

MUON IONISATION COOLING IN REDUCED RF

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Abstract

In Muon Ionisation Cooling, closely packed high-field RF cavities are interspersed with energy-absorbing material in order to reduce particle beam emittance. Transverse focussing of the muon beams is achieved by superconducting magnets. This results in the RF cavities sitting in intense magnetic fields. Recent experiments have shown that this may limit the peak gradient that can be achieved in the RF cavities. In this paper, we study the effect that a reduced RF gradient may have on the cooling performance of the Neutrino Factory lattice.

PEAK ACHIEVABLE FIELD GRADIENT

In the International Design Study (IDS) baseline Neutrino Factory cooling channel [1], focussing is provided by solenoids with opposing current on adjacent solenoids. Cooling is provided by Lithium Hydride absorbers with a thin Beryllium coating. The absorbers also act as electromagnetic seals to the RF cavity, improving the cavity's Q-factor. The conceptual geometry of the cooling channel is shown in Fig. 1. RF cavities operate at the highest achievable field gradient in order to increase the rate of cooling. Cooling hardware is as tightly packed as possible to improve the acceptance of the cooling channel. This also has the advantage of reducing muon decay losses.

It has been observed empirically that RF cavities in intense magnetic fields cannot achieve high peak field gradients [2]. Various models have been proposed. In one, the presence of magnetic fields focusses electron beamlets onto the opposite wall of RF cavities causing the wall to heat. This heating degrades the surface and successive iterations result in breakdown [3]. In another model, the magnetic field creates torsional forces that tear asperities off the wall causing breakdown [4].

In this paper, the effects of a reduced peak gradient on the IDS baseline cooling lattice performance are examined. This study extends previous work [5].

COOLING CHANNEL MODEL

We model the cooling channel using G4MICE [6] and ICOOL 3.10 [7] simulation codes. G4MICE uses the GEANT4.8.2 library [8] to simulate processes in materials and for tracking. Fields are modelled and accelerator quantities are extracted using the code's internal routines. ICOOL uses its own custom routines for transport through electromagnetic fields and materials.

Solenoids Coils are modelled in both codes by taking the sum for the field from a number of superimposed in-

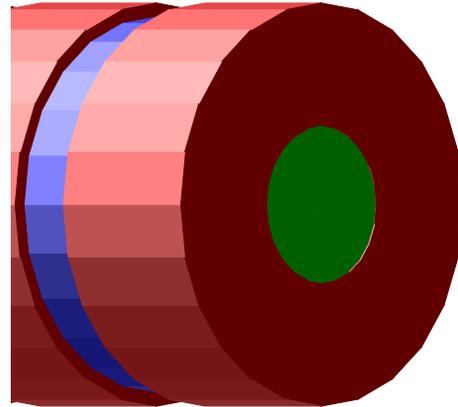


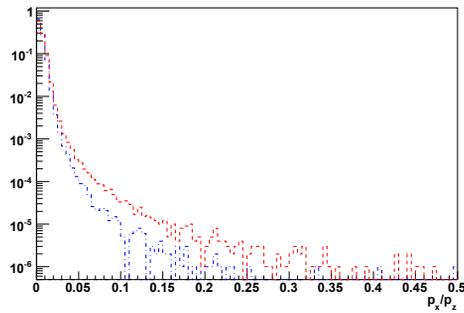
Figure 1: Isometric view of the end of the cooling channel. RF cavities with Beryllium-coated Lithium Hydride irises are alternated with superconducting solenoids to provide focussing and cooling.

finitely thin current sheets. In both ICOOL and G4MICE, the field calculated from the current sheets is then written to a field map grid for subsequent interpolation.

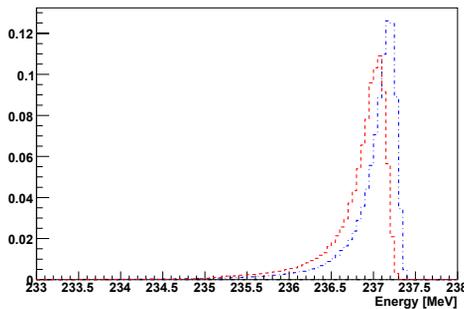
RF cavities RF cavities are modelled using a cylindrically symmetric TM010 pillbox field. In ICOOL, cavities are phased by tracking a muon of constant velocity through the cavities and then setting the reference time of the cavity to the time this muon passes through the cavity centre. In G4MICE, two phasing models are available. In the first instance, cavities are phased assuming a constant velocity reference trajectory as for ICOOL. However, a different phasing can be achieved by tracking a muon through cavities and materials allowing the muon to undergo mean energy loss in the absorber and then reacceleration in the cavity. In this case, the cavity phase and peak field is chosen iteratively so that the reference particle passes through the cavity centre at the appropriate phase and the particle gains energy equal to the energy lost in the absorber.

Material At the energy of interest, muon interactions with material are dominated by multiple Coulomb scattering and ionisation of atoms. In multiple Coulomb scattering muons scatter elastically off of atomic nuclei leading to transfer of longitudinal momentum to transverse. When atoms are ionised the muon energy is reduced, with some statistical spread that is referred to as energy straggling.

Simulation of the effects in ICOOL and G4MICE are shown in Fig. 2 for an ensemble of muons with initial mo-



(a)



(b)

Figure 2: Distribution of 214 MeV/c muons after a LiH absorber in (a) p_x/p_z and (b) energy. Distributions from ICOOL are shown with a dashed line, whereas distributions from G4MICE are shown with a dot-dashed line. ICOOL sees on average 10 % greater energy loss and 30 % more multiple scattering.

mentum of 214 MeV/c passing through a single absorber. It can be seen that these muons suffer greater energy loss and more multiple scattering in ICOOL than in G4MICE. The G4MICE model shows closer agreement with PDG values [9]. The lower energy loss is expected to lead to a smaller RF gradient required per cavity, while the smaller multiple scatter may lead to improved cooling and a lower equilibrium emittance.

COOLING SIMULATION

A beam was generated at the entrance to the cooling channel using an ICOOL simulation of the front end from pion capture through phase rotation to the match section of the cooling channel, taking MARS [10] output of a beam on target as input. The particle ensemble was then tracked through the cooling channel using both ICOOL and G4MICE.

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Baseline Channel at Nominal RF Gradient

In Fig. 3 the cooling performance in ICOOL and G4MICE for the nominal baseline cooling channel was compared. Where phasing was performed assuming constant velocity, the nominal absorber thickness and RF gradient was used. Where phasing was performed using G4MICE's iterative approach, the peak RF gradient was reduced to 13.5 MV/m so that particles gain energy in RF cavities equal to that lost in the absorbers.

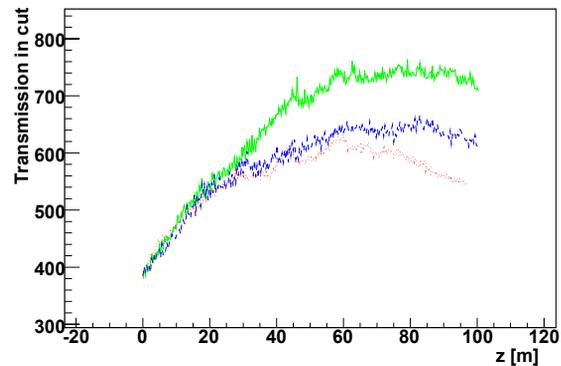


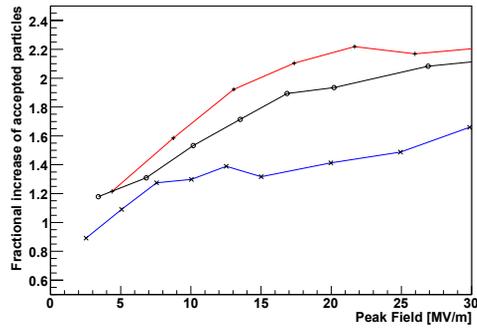
Figure 3: Number of muons in a cut of $150 < p < 300$ MeV/c and $A_{\perp}^2 < 30$ mm for various different simulation runs: (full line) G4MICE with constant velocity phasing; (dashed line) G4MICE with iterative phasing; (dotted line) ICOOL with constant velocity phasing.

The cooling performance is assessed by examining the number of muons accepted into a nominal accelerator. It is observed that the cooling channel cools considerably better in G4MICE than in ICOOL. In G4MICE the number of muons in the cooling channel increases by a factor 2 when using the constant velocity phasing model whereas in ICOOL the increase is only 1.7.

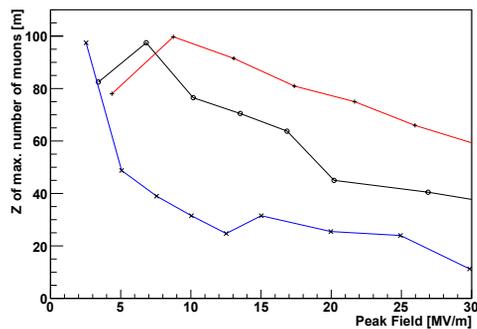
Baseline Channel with Different Gradients

When the peak RF field gradient is reduced, particles lose more energy in the absorbers than they gain in the RF fields resulting in the muon beam falling out of the RF bucket and being lost. This can be mitigated in one of two ways. Either the phase at which the RF cavities are operated can be changed so that muons pass through the cavities closer to the RF crest or the absorbers can be made thinner. In the former case the size of the RF bucket is reduced, reducing the number of muons that are transmitted along the cooling channel, while in the latter case the energy loss in the absorbers is reduced, so reducing the cooling effect.

The cooling performance and distance to peak cooling is shown as a function of cavity peak field in Fig. 4. Here the peak field for the RF cavities was changed at each point to match the energy lost in the Lithium Hydride absorbers using the G4MICE iterative phasing model. The beam was



(a)



(b)

Figure 4: (a) Fractional increase in number of muons within an acceptance of 30 mm transverse with $150 < p_z < 300$ MeV/c as a function of peak RF gradient and (b) distance to the point of peak number of muons for different phases: (+) 60 degrees off-crest; (o) 50 degrees off-crest and (x) 30 degrees off-crest. Simulated in G4MICE.

allowed to propagate for 100 m along the cooling channel and the peak number of muons in the accelerator acceptance was measured. For some configurations, particularly those running closer to on-crest, the RF bucket is small and muons are lost relatively quickly so a shorter channel is desirable. For particularly low RF gradients, it may be desirable to lengthen the cooling channel beyond 100 m, despite the increase in costs that would result.

The study was repeated in ICOOL and the results are shown in Fig. 5. In this case, simulations were run at 50 degrees off-crest and the absorber thickness was varied linearly with peak field gradient. ICOOL shows a consistently lower performance for the cooling channel.

CONCLUSIONS

Two conclusions can be drawn from this study: (i) Different modelling of material can drastically change cooling performance. LiH absorbers are particularly difficult

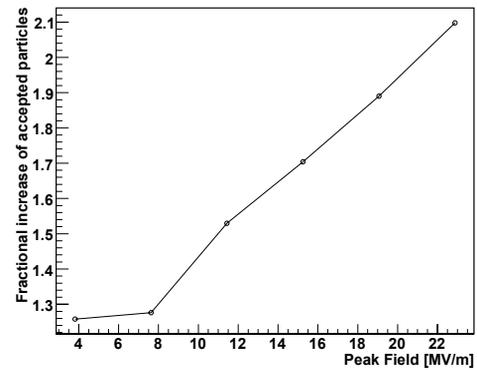


Figure 5: Fractional increase in number of muons within an acceptance of 30 mm transverse with $100 < p_z < 300$ MeV/c. Simulated in ICOOL.

to model as the density and ratio of Lithium to Hydrogen can vary between different LiH samples. (ii) The performance of the cooling channel goes roughly proportional to the peak field gradient achievable for gradients below 20 MV/m. Depending on the field gradient that can be achieved during routine operation of a Neutrino Factory, the baseline cooling channel may require re-optimisation.

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