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STOCHASTIC STACKING WITHOUT FILTERS*

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ABSTRACT

The rate of accumulation of antiprotons is a critical factor in the design of $p\bar{p}$ colliders. A design of a system to accumulate higher $\bar{p}$ fluxes is presented here which is an alternative to the schemes used at the CERN AA and in the Fermilab Tevatron I design. Contrary to these stacking schemes, which use a system of notch filters to protect the dense core of antiprotons from the high power of the stack tail stochastic cooling, an eddy current shutter is used to protect the core in the region of the stack tail cooling kicker. Without filters one can have larger cooling bandwidths, better mixing for stochastic coling, and easier operational criteria for the power amplifiers. In the case considered here a flux of 1.4×10^8 per sec is achieved with a 4-8 GHz bandwidth.

Introduction

The fast accumulation of dense antiproton beams is the most critical aspect of $\bar{p}p$ colliders now being developed at Fermilab and CERN[1,2]. And even in proposed colliders with high-energy cooling and very long beam lifetimes, a plentiful supply of $\bar{p}$'s will be needed to replace those lost in high luminosity collision regions.

The principles of "stochastic stacking" have been developed by van der Meer[3] and demonstrated at the CERN Antiproton Accumulator[4] (AA). This technique involves a system of high frequency beam pickups, amplifiers, filters, and kickers which merge newly injected $\bar{p}$'s into the stack of circulating $\bar{p}$'s. The increase in density from the injection orbit to the dense core of the stack is achieved by having the gain of the stochastic cooling system decrease (exponentially with momentum) in inverse proportion to the desired density profile. The gain as a function of momentum is primarily determined by the radial position sensitivity of the stochastic cooling pickups which are placed in a dispersive region. A series of notch filters is used to protect the dense part of the stack from the broadband thermal noise generated by the pickup terminations and preamps. Without these filters it would be impossible to maintain a high density stack core at the same time that the gain in the low density tail of the stack were high enough to merge newly injected $\bar{p}$'s at an acceptable rate.

The need for the filters can be seen as follows: the gain profile across the stack which is determined by the pickup sensitivity provides the coherent or cooling force. The dissipative forces come from thermal amplifier noise and Schottky noise from the particles in the stack and are proportional to the gain squared. Thus, at some point in the exponentially decreasing gain profile the thermal noise power overwhelms the coherent power (because the particles are too far from the pickup electrodes) and the stack core density is limited. What is done in the CERN AA is to separate the stochastic momentum cooling into two systems. One which has a low gain appropriate to the high density core and another with the high gain needed to manipulate the newly injected $\bar{p}$'s at the low density part of the stack. This high gain system has 5 notch filters which prohibit power from being transmitted at the harmonics of the revolution frequencies of the dense core.

The major difficulty with the system outlined above is that the filters are difficult to build, especially at higher frequencies where stochastic cooling is more effective. Futhermore, the use of filters implies limitations on the useful power of the amplifiers due to intermodulation distortions.

What is proposed here is a stochastic stacking technique with no filters. Instead, the stack is cooled in two separate stages each of which corresponds to a longitudinal density increase of about 10^2, instead of the 10^5 in the filtered system. Ideally the two stages would take place in two separate storage rings. However, for economy, in the prototype design presented here both stages take place in a storage ring of $\Delta p/p=3\%$ with the two stacks separated by simple shutters in the regions of interference.

The place of maximum interference is at the kicker of the high gain system. There the high power of the first system which quickly merges the newly injected $\bar{p}$'s would cause the high density core of system 2 to diffuse away. In this case, instead of filters as used at the AA, a shutter is used to protect the core.

Model and Calculation

Figure 1a and 1b show the machine apertures and electrodes at the pickup and kicker. Since shutters are used, both pickups and kickers must be at a region of high momentum dispersion. Gain shaping is accomplished by the geometry and delay of the pickup electrodes. The kicker electrodes are excited in parallel such that there is no dependence of the longitudinal kick on radial position (to preclude any unwanted betatron heating).

Figure 1c shows the density profiles for the two systems as a function of time. After an initial fill of 240 pulses (2×10^8 $\bar{p}$/pulse, 1 pulse/sec) into system 1, the shutter is opened, the dense part of the stack of system 1 is rf captured and moved to the low density tail of system 2 and deposited. Subsequent transfers take place every 2 minutes (1.8×10^{10} $\bar{p}$'s). In 8 hours, 4.1×10^{12} $\bar{p}$'s are accumulated (averaging $\sim1.4\times10^8$ $\bar{p}$'s/second). This is roughly the number of $\bar{p}$'s needed for 20 fills of the Tevatron each for a peak luminosity of 10^{30} cm^{-2} sec^{-1}.

SHUTTERED COOLING SYSTEM - APERATURE UTILIZATION

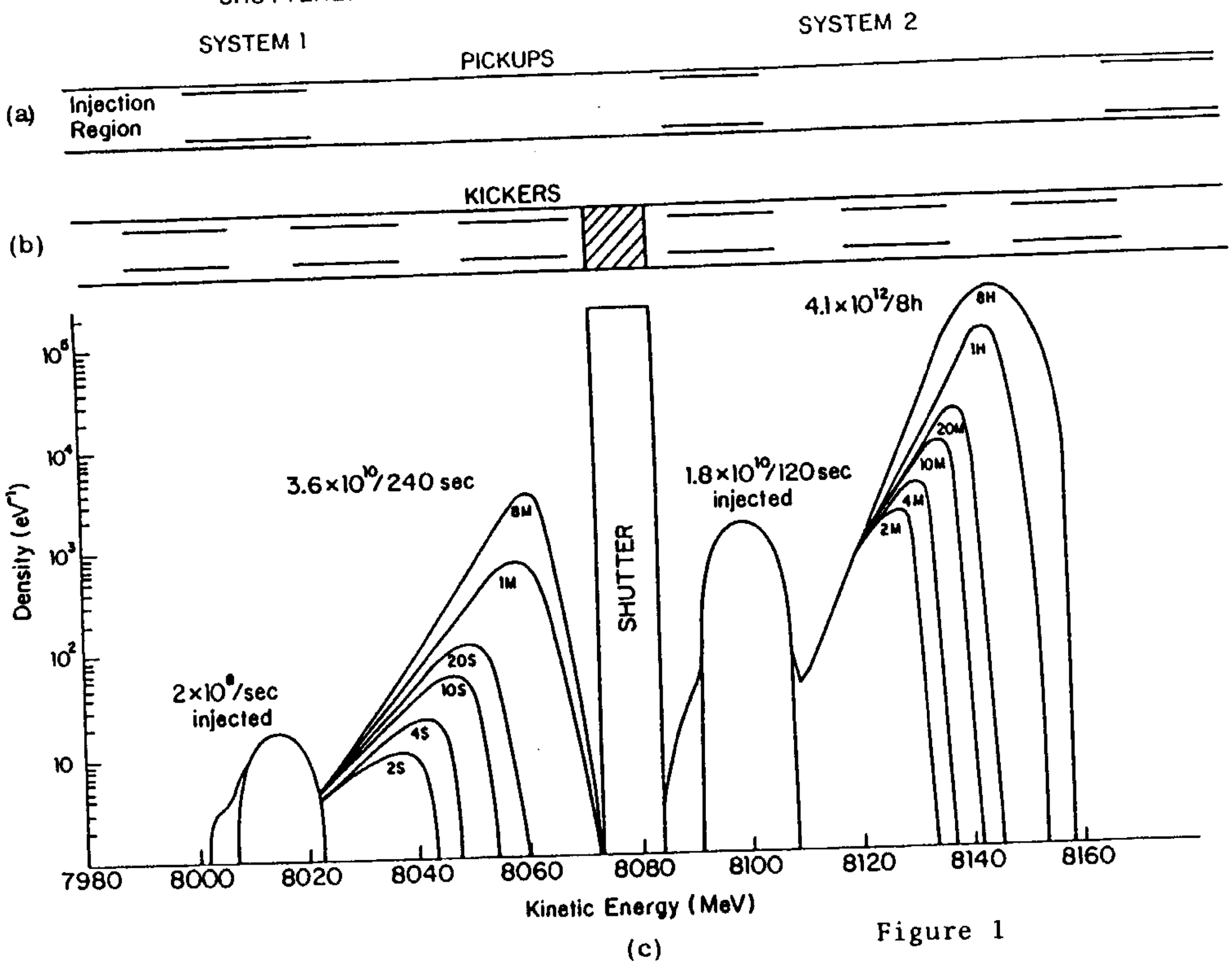


Figure 1

Table I shows the parameters of the two stochastic cooling systems. The performance figures are not yet optimized and are to be considered as an existence proof. The calculational model is based on a computer code developed by Simon van der Meer which has been modified to include discrete injections of $\bar{p}$'s by means of rf deposit.

Table I

	Case I	Case II	Case III
W (GHz)	4-8	2-4	2-8
M	0.5	0.33	0.33
η	0.004	0.021	0.008
System I			
Gain	3.25×10^{6}	4×10^{6}	4×10^{6}
$\bar{p}$ injected	$2\times10^{8}/1$ s	$1.5\times10^{8}/0.5$ s	$1.5\times10^{8}/0.5$ s
$\bar{p}$ stacked	$3.6\times10^{10}/240$s (1.5×10^{8}/s)	$1.9\times10^{10}/240$s ($.8\times10^{8}$/s)	$5.0\times10^{10}/240$s (2.1×10^{8}/s)
Initial fill time	240s	240s	240s
Refill Time	120s	120s	120s
Noise Temperature	150°K	150°K	150°K
Number of Pickups	160	160	160
P_{max}	1118W	1054W	1853W
System II			
Gain	1.75×10^{4}		
$\bar{p}$ injected	$1.8\times10^{10}/120$s		
$\bar{p}$ stacked	$4.1\times10^{12}/8$h		
stacking rate	1.4×10^{8}/s		

In general the shuttered cooling system is simpler than the AA scheme and analytic solutions are in principle possible. However, the beam feedback effects can be large. In fact one can see that by adjusting delays and pickup positions, the beam feedback effect can be used to shape the gain function. For example, the density profile of system 1 can be made more or less peaked by this technique.

While the shutters are a complication to the stochastic stacking process, there are some features which make them easier. By placing the kickers downstream of the pickups by an odd multiple of 180° in horizontal betatron phase advance one can have simultaneous radial cooling with the momentum cooling[5]. Exact rates depend on lattice functions but one can expect at least an order of magnitude decrease in betatron amplitude by the time the $\bar{p}$'s migrate from the injection orbit to the core of system 1. This allows the spacing between systems to be smaller than if allowance had to be made for large betatron oscillations. (By operating on a betatron coupling resonance there is the possibility of simultaneous cooling in all three planes with only one cooling system!).

The shutters open only once every 2 minutes (as opposed to every 2.4 sec. at the AA). Even though the shutters can be thin they must provide $\sim$40 dB of isolation of the dense core of system 2 from the kickers of system 1 and will probably require physical contact using flexible metallic fingers.

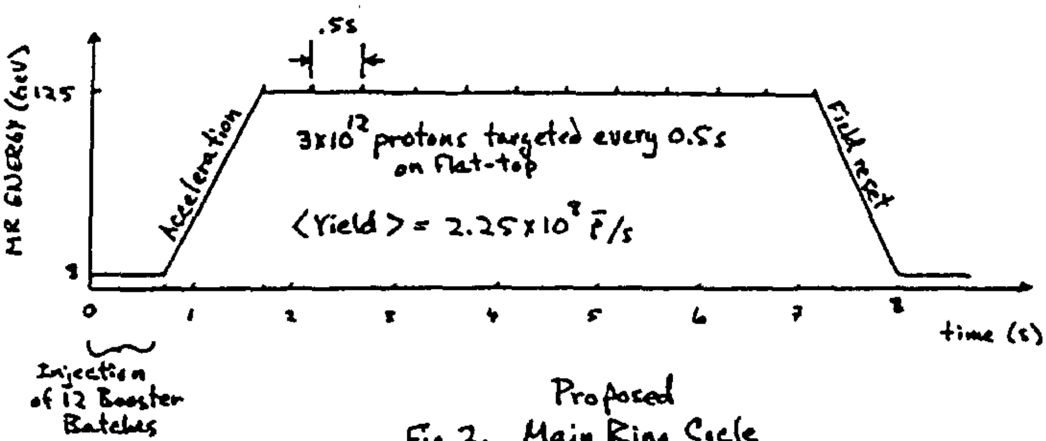
The effectiveness of the stochastic cooling system described here is due in large part to the large bandwidth (4-8 GHz) assumed in the model. That the pickup and kicker vacuum chambers are small enough in cross section that unwanted rf modes can't propagate depends on details of the lattice and the emittance of the injected pulse of $\bar{p}$'s. Closed orbit errors can be ignored in specifying vacuum chamber dimensions if steering dipoles are placed at both ends of the pickups and kickers. As well, there is the possibility of injecting $\bar{p}$ beams of very small transverse emittances using precooling in the debuncher made more effective by larger bandwidth, refrigerated preamps and pickups and more pickup electrodes.

The large electronic gain of system 1 (4×10^6) could be a problem if the kicker signals could propagate through the vacuum chamber to the pickup. This problem could be a practical limit to the upper frequency used in the stochastic cooling. Normally, $\alpha_p=0$ regions in the accumulator lattice separate the kicker from the pickups. There the beam pipe is smaller than the cut-off frequency of the 8 GHz cooling rf. This assumes that transverse emittances are $\leq 5\pi$ and that the lattice functions are like the Fermilab design report accumulator. If a larger machine acceptance were desired, consistent with the cut-off determined beam pipe size, special low β insertions could be put on each side of the kicker to prevent signal propagation and unwanted feedback. As well, various microwave absorbers are possible[6].

Higher $\bar{p}$ Production

For the accumulator design described here we have assumed that $\bar{p}$'s would be produced by the 125 GeV proton beam of the Fermilab Main Ring. The $\bar{p}$'s are focused by a Li lens, and transported to a debuncher ring where effective momentum precooling is obtained by rf bunch rotation and transverse emittances are reduced by stochastic cooling. These aspects are much like those described in the February 1982 Fermilab $\bar{p}$ Source Design Report. One noticable improvement in the debuncher transverse cooling system design since that design report has been the use of higher frequencies and lower temperature pickups and preamps. The improved performance is much more compatible with the higher fluxes and higher frequencies of the filterless stochastic stacking system described here.

In fact, with the higher flux capability of the stochastic cooling system described here, a scheme must be invented which allows the Main Ring beam to produce more $\bar{p}$'s. Moreover, the cooling system seems to handle the same number of $\bar{p}$'s per second whether the pulses are injected every 2 sec, 1 sec or 1/2 sec. The scheme for obtaining more $\bar{p}$'s is shown schematically in Figure 2.



Proposed
Fig 2. Main Ring Cycle

To obtain the needed tight bunch structure of the protons during the long MR flat top there are at least 2 possibilities. The simplest conceptually is to use a higher frequency rf system, say 424 MHz, to hold the bunches "upright" after they have been stretched and rotated 90° at 53 MHz. This is a formidable rf system[7], however, requiring some 30 MV. A second possibility is to let the protons rotate 180° by pulsing the 53 MHz rf each time a booster batch of 3×10^{12} protons is extracted toward the production target. The extraction takes place when the bunch has completed 90° of rotation and the rest of the protons in the MR are allowed to complete the rotation of 180° where they are held to wait 1/2 sec for the next extraction. The proton bunch dilution and subsequent degradation of the $\bar{p}$ debunching seem not to be a serious problem (based on MR beam studies).

<u>Limitations on the Accumulator Lattice</u>

A. For higher frequencies, in general, the basic problem is with $\eta = 1/\gamma_t^2 - 1/\gamma^2$. Nominally, the stacking rate is a strong function of bandwidth and η, $1/\tau \sim \eta W^2$. Other constraints usually imply that ηW=constant;

i) For filter cooling the constant is determined by the filter phase characteristics.

ii) For shuttered cooling - the constant can be larger than for filtered stochastic stacking. The limitation comes from too much mixing between pickups and kickers.

iii) For shuttered cooling, to the extent a lattice can be built with no mixing between pickup and kicker and perfect mixing between kicker and pickup the constant can be even larger. The flux of $\bar{p}$'s that one could stochastically stack would increase as W^2 until the Schottky bands begin to overlap. Note that Schottky band overlap in the case of filtered cooling is precluded.

B. One can ask whether an existing lattice such as the triangular accumulator in the Fermilab design report can be modified to allow shuttered stochastic stacking. We list some of the difficulties.

i) As mentioned above, to use higher frequencies implies a lower η. Shuttered cooling has less stringent requirements on lowering η than the filtered technique. Nevertheless, it seems the present Fermilab Accumulator has a minimum η at 8 GeV which is not an acceptable match to a 4-8 GHz cooling system. One could imagine using the same lattice at a lower $\bar{p}$ energy at some cost in transverse acceptance.

ii) For the model described in this paper there is also a difficulty in momentum acceptance. Basically, two stacks vs. one and an extra shutter require more momentum acceptance than the 2.3% of the Fermilab Accumulator design. A value of 3% seems to be what is needed if the same margins for error are used in comparing the two designs. The 3% can be reduced if the injection kicker shutter is not needed[8] or if smaller width is assumed for the momentum distribution of the injection pulse of system 2. A large fraction of the needed momentum aperture is for the wide core of system 2 which is caused by intrabeam scattering.

iii) Another difficulty with the existing lattice design is in the H_β phase advance between the pickup and kicker. Unlike the CERN AA where the stacking kicker systems are in dispersionless regions and betatron cooling/heating isn't possible, the shuttered cooling requires regions of high dispersions. To cool longitudinally without heating the radial dimension and to allow the effective shutter width due to betatron amplitude tolerances to be small, the horizontal betatron phase advance must be an odd multiple of 180°. However, since much of the design lattice $\alpha_p = 0$ straight section is not needed for shuttered cooling, perhaps these regions could be modified with quads to change the radial tune appropriately.

If the kicker were placed in the other dispersive region, 2/3 of the ring circumference downstream of the pickup, the horizontal betatron phase advance would be perfect. To compensate for the increased mixing between pickup and kicker one could have the kicker electrodes at different radii have different delays.

Conclusions

There exists an alternative to filtered stochastic stacking. Furthermore, stochastic stacking using shutters has some distinct advantages.

Since high-quality, high-frequency notch filters have not yet been built, there has been a tendency to be somewhat conservative by designing filtered stochastic cooling systems with low maximum frequency. There are many reasons, however, to use systems with the highest frequencies and largest bandwidths possible. First, the flux ϕ of $\bar{p}$'s accepted per unit time increases with the bandwidth W. Second, the power needed to accumulate a given flux decreases as the cube of the bandwidth $(P \sim (\phi/W)^3)$. Third, the peak core density, limited by intrabeam scattering forces, can be increased with more effective cooling as provided by larger W.

Shuttered stochastic stacking allows the use of the highest possible frequencies and bandwidths consistent with the response functions of the pickups and filters. Using the Faltin-type slot-box couplers we believe a maximum frequency of 8 GHz is possible. A bandwidth of more than one octave is also likely, although we haven't yet considered this possibility in the model.

As a final comment one can note that a shuttered stacking system is likely to be less expensive than the more conventional filtered design. Besides the development and construction costs of the filters themselves, money is saved because the amplifiers can be operated much closer to their saturated power rating. And if the choice is between a 1-2 GHz filtered system and 4-8 GHz shuttered system, the savings could be a few million dollars.

We would like to thank Drs. Chuck Ankenbrandt, Roy Billinge, Tom Collins, Jim Griffin, and Christoph Leemann for useful discussions.

Footnotes and References

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In this paper the rates for momentum cooling by the Palmer method are compared to the associated radial betatron cooling/heating.

$$\frac{1}{\tau_p} = \frac{W}{N}\{2g-g^2\ (1+\eta+\frac{<x_\beta^2>}{\alpha^2<\Delta p^2>}),$$

$$\frac{1}{\tau_\beta} = \frac{W}{2N}\{-2g_\beta\cos\theta - g_\beta^2\ (1+\eta_\beta + \frac{\alpha^2<\Delta p^2>}{<x_\beta{}^2>}),$$

$$\text{with } g_\beta = g\ \frac{\alpha_{gap}}{\alpha_{pu}}\quad\frac{\beta_{pu}}{\beta_{gap}}$$

Here $<x_\beta^2>$ is the mean square horizontal betatron displacement and $\alpha^2<\Delta p^2>$ is the mean square horizontal displacement due to momentum spread, θ is the horizontal betatron phase advance between pickup and kicker, and η_β is the amplifier noise power referred to the x_β part of the signal.

6. B. Autin and L. Faltin, "Damping of Wave Guide Modes", $\bar{p}$ Note 219 (June 1982).

7. J. Griffin, private communication.

8. As suggested by Chris Leemann, the injection kicker shutter may not be needed. Since the sensitive core of system 2 can be shielded by a shutter which opens only every 2 minutes one need only worry about the strongly cooled system 1 stack. Transient stray fields from an unshuttered single turn kicker, especially after the rf deposit region has been cleared by the cooling system, may not be a problem. In practice, the CERN AA suffers some 20% degradation of stacking rate with the injection kicker shutters left open.