STOCHASTIC COOLING IN HADRON COLLIDERS

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Abstract

Stochastic cooling in big hadron colliders is hampered by the high particle density, the bunch structure and by an unexpectedly large "RF-activity" up to very high frequencies. The more modest goal of tail cleaning in the LHC is made difficult due to the high discrimination required for pick-ups which selectively observe the beam halo only. This paper reviews sources of these difficulties, which have so far frustrated attempts to apply stochastic cooling to bunched beams at high energy.

1 INTRODUCTION

There is a wide interest in cooling the bunched beam in the large hadron colliders at collision energy. The main motivations are:

- To gain in luminosity by reducing the beam size (HERA proton ring [1]).
- To counteract the luminosity decrease due to emittance degradation (HERA [1], TEVATRON [2], RHIC [3] SP$\bar{\text{P}}$S [4]).
- To clean the beam halo (LHC).

In principle these goals could be attained by any cooling method. However, all of them are severely constrained by the harsh environment of modern colliders. Stochastic cooling, the only method to be considered in the present report, meets with difficulties which are linked to the fact that the beam is tightly bunched and that the density in the bunches is very high. In addition, the machine is very large and there are many constraints on the optics. All these characteristics are not easily reconciled with the needs of an optimised stochastic cooling system.

The present report recalls these difficulties and discusses an additional dilemma, that has shown up in experimental tests of bunched-beam stochastic cooling.

2 EXPECTED DIFFICULTIES

Features of bunched-beam stochastic cooling were identified already some time ago [5]. To make an estimate of the cooling time one can replace the bunches by pieces of a coasting beam with the particle number

$$N \rightarrow N_{eff} = N_b \cdot \frac{2\pi R}{\ell_b} \qquad (1)$$

Here N_b is the number of particles per bunch and $2\pi R/\ell_b$ (circumference of the ring/bunch length) is the bunching ratio. This definition of N_{eff} can be used for one or several circulating bunches; one just has to take N_b and ℓ_b for each individual bunch.

With the substitution of Eq. (1), the simple coasting beam relation [6] for the cooling time becomes :

$$\tau = \frac{N_{eff}}{W} \cdot constant. \qquad (2)$$

In this equation $W = \Delta f$ is the bandwidth of the cooling system and the constant, (= 5 to 50 in existing systems), is a factor, which depends on the success in solving the mixing-, noise- and power-problems [6]. In the rest of this report *constant* = 5 will be taken.

It should be clear that Eq. (2) is a crude approximation. In fact, it gives a lower limit of τ, which can only be reached when additional conditions are satisfied. The advantage of this simple form is that it clearly exhibits the influence of the particle density. In modern colliders the bunching ratio $2\pi R/\ell_b$ is very high, about 10^4 e.g. in the former SPS collider [4] and 10^5 in the LHC. In such cases a very large bandwidth is required to obtain cooling times of say 10 hours which are short enough ($\tau_{cooling} < \tau_{luminosity}$) to combat the luminosity decay.

Present technology permits a bandwidth of about 10 GHz. With the SPS collider as an example, one obtains for $N_b = 10^{10}$ particles per bunch τ = 14 hours from Eq. (2). This is just about acceptable to improve the luminosity with a life-span of one day.

Another fundamental limitation is connected to the frequency structure of the bunched beam. A bunch circulating in the machine presents a current source to a pick-up with a spectrum of equidistant lines of height

$$I_n = 2N_b e f_0 \qquad (3)$$

at the harmonics nf_o of the revolution frequency f_o up a cut-off determined by the "bunch frequency"

$$f_b = \frac{1}{T_b} = \frac{\beta \cdot c}{\ell_b} \qquad (4)$$

The roll-off of this spectrum depends critically on the exact bunch shape. For the two extremes of a Gaussian bunch (with a bunch length defined as 4 times the rmsduration $T_b = 4\sigma_t$) and a rectangular bunch (of total duration T_b) one has

$$I_{(f)} = I_n \exp\left[-\frac{\pi^2}{8}(fT_b)^2\right] \qquad \text{and}$$

$$(5)$$

$$I_{(f)} = I_n \frac{\sin(\pi fT_b)}{\pi fT_b} \qquad \text{respectively}$$

Hence the roll-off (envelope of $I_{(f)}$) is also Gaussian and linear (proportional to $1/f$) respectively. This big difference points to the difficulty of choosing the bunch model for the calculation.

The "coherent bunch spectrum" has to be compared to the Schottky noise signal used for stochastic cooling. At high frequency

$$f \ge f_\eta = \frac{f_0}{\eta \frac{\Delta p}{p}} \quad ; \ \eta = \left|\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right|, \qquad (6)$$

(where γ_t is the transition energy factor) the Schottky noise becomes continuous and the current per band of width f_0 is given by

$$ef_0 \sqrt{2N_b} \qquad (7)$$

At lower frequency, the height of the Schottky bands increases with f_η / f but this is not important for the present qualitative consideration.

One concludes that the bunch lines at low frequency are by $\sqrt{2N_b}$ i.e. typically by 5 to 6 order of magnitude higher than the Schottky noise (see Fig. 1).

The idea then is to choose the cooling band at high frequency ($f > 10\, f_b$ say) where the bunch lines have decreased by $\sqrt{2N_b}$ and "vanish" below the Schottky noise (see Fig. 1). For a bunch length $T_b = 3$ ns ($\ell_b \approx 1$ m) this condition requires a cooling band starting above 3 GHz. For a smooth bunch whose spectrum falls of with

$$(f / f_b)^k \qquad k \ge \sqrt{2N_b} = 5 \div 6 \qquad (8)$$

the lines are then well below the noise at $f = 10\, f_b$. For a rectangular bunch, a much higher band

$$f / f_b \ge \sqrt{2N_b} \qquad (9)$$

is required, which is not accessible with present microwave technology.

3 UNEXPECTED DIFFICULTIES

Observations with Schottky noise pick-ups both at the SPS [4] and at the TEVATRON [2] have revealed a very strong "RF-activity" which persists at frequencies considerably higher than 10 f_b and in fact extends up to the highest bands accessible (≈ 10 GHz).

These strong signals obstruct stochastic cooling. Their nature is not fully understood but probably two effects play a role: coherent instabilities and a tendency of intense bunches to develop a non-Gaussian structure. An explanation in this sense is given in Ref. 7.

Tests to explore this problem were performed in LEAR [8] and in the AC [9]. In LEAR the frequency spectrum of dense bunches obtained after electron cooling showed a cut-off at 5 f_b (decrease to 10^{-4} of the

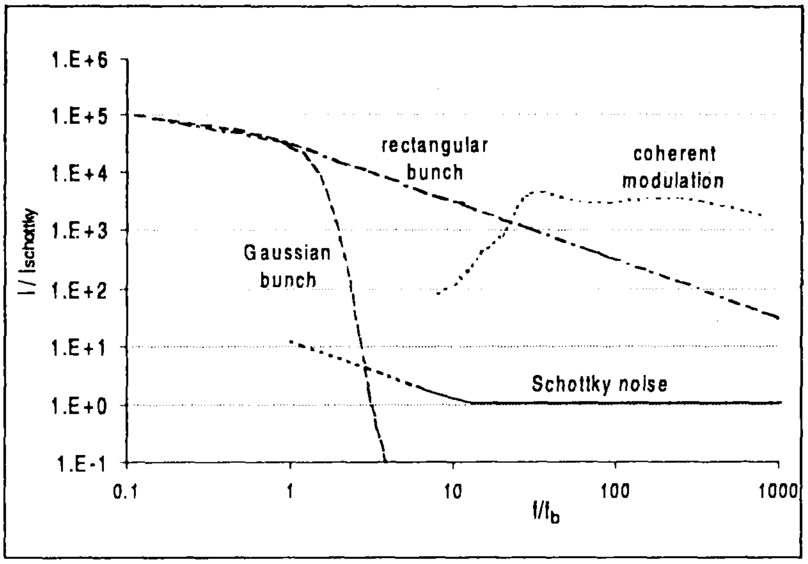

Fig. 1: Sketch of the envelopes of the bunch current spectrum.

low frequency line height) as long as the intensity was low, $N_b \leq 10^9$, for 150 nsec bunch length. However, at $N_b = 5\times10^9$, the cut-off was as high as 45 f_b thus indicating a strong intensity dependent shift.

In the AC, a 50 ns long bunch with $N_b \approx 10^7$ particles could be obtained bunching the cooled beam with the h=1 RF system. When switching off the stochastic cooling, strong coherent lines occurred up to the highest observable frequencies (about 3 GHz). They could be reduced to the noise level when the longitudinal cooling system was reactivated. Both longitudinal and transverse cooling then took over, although with a slow cooling rate, once the longitudinal system, acting as a damper, had ironed out the coherent lines.

The presence of the undesired coherent lines at very high frequencies has been a major obstacle for the successful operation of bunched-beam cooling at the CERN SPS and the FNAL TEVATRON. One may consider using networks with very steep characteristics that filter out these undesired spectral components. This has been tried at FNAL but so far with only limited success. Filters with the required specifications could be implemented using optical fibre technology and optical ring resonators.

The high peak amplitude of the pick-up signal did, however, seriously saturate the head amplifiers and led to intermodulation. Once intermodulation products are in the system, it is virtually impossible to get rid of them without perturbing the desired signal. For this reason, the provision of a passive, low-loss filter ahead of the first amplifier was discussed in 1996 to smear out the high peak amplitude signal (by modifying the phase in the passband) without changing the bandwidth of the cooling system (e.g. 4-8 GHz). This can be done using a similar technique as for chirp radar signal processing, which also applies pulse expanders and compressors.

Such filters can be realised (low loss, passive) using tapered waveguides below cut-off. Once the high peak signal problem is solved the unchanged frequency band passes through the complete cooling amplifier and filter chain and the filters can now remove the coherent lines. After the power amplifiers, the inverse dispersion filter (pulse compressor, also passive and low loss) would cancel the phase perturbation caused by the pulse expander. As an additional advantage, the required peak power of the final power amplifier can be reduced by the expansion/compression factor. The design and testing of such a system requires a considerable effort that has not been available so far.

4 HALO CLEANING

Let us now look at the somewhat different goal of bringing particles from the bunch halo back into the core by some sort of stochastic cooling.

In the LHC, this procedure could assist or even partly replace the sophisticated system of collimators necessary to avoid uncontrolled particle loss [10].

Table 1: Some LHC proton bunch parameters

Particles per bunch	10^{11}
Bunch length (4σ)	0.3 m
Circumference	27 Km
Bunching ratio	10^5

A glance at the proton bunch parameters (Table 1) convinces us, that stochastic cooling of the entire bunch, as discussed above, on any reasonable timescale is excluded with present-day bandwidth ($W \leq 10$ GHz). If, however, one could build a pick-up which only sees the 10^7 particles in the transverse halo instead of the entire 10^{11}, then the cooling of these 10^7 particles/bunch might be possible. The problem is to design a pick-up with a discrimination core/halo of 10^{-4}.

As a model we take a beam with a Gaussian density distribution in the transverse plane (x) and a pick-up as sketched in Fig. 2. The geometrical sensitivity [11] of this pick-up can be approximated by

$$\exp\left(-\frac{\pi}{h}\left|\,|x|-W\right|\right) \qquad (10)$$

see Fig. 2, with the maximum at the position ($|x| = W$) of the gap. Choosing $W = 3\sigma_x$ and respecting a vertical aperture $h = 8\sigma_y$ we find a discouragingly large aspect ratio $\sigma_x/\sigma_y = 24$ (lattice functions $\beta_x/\beta_y = 600$ for equal emittance $\varepsilon_x = \varepsilon_y$).

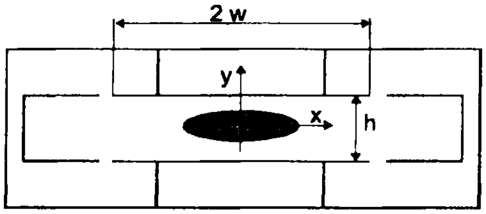

Fig. 2: Sketch of a pick-up sensitive to the beam halo.

For operation of the LHC with lead ions [10] with 10^9 particles/bunch, tail cleaning and perhaps even emittance containment would be easier. However, for these heavy ions, the luminosity life is dominated by the loss due to disintegration and charge exchange in the high-energy collisions. Therefore, the gain by cooling is less pronounced.

5 DIFFICULTIES RELATED TO WAVEGUIDE MODES IN THE BEAM PIPE

The design of microwave stochastic cooling pick-ups and kickers (both for cooling and halo cleaning) at frequencies beyond several GHz is a challenge. The availability of printed circuit techniques on ultra high vacuum (UHV) compatible substrate materials can help to reduce the difficulties due to watchmakers'-precision fine mechanics.

For the pick-up and kicker structures themselves higher order waveguide or cavity modes can already pose a serious problem and frequently lead to undesired deformation of the calculated TEM wave response. The addition of UHV compatible damping material such as certain ferrites and/or lossy ceramic dielectrics (e.g. silicon carbide) helps to control this kind of surprise. One has to fight not only TM modes, which can couple directly with the beam, but also TE modes which may couple indirectly via mode conversion, an effect that can happen at any discontinuity. These microwave modes (both TE and TM) can lead to undesired signal transmission beyond waveguide cut-off between pick-up and kicker and thus render the cooling system unusable. Installation of non magnetic, microwave-absorbing material in the beam-pipe has been used in the CERN AA and AC to prevent this kind of feedback channel.

In a large storage ring with few bunches, one can apply time-domain gating to avoid system oscillation, but for a large number of bunches this scheme will not be easily applicable Because of this difficulty, together with the other problems of bunched-beam cooling discussed before, the idea has not been persued further.

6 CONCLUSIONS AND OUTLOOK

The unexpected RF structure in the bunches up to very high frequencies turned out to be the main obstacle for successful bunched-beam stochastic cooling in large machines like the CERN-SPS and TEVATRON. Surprisingly, one of the very first experiments on stochastic cooling (ICE) did work successfully in a bunched beam mode, although with a very small bunching factor and a very long bunch.

The lessons learned from past experience and the fact that stochastic cooling of a bunched beam did work reasonably well in small machines (CERN AAC and FNAL debuncher) is however an encouragement to tackle again the problem in large machines. A possible approach for this task would be to seek a clear understanding of the physics of the residual RF in the bunch. This may require both theoretical work and experimental investigations on existing large machines. The required diagnostics in the GHz range is non standard. It will be essentially a kind of stochastic cooling pick-up. High sensitivity will be required to see the weak Schottky signals and a large dynamic range of the electronic amplifier chain is important in order not to run into intermodulation and saturation problems. The best solution certainly would be to get rid of the unwanted RF structure e.g. by means of a feedback system which has a stabilising effect on the bunch.

If it turns out that one has to live with this RF structure, a possible remedy could be the low-loss, passive pulse expander/compressor concept mentioned above, together with very selective notch filters on the revolution harmonics. As a by-product of the expander/compressor concept, the available power of the final amplifier can be considerably reduced. The design of a microwave-mode insensitive and broadband halo-cooling pick-up and kicker structure is another challenge that could be taken up in the future.

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