A NEW METHOD FOR HIGH LUMINOSITY

Ken Takayama and Ainosuke Ando

National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 305, Japan

Abstract

We propose a new method to increase a luminosity in colliding machines, where collective focussings of high current anti-charged streams are employed as final focussing lenses instead of usual high gradient magnets. It is shown that a counter streaming pair of cylindrical positron and hollow electron beams produces necessary focussing forces to lead to a high luminosity, avoiding significant beam-beam effects of thermselves. A tentative scheme to produce the kilo-ampare positron beams is briefly proposed.

Introduction

The luminosity is a measure of the collision rate for colliding beams. There is a limit to increasing luminosity through increasing the beam current because of disruptive beam-beam forces which are very non-linear. However, the effect of the forces is proportional to a ratio of the magnitude of the betatron amplitude function to the beam size at the collision point, that is, β^*/σ. This means that increasing luminosity by reducing the beam sizes does not change the current limit and luminosity becomes inversely proportional to β^*. The question is how small can we make β^*. In the conventional colliding machine, the nearest focussing magnet to the collision point is located several meter far from it to leave clear space for the central detector. The beam size grows rapidly as one leaves the collision point, $\beta(s) = \beta^* + s^2/\beta^*$, and will reach large maxima before we can get it under control and properly matched to standard cell sizes. Tremendous magnitude of β in the long straight section including the experimental area in particular makes chramaticity correction very difficult. Thus, the limit to a small β^* is the large β_{max} which it generates.

In this paper, it is demonstrated that the limit can be drastically resolved by employing additional relativistic anti-charged beams as final focussing lenses. The head-on collision with anti-charged beams, called focussing beams below, brings about pinch effects on the circulating beam which is provided for high energy colliding experiments. If the focussing beam has an uniform charge distribution or Gaussian with an enough large cross-section, the circulating particle will receive linear focussing forces in the transverse direction, associated with encounters with the focussing beam. When the intensity of the focussing beam and the spacial configuration of encounter are adjusted, the circulating beam can be focussed on the desired location.

Now we consider a low beta insertion for a circulating colliding machine, based on the present idea. Encounter with the focussing beam must be taken place on both sides of the center of the detector so as to maintain the fold-symmetry of beam optics. Then, the locations of encounter are not limited in the longitudinal direction, because both the circulating and focussing beams traverse on the common equilibrium orbit in the insertion. This fact and the property of beam focussing that pinch effects are common in the horizontal and vertical directions lead to moderate magnitudes of the betafunctions in both directions which can be easily matched to normal cell optics near exits of the detector.

Space Charge Focussing & Example

We apply the idea to the TRISTAN main ring[1], for which the low beta insertion with $\beta^*_x = 0.8$ m, $\beta^*_y = 0.05$ m has been designed and is under construction now. We will attempt to increase the luminosity by a factor of 5 by reducing the above betafunction's magnitudes; $\beta^*_x \to 0.16$ m, $\beta^*_y \to 0.01$ m. First of all, a collisional configuration as illustrated in Fig. 1 is investigated in order to fix required focussing beam's parameters but the collisional configuration given here will be known later to be unfeasible as it is. As seen in Fig. 1, high current e^+, e^- beams with a rigid cylindrical round shape and low energy which makes it easy to separate from a closed orbit of the circulating beams refered as circulating orbit are employed as focussing lenses. These focussing beams which are supplied from small storage rings are deflected on the circulating orbit and out of it by separators located nearly exits of the detector region.

The focussing beam may be characterized by the current I, radius σ_t, and longitudinal length σ_ℓ. The remained parameter for focussing is the distance, denoted by g below, from the center of the detector to the entrance of the focussing tunnel. Then, for the desired β^*_x, β^*_y, the magnitudes of the betafunctions through the low beta insertion are obtained by solving the envelope equation;

$$\rho'' + \lambda\delta(s)\rho = 1/\rho^3 \qquad (\rho^2(s) = \beta(s))$$

$$\delta(s) = \begin{cases} 0 & 0 \leqq s < g, \quad g + \sigma_\ell/2 \leqq s \\ 1 & g \leqq s < g + \sigma_\ell/2 \end{cases} \tag{1}$$

$$\lambda = \frac{ec\mu_0 I}{\pi(m_0c^2\gamma)\sigma_t^2} = 2.37 \times 10^5 \frac{I(KA)}{\gamma\sigma_t^2(mm)}$$

where primes denote derivatives with respect to s, λ stands for the restoring coefficient due to space charge forces of the focussing beam, e is the unit charge, c is the light velocity, μ_0 is the magnetic permeability in vacuum, and $m_0c^2\gamma$ is the energy of a cirulating particle, and the origin of the axial coordinate is taken to be at the collision point. We are in particular interested in the magnitudes of β_y, β'_y at the exit of the detector region, that is, $\beta_y(L)$, $\beta'_y(L)$ where L is the half length of the detector. Introducing typical values of I = 2 – 3 KA, σ_t = 0.33 cm into λ, solving Eq. (1) with the initial condition of $\beta^*_y = 0.01$ m just mentioned, setting L = 2.5 m, and minimizing for realistic values of σ_ℓ, we have $\beta_y(L)$, $\beta'_y(L)$ as functions of the parameter g as shown in Fig. 2. We find it easy to make $\beta_y(L)$ in the low value domain matched to normal cell sizes by using several quadrupole magnets.

There are several undersirable problems associated with transport of remarkably high-intensity focussing beam as required in the above examples. These problems include: (a) detuning due to space-charge forces, (b) longitudinal and transverse collective instabilities, (c) direct beam-beam interactions, and (d) ion-electron collective instabilities. Direct beam-beam interactions[2] between focussing beams are most serious of them. If these high intensity beams are single passing to go into beam dumps, we can ignore the beam-beam effects. However, at least the focussing positron beam should be recirculated, since positron accumulatin business resquires a long time period because of a rare production rate.

Hollow Beam Crushing

So it is desirable to keep counter streams away from disruptive interactions throughly. There is a possible way: Crossing of the hollow beam and the cylindrical rigid beam without spacial overlapping does not produce disruptive effects. Restoring forces inversely proportional to the distance from the center of the cylindrical rigid beam are employed in order to focus the hollow beam on the collisional location where the crushed hollow beam encounters with the circulating beam. Focussing scheme using this method is schematically shown in Fig. 3 where strobo flashing pictures represent time evolution along the circulating orbit of cylindrical rigid, hollow, and high energy circulating beams.

We consider an axially injected hollow beam encountering with a cylindrical rigid beam. The hollow beam in the equilibrium state may be characterized by terms of an averaged radius r_o, thickness δ, current I_H, energy γ_H, and axial length σ_ℓ. For the simplicity, we assume σ_ℓ to be identical to the axial length of the rigid beam. The radial equation of motion for a particle initially located on the averaged radius is written by

$$r'' + \frac{ec\mu_0 I_R}{c^2\beta^2 m_0\gamma_H\pi} \cdot \frac{1}{r} = 0 \tag{2}$$

where I_R is the current of the cylindrical rigid beam. The solution to Eq. (2) is

$$r(s) = r_o \exp\{-[\mathrm{erf}^{-1}(\frac{2}{r_o}\sqrt{\frac{G}{2\pi}}\cdot s)]^2\}$$

or

$$r'(s) = -\sqrt{2G}\,\mathrm{erf}^{-1}(\frac{2}{r_o}\sqrt{\frac{G}{2\pi}}\cdot s) \tag{3}$$

where the abbreviation $G = ec\mu_0 I_R/c^2\beta^2 m_0\gamma_H\pi$ is employed and the error function is defined by $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(-t^2)dt$. Then, the focal length is obtained by setting $s = \sigma_\ell/2$

$$\ell_f = -r(\sigma_\ell/2)/r'(\sigma_\ell/2) \tag{4}$$

Accordingly, we can find enough conditions for the crushed hollow beam to be substantially equivalent to the focussing beam mentioned in the preceding discussions: $\delta = 2\sigma_t$ when it is assumed that $r_o >> \delta$, $I_H = I_R$, and $g = \ell_f$. Noted that r_o and γ_H are not uniquely determined through the last condition. For an example of $r_o = 10$ cm, $\delta = 6.66$ mm, $I_H = 2$ KA, $\sigma_\ell = 3$ m, $g = 50$ cm which lead to minimum $\beta_y(L)$, $\beta'_y(L) \simeq 0$ as seen in Fig. 2, the last condition $g = \ell_f$ gives $\gamma_H = 10.5$, which seems not to be far beyond the current technological potential. As seen in Fig. 3, two bunches in each beam are located at an interval of a couple of focal length ℓ_f plus half focussing bunch length, since we expect beam optics for the high energy circulating beam with fold symmetry about a collision point. The arrangement in principle leads to undisturbed hollow beams after passing the interacting region.

Discussions

This method may be not received favorably in a central detector for general purposes, because it requires non-axial fields. Although there are unknown problems associated with production and transport of such a high intensity hollow beam, this is still attractive in axially field-free detectors, e.g., a toroidal field analyzer or Crystal Ball[3] for particular purposes. Moreover, the present focussing system can still work if a double layer solenoid magnet is developed as a momentum analyzer, inside the inner coil of which a field free region is remained.

In principle, high current positron beams push ion out because of the same kind charge. Thus ion experiences focussing due to the high current electron beam and defocussing due to the positron beam, that is, alternative focussing and may stay on the inner stable region. Kinematics of ion should be examined in detail including changes in the external field arising from periodic crushing of hollow beams.

A tentative scheme to accumulate positron beams up to the order of kilo-ampare is briefly proposed. First, kilo-ampare electron beams with $\sim$ 100 MeV and 30 nsec are focussed in the small region ($\sim$ 2 mm) to hit the target. Positron beams of $\sim$ 100 mA are produced in the momentum bite of $\Delta p/p = \pm$ 2.5 % and with the transverse emittance of 250 π mm·mrad which corresponds to the solid angle of 50 m steradian[4]. These positron beams are decelerated to $\lesssim$ 1 MeV by the linac structure and injected into the electron cooling ring. We will obtain a cooling time of $\sim$ msec, provided the electron current density of 10^5 A/m^2(*). Such a short cooling time can compete with gas scattering. Cooled positron beams are extracted, accelerated up to a relativistic energy and accumulated in the storage ring by a particular method like a so-called phase space painting[5]. The above process is repeated at 10 Hz.

The stored positron beam with a desired current is extracted, guided onto the circulating beam line to serve as a focussing beam, and return to the storage ring. This process will be repeated at 100 MHz.

In concluding this paper, it is emphasized that the proposed method does not compete with any other attempts to increase the substantial luminosity, e.g., multibunch mode operation[7].

References & Footnote

1. S. Kamada and Y. Kimura, Proc. of 5th Symp. on Accel. Sci. & Tech., in Japan, 308 (1984).
2. K. Takayama and A. Ando, to be published.
3. G. Gidal & et al., LBL Report LBL-91, (1983).
4. H. Herr & et al., Proc. Workshop on Physics at LEAR with Low-Energy Cooled Antiprotons, Erice, May (1982).
5. F.S. Felber et al., IEEE Trans. Nucl. Sci. NS-30, No.4, p.2781 (1983).

(*) High current as mentioned in the text and low temperature ($Te^- << Te^+$) are required for a cooling meadium. It is out of our knowledges how continuous electron beams of $\sim$ 100 A are obtained, based on the present technological potential. If it is impossible, the high current electron beams generated from diodes driven by a Marx generator connected to a pulse forming line must be, after injection, recirulated in a kind of storage ring, a part of which is occupied by the temperature exchange region. From the requirement of efficient cooling, such a storage ring will be operated at the very low energy ($\lesssim$ MeV). One may see significant disadvantageous features for such an ultra low energy machine: beam particle losses by electron-ion and electron-electron collisions, and beam instabilities including transverse and longitudinal resistive wall instabilities, negative mass instability, and resonance instability. Introducing of a toroidal magnetic field may be needed, as it is in a modified betatron[6], to prevent expansion of the stored beam induced by the sources mentioned above. Although the large energy spread can be used to help suppress beam instabilities, it is a fatal defect for a cooling meadium. So far we have not studied in any detail about temperature mixing in a toroidal field or its increasing through one cylce ($\sim$ 1 msec).

6. C.A. Kapetanakos & et al., Phys. Rev. Lett. 49, 741 (1982).
7. R. Littauer & et al., Proc. of 12th Int. Conf. on High-Energy Accel. Fermilab, 161 (1983).

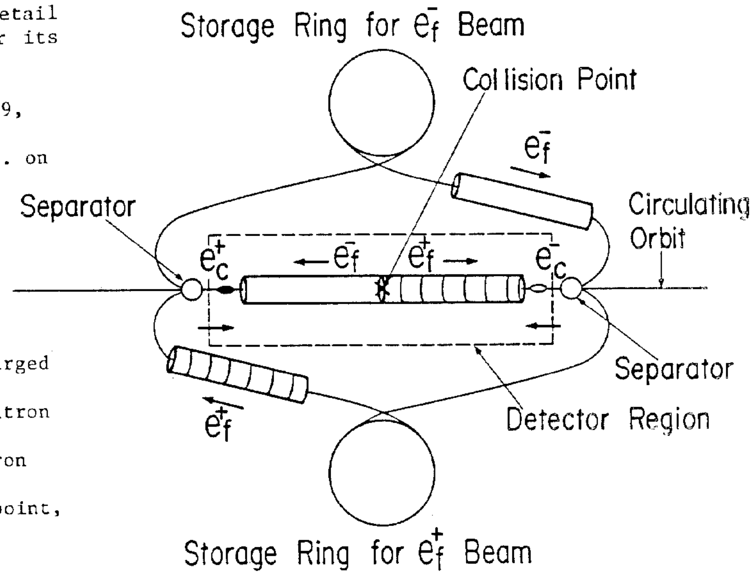

Fig. 1 Schematic representation of anti-charged beam focussing.
e_c^+, e_c^- denote the circulating positron and electron beams.
e_f^+, e_f^- are the positron and electron beams for making
e_c^-, e_c^+ focussed on the collision point, respectively.

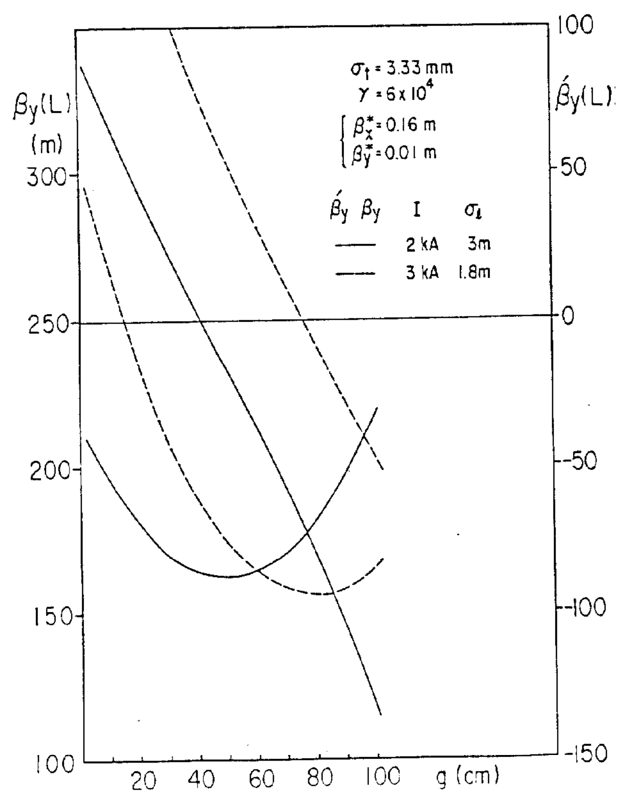

Fig. 2 Magnitudes of betafunctions and axial derivatives at the exits of the detector region as functions of the distance g to the entrances of the focussing tunnel.

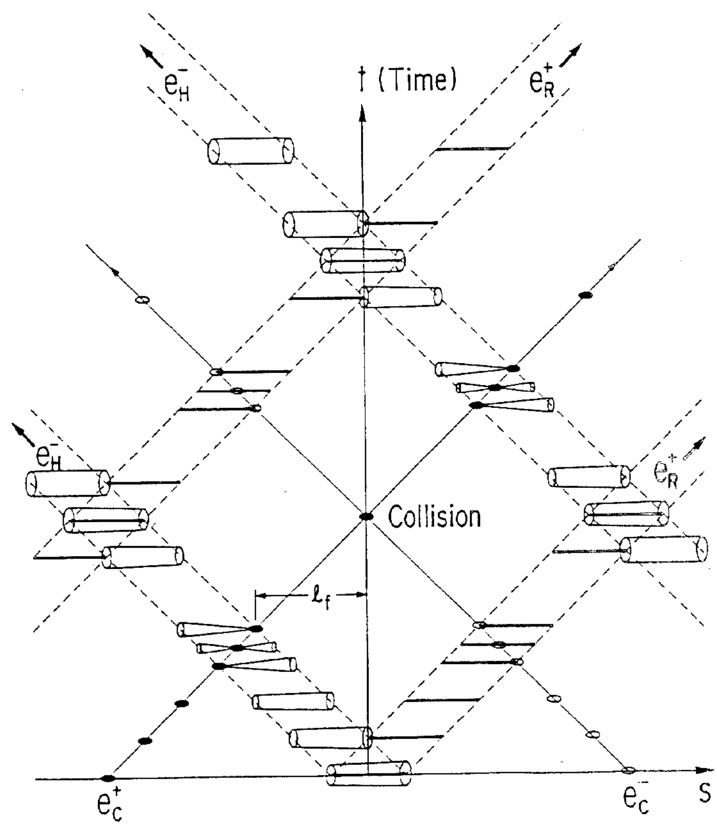

Fig. 3 Collision and focussing diagram with cylinderical rigid and hollow beams. e_R^+, e_H^- denote the cylindrical rigid positron beam and the hollow electron beam, respectively. ℓ_f is the focal length defined in the text.