

Applications of electron lenses: scraping of high-power beams, beam-beam compensation, and nonlinear optics

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Abstract. Electron lenses are pulsed, magnetically confined electron beams whose current-density profile is shaped to obtain the desired effect on the circulating beam. Electron lenses were used in the Fermilab Tevatron collider for bunch-by-bunch compensation of long-range beam-beam tune shifts, for removal of uncaptured particles in the abort gap, for preliminary experiments on head-on beam-beam compensation, and for the demonstration of halo scraping with hollow electron beams. Electron lenses for beam-beam compensation are being commissioned in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Hollow electron beam collimation and halo control were studied as an option to complement the collimation system for the upgrades of the Large Hadron Collider (LHC) at CERN; a conceptual design was recently completed. Because of their electric charge and the absence of materials close to the proton beam, electron lenses may also provide an alternative to wires for long-range beam-beam compensation in LHC luminosity upgrade scenarios with small crossing angles. At Fermilab, we are planning to install an electron lens in the Integrable Optics Test Accelerator (IOTA, a 40-m ring for 150-MeV electrons) as one of the proof-of-principle implementations of nonlinear integrable optics to achieve large tune spreads and more stable beams without loss of dynamic aperture.

Keywords: nonlinear beam dynamics; electron lens; collimation; beam-beam effects

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INTRODUCTION

Electron lenses are pulsed, magnetically confined, low-energy electron beams whose electromagnetic fields are used for active manipulation of the circulating beam in high-energy accelerators [1, 2]. The first main feature of an electron lens is the possibility to control the current-density profile of the electron beam (flat, Gaussian, hollow, etc.) by shaping the cathode and the extraction electrodes. Another feature is pulsed operation, enabled by the availability of high-voltage modulators with fast rise times. The electron beam can therefore be synchronized with subsets of bunches, with different intensities for each subset. The main advantage of the use of electron lenses for high-power accelerators is the absence of metal close to the beam, therefore avoiding material damage and impedance. Electron lenses were developed for beam-beam compensation in colliders [3], enabling the first observation of long-range beam-beam compensation effects by tune shifting individual bunches [4]. They were used for many years during regular Tevatron collider operations for cleaning uncaptured particles from the abort gap [5]. One of the two Tevatron electron lenses was used for experiments on head-on beam-beam compensation in 2009 [6], and for exploring hollow electron beam collimation in 2010–2011 [7, 8]. Electron lenses for beam-beam compensation were built for RHIC at BNL and are being commissioned [9, 10]. Current areas of research on electron lenses include the generation of nonlinear integrable lattices in IOTA at Fermilab [11, 12] and applications for the LHC upgrades: as halo monitors and scrapers, as charged current-carrying ‘wires’ for long-range beam-beam compensation, and as tune-spread generators for Landau damping of instabilities before collisions.

NONLINEAR INTEGRABLE OPTICS WITH ELECTRON LENSES

The Integrable Optics Test Accelerator (IOTA) is a small storage ring (40 m circumference) being built at Fermilab as part of the accelerator and beam physics research program. Some of the main goals of the project are the practical

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implementation of nonlinear integrable lattices in a real machine, the study of space-charge compensation in rings, and a proof-of-principle demonstration of optical stochastic cooling [11, 12].

The concept of nonlinear integrable optics applied to accelerators involves a small number of special nonlinear focusing elements added to the lattice of a conventional machine in order to generate large tune spread while preserving dynamic aperture [13]. The concept may have a profound impact in the design of high-intensity machines by providing improved stability to perturbations and mitigation of collective instabilities through Landau damping.

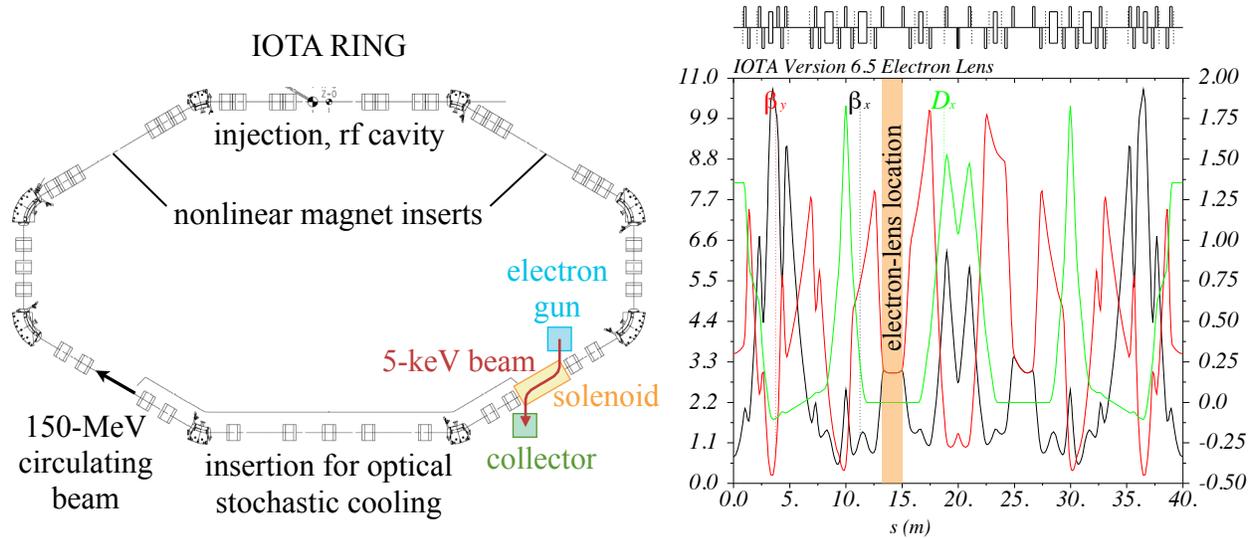
The effect of nonlinear lattices on single-particle dynamics will be investigated during the first stage of IOTA operations using low-intensity pencil beams of electrons at 150 MeV: 10^9 particles/bunch, $0.1 \mu\text{m}$ transverse rms geometrical equilibrium emittance, 2 cm rms bunch length, and 1.4×10^{-4} relative momentum spread. The beam is generated by the photoinjector currently being commissioned at the Fermilab Advanced Superconducting Test Accelerator (ASTA) facility. The goal of the project is to demonstrate a nonlinear tune spread of about 0.25 without loss of dynamic aperture in a real accelerator.

It was recently shown that one way to generate a nonlinear integrable lattice is with specially segmented quadrupole magnets [13]. There are also 2 concepts based on electron lenses: (a) axially symmetric thin-lens kicks with a particular amplitude dependence [14, 15, 16]; and (b) axially symmetric thick-lens kicks in a solenoid [17]. These concepts use the electromagnetic field generated by the electron beam distribution to provide the desired nonlinear transverse kicks to the circulating beam.

The integrability of axially symmetric thin-lens kicks was studied in 1 dimension by McMillan [14, 15]. It was then extended to 2 dimensions [16] and experimentally tested with colliding beams [18]. Let us analyze the main quantities involved in the electron-lens case. The beam in the electron lens (Figure 1, left) has velocity $v_e = \beta_e c$. The length L of the electron lens is assumed to be small in comparison with the local lattice amplitude function β . Let $j(r)$ be a specific radial dependence of the current density of the electron-lens beam (the ‘McMillan case’), with j_0 its value on axis and a its effective radius: $j(r) = j_0 a^4 / (r^2 + a^2)^2$. The total current is $I_e = 2\pi \int_0^\infty j \cdot r dr = j_0 \pi a^2$. While traversing the electron lens, the circulating beam, with magnetic rigidity ($B\rho$) and velocity $v_z = \beta_z c$, experiences the following transverse angular kick:

$$\theta(r) = 2\pi \frac{j_0 L (1 \pm \beta_e \beta_z)}{(B\rho) \beta_e \beta_z c^2} \frac{a^2 r}{r^2 + a^2} \left(\frac{1}{4\pi\epsilon_0} \right). \quad (1)$$

The ‘+’ sign applies when the beams are counterpropagating and the electric and magnetic forces act in the same



Source: G. Kafka (IIT/Fermilab) and A. Valishev (Fermilab)

FIGURE 1. Left: schematic layout of the IOTA ring; the electron lens (gun, solenoid, and collector) is shown in the lower right section. Right: calculated IOTA lattice for electron-lens operation, showing the horizontal and vertical amplitude functions β_x and β_y (left axis, in meters) and the horizontal dispersion D_x (right axis, in meters) as a function of the longitudinal coordinate s around the ring.

direction. For such a radial dependence of the kick, there are 2 noncommuting invariants of motion in the 4-dimensional transverse phase space. Neglecting longitudinal effects, all particle trajectories are regular and bounded.

The concept of axially symmetric thick-lens kicks relies on a solenoid with axial field $B_z = 2(B\rho)/\beta$ to provide focusing for the circulating beam and constant amplitude lattice functions $\beta \equiv \beta_x = \beta_y$. The same solenoid magnetically confines the low-energy beam in the electron lens. In this case, any axially symmetric electron-lens current distribution $j(r)$ generates 2 conserved quantities (the Hamiltonian and the longitudinal component of the angular momentum), as long as the betatron phase advance in the rest of the ring is an integer multiple of π .

The achievable nonlinear tune spread $\Delta\nu$ (i.e., the tune difference between small and large amplitude particles) is proportional to the electron-lens current density on axis:

$$\Delta\nu = \frac{\beta j_0 L (1 \pm \beta_e \beta_z)}{2(B\rho)\beta_e \beta_z c^2} \left(\frac{1}{4\pi\epsilon_0} \right). \quad (2)$$

For demonstrating the nonlinear integrable optics concept with electron lenses in a real machine, there are several design considerations to take into account.

The size of the electron beam should be compatible with the achievable resolution of the apparatus. Amplitude detuning and dynamic aperture of the ring will be measured by observing the turn-by-turn position and intensity of a circulating pencil beam with an equilibrium emittance $\epsilon = 0.1 \mu\text{m}$ (rms, geometrical) and size $\sigma_e = \sqrt{\beta\epsilon}$ at the electron lens. This size should be larger than the expected resolution of the beam position monitors, $\sigma_{\text{BPM}} \leq 0.1 \text{ mm}$. In the current IOTA lattice design (Figure 1, right), $\beta = 3 \text{ m}$ and $\sigma_e = \sqrt{\beta\epsilon} = 0.55 \text{ mm}$, which satisfies this requirement. Moreover, it follows that the required axial field is $B_z = 2(B\rho)/\beta = 0.33 \text{ T}$.

The aperture of the ring $A_{\text{ring}} = 24 \text{ mm}$ must be sufficient to contain a wide range of betatron amplitudes and detunings. Aperture and magnet field quality suggest a maximum tolerable orbit excursion of about $A_{\text{max}} = A_{\text{ring}}/2 = 12 \text{ mm}$. Particles at small amplitudes will exhibit the maximum detuning $\Delta\nu$. The maximum excursion A_{max} must be sufficient to accommodate particles with large amplitudes and small detunings compared to $\Delta\nu$. For the McMillan kick distribution of Eq. (1), for instance, this can be achieved by requiring $a \leq A_{\text{max}}/6 = 2 \text{ mm}$. For a typical electron lens with resistive solenoids, with $B_z = 0.33 \text{ T}$ in the main solenoid, one can operate at $B_g = 0.1 \text{ T}$ in the gun solenoid. Because of magnetic compression, this translates into a current-density distribution with $a_g = a\sqrt{B_z/B_g} = 3.6 \text{ mm}$ at the cathode. This parameter serves as an input to the design of the electron-gun assembly.

The achievable tune spread should be large enough to clearly demonstrate the effect. As a goal for the IOTA project, it was decided to set $\Delta\nu \geq 0.25$. Through Eq. (2), this requirement imposes a constraint on the current density in the electron lens. For instance, with typical electron-lens parameters, $L = 1 \text{ m}$, $\beta_e = 0.14$ (5 keV kinetic energy) and copropagating beams², one obtains $j_0 = 14 \text{ A/cm}^2$ and, for the McMillan distribution, a total current $I_e = j_0 \pi a^2 = 1.7 \text{ A}$.

The design parameters are within the current state of the art. It may be challenging to transport these currents through a resistive electron lens while preserving the desired quality of the current-density profile. The effects of imperfections and of longitudinal fields must be investigated with numerical simulations and with experimental studies in the Fermilab electron-lens test stand. The relatively large instantaneous beam power to be dissipated in the collector (8.5 kW) may require provisions for pulsed operation of the electron lens compatible with the time structure of the IOTA circulating beam. In general, the project benefits from the many years of experience in the construction and operation of electron lenses at Fermilab, and it can rely on several components that are already available at the laboratory, such as electron gun assemblies, resistive solenoids, collectors, and power supplies.

HALO CONTROL WITH HOLLOW ELECTRON BEAMS

Hollow electron beam collimation is the most mature among the electron-lens applications discussed here. A recent summary can be found in Ref. [19]. The technique was tested in the Fermilab Tevatron collider and it is now being proposed as an option to complement the LHC collimation system. It is based upon electron beams with a hollow current-density profile aligned with the circulating beam [20, 7, 8]. If the electron distribution is axially symmetric, the proton beam core is unperturbed, whereas the halo experiences smooth and tunable nonlinear transverse kicks. The size, position, intensity, and time structure of the electron beam can be controlled over a wide range of parameters.

² At the design stage, we consider the copropagating case because it is more conservative and because it may serve in the future as an electron cooler for protons, which will be injected in IOTA in the same direction as electrons.

For the LHC and its luminosity upgrades (HL-LHC), beam halo measurement and control are critical, and this technique may provide unique capabilities. LHC and HL-LHC represent huge leaps in stored beam energy. Beam halo monitoring and control are one of the major risk factors for LHC and for safe operation with crab cavities in HL-LHC. There is a need to measure and monitor the beam halo, and to remove it at controllable rates. Hollow electron lenses are the most established and flexible tool for this purpose.

A plan for electron lenses in the LHC was developed and a conceptual design was recently completed [21, 22]. The expected performance is based upon experimental measurements and numerical simulations [23]. A wide range of halo removal rates is possible, from seconds to hours, using the electron lens in continuous mode (same electron current every turn for a given bunch) or in stochastic mode (by adding random noise turn by turn to the modulator voltage).

Alternative schemes for halo control will also be investigated, as they may be cheaper than electron lenses, or they may become available sooner. These alternatives include excitations with transverse dampers, tune modulation with warm quadrupoles [24], and wire compensators. Noninvasive halo diagnostic methods, such as synchrotron-light monitoring with wide dynamic range, are being pursued with high priority. The electron lenses themselves, if they are installed, may provide a new sensitive way to measure halo populations with backscattered electron detectors, as is being demonstrated at RHIC [10, 25].

ELECTRON ‘WIRES’ AS LONG-RANGE COMPENSATORS

Electron lenses may play an important role in HL-LHC luminosity schemes with flat beams and smaller crossing angles, where no crab cavities are necessary, but for which long-range beam-beam compensation is critical. Conventional wire compensators will be tested after the current LHC shutdown. They are technically challenging and they present a risk for collimation and machine protection, because they involve water-cooled copper cables carrying 378 A at about 10 standard deviations of the proton beam size from the beam axis. Electron lenses are considered as a safer, less demanding alternative to wire compensators, with the added benefit of pulsing [26]. About 21 A over a distance of 3 m would be required for HL-LHC, with any transverse shape. Physics and integration studies were initiated to calculate the expected performance and its sensitivity to location. Energy deposition in the superconducting solenoid and radiation to the high-voltage modulator must also be addressed.

CONCLUSIONS

Electron lenses are unique devices for active beam manipulation in accelerators, with a wide range of applications. Halo scraping with hollow electron beams was demonstrated at the Fermilab Tevatron collider and, because halo measurement and control are critical for LHC and its upgrades, a conceptual design of hollow electron beam scraper for the LHC was recently completed. Electron lenses in the LHC are also a candidate for long-range beam-beam compensation. Magnetized low-energy electron beams are also relevant for the Fermilab beam physics program in the near future, as one of the most promising ways to practically implement nonlinear integrable lattices in the IOTA ring.

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