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# INTENSE ANTIPROTON SOURCE FOR A 20 TeV COLLIDER

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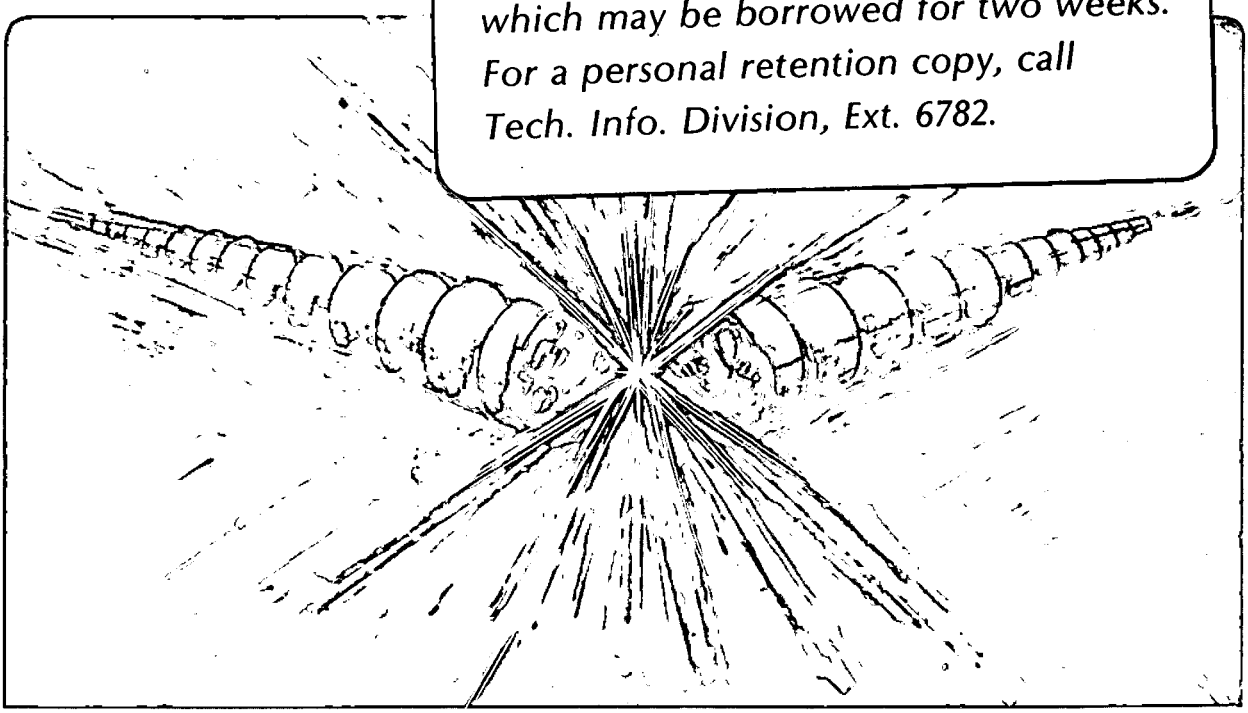

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# INTENSE ANTIPROTON SOURCE FOR A 20 TeV COLLIDER*

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$\bar{p}$'s are then injected into the debuncher where their momentum spread is reduced to 0.25% by RF-bunch rotation and adiabatic debunching. In the debuncher the transverse emittance is also reduced to 3 μm (~ 30 μm normalized) by stochastic cooling. The $\bar{p}$'s are then transferred to the accumulator, freeing the debuncher for the next batch. In the accumulator the $\bar{p}$'s are stochastically stacked while the transverse emittance is reduced to 1 μm [10 μm normalized]. After ~ 200 s the core contains ~ $6 \cdot 10^{10}$ particles of the required phase space density. These particles will be extracted, accelerated to 200 GeV in booster 1 and injected into booster 2 where a coasting beam is built up by successive RF-stacks of batches of ~ $5 \cdot 10^{10}$ cooled $\bar{p}$'s. RF-unstacking of the total accumulated beam at the appropriate harmonic and transfer to the main ring would complete the cycle. A modest cooling system in booster 2 might be used to compensate for the diluting effects of the RF-stacking process.

## Stochastic Cooling Systems

The most critical of all the cooling systems used in the outlined $\bar{p}$-source are the transverse system in the debuncher and the stochastic stacking system in the accumulator. Furthermore, high demands on bandwidth are made by any system contemplated to cool $\gtrsim 10^{13}$ $\bar{p}$'s in booster 2, if this should be desired. We examine briefly some of the characteristics of these systems.

For cooling systems with sufficiently linear electrodes transverse cooling is well described by:

$$\epsilon(t) = e^{-st}\left(\epsilon(0) - \epsilon(\infty)\right) + \epsilon(\infty) \qquad (5)$$

where $\epsilon(\infty)$ is the asymptotic value determined by the thermal noise characteristics of the system. Strictly speaking the cooling rate $s$, and therefore $\epsilon$, are functions of the revolution frequency of the particles. A conservative estimate is obtained by calculating $s = s(\omega_c)$ for a distribution $f(\omega)$ symmetric about $\omega_c$. The cooling rate $s$, including the effects of signal suppression, is then given by a simple integral that has been evaluated in reference 4 from which we obtain

$$S\,\frac{\xi}{n} = \sim 1 \quad \text{with} \quad G_0 = \frac{0.4}{\xi} \qquad (6)$$

where $n = (f_{max} - f_{min})/f_0$, $G_0$ is the overall system gain (average over the working band) and $\xi$ is defined as

$$\xi = \frac{\pi N f(\omega_c)}{n} \qquad (7)$$

Using a parabolic momentum distribution of full width $\Delta p/p$, $\xi$ becomes $0.75N(nf_0 n\,\Delta p/p)^{-1}$ and for $N = 3 \cdot 10^8$, $f_{max} = 8$ GHz, $f_{min} = 4$ GHz, and $n = 4 \cdot 10^{-3}$ we find the following values: $\xi = 5.6 \cdot 10$ sec, $n = 1.07 \cdot 10^4$, $G_0 = 3.75 \cdot 10^{-5}\,\text{sec}^{-1}$ and $s = 1.9\ \text{sec}^{-1}$. This gives a sevenfold reduction in emittance in one second, provided $\epsilon(\infty)$ is low enough. $G_0$ is completely determined by the coupling characteristics and number of pick-up (PU) and kicker (K) electrodes and the net electronic gain.[4] Assuming loop couplers made up by 70 Ω striplines in pushpull configuration for both PU's and K's we arrive, based on standard expressions[4], at the approximate system parameters summarized in Table I.

Two such systems, one for each transverse phase plane, are required. These are substantial systems

Table I: Approximate Parameters for Debuncher Transverse Cooling System

| | |
|---|---|
| Frequency Band | 4 to 8 GHz |
| No. of PU's = No. of K's | 512 loop pairs |
| Amplifier gain | $6.5 \cdot 10^6$ [~136 dB] |
| Total Power | ~ 1.8 kW [cryogenic PU's 4 dB NF preamp] |
| Cooling rate, s | $\approx 1.9\ s^{-1}$ |
| $\epsilon(\infty)$ | ~ $3.5 \cdot 10^{-7}$m [cryogenic PU's 4 dB NF] |
| $\epsilon(t = 1s)$ | ~ $3.3 \cdot 10^{-6}$ m |

but they greatly facilitate the accumulator design and their design is, at least conceptually, straightforward. A certain R and D effort is certainly required to design the electrodes, and the lattice design of the debuncher must take into account that the PU and K arrays (each > 10 m long) must be broken up into sub-arrays of only a few m length, located in fairly low $\beta$ sections in order to keep their apertures small enough for the envisaged frequency band.

The transverse cooling systems required to cool from 3 μm to 1 μm (i.e. ~ 10 μm normalized) will be located in the accumulator and are expected to be substantially more modest in terms of power requirements and length of PU and K arrays.

A stochastic stacking system similar to that of the CERN-AA-ring[5] or the FNAL $\bar{p}$-source will be used to achieve the required longitudinal phase space compression. In order to handle the flux of $3 \cdot 10^8 s^{-1}$ a frequency band of 4-8 GHz is necessary but periodic filters will not be needed because the modest $\psi_{max}/\psi_{min}$ ratio considerably reduces the thermal noise problem. The system will therefore consist simply of Σ-PU's placed in a region of high dispersion, an amplifier chain, and kickers in straight sections with dispersion $\alpha_p = 0$. The system will again, as in the AA-ring or the FNAL $\bar{p}$-source, consist of several subsystems of which we shall briefly discuss only the most complex and massive, the "stack tail" system.

Approximate system parameters can be derived analytically for a steady state configuration with $\phi(x) = \phi_0$ = constant.[3,4] This requires for an octave bandwidth

$$\mathrm{Re}\left\{G(x)\right\} \cong \frac{\alpha\phi_0}{\psi(x)}\,\frac{f_0}{f_{max}}, \quad 1 \le \alpha \le 2 \qquad (8)$$

where $x = E - E_0$, and $G(x)$ is the gain, i.e. the single-particle rate of change of energy, assumed independent of harmonic number. From the equation[4]

$$\frac{1}{\psi}\frac{\partial\psi}{\partial x} = \frac{1}{E_D} = \frac{\alpha - 1}{\alpha^2}\,\frac{[\mathrm{Re}\{G\}]^2}{|G^2|}\,\frac{1}{\ln(2)}\,\frac{|n|\,f_{max}^2}{\beta^2 E\phi_0 f_0} \qquad (9)$$

then follows $E_D = 20$ MeV with $\alpha \approx 1.4$, $n = 4 \cdot 10^{-3}$ and some allowance for the fact that G will not be purely real. With these values for $n$ and E we can accommodate 6.25 e-foldings of the density $\psi(x)$ without Schottky band overlap at the top harmonic and the actually required 5.8 e-foldings will be achieved

in a stack of < 120 MeV or $\Delta p/p = 1.2\%$ width. Some important system parameters as derived from (9) and (8) are summarized in Table II.

Table II: Accumulator Stack Tail System Parameters

| | |
|---|---|
| $f_{max}$, $f_{min}$ | 8 GHz, 4 GHz |
| $n_{pu} = n_k$ | 1024 |
| $G_A$ | $\sim 1.41 \cdot 10^6$ [~ 122 dB] |
| $P_{total}$ | ~ 1.5 kW |
| $\alpha_p/g$ | ~ 160 [i.e. $\alpha_p$ = 3m for 15 mm PU gap] |
| Schottky/Noise (ratio of diffusion terms) | $\approx 220\, e^{-\frac{x}{\xi_D}}$ |

The signal-to-noise ratio is larger than 2 for the whole stack with exception of the last (highest density) 20 MeV. A low noise core cooling system[2,3,5] with appropriately adjusted gain should make the thermal noise problem totally innocuous and provide some additional peaking of the distribution function $\psi$.

If it were desired to operate the collider with smaller transverse emittance to reduce the circulating charge, that cooling could be carried out with $10^{13}$ $\bar{p}$'s or p's stored in booster 2 ($\gamma_T \approx 25$). We calculate that a system with 256 PU's and K's, ~ 100 dB amplifier gain and a frequency band from 8 to 16 GHz would be able to cool $10^{13}$ $\bar{p}$'s at 200 GeV from $\epsilon_n = 10\ \mu m$ to $\epsilon_n = 1\ \mu m$ in ~ 3000 sec.

## Conclusion

Stochastic cooling is capable of providing a flux of $\sim 3 \cdot 10^8$ $\bar{p}$/second, adequate to fill a 20 TeV collider in ~ 12 hours for operation at $\mathcal{L} = 10^{32} cm^{-2} s^{-1}$. This represents an order of magnitude improvement over the FNAL-source design goal. It is made possible mainly by higher bandwidth (4 GHz vs. 1 GHz) and a lower $\psi_{max}/\psi_{max}$ ratio (350 vs. ~ $10^4$). Systems operating in the 4–8 GHz band are necessary, a technology which goes beyond the 2–4 GHz systems presently under development, but appears within reach with a moderate R and D effort. Stochastic cooling in the 8–16 GHz range holds the promise of small transverse emittance (< 1 μm normalized), allowing even shorter filling times or the use of lower field, larger circumference colliders, should such devices prove more cost-effective.

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