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Accelerator & Fusion Research Division

Presented at the XIV International Conference on High Energy Accelerators, Tsukuba, Japan, August 22–26, 1989

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August 1989

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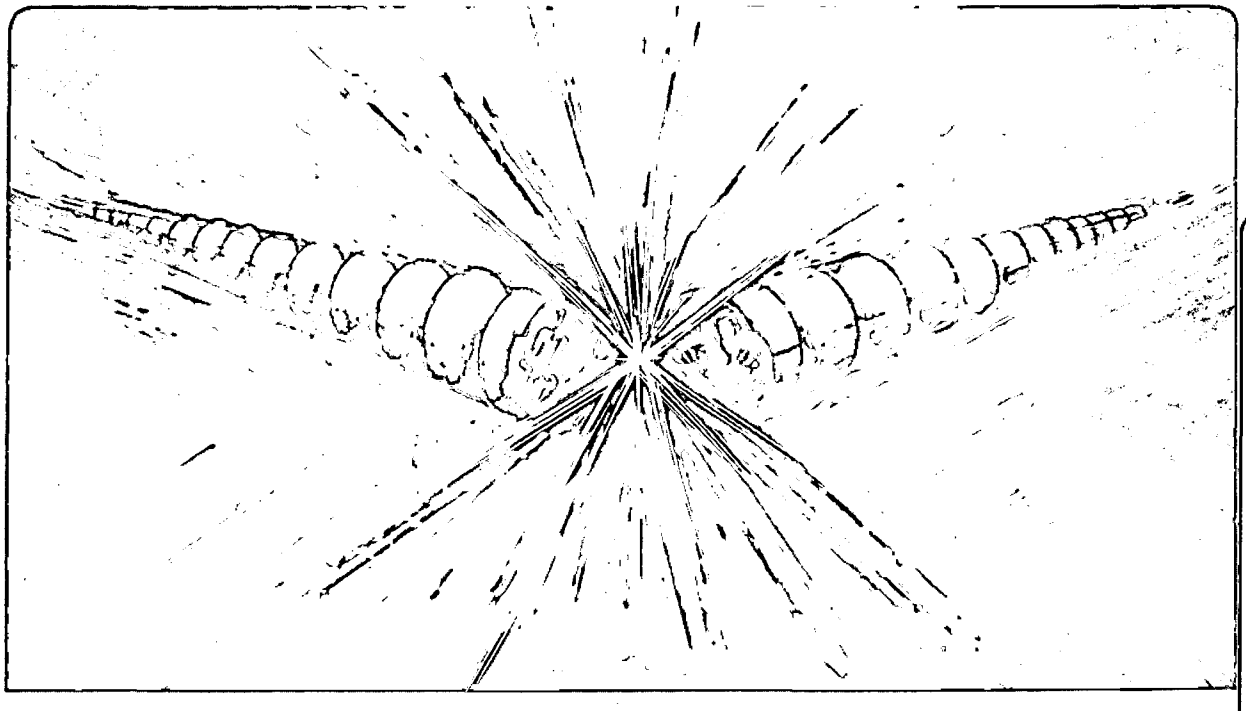

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IMPROVING THE PERFORMANCE OF POWER-LIMITED TRANSVERSE STOCHASTIC COOLING SYSTEMS*

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We present the formulas relevant to the behavior of (transverse) stochastic cooling systems which operate under the the not uncommon condition that performance is limited by available output power, and contrast the operation of such systems with non-power-limited ones. In particular, we show that for power-limited systems, the two most effective improvements are the use of pickups/kickers which operate in both planes simultaneously[1] and/or plunging of the cooling system electrodes, and present an example where increasing bandwidth is counter-productive. We apply our results to the proposed upgrade of the Fermilab $\bar{p}$ source.

INTRODUCTION

Conventional analyses of stochastic cooling systems assume that performance is not limited by available electronic gain, and that the latter quantity can be set to maximize the cooling rate. Under these conditions, one can expect an improvement of as much as a factor of 4 in the cooling time by doubling the midband operating frequency of the cooling system. In practical systems, cost-induced limitations on the maximum available output power may restrict the maximum attainable gain to be less that its optimal value; such is the case in the anti-proton sources at both CERN and Fermilab. We show that the criteria that one would employ in upgrading such power-limited systems (we limit our treatment throughout to the case of systems which cool the transverse phase space of the beam) are rather different from those for systems for which one can optimize the gain; in particular, the maximum expected improvement resulting from doubling the operating frequency of such a power-limited system is less than a factor of 2. We apply our results to the specific case of improving the performance of the Fermilab debuncher ring.

FORMULARY FOR POWER-LIMITED SYSTEMS

The cooling rate of a stochastic cooling system is given by[2]

$$\frac{1}{\tau} = \frac{W}{N}\left[2g - g^2(M+U)\right] \qquad (1)$$

where W is the signal bandwidth of the cooling system, M is the so-called mixing factor, U is the noise-to-signal ratio, and g is usually referred to as the system gain; in a transverse cooling system, it represents the fraction of the beam-sample centroid error corrected in a single pass through the pickup and kicker. For *non*-power-limited systems, one minimizes τ by setting $g = 1/(M+U) \equiv g_{opt}$, its optimum value, thereby yielding the familiar result

$$\frac{1}{\tau_{opt}} = \frac{W}{N(M+U)} \qquad (2)$$

* Work supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. D.O.E., under Contract No. DE-AC03-76SF00098.

We now consider the results for power-*limited* systems.[a] If we define g_{lim} as the maximum available (i.e. power-limited) gain, we can write

$$\frac{1}{\tau_{lim}} = \frac{1}{\tau_p}\left[2 - \frac{g_{im}}{g_{opt}}\right] \tag{3}$$

where, for analyzing power-limited systems, it is convenient to introduce the quantity

$$\frac{1}{\tau_p} \equiv \frac{1}{\tau_{opt}}\,\frac{g_{im}}{g_{opt}} \tag{4}$$

The quantity τ_p^{-1} is given by

$$\frac{1}{\tau_p} = \frac{e\,c\,f_o\,\overline{\beta}\,\alpha\,n_L\,(Z'_L)^2}{\sqrt{2}\,\pi E/e\;f_B\,Z_c}\sqrt{\frac{P_{out}\,W}{(1+\frac{1}{U})\;k(T_R+T_A)}} \tag{5}$$

where

- N = total number of particles
- e = proton charge
- f_o = particle revolution frequency
- f_B = mid-band beam (signal) frequency
- E = total proton energy (rest + kinetic)
- c = velocity of light
- $\overline{\beta}$ = (geometric) mean of beta functions at pickup and kicker
- n_L = number of kicker/pickup loop pairs
- Z_L' = single loop-pair (transverse) transfer impedance
- K_L = single loop-pair (transverse) kicker constant $= cZ_L'/\pi f_B Z_C$
- Z_C = characteristic impedance of external signal lines
- α = voltage attenuation in the pickup and kicker circuitry located between the electrodes and the amplifier circuits

Calculating τ_{opt} from Eq. 2, one can now use Eq. 4 to obtain

$$\frac{g_{im}}{g_{opt}} = \frac{\tau_{opt}}{\tau_p} \tag{6}$$

Finally, to evaluate the ability of a system to cool a beam from an initial emittance ε_i to a final emittance ε_f, one substitutes Eqs. 5 and 6 into Eq. 3, and integrates to obtain the total cooling time T_{tot}.

$$T_{tot} = -\int_{\varepsilon_i}^{\varepsilon_f} \frac{\tau(\varepsilon)\,d\varepsilon}{\varepsilon} \tag{7}$$

GENERAL CONCLUSIONS

We begin by reviewing the situation for systems which are *not* power limited. Let us assume for definiteness that we have a cooling system which operates over a one-octave frequency range. Eq. 2 shows that doubling the mid-band frequency doubles the cooling rate by doubling W. If the system is *mixing*-limited, an additional factor of two results from halving M. A similar additional factor of 2 is usually obtained for *noise-limited* systems as well: Under the combined assumptions that the length of individual pickup elements is proportional to the operating frequency, that it is possible to preserve the same pickup

[a]For a derivation of the formulas, the reader is referred to Reference 3.

impedance for the higher frequency electrodes, and that the total space available for electrodes remains unchanged, doubling the operating frequency permits a doubling of the number of electrodes, and hence a halving of U and a doubling of the cooling rate. In practice, this gain is partially offset by the increases in the preamplifier noise temperature and external circuit attenuation which accompany an increase in operating frequency. Hence overall, the cooling rate increases proportional to something between the first and second power of f_B.

Let us now consider the power-limited system. From Eq. 3, we see that the quantity which best characterizes the performance of such a system is τ_p, which is defined by Eq. 4. For $g_{lim}/g_{opt} << 1$, the power-limited cooling rate τ_{lim}^{-1} is simply given by $2\cdot\tau_p^{-1}$; as the beam cools, the gain ratio approaches unity, and the cooling rate falls by a factor of 2 to τ_p^{-1}, while at the same time τ_{opt} approaches τ_p. As the ratio exceeds unity, the system is of course no longer power limited, and the maximum cooling rate is determined by τ_{opt} from Eq. 2. The situation is illustrated in Fig. 1, where we have replaced τ_{lim} by τ_{opt} in the region where the gain ratio would exceed unity.

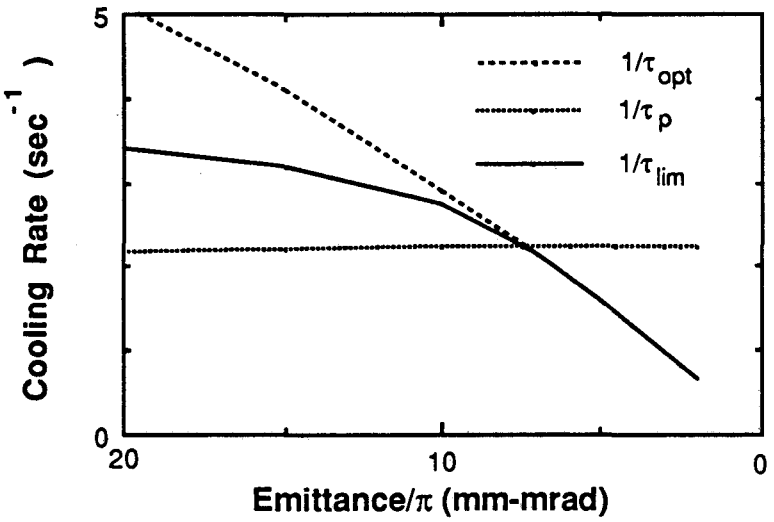

FIGURE 1 Transition from power-limited to *non*-power-limited operation as beam is cooled

Using τ_p^{-1} as our basic figure of merit, we see from Eq. 5 that most, if not all, the advantage in going to higher frequency is lost when the system is power-limited. The doubling of n_L made possible by the reduced electrode length is offset by the factor of f_B in the denominator, which arises from the 1/f dependence of the kicker constant (this is based on the reasonable assumption that it is the transfer impedance, rather than the kicker constant, which one can preserve when raising the frequency). Also, because g_{lim} decreases as $W^{-1/2}$ due to the increased noise bandwidth at higher frequency, the explicit W-dependence of τ_p^{-1} is as the one-half power, rather than the usual linear one. Moreover, this improvement is likely to be at least partly offset (possibly even *more than offset)* by increases in attenuation and amplifier noise which usually characterize a frequency increase.

As shown in Fig. 1, cooling of the beam may cause the system's operating range to span both the power-limited and noise-limited regimes. As might be surmised, (and as is shown explicitly in Ref. 3), such a system exhibits a greater than $\sqrt{2}$ improvement with a doubling of the operating frequency even prior to emerging from its power-limited condition.

An additional distinction between power-limited and non-power-limited systems concerns their scaling with beam aperture. Assuming that the pickup impedance Z_L' scales as the reciprocal of the gap width, it is straightforward to show that for the latter type of system, the time to cool to a given *fraction* of the initial emittance is independent of the initial gap. However, as shown in Ref. 3, for a power-limited system, that time *increases* as the gap increases.

To improve the performance of power-limited systems, in most cases one must either increase the available amplifier power, decrease the input noise power, increase the number of arrays (presumably by managing to increase the longitudinal density of the pickups, by means *other than* raising the frequency), or increase the detector impedance. The first two of these are being undertaken by Fermilab; we have recently managed to achieve the third as the serendipitous outcome of an effort to design a higher frequency pickup[1]; the fourth is a goal which has been pursued for non-power-limited systems as well, more or less continually, and a significant step toward it has been made by CERN in employing electrodes which follow the decreasing beam size (plunging). Clearly, the latter two schemes will improve the performance of *non*-power-limited (albeit noise-limited) systems as well.

Finally, we note a "moral" to be learned from Eq. 5. Let us consider a power-limited system, constrained within a fixed space and power budget, which we attempt to "improve" by increasing its bandwidth W as follows: We replace it with m subsystems, each of bandwidth W (but all at different frequencies), each operating at 1/m the power, and each with 1/m electrodes. From Eq. 5 we see that the cooling rate for each subsystem will be reduced by $m^{-1.5}$, and consequently the rate for the m systems in tandem will be *reduced* by $m^{-0.5}$. What should have been an improvement (according to the simple Eq. 2) has actually made things worse!

APPLICATION TO THE FERMILAB DEBUNCHER UPGRADE

We now consider how the above results apply to the proposed upgrade of the Fermilab debuncher ring. The present debuncher is required to cool a beam of 10^7 particles from an rms emittance of $20\pi/3$ to $7\pi/3$, in a cycling time of two seconds. The goal for the long-term improvement is to be able to cool a beam of from 4-to-16 $\times$ 10^7 particles from $30\pi/3$ to $7\pi/3$[b] in a cycling time of 1.5 sec.

Our calculations include the effects of two improvements in the existing electronics which are currently being undertaken to ameliorate the severely power-limited condition of the present system but which, by themselves, will not suffice to meet the above goals. The first is a straightforward increase in the maximum power available by doubling the number of output TWT's in the transverse cooling system. The second is the introduction of a notch filter in the low-level electronics to suppress the noise signal *in between* the betatron sidebands. The effect of this filter is ideally to reduce the noise bandwidth in the expression for g_{lim} by a factor of 2; our calculations assume such ideal performance. Note that because the filter supresses the noise only at frequencies at which the noise does *not* heat the beam, it leaves the value of U unaffected (however, the signal power term in Eq. 5 must now be changed from 1/U to 2/U).

We consider four basic cooling systems: a 2-4 GHz system using the present set of electrodes but with upgraded electronics referred to above, a similarly upgraded 2-4 GHz system using the new type of bi-planar[c] detector[1] (effectively twice the number of detectors in the present system), a 4-8 GHz system employing more or less conventional striplines (again, twice the number of detectors in the present system) which, to distinguish it from the bi-planar system, we shall refer to as "uni-planar"[d], and a 4-8 GHz system with a bi-planar detector (with four times the number of detectors in the present system).[e]

For reasons which will become apparent, we consider both 4-8 GHz systems at maximum power levels of 2.5 kW (the same output power capablity as the 2-4 GHz system)

[b]An alternate specification is $30\pi/3$ to $3\pi/3$; the ramifications of this alternative are discussed below.

[c]i.e., a detector capable of separately sensing motion in both transverse planes simultaneously.

[d]The $\bar{p}$ source group at Fermilab has recently developed a design for a 4-8 GHz detector[4], employing striplines arranged in two parallel arrays in order to achieve adequate lateral coverage of the beam, which possibly can also be used as a bi-planar detector, although its performance appears inferior to the corner detector of Ref. 1. We have adopted the "uni-planar"/"bi-planar" designations as a way of avoiding the separate issue of which design makes for a superior bi-planar detector.

[e]Our initial models of the bi-planar corner detector indicate that the longitudinal loop separation can be reduced to the point that the longitudinal loop density can be increased by possibly as much as 40%; however to keep our estimates conservative, we have neglected this factor in our calculations.

and 5 kW; the effects of the notch filter are included for all systems. We consider each system at intensities of N = 4, 8, and 16 x10^7. The remaining system parameters used in our calculations are listed in Table I.

We made two sets of calculations, one for fixed electrodes and one for so-called plunged electrodes, where the electrodes are moved inward to follow the envelope of the beam as the beam cools. For these calculations, we made the conservative assumption that the pickup impedance increased as the reciprocal of the electrode gap.

TABLE I Assumed Parameters for Various Choices of Electrodes

System Parameter	Upgraded 2-4 GHz	Bi-Planar 2-4 GHz	Uni-Planar 4-8 GHz	Bi-Planar 4-8 GHz
f_B (GHz)	3	3	6	6
W (GHz)	2	2	4	4
$T_R + T_A$ (°K)	140	140	180	180
α, α_p	0.64	0.64	0.5	0.5
M	10	10	5	5
Electronic Gain* (dB)	151	151	147	147
n_L	128	256	256	512

*Gain figures for 4-8 GHz are for P_{out} = 2.5 kW (per plane); for 5 kW system, values are 3 dB greater

Parameters in common :

Z_L' = 16.3 Ω/cm E/e = 8.938 GV (K.E. = 8 GeV)
Z_C = 50 Ω f_0 = .590 MHz
β = 10 m

A summary of the results of the calculations is presented in Table II; for all of the cooling scenarios we list the cooling times from an initial (full) emittance of 30π to several final emittances, including the present goal of 7π (underscored for ease of identification), and a value as low as 3π (to illustrate the effects of such small emittances). Bold-face entries are used to show the points at which the cooling system is no longer power-limited. More detailed results, showing all of the calculated quantities at a number of intermediate emittances, are presented in Ref. 3. Because the 2.5 kW 4-8 GHz systems remain power-limited down to nearly the smallest emittance, we felt it reasonable to calculate the effect on their performance of an additional doubling of the output power to 5 kW.

As anticipated, the bi-planar 4-8 GHz system outperforms the uni-planar system by roughly a factor of two throughout, by virtue of having twice as many electrodes (which, as noted above, doubles its performance in both the power-limited and non-power limited regimes). What is perhaps more surprising, is that for all but the highest intensity and lowest emittances (i.e.those smaller than presently required), not only does this advantage enable the *2-4 GHz* bi-planar system to perform adequately to meet system requirements, but actually to yield cooling times comparable to those obtained with a 4-8 GHz uni-planar system having the same total output power!

We also note that, as expected, for the 4-8 GHz system doubling the available output power is less efficacious than either bi-planarity or plunging, and its efficacy decreases in precisely those regimes, i.e. high intensity and low emittance, where the demands on the cooling system are greatest. Furthermore, it would be of even less benefit at 2-4 GHz, where (as one can see from the table) one is less severely power-limited.

In conclusion, bi-planarity and plunging offer comparable improvements in perform-

TABLE II Cooling Times for Uni- and Bi-Planar Arrays

		2 to 4 GHz				4 to 8 GHz							
		2.5 kW				2.5 kW				5 kW			
No. of Envelope		Fixed		Plunged		Fixed		Plunged		Fixed		Plunged	
Part.	Emittance	Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi
4×10^7	30π	----	----	----	----	----	----	----	----	----	----	----	----
	15π	0.83	0.47	0.62	0.37	0.72	0.39	0.53	0.29	0.53	0.28	0.39	0.21
	7π	1.75	0.99	1.01	0.64	1.37	0.72	0.77	0.42	1.03	0.55	0.57	0.32
	4π	2.86	1.61	1.29	0.84	1.93	1.01	0.88	0.49	1.50	0.79	0.67	0.38
	3π	3.68	2.05	1.43	0.94	2.27	1.19	0.93	0.52	1.82	0.96	0.72	0.42
8×10^7	30π	----	----	----	----	----	----	----	----	----	----	----	----
	15π	0.93	0.59	0.74	0.51	0.77	0.43	0.58	0.34	0.57	0.32	0.43	0.25
	7π	1.98	1.26	1.28	0.94	1.45	0.80	0.85	0.50	1.09	0.61	0.64	0.39
	4π	3.21	1.99	1.67	1.25	2.02	1.11	0.98	0.59	1.59	0.88	0.77	0.48
	3π	4.09	2.49	1.87	1.41	2.38	1.30	1.04	0.64	1.93	1.07	0.83	0.53
1.6×10^8	30π	----	----	----	----	----	----	----	----	----	----	----	----
	15π	1.19	0.92	1.03	0.86	0.87	0.52	0.67	0.42	0.65	0.40	0.50	0.33
	7π	2.53	1.91	1.88	1.60	1.60	0.94	1.00	0.65	1.22	0.74	0.78	0.53
	4π	3.99	2.86	2.51	2.14	2.21	1.29	1.18	0.80	1.77	1.06	0.96	0.68
	3π	4.98	3.48	2.83	2.42	2.59	1.51	1.27	0.87	2.14	1.28	1.06	0.76

ance, and for power-limited situations, such as that which exists at the Fermilab debuncher ring, offer performance improvements greater than those resulting from an increase in operating frequency. Moreover, the first two approaches permit one to utilize the electronics associated with the existing cooling system, thereby giving them a decided advantage in both time and cost. (As of this writing, based on the above analysis, the Fermilab beam-cooling group has decided to abandon any 4-8 GHz scenario for upgrading the debuncher.) If one can arrive at a bi-planar electrode design which admits of plunging, it would seem to be worthwhile to implement it. Otherwise, it is not clear that the mechanical complexity and expense involved in a plunged system is warranted.

ACKNOWLEDGEMENTS

In writing this paper, we have benefitted from discussions with the $\overline{p}$ source group at Fermilab. We are particularly indebted to John Marriner (who originally brought this problem to our attention) for his ready availability to answer questions about the operation of the Fermilab $\overline{p}$ source.

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