Electron Lenses for Colliders and Intense Proton Beams

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Electron lenses are unique accelerator elements, as for the first time they offer controlled non-Laplacian forces to manipulate high energy beams. The physics mechanism of the electron lens is the space-force of a beam of low energy electrons, immersed in strong longitudinal magnetic fields. The space-charge force effectively acts on accelerator's high energy beam moving along (or colliding) with the electron beam while the effect of longitudinal magnetic field is usually a minor, correctable imperfection. Transverse motion of electrons is essentially frozen along the magnetic field lines which therefore assures outstanding stability of the electron beam.

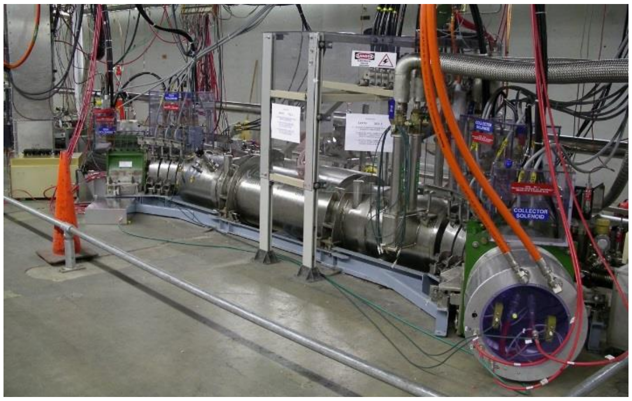

Figure 1: Tevatron electron lens in the colliders' tunnel.

Since the original proposals in the 1990s [1, 2], the electron lenses have been added to the toolbox of modern beam facilities, being particularly useful for the energy frontier superconducting hadron colliders ("supercolliders") [3]. The electron lenses usually employ low energy (~10 kV), high current (1-10 A) sub-mm size magnetized electron beams to affect beneficially high energy beam of hadrons (protons, antiprotons). The design of the lenses required advancing several technologies: high field quality solenoids and correctors (sometimes SC up to 4-6 T), high brightness electron beam generation and low loss transport (gun, collector, etc.), fast HV gun anode modulator (10 kV, 100 ns and multiples of the machine revolution frequency, e.g. 50 kHz in the Tevatron), sophisticated power recirculation electrical scheme, ultra-high vacuum and beam diagnostics systems.

Given that the electron beam transverse shapes and longitudinal current modulation patterns can be broadly varied (usually, created at an electron gun) [4] the electron lenses have become a uniquely flexible instrument. In the Fermilab Tevatron 2-TeV proton-antiproton collider, two electron lenses (TELs) were built and installed in 2001 and 2004 (see photo above), operated till the end of the Run II in 2011 and used for: compensation of long-range beam-beam effects (the TELs varied tune shift of individual 1-TeV bunches by 0.003-0.01) [5]; longitudinal collimation – removal the DC beam particles from the abort gaps – for 10 years in regular operation [6]; studies of head-on beam-beam compensation [7, 8]; and demonstration of halo scraping with hollow electron beams [9, 10]. Since 2015, two electron lenses have been installed in RHIC at BNL and have been very successfully used for head-on beam-beam compensation leading to doubling the luminosity in proton-proton collisions [11]. Effective halo collimation of RHIC beams by hollow electron beams has been recently reported [12].

World-wide efforts on the electron lenses currently cover several areas of research: a) hollow electron beam collimation of protons in the HL-LHC [13, 14]; b) long-range beam-beam compensation with electron lenses as current-bearing "wires" in the HL-LHC [15, 16, 17]; c) generation of nonlinear integrable lattices with special transverse current distribution $1/(1+r^2)^2$

– first proposed in [18] – e.g., in the IOTA ring [19, 20]; d) to generate tune spread for Landau damping of broad spectrum of coherent instabilities [9, 21] in, e.g., the LHC, FCC-hh (where electron lens can outperform some 10,000 octupoles), or FNAL Recycler; e) to compensate space-charge effects in modern high-intensity RCSs [22, 23].

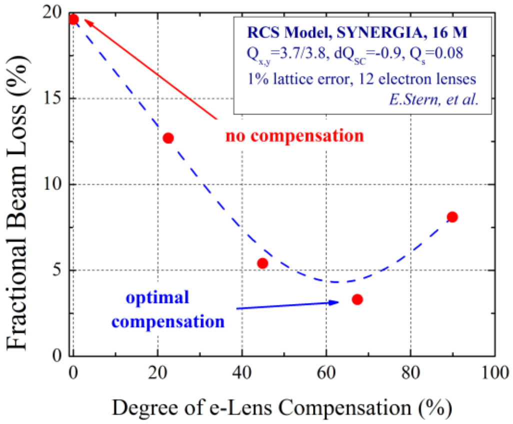

Figure 2: Fractional loss of proton beam with $dQ_{SC} \sim -1.0$ *after 1000 in a model RCS with 12 electron lenses vs the degree of SC compensation [28].*

We believe that the method of the electron lenses needs to be further developed to address needs of next generation facilities. Of special interest are:

i) development, construction and installation of the HL-LHC hollow e-beam collimators [24] and corresponding modeling [25], studies and commissioning;

ii) IOTA e-lens construction and studies (Landau damping [26], integrable dynamics with e-lenses, collimation); a particularly promising area is the compensation of space charge effects and reduced tune depression; the IOTA (Integrable Optics Test Accelerator) ring is now operational at Fermilab [27]. The experiment on space-charge compensation with an electron lens is being prepared with the goal to be ready for the IOTA operation with protons in 2020-2021;

iii) conceptual studies and initial development of the electron current sheets (jaws) above and below flat *e+ e-* beams in Super KEKB to reduce the background and protect collimators, and, possibly, to reduce the machine impedance;

iv) numerical modeling and simulations of the e-lens space-charge compensation for IOTA and ultimate intensity RCS where initial results [28] show great promise of about an order of magnitude reduction in the beam losses with electron lenses – see Fig.2;

v) development of the “passive” electron lens – electron columns [9];

vi) further development of the modeling capabilities for the lenses themselves and addressing technological challenges, such as, e.g., rapid pulse-to-pulse current modulation.

References

[1] E. Tsyganov, A. Taratin, and A. Zinchenko, Fiz. Elem. Chastits At. Yad. **27**, 675 (1996); Phys. Part. Nuclei, **27**], p. 279, 1996; see also SSCL-Report No. 519, , 1993; CERN-SL/Note No. 95-116/AP, 1995; Report No. JINR-E9-96-4, 1996.
[2] V.Shiltsev, V.Danilov, D.Finley, A.Sery, Phys. Rev. ST Accel. Beams 2(7), 071001 (1999); see also V. Shiltsev, D. Finley, Preprint FERMILAB-TM-2008 (1997), V. Shiltsev, Preprint FERMILAB-TM-2031 (1997)
[3] V.Shiltsev, *Electron Lenses for Supercolliders* (Springer, 2016).
[4] V.Shiltsev et al, Phys. Rev. ST Accel. Beams 11, 103501 (2008)
[5] V.Shiltsev et al., Phys. Rev. Lett. 99, 244801 (2007)
[6] X.L.Zhang et al., Phys. Rev. ST Accel. Beams 11, 051002 (2008)
[7] V. Shitsev, et al., New Journal of Physics, 10, 043042 (2008)
[8] G.Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
[9] V.Shiltsev, in Proc. LHC-LUMI-06 Workshop (16 –20 October 2006, Valencia, Spain); Yellow Report CERN-2007-002 (2007)
[10] G.Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
[11] W. Fischer et al., Phys. Rev. Lett. 115, 264801 (2015)
[12] X. Gu, et al., Phys. Rev. Accel. Beams 23, 031001 (2020)
[13] Conceptional Design Report, CERN-ACC-2014-0248 (2014)
[14] D.Perini et al, Proc. IPAC'19, MOPTS099 (2019)
[15] A.Valishev,G.Stancari, arXiv:1312.5006
[16] S.Fartoukh et al., PRAB 18, 121001 (2015)
[17] S.Sadovich et al, Proc. IPAC'19, WEPTS048 (2019)
[18] V. Danilov, V. Shiltsev, Fermilab Report FN-671 (1998)
[19] S.Nagaitsev, et al., Proc. IPAC'12, MOYCP01 (2012)
[20] G.Stancari et al., Proc. IPAC'15, MOBC3 (2015)
[21] V.Shiltsev et al, Phys. Rev. Lett. 119, 134802 (2017)
[22] A.Burov, W.Foster, V.Shiltsev, Fermilab Preprint FNAL-TM-2125 (2000)
[23] E.Stern et al, Proc. IPAC'18, THPAF075 (2018)
[24] see, e.g.,
https://indico.cern.ch/event/647714/contributions/2698932/attachments/1558648/2452437/Levichev_HiL_LHC.pdf#search=A%2E%20Levichev
https://indico.cern.ch/event/742082/contributions/3085144/attachments/1735974/2807819/Latest_results_HEL_Nik.pdf#search=D%2E%20Nikiforov
https://indico.cern.ch/event/865924/
https://indico.cern.ch/event/865924/contributions/3648922/attachments/1950069/3236709/HEL_rep_BINP.pdf
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https://indico.cern.ch/event/704765/contributions/2891231/attachments/1614680/2565593/Hollow_beam_instab_MMaltseva_09.03.2018.pdf
[25] M. Fitterer et al., Proc. IPAC'17, THPAB041 (2017)
[26] Yu.Alexahin, A. Burov, A. Valishev, V. Shiltsev, FERMILAB-CONF-690-APC (2020)
[27] S.Antipov et al, JINST 12 T03002 (2017)
[28] E.Stern, Yu.Alexahin, A.Burov, V.Shiltsev, Fermilab internal beams-document-6790 (2019)