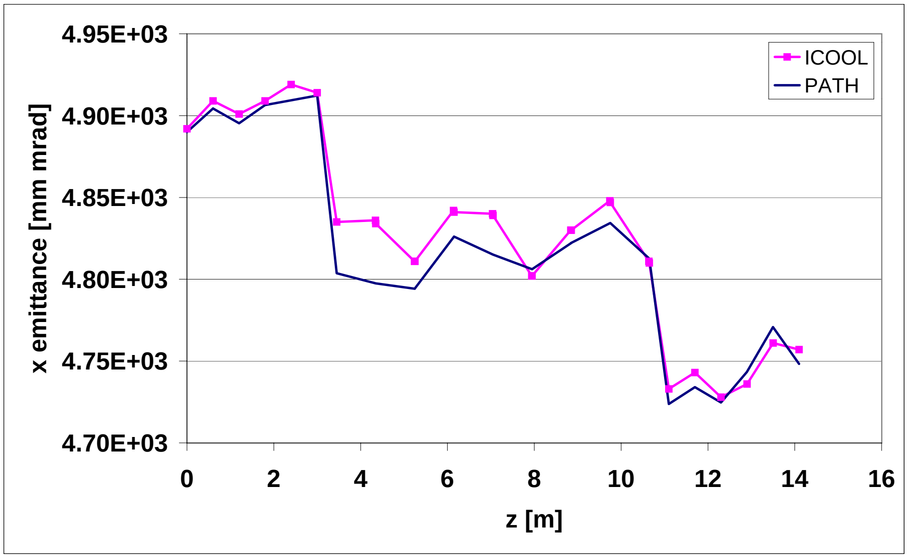

Figure 19: Horizontal emittance (r.m.s., normalized) along the channel of 8 cavities as computed by PATH and ICOOL.

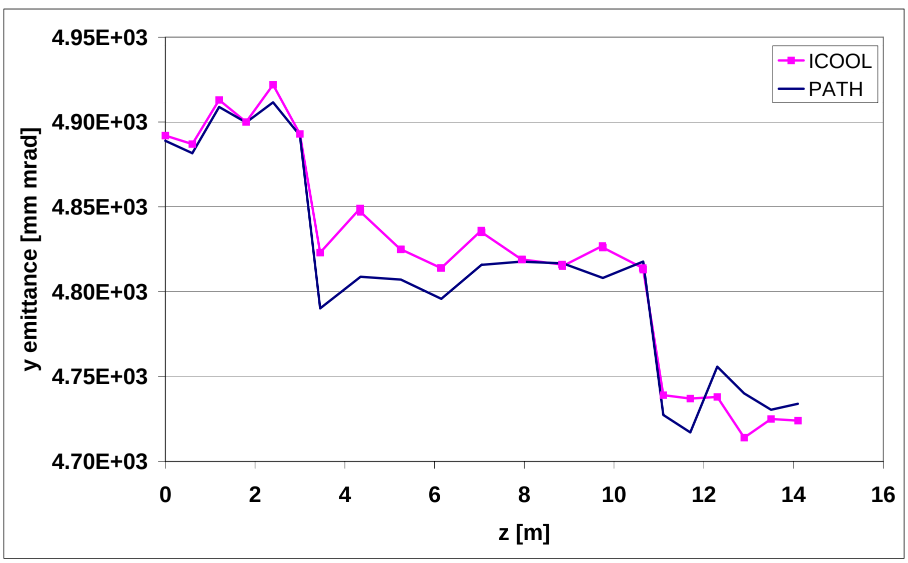

Figure 20: Vertical emittance (r.m.s., normalized) along the channel of 8 cavities as computed by PATH and ICOOL.

8 Conclusion

Two possible scenarios for a muon cooling experiment based on the 88 MHz CERN cooling channel have been simulated in detail. The reference case is a system of 8 cavities and solenoids, with an entry and exit liquid hydrogen absorber of each 47 cm length. The second system studied uses only half the number of cavities and half the absorber length. The simulations are based on the engineering designs of cavities and solenoids in order to represent in the best possible way the real experiment. It has been shown that one can achieve cooling rates that are within the measurement precision of the proposed diagnostics [5].

9 Acknowledgements

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

References

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