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INTENSE ANTIPROTON SOURCE FOR A 20-TeV COLLIDER*

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Summary

The feasibility of producing, collecting and cooling $\bar{p}$'s at a rate $> 3\cdot10^8 s^{-1}$ is demonstrated. This implies a filling time of ~ 12 hours to reach a luminosity of $\cong 10^{32}cm^{-2}s^{-1}$ in the collider.

Considerations of Collider Parameters

We consider a 20 TeV $\bar{p}p$ collider operating with bunched beams and zero crossing angle. Bunched beams are preferred because this eliminates the need for exceedingly small emittances, or conversely very large numbers of $\bar{p}$'s, and because at least for high magnetic fields ($\lesssim$ 10T) the energy loss due to synchrotron radiation must be compensated. The main attractive feature of using $\bar{p}$'s is of course the possibility of achieving colliding beam operation with only one ring. It is however essential that the p and $\bar{p}$ bunches are crossing each other only at the design interaction points and are kept apart everywhere else around the ring, e.g. by means of electrostatic deflectors. This imposes a lower limit on the distance S_B between bunches, which depends on the lattice design. If we denote by N the average number of events for a single bunch crossing [at σ_t = 100 mbarn] we can rewrite standard expressions[1] for the luminosity $\mathcal{L}$, the beam-beam tune shift ΔQ_{bb} and the number of particles per bunch N_B:[1]

$$\mathcal{L}\left[m^{-2}\cdot s^{-1}\right] = 3\cdot10^{37}\ \frac{\bar{N}}{S_B} \tag{1a}$$

$$\Delta Q_{bb} \cong 1.87\cdot10^{-6}\ \left(\beta^*/\epsilon_n\right)^{1/2}\ \bar{N}^{1/2} \tag{1b}$$

$$N_B \cong 3.84\cdot10^{12}\ \left(\beta^*\epsilon_n\right)^{1/2}\ \bar{N}^{1/2} \tag{1c}$$

where the numerical coefficients apply for $\gamma \cong 2.13\cdot10^4$ (i.e. 20 TeV), β^* is the interaction beta ($\beta_x = \beta_z$), and ϵ_n the normalized emittance ($\epsilon_x = \epsilon_z$). Combining (1a, 1b, 1c) and assuming ΔQ_{bb} = 0.005 we obtain:

$$\mathcal{L}_{max} \cong \frac{2.09\cdot10^{28}}{\beta^*}\ N_B/S_B \tag{2}$$

The controlling importance of S_B becomes evident from (1a): for S_B = 240 m, corresponding to 250 bunches in a ring of 60 km circumference $\mathcal{L}$ ($\bar{N}$=1) = $1.25\cdot10^{31}cm^{-2}s^{-1}$.

To produce $\mathcal{L} = 10^{32}cm^{-2}sec^{-1}$, we allow $\bar{N}$ = 8 and assume β^* = 2 m, ϵ_n = 10 μm to find we need $N_B = 4.86\cdot10^{10}$ and a total $N_t = 1.2\cdot10^{13}\bar{p}$'s. We shall discuss the feasibility of accumulating this number of antiprotons.

It might be of some interest to comment briefly on the effects of ring size, and therefore magnetic field. With the same emittance and bunch to bunch distance, a larger ring will require more antiprotons to reach the same luminosity. At low luminosity, corresponding to $N \simeq 1$, this can be compensated by decreasing ϵ, at higher values of $\mathcal{L}$ however, the larger ring with smaller emittance reaches a critical value of ΔQ_{bb} earlier, thus either reducing the maximum achievable luminosity, or forcing operation back to larger ϵ and therefore larger total number of antiprotons.

$\bar{p}$-Source Requirements and Phase Space Considerations

Assuming, by necessity without proof, a luminosity lifetime of at least 20 hours in the collider, we see that a $\bar{p}$ flux of $3\cdot10^8s^{-1}$ is adequate, allowing a filling time of ~ 11 hours for 1.2 10^{13} antiprotons or $\mathcal{L} = 10^{32}cm^{-2}s^{-1}$. We envisage a debuncher/accumulator complex similar in concept to that of the FNAL $\bar{p}$-source.[2] At a proton momentum p = 120 GeV/c and a $\bar{p}$ momentum $p_{\bar{p}}$ = 10 GeV/c we expect the following $\bar{p}$ flux ϕ:[2]

$$\phi \simeq 62\ \epsilon\ \frac{\Delta p}{p}\ N_p/\tau_r, \quad \text{for} \quad 2\cdot10^{-5}m \lesssim \epsilon \lesssim 4\cdot10^{-5}m \tag{3}$$

where ϵ is the unnormalized $\bar{p}$ emittance, $\Delta p/p$ the $\bar{p}$ momentum spread at the target, N_p the number of protons hitting the target and τ_r the repetition period of the process. N_p is limited by target heating, ϵ and $\Delta p/p$ by considerations regarding lattice and transport system design. We obtain the desired $\bar{p}$ flux using $\epsilon = 2\cdot10^{-5}m$ (unnormalized), $\Delta p/p$ = 0.04, $N_p = 6\cdot10^{12}$ and τ_r = 1 s. To reach the required emittance, $\epsilon_n = 10^{-5}m$, the $\bar{p}$ emittance must be cooled by a factor 20.

To estimate the required longitudinal compression assumptions must be made about the momentum spread in the final collider configuration as well as about the accumulator circumference C_A and the effectiveness of the debuncher in reducing the momentum spread of the $\bar{p}$'s. Denoting by $\psi[eV^{-1}]$ the longitudinal $\bar{p}$ density in the accumulator we write:

$$\psi_{in} \cong \frac{\phi\tau_r}{(\Delta p/p)_D E} \quad \text{and} \quad \psi_{out} \simeq \frac{C_A}{C}\ \frac{N_t}{\epsilon_\parallel} \tag{4a,b}$$

If after debunching, we have $(\Delta p/p)_D$ = 0.25% then ψ_{in} = 12 eV^{-1}. Use C_A = 800 m and $\Delta p/p$ (full width) = $6\cdot10^{-4}$ for the 250 bunches of ~ 1 m length at 20 TeV to obtain ψ_{out} = 4300 eV^{-1}, indicating an increase in longitudinal phase space density of ~ 350 that must be achieved by stochastic cooling.

$\bar{p}$ Production and Accumulation Sequence

We postulate the existence of the following rings:

	E_{max} [TeV]	B_{max} [T]	C [km]
Booster 1	0.2	1.4	4
Booster 2	1.4	8 to 10	4
Main Ring	20	8 to 10	60

Booster 1 will deliver a train of highly bunched protons, $6\cdot10^{12}$ every second, on target. $3\cdot10^8$

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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 ~ $6\cdot10^{10}$ 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 ~ $5\cdot10^{10}$ 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:

$$\varepsilon(t) = e^{-st}\Big(\varepsilon(0) - \varepsilon(\infty)\Big) + \varepsilon(\infty) \tag{5}$$

where $\varepsilon(\infty)$ is the asymptotic value determined by the thermal noise characteristics of the system. Strictly speaking the cooling rate s, and therefore ε, 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 ω_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

$$S\,\frac{\xi}{n} = \sim 1 \quad \text{with} \quad G_o = \frac{0.4}{\xi} \tag{6}$$

where $n = (f_{max}-f_{min})/f_o$, G_o is the overall system gain (average over the working band) and ξ is defined as

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

Using a parabolic momentum distribution of full width $\Delta p/p$, ξ becomes $0.75N(nf_o\eta\,\Delta p/p)^{-1}$ and for $N = 3\cdot10^8$, $f_{max} = 8$ GHz, $f_{min} = 4$ GHz, and $\eta = 4\cdot10^{-3}$ we find the following values: $\xi = 5.6\cdot10$ sec, $n = 1.07\cdot10^4$, $G_o = 3.75\cdot10^{-5}\text{sec}^{-1}$ and $s = 1.9\ \text{sec}^{-1}$. This gives a sevenfold reduction in emittance in one second, provided $\varepsilon(\infty)$ is low enough. G_o 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	$6.5\cdot10^6$ [~136 dB]
Total Power	~ 1.8 kW [cryogenic PU's 4 dB NF preamp]
Cooling rate, s	$\simeq 1.9\ s^{-1}$
$\varepsilon(\infty)$	~ $3.5\cdot10^{-7}$m [cryogenic PU's 4 dB NF]
$\varepsilon(t = 1s)$	~ $3.3\cdot10^{-6}$ 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 β 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 $3\cdot10^8 s^{-1}$ a frequency band of 4-8 GHz is necessary but periodic filters will not be needed because the modest ψ_{max}/ψ_{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 $\phi(x) = \phi_o$ = constant.[3,4] This requires for an octave bandwidth

$$\text{Re}\Big\{G(x)\Big\} \cong \frac{\alpha\,\phi_o}{\psi(x)}\,\frac{f_o}{f_{max}}, \quad 1 \leq \alpha \leq 2 \tag{8}$$

where $x = E - E_o$, 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]

$$\frac{1}{\psi}\,\frac{\partial\psi}{\partial x} = \frac{1}{E_D} = \frac{\alpha - 1}{\alpha^2}\,\frac{[\text{Re}\{G\}]^2}{|G^2|}\,\frac{1}{\ln(2)}\,\frac{|n|\,f^2_{max}}{\beta^2 E\phi_o f_o} \tag{9}$$

then follows $E_D \simeq 20$ MeV with $\alpha \simeq 1.4$, $\eta = 4\cdot10^{-3}$ and some allowance for the fact that G will not be purely real. With these values for η 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 $\Delta p/p \approx 1.2\%$ 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
α_p/g	~ 160 [i.e. $\alpha_p \approx 3$m for 15 mm PU gap]
Schottky/Noise (ratio of diffusion terms)	$\approx 220\, e^{-\frac{x}{E_D}}$

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 ψ.

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 ($\gamma_T \cong 25$). 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 $\varepsilon_n = 10$ μm to $\varepsilon_n = 1$ μm 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 $\mathcal{L} = 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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 ψ_{max}/ψ_{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.

References

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