Superbunch Hadron Colliders

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A novel concept of a high luminosity hadron collider is proposed. This would be a typical application of an induction synchrotron being newly developed. Extremely long bunches, referred to as superbunches, are generated by a multibunch stacking method employing barrier buckets at the injection into the collider and are accelerated with a step voltage induced in the induction gaps. Superbunches intersect with each other, yielding a luminosity of more than 10^{35} cm^{-2} sec^{-1}. A combination of vertical crossing and horizontal crossing must be employed in order to avoid any significant beam-beam tune shift.

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At CERN, the construction of the Large Hadron Collider (LHC) began in November 2000 and is scheduled to be completed in 2006. Recently, serious interest in the Very Large Hadron Collider (VLHC) has rapidly grown in the U.S., expecting to explore new physics beyond the LHC. Both colliders are entirely based on the conventional rf technology for acceleration and the longitudinal confinement of proton bunches. The luminosity is expressed as $L = F(k_b N_b^2 f_{\rm rev}\gamma/4\pi\varepsilon_n\beta^*)$, where k_b is the number of bunches per ring, N_b is the number of protons per bunch, $f_{\rm rev}$ is the revolution frequency, ε_n is the normalized rms transverse emittance (assumed to be the same in both planes), β^* is the beta function at the collision point, and F is the reduction factor caused by the finite crossing angle Φ. Although it is quite clear from the above expression what parameters must be improved to increase the luminosity, there are principal and practical limits on the size of beam/machine parameters: (1) the space-charge limit in the upstream accelerators imposes some limit on the ratio of the number of protons to the emittance $\Delta\nu(\approx N_b/\varepsilon_n) \le 0.25$; (2) the beam-beam limit, $\xi = N_b r_0/4\pi\varepsilon_n \le 0.004$/IP (interaction point), (r_0, classical radius of proton), is the other big constraint; (3) the capability of heat transfer in the cryogenics of the collider gives a synchrotron radiation limit, $P_{\rm rad}(\propto k_b N_b) \le$ a few watts/m; (4) time resolution of the particle detector requires a minimum bunch spacing something around 5 m and such bunch spacing is determined by the rf frequency in the upstream accelerators. In addition, a longitudinal size of each bunch is controlled by using higher frequency cavities in downstream accelerators and a collider and optimizing the rf voltage to match β^* so as to maximize the luminosity for a fixed N_b. Eventually the beam-occupation ratio against the entire accelerator circumference, $\kappa = \sqrt{2\pi}\, k_b\sigma_s/C_0$, is limited to 2% for the LHC [1] and 1%–3% for the baseline design of the VLHC [2].

If the heat deposited by synchrotron radiation on the cryogenic system can be removed by any efficient engineering efforts and the particle detector does not care about the minimum bunch spacing, the last issue to prevent the collider from reaching a much higher luminosity should be a sparse bunch population that is a limit of the conventional rf synchrotron. If the proton beams occupy most of the region along the collider circumference with an allowable momentum spread, the luminosity of hadron colliders would drastically increase. In the proposed scheme, 20%–30% of the circumference can be occupied by the proton beam instead of ~3%–4%. This situation is like continuous collisions between proton beams stored in two rings, as seen in Fig. 1.

In this Letter a novel scheme to realize such continuous collision is proposed. The luminosity is estimated to be at least 20 times higher than that in hadron colliders, based on conventional rf technology [hereafter, this type of collider is called the conventional hadron collider (CHC)]. The induction synchrotron recently being developed [3] is capable of generating an extremely long microsecond bunch called a superbunch, which keeps the same momentum spread and local intensity as that in the CHC scheme. After stacking superbunches at the final stage of the collider accelerator complex and accelerating them by a step voltage generated in the induction gaps to the collider energy, multiple superbunches in both rings are provided for collisions. The concept of a new type of collider, called a superbunch hadron collider (SHC), is described together with discussions of beam-physics issues. It is noted that the machine parameters of the SHC are the same as those of the CHC, except acceleration and interaction regions.

The first generation of coasting beam hadron collider is undoubtedly the ISR (CERN Intersecting Storage Rings)

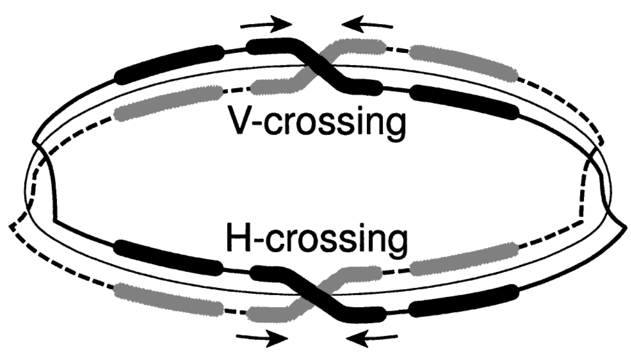

FIG. 1. Schematic view of a superbunch hadron collider.

that had been operated in the early 1970s at CERN. The ISR has demonstrated not only the novel acceleration technology of phase-displacement acceleration but also revealed various beam physics originated from space-charge effects between two casting beams of current concern [4]. Being inspired from the machine performance of the ISR and the ISABELLE design study, Keil *et al.* have carefully investigated the dependence of luminosity and beam-beam tune shifts in coasting beam colliders on machine/beam parameters and proposed a possible way to maximize the luminosity [5]. Some results will be refined in the following discussion on the SHCs.

Induction synchrotron.— A proton synchrotron employing induction cells (IC) instead of radiofrequency cavities is called an induction synchrotron (IS) and has been described in detail [3]. Acceleration and longitudinal focusing are independently achieved with different induction devices, which consist of an IC loaded by a nanocrystalline alloy and a pulse modulator rapidly switched in synchronization with beam acceleration. As schematically shown in Fig. 2, a dc-like induction acceleration is provided by the IC, which is energized with a long voltage pulse and a short reset pulse. The other type of ICs generates a pair of rectangular short pulses, forming a barrier bucket in the longitudinal phase space. The rectangular bucket can accommodate particles to its full capacity, creating a uniformly diffused longitudinal distribution of the particles. This uniformity is important for diminishing the space-charge effects in the transverse and longitudinal directions.

The ICs are energized with the solid-state power modulator using a fast switching element, such as an array of field effect transistors or a static inductive thyristor, to switch energy from a precharged capacitor bank to the IC. The switching frequency of the induction devices corresponding to the revolution frequency is quite important. The frequency or phase feedback in rf acceleration, which makes tracking against the ramping magnetic guide field possible, is replaced by an induction voltage feedback and a programmable change in the trigger timing. The status of the induction accelerating device R&D at KEK is reviewed in Ref. [6].

Multibunch stacking by barrier buckets, superbunch formation, and acceleration.— An accelerator system for a collider consists of an H^- linac, three- or four-stage booster rings, and a collider ring, as can be seen in the SSC (Superconducting Super Collider), LHC, and VLHC. In a case where the circumference of the first booster ring is sufficiently large to employ the principle of IS, a superbunch with a bunching factor of 0.76 can be created by a method called symmetric painting, which is described in detail in Ref. [7]. Then, multiple superbunches are stacked in the next booster ring, by utilizing two sets of barrier buckets. A superbunch injected into the next booster ring is captured by a matched barrier bucket. Each superbunch is moved adiabatically toward the edge of the stacking bucket and is then released into the stacking bucket in such a way that the reset timing for the edge voltage of the stacking bucket is delayed by the bunch length of the fresh bunch. After this stacking process, a newly generated superbunch is accelerated with the step voltage to the injection energy of the next ring. Superbunch formation in each booster stage depends on an accelerator complex. An example of the Fermilab accelerator complex has been presented in Ref. [8].

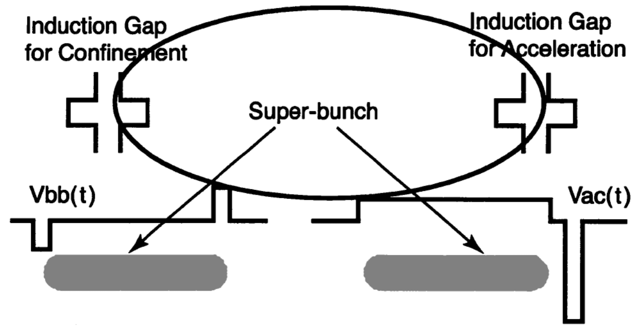

FIG. 2. Principle of the induction synchrotron.

Concept of collider.—The maximum pulse length of the accelerating induction voltage will be limited to the order of 1 μs for engineering reasons, such as the practical size of the manufactured induction core. Thus, the collider is occupied by multiple superbunches, and bunch spacing is used to reset the magnetic materials. In the case of a VLHC-size ring, the number of superbunches is several hundreds. In principle, the superbunches can occupy a considerable fraction of the ring circumference, 20%–30%, with a momentum spread determined by the barrier-bucket height. After reaching the flattop energy through collisions, a slight magnitude of accelerating voltage is held to replenish the energy loss due to synchrotron radiation, the superbunches being confined with the barrier buckets. Each of the superbunches intersects with its own counterpart in a half time period of the bunch length, as shown in Fig. 1.

The luminosity in the SHC is written in terms of that of the CHC with the same local beam density, using a function of crossing angle Φ and an effective size (2ℓ) of the particle detector,

$$L_{\mathrm{SHC}}(\Phi,\ell) = 4\,\frac{(k_{sb}\sigma_{sb})}{(k_b\sigma_s)}\,\frac{F_{\mathrm{SHC}}(\Phi,\ell)}{\sigma_s' F_{\mathrm{CHC}}(\Phi')}\,L_{\mathrm{CHC}}(\Phi') \quad (1)$$

with form factor:

$$F_{\mathrm{CHC}}(\Phi') = 1/\sqrt{1 + (\Phi'\sigma_s/2\sigma^*)^2} \qquad (\sigma^*\text{: rms beam size at IP}),$$

$$F_{\mathrm{SHC}}(\Phi,\ell) = \int_0^{\ell} \frac{\exp(-\{\gamma\Phi^2 s^2/2\beta^*\varepsilon_n[1 + (s/\beta^*)^2]\})}{[1 + (s/\beta^*)^2]}\,ds\,,$$

where k_{sb}, k_b are the numbers of superbunches and rf bunches per beam, σ_{sb} is the superbunch length (full), $\sigma_s' = \sqrt{2\pi}\,\sigma_s$ (σ_s rms rf bunch length), Φ, Φ' are the collision angles for the SHC and CHC, respectively, and 2ℓ is the effective size of a detector. For simplicity, the Gaussian distribution in the longitudinal direction for the CHC is replaced by a rectangular distribution with a bunch length, σ_s', and the number of protons per bunch, N_b, leading a uniform/peak line density, $\lambda = N_b/\sigma_s'$. Deriving the above equation, similar optics and the Gaussian distribution for both transverse directions are assumed. In the limit of $\Phi = \Phi' = 0$, $k_{sb} = k_b$, $\sigma_{sb} = \sigma_s'$, $2\ell = \sigma_s'/2$, Eq. (1) becomes $L_{\mathrm{SHC}}(0, \sigma_s'/4) = L_{\mathrm{CHC}}(0)$. The factor of $(k_{sb}\sigma_{sb})/(k_b\sigma_s')$ in Eq. (1) represents the relative ratio of beam occupation in the SHC and CHC. As mentioned earlier, the parameter is around a factor of 20. For a typical example of the VLHC stage-1 design, where $\sigma_s' = 15$ cm, $\beta^* = 0.5$ m, $\varepsilon_n = 1$ μrad, $mc^2\gamma = 20$ TeV, $2\ell = 5$ m, the normalized luminosity is shown as a function of Φ in Fig. 3. The calculation indicates that the luminosity is attractive even with large crossing angles.

Beam physics issues.—In the SHC scheme, the incoherent beam-beam tune shift is of big concern. The incoherent beam-beam tune shift can analytically be evaluated by manipulating the nonoscillating terms in the beam-beam perturbing potential. The tune shift normalized by that in the head-on collision of the CHC scheme is given in the following forms [5]:

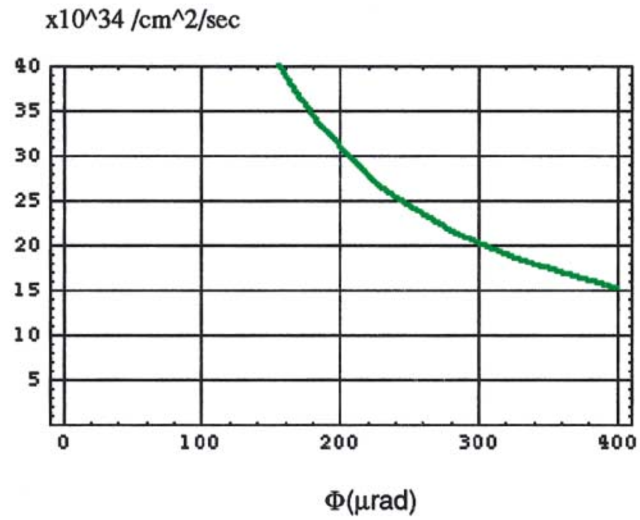

FIG. 3 (color). Luminosity as a function of the crossing angle for the VLHC stage-1 parameter.

$$\frac{(\Delta\nu_x)_\Phi^{\mathrm{SHC}}}{\xi} = \frac{8\beta^*\varepsilon_n}{\sigma_s'\gamma}\int_0^{l_{\mathrm{int}}} \frac{1 + s^2/(\beta^*)^2}{\Phi^2 s^2}\left[1 - \exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*[1 + s^2/(\beta^*)^2]}\right)\right] ds\,, \tag{2}$$

$$\frac{(\Delta\nu_y)_\Phi^{\mathrm{SHC}}}{\xi} = \frac{8}{\sigma_s'}\int_0^{l_{\mathrm{int}}} \exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*[1 + s^2/(\beta^*)^2]}\right) ds - \frac{(\Delta\nu_x)_\Phi^{\mathrm{SHC}}}{\xi}\,, \tag{3}$$

where crossing in the vertical direction is assumed and $2l_{\mathrm{int}}$ is the size of the interaction region, $2\ell \ll 2l_{\mathrm{int}} \ll \sigma_{sb}$. In the limit of $\Phi = 0$, $2l_{\mathrm{int}} = \sigma_s'/2$, Eqs. (2),(3) become unity. The numerical values for both directions are shown as functions of Φ in Fig. 4. A change in the polarity for the vertical direction beyond some critical crossing angle is notable. This is understandable from speculating that a particle is focused due to space-charge effects as it leaves from the beam-core region, while it is defocused in the core region. A longer stay outside the core region gives net focusing through the interaction region beyond a certain critical crossing angle. The characteristics strongly suggest that hybrid crossing [vertical crossing in one interaction region (IR) and horizontal crossing in the other] should be employed in the SHC scheme. The collider rings necessarily have twists. By hybrid crossing, as schematically shown in Figs. 1 and 5, the beam-beam tune shift largely diminishes for both directions. The relative tune shifts for both directions are less than 2.0 for the crossing angle beyond 150 μrad. The magnitude is sufficiently acceptable, because it is equal to the integrated head-on beam-beam tune shift in the CHC scheme with a couple of IRs.

The beam-beam tune-shift parameters during nominal operations are rather similar to those in the CHC, assuming the same local density. Recent simulations based on the weak-strong model have indicated that an incoherent tune spread due to the continuous parasitic beam-beam interaction is bounded within a tolerable level of 0.015 without any emittance blowup, assuming the crossing angle of 400 μrad. The full footprint on the tune diagram is like a wing, as shown in Fig. 6. This characteristic has already been recognized in earlier work [9]. The tune of large emittance particles locates on the tips of the wing. For the purpose of controlling the tune spread, inclined crossing

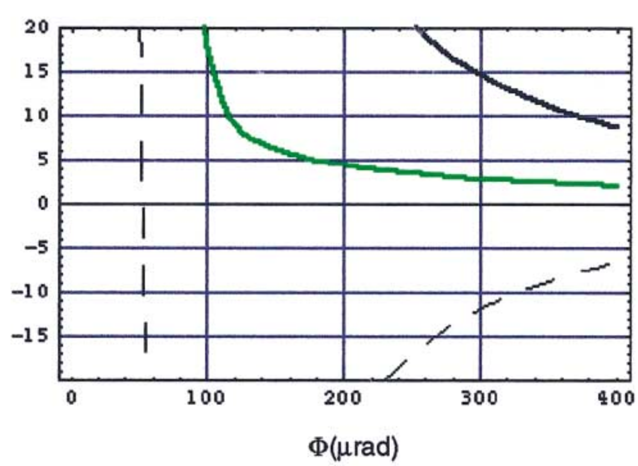

FIG. 4 (color). Normalized beam-beam tune shifts for $2l_{\mathrm{int}} = 50$ m (solid line: horizontal; broken line: vertical; green line: sum) for the VLHC stage-1 parameter.

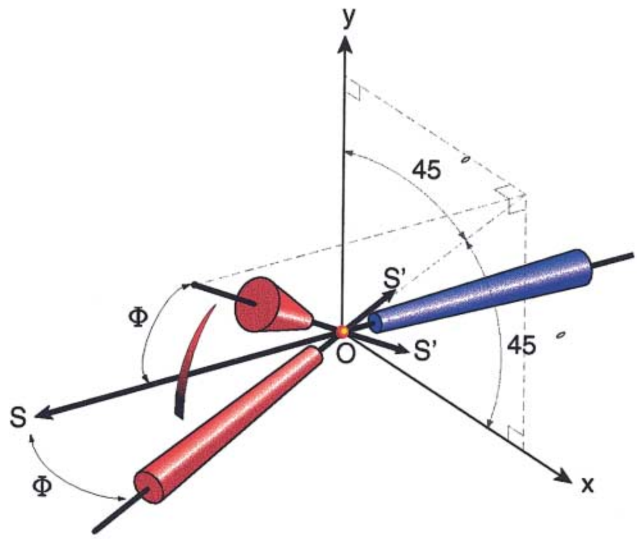

FIG. 5 (color). Schematic views of hybrid and inclined hybrid crossing. The red superbunch subject to hybrid crossing has the crossing angle of Φ on the s-x plane; the projection of the s' axis on the x-y plane of the superbunch subject to inclined hybrid crossing has $\pi/4$ from both axes.

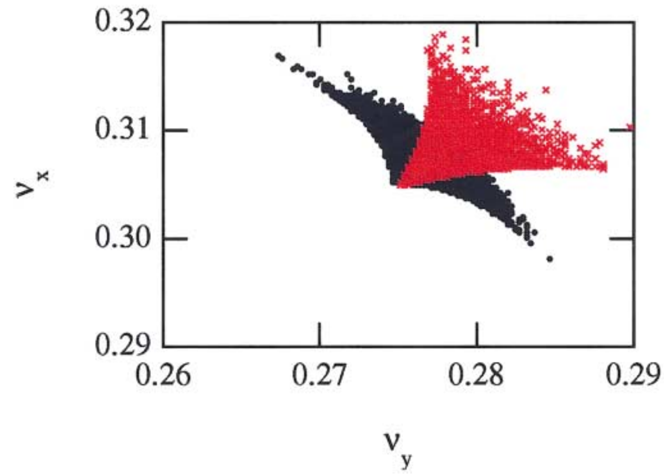

FIG. 6 (color). Tune footprints obtained by tracking particles over 1000 turns. Black dots represent particles subject to hybrid crossing; red dots show results for particles subject to inclined hybrid crossing. The crossing angle of 400 μrad was assumed and other beam/machine parameters were taken from the LHC [1].

instead of normal hybrid crossing, as shown in Fig. 5, is proposed. Figure 6 denotes that the winglike footprint is largely modified and the full width of spread is notably reduced. Inclined crossing may be another instrument for future colliders.

Physics impact.—From a physics point of view, the luminosity is essential at any collider used to search for new particles, such as Higgs and supersymmetric particles [10]. A possible disadvantage of this scheme is the longer collision area along the beam and the overlap of events in a superbunch. However, if we consider a reasonable crossing angle, 400 μrad for the LHC, we can design the collision area to be well inside the vertex detector, which covers about 1 m in the beam direction. We usually have subdetectors with good timing information (nanoseconds) to resolve the overlap of multievents within a bunch. Thus, any difficulty with a superbunch will be overcome as long as the event rate for events of interest is not very high. In addition, we note that since the local particle density is uniform over the bunch, the event rate per unit time is uniform with the SHC scheme and is even smaller than that with the CHC when the total number of particles is the same.

Summary.—A novel hadron collider based on the IS, Superbunch Hadron Collider, has been proposed. Collisions between μsec-long bunches (superbunch) have been shown to give an extremely high luminosity, that is, 10^{35} cm^{-2} sec^{-1}, assuming that the total number of protons is larger by a factor of 20 than that in the CHC. In order to decrease an unavoidable large incoherent beam-beam tune shift, hybrid/inclined hybrid collision is required. Crucial beam physics such as transverse coupled bunch instability or e-p instability will be reserved for future systematic studies. Engineering issues such as synchrotron radiation shielding are out of the scope of the present Letter. Last we emphasize that the present SHC is sufficiently worthy for consideration as a possible scheme for the coming generation of hadron colliders such as the VLHC.

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