BEAM-BEAM INTERACTION, ELECTRON CLOUD, AND INTRABEAM SCATTERING FOR PROTON SUPER-BUNCHES

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Abstract

Super-bunches are long bunches with a flat longitudinal profile, which could potentially increase the LHC luminosity in a future upgrade. We present example parameters and discuss a variety of issues related to such super-bunches, including beam-beam tune shift, tune footprints, crossing schemes, luminosity, intrabeam scattering, and electron cloud. We highlight the benefits, disadvantages and open questions.

INTRODUCTION

About 20 years after the CERN ISR stopped colliding protons against protons, its luminosity has not yet been reached by any of the succeeding hadron colliders. The impressive performance of the ISR is illustrated in Table 1.

Table 1: Parameters of past and present hadron colliders.

collider	commiss. date	energy per p [GeV]	peak lum. $\hat{L}$ $[10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$
ISR	1970	31	1.4
Sp$\bar{\mathrm{p}}$S	1980	315	0.06
Tevatron	1987	980	0.4
RHIC	2000	100	0.02 (pol.)

The Large Hadron Collider (LHC) at CERN is scheduled to come on line in 2007. With a design energy of 7 TeV, it aims at a luminosity of 10^{34} cm^{-2}s^{-1}, which is 70 times the ISR peak value. A recent feasibility study for an LHC upgrade [1] indicates various possibilities to further increase both luminosity and energy.

A characteristic feature of the ISR is that, unlike any of the later machines, it collided coasting (*i.e.*, unbunched) beams, at a high current. In a multi-TeV collider, like the LHC or its upgrade, this is not possible, since we must provide an abort gap without beam, for machine protection and beam removal, and the total current is limited by synchrotron radiation heat load. Nevertheless, there is a way to mimic the ISR. Namely, we can produce a quasi-coasting beam, if we confine one or several long bunches with a uniform ('flat') density profile by a barrier rf bucket. The collisions of such super-bunches was first proposed by K. Takayama for a VLHC [2]. It is made feasible by recent advances in rf technology [3].

From the beam dynamics perspective, super-bunches offer three distinct advantages: (i) A partial cancellation between central and long-range components of the beam-beam tune shift, which is realized by colliding the beams at two interaction points (IPs) with alternating (orthogonal) planes of crossing, so that the crossing planes are either horizontal and vertical, respectively, or, for example, tilted at 45° and 135°. The second arrangement is called 'inclined hybrid' crossing. (ii) Absence of PACMAN bunches at the head or tail of a bunch train, which, for conventional bunched beams, encounter an irregular number of long-range collisions and could suffer from a reduced beam lifetime or enhanced emittance growth. (iii) The possibility of avoiding beam-induced multipacting and electron-cloud build up. However, at the same time the particle-physics detectors face new challenges, *e.g.*, an increased number of pile-up events and an enhanced radiation damage, which is intrinsically linked to the higher luminosity.

Prospects and beam dynamics for super-bunches in an upgraded LHC have been discussed in detail in [4].

LUMINOSITY AND TUNE SHIFT

Hadron colliders are limited by the beam-beam tune shift. Based on the SPS experience, a maximum total tune shift ΔQ_{tot} (sum over all IPs) of 0.01 appears to be a realistic and conservative upper value and has been the design criterion for the LHC. For a constant beam-beam tune shift, the LHC luminosity with alternating crossing at two IPs can be raised above the nominal value by increasing the product of bunch length and crossing angle roughly in proportion to the bunch population [5]. Figure 1 suggests that a factor 5–6 increase in luminosity may be attainable for Gaussian bunches.

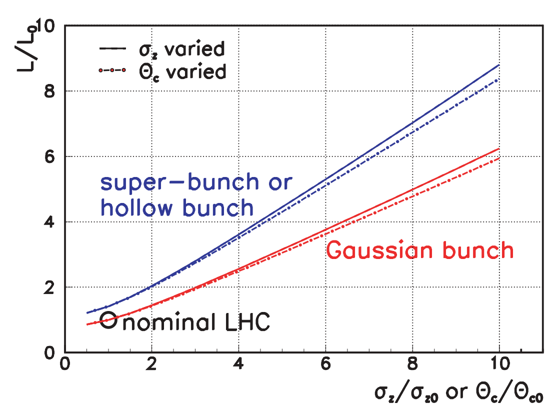

Figure 1: Relative increase in LHC luminosity vs. rms length (or crossing angle) for Gaussian or hollow bunches, maintaining a constant beam-beam tune shift with alternating crossing; axes are normalized to the nominal bunch length $\sigma_{z0} = 7.6$ cm and crossing angle $\theta_{c0} = 300\ \mu$rad, and to the luminosity at the beam-beam limit ($L_0 \approx 2.3 \times 10^{34}$ cm^{-2}s^{-1}) [5].

As also shown in Fig. 1, an additional factor of 1.4 can be gained by colliding bunches with a flat longitudinal profile, *e.g.*, super-bunches, instead of Gaussian bunches. In both cases, the parameter region of interest is (1) an rms bunch length σ_z much larger than the transverse beam size σ^*, *i.e.*, $\sigma^* \ll \sigma_z$, (2) a large Piwinski parameter $\theta\sigma_z/(2\sigma^*) \gg 1$, and (3) a full crossing angle θ which is small compared with 1 but larger than the rms IP beam divergence, or $\sqrt{\sigma^*/\beta^*} \ll \theta \ll 1$. In this regime, the luminosity for Gaussian bunches in [5] simplifies to [4]

$$L^{\text{Gaussian}} \approx \frac{f_{\text{coll}}\gamma\epsilon_N}{r_p^2\beta^*}\Delta Q_{\text{tot}}^2 \frac{\pi\theta\sigma_z}{2\sigma^*} , \qquad (1)$$

where f_{coll} is the bunch collision frequency, and ϵ_N the normalized 1-σ emittance. The expression for a uniform bunch of length l_{flat} is identical, only that σ_z is replaced by $l_{\text{flat}}/\sqrt{\pi}$. The total tune shift for either profile is [4]:

$$\Delta Q_{\text{tot}} \approx \sqrt{\frac{2}{\pi}\frac{r_p\beta^*}{\gamma\sigma^*\theta}}\lambda , \qquad (2)$$

where λ denotes the (peak) line density. Combining (1), or its equivalent for a uniform bunch, with (2) confirms that the luminosity for a flat profile is $\sqrt{2}$ higher than for a Gaussian bunch of equal total tune shift and charge [4].

Super-bunches are only one way to create a flat profile; another possibility are shorter 'hollow bunches', already available from the PS booster [6].

Table 2 compares the nominal and ultimate LHC design parameters with three tentative options for a luminosity upgrade. All upgrades employ a reduced β^*, and promise luminosities a factor 7–9 above nominal. In the second right-most column we consider a large 'Piwinski parameter', *i.e.*, $\sigma_z\theta/(2\sigma^*) \gg 1$, with enhanced crossing angle and bunch current, but still keep 2808 bunches. The two sets of numbers in this column refer to either Gaussian bunches (up) or to uniform bunches (down). The far right column contains parameters for a single super-bunch.

Figure 2 shows the transverse diffusion rate (increase of action variance per turn) on a logarithmic scale, obtained from a weak-strong beam-beam model as in [8], for super-bunches colliding at two different crossing angles in two orientations. For $\theta = 1$ mrad, the diffusion rate is much smaller than in the nominal LHC, and there is no threshold 'diffusive aperture' as for the latter (see, *e.g.*, [8]). Figure 3 displays tune footprints, calculated for amplitudes up to 10σ by a frequency-map analysis [9]. Gaussian and super-bunches are compared for two different crossing schemes. The maximum tune excursions are smaller for super-bunches and for inclined hybrid crossing.

ELECTRON CLOUD

A further important benefit of super-bunches is an almost complete suppression of the electron-cloud build up and the associated heat load. If the beam profile is uniform, only photo-electrons generated at the very end of the bunch passage can be accelerated and acquire energy in the beam field. All other electrons traverse a quasi-static beam potential without any net energy gain.

As an illustration, Fig. 4 shows the heat load per meter, simulated assuming 10% linearly rising and falling bunch edges, as a function of the super-bunch length. The luminosity is held constant, equal to 6×10^{34} cm^{-2} s^{-1} at $\beta^* = 0.25$ m and $\theta = 300$ μrad, by decreasing the number of bunches (and increasing their spacing) in proportion

Table 2: Nominal and ultimate LHC parameters compared with those for three hypothetical LHC upgrades based on either large Piwinski parameter or super-bunches [1]. The normalized transverse emittance (1σ) is 3.75 μm, and the beam energy 7 TeV, for all the cases shown.

parameter	nom.	ult.	upgrades	
no. of bunches n_b	2808	2808	2808	1
rms bunch length σ_z [cm]	7.6	7.6	7.6, 4.2	7500
rms energy spread σ_δ [10^{-4}]	1.1	1.1	1.1, 3.7	5.8
beta at IP [m] β^*	0.5	0.5	0.25	0.25
crossing angle θ [μrad]	300	315	485	1000
beam current I_b [A]	0.56	0.86	1.3, 1.3	1.0
luminosity L [10^{34} cm^{-2}s^{-1}]	1	2.3	7.3, 9.7	9.0
σ_δ IBS growth time τ_{IBS} [h]	134	86	56, 674	1712

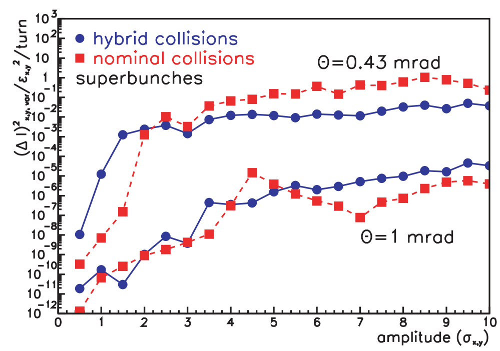

Figure 2: Simulated diffusion rate vs. amplitude for intense super-bunches of $\lambda = 8.8 \times 10^{11}$ m^{-1} [4].

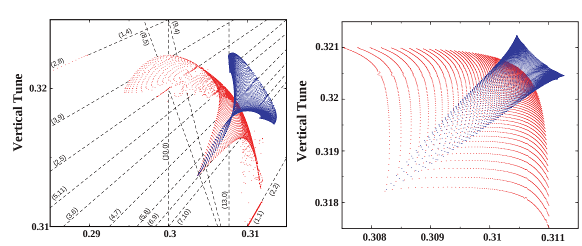

Figure 3: Tune footprints comparing $x - y$ (red) and inclined hybrid crossings (blue) for nominal Gaussian bunches at $\theta = 300$ μrad (left) and intense super-bunches of $\lambda = 8.8 \times 10^{11}$ m^{-1} with $\theta = 1$ mrad (right) [4].

to the bunch length. The maximum available cooling capacity in the LHC arcs is about 1 W/m. For total bunch lengths of 1 m or higher, the electron-cloud heat load becomes insignificant, even at a maximum secondary emission yield as large as $\delta_{\rm max} = 1.4$. This should be compared with the nominal LHC, where $\delta_{\rm max} < 1.2$ is required, or with alternative upgrade options entailing a larger number of bunches, where even for $\delta_{\rm max} = 1.1$ the cooling budget is exceeded [1].

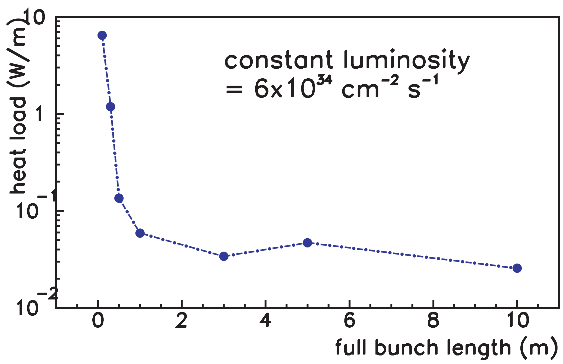

Figure 4: Simulated heat load in an LHC arc dipole due to the electron cloud vs. super-bunch length for $\delta_{\rm max} = 1.4$, and $\lambda = 8 \times 10^{11}$ m^{-1} [7].

We have simulated the emittance growth due to the interaction with an electron cloud for Gaussian and uniform bunches of identical rms length (75 mm) and bunch population [4]. The emittance growth of the uniform bunch is about 2 times smaller than for the Gaussian. The main difference, aside from the bunch profile, is the longitudinal dynamics. The regular Gaussian bunch is held in a sinusoidal rf bucket, where all particles oscillate at about the same synchrotron tune $Q_s = 0.0116$. The super-bunch is confined by steep rf barriers, so that its synchrotron tune, $Q_s = C\alpha_c\delta/(2l_{\rm flat})$, depends linearly on the particle momentum δ (where $l_{\rm flat}$ is the full bunch length, C the cirumference, α_c the momentum compaction). The larger synchrotron-tune spread has a stabilizing effect.

INTRABEAM SCATTERING

An important emittance-growth mechanism in hadron colliders is intrabeam scattering (IBS). The difference in IBS growth rates between a Gaussian bunch and a super-bunch arises solely from integrating the square of the longitudinal density $\lambda(s)$. The relation between the two IBS growth rates is

$$\frac{1}{\tau_{\rm IBS}^{\rm flat}} = \frac{2\sqrt{\pi}\sigma_z}{l_{\rm flat}} \frac{N_{b,\rm flat}}{N_{b,\rm Gaussian}} \frac{1}{\tau_{\rm IBS}^{\rm Gaussian}} , \qquad (3)$$

assuming that the momentum spread is the same. Then, for equal bunch population N_b and $l_{\rm flat} = \sqrt{2\pi}\sigma_z$, both luminosity and IBS growth rate of a uniform (super-)bunch are $\sqrt{2}$ times larger than for a Gaussian bunch. IBS growth rates can be calculated by MAD [10], which computes the Bjorken-Mtingwa expressions [11], or estimated by further approximating the simplified formula of [12] as

$$\frac{1}{\tau_{{\rm IBS},\delta}^{\rm flat}} \equiv \frac{1}{\sigma_\delta}\frac{d\sigma_\delta}{dt} \approx \frac{\sqrt{\pi} r_p^2 c N_b (\log)}{8\gamma^3 \epsilon_\perp^{3/2} l_{\rm flat} \sigma_\delta^3} \frac{1}{\sqrt{\beta_\perp}\sqrt{\frac{1}{\sigma_\delta^2} + \frac{<\mathcal{H}_x>}{\epsilon_\perp}}} , \qquad (4)$$

and $1/\tau_{\rm IBS,x}^{\rm flat} \approx \sigma_{\delta^2} < \mathcal{H}_x > /(\epsilon_\perp \tau_{{\rm IBS},\delta}^{\rm flat})$, where $(\log)$ denotes the Coulomb logarithm, and $< \mathcal{H}_x >$ the average dispersion invariant. In Fig. 5, these estimates are compared with the exact MAD computation as a function of the momentum spread. The agreement is extremely good for the transverse plane. Longitudinally, there is a discrepancy up to 30% for large values of σ_δ, which is due partly to our rough averaging and partly to the simplifications in [12]. Fig. 5 illustrates that the IBS rise times increase substantially for larger momentum spread, which amounts to another possible advantage of the super-bunches.

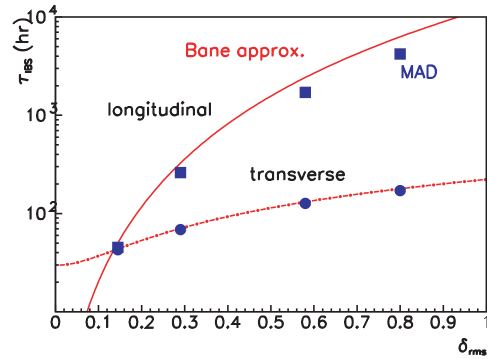

Figure 5: Intrabeam scattering growth times for super-bunches in the LHC vs. σ_δ, according to Eq. (4) (the lines) or calculated by MAD (the plotting symbols).

CONCLUSIONS

Super-bunch collisions in a future LHC upgrade promise a higher luminosity, that may reach ten times the nominal value, accompanied by an improved beam-beam dynamics, negligible heat load from electron cloud, and increased IBS rise times. The larger luminosity and IBS rise times may also be realized by hollow bunches. A number of open questions, such as PACMAN like forces acting on individual particles during part of their synchrotron motion and strong-strong beam-beam dynamics, remain to be explored.

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