Filter Momentum Cooling for the Recycler

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April 5, 1996

The Recycler lattice as currently envisioned does not have the high dispersion, low beta function location that would be needed for the Palmer cooling that was described in a previous note.[1] The purpose of this note is to investigate more fully whether filter cooling is a viable option.

DISADVANTAGES OF FILTER COOLING

The major disadvantage of filter cooling is expected to be the additional (undesired) phase shift that necessarily accompanies the creation of the 0 in the gain function. While the shape of the filter can be engineered, I have considered only the so-called correlator filter with the transfer function response:

$$T(\omega) = \frac{1 - e^{-i\omega T}}{2} \qquad [1]$$

This type of filter is used in both the Debuncher momentum cooling systems and the Accumulator Stack Tail System. It is relatively easy to construct and is a reasonable, though not unique, choice for this application.

I initially simulated a 4-8 GHz cooling system. Starting with an initial parabolic momentum distribution and a variable intensity, the system was allowed to cool for 4×10^4 sec. At the end of the amount of beam remaining, the antiproton loss rate, and the beam rms energy distribution were recorded. A typical simulation is shown in Fig. 1. An initial beam distribution of 4×10^{12} particles, relaxes to a central core with substantial tails and loss rates. In addition, a substantial fraction of the initial beam is lost.

[1] John Marriner, Main Injector Note #0167.

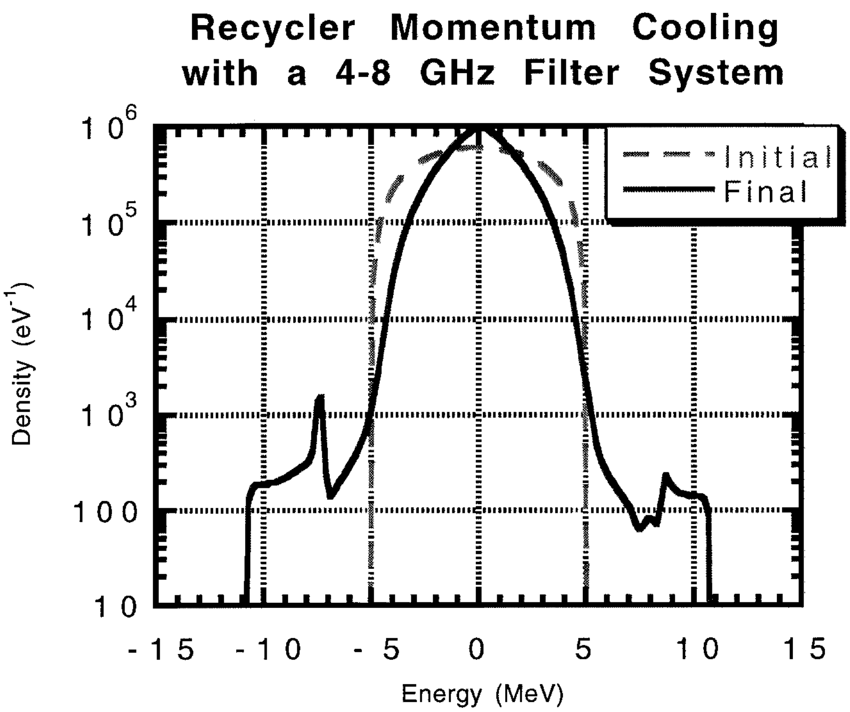

Figure 1. Initial momentum distribution and distribution obtained after cooling for about 11 hours with a 4-8 GHz momentum cooling system.

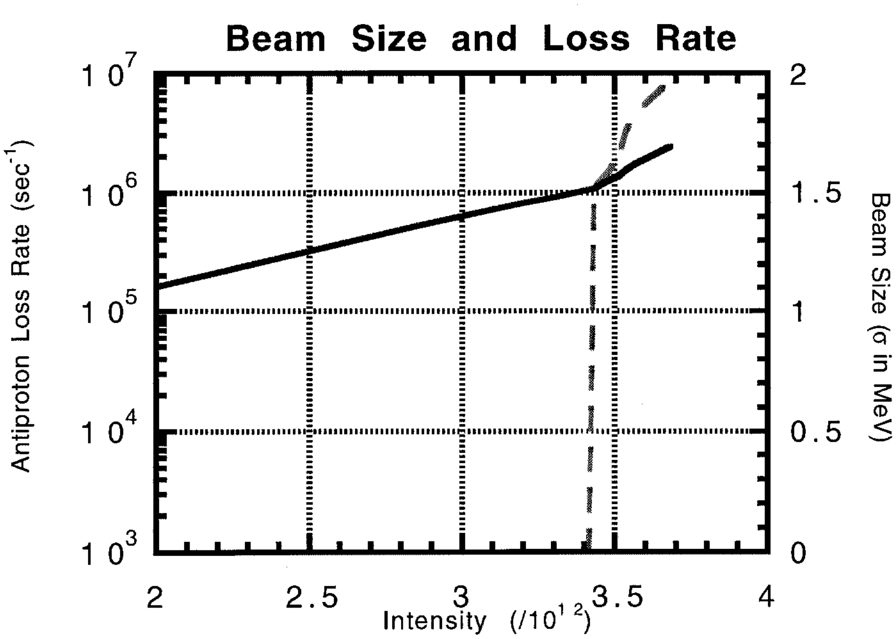

Figure 2. Beam size (σ) and loss rate for the 4-8 GHz filter momentum cooling system described in the text.

These effects are shown quantitatively in Figs. 2 and 3. Figure 2 shows the beam size (σ_E) and loss rate as a function of core intensity (the core is defined to be ±5 MeV wide). Clearly, there is a limit in the core intensity that can be achieved at about 3.4×10^{12} particles. Figure 3 shows the amount of beam that is captured into the core from the initial parabolic distribution. The fact that this fraction does not approach unity until the initial intensity is reduced to 2.0×10^{12} suggests that it will be difficult and probably impossible to inject and extract beams without significant losses.

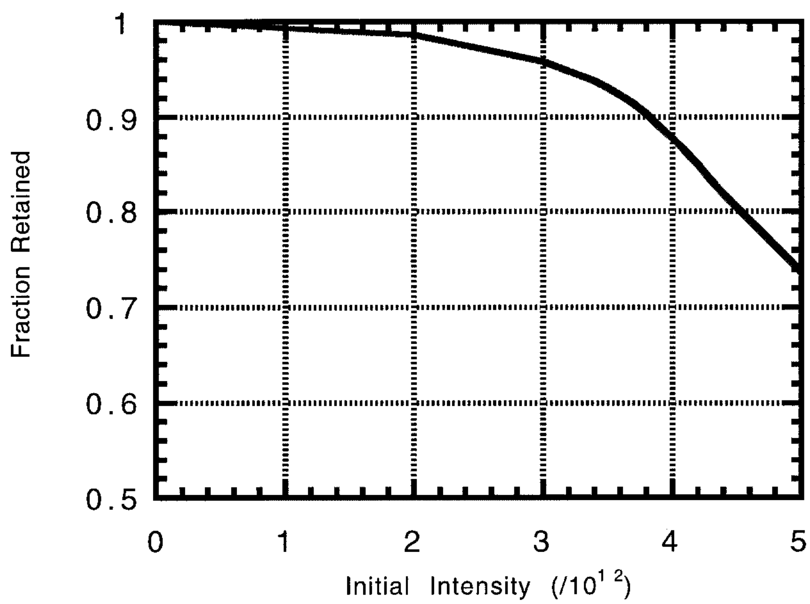

Figure 3. The fraction of beam a ±5 MeV beam that is retained with the 4-8 GHz filter momentum cooling system described in the text after cooling for about 11 hours.

ERROR ANALYSIS

The analysis presented thus far has been based on an "ideal" cooling system with a constant gain over an octave bandwidth. Such a cooling system can not be realized in practice (and in fact can not be realized even in principle because such a system violates causality).

A more detailed analysis than will be given here would be necessary to understand the errors that should be expected in this type of system. However, one can get a rough idea by assuming that the gain function is the same as a Q=1 resonator over the 4 to 8 GHz band, where the resonator is centered at 6 GHz. This model seems somewhat reasonable based on past experience. With this type of gain function the core intensity at which saturation occurs is about 2.0×10^{12}.

In the Accumulator the measured final density in the core was about 2/3 of the calculated value. This discrepancy can be attributed a larger than calculated intrabeam scattering constant. With the "D" coefficient in the Fokker-Planck equation doubled, the maximum intensity achieved before losses become significant is about 2.4×10^{12}.

However, probably the most dangerous type of error would affect system stability. The cooling system will become unstable if the real part of the system gain time the beam feedback exceeds unity. For the ideal systems simulated here, the gain is set so that the real part is equal to 0.7. A ripple in the gain of only 3 dB would cause an instability in the feedback and require the gain to be reduced. The most like source of such a gain ripple would be a cavity mode inside the pickup or kicker structure. However, gain ripple can also be a result of impedance mismatches from loose connectors, broken or poorly chosen components. As an example, it was assumed that the average gain had to be reduced to 10% of the stability limit. This large reduction in gain is perhaps a bit pessimistic, but it does correspond to the approximately 20 dB resonances that were observed in the Accumulator core betatron cooling systems before the microwave absorbers were installed. With the assumption of a gain limited to 10% of the stability limit beam loss started to occur at about 1.4×10^{12}.

The major conclusion concerning the 4-8 GHz filter cooling system is that it will not work at high intensity without excessive beam loss. The major problem is that intrabeam scattering forces the edge of the momentum distribution to lie where the real part of the gain function passes through zero. The performance of such a system would be sensitive to the types of errors that might be encountered and would deteriorate rapidly if the theoretically optimum performance were not achieved.

A 2-4 GHz Filter Cooling System Performance

Filter momentum cooling at lower frequencies such as 2-4 GHz is more viable. The maximum achievable cooling rate will be a factor of 2 smaller from the bandwidth and a factor of somewhat less than 2 from the mixing factor, but the longitudinal emittance of the beam will not suffer too much because of the strong dependence of intrabeam scattering on the momentum spread.

A 2-4 GHz momentum cooling system has been simulated, and was found (as expected) not to suffer from significantly from the beam loss problems found with the equivalent 4-8 GHz system. The final distribution obtained with an initial ±5 MeV parabolic beam distribution is shown in Fig 4. At the intensity level of 5×10^{12}, the tails of the distribution begin to show signs the beam loss mechanism that made the 4-8 GHz cooling system unattractive.

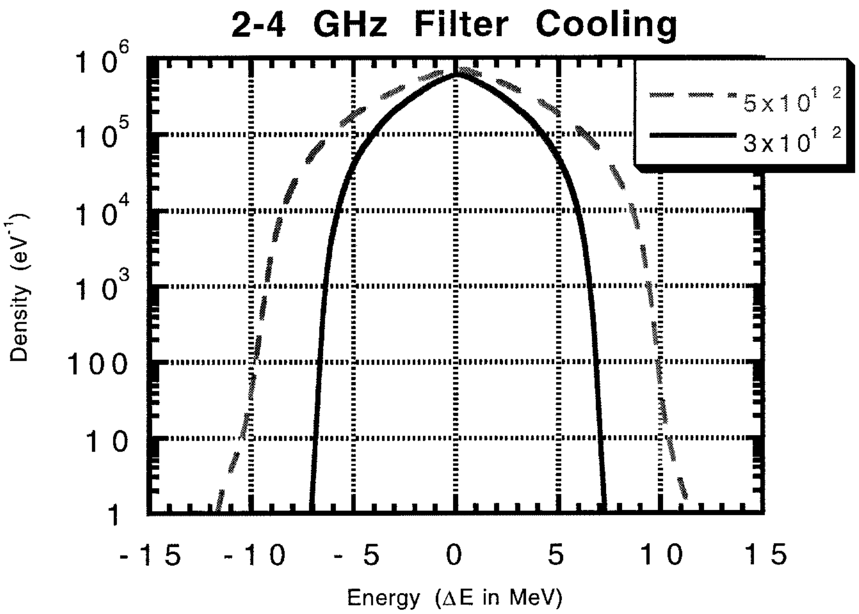

Figure 4. A simulation of Recycler momentum cooling using an ideal 2-4 GHz cooling system.

In order to get a better idea of the density of the beam, the data in Fig. 4 was integrated and plotted as a function of longitudinal emittance in Fig. 5. Most of the beam is contained within 100 eV-sec at a beam intensity of 3×10^{12}. For comparison, the performance of the 4-8 GHz cooling system described previously (see Ref. 1) is shown in Fig. 6.

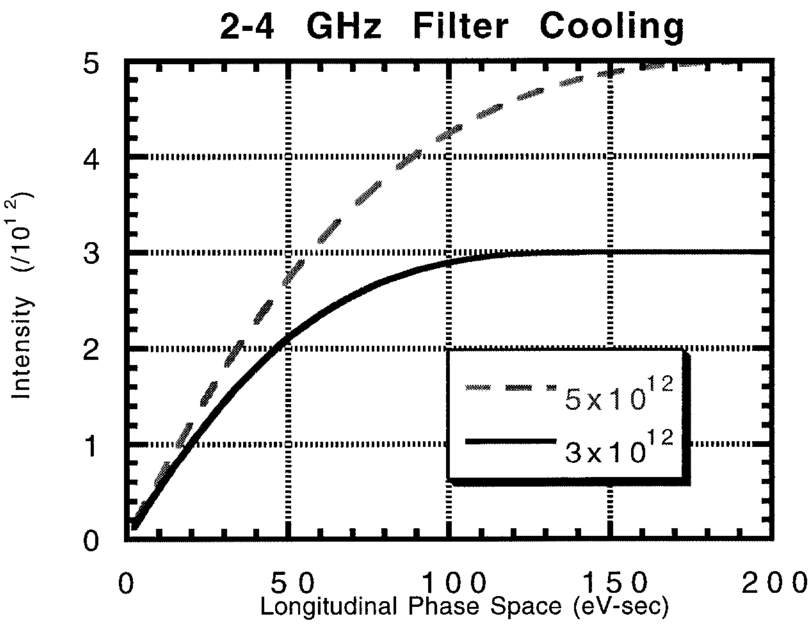

Figure 5. Beam Intensity enclosed as a function of longitudinal phase space area for the 2-4 GHz filter cooling system described in the text.

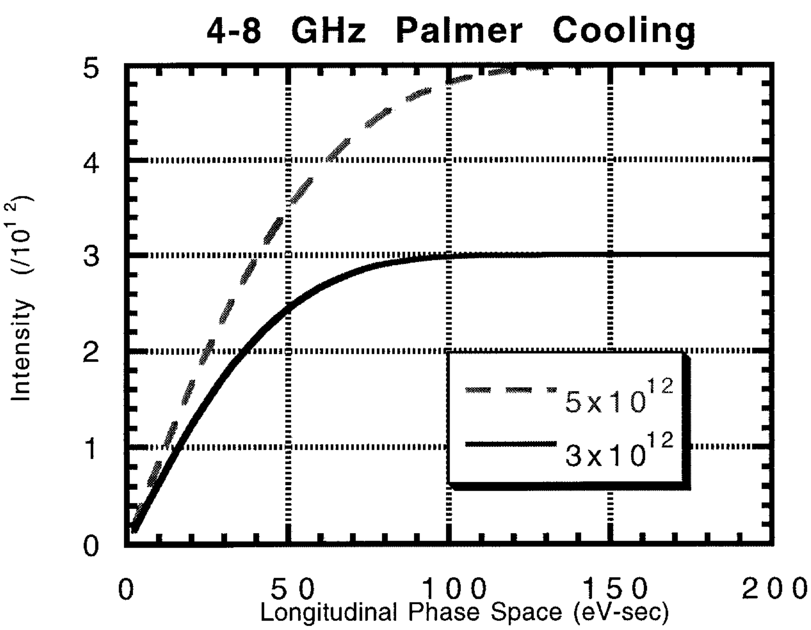

Figure 6. Beam Intensity enclosed as a function of longitudinal phase space area for the 2-4 GHz filter cooling system described in the text.

DETAILED DESIGN

The Recycler cooling system is straight-forward and conventional. The system parameters are given in Table I.

Table I. Momentum Stochastic Cooling System Parameters

No. of Pickups	32	
Pickup Impedance	50	Ω
Pickup Sensitivity	0.57	
Dispersion at PU	0	m
Pickup Gap	30	mm
Noise figure	2	dB
Minimum frequency	2	GHz
Maximum frequency	4	GHz
Maximum Beam	5×10^{12}	
Electronic Gain	100	dB
Filter Notch Depth	40	dB
Notch Dispersion	0	ppm
No. of Kickers	32	
Kicker Impedance	50	Ω
Kicker Sensitivity	0.57	
Dispersion at Kicker	0	m
Schottky Power	10	W
Amplifier Power	0	W
Total Power	10	W

COMPARISON OF 2-4 GHZ FILTER COOLING WITH 4-8 GHZ PALMER COOLING.

A comparison of Figs. 5 and 6 indicates an advantage in final density of perhaps 25% (depending on what scenario is considered) for the higher bandwidth system. Both systems were assumed to operate near their theoretical limits. The "as-built" performance will not be as good as illustrated, but it is expected that the actual performance will not be too far from the theoretical limits.

The Palmer system has a better stability margin than the filter cooling because of the suppression of the beam signal by the zero in the pickup response. In the simulation, the filter cooling was assumed to run within 3 dB of instability, a result that may be difficult to achieve in practice. Furthermore, the filter cooling system might have a problem with stability when stacking antiprotons from the Accumulator is considered. This particular aspect would have to be considered more carefully if filter cooling were to be chosen for the Recycler.

Finally, as pointed out in a previous note (Ref. 1), there is substantial flexibility in how the cooling system is phased in a Palmer cooling system. An example was given where cooling was achieved over a momentum spread of ±30

MeV. As far as I know, there is no equivalent technique that would be useful in a filter cooling system.

While all the advantages of the Palmer system described are substantial, they do not appear to me to be overwhelming. Pending a more detailed study of the stacking process, it would appear that a 2-4 GHz momentum filter cooling system is a viable choice for the Recycler.