ELECTRON LENSES FOR PARTICLE COLLIMATION IN LHC

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Abstract

Electron Lenses built and installed in Tevatron have proven themselves as safe and very reliable instruments which can be effectively used in hadron collider operation for a number of applications, including compensation of beam-beam effects [1], DC beam removal from abort gaps [2], as a diagnostic tool. In this presentation we – following original proposal [3] – consider in more detail a possibility of using electron lenses with hollow electron beam for ion and proton collimation in LHC.

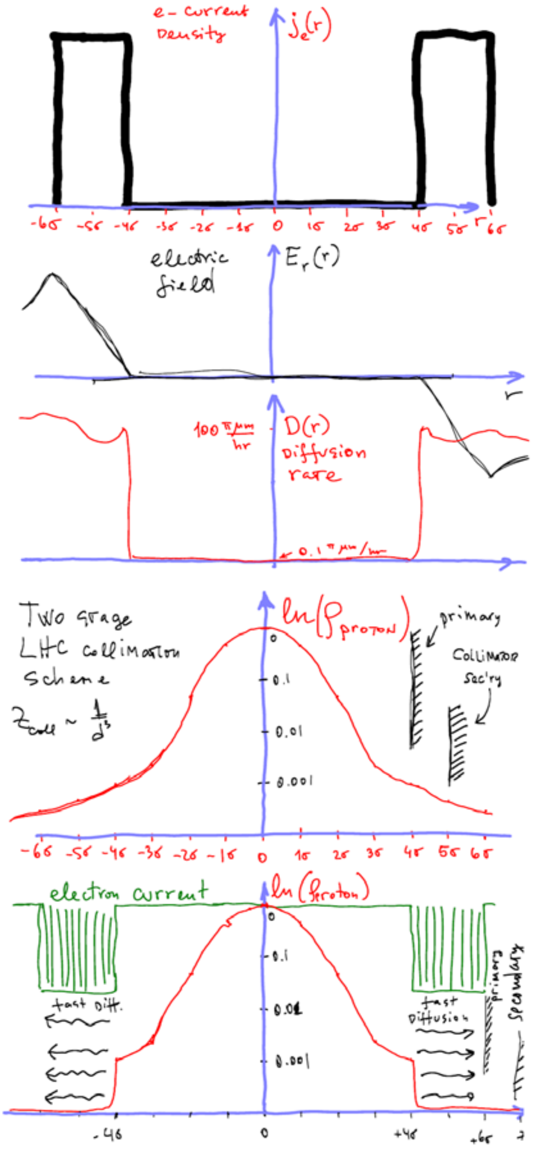

Figure 1: (top – bottom) current distribution in the e-lens for collimation; electric field and diffusion speed; cartoon of the particle distribution during halo removal by hollow beam e-lens.

HOLLOW ELECTRON BEAM FOR LHC COLLIMATION

As depicted in Fig.1, an ideal round hollow electron beam has no electric or magnetic field inside and strongly nonlinear fields outside. The non-linear field components significantly enhance transverse diffusion of high-energy particles in a storage ring with betatron amplitudes larger than e-beam size, as experimentally demonstrated in the beam studies with Tevatron Electron Lenses (see Fig.6 in Ref.[4]).

The speed of diffusion of the large amplitude particles can be greatly enhanced if the electron current varies in sync with betatron oscillations or at the nearest non-linear resonance line. The hollow e-beam can serve as primary collimator or as an enchancer – a device for faster delivery of halo particles to secondary collimators which can be then placed further from the primary one and the beam itself – see cartoon in Fig.1. Hollow eLens also offers a viable solution for a primary collimator of the LHC ion beam, because such an electromagnetic collimator does not break an ion into fragments (as any primary collimator made of usual material would do). In that case, the hollow e-beam systems would have to be installed to replace the current primary LHC collimators.

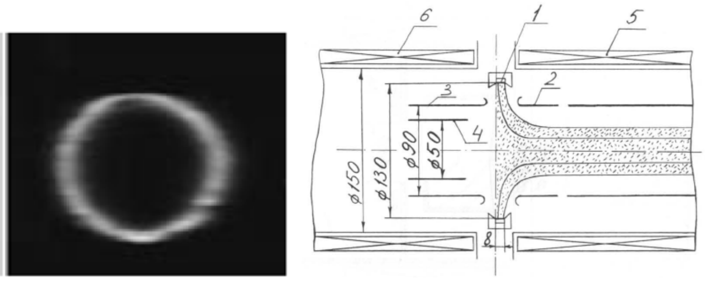

Figure 2: (a) hollow electron beam [5]; (b) cylindrical electron gun tested in [6].

Hollow electron beams are widely used in electron cooling devices [5,6] and corresponding electron guns have been developed and extensively tested – see Fig. 2.

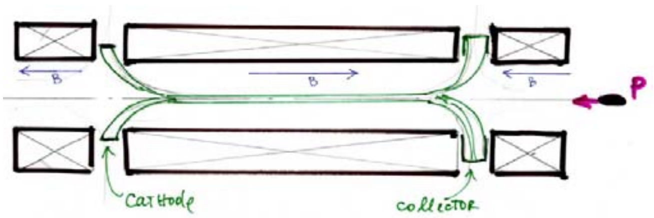

Figure 3: Electron lens configuration for collimation

Fig.3 presents possible system configuration which is needed for generation of the axially symmetric hollow electron beam for LHC collimation. Main parameters of the hollow electron beam system needed for EM collimation of ions and/or protons are presented in the Table below:

Maximum current	10-50 A
Ring cathode radius/width	25 mm/ 6 mm
Magnetic Field on Cathode	1-2 kG
Current density on cathode	j_e=1-5 A/mm^2
β–functions @ e-IR location	$\beta_x = \beta_y$ =2300 m
Beam radius/width @e-IR	Hollow 4.4mm/1.1mm
Main solenoid filed	B_m=3.2T if B_{cath}=1kG
Electron beam energy	10-20 kV
Regime of operation/ voltage	~3 kHz *sin*-modulation
Electron beam length	2(4)m
e-beam radius in/out	1.5 mm / 2 mm
Magnetic fields in collector	1kG→0kG
Ring collector radius/width	25 mm/ 12-30 mm
Beam power in collector	P_{coll}=20-50 kW

For comparison, TEL electron beam parameters are j_e=6 A/mm^2, B_m=6.5T, P_{coll}=50kW – i.e. the hollow beam parameters are not very far from those already achieved.

MODELING

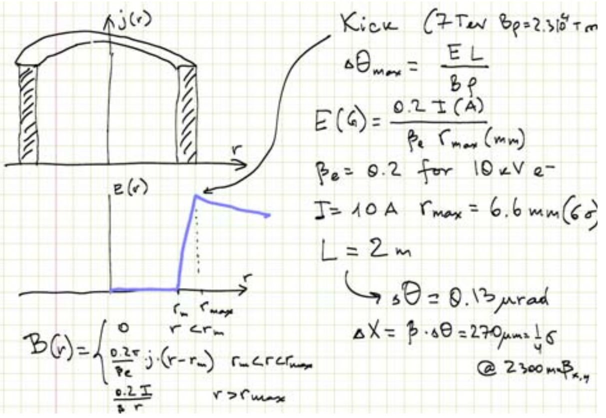

Figure 4: Cartoon of the hollow e-collimator used in the modelling.

Fig.4 above shows geometry of the radially symmetric hollow beam used in the modelling. It also presents estimate of the dipole kick produced by such a beam with 10 A of current for a 7TeV particle outside its outer bound at 6σ (6.6 mm) radius – it is about 0.13 μrad or 270 μm in amplitude. For comparison, the rms angle due to particle scattering in 1 m long carbon jaw of the LHC primary collimator is about 4.5 μrad. Advantage of the e-Collimator is that it does not destroy any particle and can in principle act over many (say, thousands) turns. In that case, every time when particle appears beyond the boundary of the electron beam, it gets a radial kick – as schematically depicted in Fig.5.

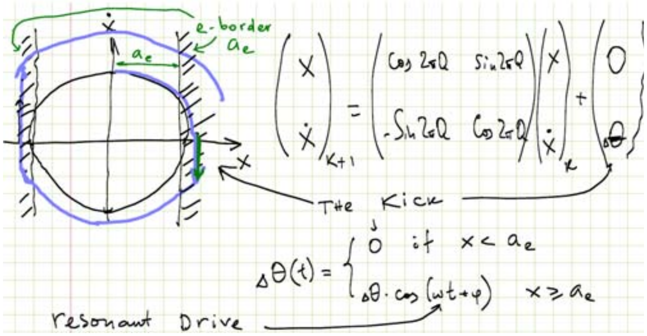

Figure 5: Phase space dynamics of the hollow e-beam collimation

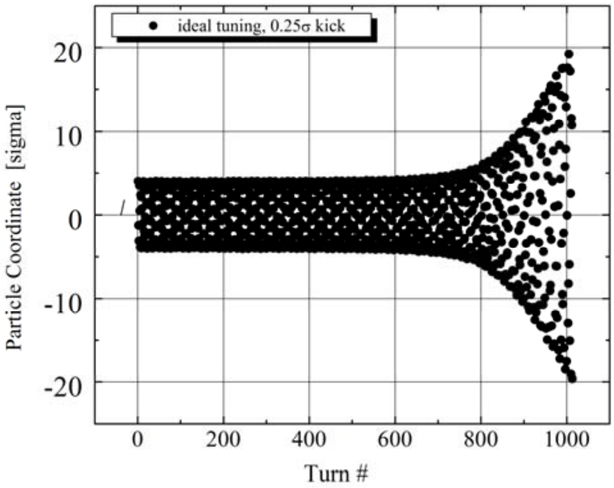

Figure 6: Particle motion driven by hollow e-beam with maximum kick of 0.25σ, in sync and in phase with betatron motion with tune *Q=0.31*.

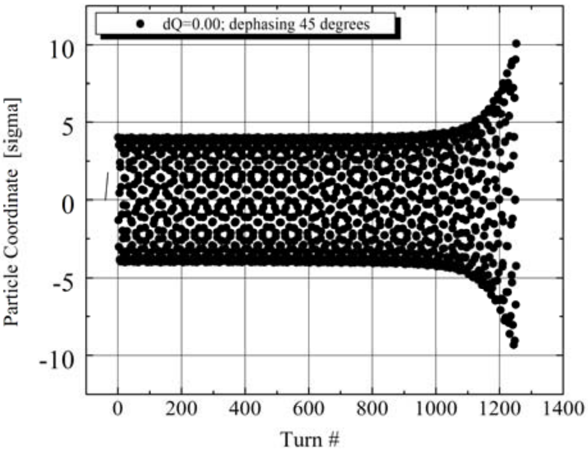

Figure 7: same as in Fig.6 but with 45 degree phase shift between e-current and particle betatron oscillations.

In the very first simulation run, presented in Fig.6, a particle which initially intercepted the e-wall boundary by

0.1σ has been driven resonantly to amplitudes as large as 10-20σ in less than 1000 turns (0.1 sec of real time in the LHC). Maximum strength of the e-beam kick is equal 0.25σ, electron current is modulated in phase with betatron motion of the particle, tune equal to *Q=0.31*. Next Fig.7 shows that even if the phase difference between e-current waveform and particles oscillations is as large as 45 degrees, the particle still achieves large amplitudes in 1000-1200 turns. At 90 degrees of the phase difference, the particle will see zero electron current and get no kick.

Due to natural tune spread (induced by beam-beam, or due to synchrotron motion), one should not worry about exact synchronization of frequency and phase with all the particles. Electron beam modulation frequency can be set close to the frequencies of interest (e.g, frequency of 4σ particles) or may cover a band of frequencies. Fig. 8 and 9 show resonant increase of particle amplitude in the case of significant frequency difference between the particle and the electron beam drive *dQ=0.002* and *dQ=0.005*, correspondingly.

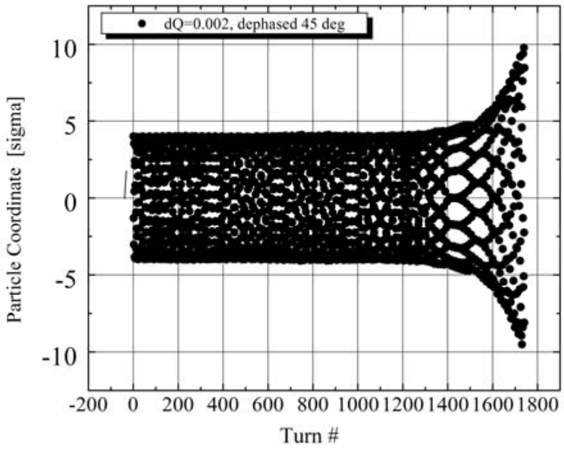

Figure 8: same as in Fig.7, with tune difference *dQ=0.002.*

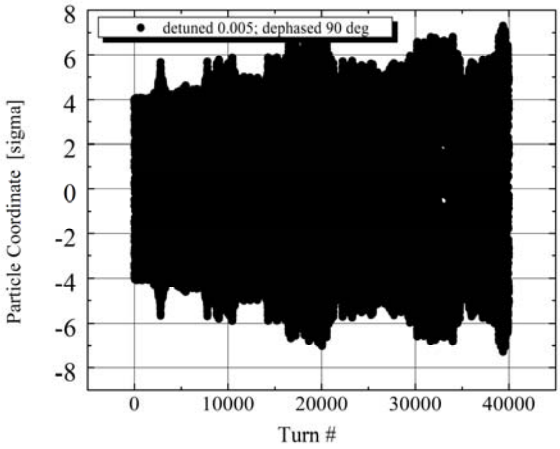

Figure 9: same as in Fig.7, with tune difference *dQ=0.005.*

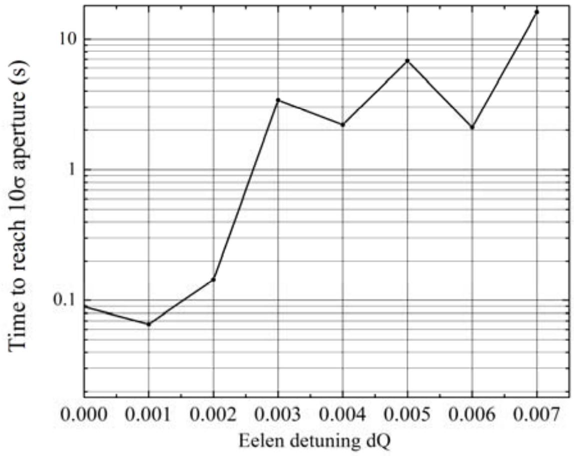

Figure 10: Collimation time (time needed to reach 10σ amplitude) vs detuning parameter *dQ*.

Figure 10 shows that the time needed (in the simulations) to reach 10σ amplitude grows with the dutuning and reaches 10 seconds for *dQ=0.007*. For most optimal operation, one can envision detuning not exceeding *dQ=0.002* which collimates (drives particles out on aperture set by secondary collimators) in about 0.1 seconds. Obviously, with larger e-beam current – and kicks – the collimation time can be reduced to shorter values as shown in Fig.11. If the secondary collimators are set closer to the beam – say 6-8σ - then, the time will be shorter, too.

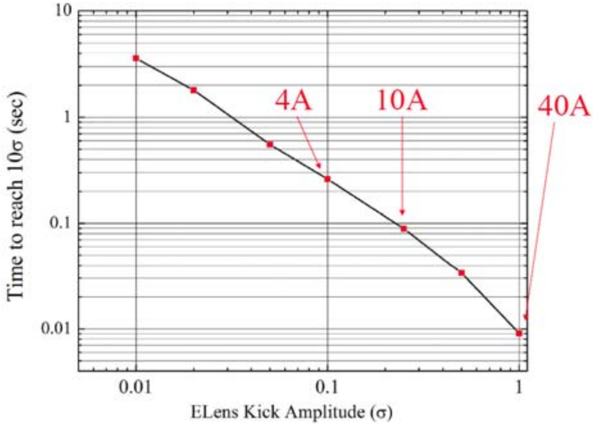

Figure 11: Collimation time (time needed to reach 10σ amplitude) vs maximum electron beam kick.

DISCUSSION, SUMMARY

So far, the hollow electron beam idea looks promising for improve the LHC collimation system: a) the e-beam technology is developed and well tested in the Tevatron Electron Lenses; b) reliability of such a system has been proven by years of operation under a hardon collider conditions; c) there is just electro-magnetic, no nuclear, interaction in the e-collimators which can work for ions and protons; d) as shown above, e-collimators seem to be strong enough to clean fast – its cleaning time (0.1-30 sec) is much faster than the diffusion time (1000's sec); e) e-collimators are “refreshable”, no beam incident can damage the electron beam the way it can damage metal or carbon jaws in conventional systems; f) because of that, no expensive damage diagnostics is need; g) collimator’s size/position are controlled by magnetic fields, therefore, no mechanical system (movers, etc) is needed.

Another foreseeable advantage of the hollow e-beam is that it cleans (removes) halo smoothly over many turns – and because of that the system will not be sensitive to orbit motion. It also promises very smooth known radiation levels on secondary collimators and in the HEP detectors. As an example, Tevatron D0 and CDF detectors enjoy smooth abort gap loss rates smoothed by TELs.

As initially reported in Ref.[2], accumulation of the DC beam particles in the Tevatron could be dangerous because of quenches on abort. TELs effectively prevent that and are used in 24/7 operation. Figure 12 shows an example of a simple experiment at the end of HEP store. In this figure, the T:IBEAM is the total beam current in the Tevatron, C:FBIPNG is the total bunched-beam current, the T:L1COLI is the average electron current in TEL1 and C:B0RATI is the abort gap loss rate as reported by the CDF detector. When the TEL was turned off (red trace), the abort gap loss rate started to grow after about 10min and the loss spikes appeared. To clean out of the DC beam in the abort gap, the dipole beam-beam kick is used to excite particle oscillations resonantly which eventually increase oscillation amplitude until the particle get lost on a limited aperture. Therefore, when the TEL was turned on, a chunk of the DC beam intensity was quickly lost so that T:IBEAM had shown a beam loss (green curve) while the lifetime of bunch beam T: FBIPNG did not change. There was also a huge spike in the abort gap counter indicating that the DC beam in the abort gap has been cleaned out by the TEL. Then the loss rate in the abort gap returned back to a steady state level, without big spikes. Excitation of a 7th order or 3rd order resonances ($Q=0.583$ or $Q=0.600$) has been found the most effective for the DC beam removal by electron lenses in Tevatron.

In various discussions, it was proposed to consider more suitable locations for the e-collimator, e.g., betatron or/and momentum cleaning long straight sections where most of the Phase I collimators are located now (instead of the space between D1 and D2 with very large beta-functions). These locations don’t have very large beta-functions, so consequently, beam size is factor of 3-4 smaller and hollow electron beam size (which is some 4-5σ inner radius) has to be smaller, too. Compression ratio of the electron beam emitted by a ring cathode should be proportionally higher, that call for higher ratio of the magnetic field in the interaction region and on the cathode B_m/B_{cath}. Minimum field on the cathode depends on the electron current density (the field should be high enough to keep electron beam stable against its own space-charge forces). Maximum field in main solenoid is limited by technology (and is about 12-15T) and available radial space between two beams. Though these changes – needed to achiev higher B_m/B_{cath} ratio – will make e-collimatort quite different from TELs (compared to the high-beta location elens), electron beam formation and dynamics as well as magnet design could be addressed in straightforward simulations.

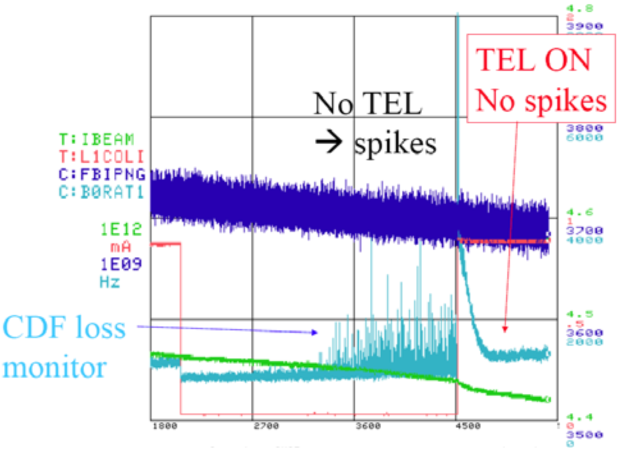

Figure 12: Beam intensity and abort gap losses during a HEP store. TEL1 was turned off and then on.

Another concern to address in simulations is axial symmetry of the electron current density distribution which is required for particles inside the electron tube to stay intact. One can see three effects/possibilities to avoid generation of dipole imperfections leading to the transverse emittance blowup of core particles: a) a set of control sector electrodes can be set near the cathode which can be used for slow or fast correction of the symmetry; b) under action of its own SC field, the electron beam rotates due to **E**×**B** drift – and that enforces the symmetry; c) the betatron frequency of the core particles is different from the frequency of the halo particles – the effect is especially big at collisions – so, setting electron beam modulation frequency far enough from the core but close to the halo tune will effectively reduce the effect on low amplitude particles.

In summary, proton or ion collimation with hollow electron beams looks very promising, it should be considered in detail, as it may complement conventional system and does not disintegrate ions.

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