ELECTRON LENSES FOR EXPERIMENTS ON NONLINEAR DYNAMICS WITH WIDE STABLE TUNE SPREADS IN THE FERMILAB INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

Recent developments in the study of integrable Hamiltonian systems have led to nonlinear accelerator lattice designs with two transverse invariants. These lattices may drastically improve the performance of high-power machines, providing wide tune spreads and Landau damping to protect the beam from instabilities, while preserving dynamic aperture. To test the feasibility of these concepts, the Integrable Optics Test Accelerator (IOTA) is being designed and built at Fermilab. One way to obtain a nonlinear integrable lattice is by using the fields generated by a magnetically confined electron beam (electron lens) overlapping with the circulating beam. The parameters of the required device are similar to the ones of existing electron lenses. We present theory, numerical simulations, and first design studies of electron lenses for nonlinear integrable optics.

INTRODUCTION

The study of neutrinos and rare processes in particle physics requires high-power accelerators to provide primary beams. The performance of these machines is limited by several factors, including tolerable losses and beam halo, space-charge effects, and instabilities. A possible path towards high-intensity rings includes these steps: developing theories and models describing high-intensity circular machines; carrying out related proof-of-principle experiments; and designing a new kind of rapid-cycling synchrotron based on nonlinear optics, wide tune spreads to suppress instabilities, and possibly self-consistent or compensated space-charge dynamics.

In particular, the Integrable Optics Test Accelerator (IOTA, Fig. 1) is a small storage ring (40 m circumference) being built at Fermilab [1–3]. Its main purposes are the practical implementation of nonlinear integrable lattices in a real machine, the study of space-charge compensation in rings, and a demonstration of optical stochastic cooling.

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 spreads while preserving dynamic aperture [4]. 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 pencil beams of electrons at 150 MeV with 10^9 particles/bunch, transverse rms geometrical equilibrium emittance in the range 0.01–0.04 μm, bunch lengths of a few centimeters, and a relative momentum spread of 1.4×10^{-4}. 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. The beam is generated by the photoinjector currently being operated at the Fermilab Advanced Superconducting Test Accelerator (ASTA) facility [5].

It was shown that one way to generate a nonlinear integrable lattice is with specially segmented multipole magnets [4]. There are also two concepts based on electron lenses: (a) axially symmetric thin kicks with a specific amplitude dependence [6–8]; and (b) axially symmetric kicks in a long solenoid [9, 10]. These concepts use the electromagnetic field generated by the electron beam distribution to provide the desired nonlinear transverse kicks to the circulating beam.

Electron lenses are pulsed, magnetically confined, low-energy electron beams whose electromagnetic fields are used for active manipulation of circulating beams [11, 12]. One of the main features 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. Electron lenses were developed for beam-beam compensation in colliders [13], enabling the first observation of long-range beam-beam compensation effects by tune shifting individual bunches [14]. They were used for many years during regular Tevatron collider operations for cleaning uncaptured particles from the abort gap [15]. One of the two Tevatron electron lenses was used for experiments on head-on beam-beam compensation in 2009 [16], and for exploring hollow electron beam collimation in 2010–2011 [17, 18]. Electron lenses for beam-beam compensation were built for RHIC at BNL, showing considerable improvements in luminosity [19–21]. Current areas of research on electron lenses include applications for the upgrades of the Large Hadron Collider: as halo monitors and scrapers [22], as charged current-carrying 'wires' for long-range beam-beam compensation [23, 24], and as tune-spread generators for Landau damping of instabilities before collisions.

In this paper, we describe the concept of electron lenses for nonlinear integrable optics and present the main design considerations for the Fermilab IOTA ring.

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NONLINEAR INTEGRABLE OPTICS WITH ELECTRON LENSES

There are several factors that determine the focusing strength of an electron lens. The cathode-anode voltage V determines the velocity $v_e = \beta_e c$ of the electrons in the device, which is assumed to have length L and to be located in a region of the ring with lattice amplitude function β. When acting on a circulating beam with magnetic rigidity $(B\rho)$ and velocity $v_z = \beta_z c$, the linear focusing strength k_e for circulating particles with small betatron amplitudes is independent of the current-density profile and is proportional to the current density on axis j_0:

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

The '+' sign applies when the beams are counter-propagating and the electric and magnetic forces act in the same direction. As discussed above, there are two concepts describing electron lenses for nonlinear integrable optics.

Thin Radial Kick of McMillan Type

The integrability of axially symmetric thin-lens kicks was studied in 1 dimension by McMillan [6, 7]. It was then extended to 2 dimensions [8] and experimentally tested with colliding beams [25]. Let $j(r)$ be a specific radial dependence of the current density of the electron-lens beam, 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 $I_e = 2\pi \int_0^\infty j \cdot r\, dr = j_0 \pi a^2$. The circulating beam experiences nonlinear transverse kicks: $\theta(r) = k_e a^2 r/(r^2 + a^2)$. For such a radial dependence of the kick, and if the element is thin ($L \ll \beta$), there are 2 independent invariants of motion in the 4-dimensional transverse phase space. Neglecting longitudinal effects, all particle trajectories are regular and bounded. The achievable nonlinear tune spread $\Delta\nu$ (i.e., the tune difference between small and large amplitude particles) is of the order of $\beta k_e/4\pi$. A more general expression applies when taking into account machine coupling and the electron-lens solenoid.

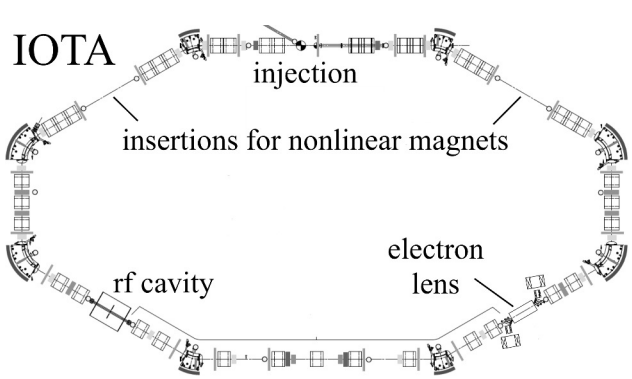

Figure 1: Layout of the electron lens in the IOTA ring.

Table 1: Typical Electron-Lens Design Parameters

Parameter	Value
Amplitude function, β	3 m
Circulating beam size (rms), σ_e	0.24 mm
Main solenoid length, L	0.7 m
Main solenoid field, B_z	0.33 T
Gun/collector solenoid fields, B_g	0.1 T
Cathode-anode voltage, V	5 kV
Beam current, I_e	1.1 A
Current density on axis, j_0	9 A/cm^2
Focusing strength, k_e	0.63 m^{-1}
Effective radius in overlap, a	2 mm
Max. radius in overlap, $6a$	12 mm
Effective radius at cathode, a_g	3.6 mm
Max. radius at cathode, $6a_g$	22 mm

Axially Symmetric Kick in Long Solenoid

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. Because the machine operates near the integer or half integer resonances, the achievable tune spread in this case is of the order of $L/(2\pi\beta)$. This scenario favors thick lenses and it is insensitive to the current-density distribution in the electron lens.

ELECTRON-LENS DESIGN

For demonstrating the nonlinear integrable optics concept with electron lenses in a real machine, there are several design considerations to take into account (Table 1).

Design Parameters

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 $\epsilon = 0.02\ \mu$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, $\sigma_{\rm BPM} \leq 0.1$ mm. In the current IOTA lattice design (Figure 1, right), $\beta = 3$ m and $\sigma_e = \sqrt{\beta\epsilon} = 0.24$ mm, which satisfies this requirement. Moreover, it follows that the required axial field is $B_z = 2(B\rho)/\beta = 0.33$ T.

The aperture of the ring $A_{\rm ring} = 24$ mm must be sufficient to contain a wide range of betatron amplitudes and detunigs. Aperture and magnet field quality suggest a maximum tolerable orbit excursion of about $A_{\rm max} = A_{\rm ring}/2 = 12$ mm.

Particles at small amplitudes will exhibit the maximum detuning $\Delta\nu$. The maximum excursion $A_{\max}$ must be sufficient to accomodate particles with large amplitudes and small detunings compared to $\Delta\nu$. For the McMillan kick distribution, for instance, this can be achieved by requiring $a \leq A_{\max}/6 = 2$ mm. For a typical electron lens with resistive solenoids, with $B_z = 0.33$ T in the main solenoid, one can operate at $B_g = 0.1$ T in the gun solenoid. Because of magnetic compression, this translates into a current-density distribution with $a_g = a\sqrt{B_z/B_g} = 3.6$ 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. This requirement imposes a constraint on the current density in the electron lens. For instance, with typical electron-lens parameters, $L = 0.7$ m, $\beta_e = 0.14$ (5 keV kinetic energy) and counter-propagating beams, one could operate at $j_0 = 9$ A/cm^2 (corresponding to a total current $I_e = j_0\pi a^2 = 1.1$ A for the McMillan distribution) to achieve $k_e = 0.63$ m^{-1}.

For the McMillan case, it is important to generate and preserve the desired beam profile. Beam transport in the electron lens, from the gun through the toroidal bends, was studied with field-line mapping first, followed by single-particle tracking and then by particle-in-cell space-charge simulations with the `bender` code [26]. Vertical drift in the horizontal bends and profile distortions were minimized. From the field calculations, kick maps were deduced, which will be used in IOTA tracking simulations with the `lifetrac` code [27] to assess the residual effects on the circulating beam.

Technical Design

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. A few features are specific to the IOTA electron lens, such as the need for accurate diagnostics, the ability to work as an electron column [28, 29] for space-charge compensation experiments, possible operation at ultrahigh vacuum levels (10^{-10} mbar) with circulating protons, the tight space constraints, and the resistive main solenoid to avoid the complications and costs of cryogenics in the IOTA area. Most of the experiments do not require a specific time structure of the electron beam, so the normal mode of operation will be continuous, requiring collectors able to dissipate a few kilowatts of beam power. Pulsed operation is foreseen for diagnostics and for parasitic studies.

CONCLUSIONS AND OUTLOOK

Electron lenses may provide a way to implement nonlinear integrable lattices in accelerators. Experiments to verify these concepts are planned in the Fermilab Integrable Optics Test Accelerator. The fundamental parameters of an electron lens for IOTA were studied, and construction with state-of-the-art technology is feasible.

The next steps involve an accurate study of the effects of imperfections and the definition of tolerances, such as the following: lattice deviations from the ideal cases (azimuthal asymmetries in the machine optics and in the electron-lens kicks, non-thin McMillan case); accuracy of the electron-gun profile; misalignments; chromatic effects (impact of chromaticity-correction sextupoles on integrability, electron-lens chromaticity). These studies will be based on numerical simulations and on experiments at the Fermilab electron-lens test stand.

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