LINEAR QUADRUPOLE COOLING CHANNEL FOR A NEUTRINO FACTORY*

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Abstract

Staging and optimization in the design of a Neutrino Factory are critically dependent on the choice and format of accelerator. Possibly the simplest, lowest-cost scenario is a nonscaling FFAG (Fixed-Field Alternating Gradient) machine coupled to a linear (no bending) transverse cooling channel constructed from the simplest quadrupole lens system, a FODO cell. In such a scenario, transverse cooling demands are reduced by a factor of 4 and no longitudinal cooling is required relative to acceleration using a Recirculating Linac (RLA). Detailed simulations further show that a quadrupole-based channel cools efficiently and over a momentum range which is well-matched to FFAG acceleration. Details and cooling performance for a quadrupole channel are summarized in this work.

INTRODUCTION

Schemes for intense sources of high-energy muons require collection, rf capture, and transport of particle beams with unprecedented emittances, both longitudinally and transversely. In comparison with high-energy hadron facilities, the transverse emittance is a factor of 1000 larger and the longitudinal emittance, is 20-100x larger even after bunching and phase rotation. Acceleration and collision of intense muon beams becomes impractical without a significant reduction, or cooling, of incipient emittances—transversely by a factor of 2.5 to 10 for a Neutrino Factory[1] and at least a factor of 1000 for a muon collider[2]. In the former the required emittance reduction is tailored to the conditions for acceleration and in the latter for the collider ring. The challenge in the design of these facilities lies in the large beam emittances further complicated by the short muon lifetime, or timescale on which these facilities must operate.

The anticipated transverse beam emittance subsequent to capture and phase rotation for both facilities is so large that it permits a relaxation of the requirements on beam spot size in the early stages relative to the final stages of ionization cooling. Staging the cooling process according to initial emittances, coupled with modest cooling factors, permits more optimal and efficient cooling channel designs and avoids much of the difficulty encountered with channels which attempt to maintain strong focusing (large, 300-500 mr, divergences) across ultra-large momentum ranges ($\geq \pm 20\%$ $\delta p/p$). Relaxation of spot size at the absorber allowed development of an efficient transverse cooling channel based simply on a quadrupole FODO cell. This work briefly describes the design of such a cooling channel[3] and its application as i) an upstream stage of beam cooling or ii) the only cooling stage in an FFAG-based Neutrino Factory. (In the present U.S. Neutrino Factory design, FFAGs are the preferred acceleration model[1] to high energy due to their significantly reduced cost and larger acceptance, implying a factor of 4 reduction in transverse cooling and total elimination of longitudinal cooling relative to recirculating linear accelerators.) Being a linear channel with no bends, this cooling channel serves to reduce the large transverse beam size delivered from muon-beam capture and bunching before it enters more restricted optical structures such as emittance-exchange channels or accelerators.

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QUADRUPOLE COOLING CHANNEL

Technical Description

With a relaxed beta ($\geq$ 1m) at the absorber, one can consider a short, alternating-gradient quadrupole lens structure. The advantages of a short FODO cell structure over a doublet or triplet quadrupole telescope are primarily in the acceptance and stability of optical parameters over a tremendous chromatic range, the dynamical range being easily $\pm 50\%$ in $\delta p/p$ in a repeating structure. However, in standard (implying repetitive) FODO-cell optics, the minimum beta in one plane is located at the maximum beta in the other. A minimum beta or beam size cannot be established simultaneously in both planes, and, therefore, the absorber cannot be located at the lowest beta point in this type of channel. The smallest beta for both planes combined is found halfway between the quadrupoles, at the "crossing point" in β_x and β_y. The increased beta does not impact or limit the cooling rate or efficiency in any way. This is due to the increased emittances just after capture and phase rotation.

The physical construction of the quadrupole cooling channel is given in Figure 1 and Table 1 with beta functions plotted in Figure 2. The aperture of the quadrupole was chosen somewhat conservatively in order to constrain its length to be equal to its aperture in order that the quadrupole field profile and therefore the optics are not fringe-field dominated. This aperture is sufficient to accommodate the proposed 2.5σ for an initial rms emittance of 20.4π mm (~40 cm radius), with appropriate pole-tip design and star-shaped vacuum chambers that extend between the quadrupole poletips by as much as 50% of their physical radius. Recent innovations suggest elimination of the liquid hydrogen absorber and its windows—the entire channel is simply filled with gaseous hydrogen. The average absorber beta and therefore the cooling factor appear not to change significantly.

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Containment windows would be located only at the beginning and end of the cooling structure.

The Simulation

Simulations by K. Makino[3,4] were performed with the program COSY[5] on the quadrupole cooling cell described in the last section:

- using full nonlinear terms;
- with/without quadrupole fringe fields[3] (including different models);
- multiple scattering (absorber + windows);
- energy loss, dE/ds, as a function of energy;
- full energy loss simulation: straggling and spin;
- a 200 MHz sinusoidal rf cavity.

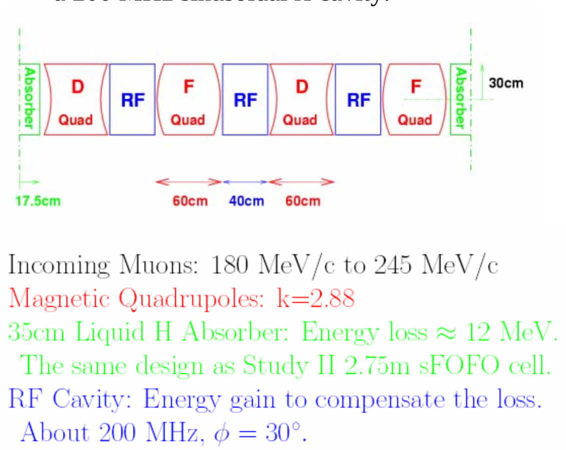

Figure 1: Layout of quad channel and parameters assumed in simulation.

Table 1: Physical specifications for quad channel.

Technical Parameters		
Quad length, bore	0.6 m	0.6 m
Poletip field, spacing	~1 T	0.4 m
Absorber length, RF cavity length*	0.35 m	0.4 - 0.7m
Total cell length	2 m	
* can extend inside magnet aperture		

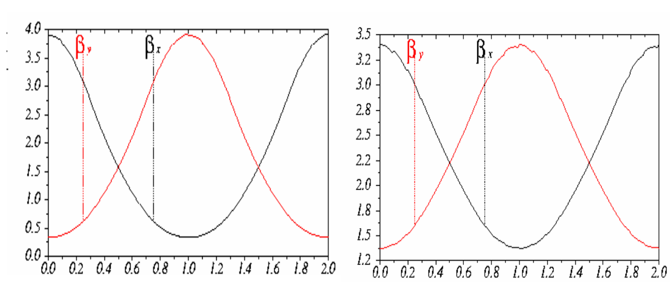

Figure 2: Beta functions (m) vs. length (m) for 155 MeV/c (left) and 300 MeV/c (right).

SIMULATION RESULTS

First the beam particles from the bunching and phase rotation stage[6] plotted in Figure 3 had to be optimally sorted into their respective bunches. The optimal bunch configuration was not the assumed 180 MHz characteristic of the upstream rf system, instead a 179 MHz structure with an offset relative to the supplied individual particle coordinates as shown in Figure 3.

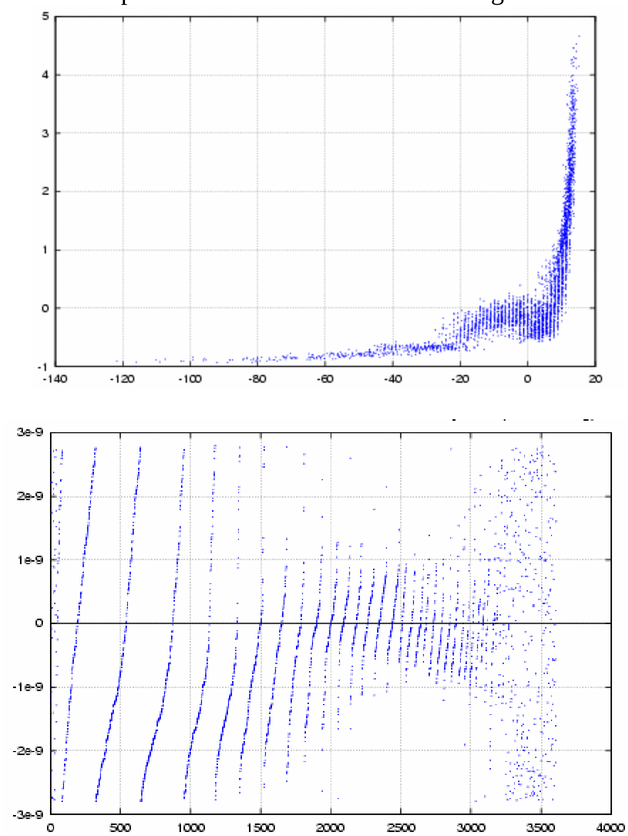

Figure 3: Particle (3611 muons) from the phase rotator stage plotted in terms of kinetic energy, $\delta k = (K-K_0)/K_0$, where K_0 is the kinetic energy of the reference momentum, 200 MeV/c, vs distance in m from this reference particle (top figure). The bottom figure represents optimal sorting of these muons into a bunch train, at. 179 MHz rf structure and bunch centers shifted relative to the reference particle/bunch (time difference in sec from bunch center is plotted against particle number).

RESULTS

This simple, relatively inexpensive channel was found to cool over a tremendous energy range, from 150 MeV/c to well past 400 MeV/c. The cooling picture is somewhat complicated initially by a rapid exchange of transverse and longitudinal emittance into angular momentum and then back (muons have a strong angular momentum component exiting the upstream phase rotation channel). The angular momentum is rapidly transferred and damped, however in the absorber due to its longer, spiraling path. This channel displays the following behavior in emittance in terms defined by [7].

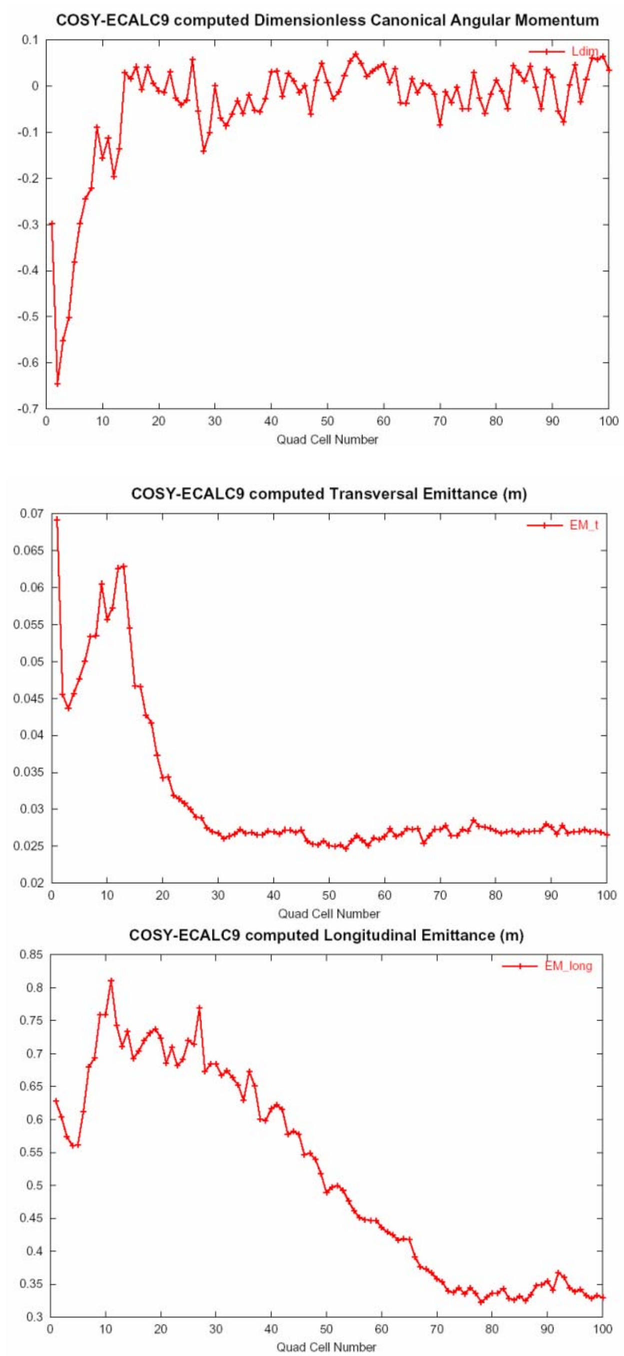

Figure 4: Plots represent canonical angular momentum, transverse emittance, and longitudinal emittance plotted vs. cell number, respectively.

It is interesting to note the exchange of transverse and longitudinal momentum into angular momentum and then back with complete damping of angular momentum by cell 15. Transverse emittance cools rapidly to within 50% of equilibrium in 20 cells. A very slow longitudinal cooling also appears to be taking place with a much longer time constant—most likely due to slightly increased path lengths of off-momentum particles through the absorber (larger amplitudes). For completeness, initial and 20 cell particle distributions are given in Figure 5.

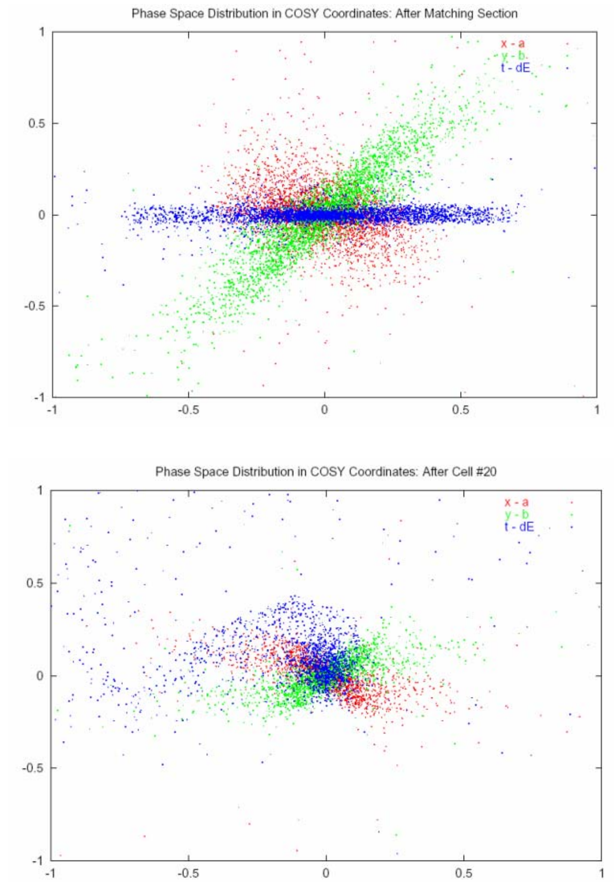

Figure 5: Initial particle distribution after matching into quad channel and distribution after 20 cells.

SUMMARY

After immediate losses in cells 1 and 2, the channel presently transmits a remaining 60% of the particles with a final cooling of about 2 per plane in transverse emittance. The next step is to trace back the surviving particles to calculate their initial emittance vs. their cooled emittance. Since included particles have a kinetic energy ranging from 25 - 900 MeV, energy cuts also need to be applied for final, comparative results.

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