Proposed Experimental Validation of Hamiltonian Perturbation Theory in IOTA

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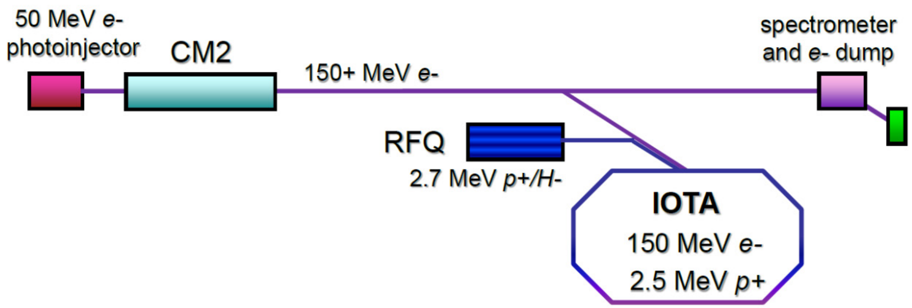
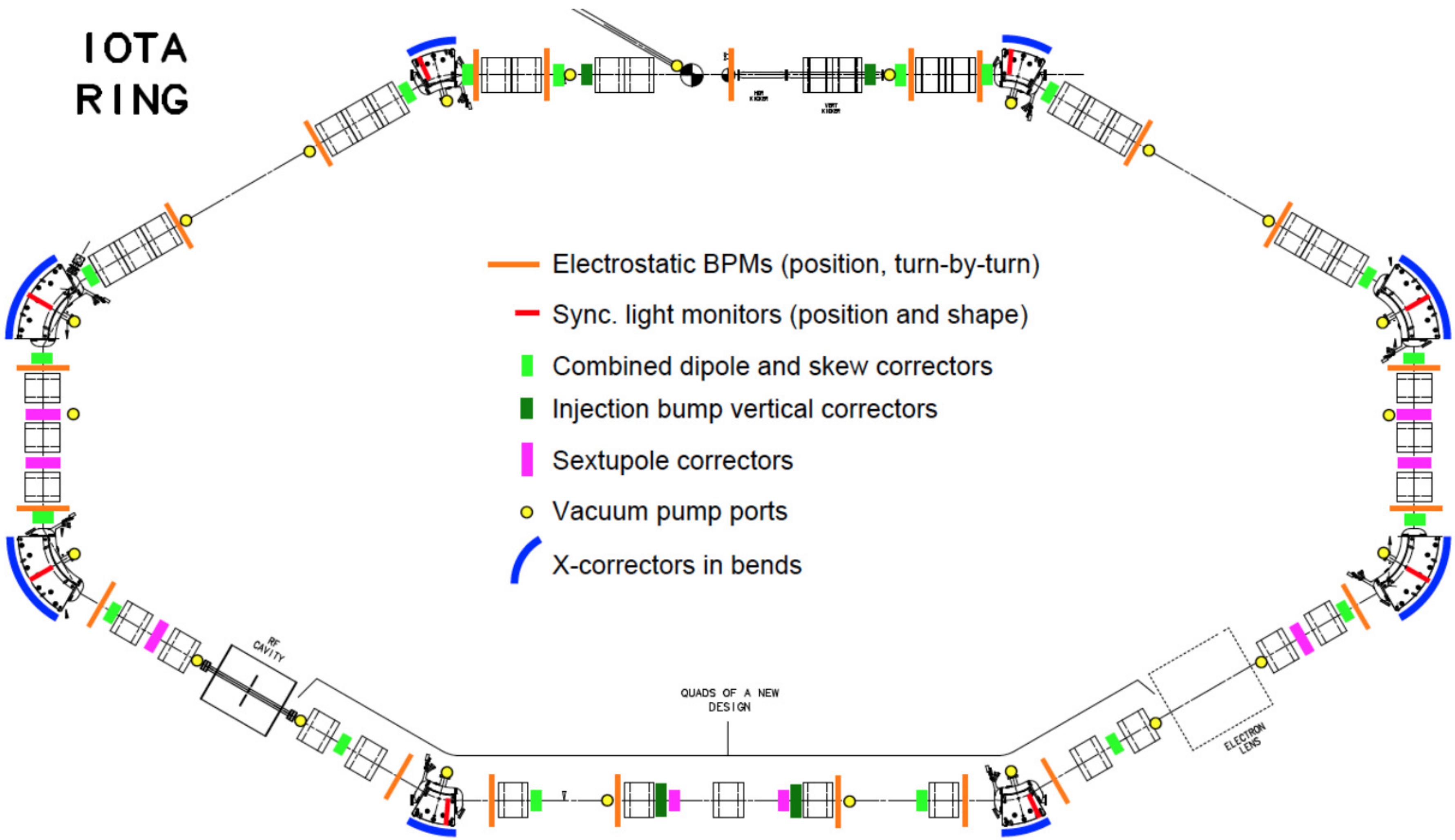
Motivation

- Hadron accelerators must advance the intensity frontier
  - High Energy Physics
    - **neutrino production; creation of exotic nuclei**
  - Basic Energy Sciences
    - **spallation neutron sources**
  - Nuclear Energy
    - **subcritical nuclear reactors; transmutation of nuclear waste**
- Orders-of-magnitude reduction in beam loss is required
  - existing systems are intensity limited
    - **require losses to be limited at ~W/m scales**
  - new ideas are required to limit instabilities & beam halo
    - **space charge, wakefields**
- IOTA – the Integrable Optics Test Accelerator
  - part of the Fermilab Accelerator Science and Technology (FAST) facility
  - proving ground for new ideas and advanced concepts w/ hadrons

Danilov & Nagaitsev, "Nonlinear accelerator lattices with one and two analytic invariants," PRSTAB **13**, 084002 (2010)



A. Valishev, "IOTA – A Brief Parametric Profile," presented at *Focused Workshop on Scientific Opportunities in IOTA* (Batavia, April, 2015); http://asta.fnal.gov/IOTA/IOTAmeeting/IOTA_Short.pdf



A Hierarchy of Lattices – definition

S.D. Webb, D.L. Bruhwiler, A. Valishev, S. Nagaitsev and V. Danilov, "Chromatic and Dispersive Effects in Nonlinear Integrable Optics" (2015), arXiv:1504.05981

- Tier 0
  - drift of specified length (1.8 m for IOTA)
    - **called the 'insertion drift'**
  - thin, symmetric, linear focusing lens with specified phase advance (0.3 for IOTA)
    - **horiz. & vert. beta functions are equal, with waist in the center**
- Toy Lattice
  - Tier 0 lattice, plus the 'nonlinear insert' (aka the 'elliptic magnet')
    - **completely fills the drift**
    - **magnet strength varies inversely with beta function of Tier 0 lattice**
    - **quadrupole component (horiz. focusing) breaks symmetry of the beta functions**
- Tier 1
  - thin lens is replaced by the quads and dipoles of IOTA (called 'the arc')
    - **dynamics is assumed to be linear**
    - **phase advance in 'the arc' is an integer multiple of π (emulates thin lens)**
    - **dispersion in the 'insertion drift' is zero**
- Tier 2
  - sextupoles are added to Tier 1 for chromaticity correction
- Tier 3
  - the 'nonlinear insert' is added to Tier 2
    - **sextupoles may be turned off**

A Hierarchy of Lattices – variations

- δp/p can be set to zero
  - we frequently zero the momentum spread to eliminate chromatic effects
- the 'small ring nonlinearities' of IOTA can be included
  - these are predominantly 2nd-order in each element
    - **in a sequence of elements, the effects can feed up to higher order**
    - **this breaks the attempted emulation of a thin lens**
    - **e.g. we observe nonlinear chromaticity and nonlinear dispersion**
  - by default, these effects are ignored in our hierarchy of lattices
    - **this is necessary for making theoretical progress**
    - **it is a good assumption for large rings**
    - **however, these nonlinearities must be included to fully understand IOTA**
- a 'compensated' arc design is required for space charge
  - space charge introduces a tune shift (reduction)
    - **this breaks the attempted emulation of a thin lens**
    - **the phase advance of the arc must be increased to accommodate**
    - **a lattice redesign is required for each value of tune shift**
    - **incoherent tune shift due to nonlinear space charge is a problem**
  - this difficulty is not present in the 'Toy lattice'

S.D. Webb, D.L. Bruhwiler, S. Nagaitsev, V. Danilov, A. Valishev, D.T. Abell, A. Shishlo, K. Danilov & J. Cary, "Effects of Nonlinear Decoherence on Halo Formation" (2013), arXiv:1205.7083

Simulation Tools

- Results presented here are based primarily on Synergia
  - developed by Fermilab's accelerator simulation group
  - important contributions through code modifications and technical support
  - J. Amundsen, Q. Lu, A. Macridin, L. Michelotti, C.S. Park, E. Stern, T. Zolkin
- Synergia has unique features that have enabled our success
  - control of linear, 2nd-order, … or fully nonlinear dynamics in each element
  - 2D space charge algorithms: both gridded Poisson and 'frozen' models

- We also use the code *`sixdsimulation`*

A. Romanov, G. Kafka, S. Nagaitsev, A. Valishev, "Lattice Correction Modeling for Fermilab IOTA Ring," TUPRO058 IPAC 2014.

  - envelope design code with linear space charge
    - **used to create the compensated lattice designs for use in Synergia**

See poster THPOA23 → tomorrow afternoon.

A. Romanov *et al.*, "Adaptive Matching of the IOTA Ring Linear Optics for Space Charge Compensation".

Hamiltonian perturbation theory

- We use the Lie operator formalism of Dragt, Finn & Forest:

A. Dragt and J. Finn, "Lie series and invariant functions for analytic symplectic maps," J. Math. Phys. **17** (1976).
A. Dragt and E. Forest, "Computation of nonlinear behavior of hamiltonian systems using lie algebraic methods," J. Math. Phys. 24 (1983).
A. Dragt, *Lie Methods for Nonlinear Dynamics with Applications to Accelerator Physics*, p. 861 (Aug. 4, 2016); http://www.physics.umd.edu/dsat/dsatliemethods.html

  - see Webb *et al*. for details regarding the approach & previous results:

S.D. Webb, D.L. Bruhwiler, A. Valishev, S. Nagaitsev and V. Danilov, "Chromatic and Dispersive Effects in Nonlinear Integrable Optics" (2015), arXiv:1504.05981

  - latest results will be presented this afternoon

See poster WEPOA31 → this afternoon.

N. Cook *et al*., "Nonlinear Dynamics, Dispersive, and Chromatic Considerations in the IOTA Lattice".

1st experiment: electrons & sextupoles

- Sextupoles can be used to correct for chromatic effects
  - two carefully phased pairs can be used
  - more commonly, several are distributed around the ring

K.L. Brown, *IEEE Trans. Nucl. Sci.* **NS-26**, 3490 (1979).
K. L. Brown and R. Servranckx, AIP Conf. Proc. **No. 127**, eds. M. Month, P.F. Dahl and M. Dienes, p. 62 (1983).

- Prediction of Hamiltonian perturbation theory:
  - correction (i.e. the required sextupoles) can make things worse
  - two (much weaker) sextupoles can equalize the x,y chromaticities

S.D. Webb *et al.*, "Chromatic and Dispersive Effects in Nonlinear Integrable Optics" (2015), arXiv:1504.05981

- Proposed experiment:
  - inject electrons off energy, $0 <= \delta p/p < 1\%$
    - uncorrected chromaticity should lead to increasingly chaotic motion
    - 'standard' correction with many sextupoles should be worse
    - Single pair of correctly phased sextupoles should retain integrable motion
      - remaining uncertainties due to nonlinear dispersion and chromaticity

An IOTA point design with finite current

- Lattice:
  - IOTA v8.2 lattice with a single nonlinear insert
    - phase advance increased by 0.03 to accommodate space charge
    - nonlinear strength parameter t = 0.2   (max is t = 0.5)
  - no sextupoles; no RF
    - RFQ bunches stream longitudinally to fill the entire ring
    - injection needs to be modeled in 3D
- 2.5 MeV proton beam:
  - normalized emittance = 8 mm-mrad RMS
    - distribution must be as close as possible to 'uniformly-filled'
    - significant scraping will be required at injection
  - $\delta p/p < 0.1$ RMS (to avoid issues with chromaticity)
    - electron cooling may be required

See talk WEA4CO02 → this afternoon.

C. Hall *et al.*, "Impact of Space Charge on Beam Dynamics and Integrability in the IOTA Ring".

2nd experiment: finite-current point design

- Simulations indicate a working point with space charge
  - parameters are provided on the previous slide
  - can this be created experimentally in IOTA?
- Proposed experiment:
  - inject protons with chicane(s) and scraping
    - required to achieve low transverse emittance
    - should help with $\delta p/p$, but may not be enough
    - if necessary, run electron cooling system
  - required diagnostics
    - measure transverse beam profile
    - if direct measurement isn't possible, measure 2nd and 4th moments
    - time evolution is required
  - look for stabile dynamics with no particle loss
    - if the distribution is not sufficiently uniform, modify injection
    - if beam size & emittance grow slowly, it may be diffusion
      - numerical results are not yet conclusive
      - theoretical work (in progress) is suggestive of space-charge-driven diffusion
    - if rapid growth or particle loss, then adjust phase advance in the arc

3rd *experiment*: *controlled beam loss*

- This is predicated on success of 'point design' experiments
  - perturbation theory offers many ways to spoil beam and lose particles
- Proposed experiment:
  - achieve stable design point of proposed 2nd experiment
  - Part 1:
    - turn up sextupoles
    - observe particle loss rate as a function of strengths
  - Part 2:
    - increase $\delta p/p$
    - scrape less at injection, or perhaps reduce current in e- cooler
  - Part 3:
    - increase strength of nonlinear insert & also modify phase advance
    - theory indicates that complete loss of confinement can be achieved
  - required diagnostics
    - particle loss monitors (not beam halo)

Summary

- Theoretical understanding of IOTA is improving
  - Hamiltonian perturbation theory
    - Lie operator approach has been essential
  - Simulations with Synergia & `sixdsimulation`
    - detailed control of phase advance, nonlinearity is required
- We've found a working point with space charge
  - we (and others) can no build on this exciting development
  - much more work to do!

See talk WEA4CO02 → this afternoon.

C. Hall *et al.*, "Impact of Space Charge on Beam Dynamics and Integrability in the IOTA Ring".

- 3 strawman experiments have been proposed
  - hope this will stimulate constructive discussions & new ideas
  - we want to be ready before IOTA is!