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FIRST RESULTS OF THE IOTA RING RESEARCH AT FERMILAB*

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Abstract

The IOTA ring at Fermilab is a unique machine exclusively dedicated to accelerator beam physics R&D. The research conducted at IOTA includes topics such as nonlinear integrable optics, suppression of coherent beam instabilities, optical stochastic cooling, and quantum science experiments. Here we report on the first results of experiments with implementations of nonlinear integrable beam optics. The first of its kind practical realization of a two-dimensional integrable system in a strongly-focusing storage ring was demonstrated allowing among other things for stable beam circulation near or at the integer resonance. Also presented are the highlights of the world's first demonstration of optical stochastic beam cooling and other selected results of IOTA's broad experimental program.

INTRODUCTION

The Fermilab Accelerator Science and Technology facility (FAST) is presently under development as a center for accelerator and beam physics research [1]. The facility takes its beginnings in the early 2000's when the construction of ILC test accelerator began with the goal to demonstrate the operation of a short section of the ILC linac with beam [2,3]. Later, the theory of nonlinear integrable optics gained renewed interest in the accelerator community [4] and a small electron ring was proposed to test the novel accelerator lattices [5]. This ring, the Integrable Optics Test Accelerator (IOTA) became the centerpiece of the IOTA/FAST facility, which is at present the only dedicated machine for intensity-frontier accelerator R&D in the USA. The many advanced features and the small scale of the facility together with the flexibility its accelerators establish a unique capability for testing novel accelerator science concepts and technologies, national and international collaboration, and training of the future accelerator experts.

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IOTA/FAST Machines and Capabilities

The operational machines at the facility are the FAST SRF electron linac [6, 7] and the IOTA storage ring (Fig.1). A low-energy proton linac for injection of proton beams into IOTA is under construction with the planned completion in 2021.

The FAST electron linac features the following main components: i) an RF photo-gun producing electron bunches at the energy of 4.5 MeV with transverse emittance of 0.6 mm-mrad (r.m.s. normalized), and charge of up to 3.2 nC at the frequency of up to 9 MHz; ii) a low-energy accelerating section with two 1.3 GHz SRF Capture Cavities capable of accelerating the beam to 50 MeV, and an 18-m long transport line with a bunch compressor chicane and various beam instrumentation and manipulation devices; iii) a high-energy accelerating section with a single 1.3 GHz ILC-type SRF cryomodule and some 100 m of transport beamline terminating at the high-energy beam absorber. The linac was commissioned to the design energy of 300 MeV [7]. The design beam structure consists of 1-ms long trains of 3000 bunches 333 ns apart at the frequency of 5 Hz. The typical mode of operation for beam injection into IOTA uses single bunches at the repetition rate of 1 Hz.

IOTA is a 40-m circumference storage ring, designed to satisfy the requirements of a diverse beam physics research program using either electron or proton beams. The ring features a conventional linear focusing lattice with 8 sector bending magnets and 40 individually powered quadrupole magnets. The stretched-octagon layout with four 2-m long straight sections and two 6-m long sections allows for the placement of the essential beam manipulation and instrumentation devices as well as for the installation and easy replacement of experimental insertion devices. The 2-in diameter vacuum chamber was incorporated to permit circulation of large-size proton beam and to perform studies of large-amplitude oscillations with electron beams. The maximum design beam momentum in IOTA is 150 MeV, and to date the ring has been commissioned with electron beams

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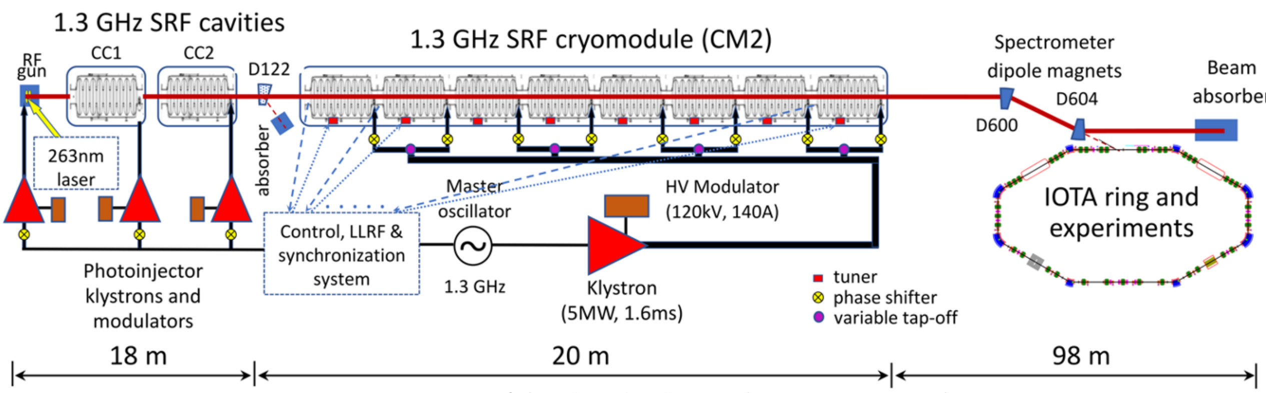

Figure 1: Layout of the IOTA/FAST accelerators (not to scale).

at 47 MeV and 100 MeV [8]. At these energies, electrons emit ample amount of synchrotron radiation in the visible part of the spectrum thus affording beam observation using a broad range of optical instrumentation. Each of the 8 dipole magnets is equipped with a light-output port and an optical instrumentation station [9]. The ring is also equipped with a conventional capacitive pickup BPM system with 21 points of observation [10]. The BPM resolution in the closed orbit mode is at a 1 µm level, and the turn-by-turn mode resolution is ≈100 µm at the beam current of 1 mA. A unique capability of IOTA is the reproducible long-term storage of single electrons, which opens the opportunities for quantum science research as well as for advanced particle tracking measurements [11]. The main parameters of IOTA operation with electron beam are listed in Table 1.

Table 1: IOTA Parameters for 100 MeV Electron Operation

Parameter	Value
Beam current	0-5 mA (in 1 bunch)
Revolution frequency	7.5 MHz
RF Frequency	30 MHz (q=4)
RF Voltage	<1 kV
Synchrotron tune	$1 \div 6 \times 10^{-4}$
Betatron tunes (x,y)	5.3, 5.3
SR damping decr. (x,y,s)	2, 0.7, 0.3 s
Emittance (x,y)	100, 25 nm
Momentum spread	$1 \div 3 \times 10^{-4}$

RESEARCH PROGRAM

The high-impact research pursued by the IOTA/FAST team seeks to address the grand challenges of accelerator and beam physics [12]. The IOTA research program is primarily motivated by the needs of the future high-intensity HEP facilities and aims to push the maximum beam intensity and brightness of future proton rings while minimizing the accelerator scale and cost. Along this direction, the key research areas are i) the mitigation of beam loss and quality degradation caused by coherent beam instabilities through their suppression by Landau damping; ii) the research on improvement of beam quality and brightness such as the mitigation of space-charge and beam cooling. The main candidate technologies being pursued by the IOTA team are the Nonlinear Integrable Optics (NIO) [13], Electron Lenses [14], and Optical Stochastic Cooling [15].

In addition to the priority research, the flexibility of the facility accelerators and its operation model allow opportunities for experiments concurrent with the main program. The studies in this category are often driven by external partners both nationally and internationally and involve academia and graduate students. Example directions include photon science experiments, development of novel beam instrumentation, aspects of high-current SRF operation, machine learning and quantum science initiatives.

In order to encourage a vibrant scientific program, establish transparent resource and schedule priorities, and ensure adequate planning and conduct of experiments, the IOTA team implemented a simple and effective process [16]. The IOTA/FAST Scientific Committee (ISC) reviews and approves proposals, works with experts on the development of experimental plans, establishes priorities and follows the progress of the program. Such approach allows for efficient utilization accelerators and sharing of the beam time. The facility beam operations are conducted in compact periods, referred to as 'runs' interleaved with periods of machine development, maintenance, and experiment assembly. Since the completion of IOTA assembly in August of 2018 and the subsequent commissioning, the team conducted three experimental runs: the 70-day run 1 in 2019, the 85-day run 2 in 2019/20 and the ongoing run 3, which started in October of 2020.

The program of run 2 included 9 experiments, of which 7 were done in IOTA and 2 made use of the FAST linac. The IOTA experiments included the studies of Nonlinear Optics [17], coherent beam instabilities, intra-beam scattering [18], and photon science with single and multiple electrons [19–21]. In all, 60 8-hour shifts were allocated to the run 2 experimental program. It should be noted that run 2 was cut short because of the COVID-19 pandemic and some experiments did not complete data taking.

The ongoing run no. 3 is focused on the proof-of-principle demonstration of the Optical Stochastic Cooling, a novel beam cooling technique originally proposed some 30 years ago but never tested experimentally.

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The results of experiments in the first IOTA run were presented previously [8]. In this report we present the highlights of run 2 and run 3 programs.

NONLINEAR INTEGRABLE OPTICS

The overarching goals of the NIO experiments in IOTA are i) the demonstration of a practical implementation of the NIO concept [4] in a real accelerator [1]; ii) the study of fundamental aspects of stability of such lattices to imperfections; and iii) demonstration of benefits of NIO lattices in high-intensity synchrotrons [13].

The NIO research program is comprised of two major parts:

1. Studies with electron beams with focus on the aspects of single-particle betatron dynamics, allowed by the properties of 100–150 MeV electron beams: the suppressed collective effects and the small transverse size of electron beam compared to the available machine aperture.

2. Studies with proton beams, which deal with the physics of space-charge dominated beams in strongly nonlinear lattices. The 2.5 MeV kinetic energy proton beam in IOTA will be strongly affected by the space-charge forces. Additionally, the long proton bunches allow for the investigation of coherent intra-beam motion and the impact of NIO on coherent beam stability. The demonstration of practical benefits for high-intensity and high-brightness hadron beams is the ultimate goal of IOTA NIO research program.

The studies in run 2 dealt with the first part of the NIO research. Initial NIO experiments in run 1 [8, 22, 23] demonstrated that a record-high nonlinear amplitude-dependent betatron tune shift can be attained in IOTA with the use of NIO lattice. However, the status of IOTA lattice tuning and, most importantly, of the BPM system prevented the implementation of the full-breadth research program in run 1. Extensive machine upgrades during the 2019 summer shutdown enabled a better quality research program in run 2.

The run 2 experiments implemented two types of NIO lattices:

- System with one invariant of motion, also referred to as the Quasi-Integrable or Hénon-Heiles-type system, implemented with a quasi-continuous octupole focusing channel [1, 24], denoted below as QI.

- System with two invariants of motion, also called the Danilov-Nagaitsev system [4], implemented with a quasi-continuous nonlinear elliptic-potential focusing channel, denoted as DN.

The NIO experiments in run 2 sought to demonstrate that i) Large values of amplitude-dependent nonlinear tune shift can be achieved without reduction of dynamical aperture; ii) Theoretically predicted invariants of the motion, calculated from measured turn-by-turn bunch coordinates, are conserved over the course of observation; iii) The NIO systems are substantially stable to perturbations and imperfections of implementation, such as the errors in β-functions and phase advances of the T-insert, dispersion, alignment errors, natural machine nonlinearities, and artificially introduced nonlinearities (sextupoles).

All versions of the NIO lattices in IOTA rely on the so-called T-insert concept [5], where the nonlinear focusing is implemented in a relatively short straight section of the machine circumference, while the remainder of the ring can be represented by a thin axially symmetric focusing lens (T-insert). In the case of IOTA, the two sections dedicated to nonlinear focusing magnets are each 1.8 m long.

The nominal IOTA NIO optics is mirror-symmetric with respect to the L-R axis and has the betatron tunes $Q_x = Q_y = 5.3$ (phase advance of 5 in the T-insert and $Q_0 = 0.3$ in each of the nonlinear straights. This corresponds to a β-function of 0.65 m in the middle of the nonlinear sections.

All of the IOTA NIO concepts rely on precise tuning of the optics, and the project strives to achieve better that 1% precision in β-functions and better than 0.001 precision in horizontal and vertical phase advances through the nonlinear sections [25]. An important optics design parameter is the momentum compaction α_p, which was maximized to be approximately 0.07 in order to minimize the coupling between the transverse and longitudinal degrees of freedom.

The upgrades after run 1 led to a marked improvement in the machine lattice model reconstruction. Two methods were used to tune the IOTA lattice: the slower LOCO tool provided the baseline focusing configuration, which was then fine-tuned on a day-to-day basis using turn-by-turn kicked beam tune and phase adjustments. We estimate that the β-functions were within 3% of the design values. The errors in betatron tune and phase advance through nonlinear sections were kept below 2×10^{-3}.

The QI experiment makes use of 17 discrete octupoles to approximate a continuous potential of a Hamiltonian with one invariant of motion, the Hamiltonian itself. This system is also known as a Hénon-Heiles system of octupole type. Changing the strength of the octupole insert does not affect the small-amplitude tune of the system, whereas the amplitude-dependent detuning varies linearly with octupole strength. The experimental configurations were typically labelled by the current in the central (strongest) octupole magnet. This value can be converted into an equivalent t-value for comparison with the DN case. In run 2, the best configuration, i.e. a dynamic aperture near the physical limit, was expected at the octupole current of 1.0 A.

A representative run 2 data set is shown in Fig. 2. The observed detuning was in agreement with simulations. At the dynamic aperture limit, a tune shift of 0.04 was achieved.

The DN experiment makes use of the specially designed nonlinear magnet [26] to implement a Hamiltonian system that possesses two invariants of the motion: the Hamiltonian itself, similarly to the QI case, and a second function

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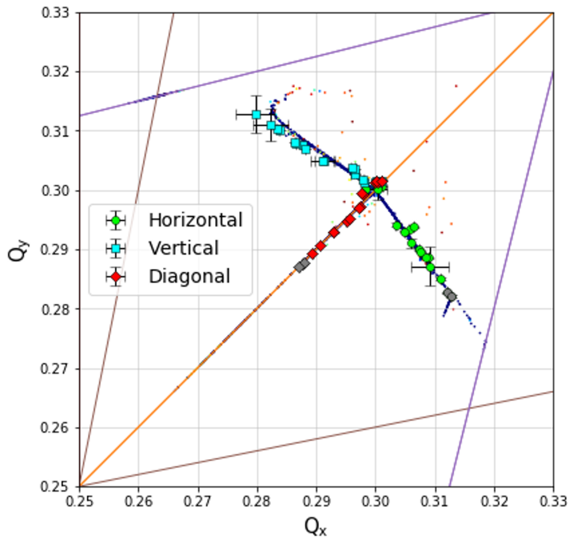

Figure 2: QI data from run 2. The green, cyan and red points represent the measured tunes for different values of the horizontal, vertical and diagonal single-turn transverse kicks. Gray points denote rejected data. The small dots are the results of numerical tracking simulations.

quadratic in momenta [4]. The magnet bore creates the smallest aperture restriction of the ring: $\pm$ 5.3 mm vertically and $\pm$ 3.2 mm horizontally at the mid-point of the magnet. The magnet comprises 18 individually shaped and independently powered sections. At the beam energy of 100 MeV, the dimensionless t strength can be varied between -1 and $+1$. At the t value of 0.5, the vertical small-amplitude fractional betatron tune reaches the value 0 — the magnet is capable of creating conditions for crossing the integer resonance line.

The maximum predicted nonlinear amplitude-dependent tune shift is 0.08 at $t = 0.43$ and 0.11 at $t = 0.48$. During run 1, a tune shift 0.053 was achieved with a nonlinear potential strength of $t = 0.43$. However, beam loss was observed. During run 2, extensive measurements were done at three strengths: $t = 0.218$, $t = 0.363$, and $t = 0.420$, in both nominal and perturbed configurations. The experiments at $t = 0.420$ showed significant beam loss and had quality issues that prevented a direct comparison with run 1. However, for $t = 0.363$, a large tune shift of 0.08 was achieved. This value is similar to what was achieved in run 1 at $t = 0.43$. These larger tune shifts indicate that lattice tuning had been significantly improved, approaching the required conditions for the DN nonlinear integrable system.

In run 2, we explored the effect of continuous change of the value of the strength t to study the effect of resonances on the nonlinear integrable system. The studies were extended beyond the value $t = 0.5$ (integer crossing). Remarkably, the beam crossed the integer resonance at $t = 0.5$ without loss. The beam could be left circulating on the integer resonance at $t = 0.5$ for 110 s.

The DN system possesses a unique property - when crossing the integer resonance at $t = 0.5$, the phase space topology changes and the beam splits into two beamlets in the vertical plane [27]. Remarkably, in agreement with the theoretical predictions, two stable beamlets were observed when the nonlinear strength was increased beyond $t = 0.5$. With increasing t-strength, the distance between the two beamlets increased nonlinearly up to $t = 0.90$, when the beamlets hit the mechanical aperture of the beam pipe. Figure 3 shows the image of the beamlets at $t = 0.55$.

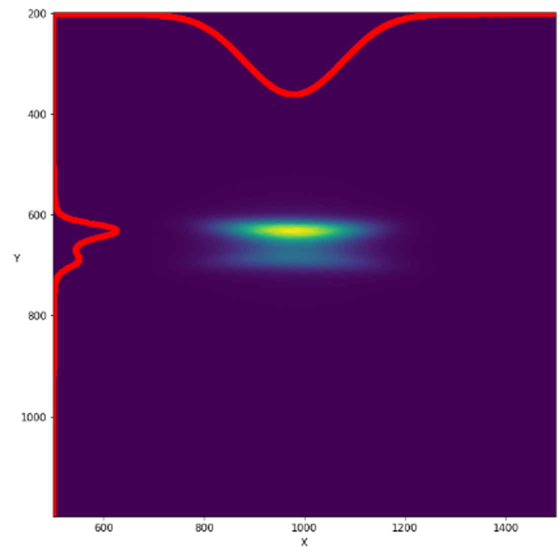

Figure 3: Image recorded by one of the synchrotron-light diagnostic cameras when the strength of the nonlinear magnet was increased beyond $t = 0.5$ (integer resonance).

LANDAU DAMPING WITH QI OPTICS

One of the expected benefits of the stable strongly nonlinear lattice is the suppression of transverse instabilities via Landau damping. Traditional dampers are negative feedback systems used for suppressing beam oscillations resulting from coherent beam instabilities. In the IOTA experiment, the sign of the feedback was reversed to produce positive feedback or anti-damping similar to an instability. Using the anti-damper system, we examined the threshold of transverse instabilities as a function of the lattice nonlinearity.

The transverse damper system consists of a BPM pickup, a preamplifier right at the pickup, a BPM analog module, difference amplifier, one turn notch filter, high power radio frequency (RF) amplifier, and strip line kicker [28].

The studies made use of the QI NIO lattice described above. As was established by the NIO studies, the current of 1 A provides the largest dynamical aperture that is equal to the machine physical aperture. At this setting, the maximum attained full aperture nonlinear tune shift was 0.04. The chromaticity correction sextupoles were not powered during the studies, which left the natural chromaticity uncorrected at -10 units horizontally and -7 vertically.

The instability data was collected by setting the system up in anti-damping mode with low gain so that the beam remained stable. The system gain was then stepped in 1 db increments until a fast instability is observed for which the gain and total beam loss was recorded. The transverses beam size was monitored via the sync light system and was

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required to be nominal or better before inducing another instability. This allowed for multiple instabilities to be induced for each injection. The procedure was repeated for a variety of beam intensities and octupole current settings. Figure 4 shows the measured anti-damping gain as a function of octupole current. A clear evidence for a two-fold increase of the instability threshold with octupole current was observed.

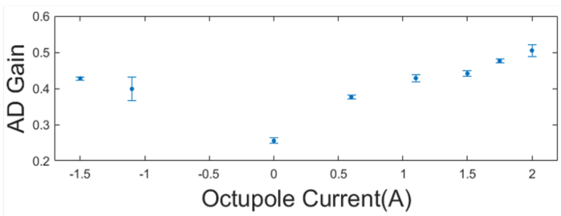

Figure 4: Measured anti-damping gain as a function of QI octupole current.

OPTICAL STOCHASTIC COOLING

The Optical Stochastic Cooling (OSC) [29,30] is based on the same principles as the well-tested microwave stochastic cooling [31] while using much shorter optical wavelengths resulting in a possibility of cooling much denser beam. A transition from the microwave stochastic cooling, which uses typical wavelengths of about 5 cm and relative bandwidth of 50%, to the OSC with a wavelength of 1–2 µm and relative bandwidth of 5–20% allows increasing the cooling rates by more than 3 orders of magnitude. Owing to the much smaller wavelength, usage of conventional electromagnetic pickups and kickers is not possible for OSC. Instead, undulators are used for both the pickup and the kicker. In the OSC apparatus a particle emits EM radiation in the first (pickup) undulator. Then, the radiation is amplified in an optical amplifier (OA) and is focused into the second (kicker) undulator where it produces a longitudinal kick to the same particle which generated the radiation. A magnetic chicane between the undulators appropriately delays each particle in the bunch with respect to its radiation, such that the longitudinal kick is corrective.

In IOTA the OSC apparatus [15] was installed in one of the two long (6 m) straight sections. The magnetic chicane bends particles in the horizontal plane and also provides space for the optical focusing system. The charged beam optics is arranged so that horizontal and longitudinal motions are coupled in the chicane resulting in particle cooling in both degrees of freedom. Cooling in the vertical plane is produced through coupling of the horizontal and vertical betatron modes outside of the cooling straight.

Although OSC was proposed as a cooling method to be used for hadrons or nuclei, the IOTA experiment uses electrons. The use of 100 MeV electrons greatly reduces the cost of the experiment but does not limit its generality and applicability to future hadron colliders and storage rings. The IOTA research scope allows testing most of the experimental techniques required for the OSC application in hadron colliders. Despite the emittance and momentum spread of the IOTA electron beam being significantly smaller than in a typical 100 MeV electron storage ring, their values are close to a typical emittance and momentum spread of high energy hadron colliders. The demonstration of OSC in IOTA does not require the same high-gain OA as for a proton collider, which greatly simplifies the OA design.

The OSC studies are carried out in two stages. In the first phase, presently executed in run 3 the EM radiation is refocused from the pickup undulator to the kicker undulator without amplification. This 'passive cooling' results in a cooling rate that exceeds the natural SR damping by one order of magnitude. The implementation of 'active cooling' involving an OA is planned for the second phase in around 2023.

The implementation of OSC is a challenging endeavor: i) the electron beam and the light must overlap through the kicker undulator within the width of under 200 µm and angle of less than 0.1 mrad; ii) the beam and light must arrive simultaneously with the absolute timing better than 0.3 fs; iii) the magnetic bypass and the light path must be stable to much smaller than the wavelength (1 µm), which corresponds to the jitter of <0.3 fs.

We are happy to report that the IOTA team successfully demonstrated world's first 6-dimensional Optical Stochastic beam Cooling on 20 April 2021. A convincing observation was made using the synchrotron light cameras for the transverse beam size and a streak camera for the bunch length.

SUMMARY AND OUTLOOK

IOTA/FAST is a unique R&D facility dedicated to accelerator science research. Over the last five years IOTA saw remarkable progress in construction, commissioning and first research with electron beams. The key results of the first experimental runs are i) the demonstration of Nonlinear Integrable Optics; ii) photon science experiments; iii) and the demonstration of Optical Stochastic Cooling.

IOTA supports a growing portfolio of collaborative experiments and serves as a platform for technological developments, synergistic research and training.

The next runs will pursue the continuation of NIO studies, investigation of space-charge effects [32, 33], realization of Electron Lens with a broad program [14], and continuation of the OSC program [15].

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