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Recent Results and Opportunities at the IOTA Facility

Aleksandr Romanov *on behalf of IOTA collaboration*

North American Particle Accelerator Conference

4 September 2019

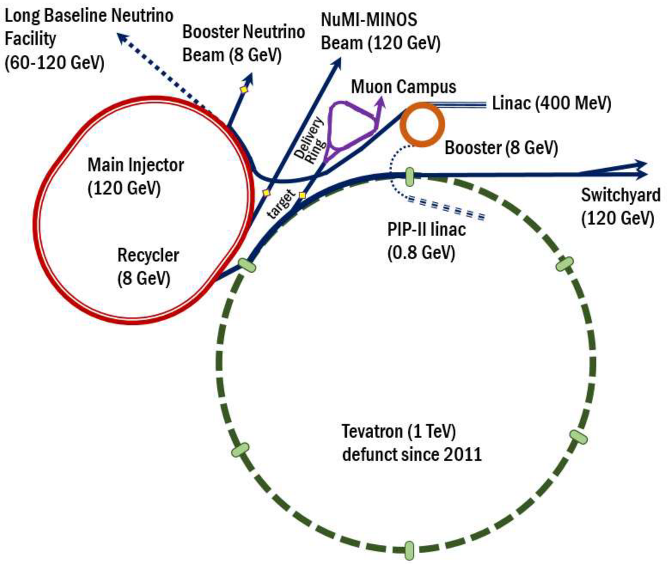
Presentation overview

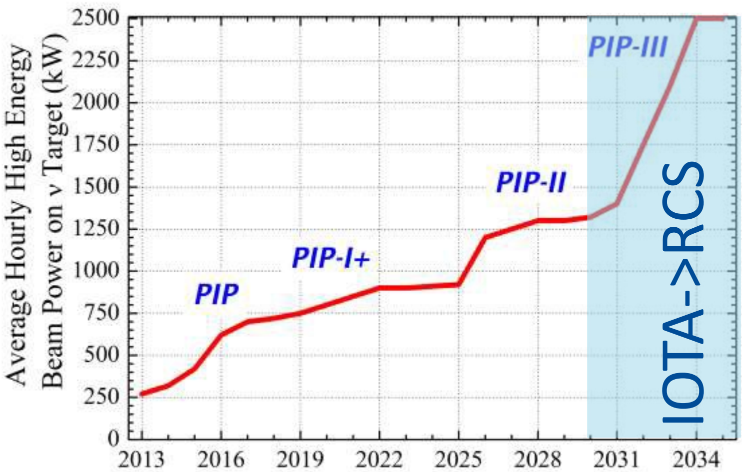
- Why IOTA?
- IOTA commissioning
- Results of the first run
- Future plans

Accelerator and beam physics at Fermilab

Of particular interest to us:

- Mitigation of beam losses at high-intensity:
  - Booster, Recycler and MI are intensity-limited by losses (~1 W/m).
- Mitigation of instabilities in high-brightness beams:
  - Fast instabilities which can not be suppressed by external dampers, e.g. an “electron cloud” instability (observed in the Recycler)
- Beam cooling
  - Future colliders
  - Quantum limits/properties of beams
- System integration and optimization





Challenges of high-power beams

- Uncontrolled beam losses
  - Keep losses at < 1 W/m
    - Fermilab Booster is presently running at the limit of losses (~400 W)
  - Space-charge causes beam halo!
- Beam instabilities (loss of entire beam, emittance degradation)
  - Common resistive-wall instabilities can be mitigated by external dampers
  - As beam space-charge increases, there are more severe types of instabilities appear, e.g. an “electron cloud” instability (observed in the Recycler) can be very fast and can not be damped by dampers
  - Connection to linear accelerators (only BNS damping at present to suppress the BBU instability)

Instability mitigation – Landau damping with nonlinear magnets

COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

B. Richter

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

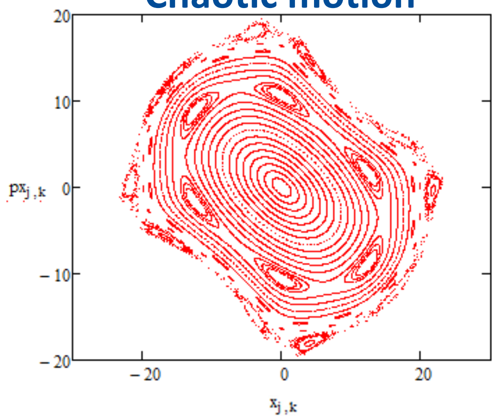
Report at HEAC 1971

- Landau damping – the beam's "immune system". It is related to the spread of betatron oscillation frequencies. The larger the spread, the more stable the beam is against collective instabilities.
  - The spread is presently achieved by adding special magnets -- octupoles
- External damping (feed-back) system – presently the most commonly used mechanism to keep the beam stable.

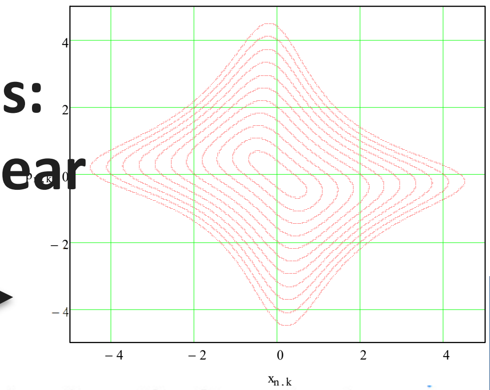
Are there “magic” nonlinearities with zero resonance strength?

Yes, we call them “integrable”

Chaotic motion



Integrable motion



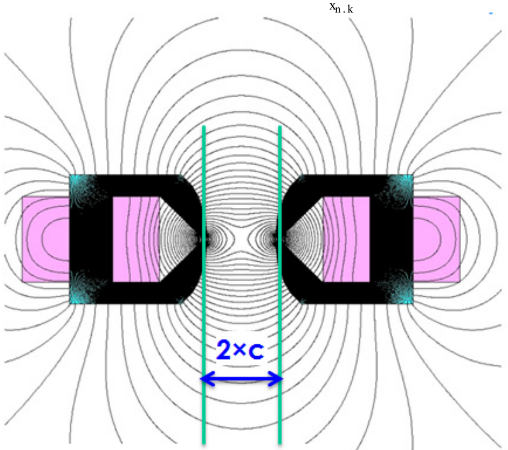
Nonlinear beam dynamics: A new concept for nonlinear focusing in rings

Two integrals of motion :

$$H_\perp = \frac{1}{2}(P_x^2 + P_y^2) - \frac{\tau c^2}{\beta(s)} U\left(\frac{X}{c\sqrt{\beta(s)}}, \frac{Y}{c\sqrt{\beta(s)}}\right)$$

$$I = \left(xp_y - yp_x\right)^2 + c^2 p_x^2 + \frac{2c^2 t \cdot \xi\eta}{\xi^2 - \eta^2}$$

$$\left(\eta\sqrt{\xi^2 - 1}\cosh^{-1}(\xi) + \xi\sqrt{\eta^2 - 1}\left(\frac{\pi}{2} + \cosh^{-1}(\eta)\right)\right)$$



Magnet cross section
V.Kashikhin

There are several examples suitable for accelerators

[1] V. Danilov and S. Nagaitsev, PRAB 13, 084002 (2010)

Accelerator Science at IOTA/FAST

I. **IOTA Ring** – **priority research focused on high-intensity *proton* rings**, driven mostly by Fermilab
   – Nonlinear Integrable Optics
   – Optical Stochastic Cooling
   – Space-charge compensation
   – Suppression of coherent instabilities

II. **FAST e- Linac and IOTA** – **opportunities concurrent with main IOTA program**, driven mostly by external partners
   – Radiation generation
   – High average current experiments (ILC-like electron beams)
   – Collaboration with the FACET-II team
   – EIC R&D
   – Quantum science: single and few-electron experiments

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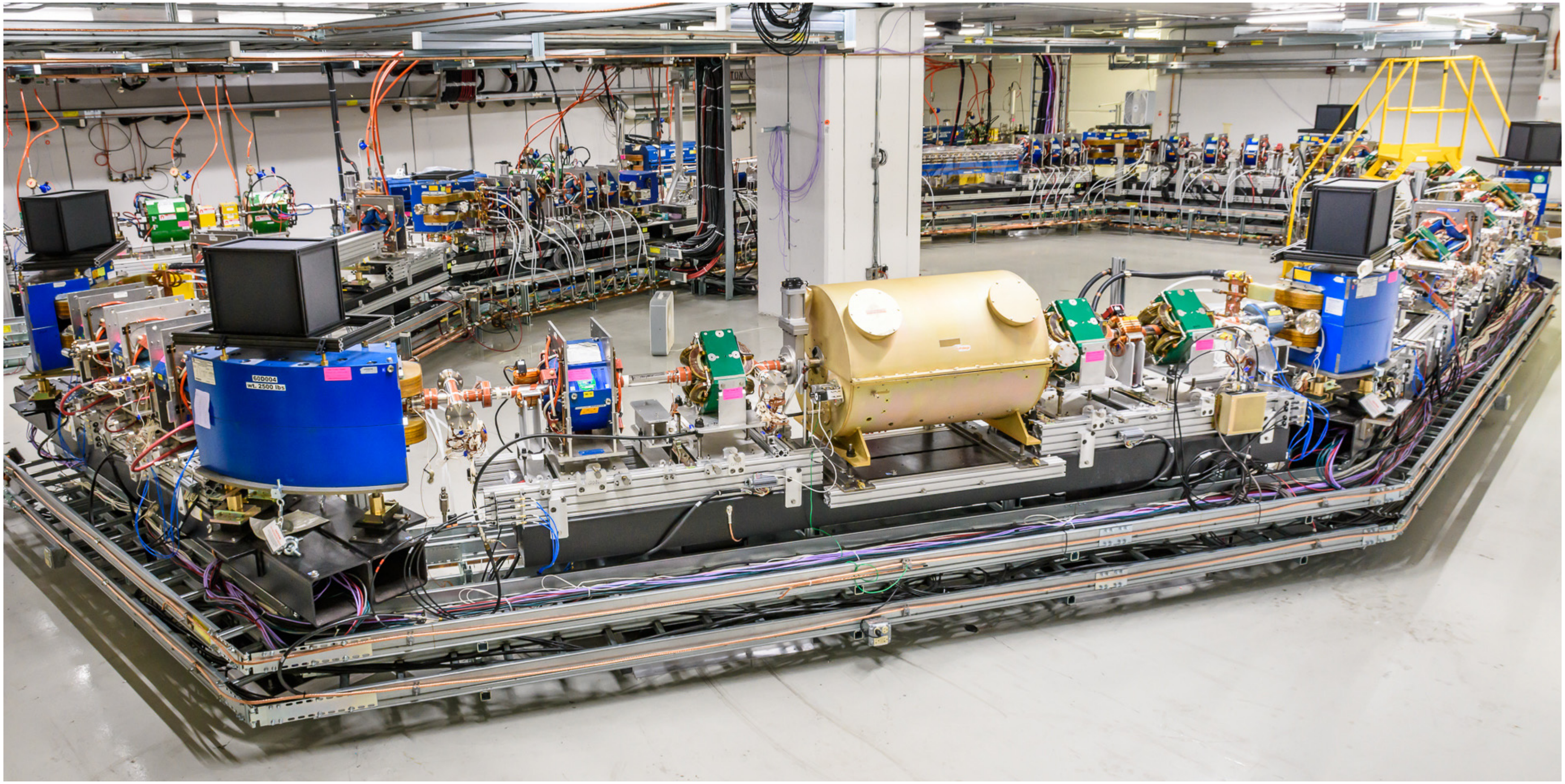
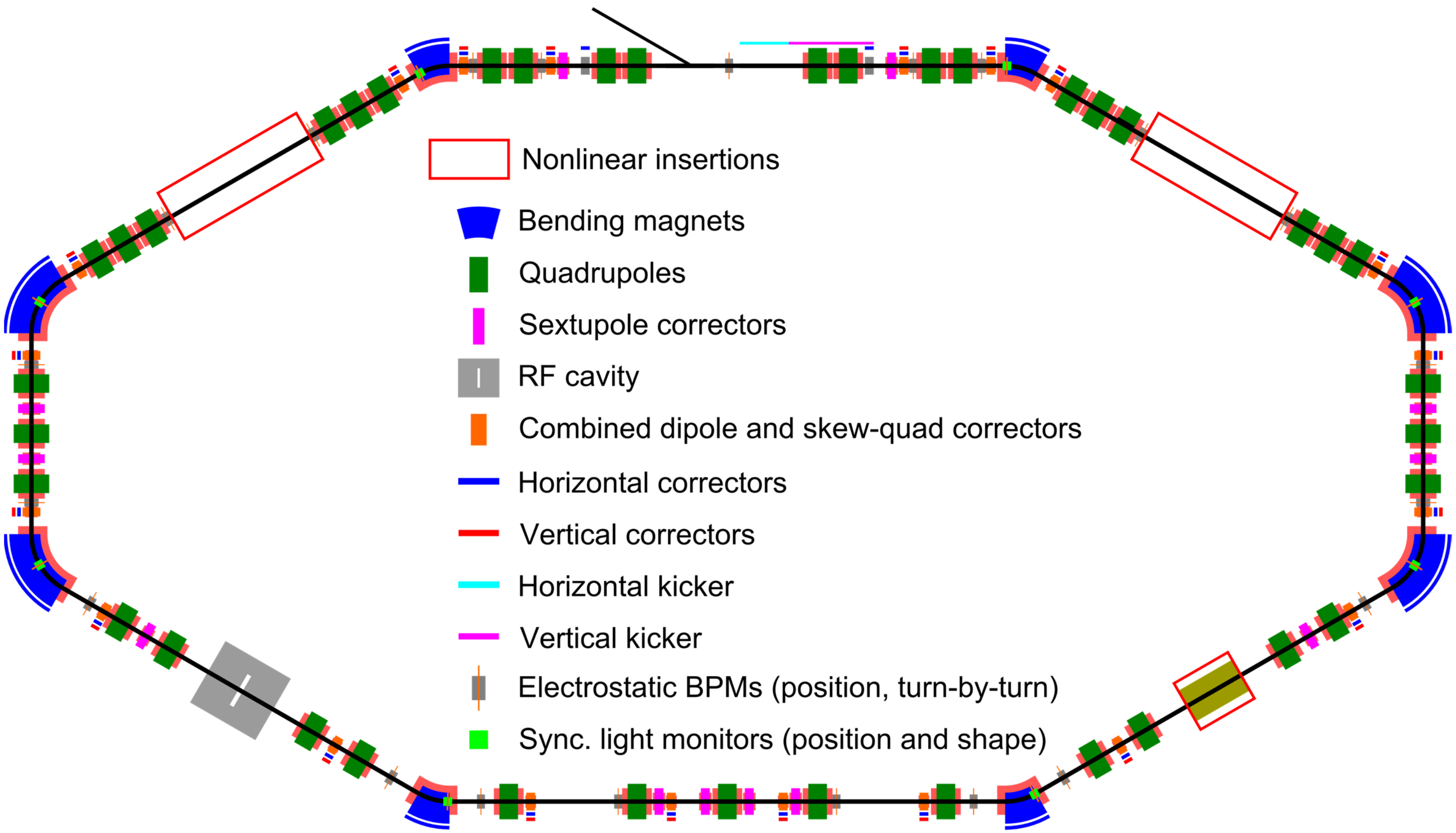
IOTA Assembly Completed 7/29/2018



IOTA is…

- Integrable Optics Test Accelerator
  - Storage ring for electrons and protons

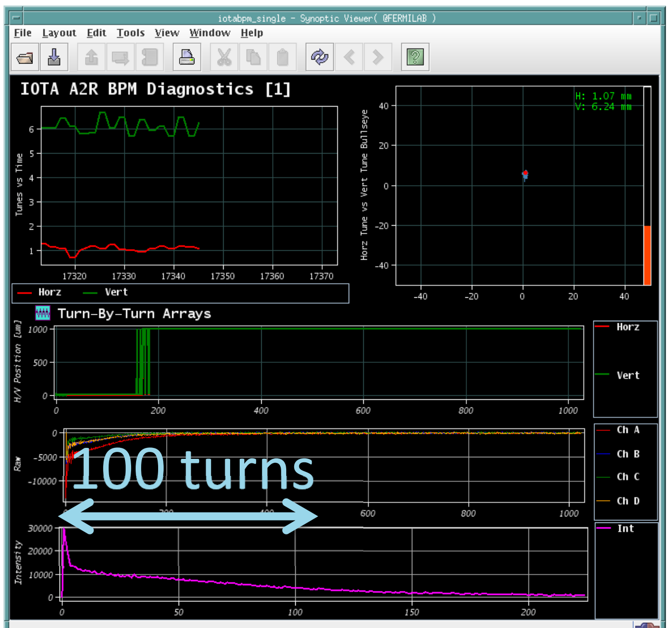


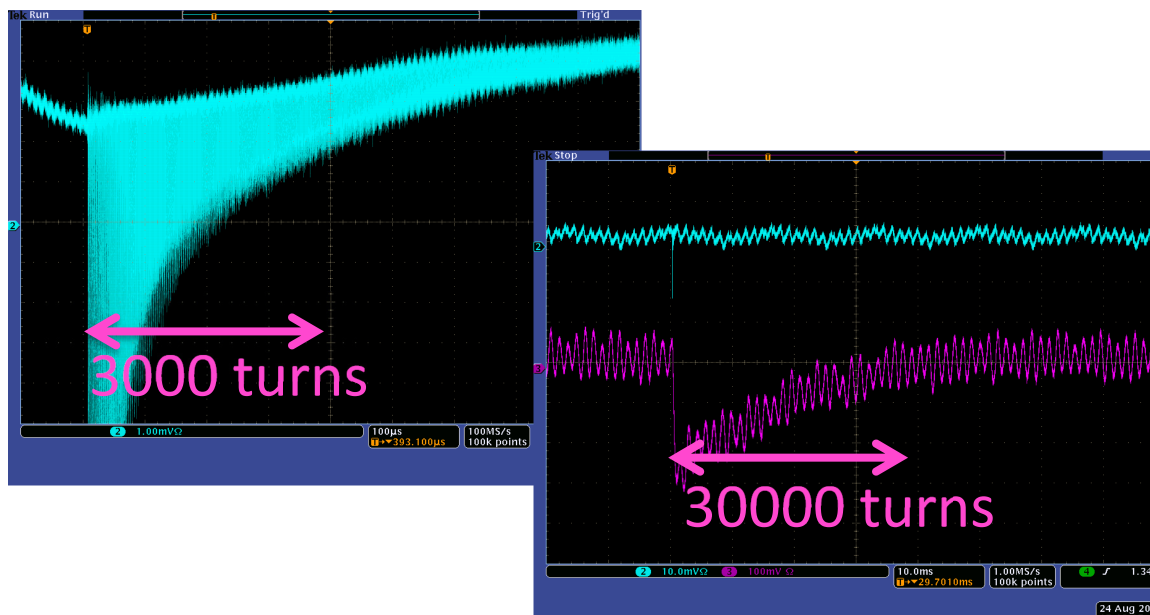
IOTA paramteres

Momentum	< 200 MeV
Perimeter	40 m
RF voltage	<1 kV
RF frequency	30 MHz & 2.18 MHz
3 Experimental straights	2x180 cm, 1x150 cm
Main vacuum chamber aperture (R)	25 mm
Lambertson and kickers aperture (R)	20 mm
Electrons	10^{9} e, 1.2 mA
Protons	10^{11} p, 9 mA
Vacuum	6×10^{-10} torr

Technical run with 47 MeV electrons

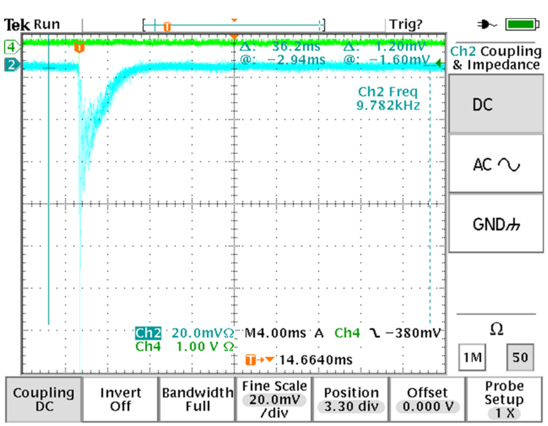
- 8/10 – CC1/2 cold
- 8/13 – CC1/2 coupler conditioning complete, beam to LEA
- 8/17 beam through linac
- 8/20 linac tuned for IOTA injection
- 8/21 – first turn at 7PM, 3 turns by 8PM, 10-15 turns by 9PM
- 8/24 – beam circulation for 40ms

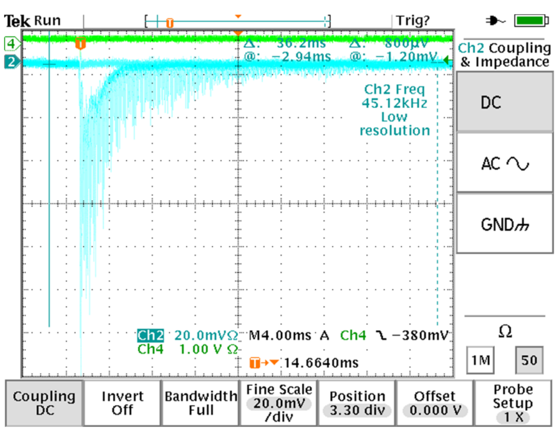




Commissioning at 100 MeV

- 9/27 – Linac at 2K
- 10/3 – Repaired RF cavity installed
- 10/10 – Beam through linac to IOTA at 100MeV
- 10/12 – First turns and betatron capture at 100MeV
- 10/16 – RF capture established, beam lifetime ~5 min

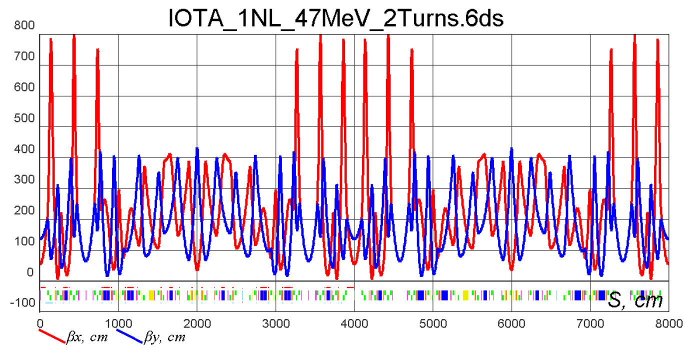


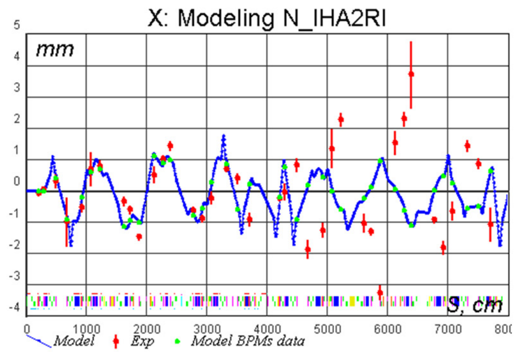


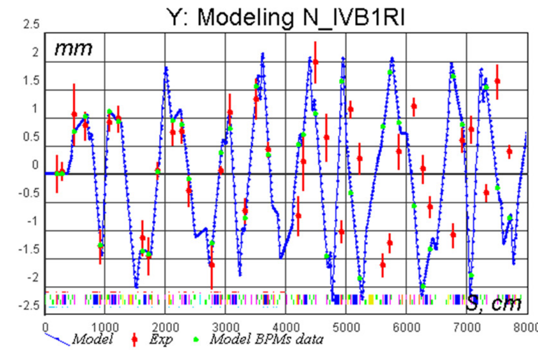
Automated lattice control at IOTA

- Extensive preparations were made to have automated on-line diagnostics and corrections tools for quick IOTA commissioning

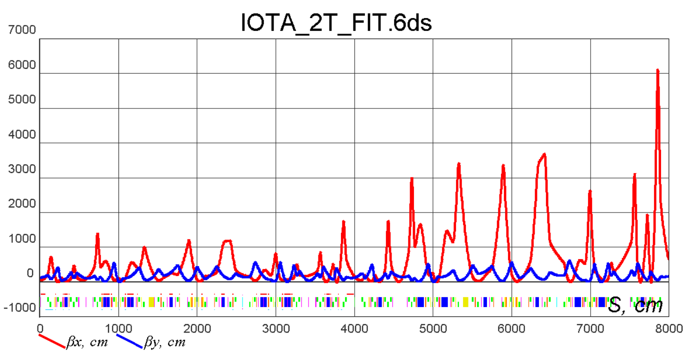
Model lattice and corresponding sample responses compared to measured

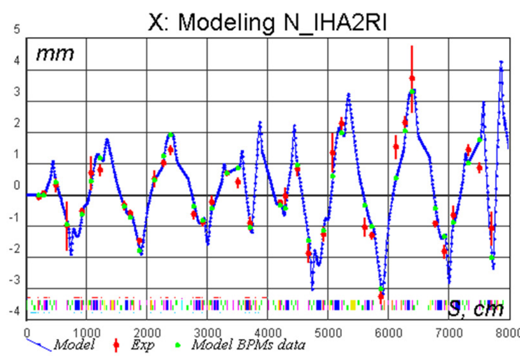


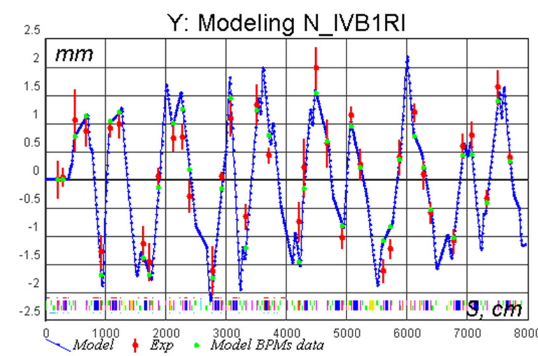




Fitted model has clear instability in X plane







- **First correction iteration made stable betatron lattice**

Commissioning Results

- By the end of the run IOTA/FAST was tuned up very well
  - 3.2 nC pulse charge in linac, good transmission, stability
  - 4.8 mA in IOTA (design 1.2mA) at 100MeV
    - Close to 100% injection efficiency
  - Turn-key operation: 1 hour turn-on to circulating beam
  - Excellent IOTA stability
  - Adequate beam performance
- Required configuration/tuning was not achieved in some aspects, most notably
  - IOTA energy (by choice)
  - IOTA lattice precision and flexibility
- Much learned about system performance and next steps
  - Plan for shutdown has been formulated

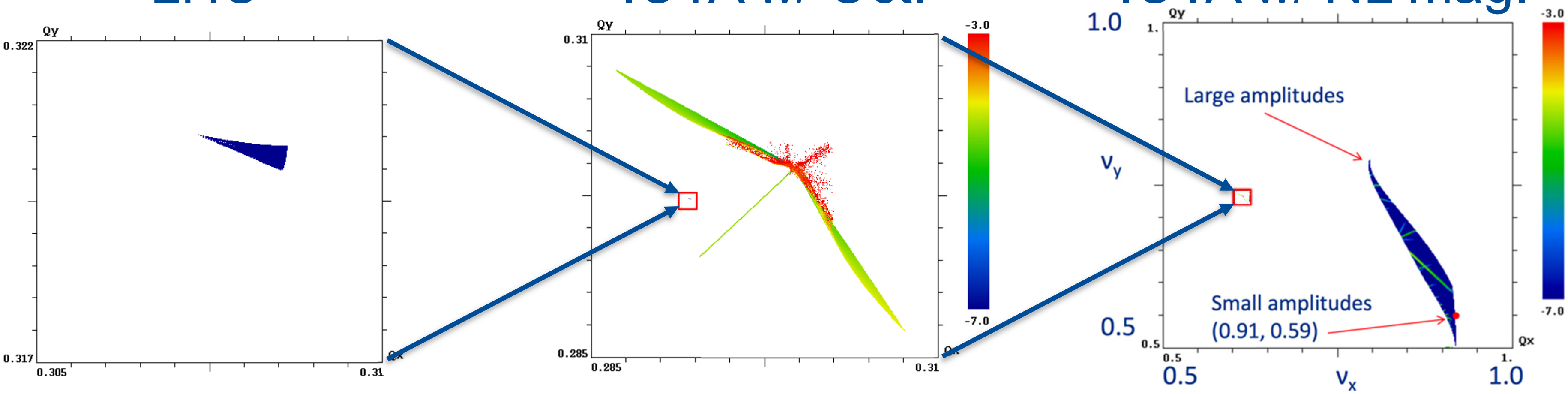
Presentation overview

- Why IOTA?
- IOTA commissioning
- Results of the first run
  - NIO with 2 Invariants of Motion – Special Magnet (TUZBB6)
  - Henon-Heiles Type System with Octupoles (TUPLM08)
  - Antidamper experiment
  - Fluctuations in undulator radiation (THYBA5)
  - Experiments with a single electron
- Future plans

NIO could yield important benefits for future HEP machines

- **Reduced chaos in single-particle motion:** e.g helpful for space-charge suppression
- **Strong immunity to collective instabilities via Landau damping:** provides for higher beam current and brightness
- **Low cost:** brighter beams produce a cascade of cost savings throughout the design, engineering and construction of accelerators

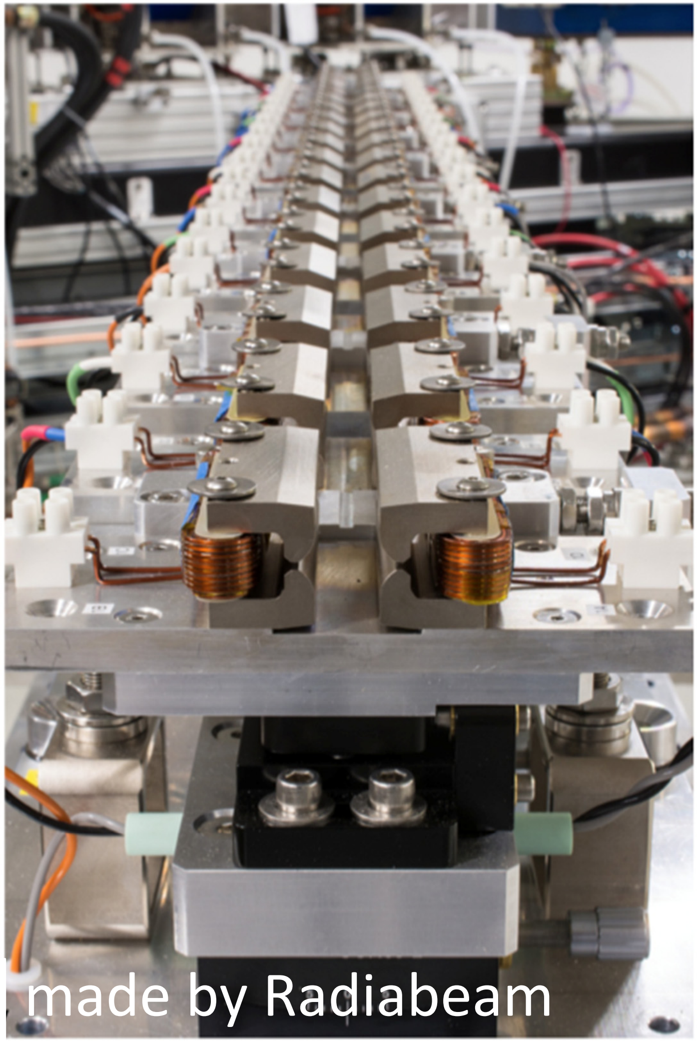
LHC | IOTA w/ Oct. | IOTA w/ NL mag.

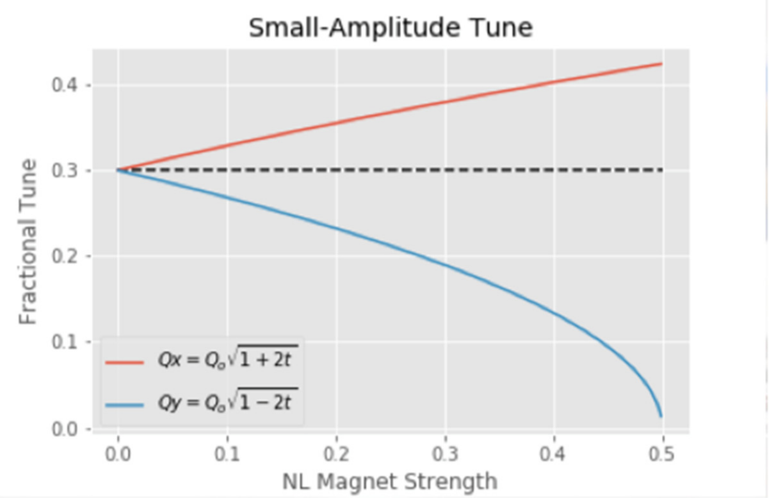


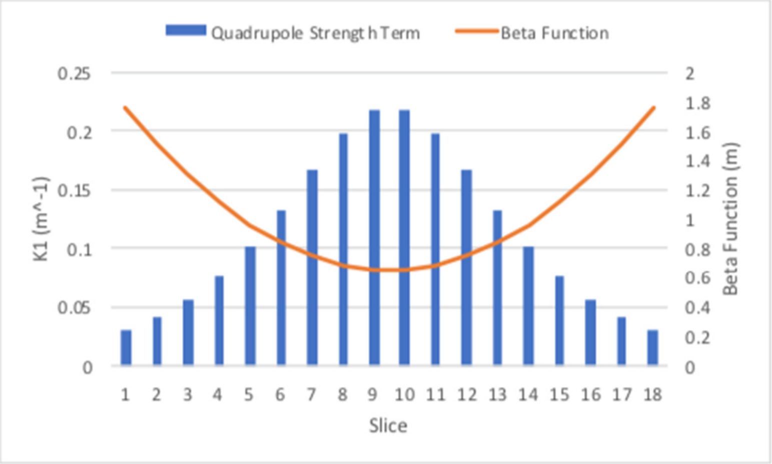
$\Delta Q = 0.001$ | $\Delta Q = 0.025$ | $\Delta Q = 0.25$

NIO with 2 Invariants of Motion – Special Magnet

(S.Szustkowski, NIU)







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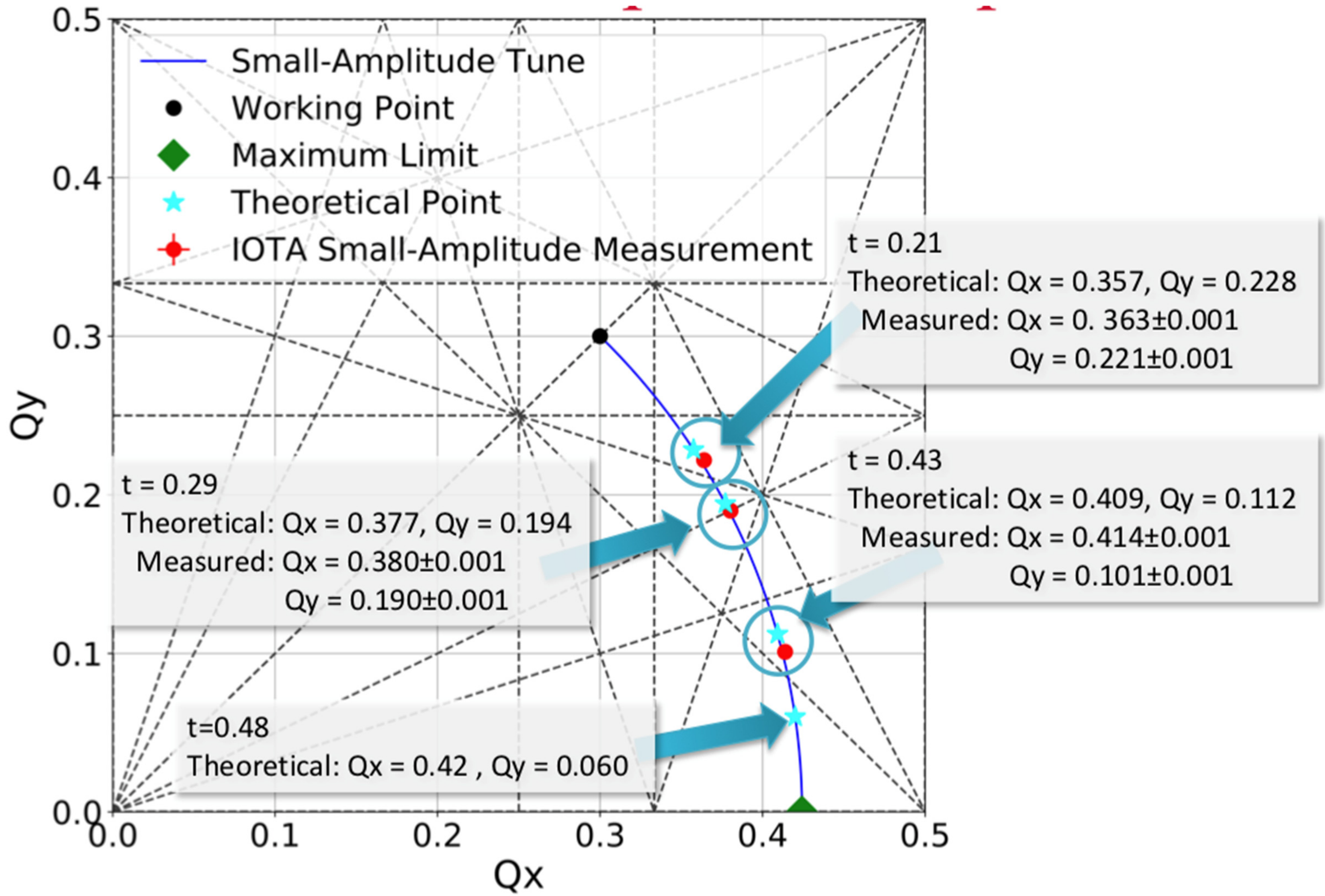
NIO with 2 Invariants of Motion: Small-Amplitude Tune



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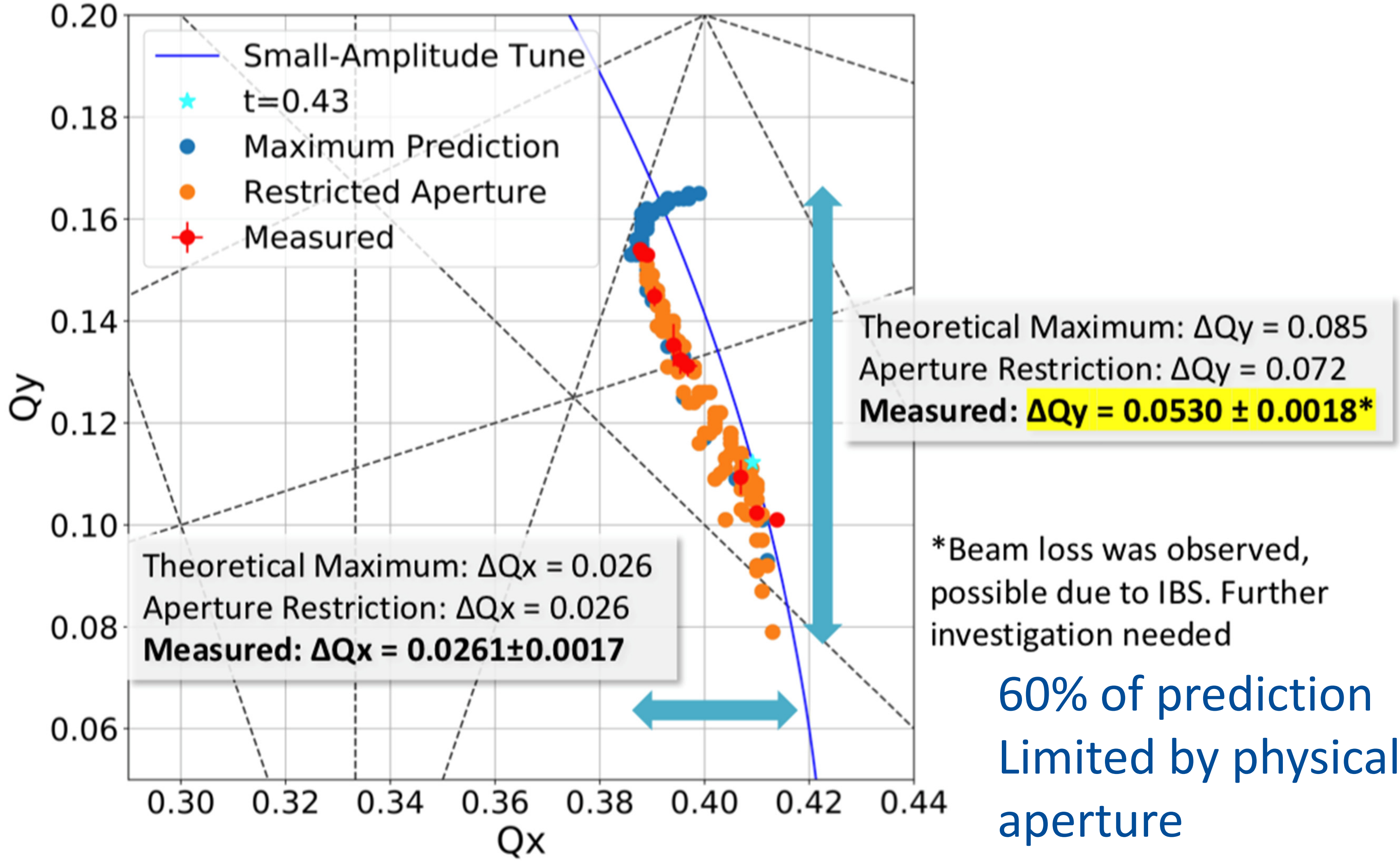
Results – Amplitude-Dependent Tune, t=0.43



*Beam loss was observed, possible due to IBS. Further investigation needed

60% of prediction
Limited by physical aperture

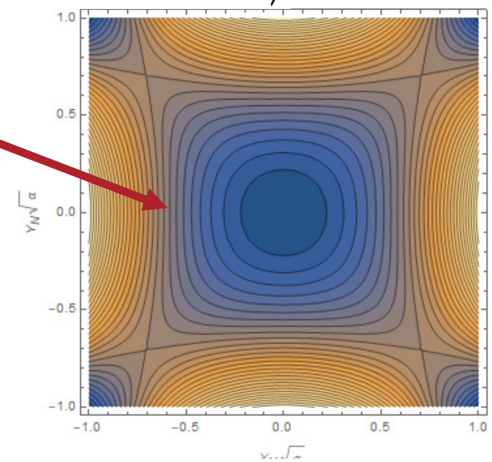
Henon-Heiles Type System with Octupoles

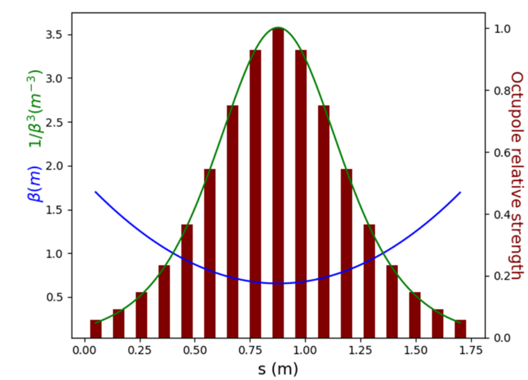
(N.Kuklev, U.Chicago)

- 1 invariant of motion, 'quasi-integrable'

$$H = H_0 + U = \frac{1}{2}\left(P_x^2 + P_y^2 + x_N^2 + y_N^2\right) + \alpha\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2}\right)$$

- Theoretical stability limit – $1/\sqrt{2\alpha}$
  - (lower due to chaotic layer, $\sim 0.6/\sqrt{\alpha}$)
  - Tune spread = 0.4
- Implementation in IOTA with discrete elements
  - Imperfections complicate the dynamics
  - Performance predictions (at DA limit)
    - 0.12 ideal case
    - 0.08 for 18 octupoles





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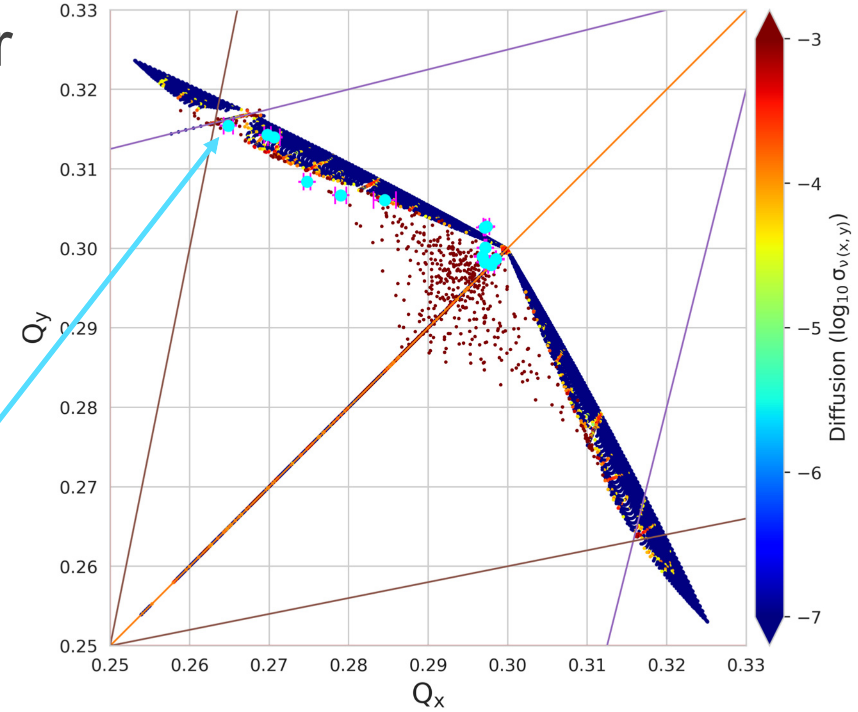
NL System with Octupoles: Results

- Extracted tunes overlaid on updated FMA (run 1 lattice)
- Clear improvement vs single octupole
  - From extinction scans, know both have ~same DA
- Best case: 0.025-0.03 (0.045 for 2 branches)
- 50-70% of ideal simulation performance
  - Limited by physical aperture restriction!

0.75 Vkick
1A octupoles
ICA+NAFF



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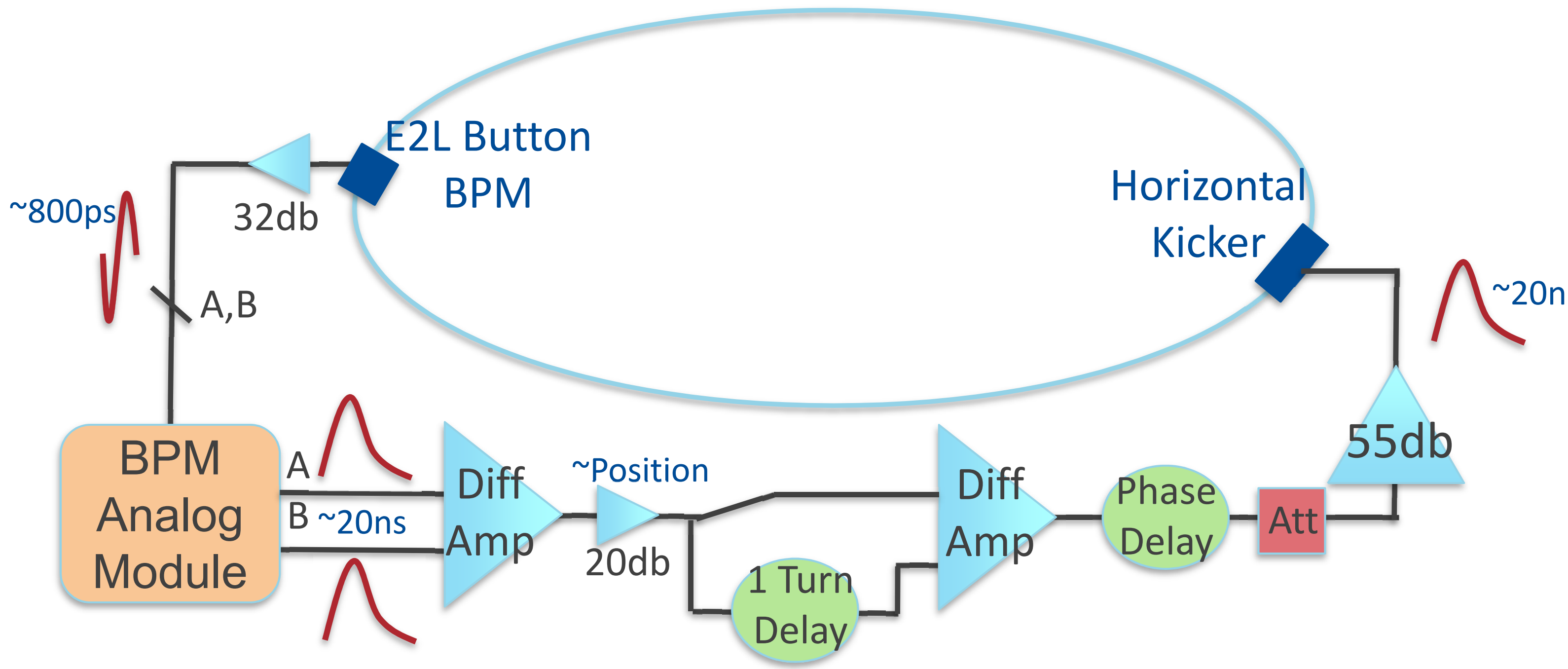
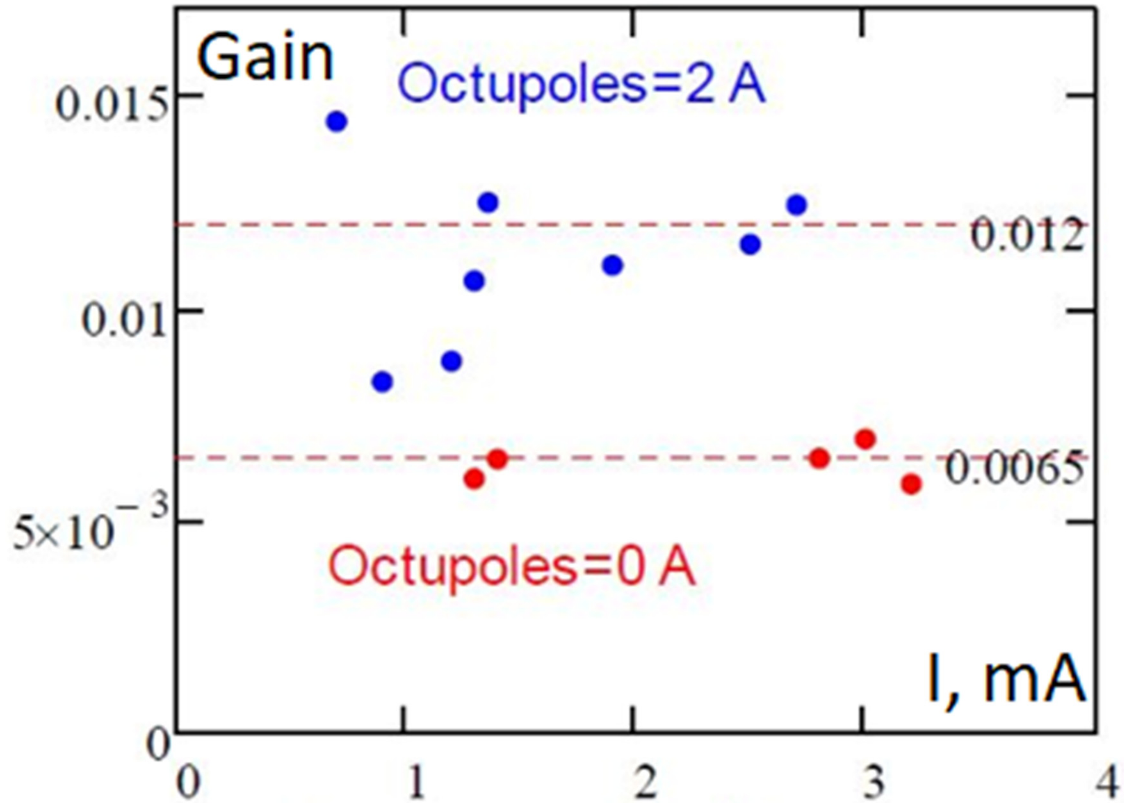
Antidamper experiment: setup

(N. Eddy, Fermilab)

- Use a transverse damper to excite controlled instability
- Demonstrate instability threshold change when powering quasi-integrable nonlinear optics with octupoles



Antidamper experiment: results



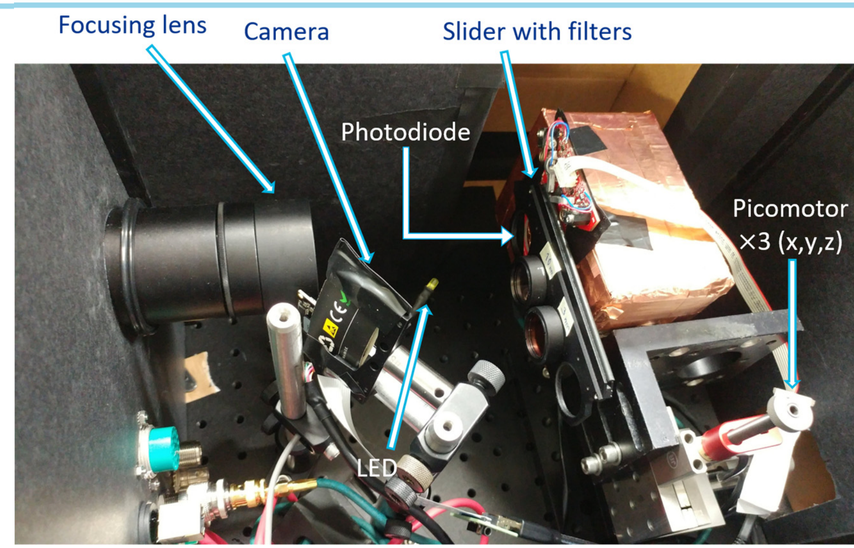
- Demonstrated approximately **factor of 2 increase** in the instability threshold with octupoles at 2A as compared with 0A

N.Eddy, V.Lebedev

Fluctuations in undulator radiation

(I. Lobach, U.Chicago)

UChicago, Fermilab, SLAC, ANL



- In the experiment we study the fluctuation in the number of photoelectrons, namely, the variance:

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N}^2 \rangle - \langle \mathcal{N} \rangle^2 = \langle \mathcal{N}_{\mathrm{ph}} \rangle + \frac{1}{M} \langle \mathcal{N}_{\mathrm{ph}} \rangle^2$$

- We installed an undulator from SLAC in the IOTA ring.
- And built an radiation intensity detector. The amplitude of the output voltage was proportional to the number of photoelectrons generated in the photodiode.

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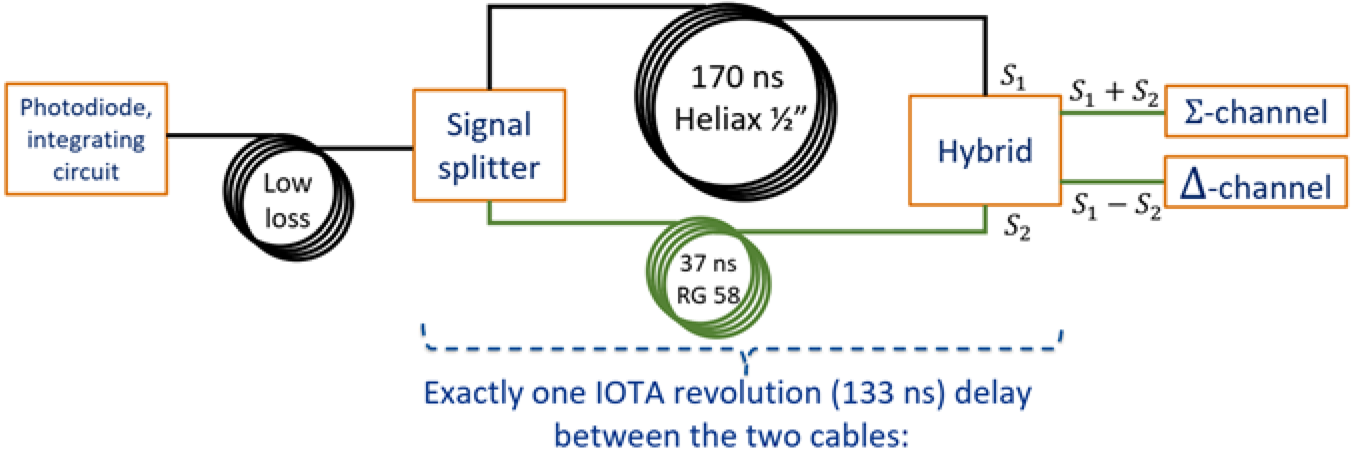
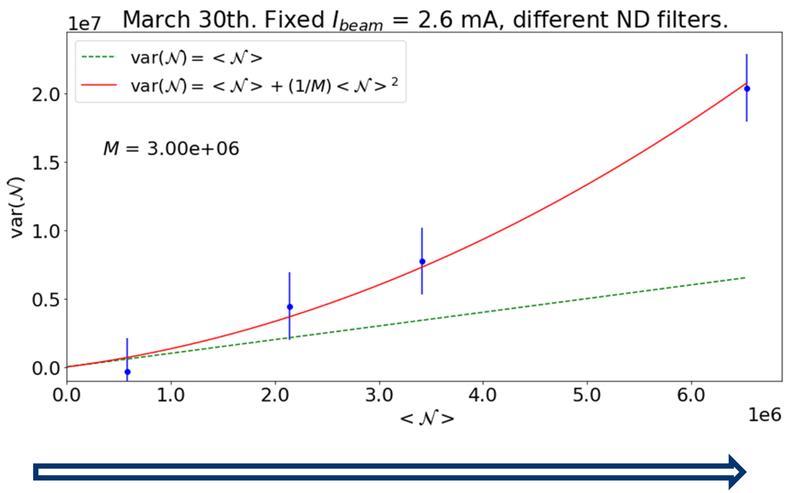
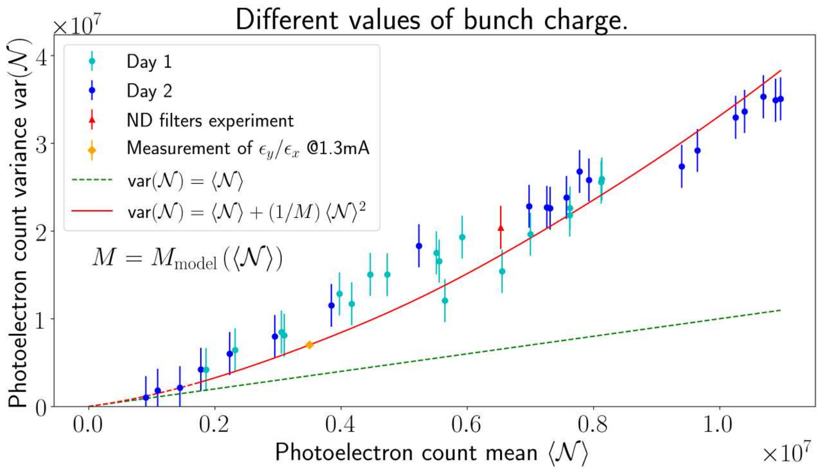
Fluctuations in undulator radiation: results



RMS fluctuation $\sim 10^{-4} - 10^{-3}$





Decreasing optical density of the filters

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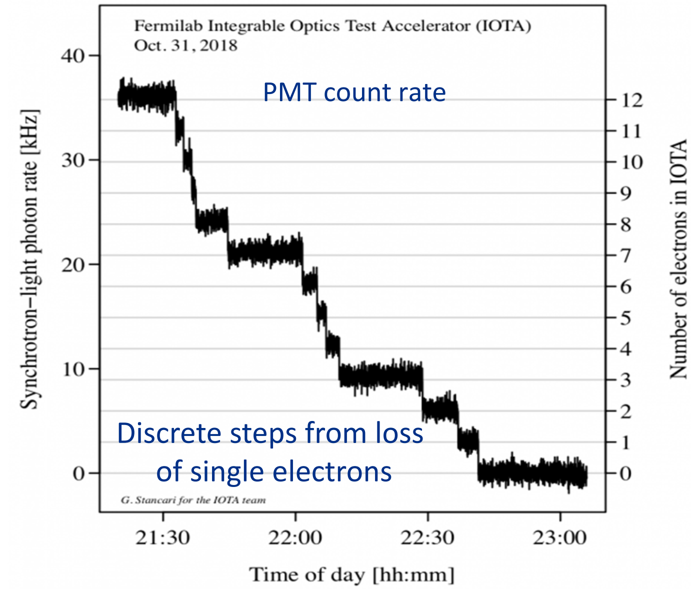
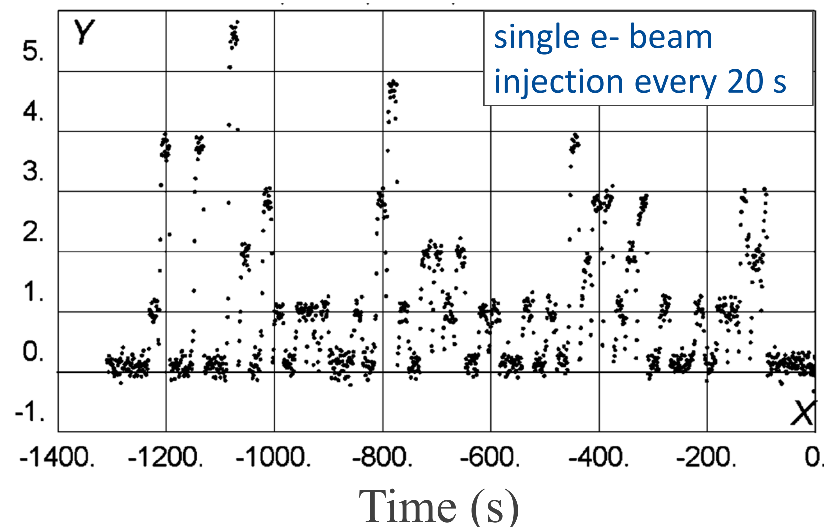
Experiments with a single electron

- IOTA demonstrated storage of a **single relativistic electron** for long periods of time (~10 minutes).
- High particle energy (100 MeV) enables observation of SR emission
- This opens the way to a wide variety of quantum experiments
- Recent One-day **Workshop on Single-Electron experiments in IOTA** – 30 participants from U.Chicago, LANL, SLAC, ANL, Princeton, RadiaBeam, BNL, UC Berkeley, Fermilab





Experiments with a single electron

(A. Romanov, G. Stancari, Fermilab)

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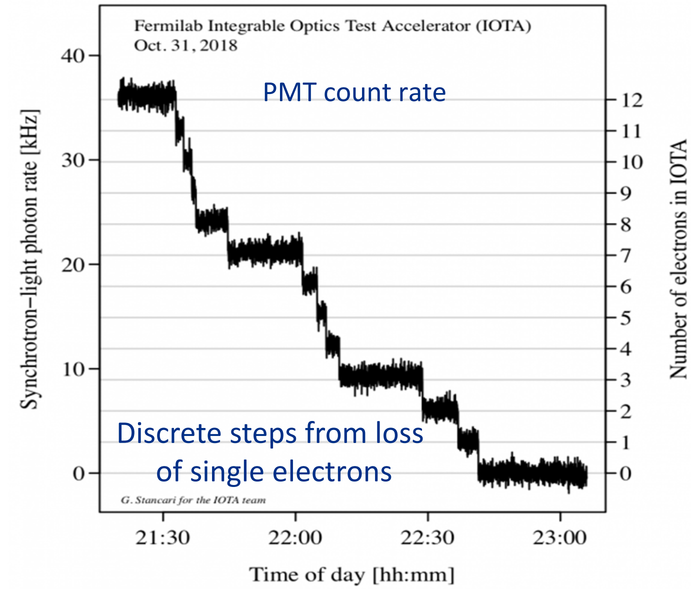

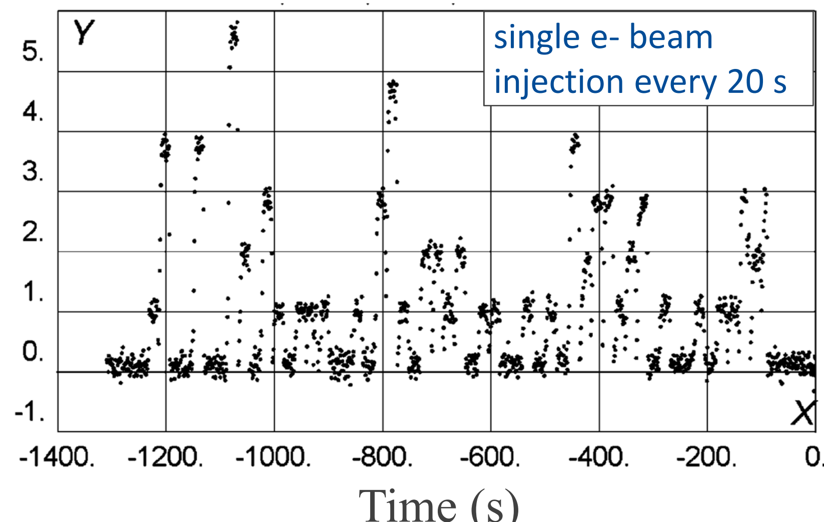

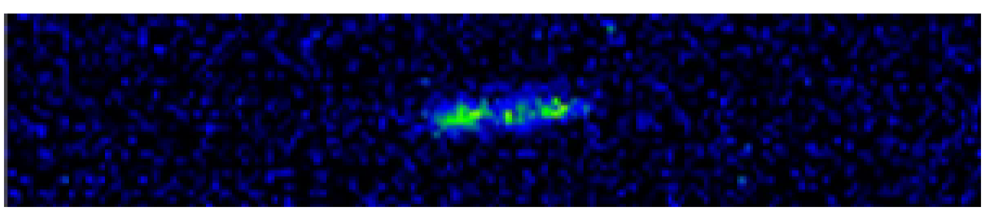

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- Why IOTA?
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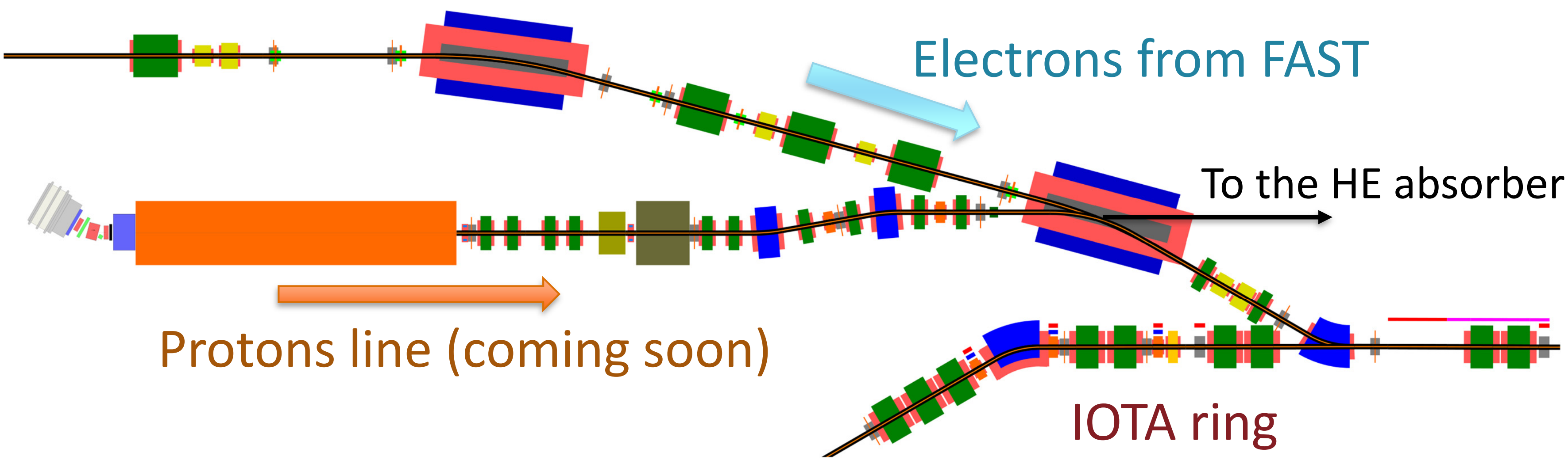
- Future plans
  - 2nd run for NL studies
  - Electron lens
  - Optical Stochastic Cooling experiments (TUPLM21)
  - Protons program

Coming soon: Protons program

- Proton source energy: 50 keV
- Injection energy: 2.5 MeV
- Number of injected protons: 1×10^{11}
- Geometric RMS emittance (x&y): 3 µm
- $\Delta p/p$, RMS: 2×10^{-3}

Commissioning in 2020



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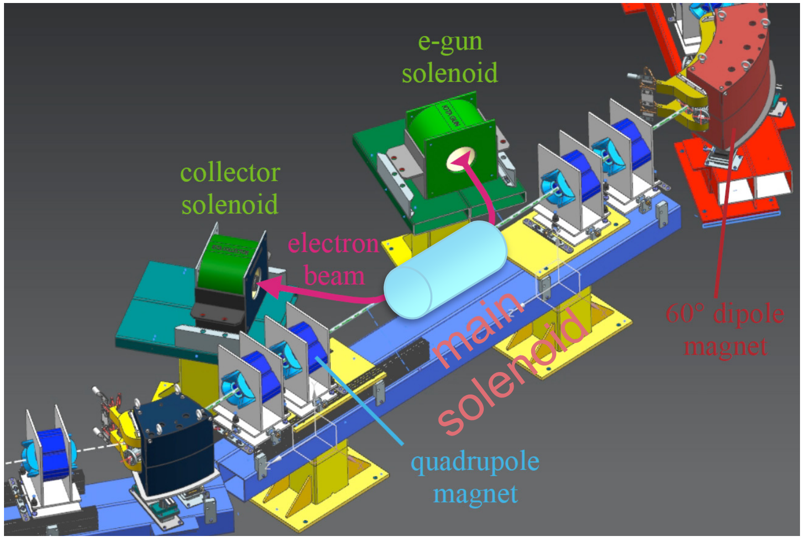
Coming soon: Electron lens

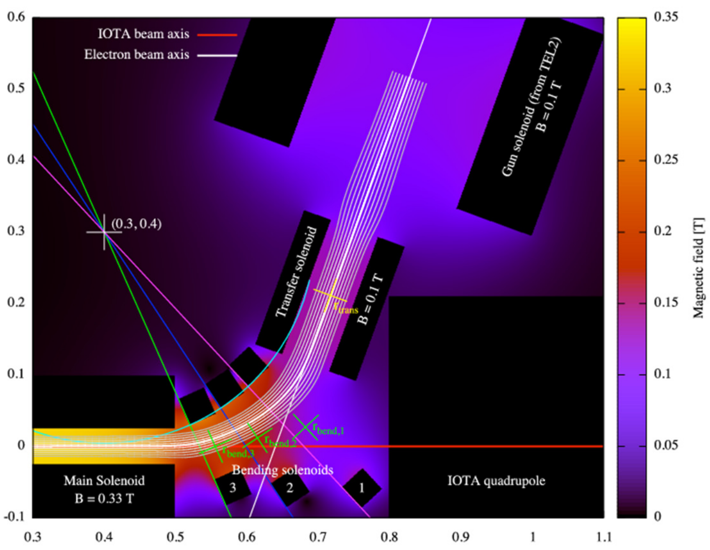
Research with stored electrons:

- Novel nonlinear element for integrable optics (using space charge)

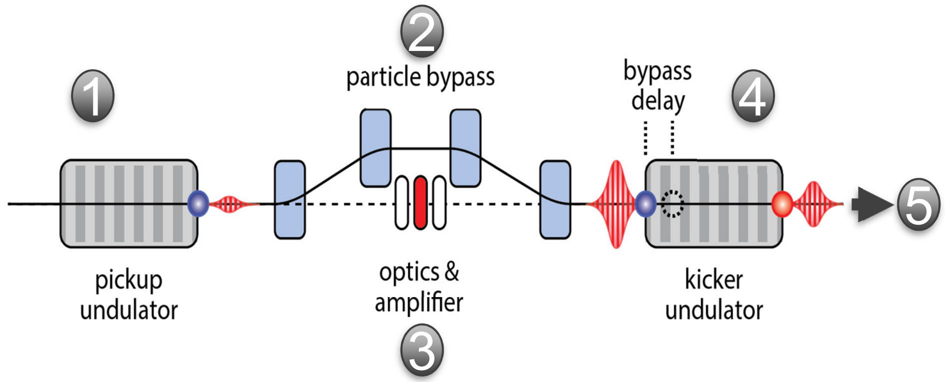


Research with stored protons:

- Space-charge compensation and Landau damping
- Electron cooling: extending performance of IOTA for space-charge studies; cooling studies in a NIO lattice

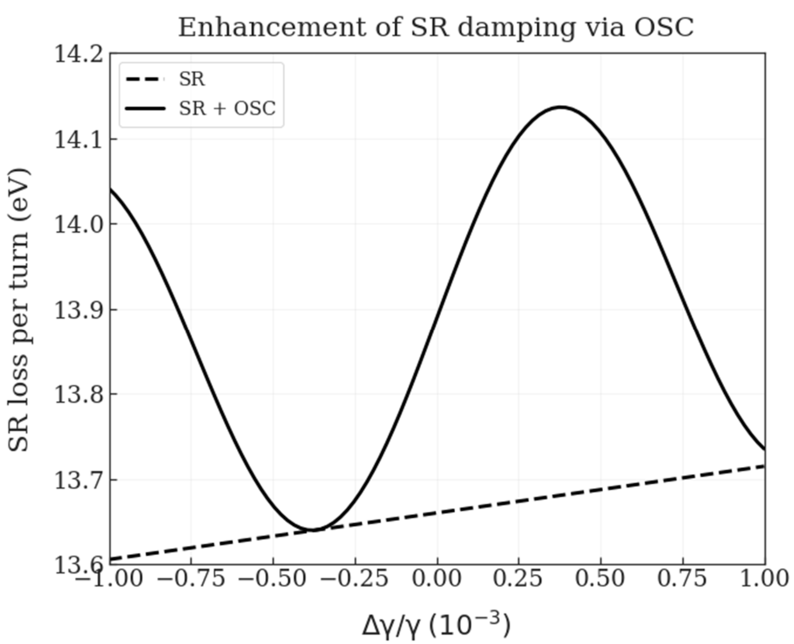


Coming soon: Optical Stochastic Cooling



1. Wavepacket generated
2. Particle delayed in bypass
3. Wavepacket amplified and focused
4. Corrective kick applied
5. Cooling accumulates over many passes

- **10^3 – 10^4 increase** in cooling rate over SC and extension into an energy range where no operational cooling solutions exist
- **IOTA's OSC dominates sync. rad. damping by ~20-40x without any optical amplification**



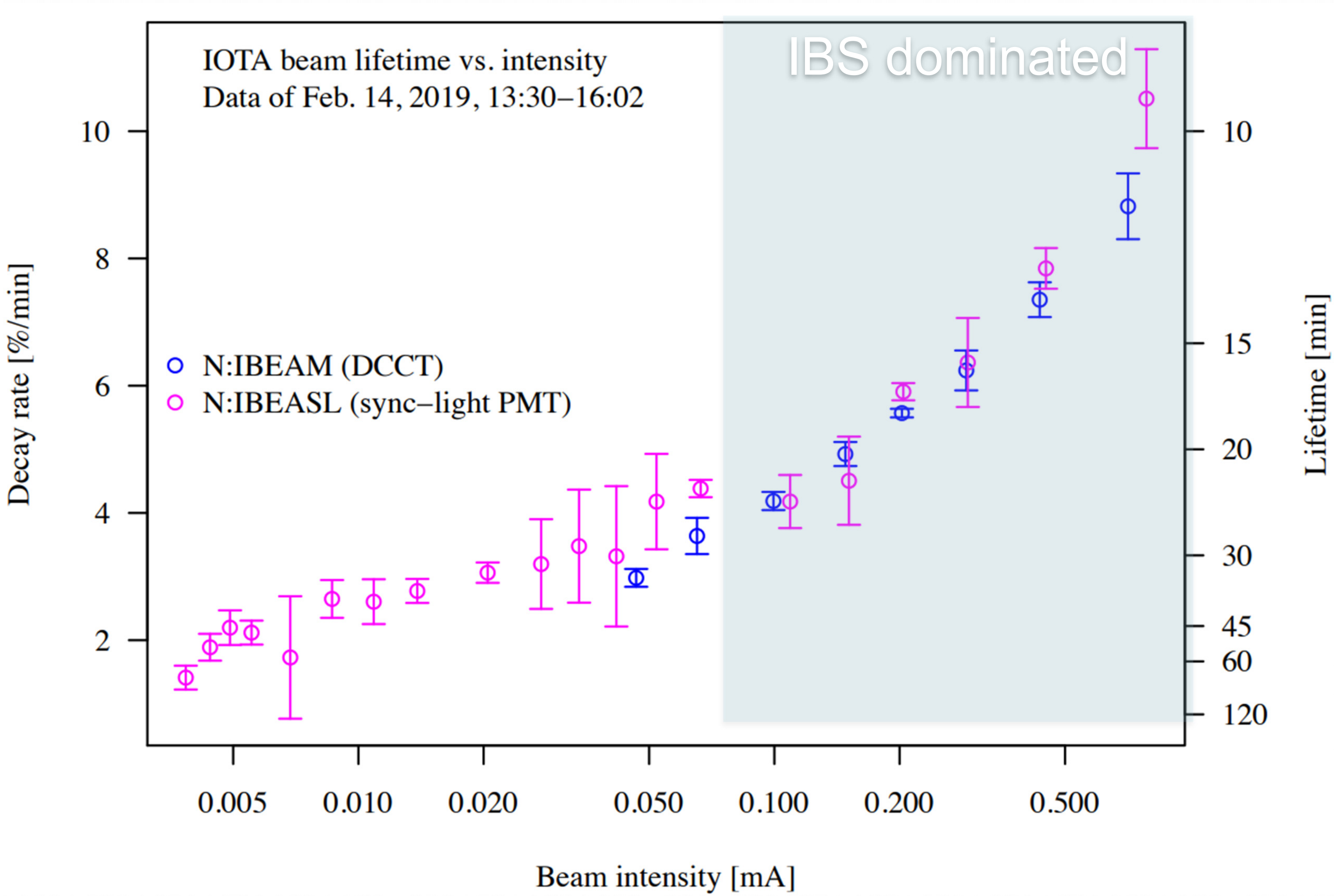
Summary

- Fermilab has a rich tradition of a world-class accelerator science program, established by R. Wilson and H. Edwards, with its emphasis on operational HEP machines.
  - IOTA pushes exploration of new physics beyond HEP boundaries by addressing universal accelerator physics grand challenges.

- We have a very exciting science program in our new IOTA ring. IOTA/FAST is a unique R&D facility dedicated to the future of intensity-frontier research:
  - Electrons and protons, linacs and rings -- concurrently
- The IOTA science program explores a wide variety of fundamental topics in accelerator and beam physics
- IOTA also constitutes an excellent platform for technological developments that may be vital for realizing next-gen. facilities.

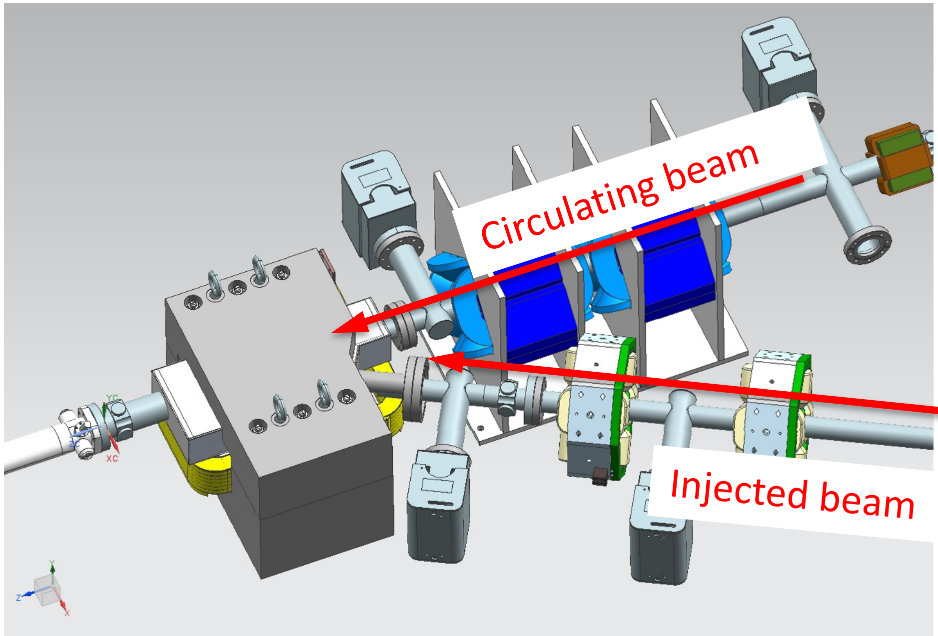
Additional slides

Beam Intensity and Lifetime



Injection

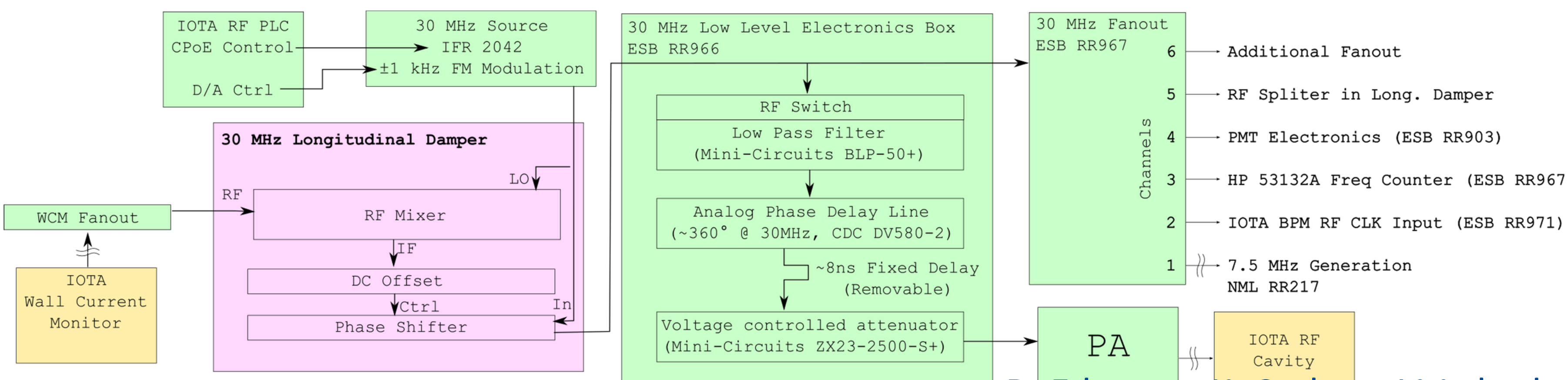
- Electrons come from the FAST superconducting linac
- Lambertson magnet is used to deliver injected beam to ~30 mm below the IOTA's ideal orbit
- Aperture is 25mm in radius with few limitations
  - 20 mm radius in Lambertson and kickers
  - 12 mm radius in octupoles chanel
  - 4 mm hor. and 5.5 mm vert. aperture in the NL magnet
- Vertical kicker max strength is 25 mrad for 100 MeV electrons
- Field in combined correctors limited to 120x10 G*cm
- Field in bump correctors limited to 1x10 kG*cm



Fermilab

RF damper and resulting performance

- Initial RF design relied on the relatively low Q factor to damp beam induced high-order modes
- Passive damping works only up to about 1 mA of current, which is close to the design value of 1.2 mA
- Active damper was designed to achieve higher beam currents for better BPMs performance
  - As a result maximum stored beam current increased up to 4.8 mA, 4 times the design value.



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