ELECTRON LENSES AND COOLING FOR THE FERMILAB INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

Recently, the study of integrable Hamiltonian systems has led to nonlinear accelerator lattices with one or two transverse invariants and wide stable tune spreads. These lattices may drastically improve the performance of high-intensity machines, providing Landau damping to protect the beam from instabilities, while preserving dynamic aperture. The Integrable Optics Test Accelerator (IOTA) is being built at Fermilab to study these concepts with 150-MeV pencil electron beams (single-particle dynamics) and 2.5-MeV protons (dynamics with self fields). 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 required parameters are similar to the ones of existing devices. In addition, the electron lens will be used in cooling mode to control the brightness of the proton beam and to measure transverse profiles through recombination. More generally, it is of great interest to investigate whether nonlinear integrable optics allows electron coolers to exceed limitations set by both coherent or incoherent instabilities excited by space charge.

INTRODUCTION

In many areas of particle physics, such as the study of neutrinos and of rare processes, high-power accelerators and high-brightness beams are needed. The performance of these accelerators is limited by several factors, including tolerable losses and beam halo, space-charge effects, and instabilities. Nonlinear integrable optics, self-consistent or compensated dynamics with self fields, and beam cooling beyond the present state of the art are being actively pursued because of their potential impact.

In particular, the Integrable Optics Test Accelerator (IOTA, Fig. 1) is a research storage ring with a circumference of 40 m being built at Fermilab [1, 2]. 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. IOTA is designed to circulate pencil beams of electrons at 150 MeV for the study of single-particle linear and nonlinear dynamics. For experiments on dynamics with self fields, protons at 2.5 MeV (momentum 69 MeV/c) will be used.

In accelerator physics, nonlinear integrable optics 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 [3], thus providing improved stability to perturbations and mitigation of collective instabilities through Landau damping.

One way to generate a nonlinear integrable lattice is with specially segmented multipole magnets [3]. There are also two concepts based on electron lenses [4]: (a) axially symmetric thin kicks with a specific amplitude dependence [5–7]; and (b) axially symmetric kicks in a thick lens at constant amplitude function [8, 9]. These concepts use the electromagnetic field generated by the electron beam distribution to provide the desired nonlinear transverse kicks to the circulating beam.

In IOTA, the electron lens can also be used as an electron cooler for protons. In this paper, we present a preliminary exploration of the research opportunities enabled by the cooler option: beam dynamics with self fields can be studied in a wider brightness range; spontaneous recombination provides fast proton diagnostics; and, lastly, perhaps the most interesting question is whether the combination of electron cooling and nonlinear integrable optics leads to higher brightnesses than presently achievable.

NONLINEAR INTEGRABLE OPTICS WITH ELECTRON LENSES

Electron lenses are pulsed, magnetically confined, low-energy electron beams whose electromagnetic fields are used for active manipulation of circulating beams [10, 11]. 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 have a wide range of applications [12–22]. In particular, they can be used as nonlinear lenses with tunable kicks and controllable shape as a function of betatron amplitude.

The goal of the nonlinear integrable optics experiments, including the ones with electron lenses, is to achieve a large tune spread, of the order of 0.25 or more, while preserv-

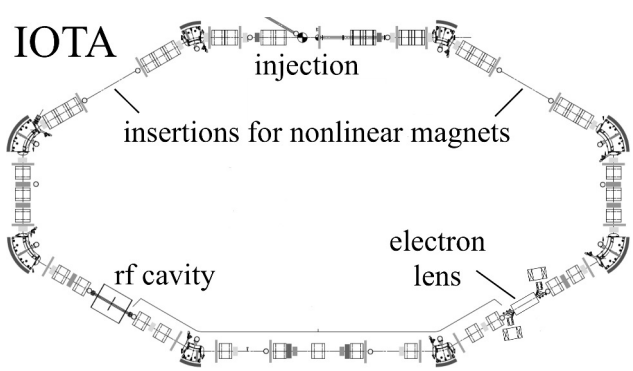

Figure 1: Layout of the IOTA ring.

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ing the dynamic aperture and lifetime of the circulating beam. Experimentally, this will be observed by recording the lifetime and turn-by-turn position of a low-intensity, low-emittance 150-MeV circulating electron bunch, injected and kicked to different betatron amplitudes, for different settings of the nonlinear elements (magnets or electron lenses).

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 $\beta_{\rm lat}$. 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 proportional to the electron 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. For small strengths and away from the half-integer resonance, these kicks translate into the tune shift

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

for particles circulating near the axis.

There are two concepts of 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 [5, 6]. It was then extended to 2 dimensions [7] and experimentally tested with colliding beams [23]. 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 $I_e = j_0\pi a^2$. 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, if the element is thin ($L \ll \beta_{\rm lat}$) and if the betatron phase advance in the rest of the ring is near an odd multiple of $\pi/2$, 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 $\beta_{\rm lat} k_e/4\pi$ (Eq. 2). A more general expression applies when taking into account machine coupling and the electron-lens solenoid. For the thin McMillan lens, it is critical to achieve and preserve the desired current-density profile.

Axially Symmetric Kick in Constant Beta Function

The concept of axially symmetric thick-lens kicks relies on a section of the ring with constant and equal amplitude functions. This can be achieved with a solenoid with axial field $B_z = 2(B\rho)/\beta_{\rm lat}$ to provide focusing for the circulating beam and lattice functions $\beta_{\rm lat} \equiv \beta_x = \beta_y$. 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. At large electron beam currents in the electron lens, the focusing of the electron beam itself dominates over the solenoid focusing and can be chosen to be the source of the constant amplitude functions. Because the machine operates near the integer or half integer resonances, the achievable tune spread in this case is of the order of $L/(2\pi\beta_{\rm lat})$. This scenario favors thick lenses and it is insensitive to the current-density distribution in the electron lens.

Several operating scenarios for the IOTA electron lenses are possible within the currently available parameter space [4]. The feasibility and robustness of these designs against deviations from the ideal cases are being studied with analytical calculations and numerical tracking simulations.

Typical electron-lens parameter ranges for IOTA are shown in Table 1.

Table 1: Typical Electron-Lens Parameters for IOTA

Parameter	Value
Cathode-anode voltage, V	0.1–10 kV
Beam current, I_e	5 mA – 5 A
Current density on axis, j_0	0.1–12 A/cm^2
Main solenoid length, L	0.7 m
Main solenoid field, B_z	0.1–0.8 T
Gun/collector solenoid fields, B_g	0.1–0.4 T
Max. cathode radius, $(a_g)_{\rm max}$	15 mm
Amplitude function, $\beta_{\rm lat}$	0.5–10 m
Circulating beam size (rms), σ_e	0.1–0.5 mm (e^-)
	1–5 mm (p)

ELECTRON COOLING IN IOTA

We investigate the benefits of an electron cooler in the ring and the possible difficulties of running an electron lens in cooling configuration.

Electron cooling in IOTA would extend the range of available brightnesses for space-charge experiments with protons. It would also provide a flow of neutral hydrogen atoms through spontaneous recombination for beam diagnostics downstream of the electron lens. Of greater scientific interest is the question of whether nonlinear integrable optics allows cooled beams to exceed the limitations of space-charge tune spreads and instabilities. Here we discuss these three aspects in more detail.

Electron Cooling of Protons

Proton parameters are shown in Table 2. The parameters are chosen to balance the dominant heating and cooling

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Table 2: Proton Parameters for Cooling in IOTA

Parameter	Value
Kinetic energy, T_p	2.5 MeV
Normalized velocity, β_p	0.073
Number of particles, N_p	5×10^9
Beam current, I_p	0.44 mA
Normalized rms emittance, ϵ_{pn}	$0.3 \rightarrow 0.03$ μm
Rms beam size at cooler, y_p	4→1.3 mm
Momentum spread, σ_p/p	5×10^{-4}
Space-charge tune shift, $\Delta\nu_{sc}$	$-0.028 \rightarrow -0.28$
Transv. temperature (avg.), $\langle kT_{p\perp}\rangle$	5→0.5 eV
Long. temperature, $kT_{p\parallel}$	0.6 eV

mechanisms, while achieving significant space-charge tune shifts. To match the proton velocity, the accelerating voltage in the electron lens has to be $V = 1.36$ kV.

At these energies, proton lifetime is dominated by residual-gas scattering and by intrabeam scattering, due to emittance growth in the absence of cooling. (Charge neutralization is discussed below.) At the residual gas pressure of 10^{-10} mbar, the lifetime contributions of emittance growth due to multiple Coulomb scattering and of losses from single Coulomb scattering are 40 s and 40 min, respectively.

Intrabeam scattering has a stronger effect. Whereas the transverse emittance growth time is 120 s, the longitudinal growth time can be as small as 2.5 s, indicating a possible heat transfer from the longitudinal to the transverse degrees of freedom, which must be mitigated by keeping the effective longitudinal temperature of the electrons (which is dominated by the space-charge depression and therefore by the density n_e) low enough. At the same time, one needs to ensure that the heating term of the magnetized cooling force is negligible. One can achieve cooling rates of about 20 ms and reduce the transverse emittance by about a factor 10, with a corresponding increase in brightness.

Diagnostics through Recombination

IOTA is a research machine and diagnostics is critical to study beam evolution over the time scales of instability growth. The baseline solution for profile measurement consists of ionization monitors, with or without gas injection. In IOTA, with $N_p = 5 \times 10^9$ circulating protons, for a residual gas pressure of 10^{-10} mbar, one can expect 9 ionizations per turn, or a ionization rate of 4.9 MHz.

Spontaneous recombination $p + e^- \rightarrow H^0 + h\nu$ has proven to be a useful diagnostics for optimizing the cooler settings and to determine the profile of the circulating beam.

Neutral hydrogen is formed in a distribution of excited Rydberg states, which have to survive Lorentz stripping through the electron lens toroid and through the next ring dipole to be detected. For IOTA parameters and magnetic fields, atomic states up to $n = 12$ can survive. The corresponding recombination coefficient is $\alpha_r = 9.6\times10^{-19}$ m^3/s for $\sqrt{kT_e} = 0.1$ eV (and scales as $1/\sqrt{kT_e}$).

The total recombination rate R is also proportional to the fraction of the ring occupied by the cooler, $L/C = (0.7\text{ m})/(40\text{ m})$ and to the electron density, n_e:

$$R = N_p \alpha_r n_e (L/C)(1/\gamma^2) \quad (3)$$

For $N_p = 5\times10^9$ and $n_e = 5.8\times10^{14}$ m^{-3}, one obtains a rate $R = 48$ kHz, which is small enough not to significantly affect beam lifetime, but large enough for relatively fast diagnostics complementary to the ionization profile monitors.

Electron Cooling and Nonlinear Integrable Optics

A new research direction is suggested by these studies: in the cases where electron cooling is limited by instabilities or by space-charge tune spread, does nonlinear integrable optics combined with cooling enable higher brightnesses? It seems feasible to investigate this question experimentally in IOTA.

The more straightforward scenario includes electron cooling parameters such as the ones described above. Integrability and tune spreads are provided separately by the nonlinear magnets. Space-charge tune spreads of 0.25 or more, and comparable nonlinear tune spreads, are attainable.

An appealing but more challenging solution would be to combine in the same device, the electron lens, both cooling and nonlinearity (a lens of the McMillan type, for instance). If successful, such a solution would have a direct impact on existing electron coolers in machines that are flexible enough to incorporate the linear part of the nonlinear integrable optics scheme (the T-insert described in Ref. [3]). Preliminary studies indicate that it is challenging to incorporate both the constraints of cooling and the high currents needed to achieve sizable tune spreads, unless one can suppress the space-charge depression. This option is still under study.

As a general comment, we add that instabilities are often driven by impedance. In a research machine dedicated to high-brightness beams, it is useful to be able to vary the electromagnetic response of the beam environment. For this reason, positive feedback with a transverse damper system is being proposed to explore the stability of cooled and uncooled beams with self fields in linear and nonlinear lattices.

CONCLUSIONS

In the Fermilab Integrable Optics Test Accelerator, nonlinear lenses based on magnetically confined electron beams will be used for experimental tests of integrable transfer maps.

With circulating protons, electron lenses can also be used as electron coolers. Cooling times of less than a second can be achieved, allowing one to access a wider range of equilibrium brightnesses for the planned experiments of beam dynamics with self fields.

A recombination detector downstream of the electron lens will complement ionization monitors for measurements of transverse parameters and instabilities.

An electron cooler in the nonlinear integrable lattice also enables new research on the nature of brightness limits for

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high-intensity cooled beams. Having the electron lens act both as nonlinear element and as cooler seems challenging. However, one can rely on the IOTA nonlinear magnets for stable tune spread generation. In addition, the damper system will enable research on beam stability with controlled excitations.

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