First Integrable Optics Experiment at IOTA

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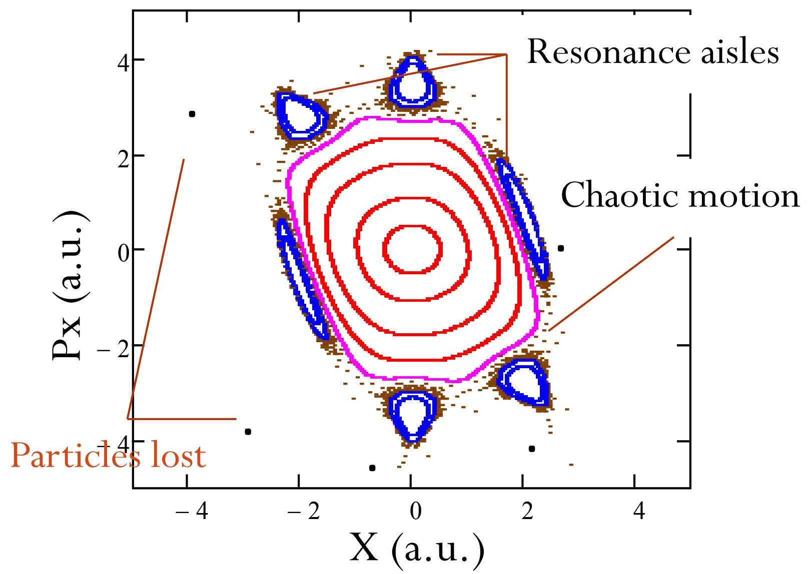
Motivation: Linear Dynamics

- Linear focusing lattice – betatron tunes of different particles are almost equal
  - Hamiltonian depends on time
  - Nonlinearities (both magnet imperfections and specially introduced) make single particle motion unstable due to resonances
- Stability depends on initial conditions

Phase space of 1D motion in linear lattice with 1 octupole nonlinearity

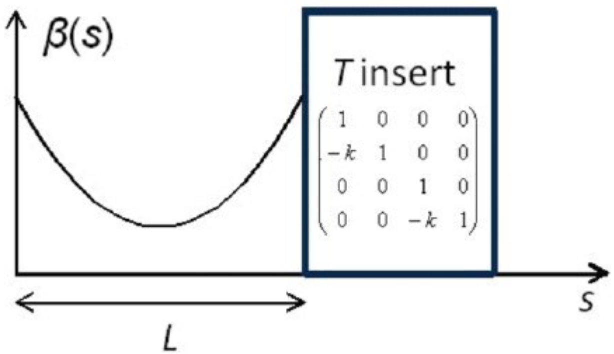


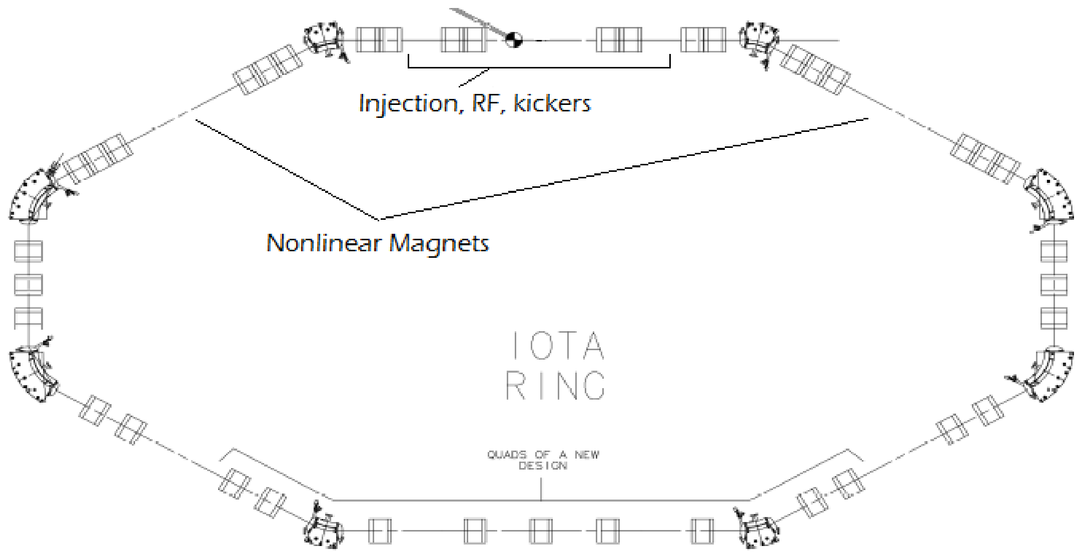
Motivation: Nonlinear Dynamics

- Tunes depend on amplitude
- Landau Damping increases with the spread of betatron oscillation frequencies. Larger tune spread –> beam more stable against collective instabilities.
  - Can created by adding octupole magnets
- If the system is integrable – no resonances
- IOTA Goal: create practical nonlinear accelerator focusing systems with a large frequency spread and stable particle motion.

Integrable Optics Test Accelerator

Danilov, Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002 (2010)





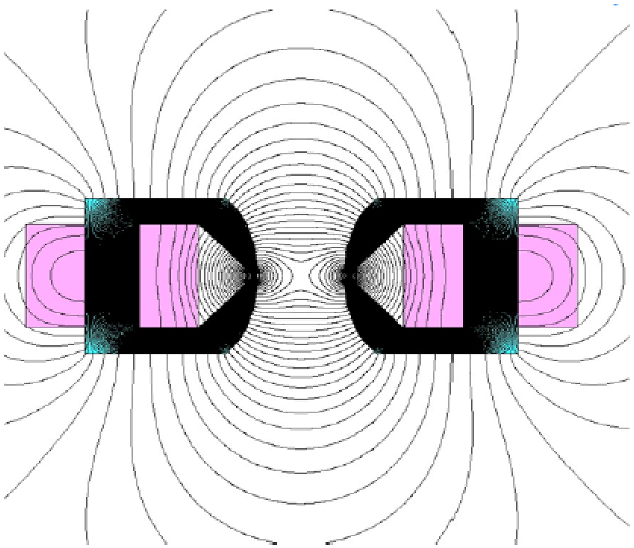
$$U(x,y) = t \cdot \mathrm{Re}\left[(x+iy)^2 + \frac{2}{3c^2}(x+iy)^4 + \frac{8}{15c^4}(x+iy)^6 + \frac{16}{35c^6}(x+iy)^8 + \ldots\right]$$

Electron Energy	150 MeV
Beam transverse size	~ 0.1 mm
Circumference	40 m
Length of NL magnets	1.8 m
Phase advance over NL section	0.3

Need a Special Magnet

- Can we do anything with just conventional magnets?
  - Quadrupoles
  - Octupoles

Cross-section and field lines



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Quasi-integrable optics

- Octupole magnet strength ~ $1/\beta(s)^3$

$$U(x_N, y_N; s) = \beta(s) V(x_N \sqrt{\beta_x(s)}, y_N \sqrt{\beta_y(s)}; s)$$

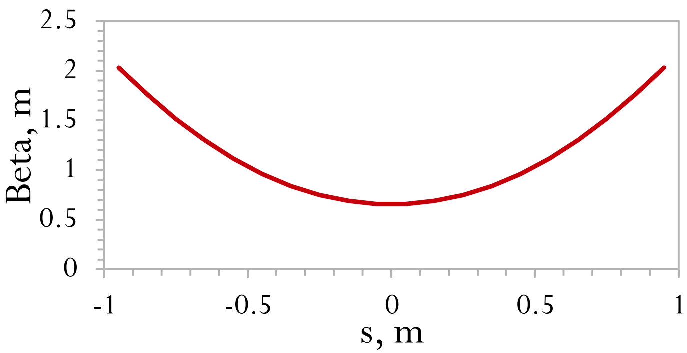
$$U = U(x_N, y_N)$$

- Hamiltonian does not depend on s:

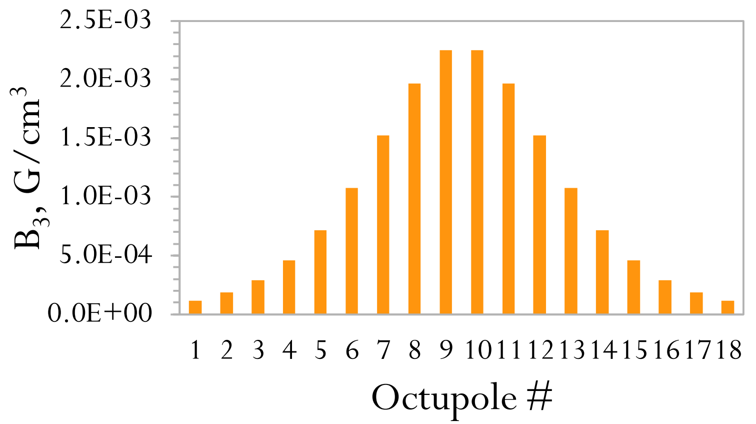
$$H = \frac{1}{2}(p_x^{\;2} + p_y^{\;2} + x_N^{\;2} + y_N^{\;2}) + U(x_N, y_N)$$

- Questions:
  - What about the 3rd degree of freedom?
  - Imperfections
- 6D Simulations required

Beta-function in NL magnet section



18 10cm-long octupole magnets



t = 0.4, c^2 = 0.01 cm, l = 10 cm

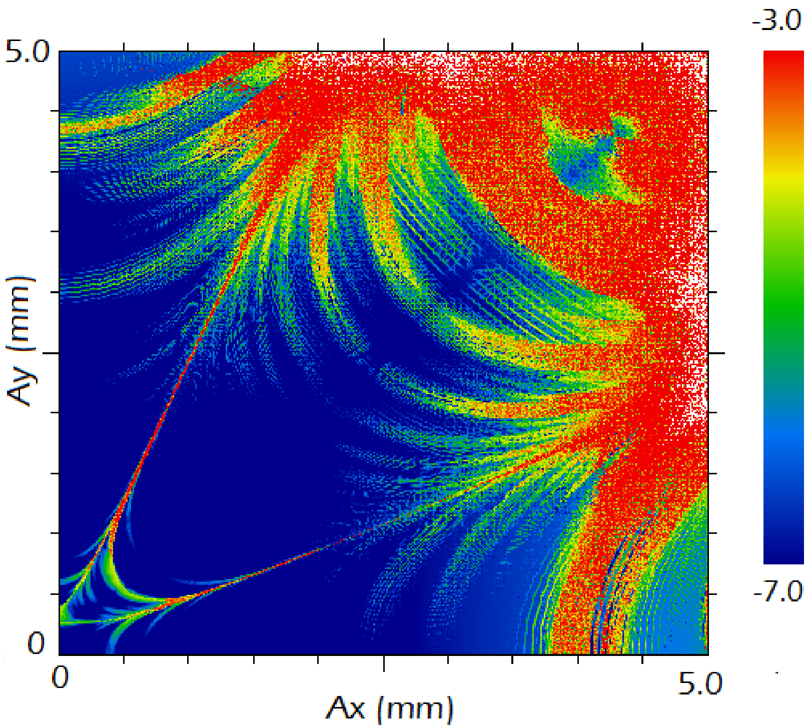
Frequency Map Analysis

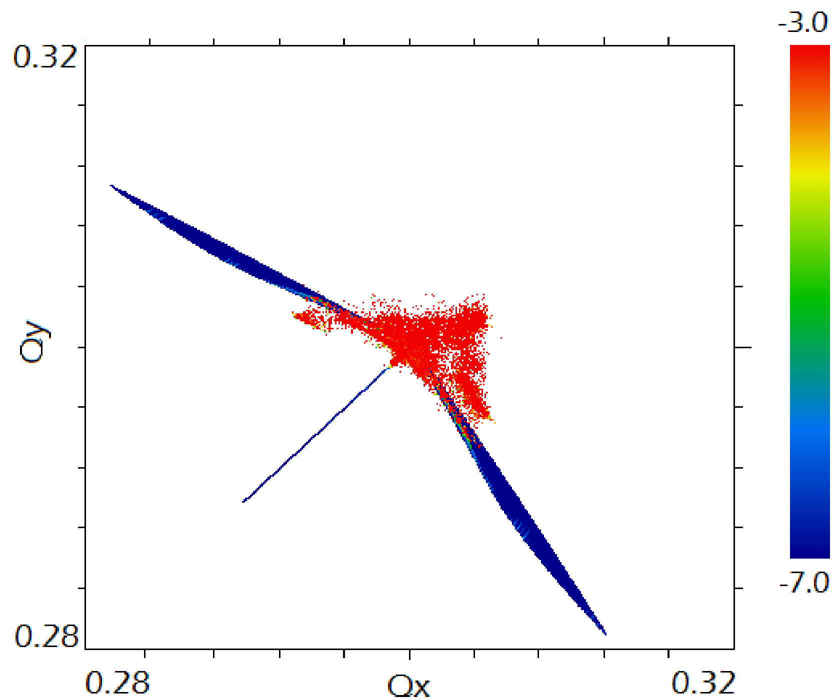
- Lifetrac code by D. Shatilov
  1) Tracking for $\sim 10^3$-10^4 turns
  2) FFT, find fundamental frequency
  3) Plot deviation

- No deviation – sufficient but not necessary condition for particle stability

- Model includes:
  - Dipoles
  - Dipole fringe fields
  - Quadrupoles
  - RF
  - No sextupoles

Frequency Map Analysis: 1 Section, Octupole Magnet



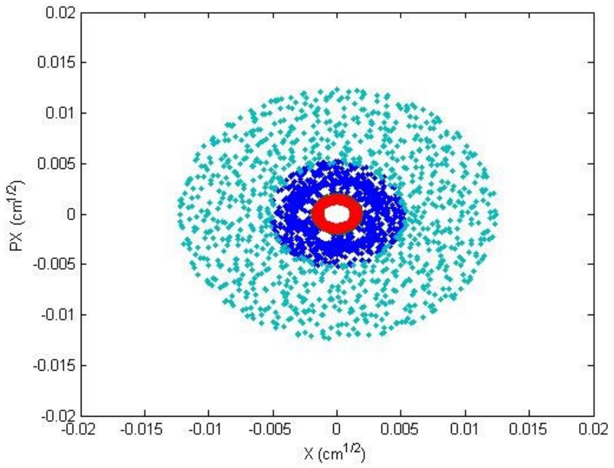


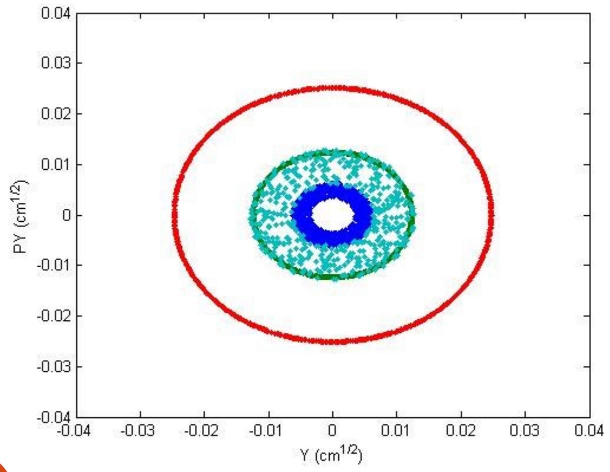
Stable region: 2.5 x 2.5 mm

Tune spread: 0.03

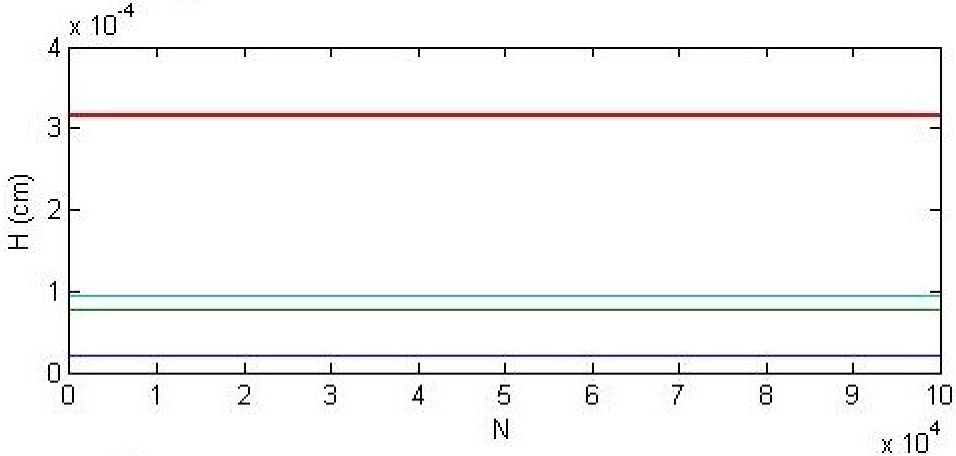
Tracking

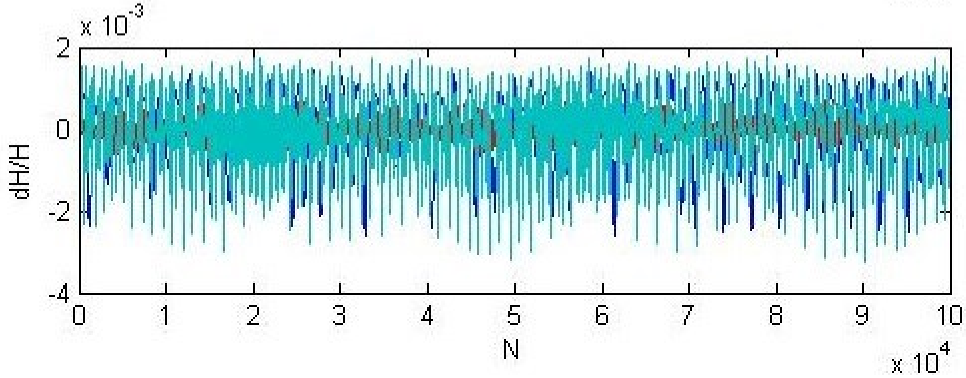
Motion is bounded





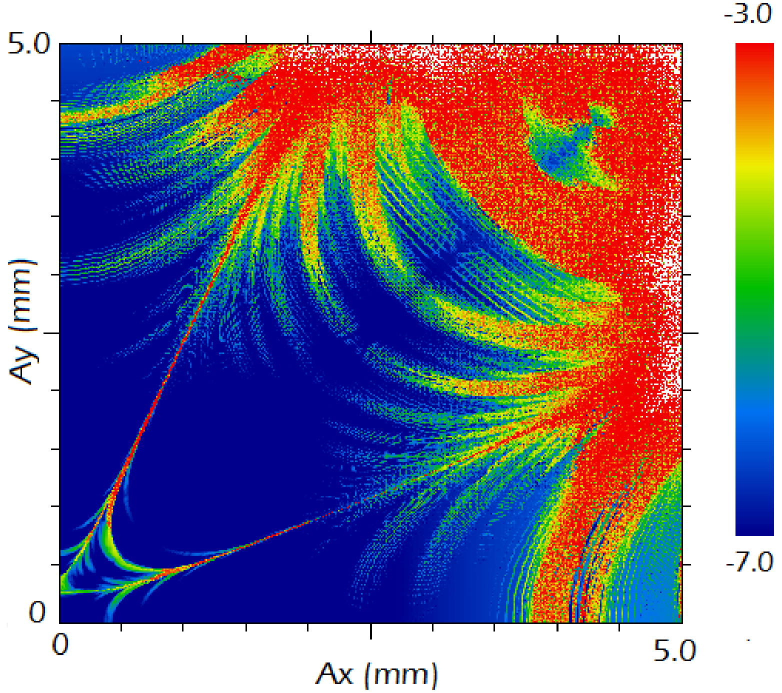
Hamiltonian is conserved



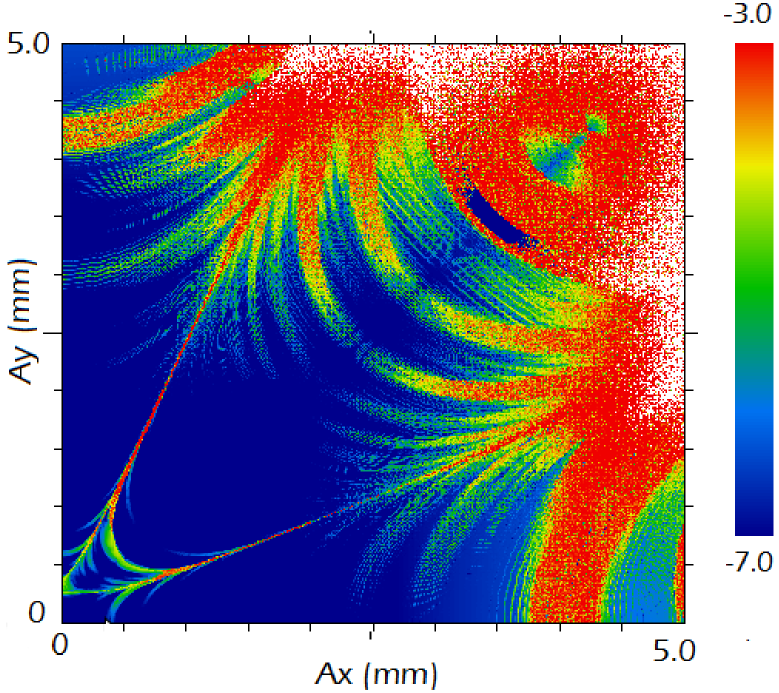


Imperfections: stable region reduces insignificantly

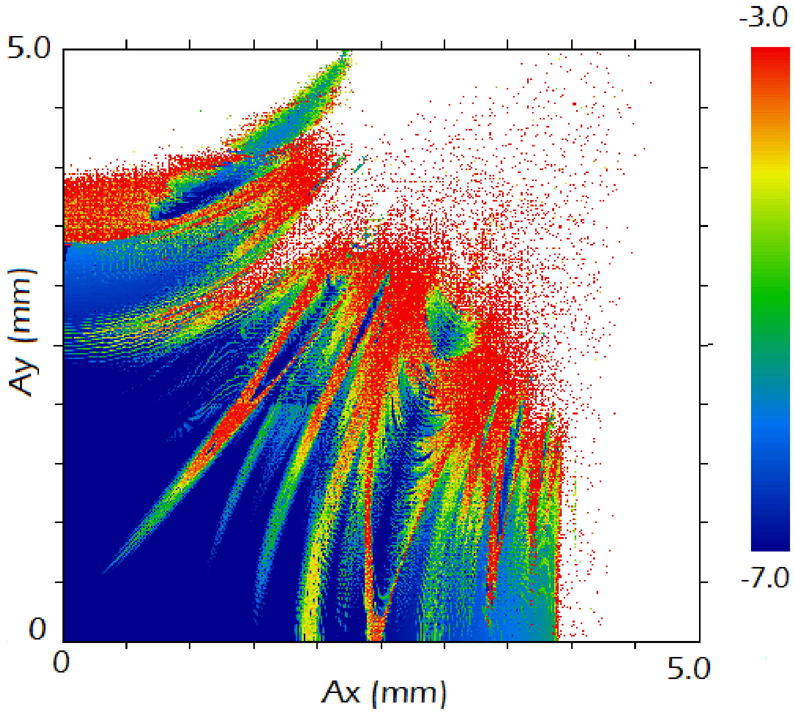
No imperfections

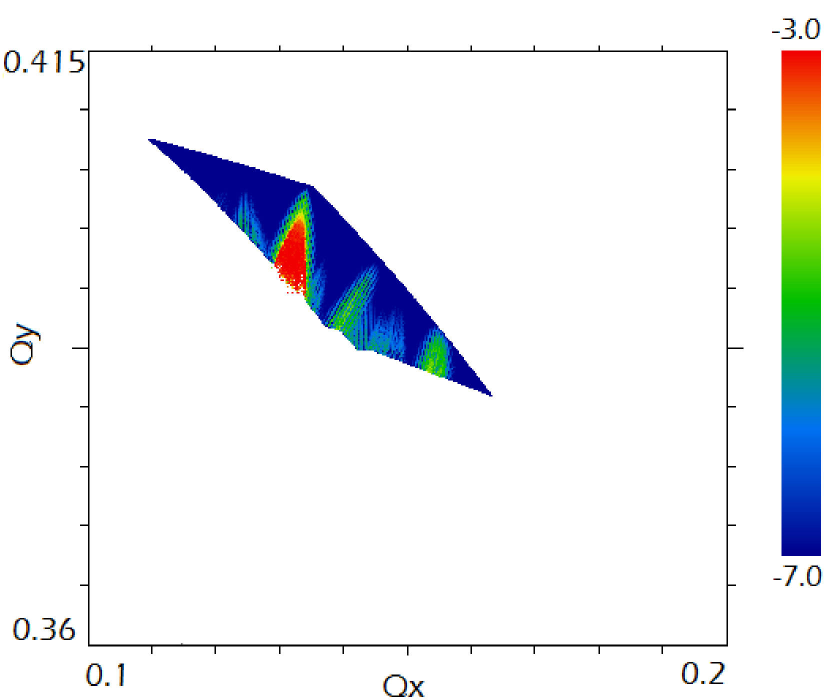


Random error, $\sigma = 0.1$



FMA: 1 Section, Quadrupole + Octupole





Stable region: 2.5 x 1.8 mm

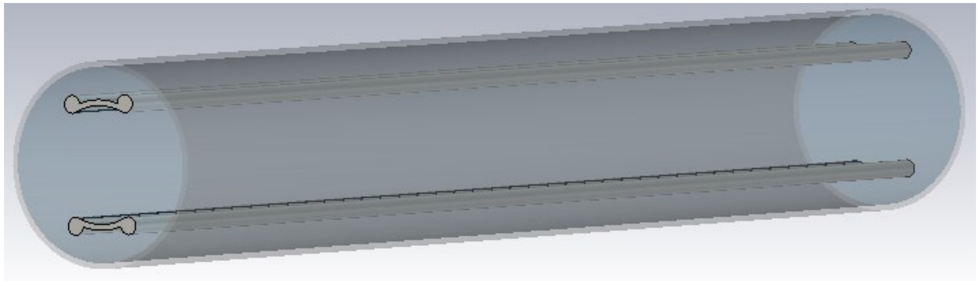
Tune spread: 0.05

Experimental Procedure

- Two kickers, horizontal and vertical, place particles at arbitrary points in phase space
- BPM measures beam position on every turn -> Poincare map: $\begin{pmatrix} x \\ y \end{pmatrix}_n$
- As electrons lose energy due to synchrotron radiation in ~ 1sec or 10^7 turns, they will cover all available phase space
- Do Fourier on ~ 1 ms, 10^4-turn-long samples –> betatron frequencies
- Repeat
- Study $Q_i(A_x, A_y)$ -> tune spread
- Final goal – dependence of betatron frequency on amplitude

Two Kickers Create an Arbitrary Kick in 2D

- Horizontal + vertical stripline kickers
- Rectangular pulses up to 25 kV
  ~ 100 ns duration.
- Repetition rate < 1 Hz
- Adjustable voltage 0 – V_{max}
- Fit inside quadrupole magnets to save space

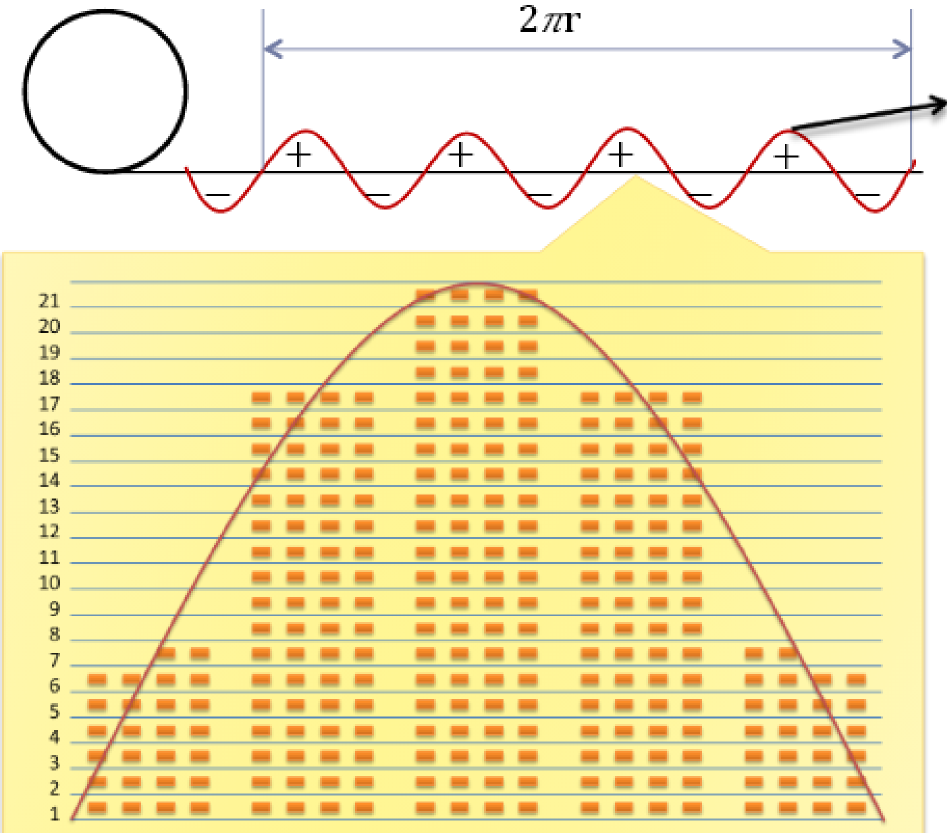


Voltage	± 25 kV
Radius:	
• Pipe	33 mm
• Plates	20 mm
Thickness:	
• Pipe:	2 mm
• Plates:	2 mm
Opening angle	70 deg
Edge rounding radius	3 mm
Wave impedance:	
• Odd mode	50 Ohm
• Even mode	55 Ohm
E-field in the center	12 kV/cm
Length:	
• Horizontal	55 cm
• Vertical	100 cm

Beam Position Can Be Measured Precisely

- 20 horizontal and vertical BPMs
  - Button type
  - 1 μm closed orbit resolution
  - 100 μm turn-by turn resolution
- 8 SR ports to measure beam size

PCB-Based Octupole Magnet
V. Vorobiev, PARTI-2013



Parameter	Value
Tube radius	12.7 mm
Peak current	201.18 A
Wire thickness	0.035 mm
Wire width	0.25 mm
Wire current	0.37 A
Wire material	copper
Power/m	630 W/m
Current density	42 A/mm^2
# of turns	21
Insulator type	Kapton
Adhesive	Acryl/epoxy
Total substrate thickness/layer	0.05 mm
Total coil thickness	1.8 mm

*http://www.temflexcontrols.com/pdf/aa24.pdf

Sources of Error

- Beta functions: 0.01 (relative)
- Phase advance: 0.001
- BPMs: 0.1 mm
- Bunch transverse size: ~ 0.1 mm
- Bunch length: 2 cm
- FFT: $\Delta Q \sim 10^{-4}$
- Energy loss during 1 ms sampling window
- Errors in NL potential
- Overall: $\delta A \sim 0.1\ \mathrm{mm},\ \delta Q \sim 10^{-4}$

Summary

- It is possible to achieve tune spreads ~ 10^{-2} with just conventional magnet components and still retain large dynamic aperture

Next Steps

- Search for optimal combination in terms of tune spread/size of dynamic aperture/complexity of the potential
- Compare with full nonlinear potential

Thank You for Your Attention