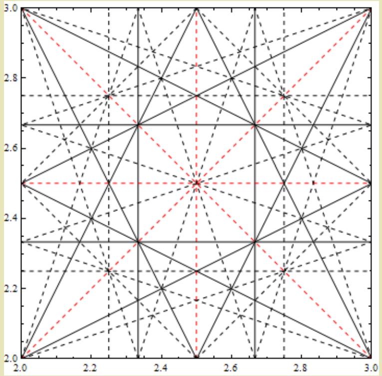
INSTITUTE FOR RESEARCH IN
ELECTRONICS
& APPLIED PHYSICS

Early tests and simulations of a quasi-integrable octupole lattice at the University of Maryland Electron Ring

Kiersten Ruisard, Heidi Baumgartner, Brian Beaudoin, Irving Haber, David Matthew, Timothy Koeth

Institute for Research in Electronics and Applied Optics,
University of Maryland, College Park

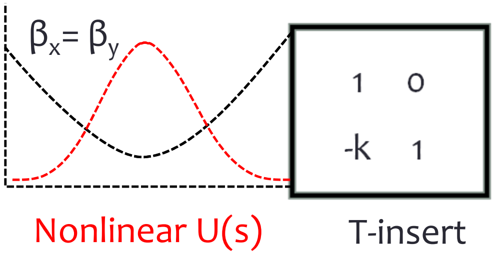
Nonlinear Integrable Optics



In linear lattice, tune resonances drive beam loss and halo formation.

Space charge has complex interaction with tune resonance

Danilov, Nagaitsev, Phys. Rev. ST Accel. Beams 13, 2010



Add (unspecified) nonlinear potential to Hamiltonian:

$$H = \frac{p_x^2 + p_y^2}{2} + K(s)\frac{x^2 + y^2}{2} + V_{NL}(x, y, s)$$

Choose U(x,y) to be independent of s, H is conserved

For integrability, find U(x,y) that gives second invariant and satisfies Laplace's equation

Recall U(x,y) must be independent of s in *normalized particle frame*

$$x_N = x \Big/ \sqrt{\beta(s)} \qquad p_{x,N} = p_x\sqrt{\beta(s)} - \frac{\beta'(s)\,x}{2\sqrt{\beta(s)}}$$

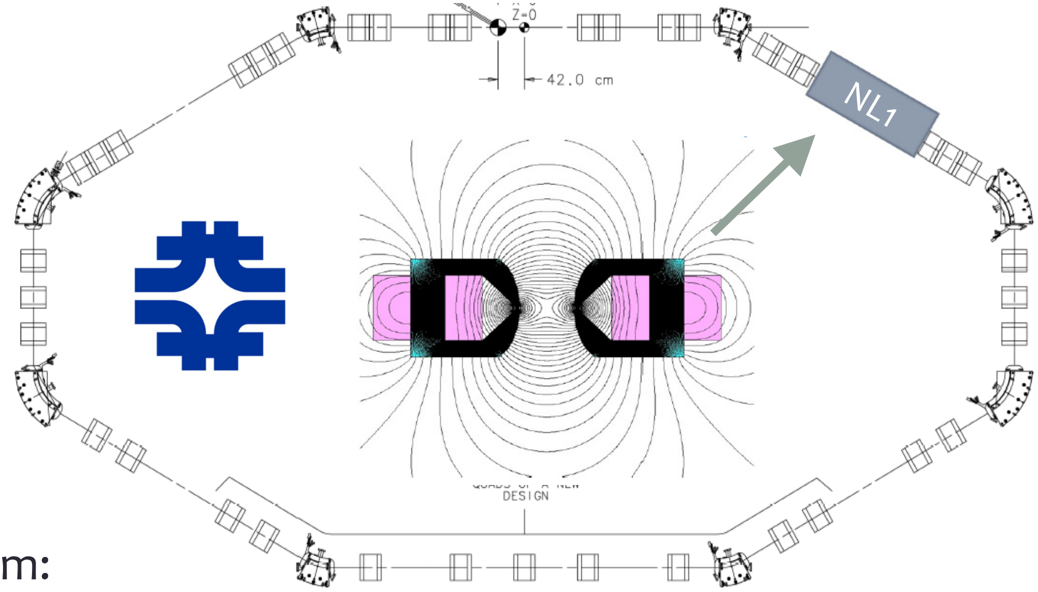
Nonlinear field V in lab frame must scale with envelope function:

$$U(x_N, y_N) = \beta(s)\,V\left(x_N\sqrt{\beta(s)}, y_N\sqrt{\beta(s)}, s\right)$$

Normalized Hamiltonian is conserved!

Integrable Optics Test Accelerator

Test quasi- and fully integrable lattices
Achieve high tune shift 0.25
Under construction
150 MeV electron beam,
2.5 MeV proton beams

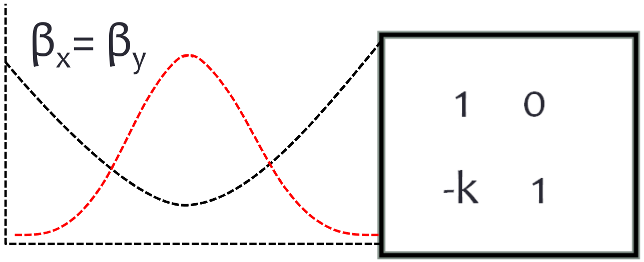


Quasi-integrable Octupole lattice with octupole potential in this form:

$$V(x,y,s)=\frac{1}{\beta^{3}(s)}\frac{\kappa}{4}\left(x^{4}+y^{4}-6x^{2}y^{2}\right)$$

Leads to 1 invariant of motion:

$$H_N=\frac{1}{2}\left(p_{x,N}^2+p_{y,N}^2+x_N^2+y_N^2\right)+U(x_N,y_N)$$



Octupole strength T-insert

University of Maryland Electron Ring

System Parameters

Beam Length 20-140ns

Circulation Time 197ns

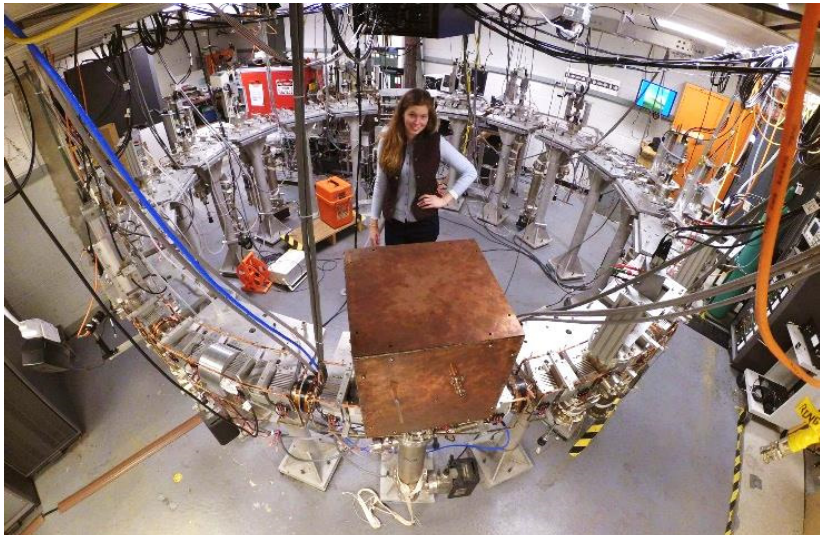
Circumference 11.52 m

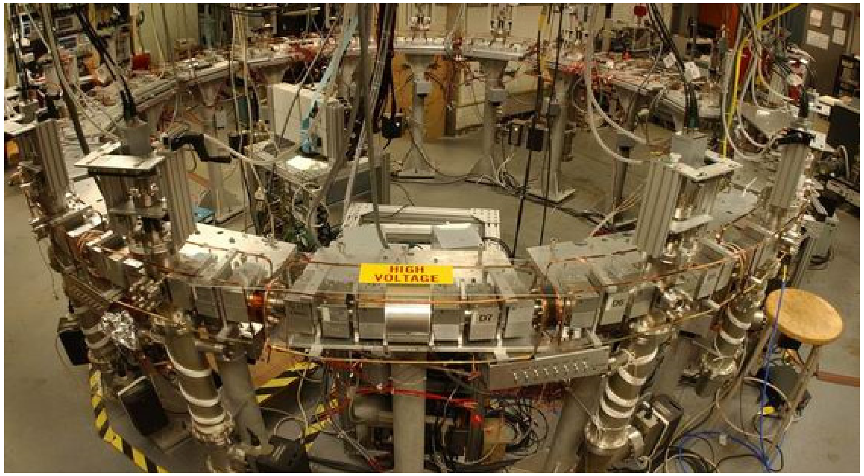
Beam energy 10 keV

Beam current 0.6 - 100mA

Beam radius 0.25 - 10mm

Tune $\nu_x \sim \nu_y \sim 6.6$





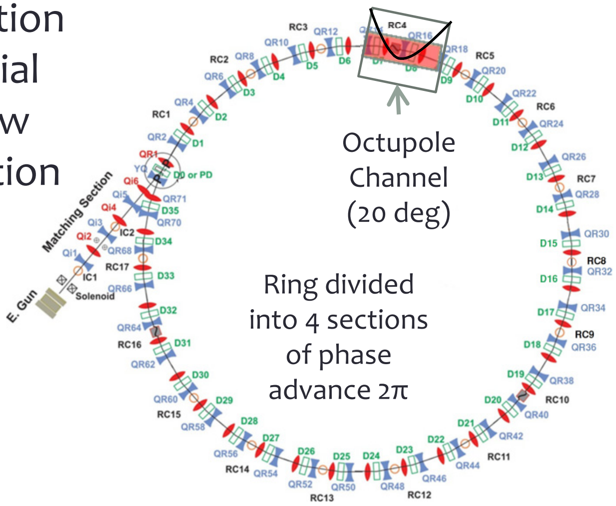
$$\frac{\nu}{\nu_o} = 0.85 - 0.14$$

We (typically) operate in high intensity, “extreme” space charge regime

Two pathways to quasi-integrability

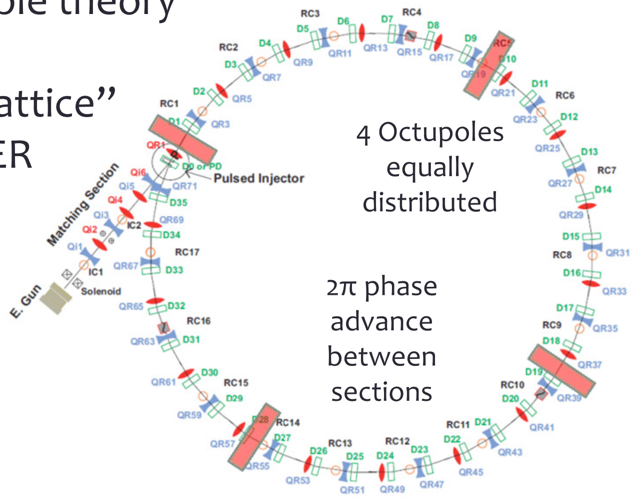
Single Channel:
- IOTA-like
- Meets requirements of H conservation
- Needs special mounts, new lattice solution
- The deep unknown

Distributed Octupoles:
- Quick and easy
- Perhaps it will work?
- Approximation to quasi-integrable theory
- Uses FODO "alternative lattice" mode of UMER



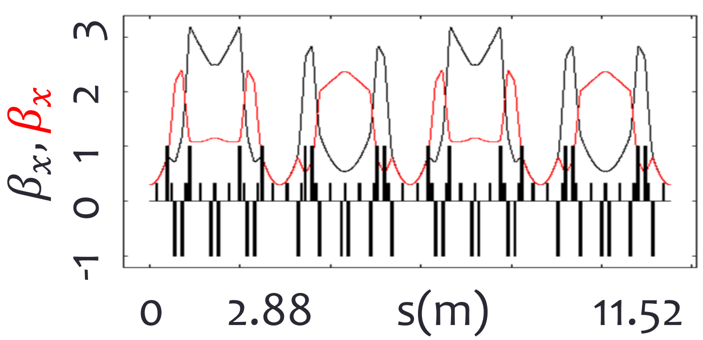
Octupole Channel (20 deg)

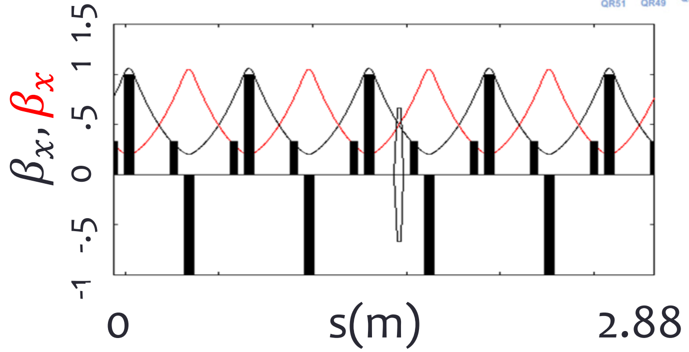
Ring divided into 4 sections of phase advance 2π



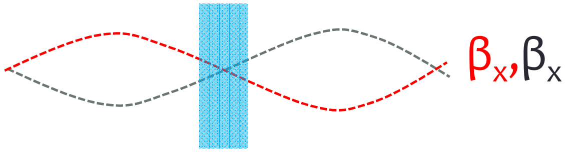
4 Octupoles equally distributed

2π phase advance between sections





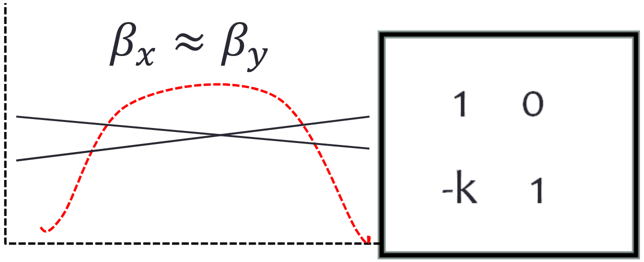
Distributed Octupole Lattice



$\beta_x \approx \beta_y$ in dipole

$$\Delta\Psi_{oct} \approx 0.07 * 2\pi$$

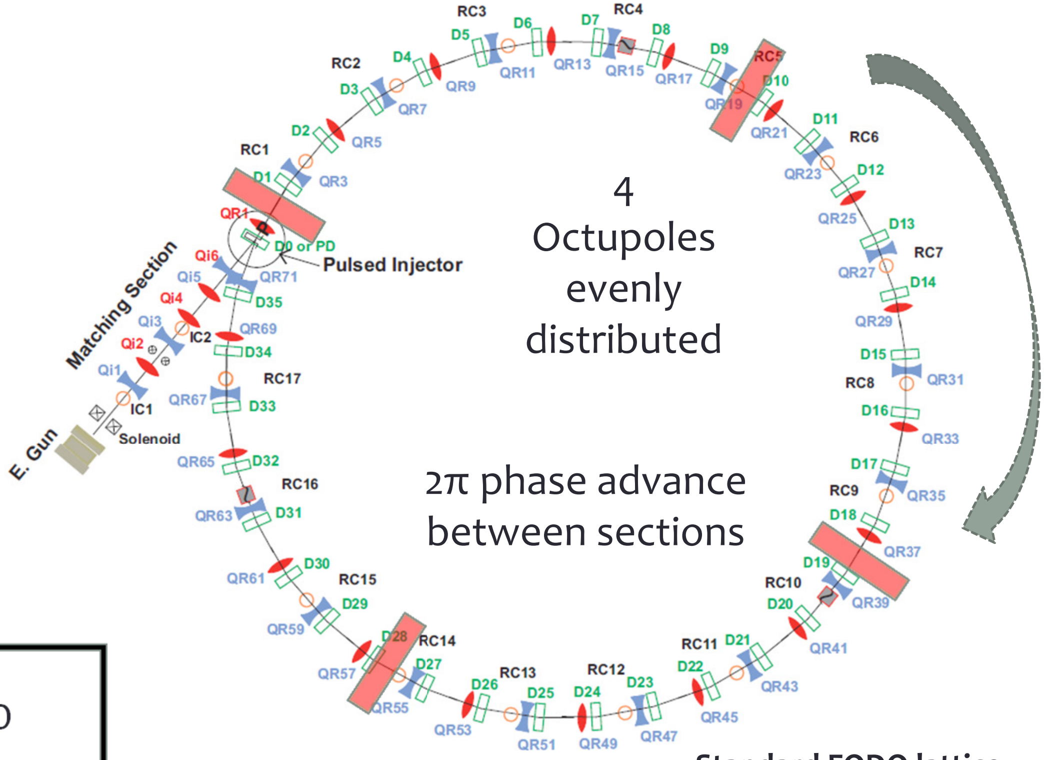
$$\Psi_{ring} = 4.07 * 2\pi$$



$$\begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix}$$

Octupole strength

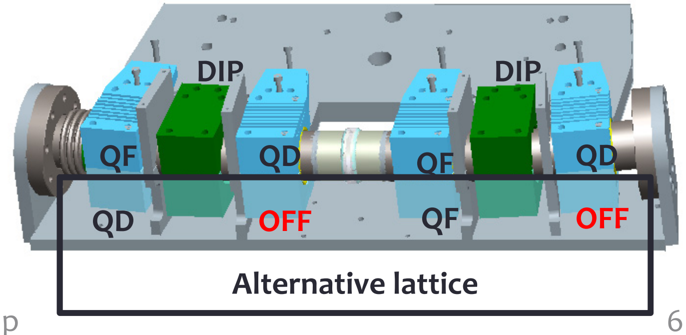
T-insert



4 Octupoles evenly distributed

2π phase advance between sections

Standard FODO lattice:

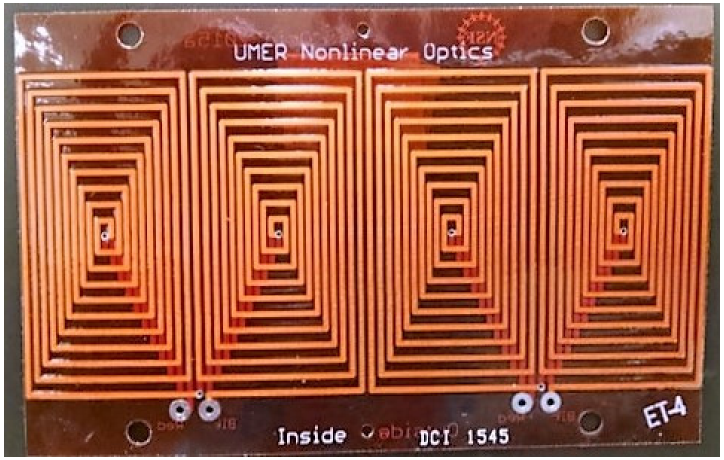


Alternative lattice

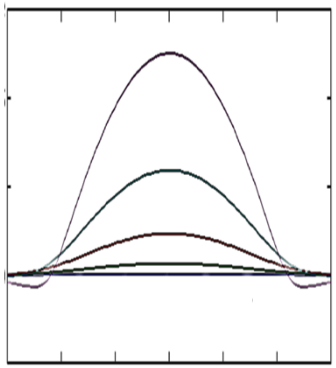
Printed Circuit Octupoles

Manufactured October 2015, peak field ~ $75\ T/m^3/A$

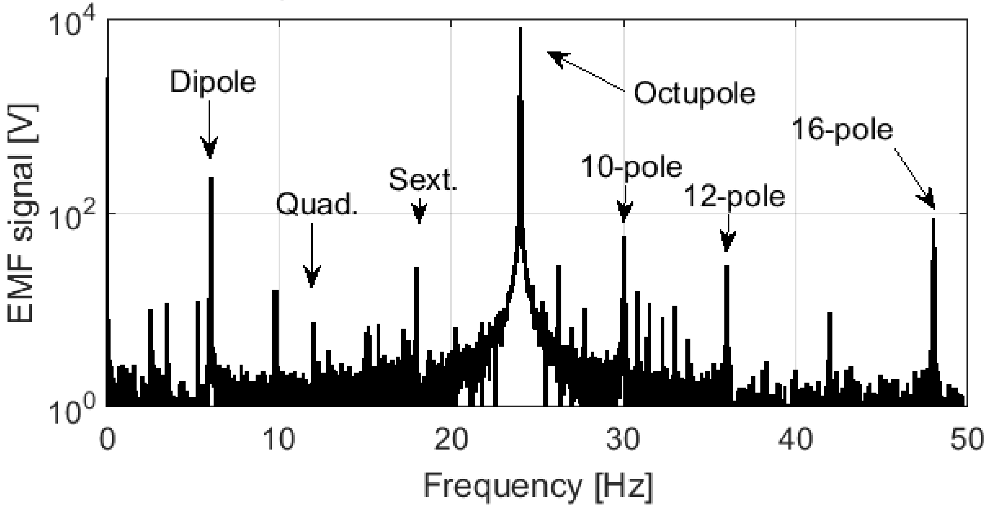
Half of UMER octupole



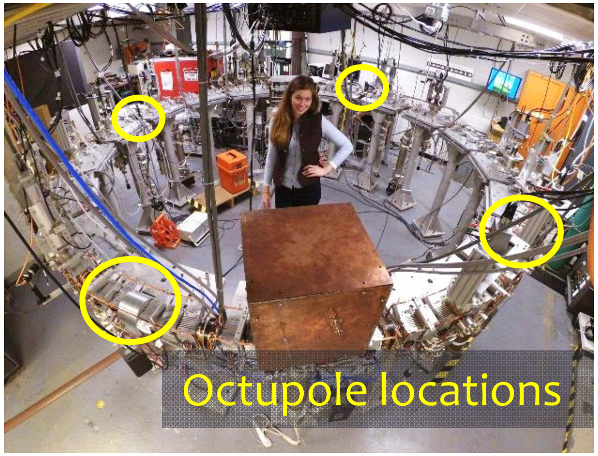
Maxwell 3D prediction for longitudinal profile



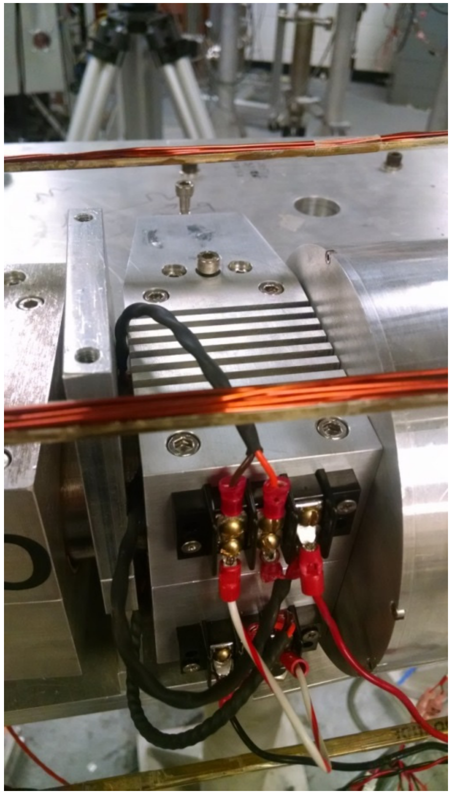
Rotating coil data



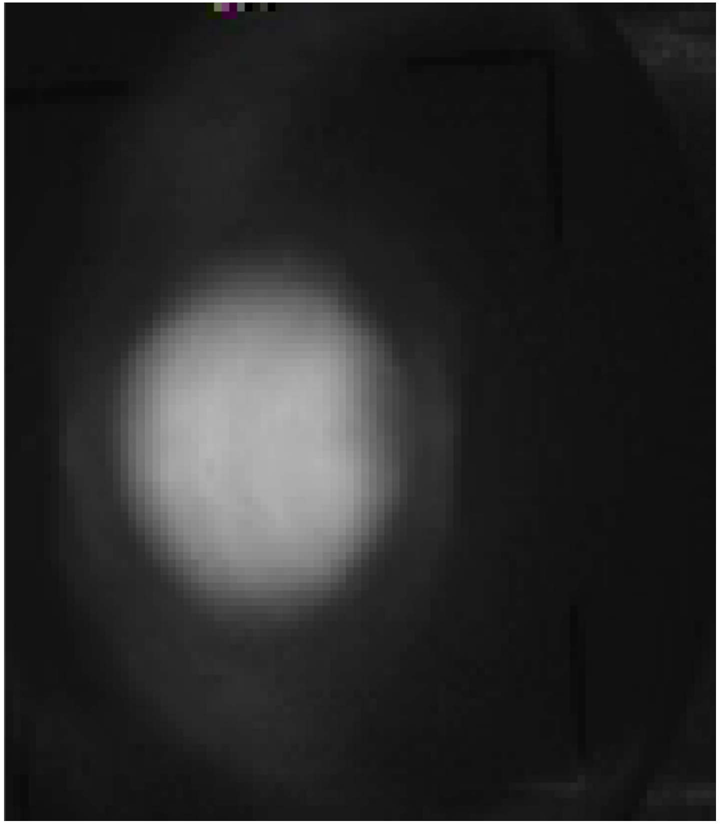
Octupoles installed for distributed lattice



Jan. 2016

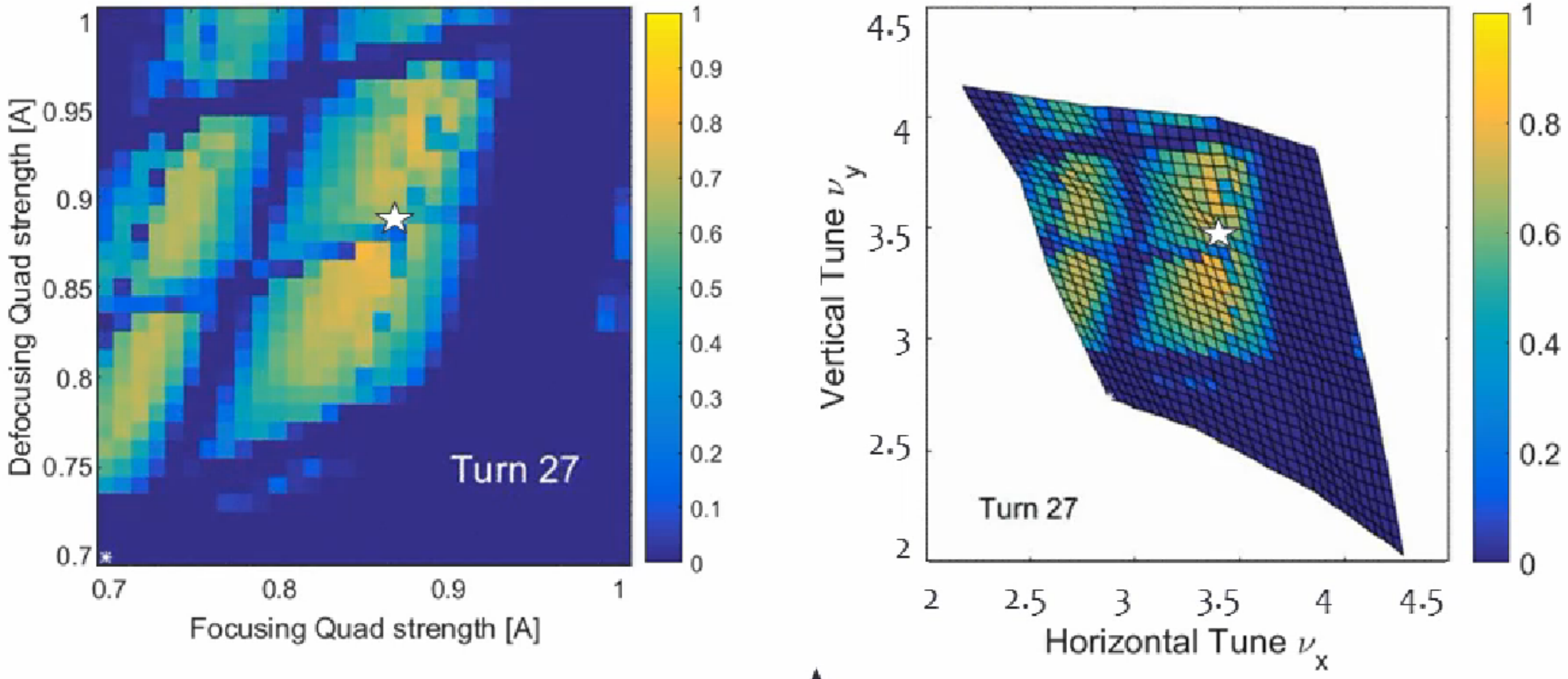


First beam through octupoles



Alternative Lattice Tune Scan Measurement

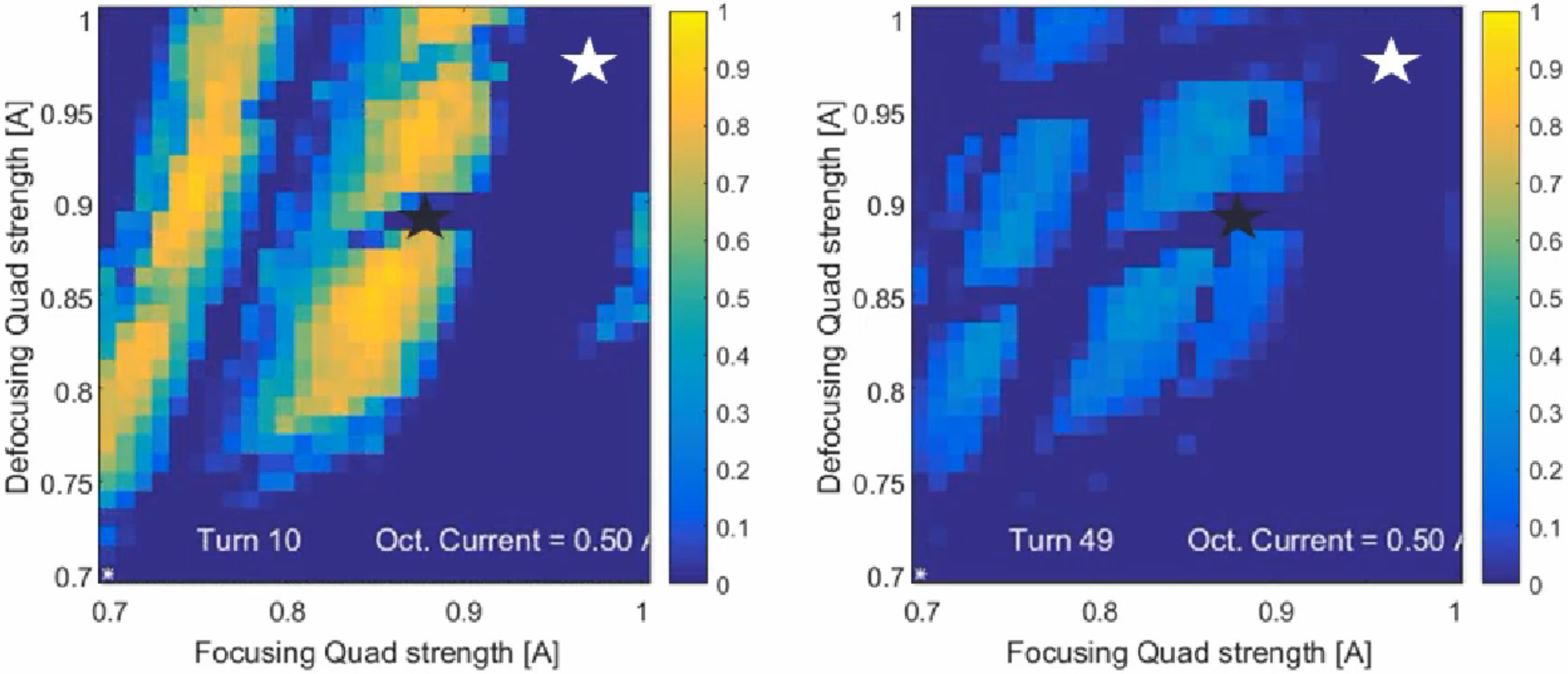
Measurements taken Feb. 2016. with pencil beam
Beam survival plots, Alternative lattice, no octupole fields. (Yellow=transmission, Deep blue= all beam lost)



★ Nominal Operating Point

Octupole Lattice Tune Scan

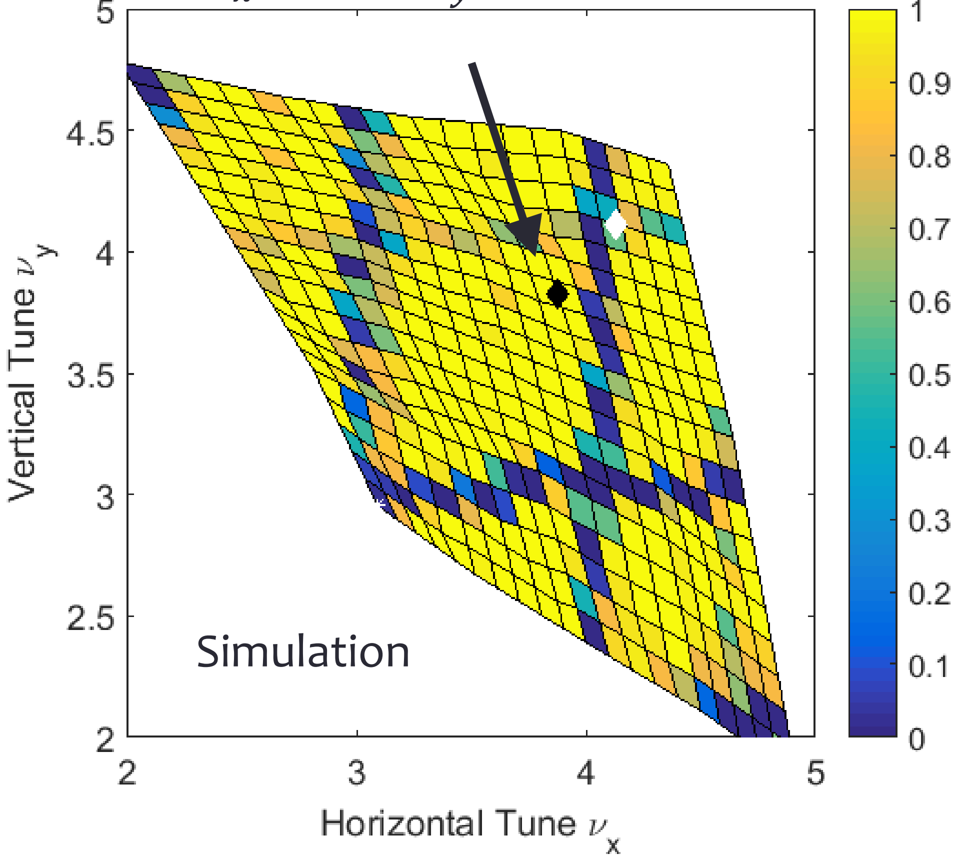
Measurements taken Feb. 2016. with pencil beam
Beam survival plots with octupole fields. (Yellow=transmission, Deep blue= all beam lost)

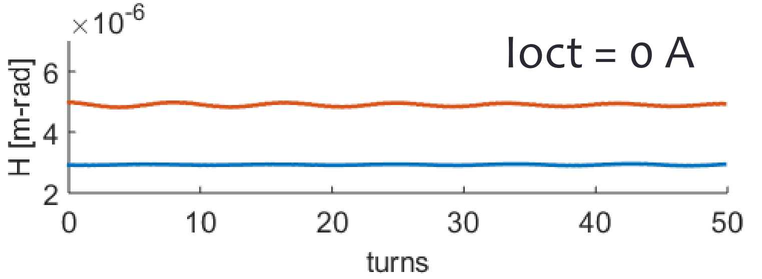


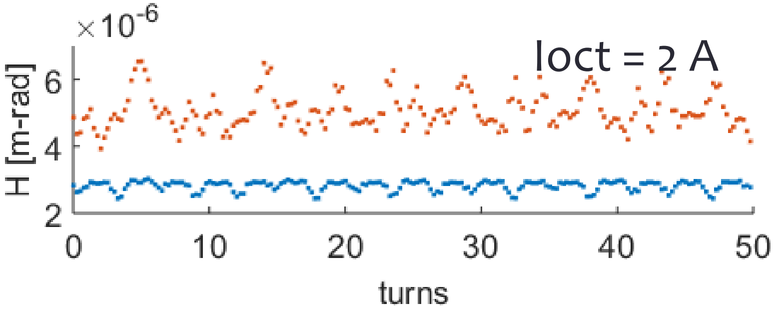
★ Nominal Operating Point (tuned up beam to here)
☆ Desired Operating Point (near 2π phase advance)

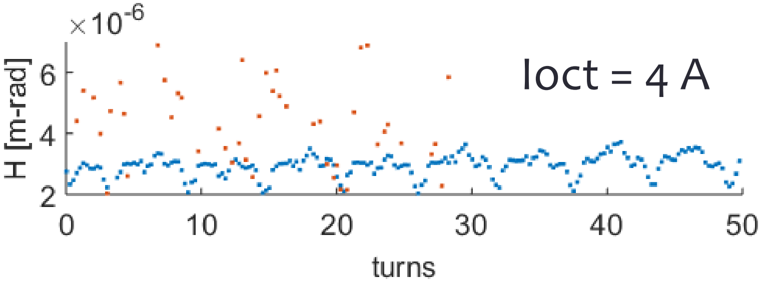
WARP simulations of octupole lattice

$\nu_x = 3.88, \nu_y = 3.83$

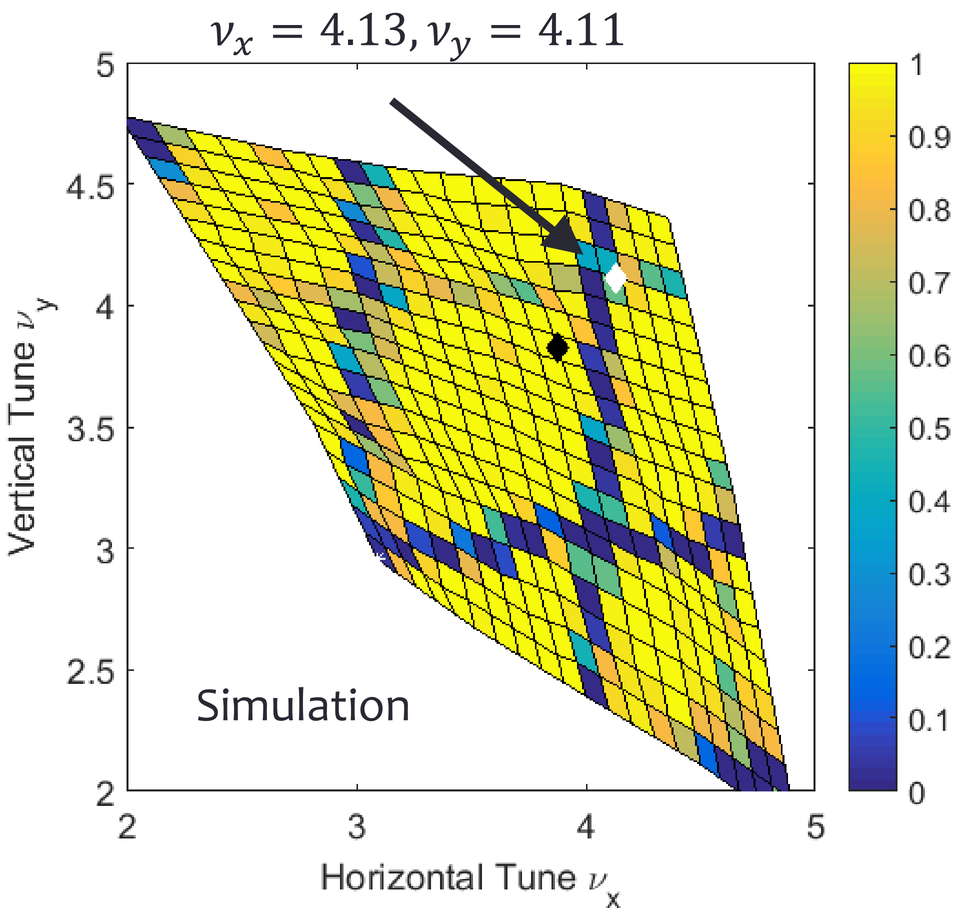




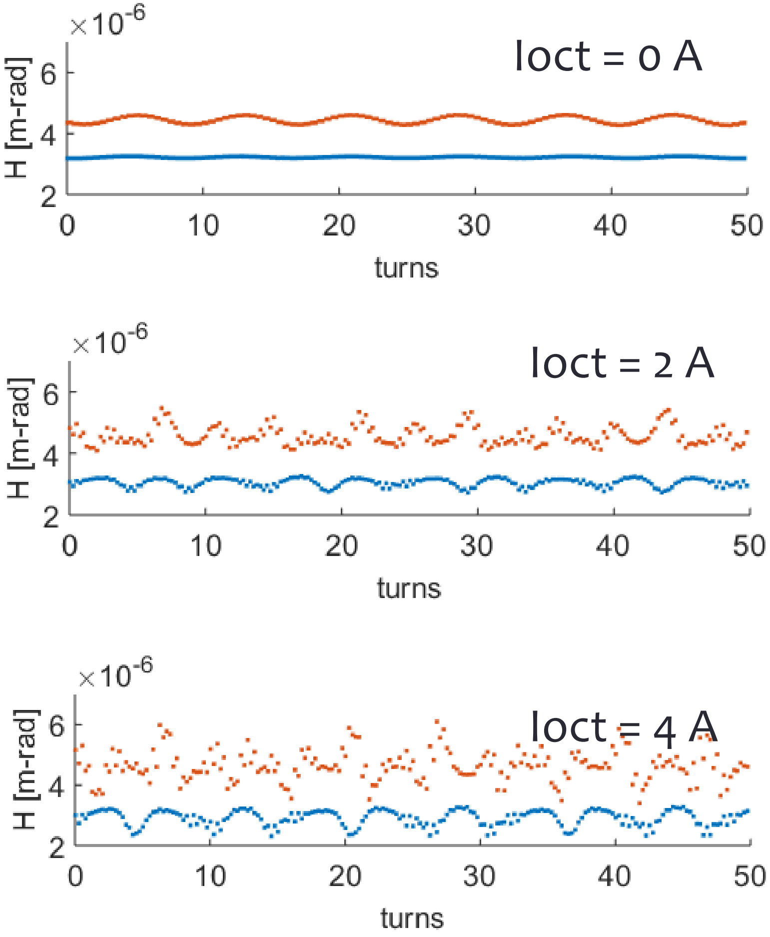




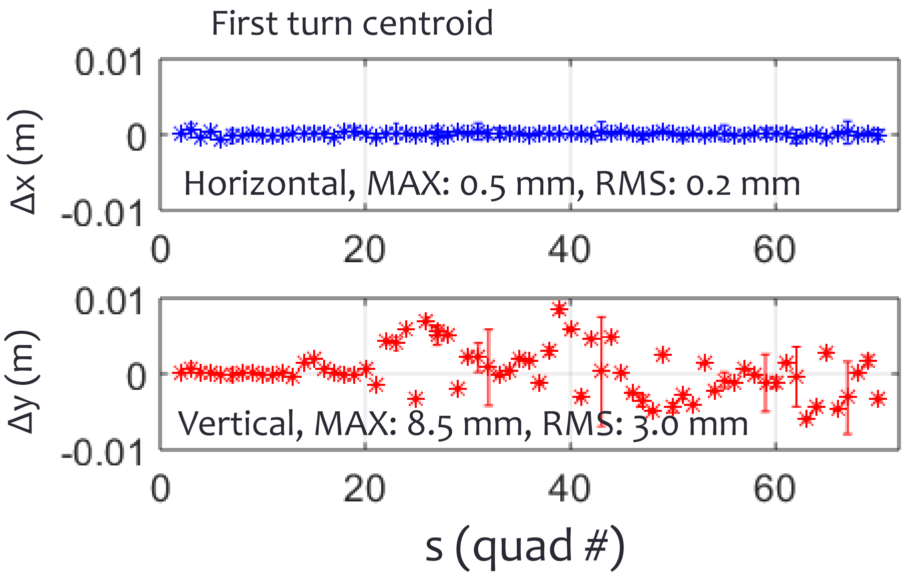
WARP simulations of octupole lattice



$\nu_x = 4.13, \nu_y = 4.11$

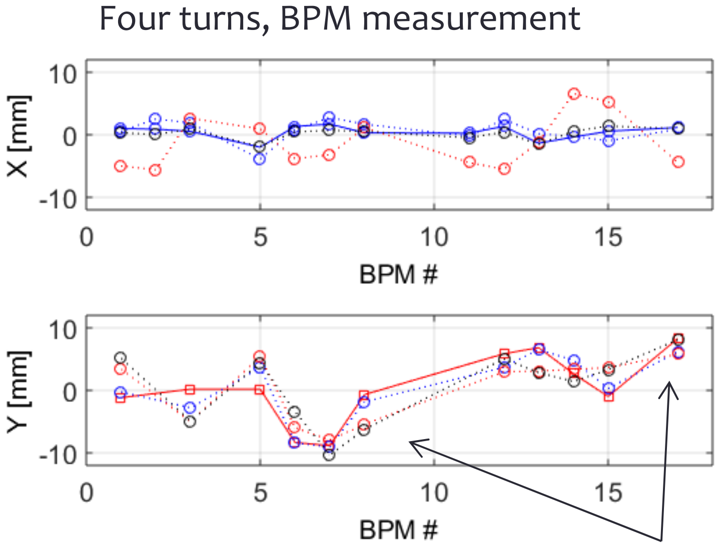


Error Sources


First turn centroid

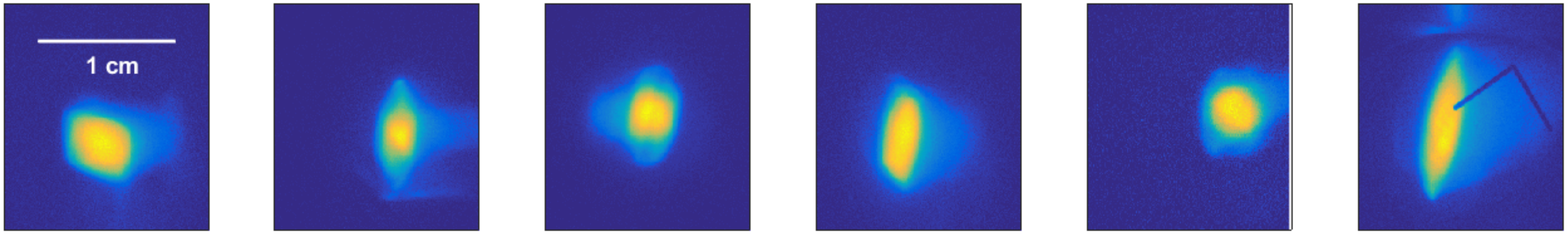
Horizontal, MAX: 0.5 mm, RMS: 0.2 mm

Vertical, MAX: 8.5 mm, RMS: 3.0 mm


Four turns, BPM measurement

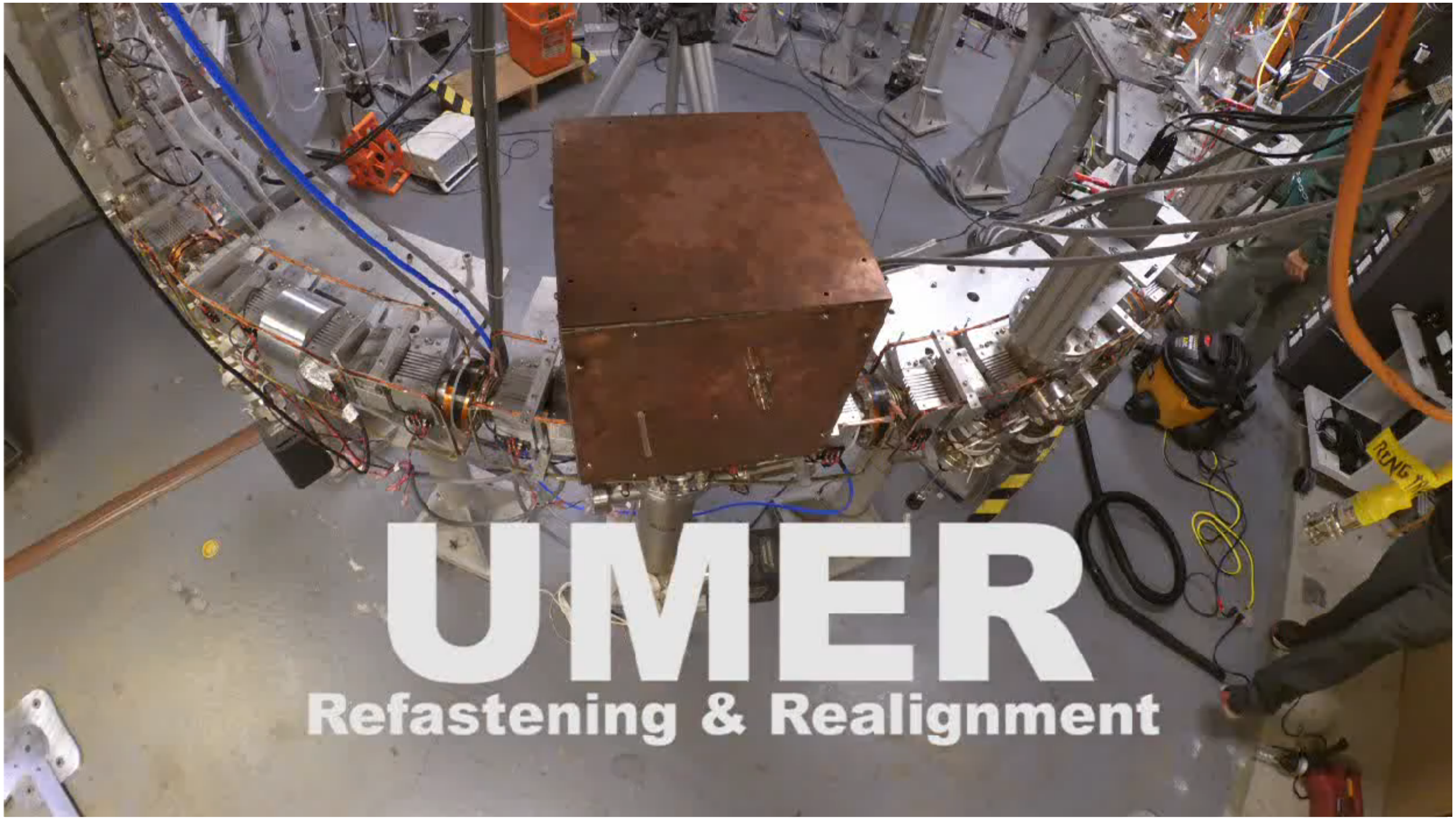
Additional vertical correctors necessary

First turn beam profile measurements for 0.6 mA “pencil” beam



Ring Improvements

Longest vacuum break in UMER operational history: Feb. 23 – Jun 17.



Ring Improvements

Longest vacuum break in UMER operational history: Feb. 23 – Jun 17.

Credits:

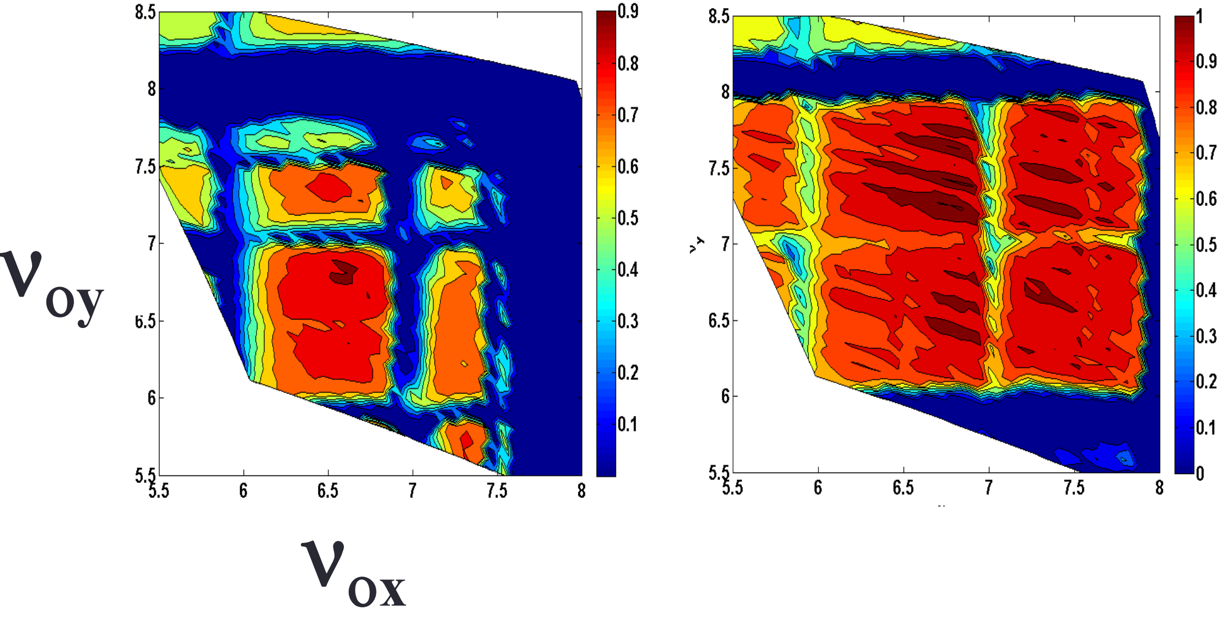
Heidi Baumgartner (producer)
Fermilab IOTA group (manufactured floor hole template)

Labor and planning:
Dave Sutter
Eric Montgomery
Brian Beaudoin
Santiago Bernal
Tim Koeth
Rami Kishek
Irving Haber
Dave Matthew
Ana
Matt Teperman
Kiersten Ruisard

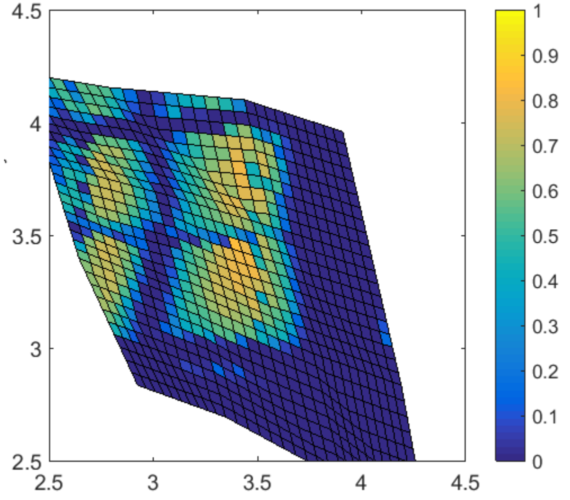
Ring Improvements

Improvement to dynamic aperture after fixing “dogleg” misalignment (40 deg. of ring misaligned up to 8 mm in quadrupole position)

10th turn beam survival plots for 6 mA beam in standard FODO lattice (2011 data):



Hope for the alternative lattice (2016 data)?



Final Thoughts

- A distributed octupole lattice was tested
- Intuition gained "in hindsight," effects seems not be large enough to stand out above lattice errors/integer stop band
- Recently completed ring re-anchoring and re-alignment, as well as improved vertical steering, may improve signal in region of interest.
- Space charge effects still open question, "low-current" beam (60 μA) may fare better
- Priority: keep pressing forward with mechanical design for single-channel lattice.

Acknowlegements:

- The UMER group (Rami Kishek, Santiago Bernal, Dave Sutter, Eric Montgomery)
- IOTA collaboration, especially Sergey Antipov, Sasha Valishev, Sergei Nagaitsev, David Bruwhiler, Stephen Webb

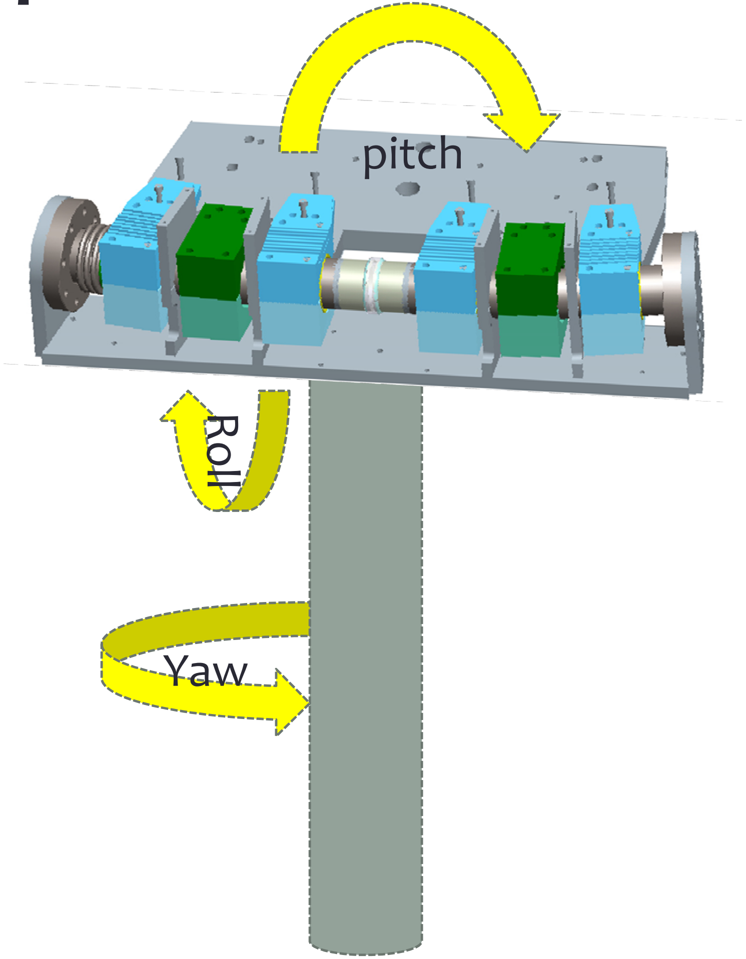
UMER beams and diagnostics

I [mA]	ε_n,rms [mm]	a_{ave} [mm]	s/s_o	c_s/v_o
0.6	0.4	1.6	0.85	0.005
6.0	1.3	3.4	0.62	0.013
21	1.5	5.2	0.32	0.022
78	3.0	9.6	0.17	0.033
104	3.2	11.1	0.14	0.035

Diagnostic	Quantity	Location	Measured Characteristic
Bergoz Current Monitor	1	Injection Line	Current vs. Time
Wall-Current Monitor	1	RC10	Current vs. Time
Beam Position Monitor	15	IC2 and 14 ring chambers	Position / Current vs. Time
YAG Crystals	1	RC17	Beam imager
Fast Screens	4	IC1 + RC3, 8, 14	Beam imager (time-resolved)
Slow Phosphor Screens	12	IC1, IC2 + Remaining RCs	Beam imager
Turn-by-turn imager	3	RC3, 8, and 14	Beam imager after Turn 1
Energy Analyzer	1	RC15	Energy profile and spread vs. time
Tomography	16	In combination with any screen	Transverse phase-space / emittance
Halo Monitor	16	In combination with any screen	High-Dynamic Range Halo Profile

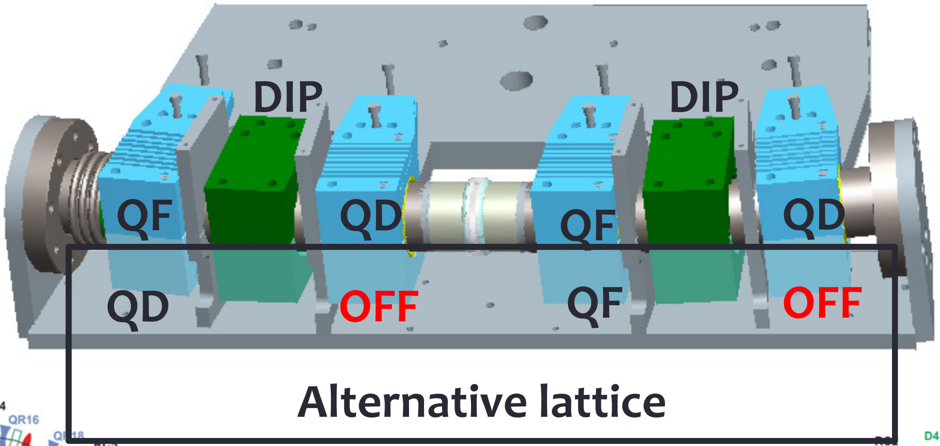
UMER realignment parameters

Axis	Goal tolerance	Met?
Transverse, radius	0.125 µm	No, currently 0.600 µm
Transverse, height	0.125 µm	Yes
Longitudinal	0.500 µm	Yes (for 70 % of ring)
Roll	0.5 mrad	Yes
Pitch	0.5 mrad	Yes (all but 1 section)
Yaw	0.5 mrad	Only for half the ring

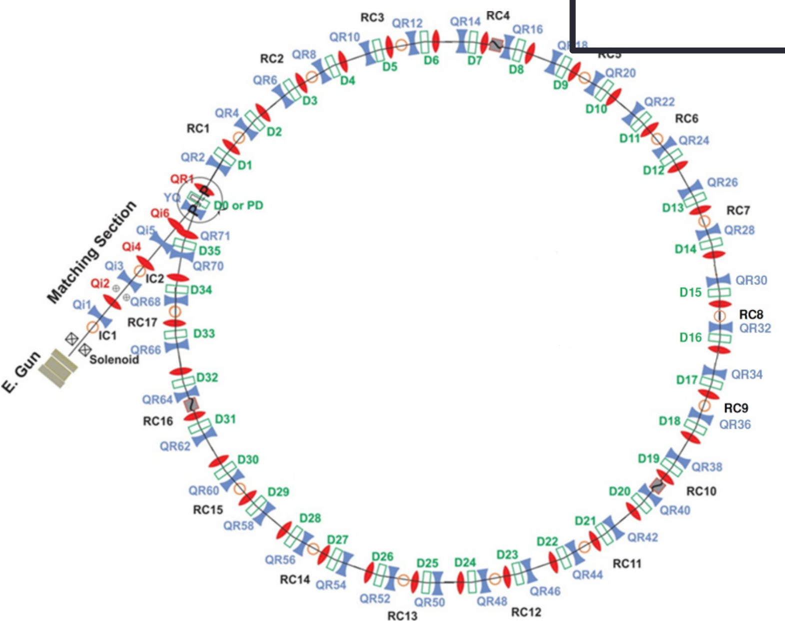


UMER Alternative Lattice

Standard FODO lattice:

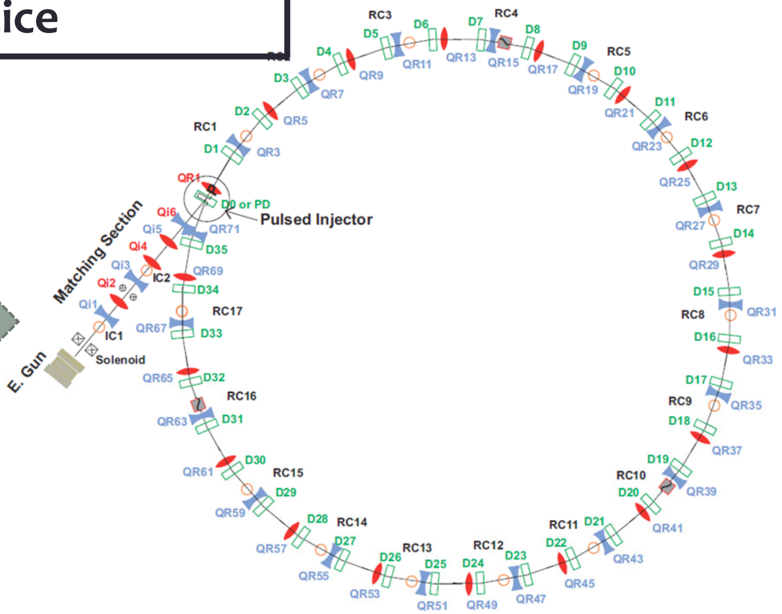


Alternative lattice

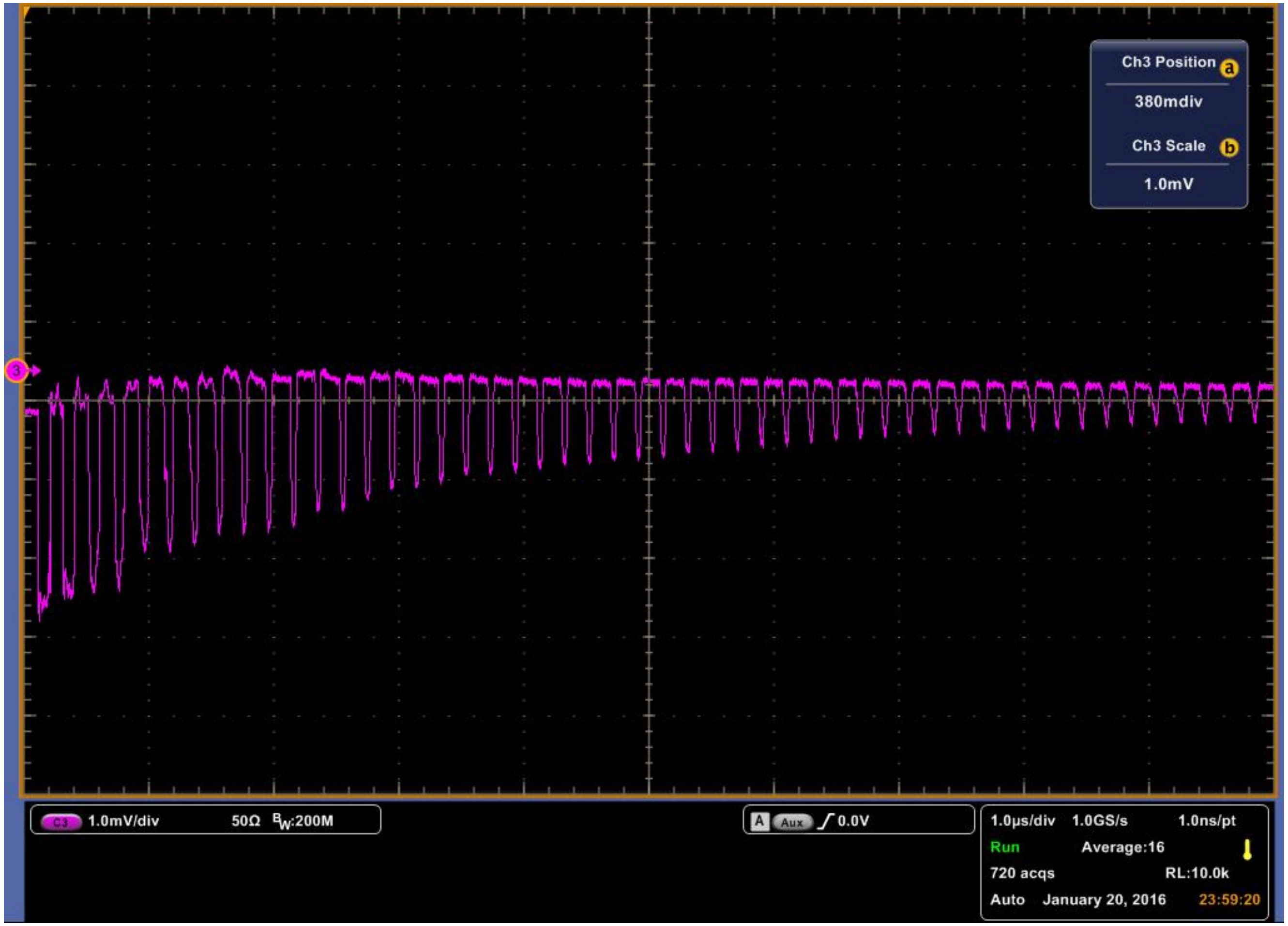


Turn off half of quads

(36 ---> 72)



Pencil beam at nominal operating point, wall current monitor



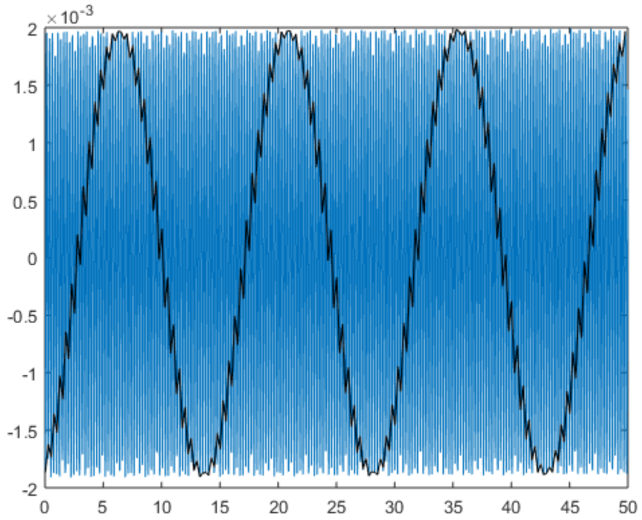
Ch3 Position a
380mdiv
Ch3 Scale b
1.0mV

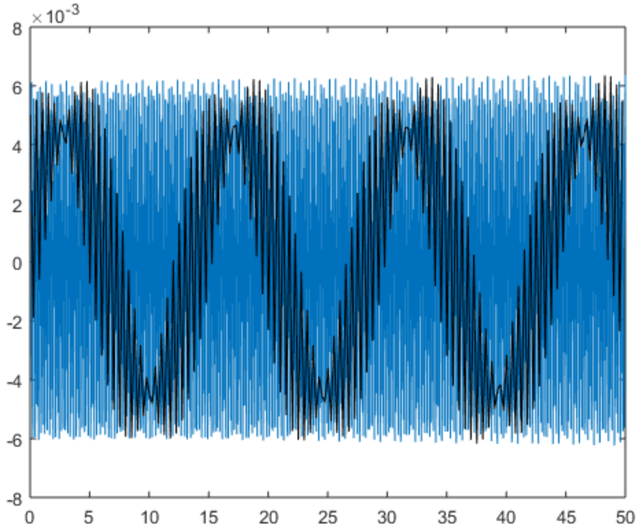
C3 1.0mV/div 50Ω BW:200M

A Aux 0.0V

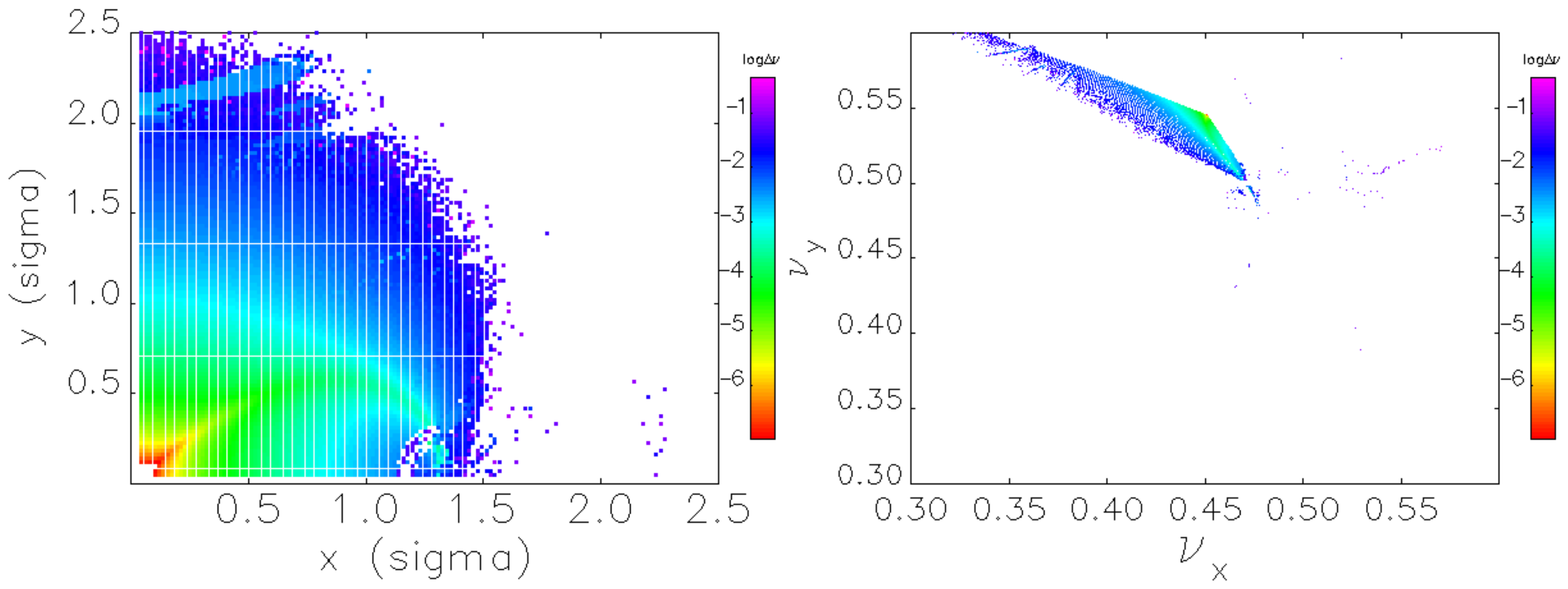
1.0µs/div 1.0GS/s 1.0ns/pt
Run Average:16
720 acqs RL:10.0k
Auto January 20, 2016 23:59:20

Pseudo-continuous motion

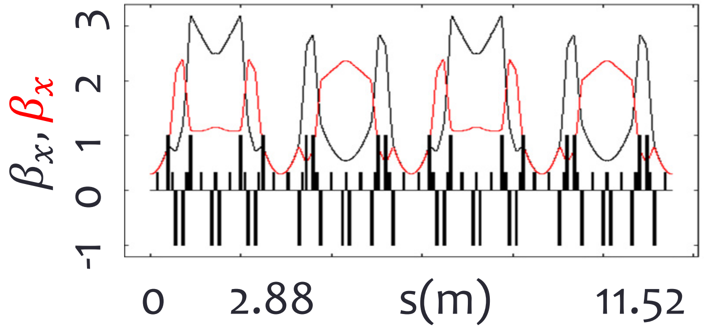




Octupole lattice in Elegant

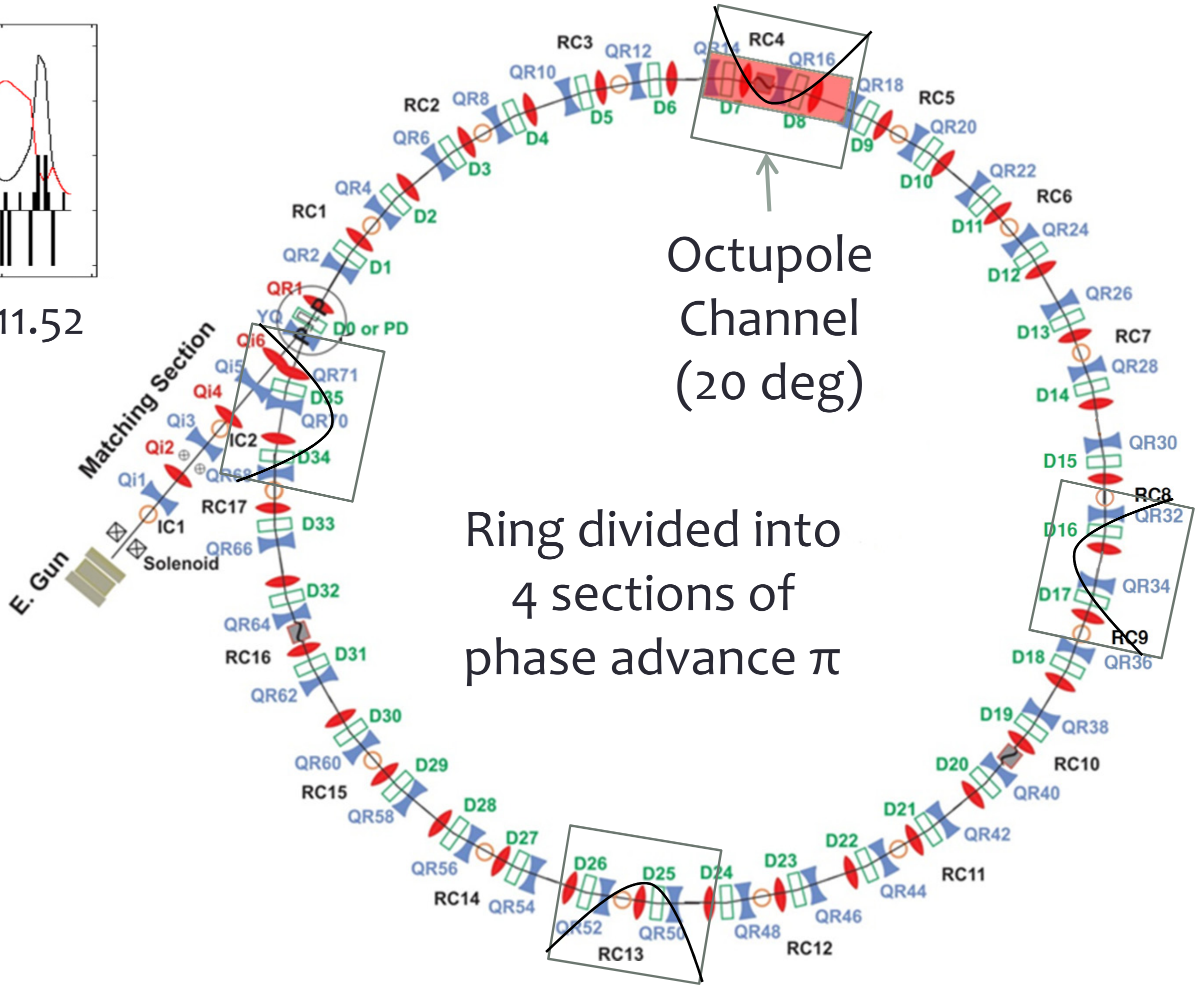


Single Channel Experiment @ UMER



$$\Delta\Psi_{channel} = 0.23 * 2\pi$$

Families of 5 quadrupoles

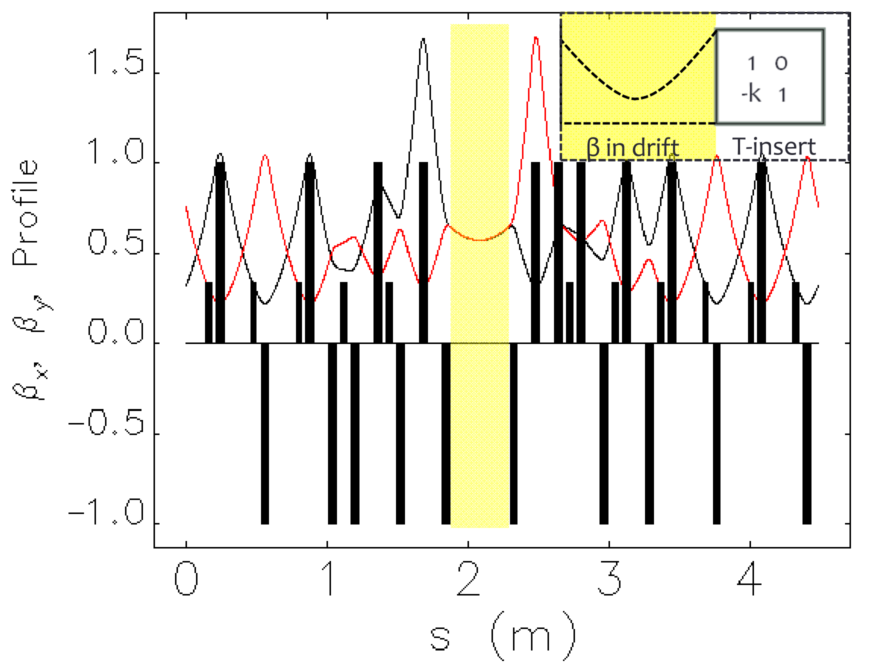


Octupole Channel (20 deg)

Ring divided into 4 sections of phase advance π

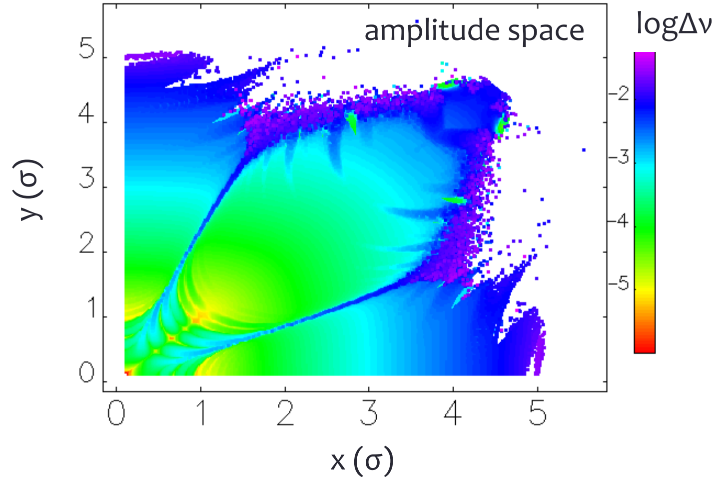
IOTA-like lattice at UMER

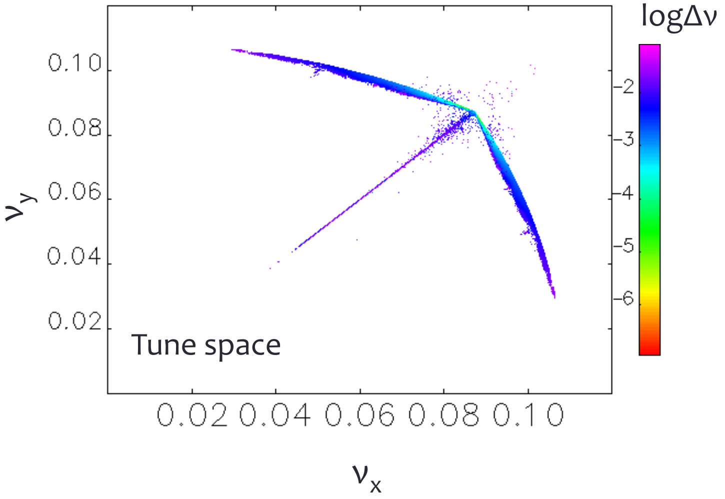
“0-current” Lattice Functions with **Elegant**



Fractional tune 0.08 in octupole channel. Possible to increase fractional tune with the use of solenoid lenses.

Frequency analysis of IOTA-like UMER (toy model)

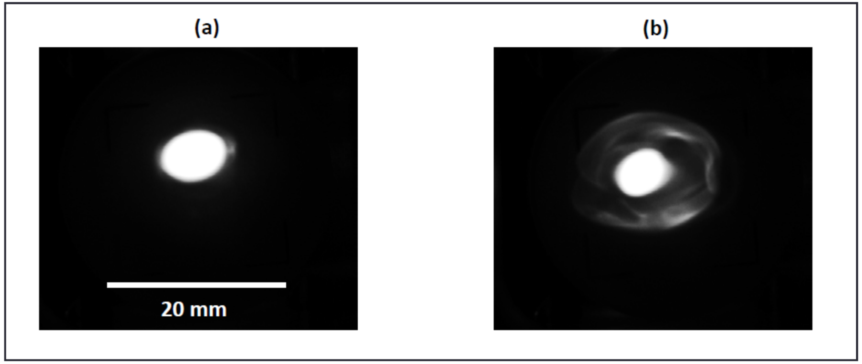




Generating beam halo in UMER

Electric quadrupole prototype

Beam halo through quadrupole mismatch
Phosphor screen images



Beam halo from driven envelope oscillations
PIC code phase space plots