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# Magnetic System for the IOTA Electron Lens:
# Scope of Work for the DOE 2020 Phase I SBIR Proposal with RadiaBeam

Giulio Stancari* and Alexander Valishev

*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

Ivan Gadjev, Alex Murokh, and Alexander Smirnov

*RadiaBeam Technologies, Santa Monica, California 90404, USA*

Christopher Hall

*RadiaSoft, Boulder, Colorado 80301, USA*

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* stancari@fnal.gov

## I. INTRODUCTION

The Fermilab Integrable Optics Test Accelerator (IOTA) is a storage ring dedicated to beam physics research. It can store electrons at 100–150 MeV or protons at 2.5 MeV [1].

Key parts of the research program rely on the IOTA electron lens [1]. Electron lenses are very flexible tools used to affect beam dynamics in storage rings. They use magnetically confined, low-energy electron beams. By shaping the transverse and longitudinal profiles of the low-energy electron beam, various effects on the circulating beam can be achieved [2].

The first electron lenses were used in the Fermilab Tevatron collider for beam-beam compensation, abort-gap cleaning, and beam halo control. In the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, electron lenses were used to increase luminosity through beam-beam compensation and to study ion halo control. Hollow electron lenses for halo control and collimation will be built for HL-LHC, the high-luminosity upgrade of the Large Hadron Collider at CERN.

The goal of the IOTA electron lens project is to demonstrate novel applications of electron lenses:

- Nonlinear integrable optics, in two configurations — McMillan and axially symmetric.
- Space-charge compensation in storage rings.
- Tune-spread generation for Landau damping.
- Electron cooling and the interaction of electron cooling with nonlinear integrable optics.

The multiple functions of the device, together with its compact size, constitute the main design challenges.

## II. IOTA ELECTRON LENS PARAMETERS

In IOTA, the electron lens will be installed in the D Right straight section (Figure 1). The length of the section is 1.4 m. The low-energy electron beam is generated in the electron gun and transported through a series of solenoids to the overlap region, where it interacts with the IOTA circulating beam (electrons or protons). The main parameters are summarized in Table I.

## III. SCOPE

Fermilab is seeking a collaboration with RadiaBeam for the design, engineering and construction of the IOTA electron-lens magnetic system.

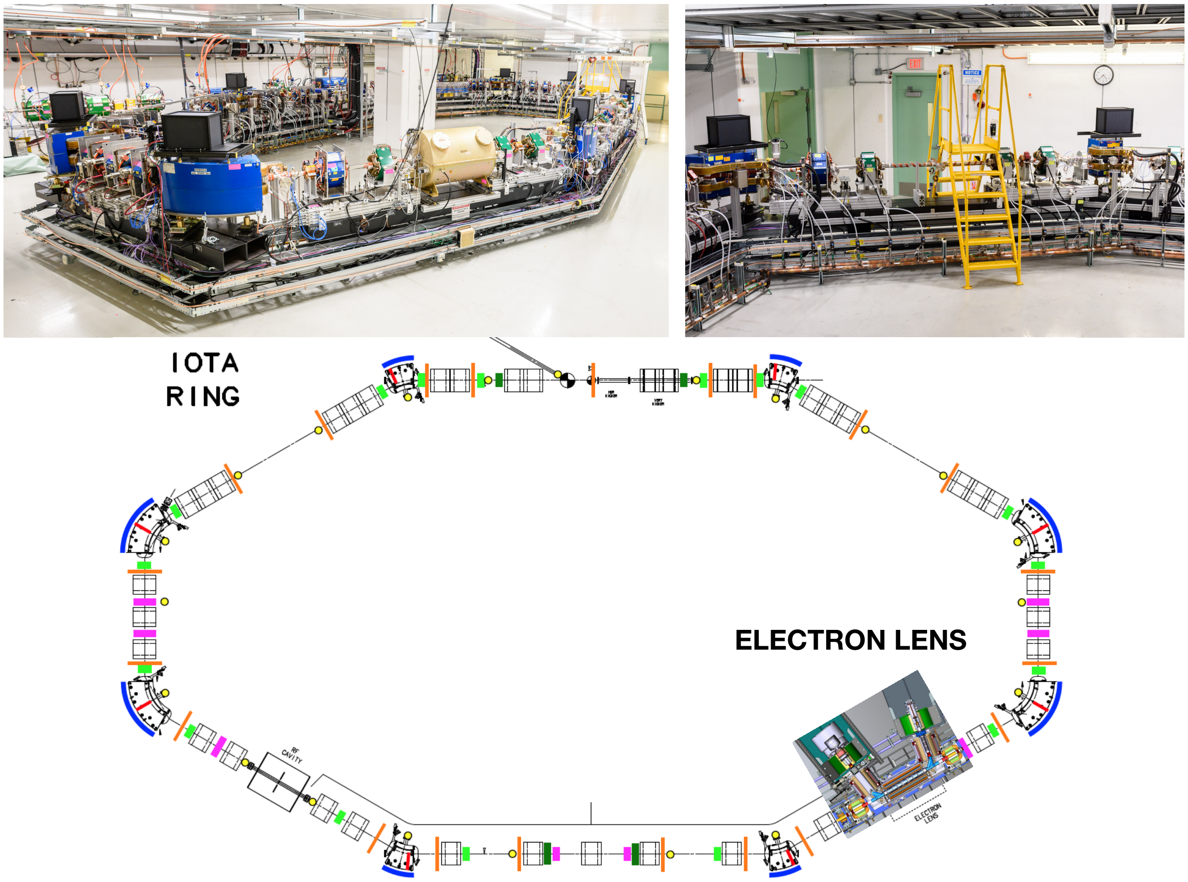


Figure 1. IOTA layout and location of the electron lens.

The main purpose of the magnetic system is to guide the low-energy electron beam and to preserve the current-density distribution generated at the electron gun.

A baseline design was developed in collaboration with the Mechanical Engineering group at CERN (Figure 2).

The system includes the following components:

- Gun and collector solenoids with 4 corrector coils each
- 2 transport solenoids with 4 corrector coils each
- 2+2 short solenoids for the toroidal sections
- 1 main solenoid with 8 corrector coils, 4 short ones upstream for horizontal and vertical position adjustments and 4 long ones downstream for horizontal and vertical angle adjustments.
- 2 orbit correctors (not shown in Figure 2)

The gun and collector solenoids are already available. They are being reused from one of the Tevatron electron lenses (TEL-2).

In the current configuration, the main solenoid is superconducting to make the coils more compact, to improve field quality, and to lower power consumption. The cryogenic solution is a stand-alone, dry system based on 2 cryocoolers. These systems are reliable, well supported and reasonably priced. Cool-down times were estimated in Ref. [3] and are compatible with IOTA operations. Issues of quench protection and vibration damping are being investigated.

## IV. FUNCTIONAL REQUIREMENTS

Operation of the electron lens and beam physics goals dictate the functional requirements. In addition to the parameter ranges in Table I, the following constraints should be taken into account.

- The main solenoid should be as long as possible, with a minimum length of 0.7 m.
- The inner bore of the main solenoid should accommodate the beam pipe (50 mm diameter), flanges, and feedthroughs for instrumentation. The bore in the current baseline model is already close to the minimum.
- Electron beam transport efficiency should be better than 99% for all magnetic field configurations of gun, collector and main solenoids and for maximum beam size diameters of 30 mm.

| Parameter | Value |
|---|---|
| Cathode-anode voltage, $V$ | 0.1 – 10 kV |
| Electron-gun perveance, $P$ | (3 – 6) $\times 10^{-6}$ A/V$^{3/2}$ |
| Peak current, $I = P \cdot V^{3/2}$ | 5 mA – 3 A |
| Cathode diameter | <30 mm |
| Current-density distribution | McMillan, Gaussian, flat |
| Main solenoid field | 0.1–0.8 T |
| Gun and collector solenoid fields | 0.1–0.4 T |
| Lattice amplitude functions | 2–4 m |
| Circulating beam size (rms), $e^-$ | 0.1–0.5 mm |
| Circulating beam size (rms), $p$ | 1–5 mm |

Table I. IOTA electron lens parameters.

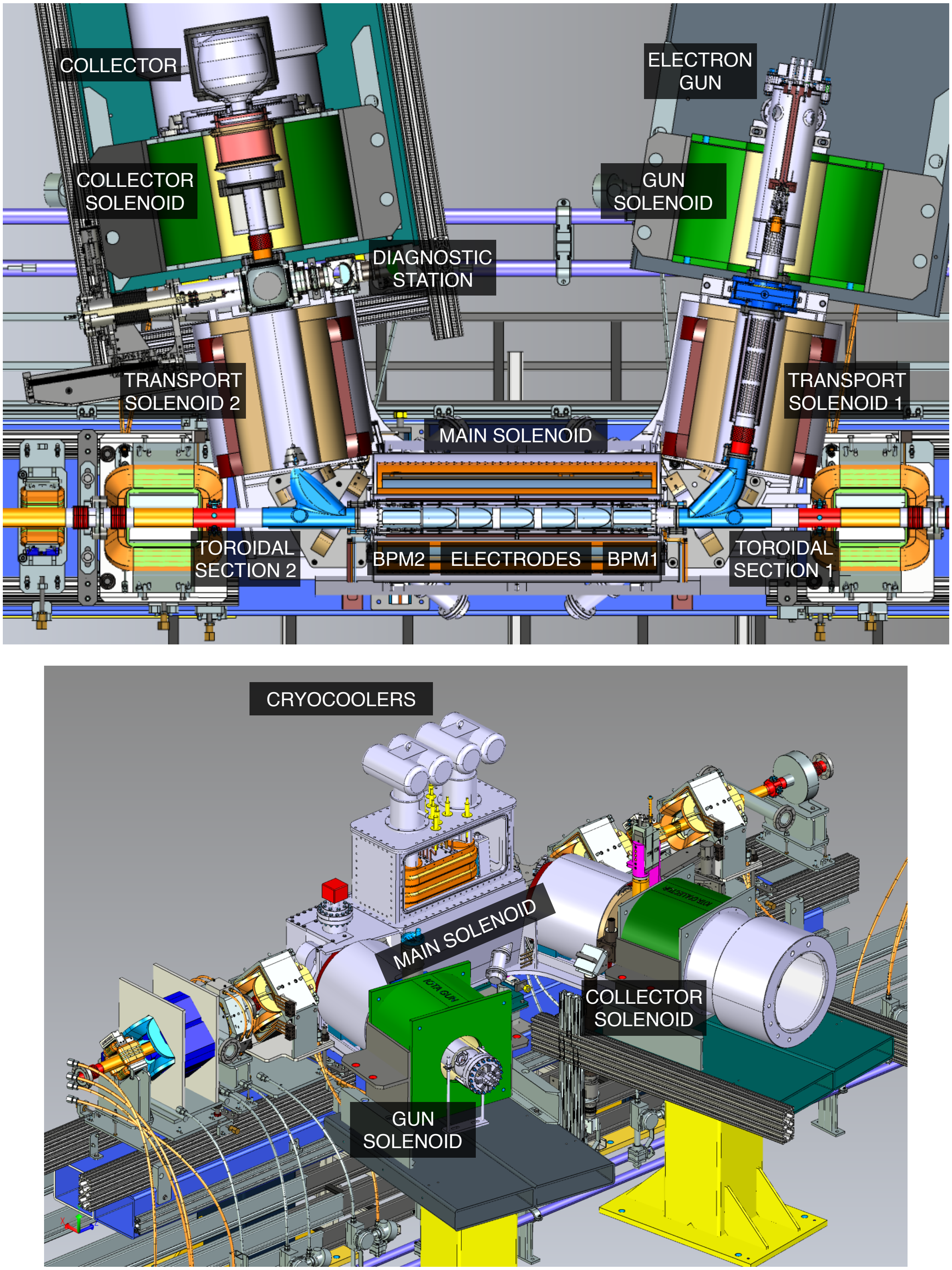


Figure 2. Layout of the IOTA electron lens.

- Gun, main and collector solenoids need to operate independently to set the desired beam size in the interaction region and in the collector. The fields in the transport solenoids are scaled proportionally to the main solenoid field.

- The minimum magnetic field seen by the low-energy electron beam should be as large as possible and at least 0.1 T.

- The distance between the axis of the main solenoid and the trajectory of the low-energy beam with correctors off should be within 1 mm.

- The trajectory of the low-energy beam in the main solenoid should be adjustable in both horizontal and vertical positions and angles. The position adjustments should have a range of $\pm 10$ mm with 0.03 mm resolution. Angles should be adjustable in the range $\pm 5$ mrad with resolution 50 $\mu$rad.

- Field distortions in the good field region of the main solenoid should be $(B_{\perp}/B_z) < 2 \times 10^{-4}$.

- The good field region of the main solenoid should be at least 0.6 m long and have a transverse diameter of 30 mm.

## V. TASKS

Work during Phase I of the SBIR grant can be subdivided into the following tasks.

1. Evaluate and compare the superconducting and resistive options.

2. Optimize the existing baseline layout and field configuration to maximize the length of the main solenoid, the transport efficiency and the minimum field on the trajectory of the low-energy electron beam. The injection and extraction angles and the number of coils in the toroidal section can be modified if needed.

3. Design orbit correctors for the circulating beam to compensate for the transverse kicks due to the toroidal sections. The orbit correctors should be placed between each toroidal section and the adjacent ring quadrupole.

4. Estimate and minimize the distortions of the current-density profile of the electron beam due to space charge in the case of McMillan and Gaussian initial distributions.

5. Develop a conceputal engineering design of the magnetic system.

If Phase I is succesful, fabrication, testing and delivery of the magnetic system will take place during Phase II.

The work will be conducted in close collaboration among the Fermilab, RadiaBeam and CERN teams.

## VI. DOCUMENTATION

At the end of Phase I, RadiaBeam will provide the following documentation to the Fermilab team:

- A written report detailing the design principles and the main conclusions.
- Drawings in CAD and PDF formats.
- A full set of calculated magnetic field maps.
- Scripts and input files used for field calculations and particle tracking.

## VII. RESOURCES

Fermilab maintains a web page with project resources and information [4]. The page includes links to the current baseline engineering design.

A storage area was set up in Fermi Redmine [5] and in Open Science Framework [6] to exchange documents and files.

## ACKNOWLEDGMENTS

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