WASTE

BNL-22272

Workshop on Phase Space Cooling*

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A two-day workshop was held on August 5 and 6, 1976 to discuss phase space damping ("cooling") of particle beams. Interest in this topic derives chiefly from the possibility that antiproton beams produced by collision of an intense proton beam with a target can be compressed in phase space. This could make it possible to accumulate antiproton beams in a storage ring repeatedly, thus leading to a relatively high stacked $\bar{p}$ beam suitable for $\bar{p}p$ collisions with interesting luminosities.

Two cooling techniques have been developed: In stochastic cooling (invented by Van der Meer at CERN) the spread of amplitudes in a beam is reduced by a feedback signal derived from the statistical fluctuations in the beam. In electron cooling (first proposed by Budker in Novosibirsk) an electron beam having the same mean velocity as the heavy particle (proton or antiproton) beam coincides with the heavy beam in part of the orbit. Viewed in the center-of-mass system, the electrons are "cold" and the protons "hot", and in the approach to thermal equilibrium the protons are cooled down; in the lab system this means their fluctuations from the mean are reduced.

In the workshop, both these cooling techniques were discussed, especially with a view to their application to the production of intense high-quality antiproton beams suitable for colliding beam physics.

M.Q. Barton described the work on electron cooling at Novosibirsk, where he had visited earlier in the year. In a small experimental

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storage ring there, proton beams of about 65 MeV have been cooled by 35 keV electrons. Damping times as short as 50 milliseconds have been observed with the beam dimensions shrinking by factors as large as 100.

Theory indicates that the damping time should scale approximately as

$$\tau_p \sim \beta_Y^4 \langle \theta \rangle^3 / J$$

where $\langle \theta \rangle$ is the larger of the angular spreads of the electron and ion beam, and J the electron current density. Extrapolating from the 65 MeV experiment at Novosibirsk to, say, 2 GeV, one may envisage cooling times of the order of 5 seconds for a narrow beam. However, it should be noted that, because of the θ^3 dependence, the cooling works best for beams that are already narrow, and works more poorly for wider ones.

Stochastic Cooling

In this method the mean deviation from nominal of the transverse or longitudinal momentum is measured for a sample of the beam, and then a correction is applied. The process is continued for other samples constituting the whole beam, and repeated indefinitely. Damping depends on maintaining the randomness of the sample, specifically the statistical randomness relation

$$\langle \bar{x}^2 \rangle = 1/N \langle x^2 \rangle \quad (1)$$

where the bar denotes sample averages, and the bracket ensemble averages. Here x stands for the variable to be "cooled", and N is the number of particles in the sample.

On one pass of the cooling system, x for each particle is reduced by a factor g times the mean value $\bar{x}$ measured for the sample. This reduces the variance $\langle x^2 \rangle$ by $(2g - g^2)\bar{x}^2$. If the randomness relation (1) continued to hold, this could be repeated indefinitely, and exponential

damping could be obtained. The theory of this process predicts a cooling rate

$$\frac{d}{dt} \langle x^2 \rangle = \langle x^2 \rangle F \frac{W}{N_p} \left[g - \frac{g^2}{2} \left(1 + \frac{n^*}{s} \right) \right] \quad (2)$$

where W = bandwidth of feedback system
 N_p = total number of particles in beam
 g = fraction of $\bar{x}$ corrected per pass
 n^*/s = ratio of pickup noise to signal
 $F = 1$ for transverse, $F = 2$ for longitudinal cooling.

This expression is valid if the randomness relation (1) remains satisfied. However, randomness tends to be destroyed by the feedback process, but as Van der Meer already showed in his first paper on the subject,¹ it is restored if the particles have a spread of angular velocities so that the identity of the particles making up the pickup sample changes with time. A relevant "mixing parameter" is

$$M = \frac{4\pi}{F(g - g^2/2)} \frac{W \langle \Delta \omega \rangle_{\text{rms}}}{\omega^2} \quad (3)$$

which is the rms spread in azimuth of the beam in $[F(g - g^2/2)]^{-1}$ revolutions, divided by the effective angular pickup sample length $\omega/2W$.

E. Courant showed computer calculations which indicate that the effective damping rate is close to that given by (2) when $M \geq 3$, and reduced by a factor of approximately $0.7 M^{1/2}$ for $M \leq 1$.

Some important features of the theory² are: With noise large compared to the signal, one can still obtain damping if one makes the gain parameter g smaller than $2s^*/n^*$.

For longitudinal (energy) damping and $n^* \gg s^*$, the amplifier power goes mostly into amplifying noise. If the available amplifier power

1. S. Van der Meer, CERN Report CERN/ISR-PO/72-31 (1972).
2. See, for example: L. Thorndahl, CERN Report CERN/ISR-RF/75-55 (1975).

and bandwidth are given, g must be restricted and the damping rate becomes

$$\frac{1}{\tau} = \frac{2}{\pi} \frac{\omega W e^2 Z}{(\Delta p c)_{\text{rms}}} \sqrt{\frac{P}{P_n}} \quad (4)$$

where Z is the geometric mean of input and output impedances, P is the amplifier power, P_n the pickup noise power, $(\Delta p)_{\text{rms}}$ the absolute rms momentum spread of the beam; then the damping rate becomes independent of the beam current. With parameters such as: $P = 10$ kW, $P_n = 10^{-12}$ W, $W = 100$ MHz, $\omega/2\pi = 10^5$ Hz, $Z = 100 \Omega$, $(\Delta p)_{\text{rms}} = 5 \times 10^8$ eV/c ($\Delta p/p = 0.01$ at 50 GeV) we obtain a damping time of the order of one hour, independent of current.

B. Zotter (CERN) reported on some recent tests of stochastic cooling in the CERN ISR. Earlier experiments³ showed that cooling rates in accordance with theory were obtained with a vertical feedback system; however, the rate was very slow (2% per hour). More recent experiments, however, are more ambiguous: observed cooling rates are slower than theory by a factor of 3 or more. Further investigations are planned.

Use of Cooling Techniques for Antiproton Beams

To produce an antiproton beam containing N particles in a time T one may produce a fraction N/k of that beam k times and cool each burst in a time T/k .

According to the 1974 ISABELLE design study, an antiproton beam of the order of 5×10^{10} particles (1 milliampere) is obtainable without cooling techniques. This requires 10 ISA cycles or approximately one hour. To enhance this by cooling, one would have to cool the $\bar{p}$ beam's phase space by a factor of around 10 (three exponential times) before injecting the next batch of antiprotons; thus, the overall stacking rate may be around 2×10^{10} $\bar{p}$ per hour. In 24 hours one might obtain as much as 5 to 10 milliamperes, or a luminosity around $5-10 \times 10^{29}$ $\text{cm}^{-2} \text{sec}^{-1}$.

3. P. Branham, G. Carron, H. Hereward, K. Hübner, W. Schnell and L. Thorndahl, Nucl. Instrum. & Methods 125, 201 (1975).

It is assumed here that the antiprotons are produced at 30 GeV by the 200 GeV protons of one ISA ring, and cooled in the other ring. Cooling times could be reduced by producing the antiprotons at lower energy, but there the production efficiency is lower.

C. Rubbia (Harvard) proposed an alternate scheme: Produce $\bar{p}$ at ~ 4 GeV/c directly from the AGS 30 GeV protons. Build a special large acceptance ring for 4 GeV/c, which has a total momentum acceptance of 25%, he estimates that 4×10^8 antiprotons can be injected in this ring per AGS pulse (10^{13} protons). If these antiprotons can then be cooled very fast, one could stack 10^{12} $\bar{p}$ per hour. However, this implies a cooling system that can reduce the energy spread by a factor of 10 in the order of a second. This might be accomplished by "peeling" off a small part of the beam at a time, decelerating it and cooling it with electrons. It would seem difficult to do this for the whole beam in 1 second; more likely the cooling time is the bottleneck, and the effective stacking rate would be smaller than 10^{12} per hour by one or two orders of magnitude.

R. Palmer (BNL) pointed out that the 1974 ISA scheme is based on the ISA beam that is optimized for pp collisions, not for $\bar{p}$ production. By operating the ISA ring in a different mode, one could optimize it for $\bar{p}$ production. With vertical multiturn stacking and a small momentum spread in the ISA ring, one could conceivably bunch the beam much more than in the 1974 scheme and longitudinally stack the antiprotons from 100 ISA cycles instead of 10 as envisaged in 1974, thus increasing the luminosity to well above 10^{30} even without cooling.

Conclusions

It is not clear whether cooling techniques can help appreciably in obtaining high intensity antiproton beams suitable for colliding beam experiments. Electron cooling suffers from the drawback that the damping time increases very rapidly with energy; therefore, antiprotons would have to be produced at very low energies -- or else decelerated -- in order to be cooled by this method.

Stochastic cooling is inherently slow, especially with high intensity beams, and requires a large product of bandwidth and amplifier power, together with a very low noise pickup system. With optimal performance of the cooling systems, one may at best hope for an increase of an order of magnitude in the antiproton beam intensity obtainable as compared to schemes without cooling. (This rather pessimistic conclusion represents the present reporter's opinion, which may not be shared by all participants in the workshop.)