Ionisation Cooling in FFAG's: Progress Since NuFact'01

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Abstract

Although Japan's unique FFAG scenario for a neutrino factory does not rely on ionisation cooling of the muon beam, moderate cooling in the first FFAG could be beneficial for the overall muon yield, and, perhaps even more important, reduce the final emittances in the decay ring.
Using basic cooling theory, one can show that this appears possible. In the Nufact'01 contribution on 'Ionisation Cooling in FFAG's' [1], the addition of absorbers into the superconducting 0.3-1 GeV/c Japanese FFAG was investigated. The cooling absorbers were 7 mm Beryllium sheets in the median plane of the RF cavities. Be was chosen because Be windows are a known design to increase field strength and -quality of large aperture cavities. Obviously metallic Lithium or a sandwich of Lithium Hydride between thin metallic Be sheets are preferable from the cooling viewpoint. We have thus complemented the results for Be by equivalent inserts of pure Lithium and Lithium Hydride. For each material two thicknesses were compared.

1 Simulation of Ionisation Cooling in the 0.3-1 GeV/c FFAG of Japan's Neutrino Facility:

As in [1] we use in the following the parameters of the first *(superconducting)* FFAG in the FFAG chain proposed in the scenario of the Japanese Neutrino Facility.

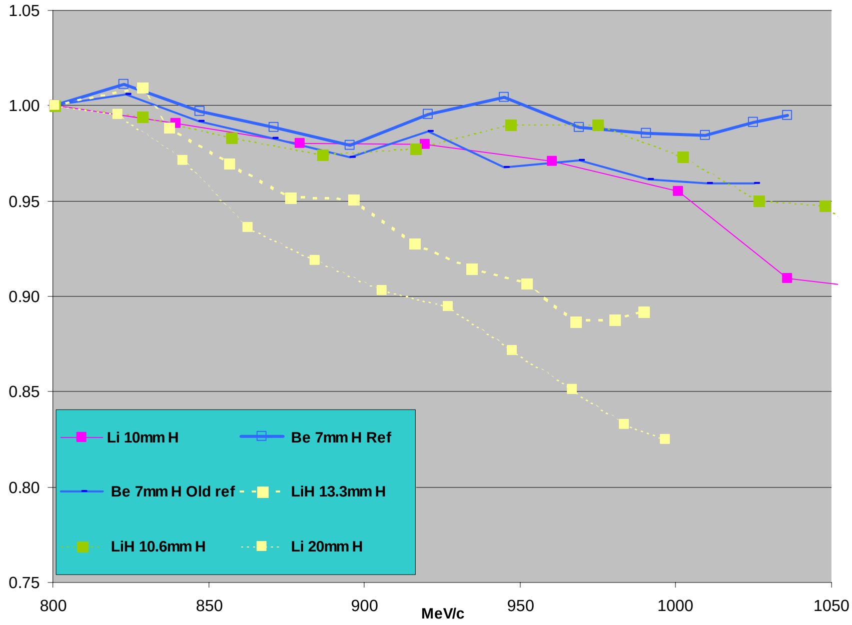
- 10 m mean radius, 16 periods, acceleration of muons from 0.3 - 1 GeV/c.
- With the nominal average RF gradient of 1 MV/m this is achieved in 11 revolutions. Transmission due to the finite muon lifetime is then 83%.
- Transverse acceptances of 10000-20000 π mm mrad allowing muon capture yields of $\cong$ 0.3 and $\cong$ 0.5, respectively.
- Peak RF voltage: 62.7 MV (i.e. 4.5 MV for each of the 14 cavities), corresponding to a maximum average gradient of 1 MV/m, harmonic number h=1. The effective average RF voltage gradient is 0.8 MV/m due to phase slip far above transition.

The lattice of this reference FFAG provides beta values of $\beta_{x,\,y}$ of 1.4, 1.7 m, respectively, in the centre of the straight sections, which is about 3-4 times too large for efficient cooling of the postulated initial emittances. Consequently the equilibrium emittances are larger by this factor and one can demonstrate a cooling effect only for still larger beams. In this study a thin annulus of 4000 π in each phase plane was injected, corresponding to 2000 π mm mrad rms physical emittance (15000 π normalised). Such an annulus is supposed to represent the muons with the largest emittances accepted at injection.

Due to their intrinsic non-linearity FFAG's are difficult to simulate with codes based on linear beam optics. In the ACCSIM code [2] used, the non-linear magnetic field of the FFAG was represented by a multipole expansion up to dekapole terms around a central radius, and approximated by thin lenses inserted at short interval into all magnets. This method approximates well the non-linear fields over about 0.5 m of radial range but does not reproduce the chromaticity zero of the scaling FFAG. This seriously limits the possible tracking range as integer stopbands would inevitably be crossed. For this reason, only the upper end of 0.8 – 1 GeV/c of the acceleration range could be simulated.

2 Simulation Results:

Two window thicknesses for both Li and LiH_2 were used in the simulation; the thicker ones being about equivalent in energy loss to the Be reference of Nufact'01. The cooling of the normalised rms emittances is represented in Fig. 1 for the simulated acceleration range from 800 to 1000 MeV/c..



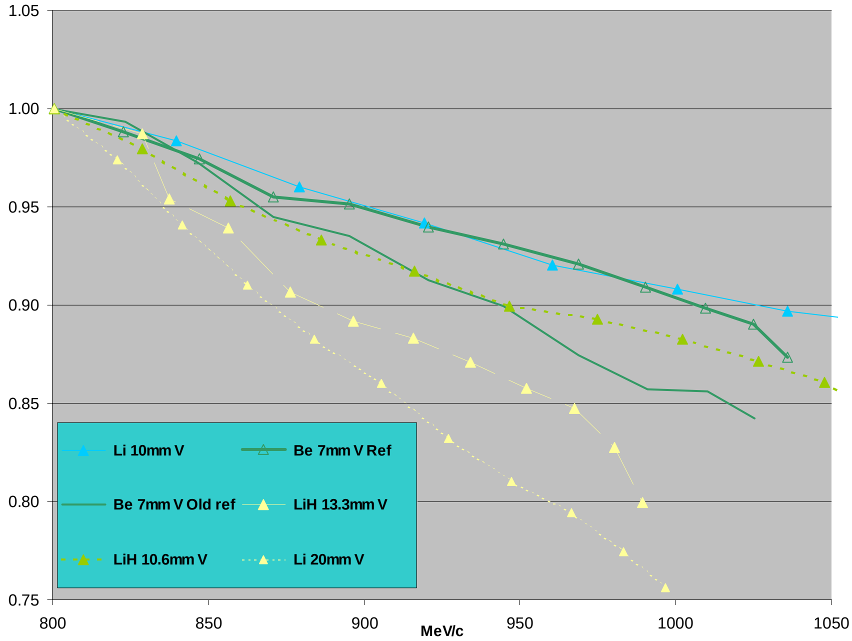


Fig. 1. Results of the tracking with ACCSIM [2] of initial annuli in phase space of 4000 π mm mrad, corresponding to an r.m.s. emittance of 2000 π mm mrad (physical) or 15000 π mm mrad (normalized). Show is the cooling factor of normalised rms emittances in the horizontal (top) and vertical (bottom) plane w.r.t. the initial value at 800 MeV/c.

Table 1 compiles some quantities of interest. Unfortunately, some modifications of the ACCSIM code have somewhat lowered the performance of the Be reference case since Nufact'01. We have thus to compare the gain by the above materials with the new reference results. The old (Nufact'01) Be Reference is also shown.

Table 1. Comparison of cooling performances of Be, Li, and LiH_2 windows

Material, Thickness	Energy Gain per turn (max.) MeV	Muon trans-mission	Cooling factor of rms normalised emittance		Figure of Merit: Muon transmission / Cooling	
			Horizontal	Vertical	Horizontal	Vertical
None	62.7	0.965	**1**	**1**	**0.965**	**0.965**
Be 7mm (old reference Nufact'01)	25	0.91	0.959	0.856	0.944	1.057
Be 7 mm (new reference)	25	0.91	0.985	0.909	0.928	1.006
LiH_2 13.3 mm	20	0.89	0.892	0.799	0.992	1.107
LiH_2 10.6 mm	30.3	0.93	0.974	0.883	0.65	1.048
Li 20 mm	21.4	0.89	**0.825**	**0.756**	**1.085**	**1.184**
Li 10 mm	40.6	0.95	0.95	0.91	0.991	1.042

3 Conclusions:

Not unexpectedly, the use of the lighter materials Li and LiH_2 for the RF cavity windows give better cooling results for comparable muon transmission than the usually proposed Be. If one considers the ratio transmission over cooling factor as a figure of merit, thicker windows perform significantly better. For the "best" case of 20 mm Li windows, the cooling factors around 0.8 achieved over the comparatively limited top energy range of acceleration suggest that *cooling factors of 0.5* could be reached over the full acceleration cycle. The cooling performance could be further improved by a lattice design featuring lower beta function waists in the centre of the straight sections.

References:

[1] H. Schönauer: Ionisation Cooling in FFAG Neutrino Factories, Proc. NuFac'01, May 2001, Tsukuba, Japan , to be published.

[2] F. W. Jones: Development of the ACCSIM Tracking and Simulation Code, Proc. 1997 Particle Accelerator Conference, Vancouver, 1997, p.2597.