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IONISATION COOLING IN FFAG'S

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Japan's unique scenario for a neutrino factory is at present the only one that does not rely on ionisation cooling of the muon beam. This is made possible by the large intrinsic acceptances of the FFAG accelerators replacing the linacs and recirculators of the other scenarios. Nevertheless, it is shown, using basic cooling theory, that moderate cooling in the first FFAG could be beneficial for the overall muon yield. Moreover, a solution using Be windows in the radio-frequency accelerating cavities would improve their performance. Simulation results obtained with the ACCSIM code essentially corroborate the theoretical cooling predictions, although showing a yet unexplained emittance exchange mechanism between the transverse phase spaces.

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Ionisation Cooling in FFAG Neutrino Factories

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Abstract

Japan's unique scenario for a neutrino factory is at present the only one that does not rely on ionisation cooling of the muon beam. This is made possible by the large intrinsic acceptances of the FFAG accelerators replacing the linacs and recirculators of the other scenarios. Nevertheless, it is shown, using basic cooling theory, that moderate cooling in the first FFAG could be beneficial for the overall muon yield. Moreover, a solution using Be windows in the radio-frequency accelerating cavities would improve their performance. Simulation results obtained with the ACCSIM code essentially corroborate the theoretical cooling predictions, although showing a yet unexplained emittance exchange mechanism between the transverse phase spaces.

Key words: neutrino factory, ionissation cooling, FFAG
PACS:

1 Transverse Ionisation Cooling at Higher Energies?

Ionisation cooling is an integral part of almost all neutrino factory scenarios except for the FFAG (Fixed Field Alternating Gradient) acccelerator based Japanese one [1]. The intrinsically large acceptances of this machine type allow to conceive a scenario with muon beams of larger emittances, avoiding thus the technical complications and additional cost of cooling insertions. This simplification comes at the expense of performance, especially of reduced yield into the useful solid angle of the neutrino beam.

Ionisation cooling is usually performed at the lowest muon energies, where the heating effect of energy straggling is least, before any acceleration, because of the tight limits to longitudinal emittance for subsequent acceleration in recirculating linacs. In an FFAG scenario, no phase rotation is envisaged as bunches of large momentum spread can be accelerated. In this situation the heating due to energy straggling is less fatal and cooling at somewhat higher energies, up to about 1 GeV/c, where muon lifetime is already less critical, can be considered. In fact, there is an equilibrium momentum spread for this process, nearly independent of energy and ensuring some cooling of large momentum amplitudes. It happens to be ≈ 11.5 % for both liquid H_2 and Be.

2 Ionisation Cooling in Japan's FFAG Based Neutrino Facility

In order to assess the potential benefits we use the parameters of the first (superconducting) FFAG in the proposed chain in the scenario of the Japanese Neutrino Facility. This machine of 10 m mean radius and 16 periods accelerates muons from $0.3 - 1$ GeV/c. With the nominal average RF gradient of 1 MV/m this is achieved in 11 revolutions. The concomitant transmission due to the finite muon lifetime is 83 %. Transverse acceptances of $10000 - 20000\ \pi$ mm mrad are considered, providing muon capture yields of ≈ 0.3 and ≈ 0.5, respectively.
By inserting absorbers for ionisation cooling in this FFAG one can hope for modest transverse cooling, by a factor of about two. With the same, already quite ambitious RF system, more revolutions are needed and the muon decay losses will increase. Nevertheless, a net gain can be achieved by optimising parameters, and the resulting emittance reduction should pay off in the higher-energy machines and in the decay ring.
Several cooling schemes have been be considered:

(1) Conceptually the simplest is a distributed absorber that can be imagined as pressurised hydrogen gas filling the beam pipe. This implies elevated gas pressure in the RF cavities, which may then benefit from Paschen's law to raise breakdown field strength [2]. The cooling performance is mainly limited by β_T, the transverse Twiss function, which has to be averaged over the whole ring, and cannot be arbitrarily compressed. This problem can be avoided by
(2) Liquid H_2 absorbers in one or two straight sections designed as low-beta insertions. Some exchange of emittances could be obtained by a slight wedge shaping of full-aperture absorbers. Orbits are strongly distorted by the localized energy loss.
(3) A more elegant variant consists in inserting thin conducting absorbers in the symmetry plane of all RF cavity gaps. Be windows are a valuable tool to increase field quality and shunt impedance of large aperture cavities [3]. The lesser cooling quality of Be would need to be compensated by a lattice design providing very low β_T values ($\leq 0.5m$) locally at the centre of the RF cavity sections.

3 Performances to be Expected

A simple spreadsheet program based on elementary ionisation cooling theory [4] allows to determine the effect of the main parameters on cooling (average transverse

beta, initial normalised emittance, absorber density) and on transmission (effective RF voltage gradient). It allows to optimise transverse ionisation cooling for minimum decay loss for an envisaged cooling performance. For the FFAG serving as an example, one finds for the hydrogen gas-filled FFAG (Scheme 1) an optimum pressure of $\approx$ 16 bar and for Scheme 3 a total Be thickness in the ring of $\approx$ 9.4 cm. This corresponds to RF windows of 6.5 mm thickness in the 14 RF cavities of this machine. Fig. 1 shows the cooling performances for Schemes 1 and 3, respectively. Efficiency depends essentially on the ratio between the initial and the equilibrium normalised emittance, the latter being proportional to the transverse beta function β_T. Its value of 2 m adopted in Scheme 1 corresponds to the average β_V of the reference machine; a value of 0.4 m is assumed for Scheme 3, which, although a challenge to the lattice design, still appears feasible.
Note that the transmission has to be related to its no-cooling value in vacuum of 0.83.

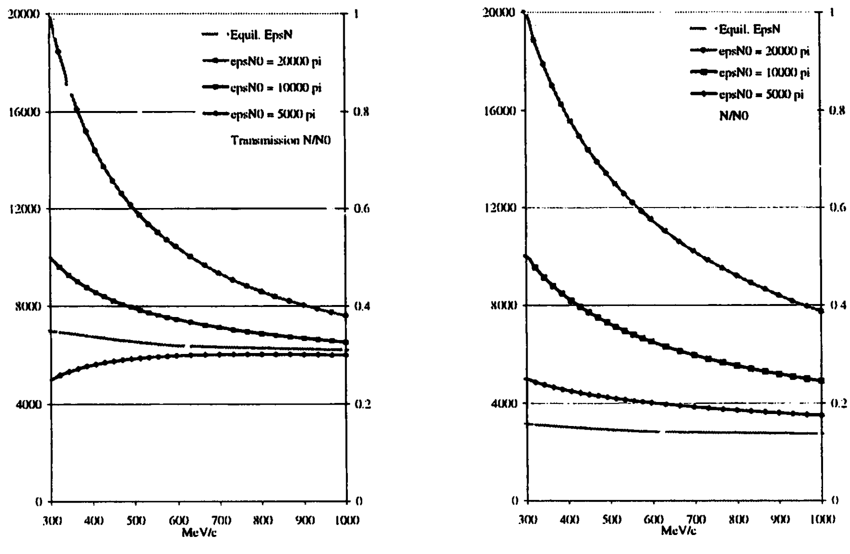

Fig. 1. Left: 16 bar H_2-gas filled FFAG with average $\beta_T = 2$ m. The cooling of initial emittances of 20000, 10000 and 5000 π mm mrad is shown during acceleration from 0.3 to 1 GeV/c. Right: Idem for FFAG with 7 mm Be windows in 14 cavities. Local $\beta_T = 0.4$ m.

4 Simulation Results

Due to their intrinsic non-linearity and the huge momentum spread of the muon beam, FFAG's are difficult to simulate with codes based on linear beam optics. Nevertheless an attempt was made to track Scheme 3 through the final accelera-

tion from 0.8 to 1 GeV/c with the *ACCSIM* code [5]. The limited energy range is imposed as the linear approximation features non-zero chromaticity, contrary to a genuine scaling FFAG where it is zero. No code is available to deal with the distributed gaseous absorber. For a given energy spread of ±150 MeV, the momentum spread at these energies is only (!) $\pm0.16 - 0.19$; the non-linear field was locally multipole expanded up to decapole terms, and thin lenses inserted at short interval into all magnets. The approximation made sens by confirming the results of the dynamic aperture survey [6], namely, that the reference of $k = 15$ suffers from an unsuitably small horizontal acceptance. Following the findings of the survey, the value was changed to $k = 12$. The lattice of the reference FFAG provides beta values of $\beta_{H,V}$ of 1.4, 1.7 m, respectively, in the straight sections, i.e. $3 - 4$ times the postulated ones. Consequently the equilibrium emittances are larger by this factor and one can demonstrate a cooling effect only for even larger beams.
Two ideal binomial distributions were generated as starting ensembles at 0.8 GeV/c, both of 2000π mm mrad rms physical emittance (15000π normalised): one with an exponent of 0.00001 (thin annulus of 4000π in phase space), the other with one of 1.5 (parabolic projection), in both planes. The average RF voltage gradient was 0.8 MV/m due to phase slip far above transition. Results are displayed in Fig. 2 and compared to the computed theoretical cooling effect for the β_T values of the relevant plane.
The common feature of the results of both distribution is a kind of emittance exchange: cooling in the vertical plane appears faster than predicted while cooling is slowed down in the horizontal plane - even some initial heating can be observed. The latter is obviously a filamentation effect due to mismatch of the ideal, mathematically-generated distribution to the trajectories deformed by the strong multipoles. The blow-up is subsequently rapidly cooled down.

5 Conclusions

The *ACCSIM* simulation essentially confirms the feasibility of moderate transverse ionisation cooling in an FFAG similar to the one foreseen in Japan's Neutrino Factory. An emittance exchange mechanism favouring vertical cooling at the expense of the horizontal one remains to be identified by further studies. The concept of beryllium windows inserted in the gap of the high-gradient RF cavities appears not only comparatively simple to realise but promises considerable enhancement of their performance. Its ultimate cooling performance depends most certainly on the lattice design and the minimum beta function values achievable at the locations of the RF cavities.

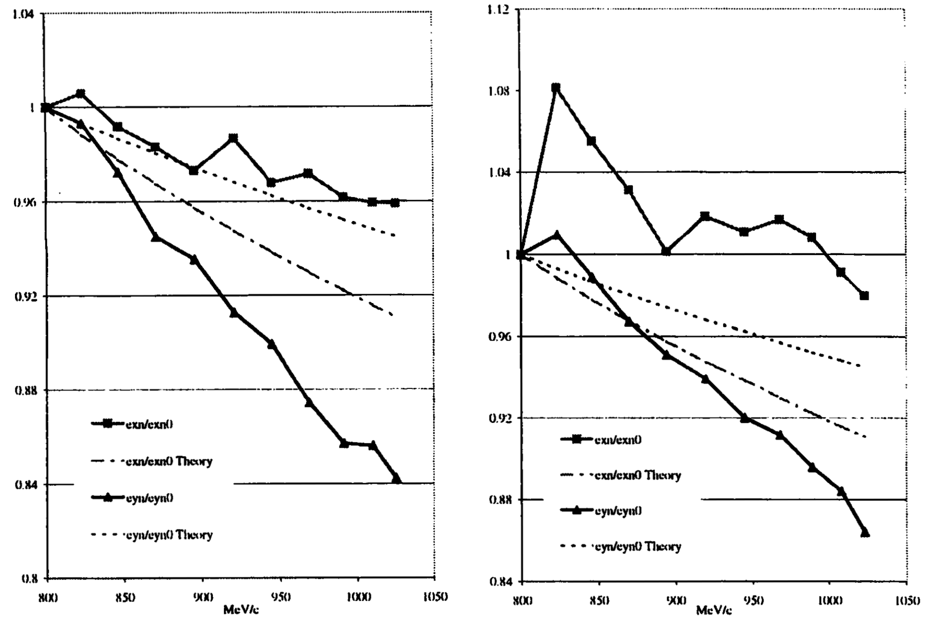

Fig. 2. ACCSIM simulation vs. theoretical evolution of relative normalised emittances. Left: FFAG with 7 mm Be windows in the RF gaps. Acceleration and cooling from 0.8 to 1 GeV/c of annuli of 2000π mm mrad physical rms emittance in both phase spaces. Right: Idem for binomial distributions ($m = 1.5$) of 2000π mm mrad in both transverse phase spaces.

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