Nonlinear Integrable Optics (NIO) in IOTA Run 2

PERSONNEL

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INTRODUCTION

The overarching goals of the Nonlinear Integrable Optics (NIO) experiments in IOTA are i) the demonstration of a practical implementation of the NIO concept [1] in a real accelerator [2]; 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 [3].

The NIO research program in IOTA 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 100-150MeV electron beams in IOTA: the strongly suppressed collective effects, and the small transverse size of electron beam compared to the available machine aperture. These factors mean that the transverse motion of an electron bunch as observed by the machine beam position monitors (BPM) can be effectively treated as the motion of a single particle.

2. Studies with proton beams, which deal with the physics of space-charge dominated beams in strongly nonlinear lattices. The 2.5MeV 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.

This proposal deals with the first phase of the NIO research. Initial NIO experiments in Run 1 [4–6] 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 realization of the full-breadth research program in Run 1. Extensive machine upgrades during the 2019 summer shutdown will allow for a better quality research program in Run 2.

The present document covers three types of NIO lattice, which we plan to study during Run 2:

- System with one invariant of motion, also referred to as the Quasi-Integrable or Henon-Heiles Type system implemented with a quasi-continuous octupole focusing channel [7, 8] further called QI.
- System with two invariants of motion, also called the Danilov-Nagaitsev system [1] implemented with a quasi-continuous nonlinear Elliptic-potential focusing channel, further DN.
- Quasi-Integrable system with one invariant of motion similar to QI, but implemented with a version of symplectic integrator based on a small number of discrete octupole magnets [9], further referred to as SIQIS.

These experiments largely rely on common machine configuration, methods of measurement and data acquisition and can be executed concurrently, which motivates combining them in a single proposal.

In the subsequent sections of this document, we briefly review the theoretical background for each experiment, then describe the common experimental setup, specific goals and methods, and potential limitations. We conclude with the experimental plan and preliminary schedule.

THEORETICAL BACKGROUND AND PURPOSE

Common features

All versions of NIO lattices in IOTA rely on the so-called T-insert concept [10], 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 for placement of nonlinear focusing magnets are BR, occupied by the DN magnet [11], and BL, occupied by the octupole string - a sequence of 17 discrete equal-length octupole magnets [8]. Both sections have the length of 1.8m (see Fig. 1).

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, Fig. 2). This corresponds to the β-function of 0.65m at the middle of BL, BR. The lattice can be tuned to have Q_0 between approx. 0.25 and 0.35 without the loss of mirror symmetry. The realization of SIQIS experiment requires a special case optics with $Q_0 = 0.42$, which can be achieved in an asymmetric lattice C. All of the IOTA NIO concepts rely on a precise tuning of the optics, and the project strives to achieve better that 1% precision in β-function, and better than 0.001 precision in the phase advance (both X and Y planes) through the BL, BR sections [12]. An important optics design parameter is the momentum compaction α_p, which was maximized to be approx. 0.07 in order to minimize the coupling between the transverse and longitudinal degrees of freedom.

A. Experiment QI

The QI experiment aims to implement a time-independent Hamiltonian [7]

$$H = \frac{1}{2}(x^2 + y^2 + p_x^2 + p_y^2) + \frac{2t}{3c^2}(x^4 - 6x^2y^2 + y^4).$$

Here t is the dimensionless strength parameter and c is the elliptic-potential scaling factor [1]. The Hamiltonian is an invariant of the motion. The QI system has a bounded nonlinear betatron motion within bounds of a separatrix defined by t and c. For IOTA parameters, $c = 0.01$m, and t can be varied from -1 to 1 (for the beam energy of 100MeV). The maximum nonlinear detuning is achieved for $t = 0.4$.

The ideal continuous octupole focusing is piece-wise approximated with 17 discrete octupole magnets in BL straight. The magnets have the physical yoke length of 7 cm and are equally spaced with center-to-center distance of 10.588cm. The magnets are powered by individual bipolar 2-A power supplies.

The numerical simulations predict that for IOTA parameters, the maximum attainable tune shift is approx. 0.06 (see Fig. 3).

B. Experiment DN

The DN experiment makes use of the specially designed nonlinear magnet [11] to implement a Hamiltonian system that posesses two invariants of the motion: the Hamiltonian itself, similarly to the QI case, and a second function quadratic in momenta [1]. The nonlinear magnet designed and constructed by RadiaBeam Technologies is installed in IOTA section BR. The magnet bore creates the smallest aperture restriction of the ring at ± 5.3mm vertically and ± 3.2mm horizontally, at the mid-point of BR. The magnet is comprised of 18 individually shaped and independently powered sections. The dimensionless t strength can be varied between -1 and +1 (at the beam energy of 100MeV). At t value of 0.5 the vertical small-amplitude fractional betatron tune reaches 0 and thus the magnet is capable of creating conditions for crossing the integer resonance line.

The important feature of the DN case is that the small-amplitude betatron tunes are a function of t unlike the octupole-driven QI case. Figure 4 shows the predicted and measured in Run 1 dependence of Q_x and Q_y on the magnet strength.

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. Figure 5 shows the predicted DN experiment performance as well as the Run 1 data.

C. Experiment SIQIS

The SIQIS experiment seeks to advance the QI approach by implementing the Henon-Heiles type system using the symplectic Euler approach [9]. The advantage of the proposed approach is in the use of a much smaller number of individual thin octupole magnets to achieve performance equal to that of the QI case. The SIQIS approach also offers a significant flexibility over QI as it is can be implemented with non-equidistant magnets and in much shorter drifts.

The configuration proposed for IOTA in Run 2 makes use of the existing octupole positioning and hence does not require any mechanical reconfiguration of the ring. The scheme is based on 5 octupoles, numbers 6, 8, 9 (middle of BL), 10, and 12 (Fig. 6). It does, however, demand the implementation of a special lattice configuration with the phase advance of Q_0 of 0.4168 and the virtual drift length in BL equal to 1.37m. Such lattice design has been developed (see Fig. 7) and can be implemented by removing the condition of the mirror symmetry. The implementation of a stronger-focusing lattice would also benefit the QI experiment as the maximum nonlinear tune shift scales linearly with the unperturbed tune advance Q_0. The negative aspect of the strong-focusing lattice is in the higher natural chromaticity (-16 units horizontally, compared to -10 in the nominal lattice). This can be overcome by employing the chromaticity correction sextupole magnets in the CR and CL sections. The SIQIS experiment is also restricted in the reachable tune shift due to the limited octupole strength and power supply capacity. The footprint is plotted in Fig. 8.

Purpose of the studies

All of the above experiments seek to demonstrate that

1. Large values of amplitude-dependent nonlinear tune shift can be achieved without reduction of dynamical aperture
2. Theoretically predicted invariants of the motion, calculated from measured turn-by-turn bunch coordinates, are conserved over the course of observation
3. The NIO systems are substantially stable to perturbations and imperfections of implementation, such as the errors in β-function and phase advance of the T-insert, alignment errors, natural machine nonlinearities, artificially introduced nonlinearities (sextupoles).

METHOD OF MEASUREMENT

The experiments will rely on the reconstruction of transverse phase-space dynamics of a single bunch after betatron oscillations are induced by a transverse kicker pulse. The beam will be injected into IOTA, for which the vertical closed orbit must be distorted to position it close to the knife of the Lambertson magnet. After the injection, the orbit distortion will be removed and trajectory will be centered in all quadrupole magnets as well as through the BL and BR straight sections to ensure maximum available aperture for the beam motion.

The transverse beam oscillations will be induced by a single-turn high voltage pulse applied to horizontal and/or vertical stripline kicker plates. The IOTA kickers are capable of exciting beam oscillations up to the full aperture size.

The turn-by-turn horizontal and vertical beam centroid positions will be recorded synchronously at all 21 BPMs for a minimum of 2000 turns. The start of the BPM record will be synchronized with the kicker pulse.

In addition to the bunch coordinates, the beam intensity will be monitored and recorded using the BPM system as well as the DCCT device.

The data will be saved to the shared Y: drive during the studies and later uploaded to a Fermilab Redmine project storage [14]. The data will be analyzed offline to reconstruct the phase-space dynamics and betatron tunes. We plan to utilize the method based on the decomposition of turn-by-turn data into spatial and temporal modes using the known lattice transport maps [15].

REQUIREMENTS

The necessary instrumentation includes the complete IOTA instrumentation suite:

- Beam position monitor system with all 21 BPMs operational in turn-by-turn mode and in closed orbit mode. The required resolution is 10μm in closed orbit and 100μm in turn-by-turn mode. Beam intensity signal is also required. These requirements determine the typical beam current range of 0.5-1mA. Otherwise it would be preferred to operate at smallest values of the beam current to avoid the emittance degradation caused by intra-beam scattering.

- Synclight camera system for beam size and position monitoring. The required position resolution is better than 10μm [12].
- Current measurement with DCCT.

The vertical and horizontal stripline kickers must function synchronously with the BPM system. The kicker voltage must be continuously controlled in the range between 0 and 6kV for the vertical kicker and from 0 to 20kV for the horizontal kicker for full-aperture kicks.

All functions of the 6DSim software must be operational: closed orbit data collection from BPMs and synclight cameras; ACNET interface.

RUN PLAN

The run plan is logically divided into three phases addressing the following main goals:

1. Goal 1: 3×8 hour shifts to demonstrate the magnitude of nonlinear detuning without degradation of dynamical aperture in agreement with predictions for QI and DN experiments. The first shift will be dedicated to orbit centering through BL and BR sections and lattice tuning. Shifts 2 and 3 would be spent acquiring turn-by-turn BPM data for various amplitudes of H/V kicks and t values.
2. Goal 2: 3×8 hour shifts to demonstrate the invariant conservation for QI and DN experiments. Two shifts would be dedicated to collecting turn-by-turn data for different machine configurations including the intentional lattice errors. The third shift is planned for commissioning of the high-tune lattice for SIQIS experiment.
3. Goal 3: 6×8 hour shifts for systematic studies of integrability conservation in all three systems. Variation of sextupole strength, Q_0 for QI option (with particular interest towards values near 1/4 integer resonance), study of the effect of integer resonance on dynamics in DN system.

The main risk associated with the proposed schedule is related to the machine performance at the beam energy of 100MeV and the possibility of the need to commission 150-MeV operations: the BPM system resolution becomes poor at beam currents below 1mA. The IBS effect is significant at this current and manifests itself in the increased bunch momentum spread, which in turn leads to the faster decoherence of the dipole oscillations. The precise reconstruction of turn-by-turn phase space coordinates requires a large number of turns in the test signal. Our simulations suggest that a reduction of the momentum spread from present values (approx. 0.002) by raising the beam energy to 150MeV would produce a marked improvement of the turn-by-turn signal quality.

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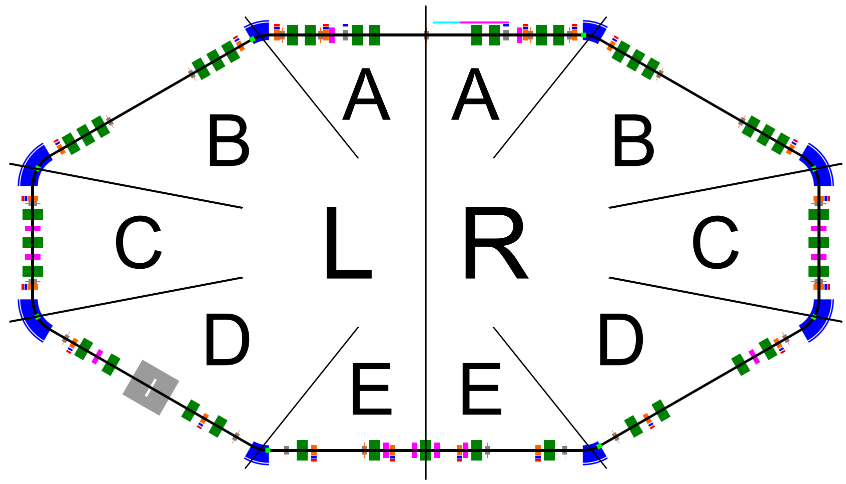

FIG. 1. IOTA layout and naming convention.

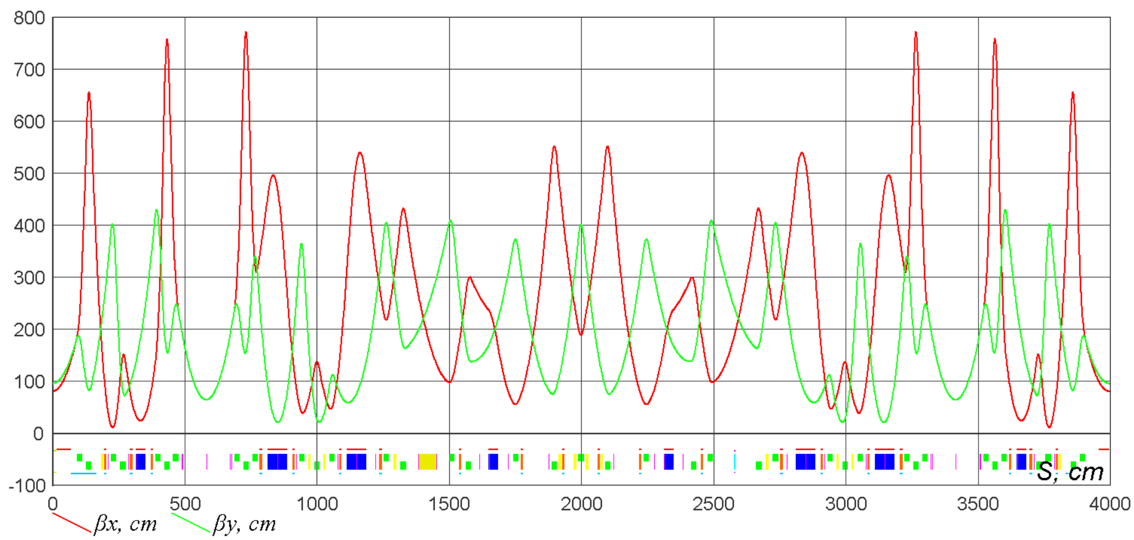

FIG. 2. Beta-functions for the nominal IOTA NIO optics. Origin at injection point A, going clockwise.

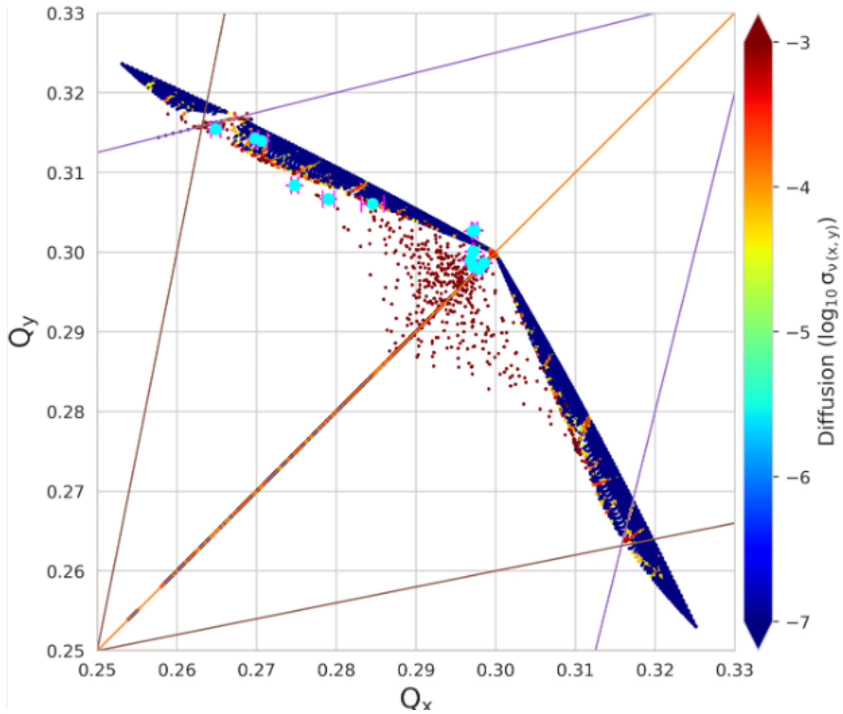

FIG. 3. Betatron tune foot print for QI experiment. Simulation for IOTA at 100MeV with Elegant code at $t = 0.4$. Cyan points display the Run 1 data.

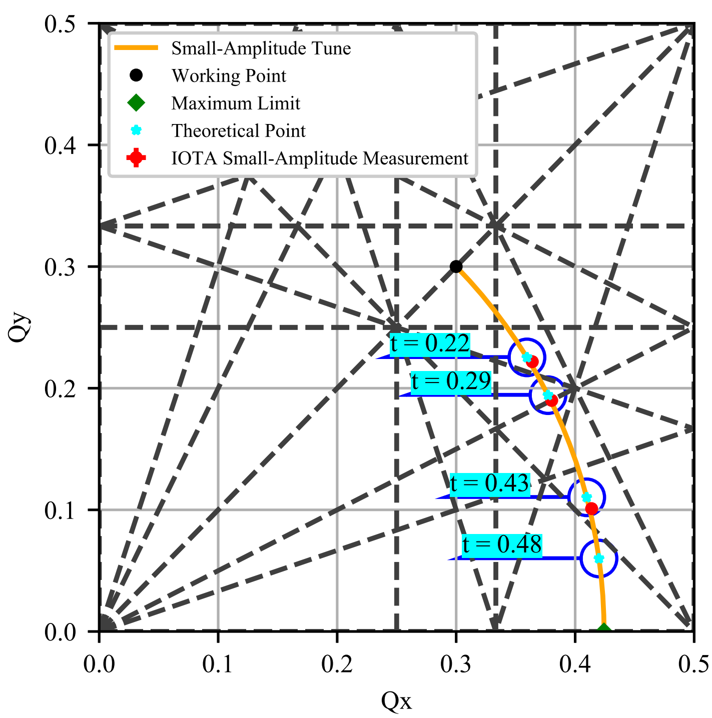

FIG. 4. DN small amplitude tune as function of nonlinear magnet strength.

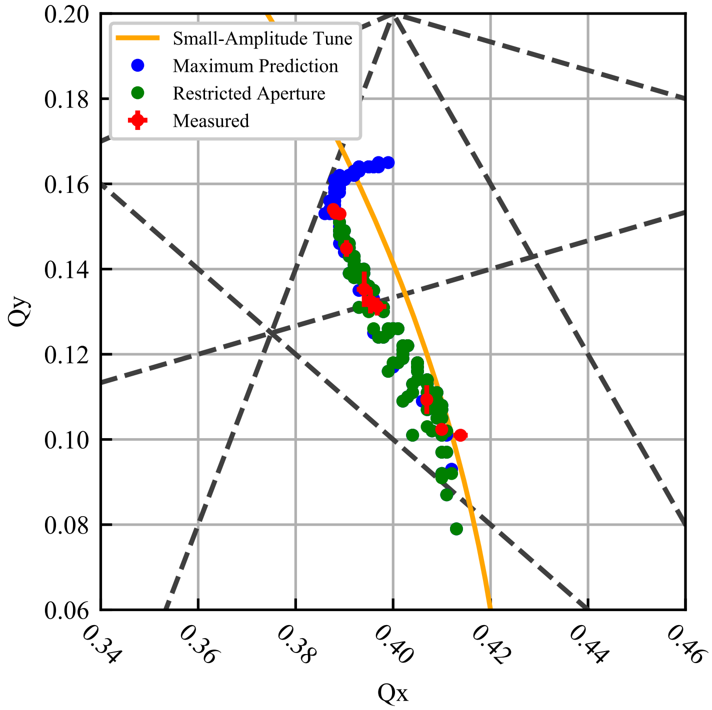

FIG. 5. DN tunes as function of betatron amplitude. Simulation for IOTA at 100MeV with MAD-X code at $t = 0.43$. Red points display Run 1 data.

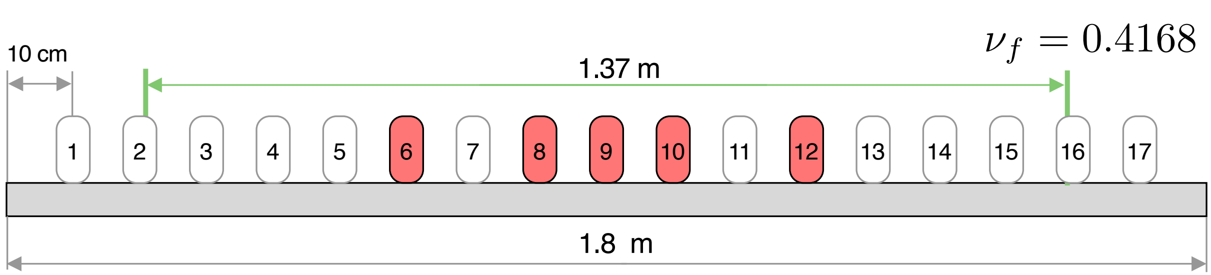

FIG. 6. Layout of octupole magnets for SIQIS experiment.

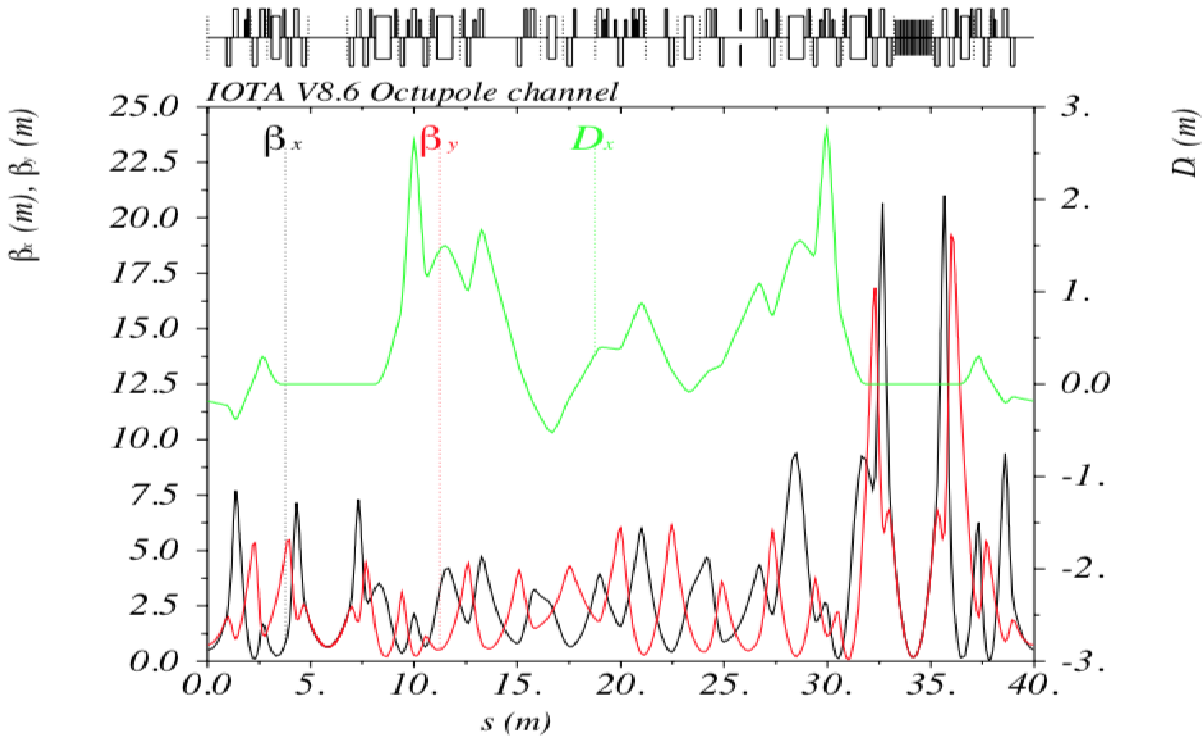

FIG. 7. Lattice functions for SIQIS experiment. Origin at injection point. β-function at the middle of BL section is 0.18m.

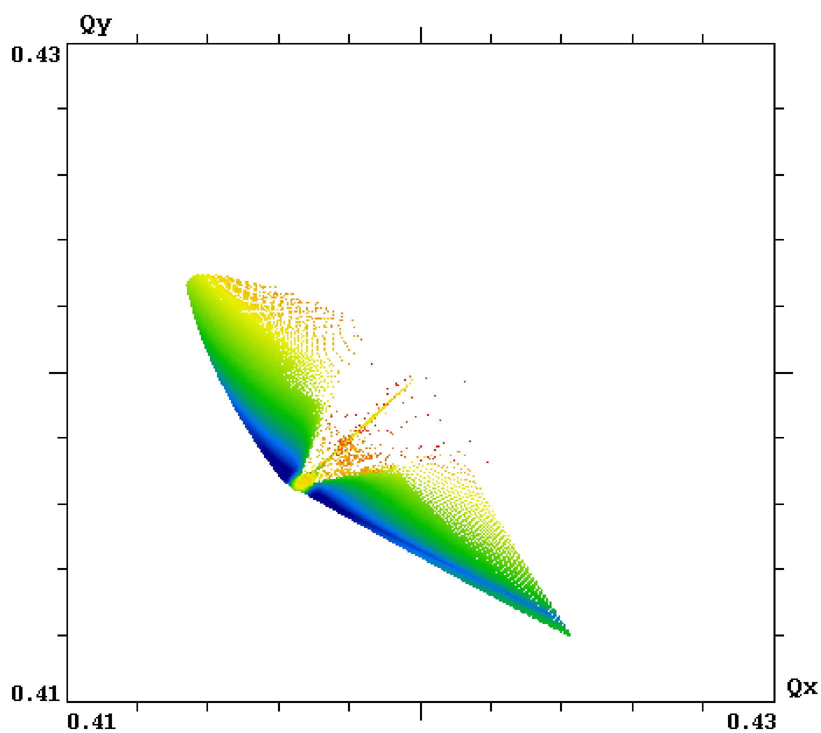

FIG. 8. Tune footprint for SIQIS experiment. Simulation for IOTA at 100MeV with Lifetrac code.