IOTA – A BRIEF PARAMETRIC PROFILE

Brief description of the IOTA prepared for "Focused Workshop on Scientific Opportunities in IOTA, April 28-29 2015"

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1.0 Introduction and Motivation

The 2014 Particle Physics Project and Prioritization Panel (P5) provided an updated strategic plan for the US HEP program necessary to realize a twenty-year global vision for the field [1]. This plan describes a prioritized set of projects and their timelines, which are required to address the science drivers identified by P5, and recommends the neutrino program as a centerpiece of the domestic US accelerator-based HEP and the construction of a MW-class proton source based on the 0.8 GeV PIP-II SRF linac as a major accelerator facility over the next decade. Since accelerators are a major instrument of discovery for the field of HEP, advances in accelerators and realignment of the accelerator R&D activities with the P5 plan are essential for its success. Along these lines, the focus of the proposed Fermilab R&D program is to explore transformative concepts enabling the next generation cost-effective multi-MW proton beam facility for neutrino research [2]. Superconducting multi-GeV CW linacs could become a feasible option with substantial cost reduction in the high power SRF technology. Alternatively, attainment of the required beam intensities in typically less expensive ring synchrotrons could be possible with greatly reduced particle losses due to space-charge forces, and collective and incoherent beam instabilities. Thus, experimental studies of novel techniques to control beam instabilities and particle losses, such as integrable beam optics and space-charge compensation are one of the highest priorities of Fermilab's Accelerator R&D program centered at the IOTA/ASTA facility. The ultimate objectives of the IOTA R&D program are to carry out experimental studies of high beam intensity effects and to establish a center of excellence in beam theory, modeling and high-performance computation, to describe and reliably predict the behavior of the existing and new Fermilab accelerators in the multi-MW era. The program is designed to be fully coordinated with other National Laboratories and complemented by strong University partnerships focusing both on science and education. Training of the next generation accelerator scientists and engineers remains a high priority.

2.0 IOTA Program Goals

- Construct and commission the IOTA storage ring and its proton and electron injectors, and establish reliable and time-effective operation of the facility for accelerator research program.
- Carry out transformative beam dynamics experiments such as: (i) *integrable optics* with non-linear magnets and with electron lenses; *space-charge compensation* with electron lenses and electron columns; (ii) *optical stochastic cooling* of particle beams and exploration of the fundamental nature the *quantum wave-function of a single electron*; and (iii) innovative emittance exchange, crystal channel radiation and laser-beam interactions.

The following phases are planned:

2.1 Phase 1: FY15-17

1) Construction of main elements of the IOTA/ASTA facility: a) IOTA storage ring; b) electron injector based on existing ASTA electron linac; c) proton injector based on existing HINS proton source; d) special equipment for Advanced Accelerator R&D experiments.

2) Commissioning of the IOTA ring with electron beam.
3) Study of single-particle dynamics in integrable optics with electron beams.

2.2 Phase 2: FY18-20

1) Commission IOTA operation with proton beams.
2) Carry out space-charge compensation experiments with nonlinear optics and electron lenses.

2.3 Phase 3: FY21 and beyond.

1) Study the application of space-charge compensation techniques to next generation high intensity machines.
2) Expand the program beyond these high priority goals to allow Fermilab scientists and a broader accelerator HEP community to utilize unique proton and electron beam capabilities of the IOTA/ASTA facility.

In support of and parallel to the experimental R&D program, a modeling and simulation campaign will be undertaken to develop expertise in theoretical and numerical modeling of high-intensity accelerators, further develop computational tools that will allow quantitative beam loss and beam stability predictions, further develop and maintain the tools necessary to support the high-power target program, and continue to deploy applications in support of Fermilab accelerator operations and design campaigns. IOTA research will be augmented with studies at existing Fermilab accelerators where possible.

3.0 IOTA/ASTA Facility

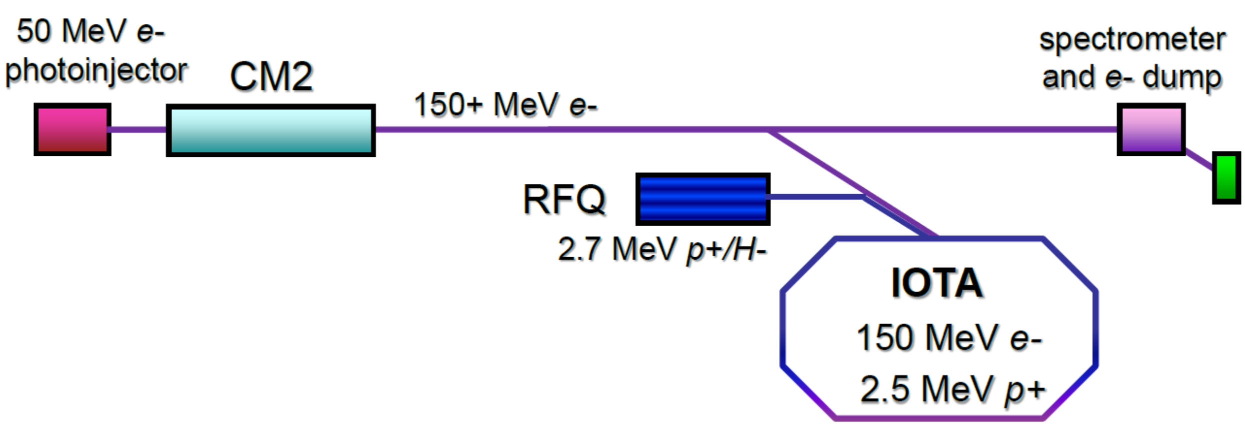

Figure 1. Schematic of the IOTA/ASTA facility.

The main components of the facility include (see also schematic in Fig. 1):

3.1 Electron injector

The electron injector for IOTA ring is based upon the ASTA facility, a superconducting RF linac capable of producing ILC-type electron beams (3 MHz within a 1 ms macro-pulse) with an energy up to 300 MeV [3]. For the purpose of injection into IOTA, a single bunch of electrons with much reduced number of particles and momentum spread will be produced. The main electron injector beam parameters are listed in Table 1.

Electron beam energy	150 MeV
Number of electrons/pulse	2×10^{9}
Transverse emittance r.m.s. normalized	$2\ \pi\ \mu$m
Momentum spread	10^{-4}

Table 1. Parameters of the IOTA electron injector

3.2 Proton Injector based on existing RFQ-based proton source

The proton injector for IOTA is based on the existing HINS RFQ [4]. The source can provide 2.5 MeV kinetic energy beams at 325 MHz with the main parameters listed in Table 2.

Proton beam energy	2.5 MeV
Proton beam momentum	70 MeV/c
Relativistic beta	0.073
RF structure	325 MHz
Average beam current	<8 mA
Transverse emittance r.m.s. normalized	$0.29\ \pi\ \mu$m
Momentum spread, r.m.s.	3.7×10^{-3}
Pulse rate	0.2 / 1 Hz
Pulse width	1 ms @ 0.2 Hz 0.1 ms @ 1 Hz
Maximum number of protons for single-turn injection	8.8×10^{10}

Table 2. Parameters of proton injector

3.3 IOTA ring

The currently planned experiments are:

1) Achievement of large nonlinear betatron tune shift with amplitude without degradation of dynamic aperture by *painting* the accelerator aperture with a *pencil* electron beam with small space charge. These experiments aim to study the stability of single particle motion in nonlinear integrable lattices. The options for constructing nonlinear integrable optics include:
   a) Quasi-integrable optics with octupole magnets [5].
   b) Full 2D integrable solution with Elliptic potential [5].
   c) 2D generalization of McMillan mapping with electron lens [6].
2) Test nonlinear integrable optics with space charge using high intensity proton beams.
3) Study space charge compensation
   a) With electron lens.
   b) Using self-generated electron columns.
4) Conduct a proof-of-principle experiment on optical stochastic cooling [7].

The experimental requirements determine the following design criteria for the ring, which must:

1) Be capable of circulating either proton (up to 2.5 MeV kinetic energy) or electron (up to 150 MeV) beams.
2) Have significantly large beam pipe aperture to accommodate large-amplitude oscillations of pencil beams and large size proton beam.

3) Have significantly long straight sections to accommodate the experimental apparatus, and small enough footprint to fit in the existing machine hall.
4) Possess significant flexibility of the lattice to accommodate all experimental options.
5) Allow for precise control of the optics quality and stability.
6) Present a cost-effective solution based on conventional technology (magnets, RF).

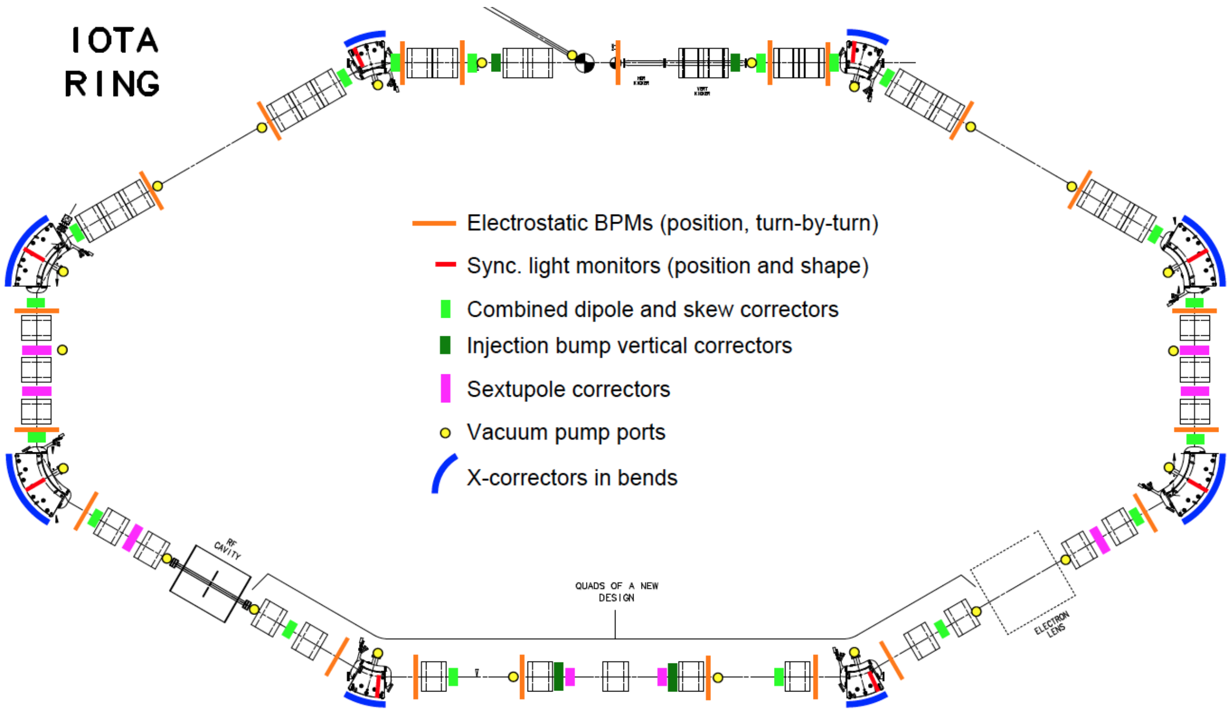

Figure 2. Layout of the IOTA storage ring.

Figure 2 shows the ring layout. The ring has the circumference of 40 m and fits in a 16×9 m footprint. The six long straight sections will accommodate (from top, clockwise) a) injection system, 5 m; b) elliptic potential nonlinear insert, 1.8 m; c) electron lens, 1.8 m; d) optical stochastic cooling, 5 m; e) RF cavity, 1.8 m; f) octupole nonlinear insert, 1.8 m. The beam pipe is a 2” round stainless steel pipe in straight sections, and 48×48 mm custom Aluminum chamber in dipole magnets. The ring lattice components include

1) 8 sector bending magnets – 4 30-degree, 4 60-degree, C-shape with the pole-to-pole gap of 59 mm, bending radius of 0.7 m, and maximum bending field of 0.7 T. The magnets will be powered in series.
2) 39 quadrupole magnets – 71 mm bore, 0.2 m magnetic length. Quadrupoles are grouped into 24 independent circuits, which ensures significant flexibility of the optics.
3) 8 sextupole magnets for chromaticity correction (4 circuits).
4) 20 combined function corrector magnets, incorporating horizontal and vertical orbit correctors as well as skew-quadrupole correctors.
5) Dual-frequency RF cavity – 1 kV at 30 MHz (4-th revolution harmonic for electron operation, beam density modulation for proton operation to enable beam position monitor functioning), and 0.2 kV at 2.8 MHz (40^{th} revolution harmonic for proton operation).
6) Horizontal and vertical stripline kickers for beam injection and full-aperture single-turn kicks during pencil beam experiments.

The beam instrumentation system consists of 21 button-type electrostatic pick-up Beam Position Monitors (5 μm resolution for closed orbit measurement and 100 μm single turn resolution), a current monitor, and 8 points of beam size and position measurement based on synchrotron radiation. The vacuum system with 21 ion pumps will provide 10^{-9} Torr or better pressure.

Figure 3 shows the lattice functions for one of the configuration options (integrable optics with two nonlinear inserts, labeled with blue, where β_x=β_y over the 1.8 m drift). Table 3 summarizes the lattice and beam parameters for the electron beam operation in this configuration.

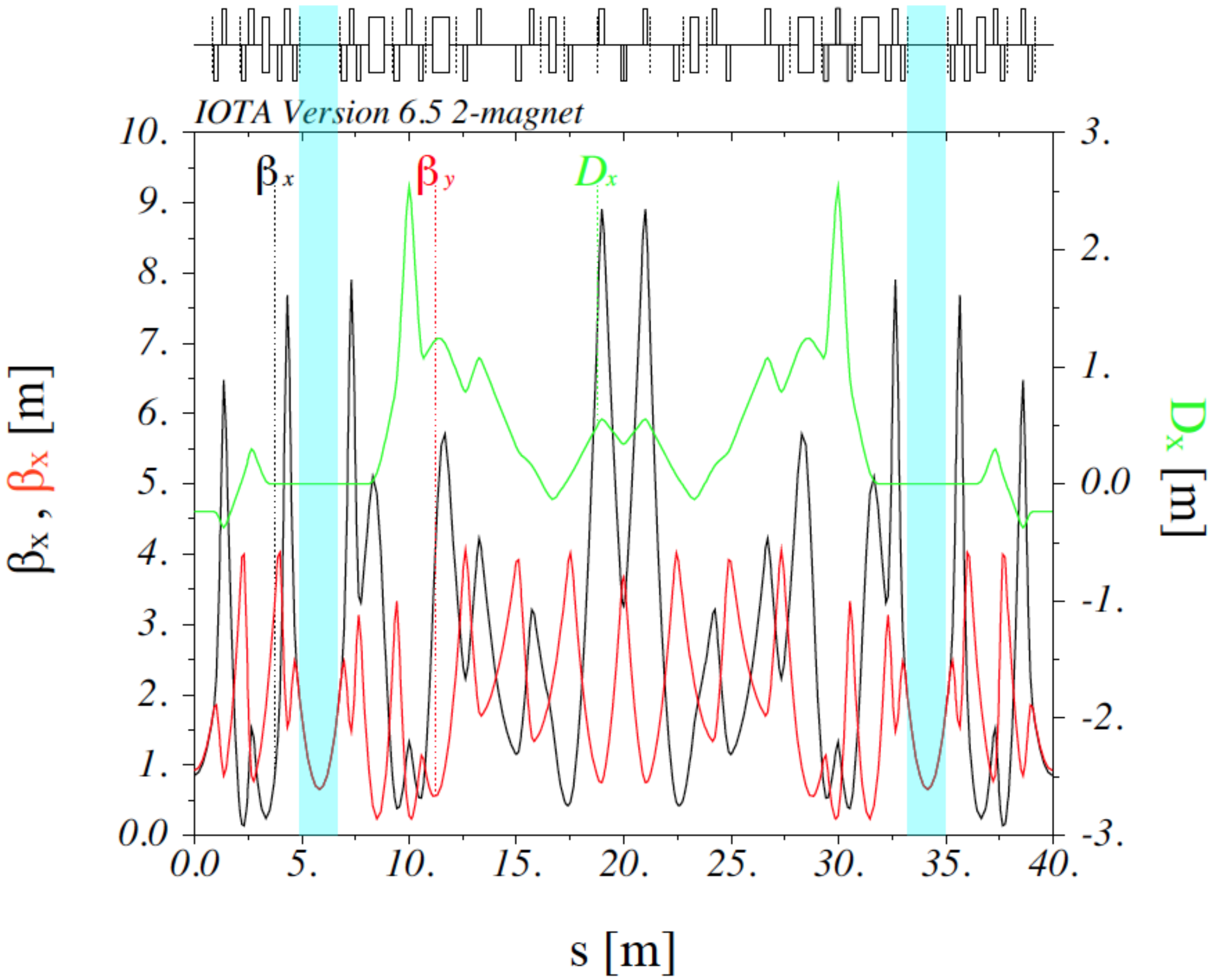

Figure 3. IOTA lattice functions.

Beam energy, *E*	150 MeV
Circumference, revolution period, C_0, T_0	39.97 m, 133.3 ns
Betatron tunes, Q_x, Q_y	5.1, 5.1
Maximum beta-function, β_x, β_y	8.5, 4 m
Momentum compaction, α_p	0.067
RF voltage, frequency	1 kV, 30.0 MHz
Synchrotron tune, Q_s	5.3×10^{-4}
Number of particles, current, N_e, I_e	2×10^{9}, 2.4 mA
Equilibrium beam emittance, ε_x, ε_y	0.04, 0.04 μm

Beam energy spread, bunch length, σ_E, σ_z	1.35×10^{-4}, 10.8 cm
Radiation damping times, τ_x, τ_y, τ_z	0.9 s, 0.9 s, 0.24 s

Table 3. Parameters of the IOTA storage ring.

References

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