Quasi-Integrable Optics Experiment at IOTA

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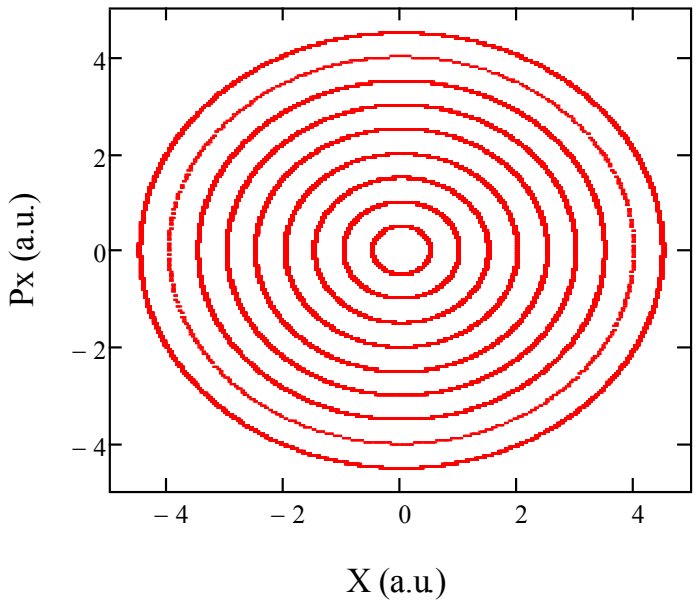
Motivation: linear dynamics

- Linear focusing lattice – betatron tunes of different particles are almost equal
- In ideal case, particle motion is unconditionally stable

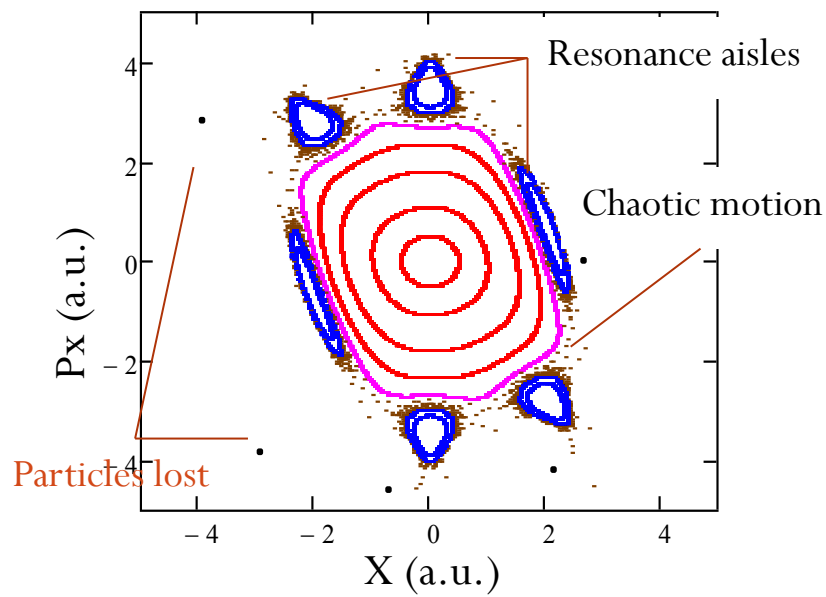
Phase space trajectories of perfectly linear 1D motion in normalized coordinates



Motivation: linear dynamics

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

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

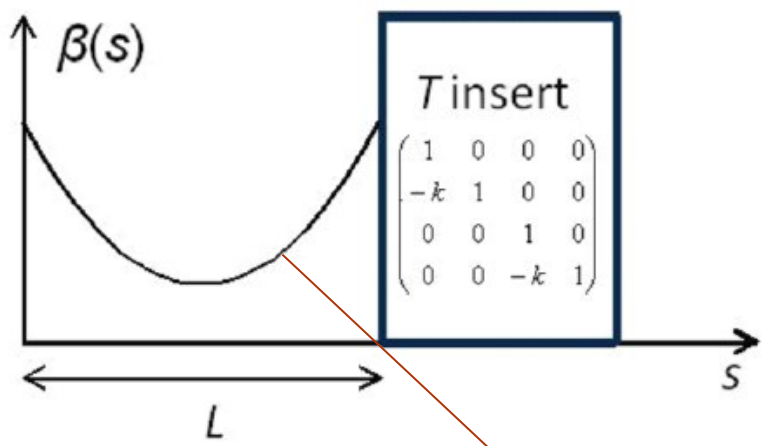


Motivation: nonlinear dynamics

- 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.

Nonlinear lattice with two invariants

- Danilov, Nagaitsev, Phys. Rev. ST Accel. Beams 13, 2010
- Element of periodicity:



Nonlinear potential, in elliptic coordinates

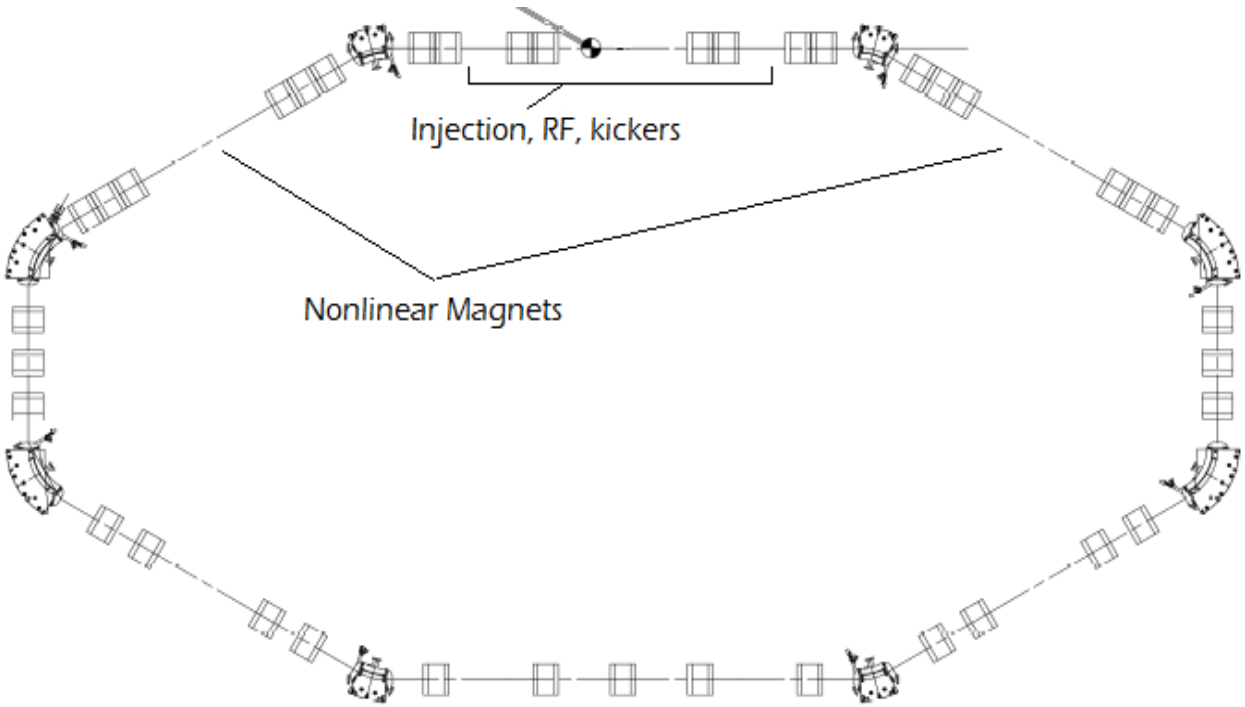
$$U(x,y) = \frac{f(\xi) - g(\eta)}{\xi^2 - \eta^2}$$

- Two invariants of motion:

  1) Hamiltonian

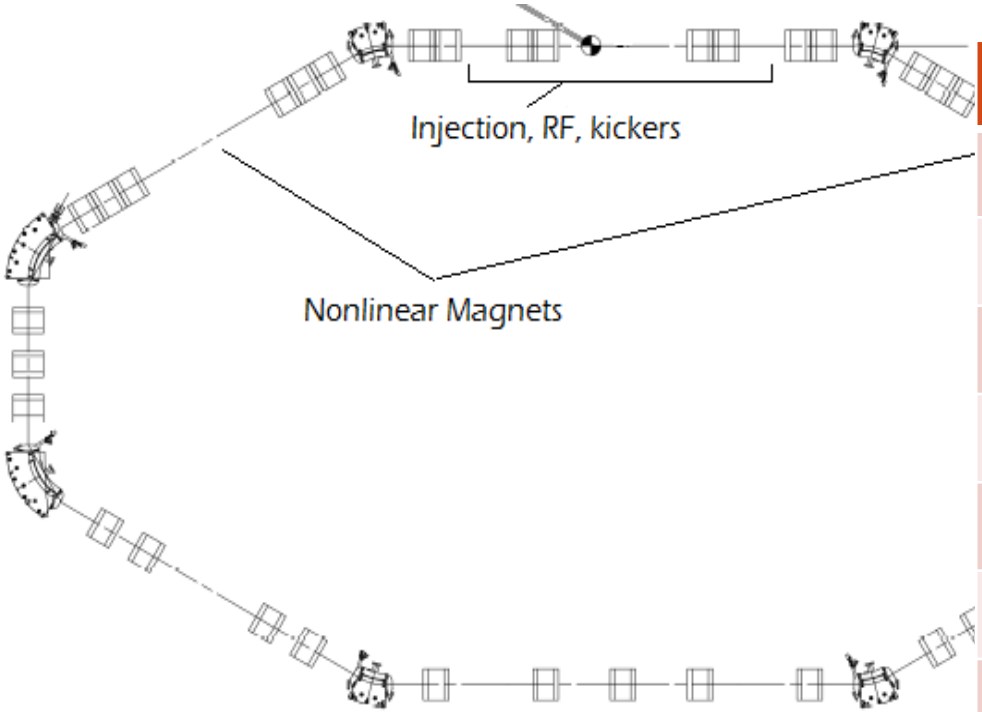
  2) $I_2(x,p_x,y,p_y)$

Integrable Optics Test Accelerator



- 40 m circumference
- 4 30° and 60° dipoles
- 39 quadrupoles
- 2 drifts for nonlinear magnets

IOTA parameters

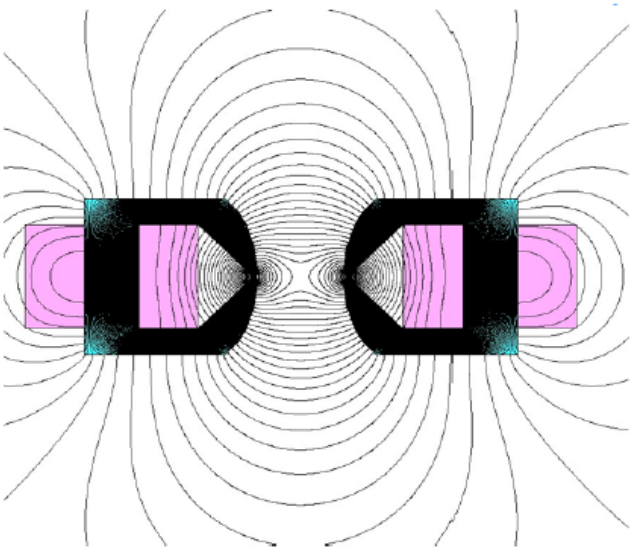


Electron Energy	150 MeV
Number of particles	10^9
Ring Circumference	40 m
Length of NL magnets	1.8 m
Phase advance per NL section	0.3
Synchrotron damping time	~ 1 sec
Equilibrium beam size	~ 0.1 mm
RF harmonic number	4
Bunch length	5 cm

Need a special magnet

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

Cross-section and field lines



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

Quasi-integrable Optics

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

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

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

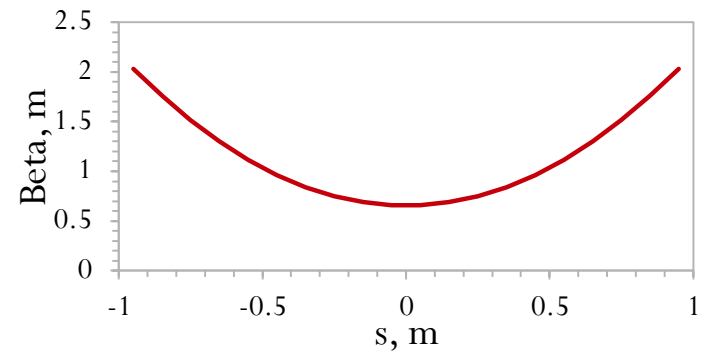
- Hamiltonian does not depend on s:

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

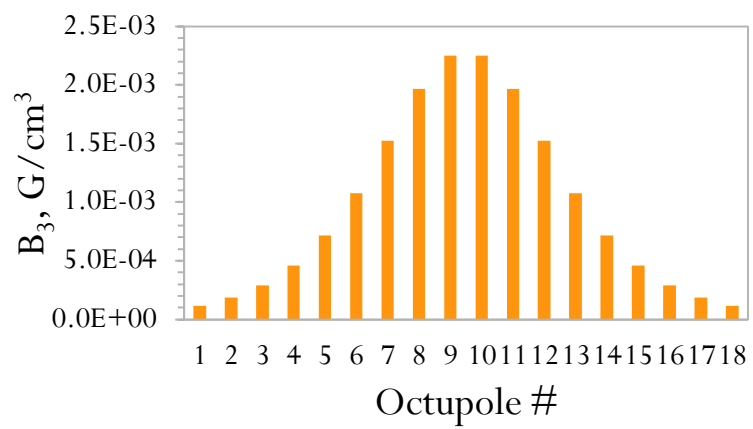
- Questions:
  - What about the 3rd degree of freedom?
  - Imperfections

- 6D Simulations required

Beta-function in NL magnet section



18 10cm-long octupole magnets

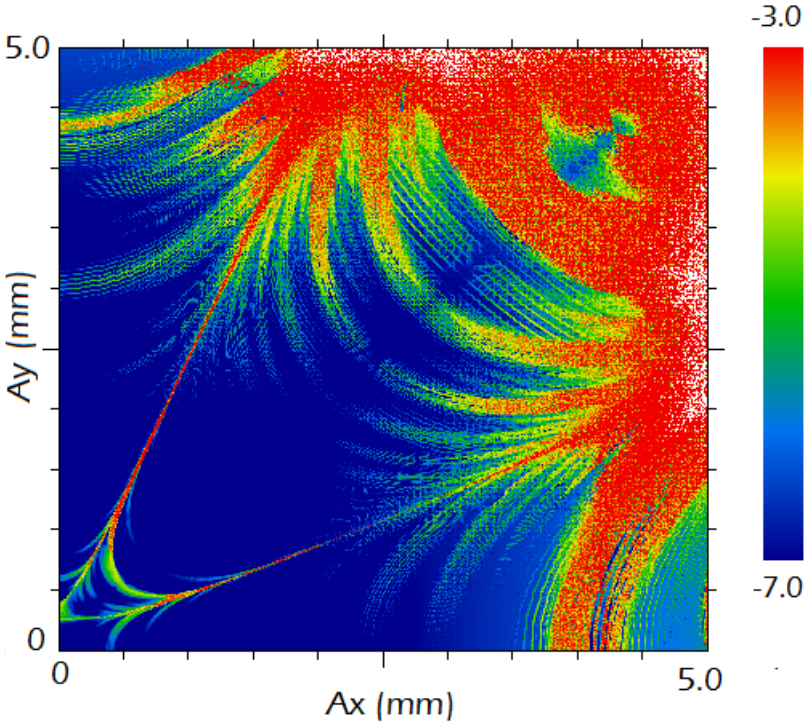


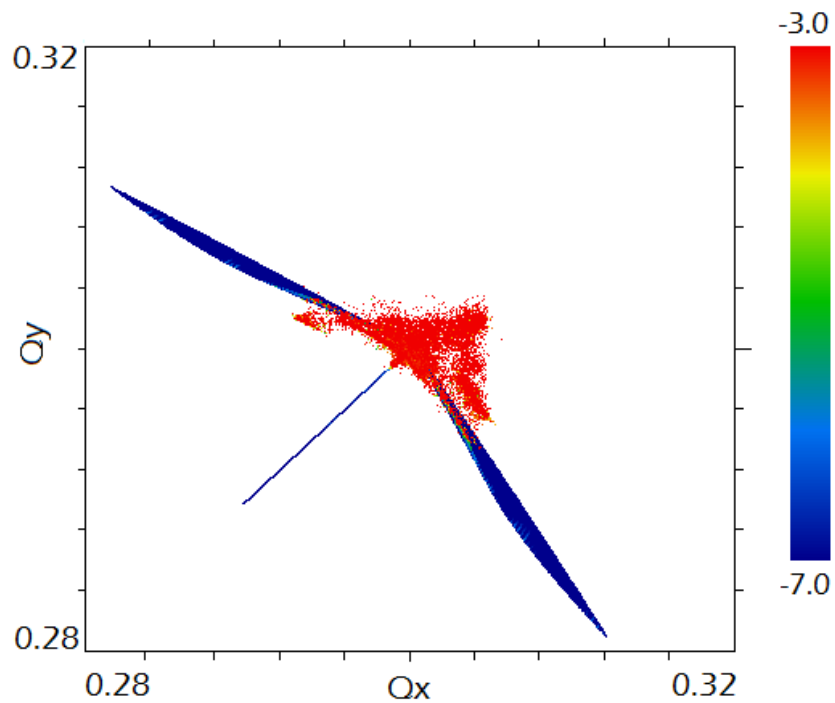
t = 0.4, c^2 = 0.01 cm, l = 10 cm

6D simulations

- Lifetrac code by D. Shatilov
  - Tracking
  - Frequency map analysis
- Model includes:
  - Dipoles, dipole fringe fields
  - Quadrupoles
  - RF
  - Octupoles
  - No sextupoles
- Betatron and synchrotron motion
- Chromaticity

Frequency map analysis: 1 section, octupole magnet





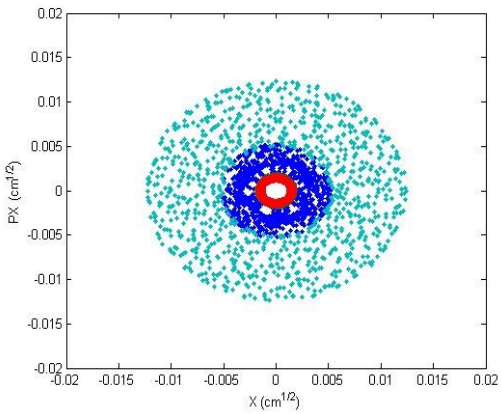
Stable region: 2.5 x 2.5 mm

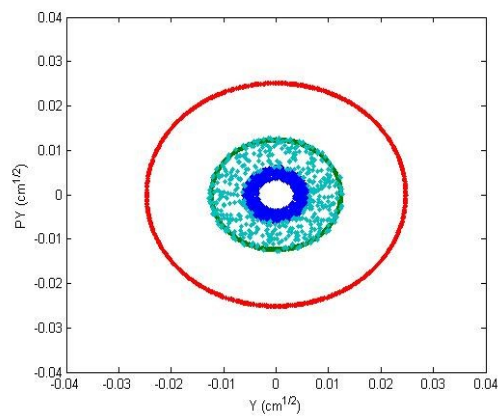
Tune spread: 0.03

Tracking

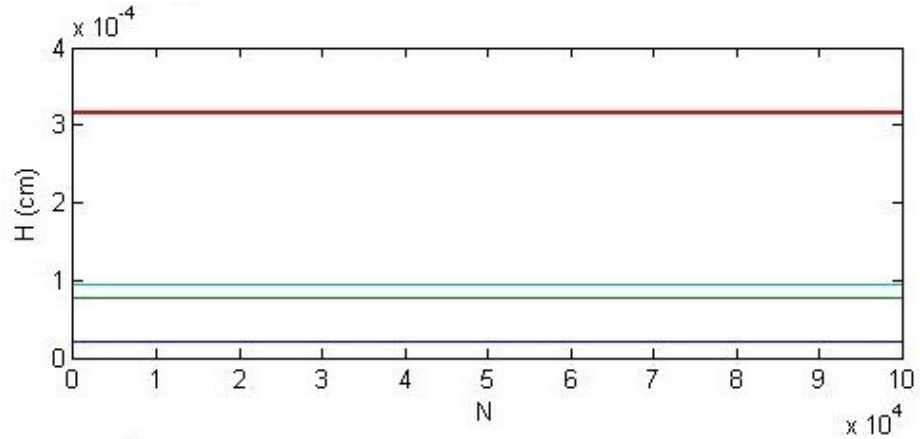
Simulated time – 1sec: no particles lost within stable region

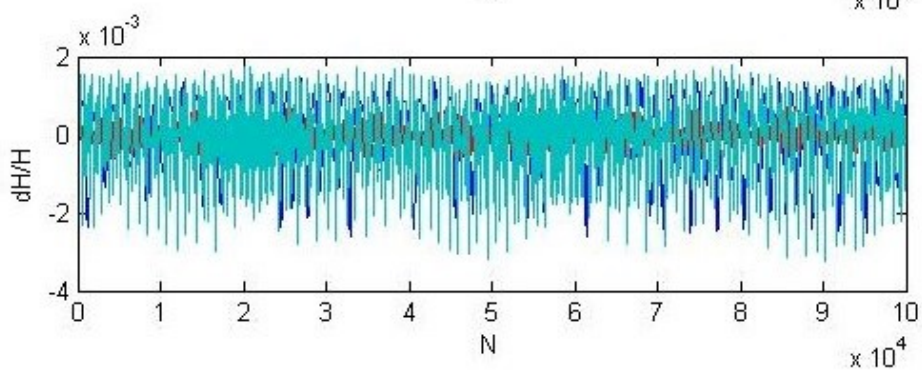
Motion is bounded



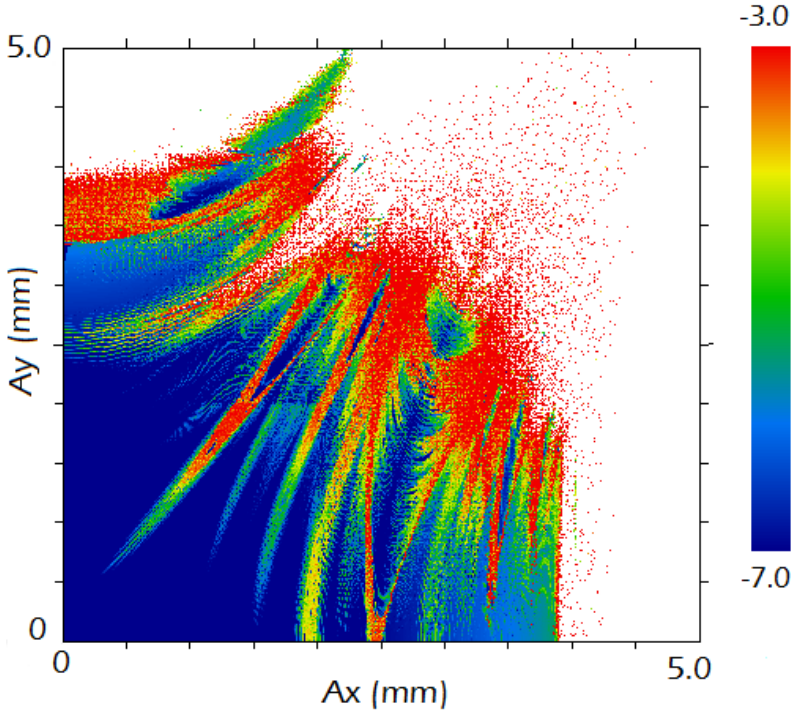


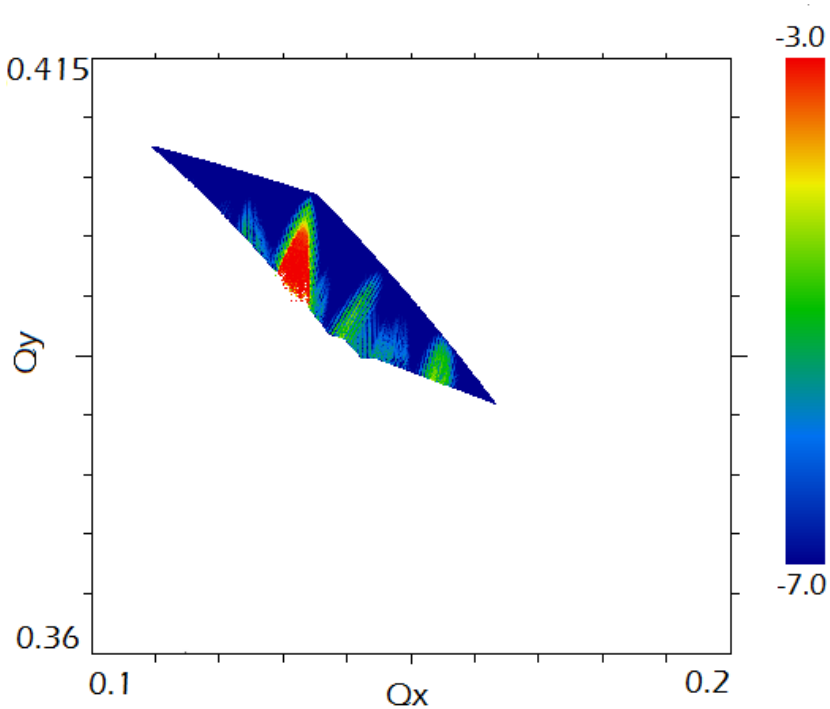
Hamiltonian is conserved





FMA: 1 section, quadrupole + octupole



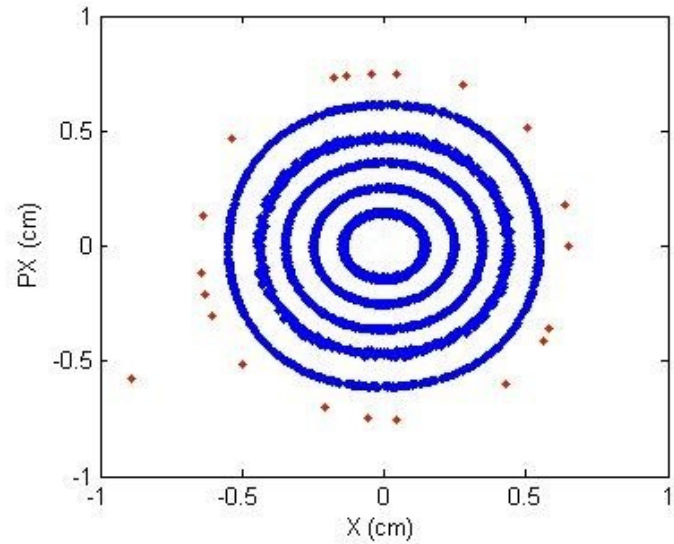


Stable region: 2.5 x 1.8 mm

Tune spread: 0.05

Experimental procedure

- Two kickers, horizontal and vertical, place particles at arbitrary points in phase space
- Measure beam position on every turn to create Poincare map $(x, y)_n$
- As electrons lose energy due to synchrotron radiation,
  they will cover all available phase space
- Can control the strength on the nonlinearity

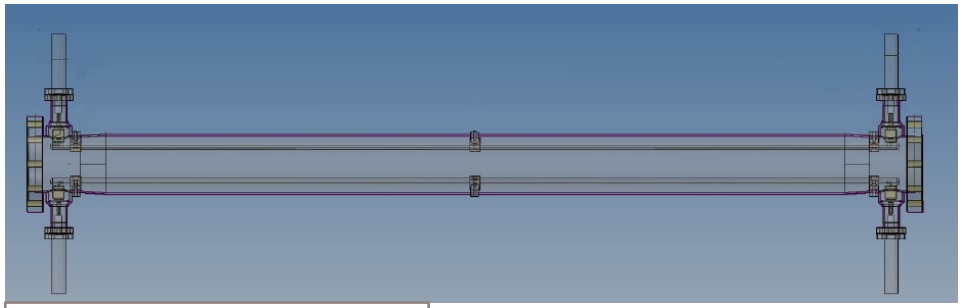


- Final goal – dependence of betatron frequency on amplitude

Two kickers create an arbitrary transverse kick

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

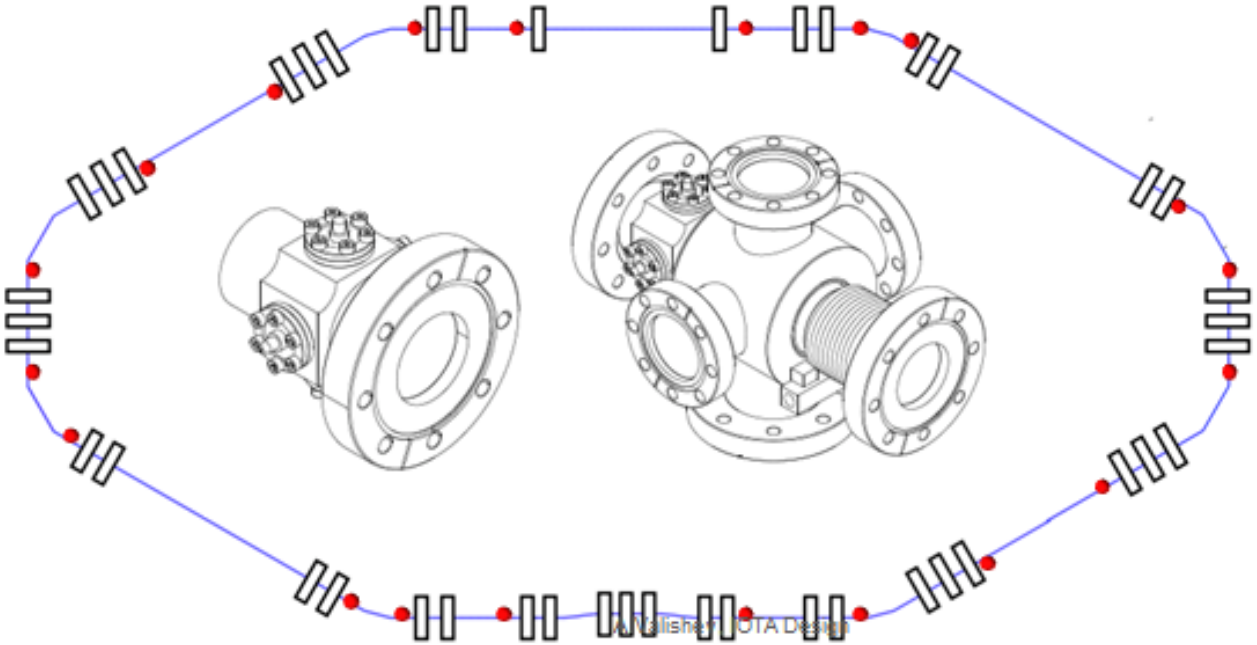
Voltage	± 25 kV
Radius:	
• Pipe	33 mm
• Plates	20 mm
Thickness:	
• Pipe:	2 mm
• Plates:	2 mm
Opening angle	70 deg
Edge rounding radius	3 mm
Wave impedance:	
• Odd mode	50 Ohm
• Even mode	55 Ohm
E-field in the center	12 kV/cm
Length:	
• Horizontal	55 cm
• Vertical	100 cm



Courtesy A. Didenko

Beam position can be measured precisely

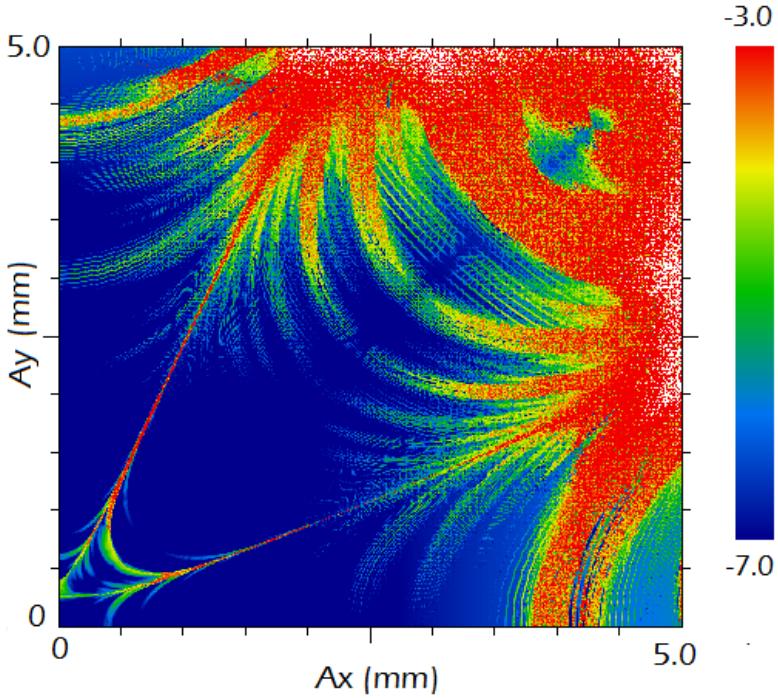
- 20 horizontal and vertical BPMs
  - Button type
  - 1 μm closed orbit resolution
  - 100 μm turn-by turn resolution
- 8 SR ports to measure beam size



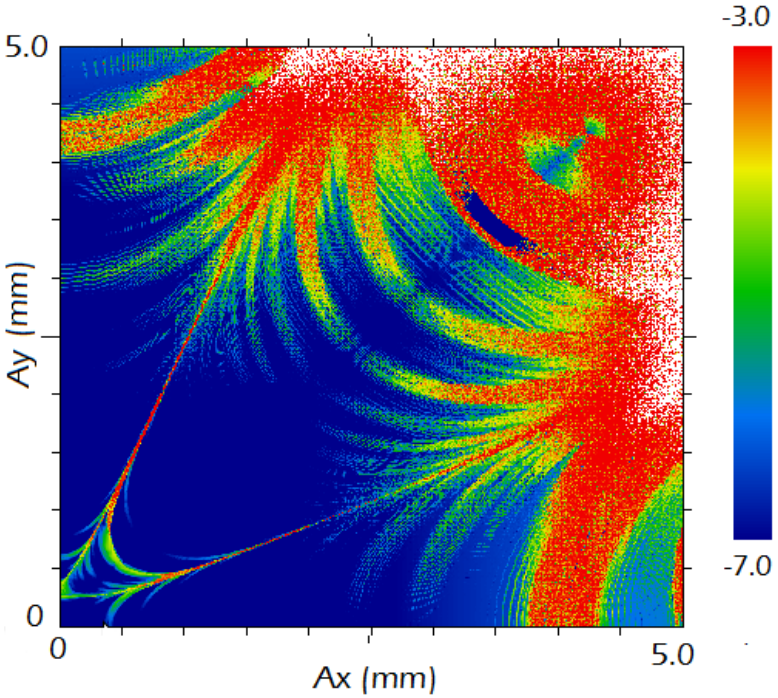
A. Valishev, IOTA Design

Octupole imperfections: stable region reduces insignificantly

No imperfections

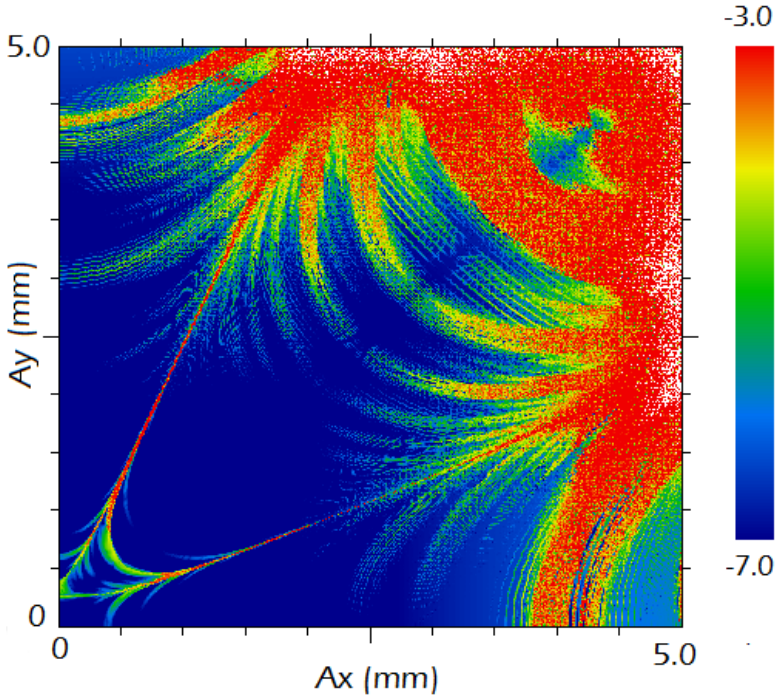


Octupole error, $\sigma = 0.1$

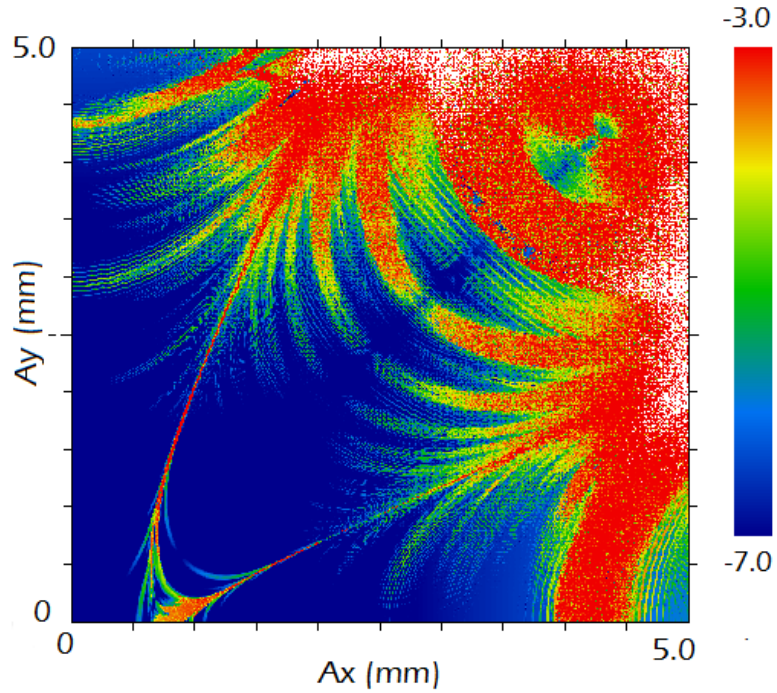


Lattice imperfections: stable region reduces insignificantly

No imperfections



$\Delta\beta = 1\%, \ \Delta\Phi = 3\cdot 10^{-3}$



Sources of error

- Lattice imperfections
  - Beta functions: 0.01 (relative)
  - Phase advance: 0.001
- Octupole magnet errors
  - Less than 0.1
- Bunch transverse size
  - ~ 0.1 mm, RMS
- Other:
  - BPM resolution
  - FFT
  - Energy loss

Overall: $\delta A \sim 0.1$ mm, $\delta Q \sim 10^{-3}$

Summary

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

Next steps

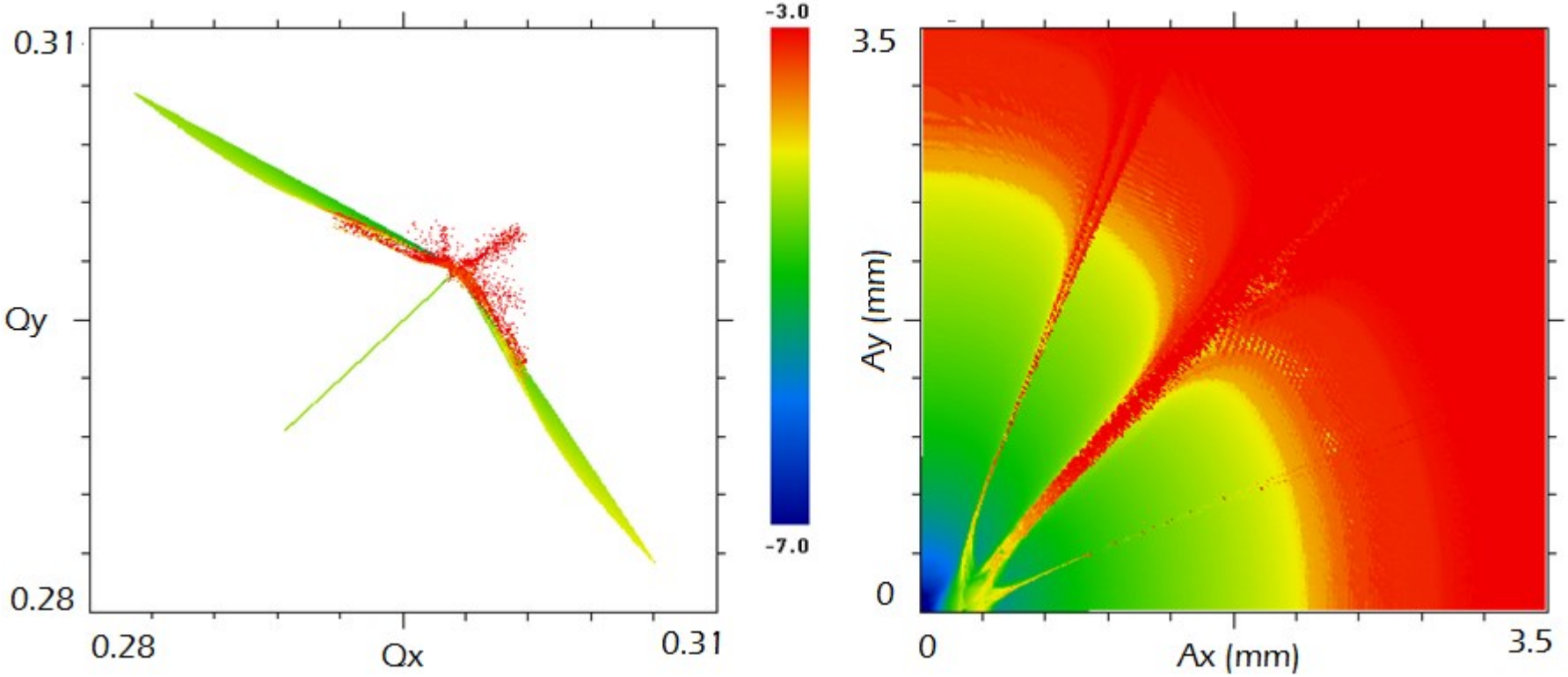
- Search for optimal combination in terms of tune spread/size of dynamic aperture/complexity of the potential
- Compare with full nonlinear potential

Thank You for Your Attention

Backup slides

Thick octupoles

- While dynamic aperture is limited, the attainable tune spread remains large



Courtesy A. Valishev

Optic functions in the nonlinear section

- Equal beta functions in x and y
- Zero dispersion