ANTIPROTON PRODUCTION AND ACCUMULATION FOR A 20 TEV $\bar{p}p$ COLLIDER*

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Summary

The feasibility of producing, collecting and cooling $\bar{p}$'s at a rate $> 3 \cdot 10^8 s^{-1}$ 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.

Accelerator and Collider Configuration

Table I summarizes the basic parameters of the accelerator complex studied by the "conventional $p^{\pm}$ p collider" subgroup on which we base our considerations.

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

Table I: Basic Ring Parameters of 20 TeV Collider

With $\beta^* = 2m$, $\epsilon_x = \epsilon_z = 10\mu m$ (normalized) and 250 bunches (estimated from the requirements imposed by electrostatic beam separation) the following performance figures are derived:

Luminosity: $\mathcal{L} \simeq 1.25\ 10^{31} \langle n \rangle\ [cm^{-2}s^{-1}]$ (1)

Beam-Beam tune shift: $\Delta Q_{bb} \simeq 10^{-3} \langle n \rangle^{1/2}$ (2)

No. of $\bar{p}$'s (or p's) per bunch: $N_B \simeq 1.8\ 10^{10} \langle n \rangle^{1/2}$ (3)

where $\langle n \rangle$ is the average number of events per bunch collision (at $\sigma = 100$ mbarn). Up to $\mathcal{L} \simeq 3 \cdot 10^{32} cm^{-2}s^{-1}$ luminosity is controlled by the tolerable $\langle n \rangle$ rather than by ΔQ_{bb}.

For $\epsilon_N < 10\ \mu m$, which can be achieved by stochastic cooling, the required number of $\bar{p}$'s decreases correspondingly, allowing shorter filling times or a lower $\bar{p}$ flux or the use of a lower field, larger diameter ring. It remains however to be shown that luminosity lifetime is not adversely affected if we plan to operate with very small emittance ($\epsilon_N \lesssim 1\ \mu m$).

With $\frac{\Delta p}{p} \simeq 6 \cdot 10^{-4}$ at 20 TeV and a bunch length of ~ 1m we obtain $\epsilon_{\parallel}$/bunch $\simeq$ 30 eVs, or $\epsilon_{\parallel} \cong 7.5 \cdot 10^3$ eVs for all 250 bunches. An RF-system of ~ 10 MV peak voltage is compatible with these bunch parameters and will at a phase stable angle of a few degrees compensate for the synchrotron radiation energy loss (~ 200 keV/turn).

$\bar{p}$ - Source Requirements

We make, without further proof, the crucial assumption that the luminosity lifetime in the collider is at least 20 hours. Then a filling time of 10 to 12 hours (for $1.2 \cdot 10^{13}$ $\bar{p}$'s or $\mathcal{L} \simeq 10^{32} cm^{-2}s^{-1}$) corresponding to a $\bar{p}$ flux of ~ $3 \cdot 10^8\ s^{-1}$ seems perfectly adequate.

We envisage the use of Booster 1, which can be cycled fairly rapidly, as proton source, and the use of a debuncher and an accumulator ring as planned for the FNAL $\bar{p}$ - source.[1] At p_p = 120 GeV/c, $p_{\bar{p}}$ = 10 GeV/c and for a target and collector (lithium lens) configuration similar to that of the FNAL-source we obtain for the number of $\bar{p}$'s produced:

$$N_{\bar{p}} \simeq 62 \cdot N_p \cdot \epsilon \frac{\Delta p}{p}\ ,\ \text{for } 2 \cdot 10^{-5} m \lesssim \epsilon \lesssim 4 \cdot 10^{-5}\ m \quad (4)$$

where N_p is the number of protons on target, ϵ the unnormalized $\bar{p}$ emittance and $\frac{\Delta p}{p}$ the $\bar{p}$ momentum spread Table II gives an example parameter set meeting our flux requirements:

Proton Momentum	P_p	120 GeV/c
$\bar{p}$ production momentum	$P_{\bar{p}}$	10 GeV/c
Repetition period	τ_r	1s
No. Protons on target	N_p	$6 \cdot 10^{12}$*)
$\bar{p}$ emittance	ϵ_x, ϵ_z	20 μm [unnormalized]
$\bar{p}$ momentum spread	$\frac{\Delta p}{p}$	4%
No. of p's per pulse	$N_{\bar{p}}$	$3 \cdot 10^8$
p flux	ϕ	$3 \cdot 10^8 s^{-1}$

Table II: $\bar{p}$-Production Parameters

The debuncher is assumed to reduce $\frac{\Delta p}{p}$ to 0.25%[1] corresponding to a longitudinal $\bar{p}$ density $\Psi_{in} \simeq 12\ eV^{-1}$. Assuming a circumference of ~ 800 m for both debuncher and accumulator we therefore have to provide a longitudinal phase space compression of only 350 to reach $\Psi_{max} \simeq 4.3\ 10^3 eV^{-1}$, as derived from $N_{\bar{p}}$ and $\epsilon_{\parallel}$ in the collider, while the transverse emittances must be reduced by a factor 20.

Description of $\bar{p}$ Cooling and Accumulation

As indicated above, $3 \cdot 10^8$ $\bar{p}$'s are injected every second into the debuncher where the momentum spread is reduced to 0.25% by RF-bunch rotation and adiabatic debunching. While the $\bar{p}$'s reside in the debuncher their emittance is reduced to 3μm (~ 30μm normalized) by stochastic cooling. They are then transferred to the accumulator where they are stochastically stacked[2] and where the transverse emittance is reduced to 1 μm [unnormalized]. After ~ 200 s the core of the stack contains ~ $6 \cdot 10^{10}$ particles of the required phase space density of ~ $4.3 \cdot 10^3$ eV^{-1}. There exist many options for further processing of the antiprotons whose details with regard to RF-system requirements, beam stability, extraction and injection manipulations need to be worked out. One extreme possibility is to extract a single bunch (~ $5 \cdot 10^{10}$ particles) from the

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*) might require target sweeping[1]

accumulator, accelerate it through boosters 1 and 2 and hold it at 1.4 TeV in the main ring, repeating the procedure 250 times. Another possibility is to accelerate in booster 1 to 200 GeV and create an RF-stacked, coasting beam in booster 2. Such a procedure, which again could be performed in many variations, will result in a coasting beam of $1.2 \cdot 10^{13}$ $\bar{p}$'s with $\frac{\Delta p}{p} \sim 4.5 \cdot 10^{-3}$ (assuming a dilution factor of 1.5). A modest stochastic cooling system could reduce this to the desired $\frac{\Delta p}{p} \simeq 3 \cdot 10^{-3}$. A coasting beam in booster 2 also allows one to cool the beam further transversely; a normalized emittance of 1 μm seems perfectly feasible. This is not required for the present collider concept, but would allow for variations in collider circumference or number of $\bar{p}$'s required.

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:

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

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[3]:

$$S\,\frac{\xi}{n} = R(G_o\zeta) \qquad (6)$$

where $n = (f_{max} - f_{min})/f_o$, G_o is the overall system gain (average over working band) and R(x) is a simple integral[3]. ξ is defined as:

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

$$\zeta \cong \frac{0.75\ N}{f_o n \frac{\Delta p}{p} n}, \text{ for a parabolic distribution of full width } \frac{\Delta p}{p} \qquad (7b)$$

For $G_o\xi = 0.4$ we obtain $s\,\frac{\xi}{n} \simeq 1$[3], and with $\eta = 4 \cdot 10^{-3}$, $f_{max} = 8$ GHz, f_{min} 4 GHz the following values follow: $\xi \simeq 5.6\ 10^3$, $n \simeq 1.07\ 10^4$, $G_o \simeq 3.75\ 10^{-5}[s^{-1}]$, and $s \simeq 1.9\ s^{-1}$ which implies a sevenfold reduction of the emittance 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.[3] Assuming loop couplers made up by 70 Ω striplines in push-pull configuration for both PU's and K's we arrive, based on standard expressions[3], at the approximate system parameters summarized in Table III.

Two such systems, one for each transverse phase plane, are required. These are substantial systems but they greatly facilitate the accumulator design and their design is, at least conceptually, straight forward. A certain R and D effort is certainly required to design optimal 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 range.

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

Table III Approximate Parameters for Debuncher Transverse Cooling System

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.

An analogous analysis shows that a system with 256 PU's and K's, ~ 100 dB amplifier gain and a frequency range from 8 to 16 GHz installed in booster 2 ($\gamma_t \simeq 25$) will be able to cool ~ 10^{13} $\bar{p}$'s at 200 GeV from $\varepsilon_N = 10$ μm to $\varepsilon_N = 1$ μm in ~ 3000 s.

A stochastic stacking system similar to that of the CERN-AA-ring[4] or the FNAL p-source will be used to achieve the required longitudinal phase space compression. In order to handle the flux of $3\ 10^8 s^{-1}$ 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 will 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.[2,3] This requires for an octave bandwidth

$$\mathrm{Re}\Big\{G(x)\Big\} \cong \frac{\alpha\ \phi_o}{\Psi(x)}\ \frac{f_o}{f_{max}}\ ,\quad 1 \leq \alpha \leq 2 \qquad (8)$$

where $x = E - E_o$, and G(x) is the gain[3], i.e. the single particle rate of change of energy, assumed independent of harmonic number.

From the equation[3])

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

then follows $E_D \simeq 20$ MeV with $\alpha \simeq 1.4$, $|n| = 4 \cdot 10^{-3}$ and some allowance for the fact that G will not be purely real. With these values for n and E_D 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 $\frac{\Delta p}{p} \approx 1.2\%$ width. Some important system parameters as derived from (9) and (8) are summarized in Table IV.

f_{max}, f_{min}	8 GHz, 4 GHz
$n_{pu} = n_k$	1024
G_A	$\sim 1.41\ 10^6$ [~ 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)	$\approx 220\ e^{-\frac{x}{E_D}}$

Table IV: Accumulator Stack Tail System Parameters

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[1,2,4] with appropriately adjusted gain should make the thermal noise problem totally innocuous and provide some additional peaking of the distribution function ψ.

Conclusion

Stochastic cooling is capable of providing a flux of ~ $3 \cdot 10^8$ $\bar{p}$/second, adequate to fill a 20 TeV collider in ~ 12 hours for operation at $\mathcal{L} \approx 10^{32} cm^{-2} s^{-1}$. This represents an order of magnitude improvement over the FNAL-source design goal. It is made possible mainly due to 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 ($\lesssim$ 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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