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ELECTRON LENSES FOR COMPENSATION OF BEAM-BEAM EFFECTS: TEVATROTRON, RHIC, LHC

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Abstract

Since previous BEAM'06 workshop a year ago, significant progress has been made in the field of beam-beam compensation (BBC) – it has been experimentally demonstrated that both Tevatron Electron Lenses (TEL) significantly improve proton and luminosity lifetimes in high-luminosity stores. This article summarizes these results and discusses prospects of the BBC in Tevatron, RHIC and LHC.

INTRODUCTION

Essentially, an electron lens is very stable ~2mm diameter and 2m long, very straight cylinder of about 10^{12} electrons with kinetic energy of 5 to 10kV, immersed in 3T longitudinal magnetic field for stability reasons. Such a charged cylinder generates up to 0.3MV/m radial electric field attracting protons. For such kind of "controlled electron cloud" one can control charge density, diameter, length, transverse position, timing, velocity, shape, angle, direction – that makes it quite a versatile tool.

The figure of merit for eLens space charge action is the tune shift it induces [1]:

$$dQ_{x,y} = \mp \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e \cdot L_e \cdot r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p} \qquad (1)$$

where J_e is the current. For example, the 1st Tevatron Electron Lens TEL1 can move the tune of 980 GeV protons by about 0.01, i.e. it's is a very strong instrument. Note that because in many applications the size of the electron beam a_e should be equal or proportional to the rms size of high-energy beam, the tune shift Eq.(1) is independent on the machine parameters and scales as (J_e/*normalized emittance)*. Therefore, eLens tuneshifts in RHIC, Tevatron and LHC should be about the same for the same J_e of few Amperes.

Two electron lenses were built and installed in the Tevatron and have proven themselves safe for operations: first, for abort gap cleaning (for >5 years in 24/7 operation since 2002), and, more recently, for beam-beam compensation itself.

BBC BY TEVATRON ELECTRON LENSES

We follow Ref.[2] in description of the demonstration of BBC in Tevatron. One of the most detrimental effects of the beam-beam interaction in the Tevatron is the significant attrition rate of protons due to their interaction with the antiproton bunches in the main IPs (B0 and D0) and due to numerous long-range interactions. The effect is especially large at the beginning of the HEP stores where the positive proton tune shift due to focusing by antiprotons at the main IPs can reach ξ=0.016-0.020. Fig. 3 shows a typical distribution of proton loss rates at the beginning of an HEP store. In the Tevatron, 36 bunches in each beam are arranged in 3 trains of 12 bunches separated by 2.6 μs long abort gaps. Proton bunches #12, 24, and 36 at the end of each bunch train typically lose about 9% of their intensity per hour while other bunches lose only (4-6)% /hr. These losses are a very significant part of the total luminosity decay rate of about 20% per hour (again, at the beginning of the high luminosity stores). The losses due to inelastic proton-antiproton interactions at the two main IPs are much smaller (1.1–1.5%/hr). Fig.1 shows large bunch-to-bunch variations in the beam-beam induced proton losses within each bunch train but similar rates for equivalent bunches, e.g. #12, 24, and 36.

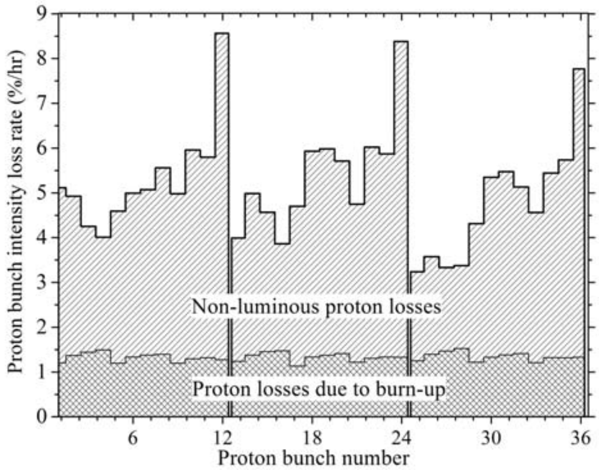

Figure 1: Proton-bunch intensity loss rates at the beginning of the Tevatron store #5155, Dec. 30, 2006, with initial luminosity $2.5{\cdot}10^{32}$ cm^{-2} s^{-1}.

In the BBC demonstration experiment, we centered and timed the electron beam of the A11 TEL2 onto bunch #12 without affecting any other bunches. When the TEL2 peak current was increased to J=0.6A, corresponding to the vertical tune shift of $dQ=0.0015$, the lifetime $\tau=N/(dN/dt)$ of bunch #12 went up to 26.6 hours from about 12 hours - see Fig.2 At the same time, the lifetime of bunch #36, an equivalent bunch in the third bunch train, remained low and did not change significantly (at 13.4 hours lifetime). When the TEL2 current was turned off for fifteen minutes, the lifetimes of both bunches were, as expected, nearly identical (16 hours). The TEL2 was then turned on again, and once again the lifetime for bunch #12 improved significantly to 43 hours while bunch #36 stayed poor at 23.5 hours. This experiment demonstrates a factor of two improvement in the proton lifetime due to compensation of beam-beam effects with the TEL.

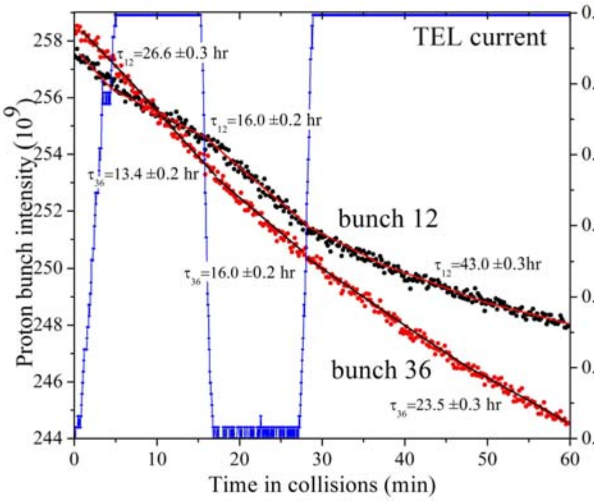

Figure 2: Proton-bunch intensity loss rates at the beginning of the Tevatron store #5119, Dec. 12, 2006, with initial luminosity $2.5 \cdot 10^{32}$ cm^{-2} s^{-1}.

Another electron lens, TEL1 (installed at the location of high horizontal beta-function, and therefore, shifting mostly horizontal tune) has demonstrated similar effect. Besides reduction of the intensity loss, the lenses improve luminosity lifetime by as much as 12% and therefore can increase luminosity integral per HEP store.

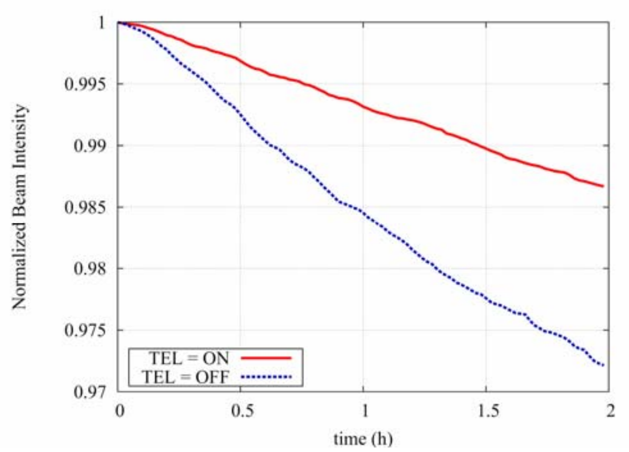

Figure 3: LIFETRAC simulations of the Tevatron proton bunch intensity with TEL off(blue line) and on (red).

Positive effect of the TEL2 on proton lifetime has been observed in the LIFETRAC tracking code simulations as well [3] – see Fig.3. Though high proton losses in the Tevatron are due to a complex combination of head-on and long-range effects, the TEL-induced lifetime improvement is thought to be mainly due to the long-range beam-beam tune shift compensation. Compensation of the non-linear effects due to head-on collisions awaits further experiments.

HEAD-ON BBC IN LHC

Currently, it is believed that beam-beam effects with nominal beam-beam parameter of ~ 0.003 per IP will not limit operation of the LHC with 3 IPs.On the other hand, operation with twice or more protons per bunch may be necessary if the total beam power will need to be limited by other considerations (e.g. collimation system efficiency or electron cloud). In that case, both head-on and long-range beam-beam interactions are expected to be unbearable.

According to [1], a complete compression of head-on tune footprint is possible if the number of electrons in the electron is $N_e = N_{ip} N_p /(1+\beta_e)$. For the LHC parameters $N_p = 2.3\ 10^{11}$, and four head-on interaction points $N_{ip} = 4$, so for 10 kV electrons ($\beta = 0.2$) one needs $N_e = 8.8\ 10^{11}$, or about 2.4A DC, and the electron transverse beam profile which exactly matches the proton beam profile (presumed to be Gaussian with an rms sigma of 0.3-1.0 mm depending on location of LEL). Head-on beam-beam compensation together with "wire" long-range beam-beam compensation [4] could be used to compress total footprint to an acceptable value as shown in Fig. 4 from [5]. Therefore, the electron lenses combined with current carrying wires for long-range beam-beam compensation are believed to allow to reach higher collider luminosities without significant increase of particle loss rates or emittance growth rates.

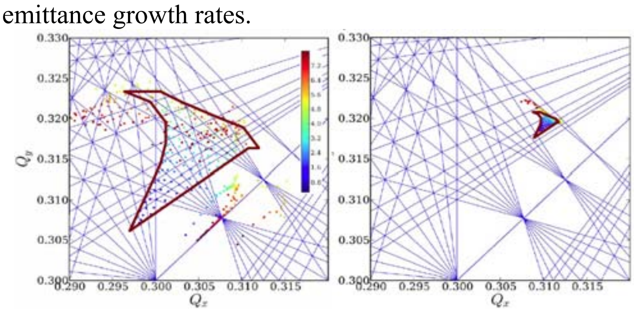

Figure 4: LHC footprint reduction by electron lens for full head on compensation by electron lenses and long-range compensation by wires. Left plot - the LHC with beams with *Np*=2.3e11/bunch and no e-lens, right – with beam-beam compensation provided by wires and head-on LELs ([5], courtesy of U.Dorda).

A 70 m long drift section between D1 and D2 dipoles has been proposed as a possible location for the LEL (LHC Electron Lenses). Optical functions of the LHC collider lattice with β*=55cm are presented in Fig.5

from [6]. Advantages of that location are large proton beam size (1.1mm) that makes easier electron beam compression needed to match the proton profile, almost equal beta-functions, very small dispersion and close to 90 degree phase advance from the main IPs (which are about 110 m away).

The most important questions needed to specify the LEL parameters include whether full tune-spread compensation neede whatsoever and how may it affect single- and multi-bunch coherent stability. What is optimal degree of the head-on compensation? For example, it is thought to be necessary to avoid "footprint folding" which usually leads to faster diffusion.

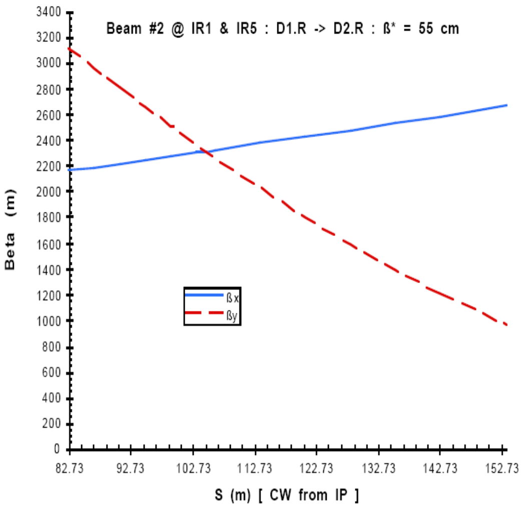

Figure 5: LHC optical functions at the proposed LEL location.

It may be very possible the LELs will need to be used only for particle compensation – e.g. to the maximum tolerable tunespread of *dQ_spread* = 0.010. It has been pointed out that there are strong arguments for a better coherent beam-beam stability if the tunespread is compensated to the level of d*Q_spread=0.003* [7]. Similar questions are posed by a team of BNL researchers exploring possibility of the head-on BBC with electron lenses in RHIC [8].

Yet another possibility to consider is the use of electron beam for long-range beam-beam compensation, as a kind of "electron wire". It will work the way similar to copper wires [4] but can be placed much closer to the beam. Indeed, the copper wire can be placed only in the shadow of collimators and thus can be employed only for reasonable beam-beam separation of about 5-7σ or more.

The Electron Lens can act as "electron wire" at <u>any</u> separation; in addition, it is quite easy to vary the eLens current with 375ns rise time and f_r =439kHz. The requirement of integrated current of 80Am can be satisfied by using longer e-beam (6-8 m). If only long-range tune shift compensation is needed, then a head-on elens can be used. In that case, the e-beam length and current need to be about the same as in the Tevatron Electron Lenses.

SUMMARY, NEXT STEPS

In summary, experimental demonstration of compensation of the beam-beam effects in the Tevatron with use of electron lenses (which double proton beam lifetime in high-luminosity HEP stores, as reported in Ref.[1]) has greatly increased interest to the idea of using similar lenses for BBC in LHC. Seems that head-on BBC with electron lens(es) combined with long-range wire compensation is the most promising method.

Extensive theoretical studies and numerical tracking of the electron lenses for BBC in LHC are needed before undertaking expensive hardware R&D. We are at the very beginning of the systematic studies in that direction. A new task "LHC Electron Lenses" has been created within US LARP. Design, fabrication and tests of electron gun with Gaussian current profile is planned as well. Significant efforts on the same compensation method in RHIC has been started in BNL , and one should hope that they will be of importance for the LHC considerations.

This presentation summarizes discussions on the subject of the Electron Lens Beam-Beam Compensation among a group of interested people including Yu.Alexahin, V. Kamerzdhiev, J.Johnstone, T.Sen (FNAL), W. Fischer and Y.Luo (BNL), F. Zimmermann, J.P. Koutchouk and U.Dorda (CERN).

REFERENCES

[1] V.Shiltsev, *et al.* , *Phys. Rev. ST Accel. Beams* **2**, 071001 (1999).
[2] V.Shiltsev, *et al.* , *Phys. Rev. Lett.* **99** 244801 (2007)
[3] V.Kamerdzhiev, *et al.*, *Proc. IEEE PAC 2007 (Albuquerque, NM, USA)*, p.1703.
[4] J.P.Koutchouk, in *Proc. PAC'2001, Chicago,* p.1681.
[5] U.Dorda, *et al*, *et al.*, *Proc. IEEE PAC 2007(Albuquerque, NM, USA)*, p.1589.
[6] J.Johnstone, LARP-doc-560 (2007)
[7] Yu.Alexahin, presented at the Workshop on Beam-Beam Compensation (July 2007, SLAC)
[8] Y.Luo, W.Fischer, presented at the Workshop on Beam-Beam Compensation (July 2007, SLAC)