ELECTRON LENS FOR THE FERMILAB INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

The Integrable Optics Test Accelerator (IOTA) is a research machine currently being designed and built at Fermilab. The research program includes the study of nonlinear integrable lattices, beam dynamics with self fields, and optical stochastic cooling. One section of the ring will contain an electron lens, a low-energy magnetized electron beam overlapping with the circulating beam. The electron lens can work as a nonlinear element, as an electron cooler, or as a space-charge compensator. We describe the physical principles, experiment design, and hardware implementation plans for the IOTA electron lens.

INTRODUCTION

High-power accelerators and high-brightness beams are needed in many areas of particle physics, such as the study of neutrinos and of rare processes. The performance of these accelerators is limited by tolerable losses, beam halo, space-charge effects, instabilities, and other factors. Nonlinear integrable optics, self-consistent or compensated dynamics with self fields, and beam cooling beyond the present state of the art are being studied to address these issues. Moreover, nonlinearity, chaos, and the quest for integrability under controlled experimental conditions sheds light on the behavior of dynamical systems in general.

The Integrable Optics Test Accelerator (IOTA) 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 study single-particle linear and nonlinear dynamics with pencil beams of 150-MeV electrons. For experiments on space-charge dynamics, 2.5-MeV protons will be injected.

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]. This provides improved stability to perturbations and mitigation of collective instabilities through decoherence and 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 operations with protons, the electron lens can also be used as an electron cooler [10] and as a space-charge compensator [11–13].

In this paper, we summarize the functions of the electron lens in IOTA and discuss current plans to build and test the experimental apparatus.

ELECTRON LENS IN IOTA

In an electron lens, the electromagnetic field generated by a pulsed, magnetically confined, low-energy electron beam is used to actively manipulate the dynamics of the circulating beam [14–16]. Electron lenses have a wide range of applications [17–26]. In particular, they can be used as nonlinear elements with tunable shape as a function of betatron amplitude.

Nonlinear Integrable Optics

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 preserving 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).

There are two concepts of electron lenses for nonlinear integrable optics: thin radial kick of McMillan type and thick axially-symmetric nonlinear lens in constant amplitude function.

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 used to improve the performance of colliders [27]. To implement this concept, the electron lens has to have a specific current-density distribution: $j(r) = j_0 a^4/(r^2 + a^2)^2$, where j_0 is the current density on axis and a is a constant parameter (effective radius). Moreover, the betatron phase advance in the rest of the ring must be near an odd multiple of $\pi/2$. In this scenario, the electron

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gun and magnetic transport system must be able 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. The same solenoid magnetically confines the low-energy beam in the electron lens. In this case, any axially symmetric electron-lens current distribution generates two conserved quantities, 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 the source of the constant amplitude functions. This scenario favors long solenoids, low beta functions, and it is insensitive to the current-density distribution in the electron lens. Although in IOTA the achievable tune spread is smaller in this case than it is in the McMillan case, this scenario is more robust and will probably be the first one to be studied experimentally, using existing Gaussian or similar electron guns.

Electron Cooling

Electron cooling in IOTA would extend the range of available brightnesses for proton experiments with large self fields. It would also provide a flow of neutral hydrogen atoms through spontaneous recombination for beam diagnostics downstream of the electron lens. There are also scientific questions related to nonlinearities and cooling that can be investigated in IOTA, such as whether nonlinear integrable optics allows cooled beams to exceed the limitations of space-charge tune spreads and instabilities. Some of these aspects were discussed in Ref. [10]. Electron cooling poses strict requirements on the field quality in the main solenoid.

Space-Charge Compensation

Although space-charge compensation is commonly used in linacs, its implementation in rings is still an active field of research. Charge neutralization over the circumference of the ring is usually not practical. Local compensation schemes require high charge densities, which in turn can cause beam scattering, distortions of the lattice, and beam-plasma instabilities. Because an electron lens is based upon magnetically confined electron beams, some of these effects can be mitigated.

There are two ways an electron lens can be used as a space-charge compensator. One relies on an electron gun that generates the required charge distribution in transverse space and in time, to reproduce the bunch shape of the circulating beam [11]. In the other scheme, the so-called ‘electron column’, the electrons are generated by ionization of the residual gas and trapped axially by electrodes and transversely by the solenoidal field, in a configuration similar to a Penning-Malmberg trap [12]. The electron gun and collector are not necessary.

The physics of the interaction between circulating bunches and electron plasma is still a very open field of research [28]. However, the required gun, solenoid, and electrode parameters are similar to those of an electron lens, and therefore theory and experiment can be studied in IOTA.

APPARATUS

Construction of IOTA is planned for 2016–2018, and the electron lens should be ready for experiments at the time of commissioning of the ring.

Several Tevatron components can be reused. The gun and collector assemblies of the two Tevatron electron lenses (TEL-1 and TEL-2) were removed from the accelerator tunnel and tested for ultra-high vacuum. Gun and collector solenoid will be re-measured before final installation. Some existing magnet and high-voltage power supplies from the Tevatron are also available.

Convex thermionic dispenser cathodes for generating Gaussian beams have been purchased. They will be used for the thick nonlinear lens experiments. The design of the McMillan electron gun is still in progress.

Whereas the existing gun and collector solenoids from the Tevatron are adequate for IOTA, the toroidal bends and the main solenoid need to be redesigned because of cost and infrastructure (resistive solenoid in IOTA vs. superconducting solenoid in Tevatron) and because of the tight spaces for components in the small ring.

Girders and supports for the electron lens and adjacent components were designed. Manufacturing is almost complete.

In the next few months, we plan to set up a test installation in straight configuration (gun assembly, diagnostics, collector assembly) to check out the subsystems and test electron beam diagnostics.

The total beam current will be measured at the collector. A diagnostic cube with retractable devices will be installed upstream of the collector to measure the current profile.

The beam tube inside the main solenoid will be instrumented with beam-position monitors and cylindrical pickup electrodes, which can also be used for ion clearing and for electrostatic confinement.

A recent overview of the apparatus was given in Ref. [29].

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, for electron cooling of protons, and for studies of space-charge compensation.

The combination of these three functions and the limited physical space make the design of the apparatus challenging, but no major obstacles have been encountered so far. The hardware (in part reused from previous experiments, in part redesigned) will be assembled first in a straight test setup and successively incorporated in the IOTA ring.

Several aspects are under study, such as the design of the new McMillan electron gun and the development of experimental configurations, including the sensitivity of integrable dynamics to imperfections.

Research on electron lenses is linked to several applications (collimation, beam-beam compensation, tune-spread generation, . . .) and it provides a flexible way to contribute to the physics program of the Fermilab Accelerator Science and Technology (FAST) facility.

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