Nonlinear Optics at University of Maryland Electron Ring

Lessons learned in simulation

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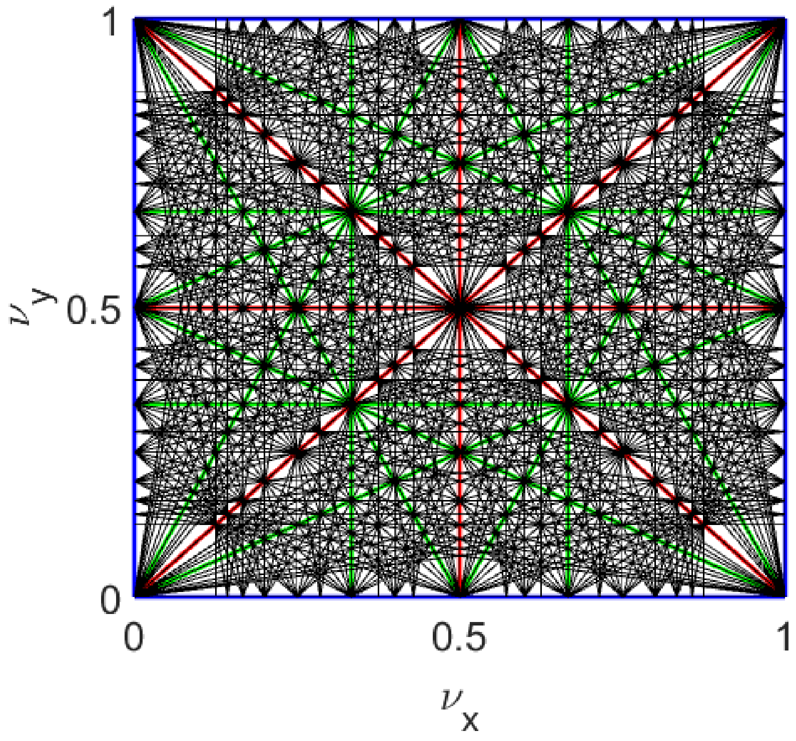
ICAP Key West

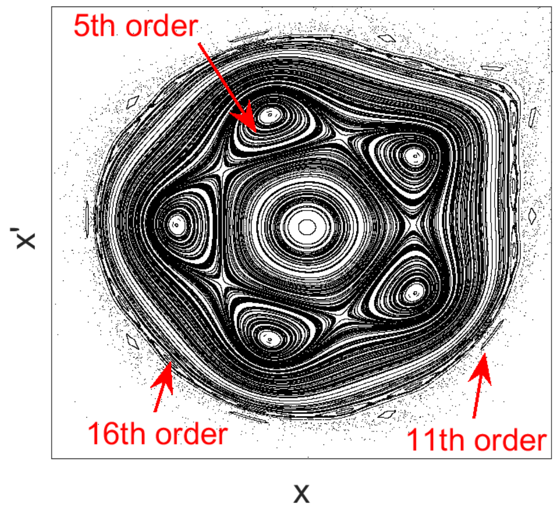
Outline

- Motivation
- Introduction to UMER
- Design and parameters of UMER experiment
  - Nonlinear (octupole) insert
  - Linear optics
  - Simulated transport in lattice as-designed
- Simulation-informed decision for octupole insert configuration
- Comparing tune spreads across several operating points

Nonlinear optics in accelerators should decrease sensitivity to resonant instability

Resonant conditions, to order 8





Integrable/quasi-integrable optics introduces nonlinearity while maintaining invariants

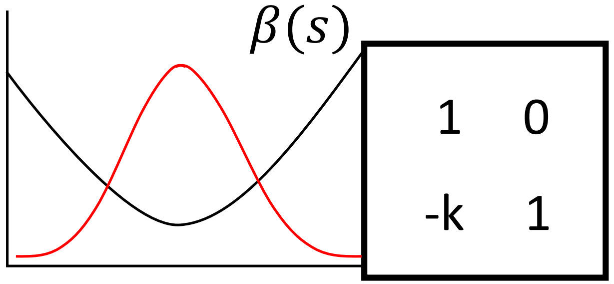
(Henon-Heiles system, A. Valishev talk, Sat.)

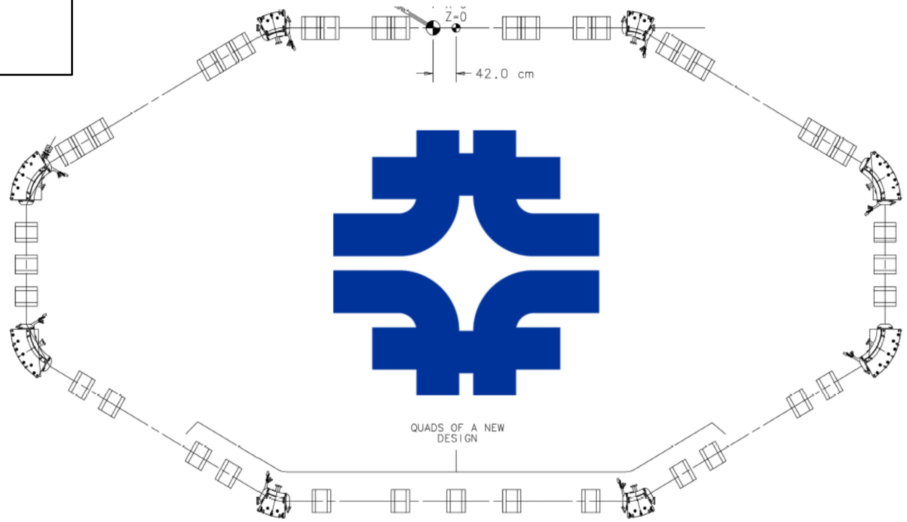
If octupole potential has the form $V(x,y,s) = \frac{1}{\beta^3(s)}\frac{\kappa}{4}(x^4 + y^4 - 6x^2y^2)$

Orbits follow 1 known invariant of motion:

$$H_N = \frac{1}{2}(x'^2_N + y'^2_N + x^2_N + y^2_N) + \frac{\kappa}{4}(x^4_N + y^4_N - 6x^2_N y^2_N)$$

Danilov, Nagaitsev, Nonlinear accelerator lattices with one and two analytic invariants, Phys. Rev. ST Accel. Beams 13, 2010

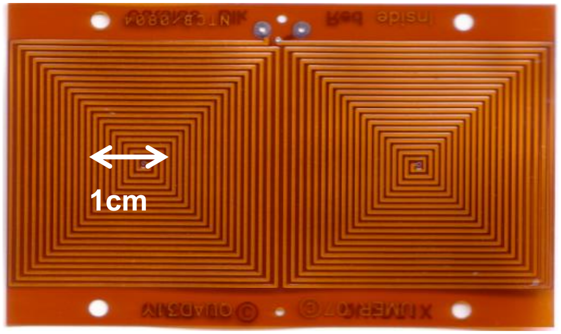


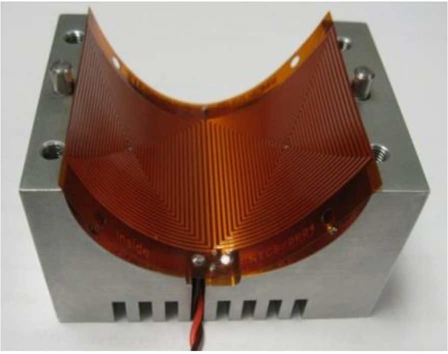


University of Maryland Electron Ring

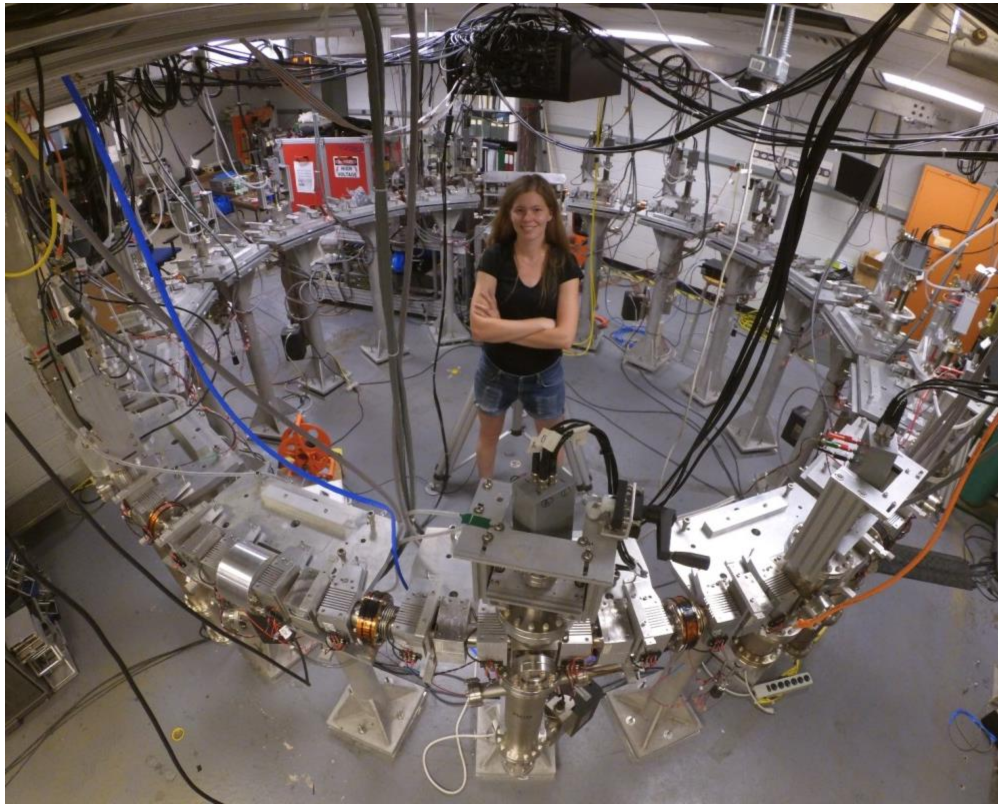
		Extended range
Electron energy	10 keV	
Ring circumference	11.52 m	
Beam current	0.6 - 100mA	$10 - 100\ \mu A$
Tune $\nu_x \sim \nu_y$	6.7	
$\Delta\nu / \nu_0$	$0.85 - 0.14$	$1.00 - 0.95$
$\Delta\nu$	$0.94 - 5.6$	$0.005 - 0.3$
confinement	1k turns	10k* turns

Bernal, S., et al. In *AIP Conf. Proc. vol. 1812 (Proceedings of AAC workshop, 2017)* National Harbor, MD
Ruisard, K. (2018). University of Maryland College Park.





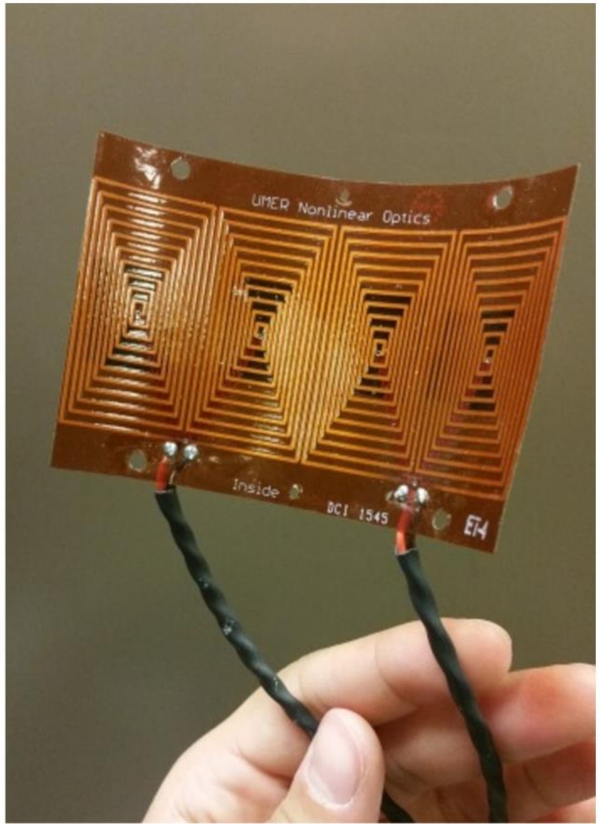
Printed circuit board quadrupole magnets

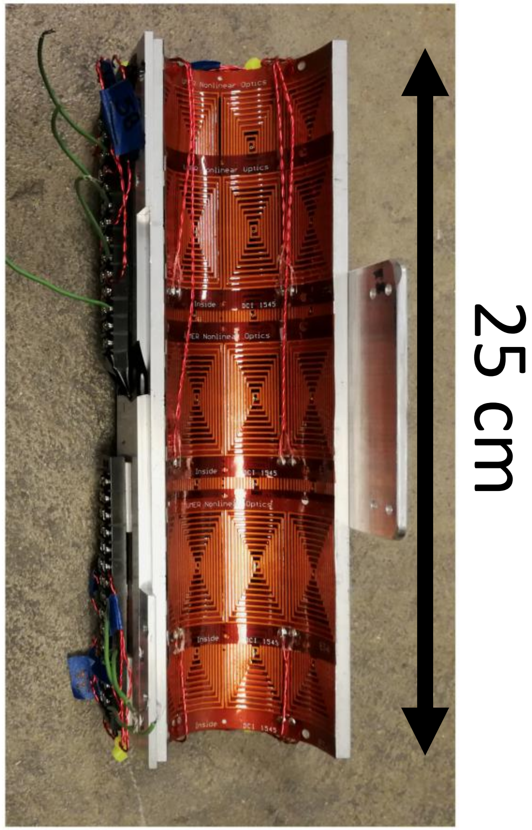


* To be demonstrated

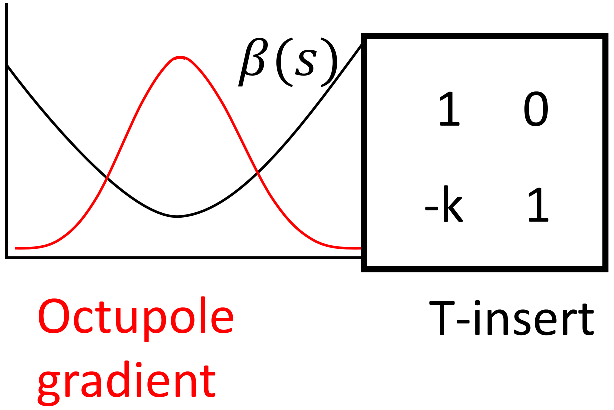
Overview of UMER Octupole Lattice Design

Nonlinear insert is comprised of multiple short PCB octupoles

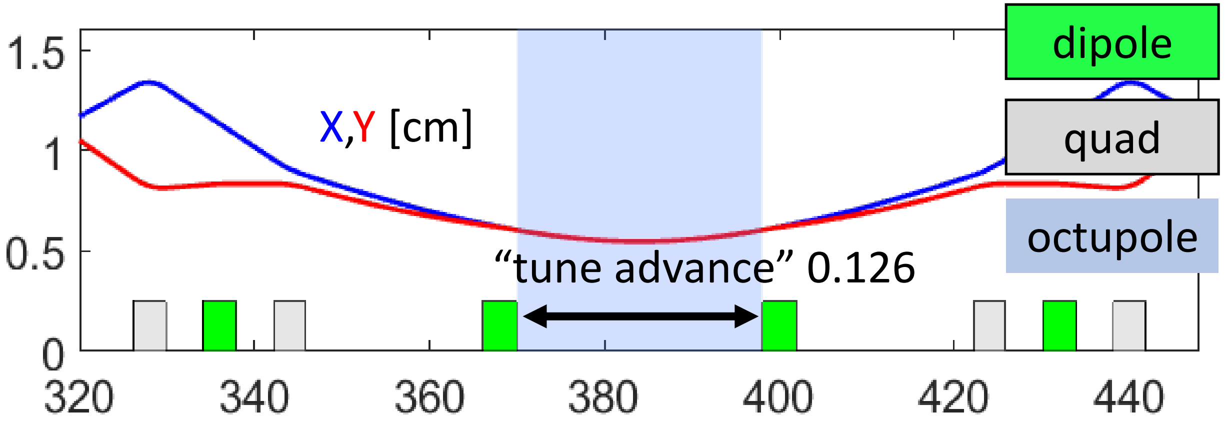


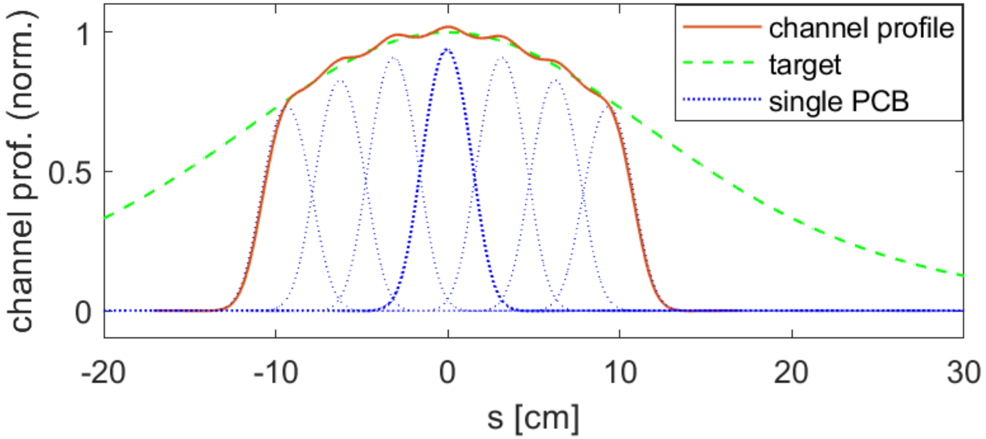


Baumgartner, H. et al, In *Proceedings of IPAC2018,* Vancouver, Canada.
Baumgartner, H., et al, In *Proceedings of NAPAC2016,* Chicago, IL.



Requirements:
Round beam
$\beta_x(s) = \beta_y(s)$
Octupole strength
$$\frac{d^3 B_x}{dy^3} \propto \frac{1}{\beta^3(s)}$$

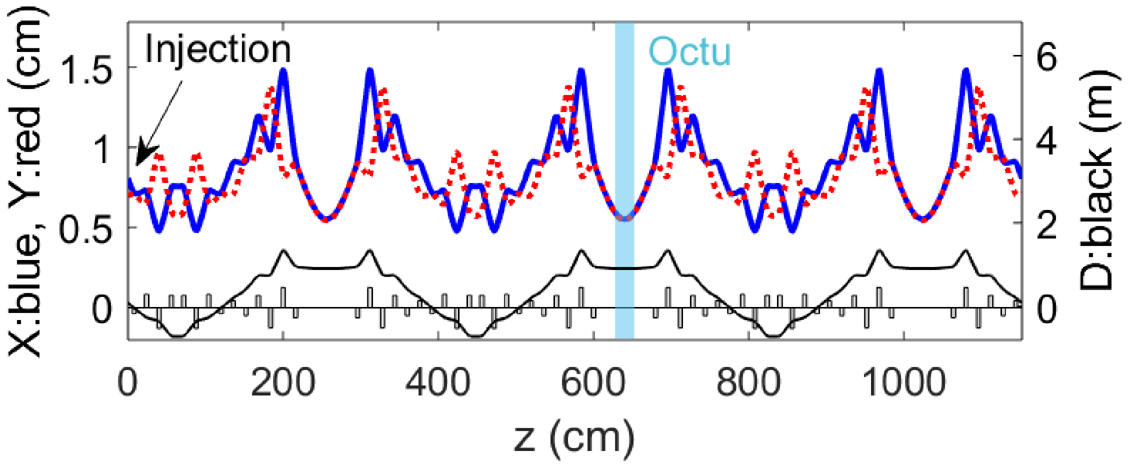


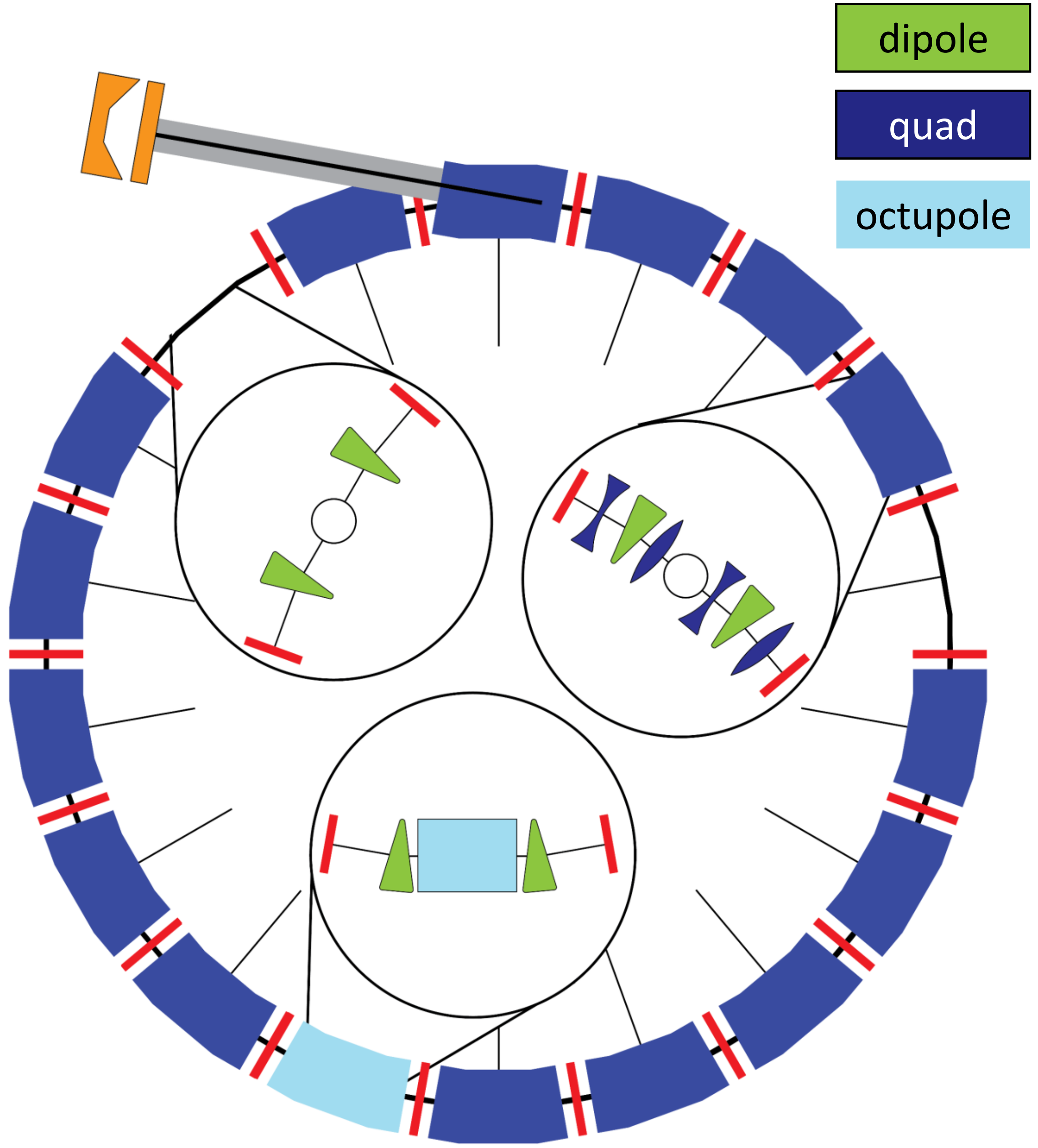


Design of quadrupole focusing lattice

Linear lattice tune	Full ring tune
$\boldsymbol{\nu_x = 2.998}$	$\boldsymbol{\nu_x = 3.124}$
$\boldsymbol{\nu_x = 3.002}$	$\boldsymbol{\nu_y = 3.128}$

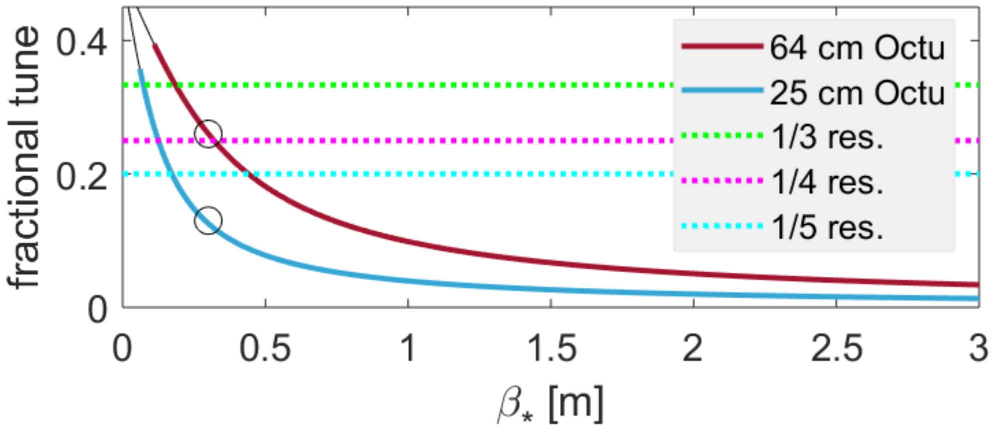
Solution assumes $\epsilon = 100\ \mu m$ and $I_{beam} = 60\ \mu A$

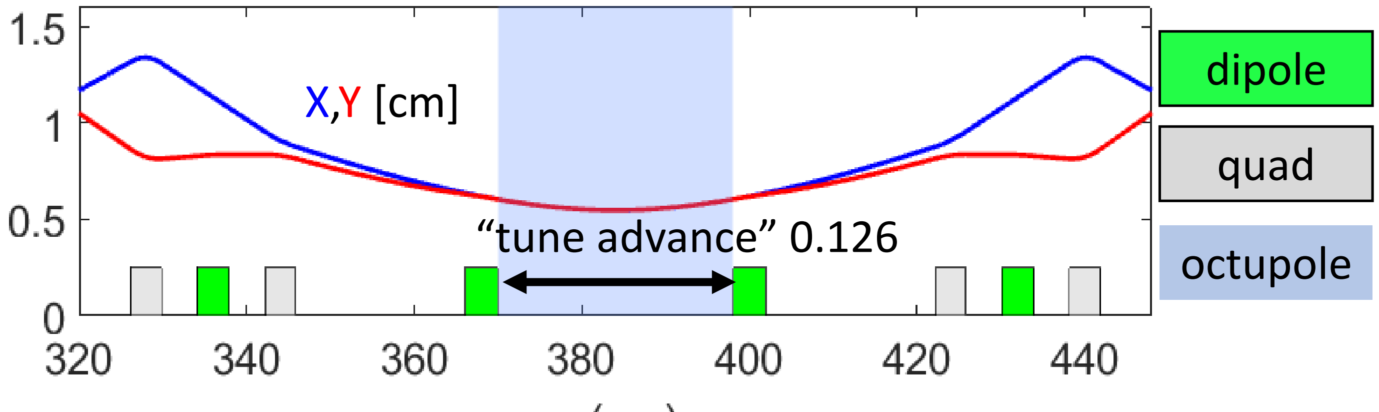


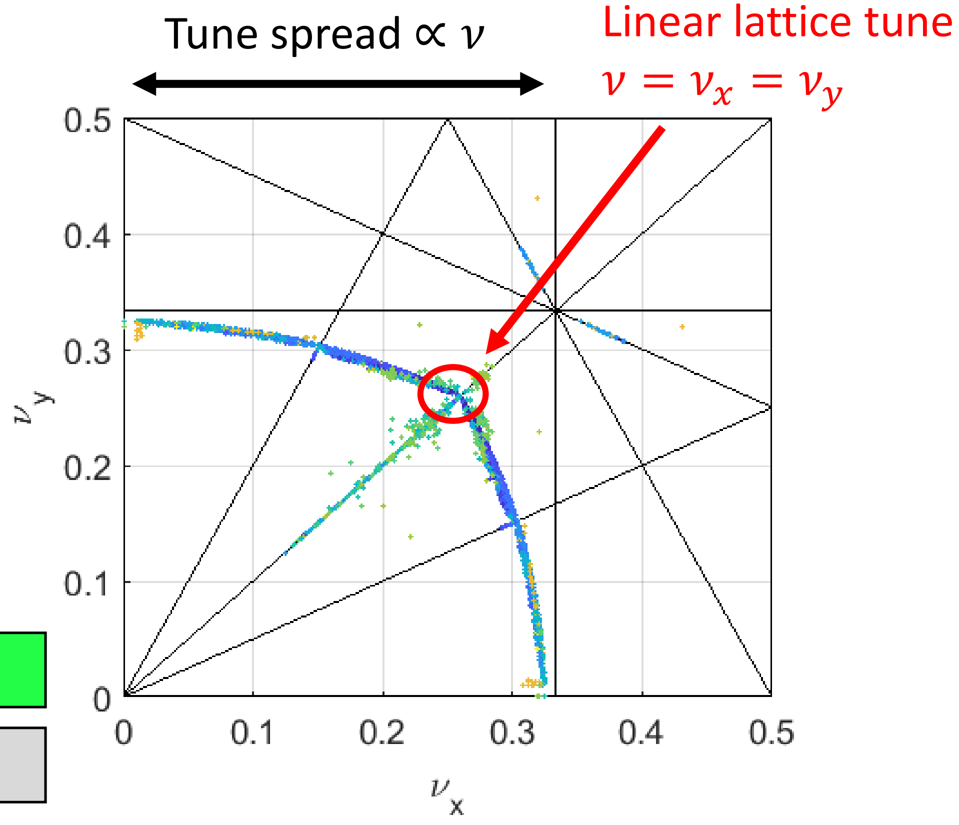


Choice of operating point (lattice tune) is made to maximize octupole-induced spread

- For large-emittance ($100\ \mu m$) beams, waist size $\beta_* = 0.3\ m$ is smallest waist

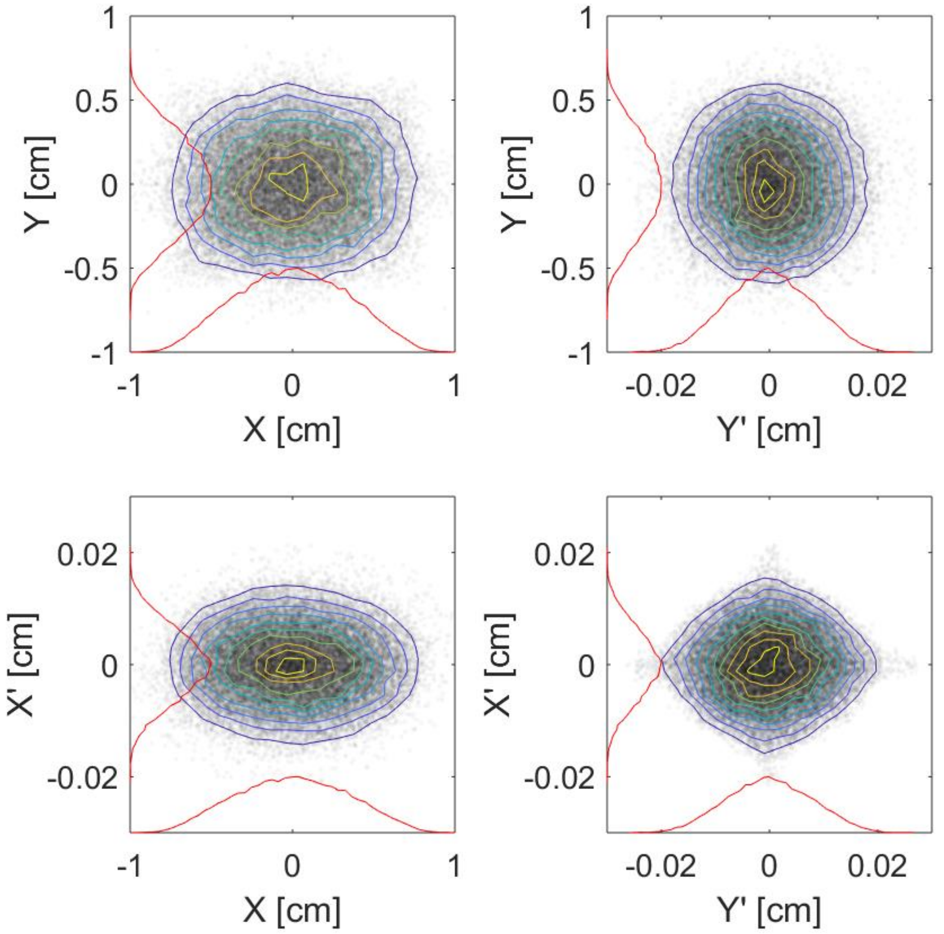


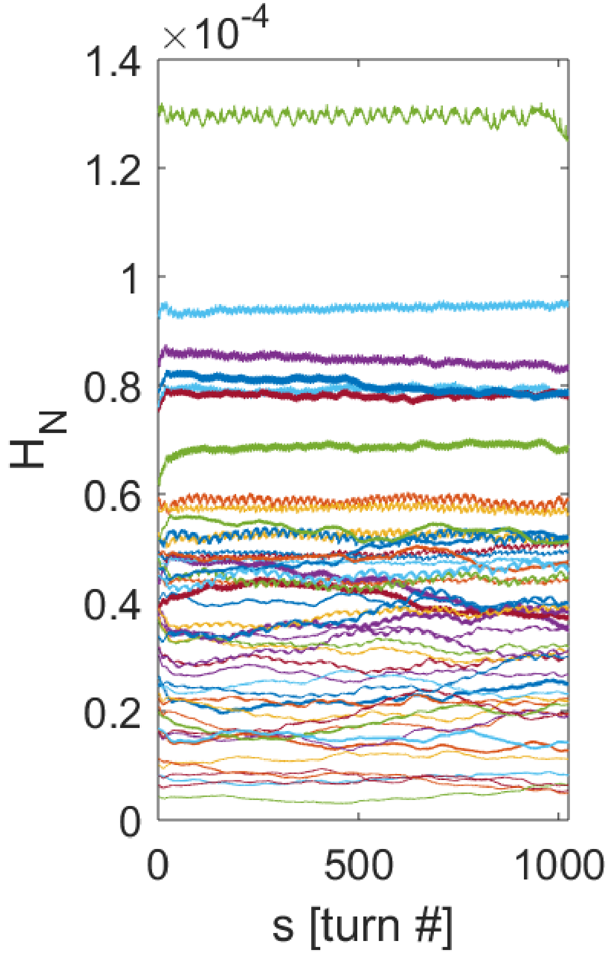


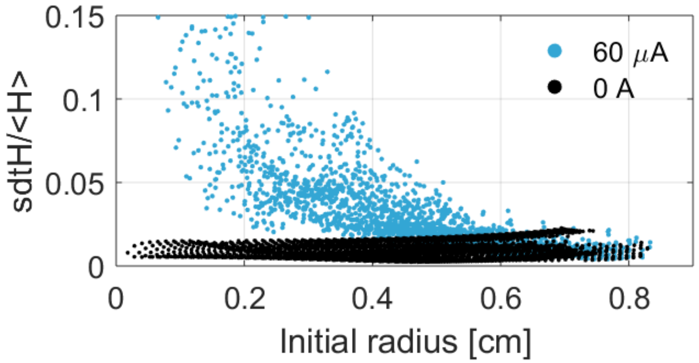


Simulation of lattice as designed*

WARP 2D-slice PIC model; 60 μA beam with 0 A “witness” distribution





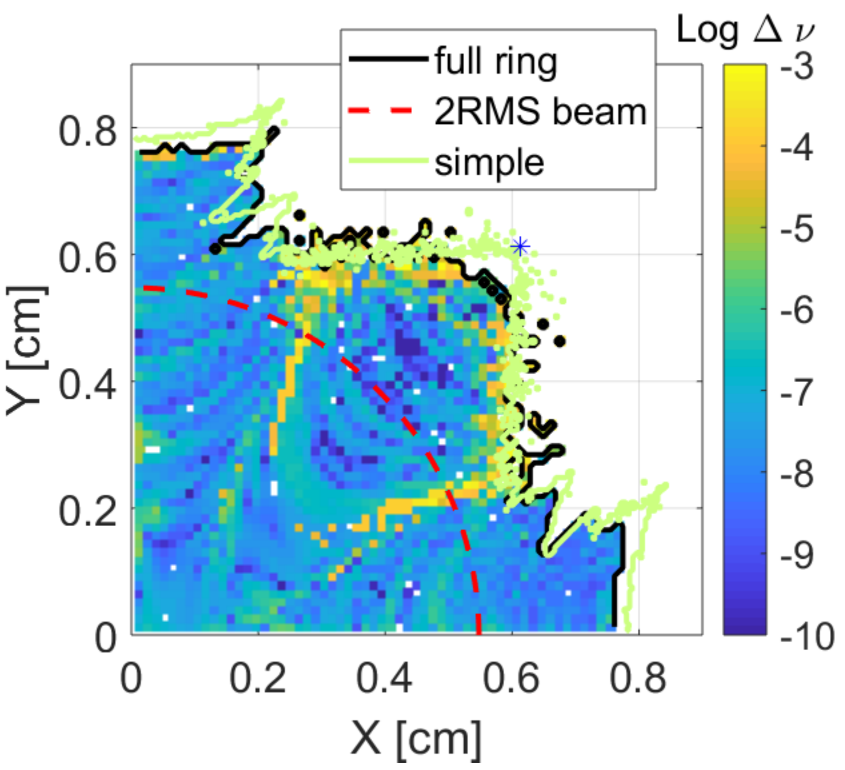


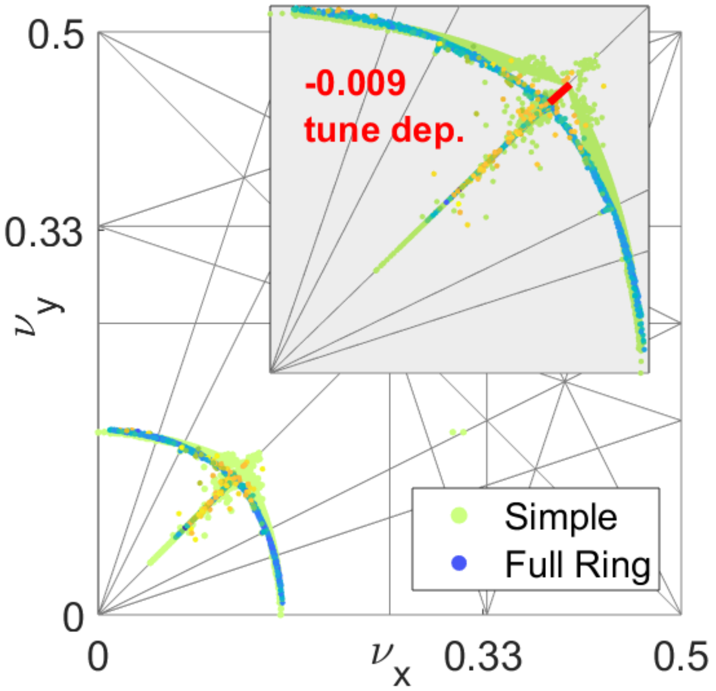
Space charge starts to break invariant conservation, but has minor effect on ``macro” qualitites

*HE quadrupole model, without dipole bends

Simulation of lattice as designed

WARP 2D-slice PIC model; 60 μA beam with 0 A "witness" distribution



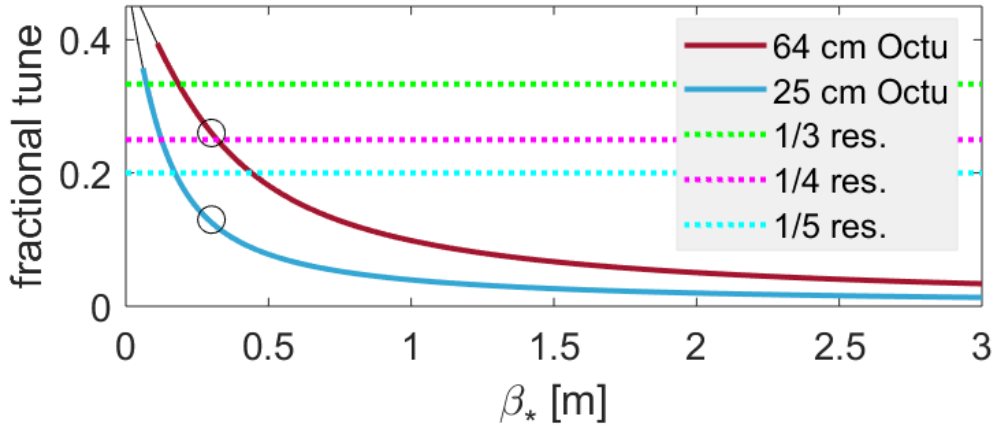


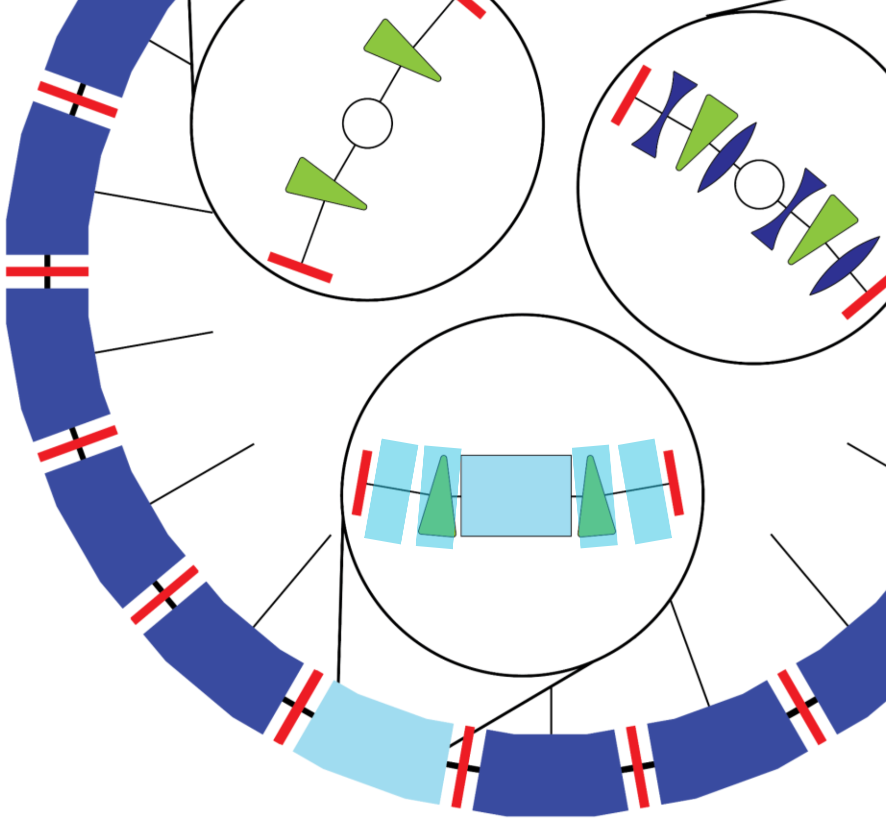
β_*	0.3 m
ν_x	3.124
ν_y	3.128
Peak Oct. Strength	$50\ T/m^3$ ($\kappa = 3984$)
I_{beam}	$60\ \mu A$

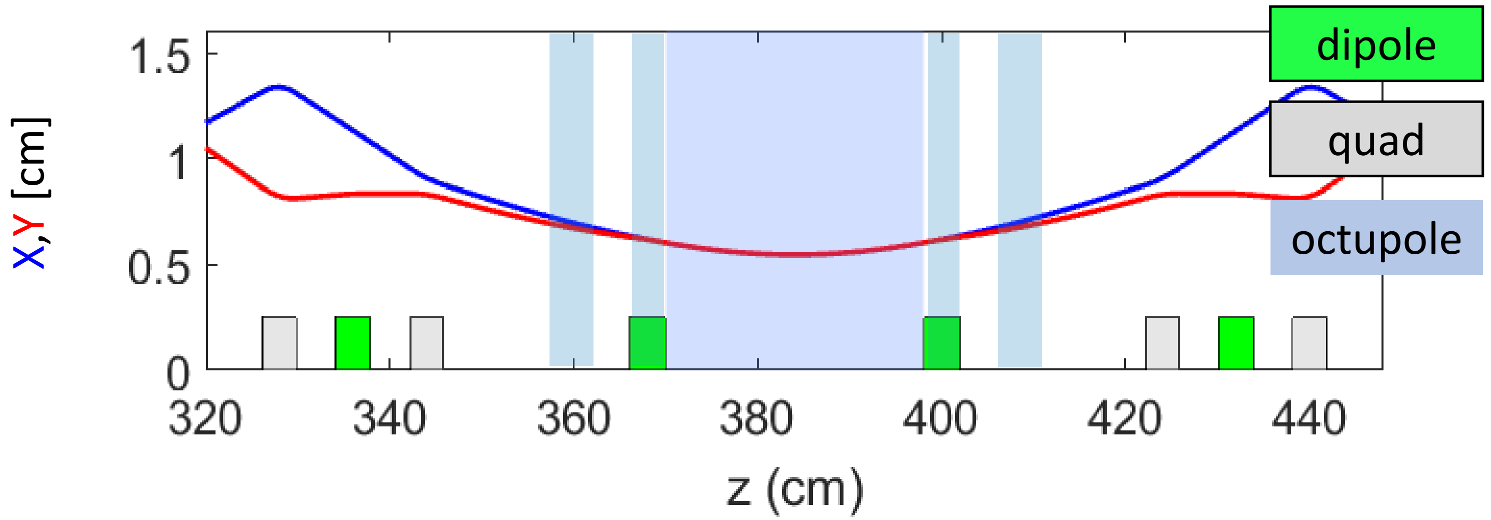
Max $\Delta\nu$	0.11
$RMS\ \Delta\nu$	0.016
Stable aperture	0.62 cm
$\left\langle \frac{stdH_N}{H_N} \right\rangle$	7.7% (<1% w/o SC)

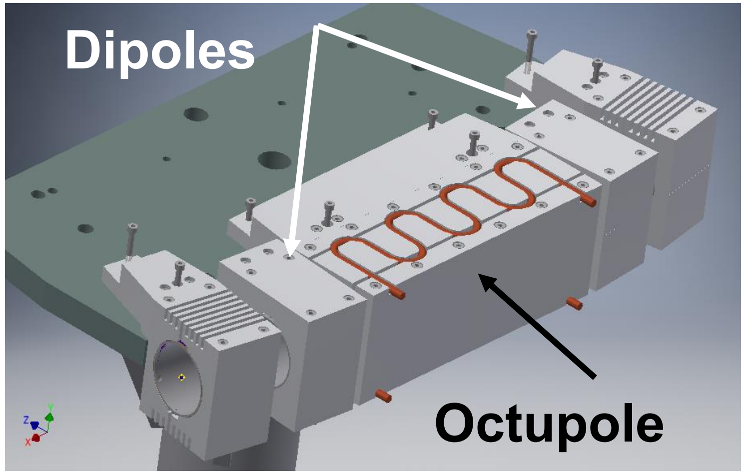
Effect of octupole configuration on stability

Original design parameters specified a **64 cm** octupole insert



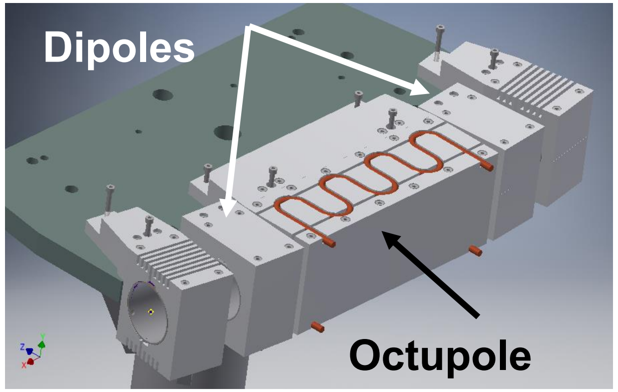




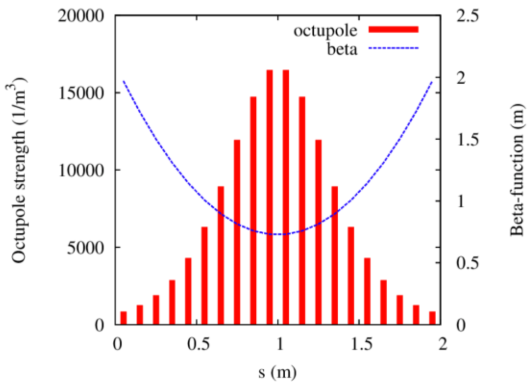


We compared three configurations for the “octupole section”

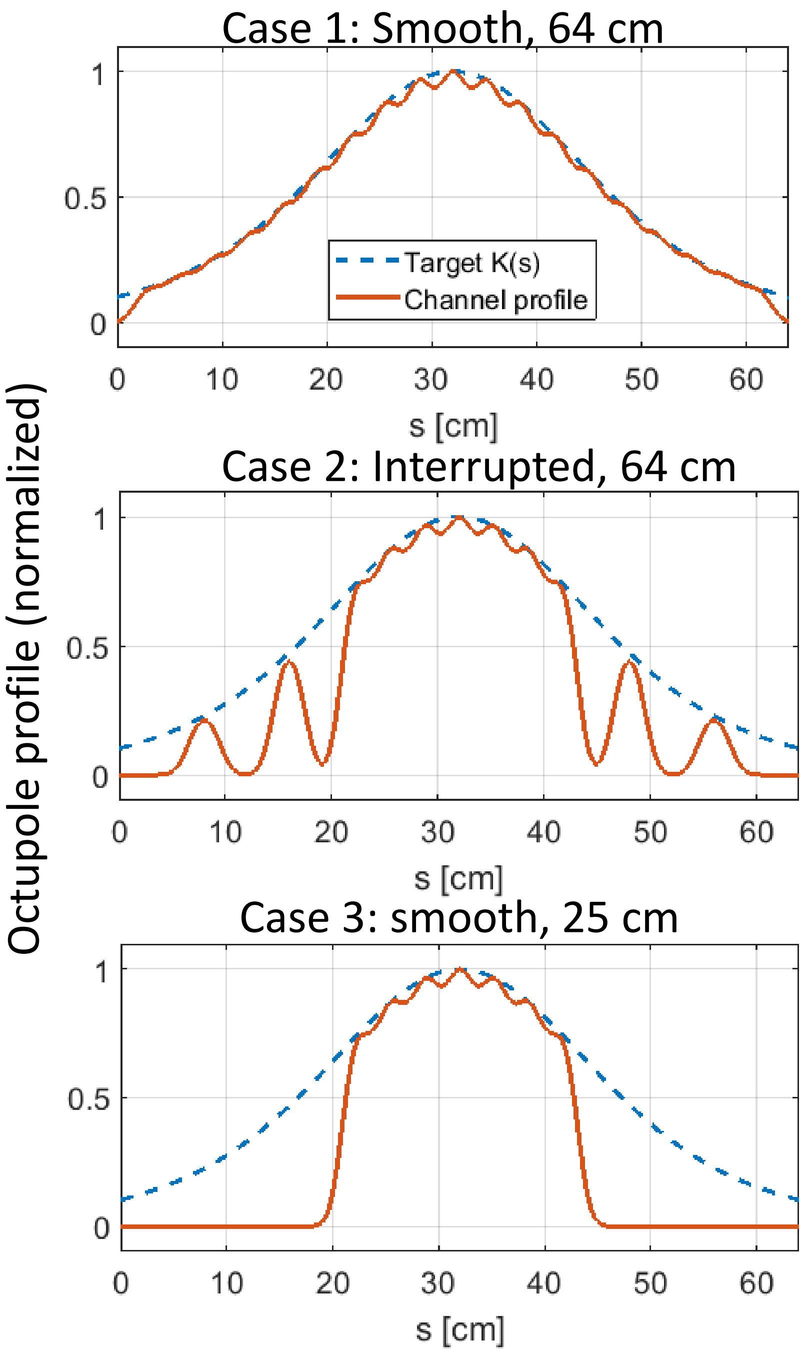
$$\text{Target } G_3(s) = \frac{d^3B_y}{dx^3} \propto \frac{1}{\beta^3(s)}$$



UMER 20° section

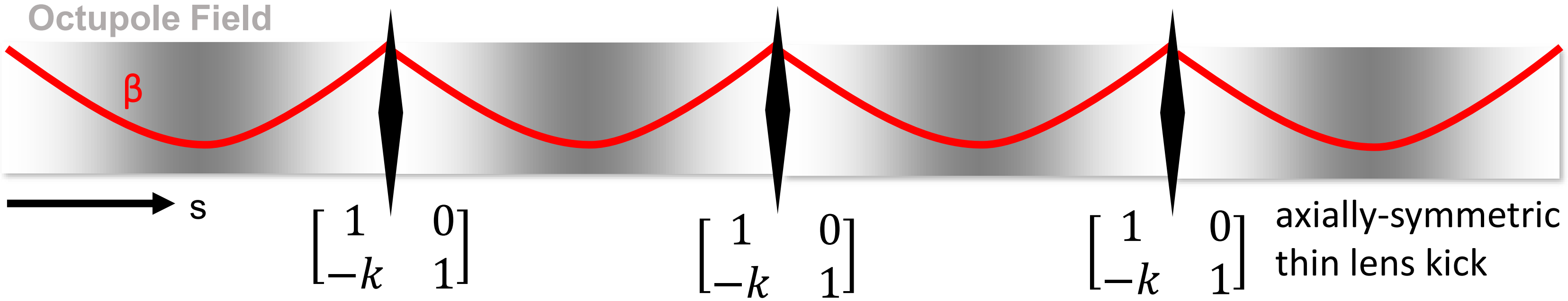


IOTA octupole, from A. Valishev talk, Sat.



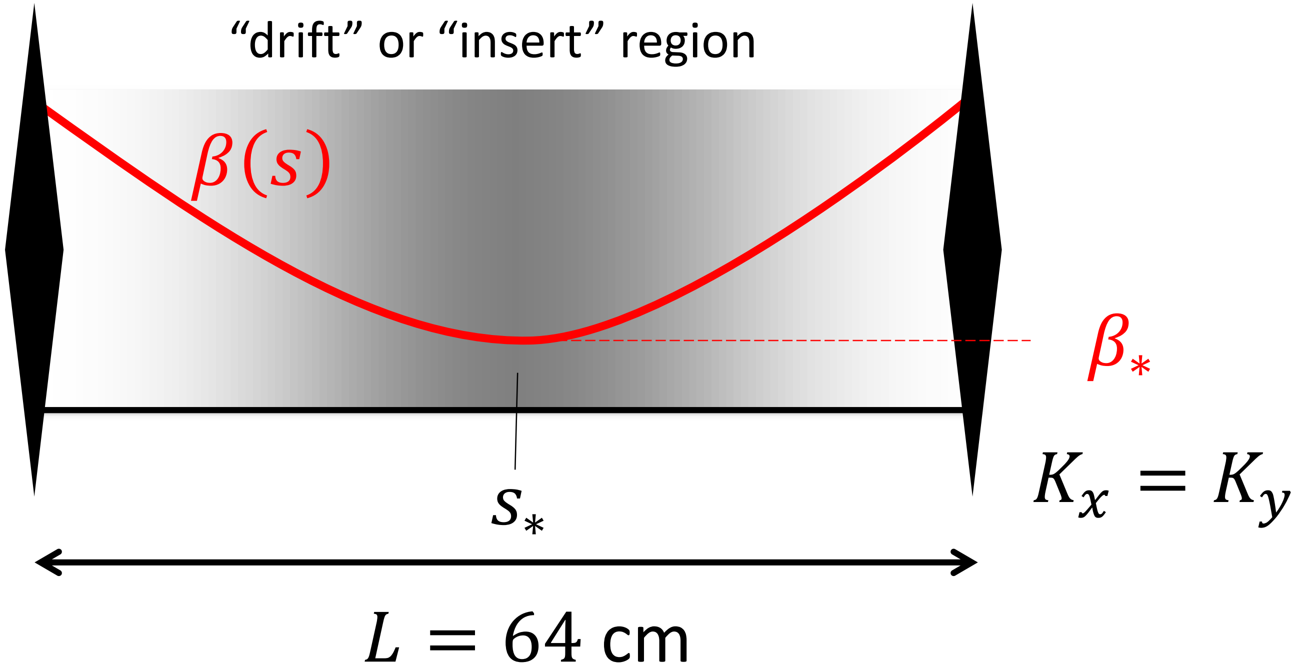
* Not actually possible given mechanical constraints

Simple "FOFO" model is used to probe dynamics in octupole insert only

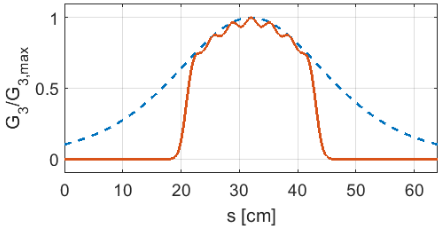


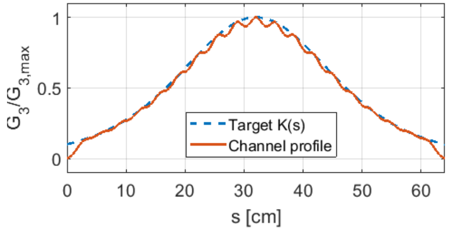
Fractional tune:

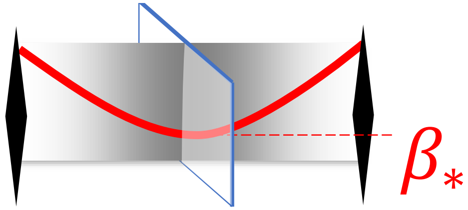
$$\nu = \frac{1}{2\pi}\int_0^L \frac{ds}{\beta(s)}$$



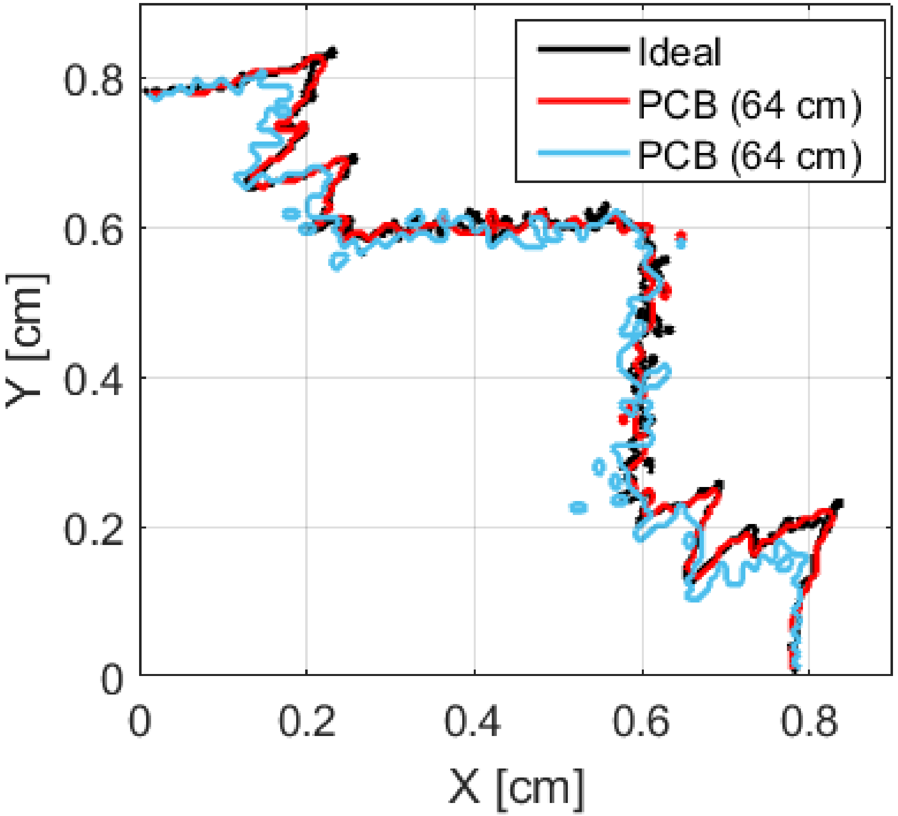
Dynamics are robust for “realistic” octupole potential

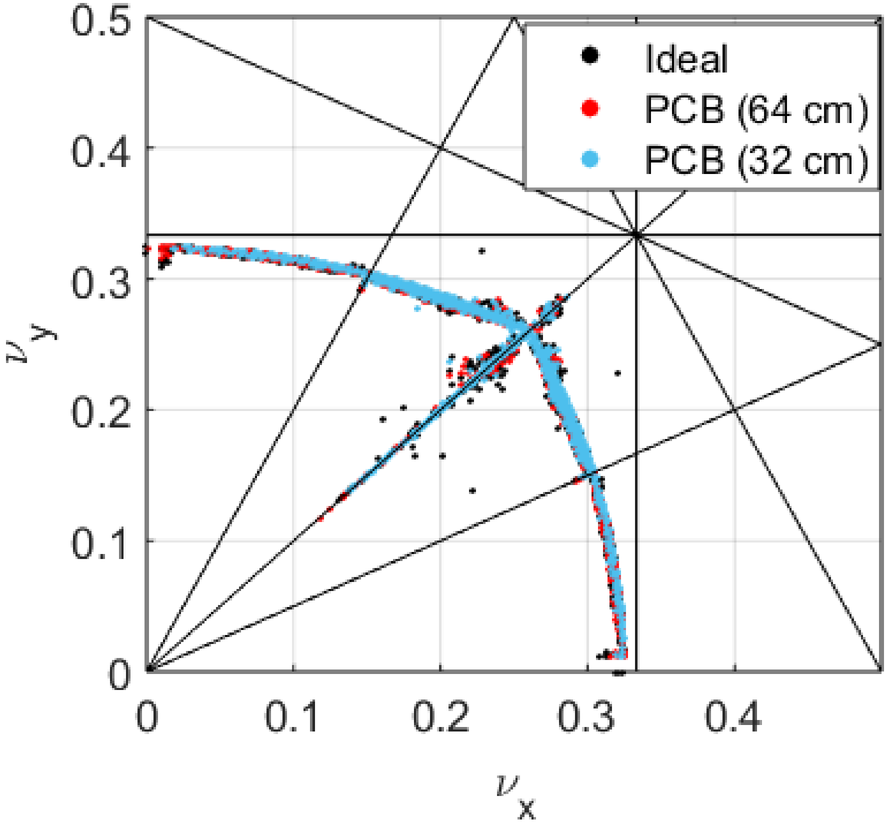




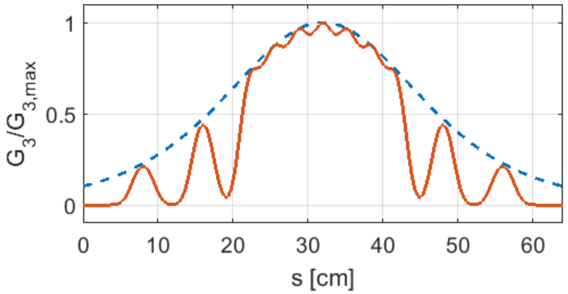


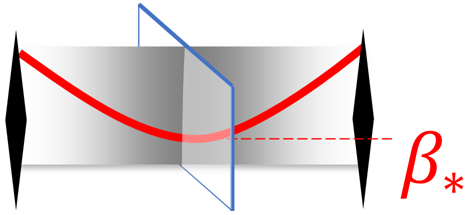
Gridded field element generated from Biot-Savart solution for octupole printed-circuit “as designed”

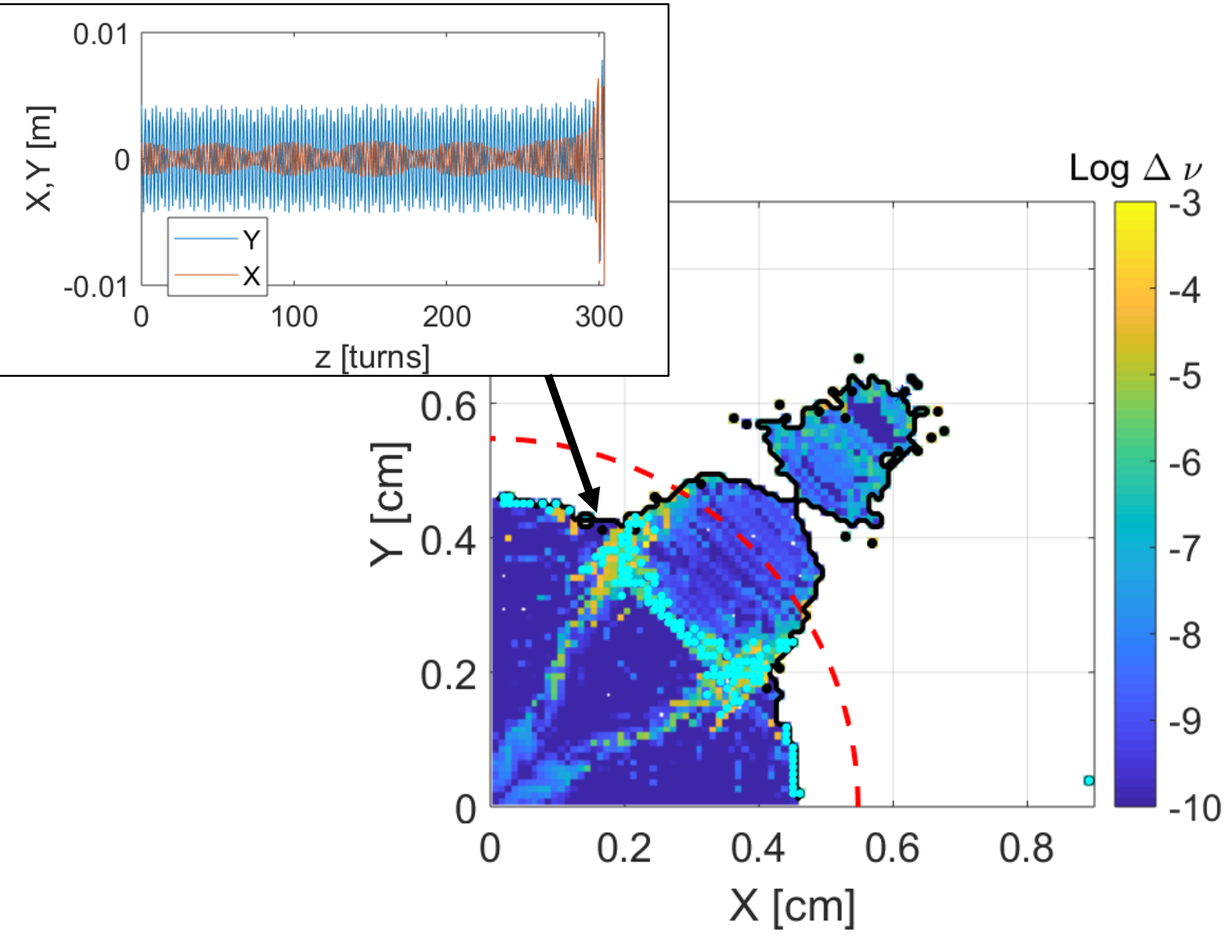


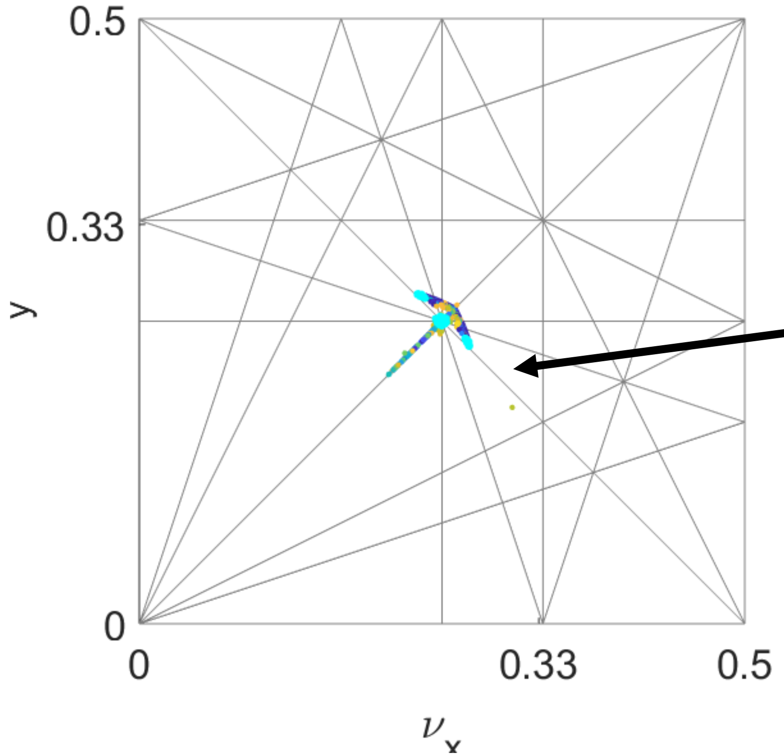


…but not to interrupted octupole







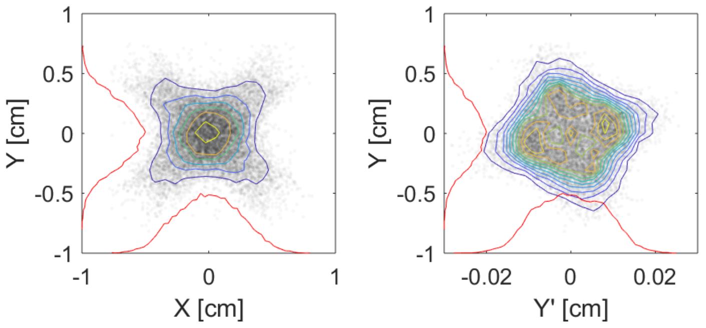


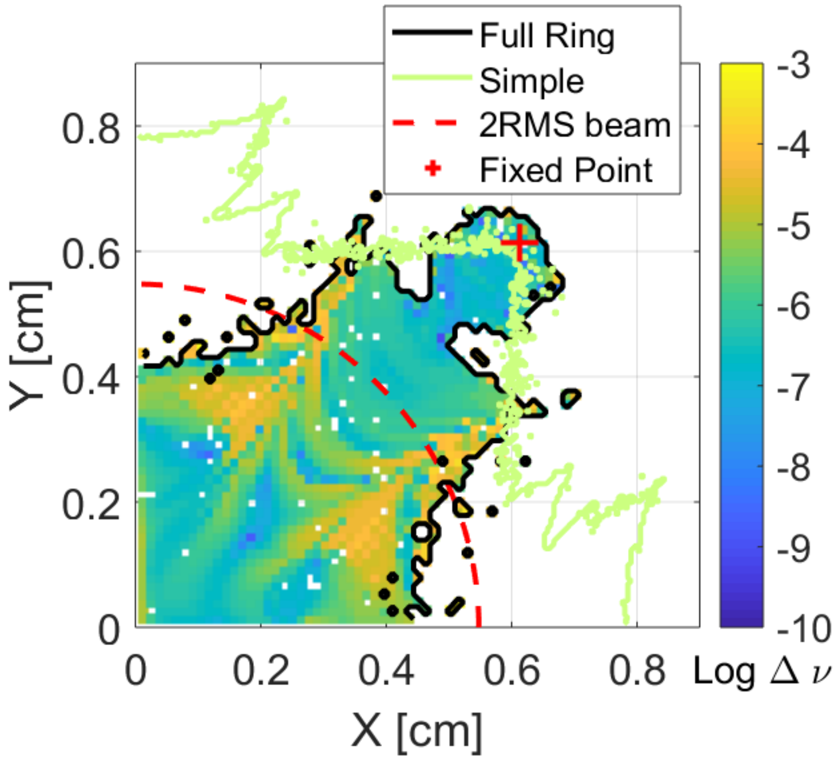
Loss appears to be bounded by X+Y coupling resonance (cyan)

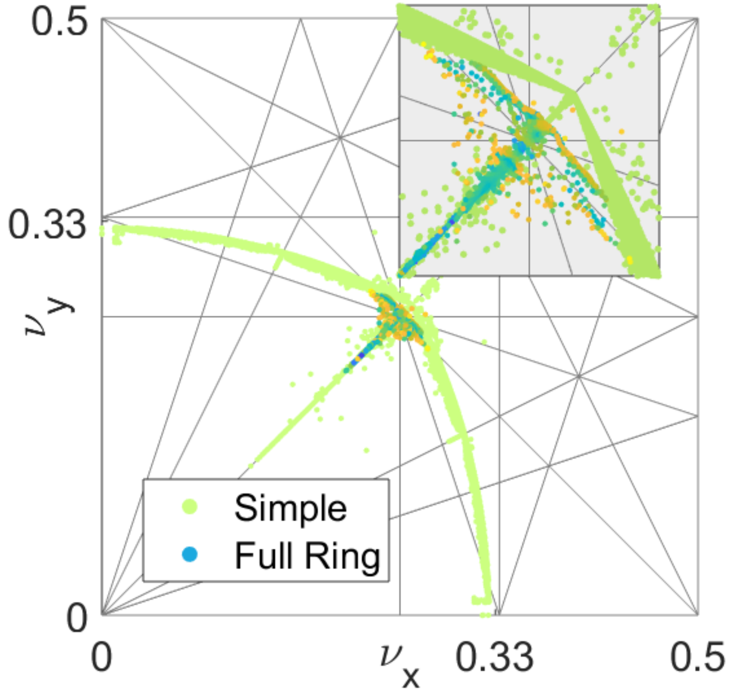
So we let go of our 64-cm octupole idea…

Simulations of ring with 25-cm octupole insert

Operation at $\nu = 3.26$ is affected by fourth order resonance



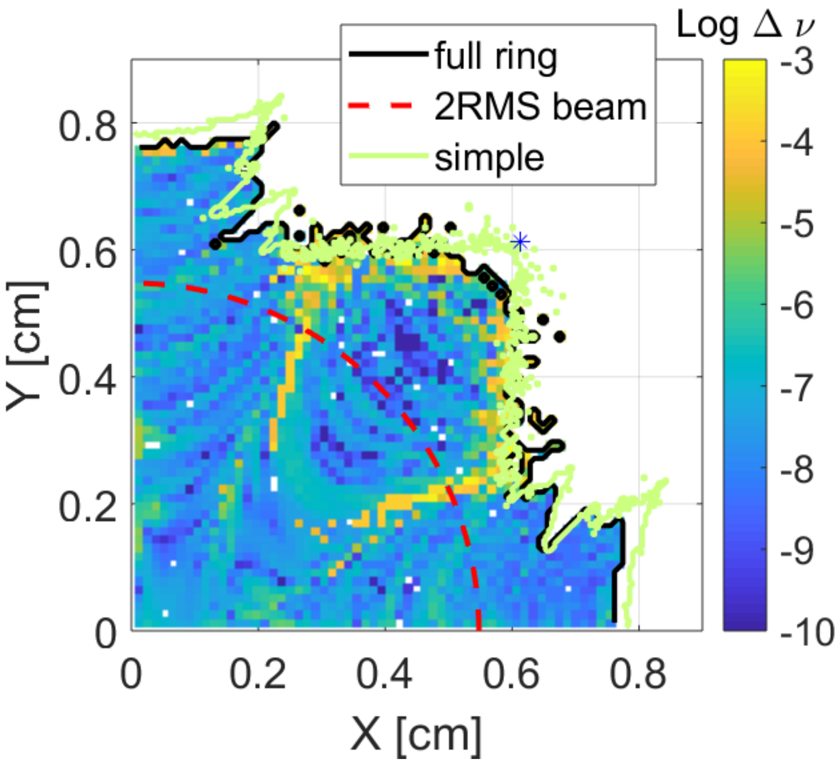


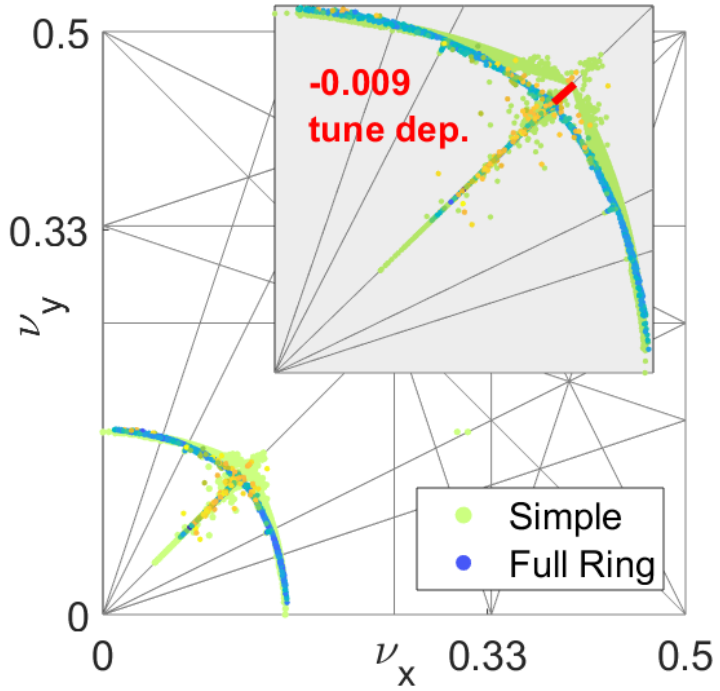


β_*	0.3 m
ν_x	3.260
ν_y	3.263
Peak Oct. Strength	$50\ T/m^3$
I_{beam}	$60\ \mu A$

Max $\Delta\nu$	0.02
$RMS\ \Delta\nu$	0.01
Stable aperture	0.44 cm
$\left\langle \frac{std H_N}{H_N} \right\rangle$	9.4%

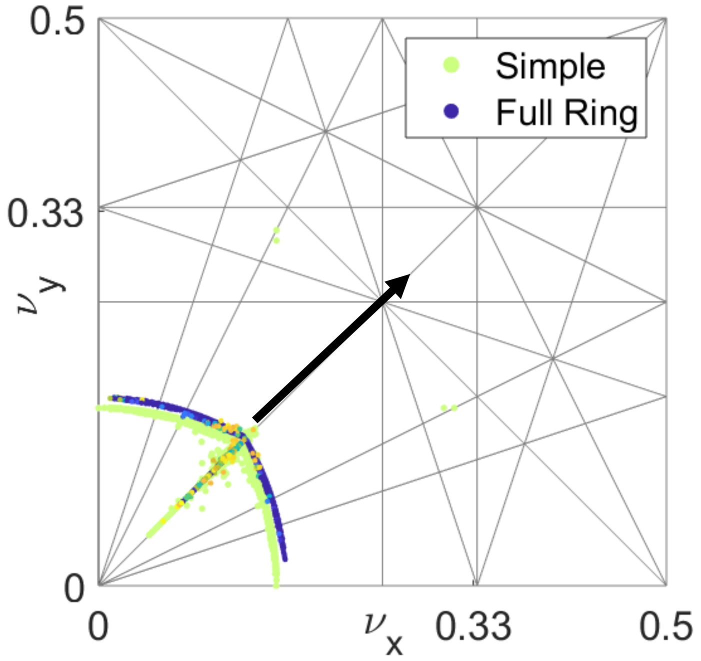
Lowering lattice tune (3.13) improves performance and has better agreement with simple model





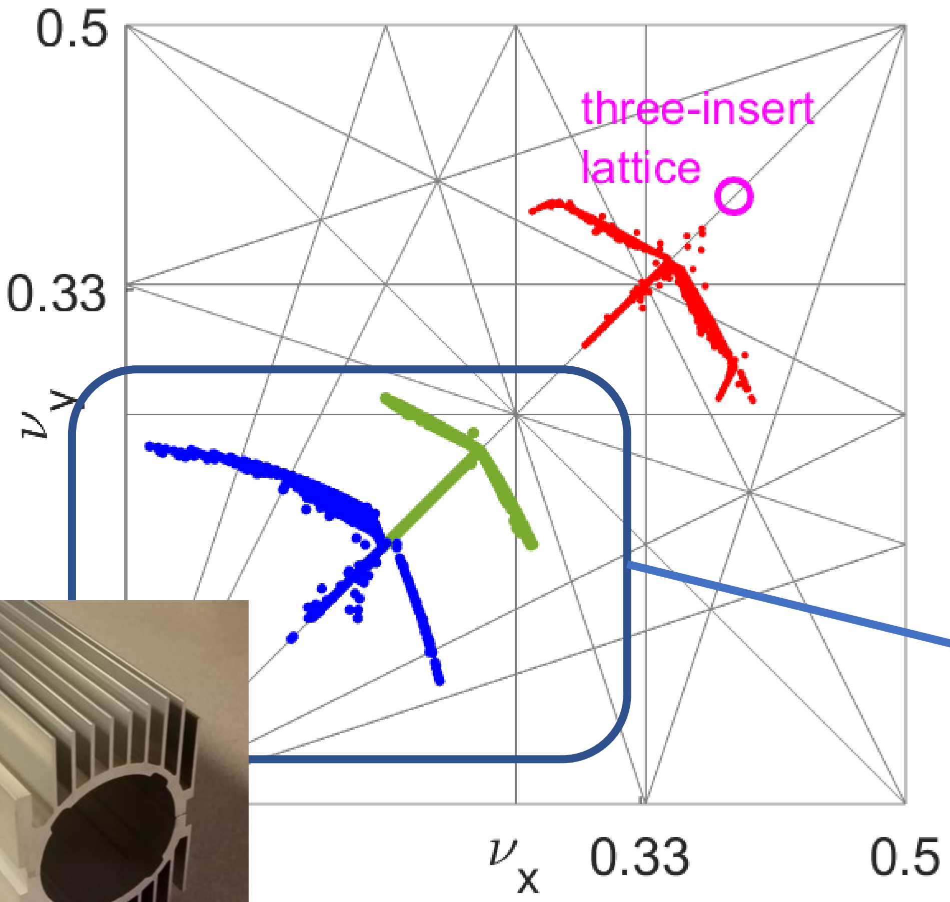
β_*	0.3 m
ν_x	3.124
ν_y	3.128
Peak Oct. Strength	50 T/m^3
I_{beam}	60 μA

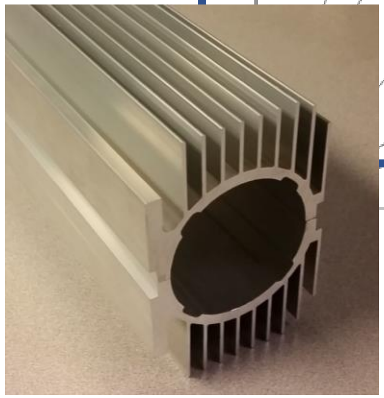
Max $\Delta\nu$	0.11
$RMS\ \Delta\nu$	0.016
Stable aperture	0.62 cm
$\left\langle \frac{stdH_N}{H_N} \right\rangle$	7.7%



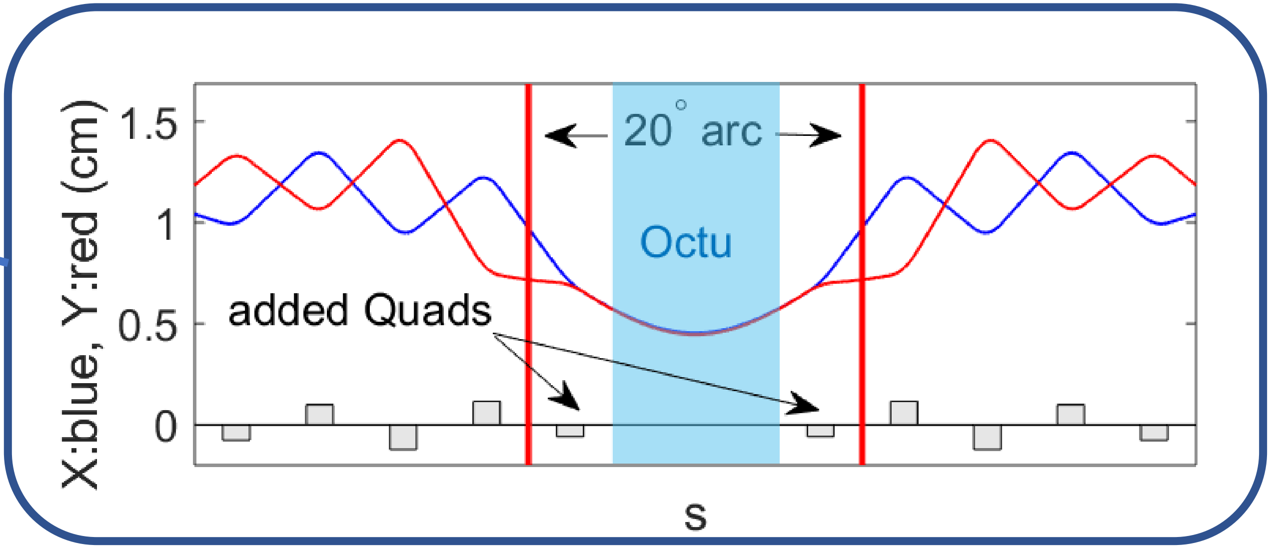
To what extent can we maximize tune spread?

Flexibility of optics allows for options

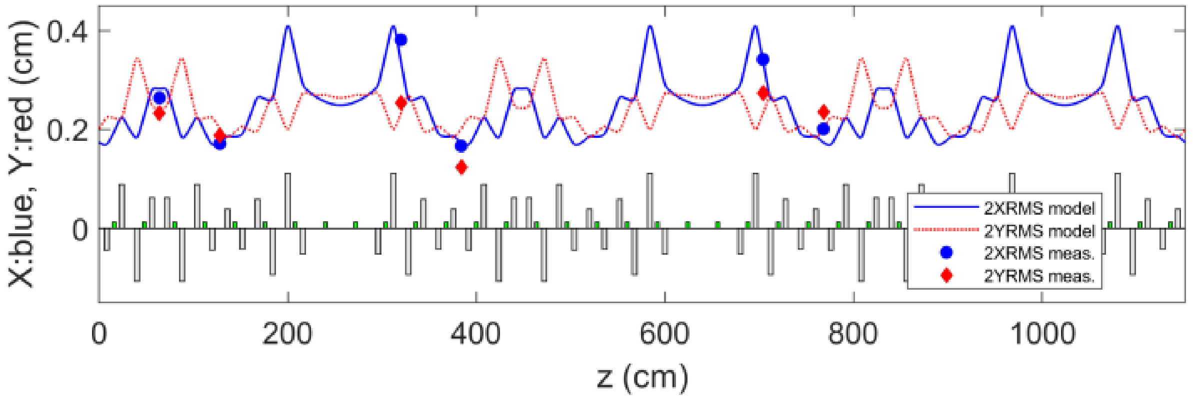


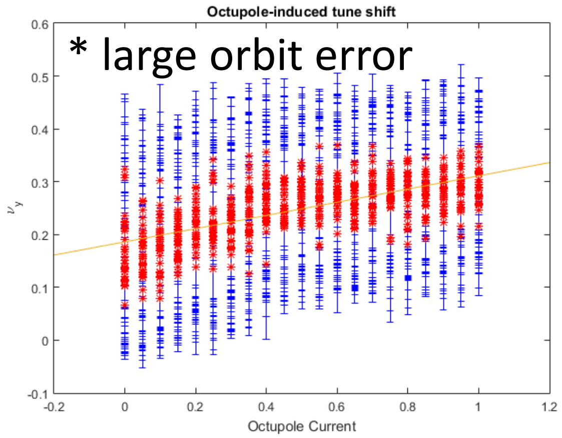


β_*	ν_x	ν_y	Peak Oct.
0.30	3.357	3.344	$50\ T/m^3$
0.20	3.159	3.189	$150\ T/m^3$
0.16	3.231	3.230	$150\ T/m^3$



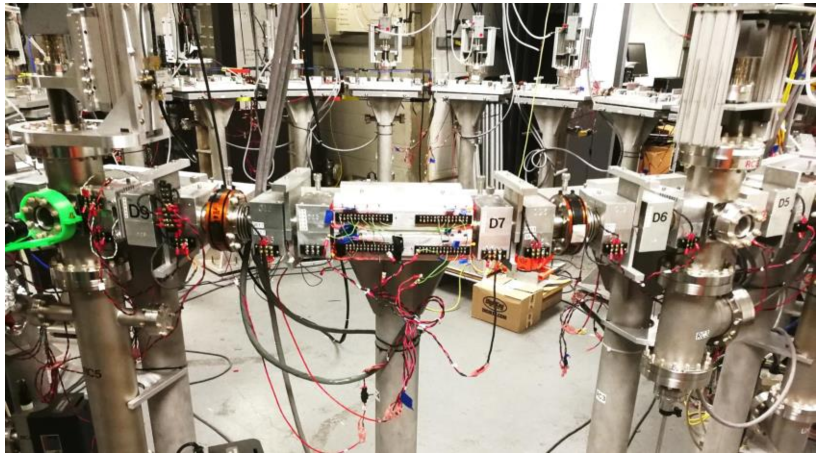
Status of experimental preparation at UMER



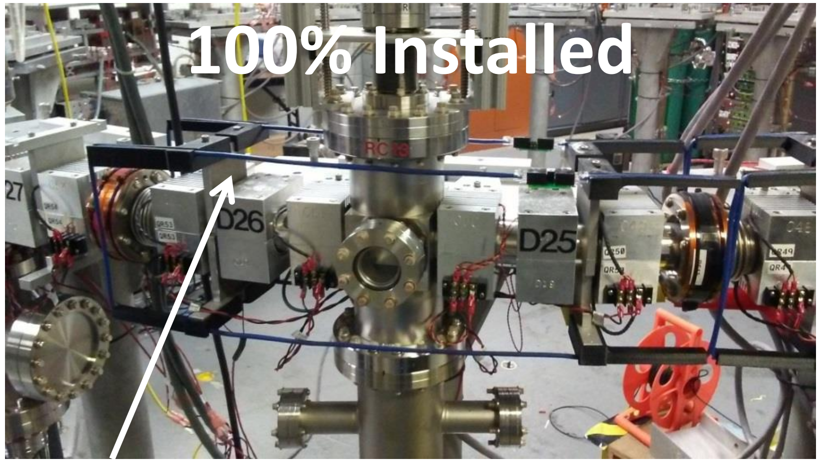


Top: Injected low-emittance high charge beam into lattice as designed.
Left: Initial measurement of amplitude-dependent tune shift from octupole insert.

Ruisard et al, IPAC 2018
Baumgartner et al, IPAC 2018



25-cm octupole element installed on UMER



Radial-field cancelling Helmholtz coils

Summary

- Pushed particles through model of UMER octupole lattice at $\nu_x = \nu_y = 3.13$ operating point
- Clear preference for short (25-cm) octupole insert instead of ``distributed” 64-cm octupole section
- Strong effect from fourth order resonance when full ring is considered excludes operating at $\nu_x = \nu_y = 3.26$
- Possible to increase tune spread by adjusting linear optics

Future Effort

- Tuning/characterization of low-current beams in modified lattice
- Add effects in simulation
  - Gridded field models, lattice errors, dispersion
  - Balance driving terms against nonlinear effects

Thanks for your attention!

Acknowledgments:

UMER group:

Rami Kishek, Dave Sutter, Levon Dovlatyan, Eric Montgomery

Heidi Komkov (UMER octupoles), Santiago Bernal (low-current beams)

IOTA collaboration

FNAL support for UMER realignment prior to nonlinear optics experiments

ORNL for supporting presentation of this work

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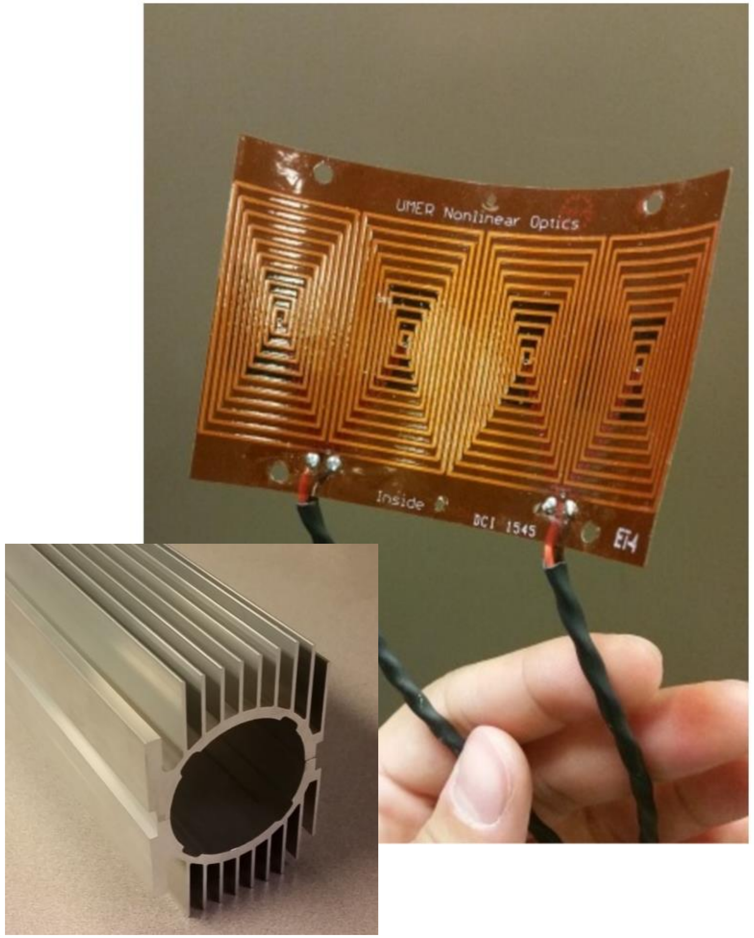
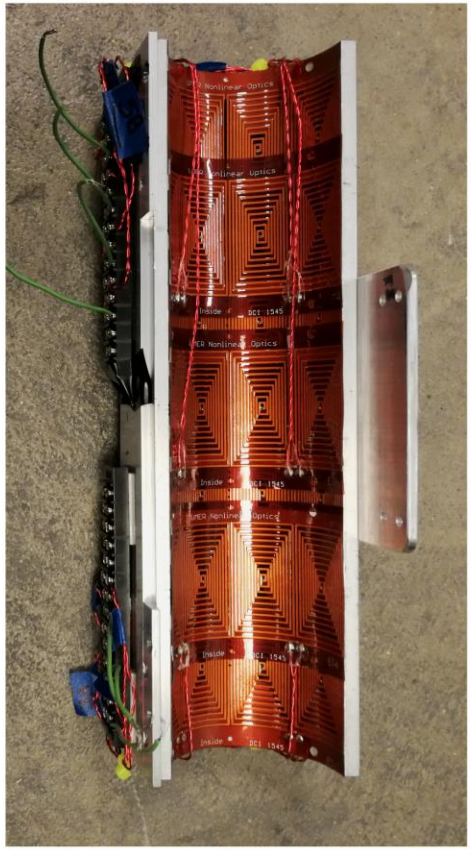
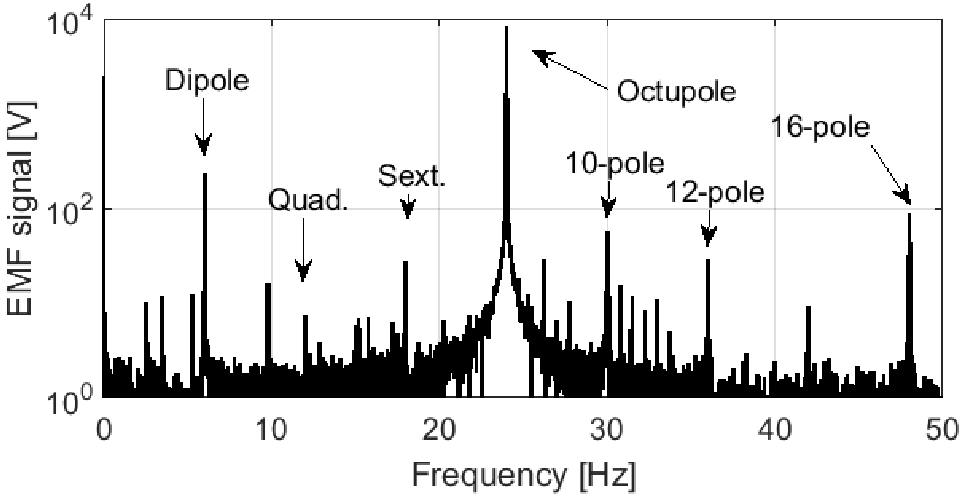
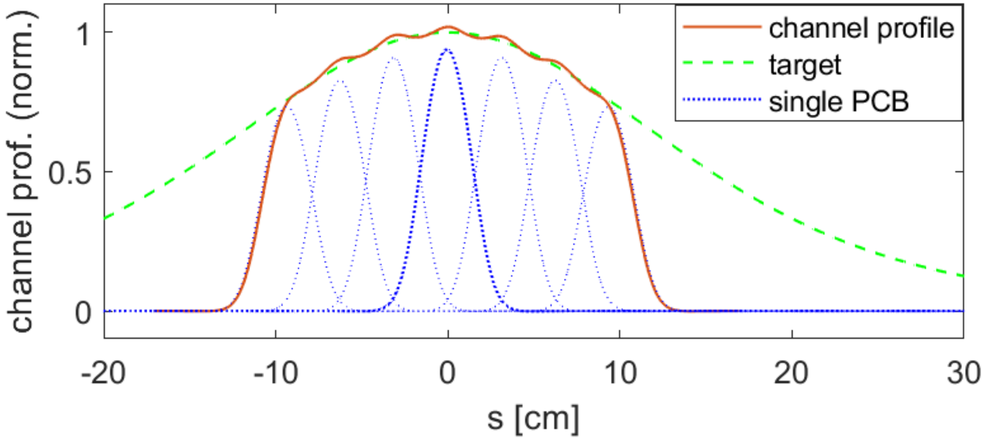
Back-up Slides

UMER octupole insert design





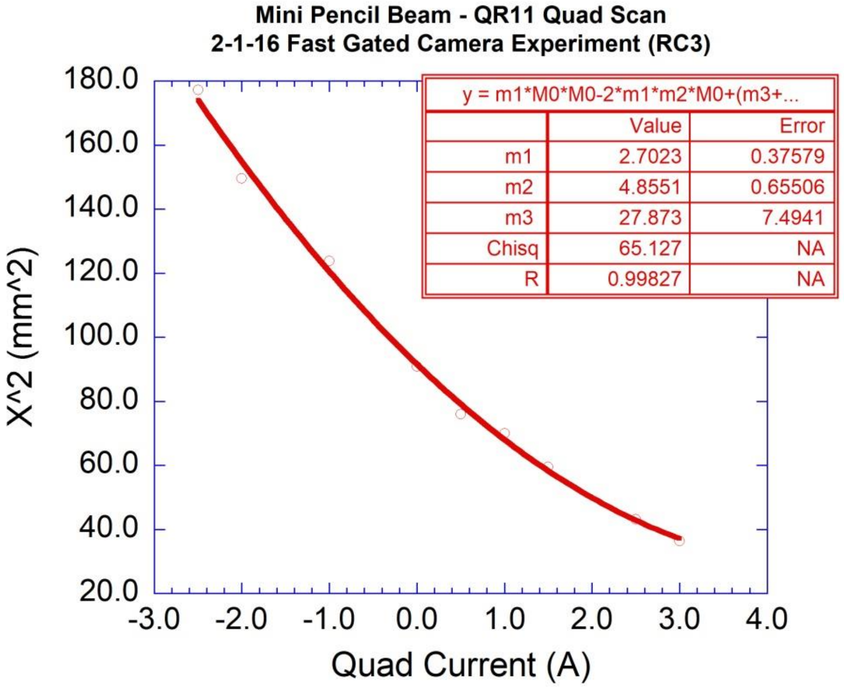




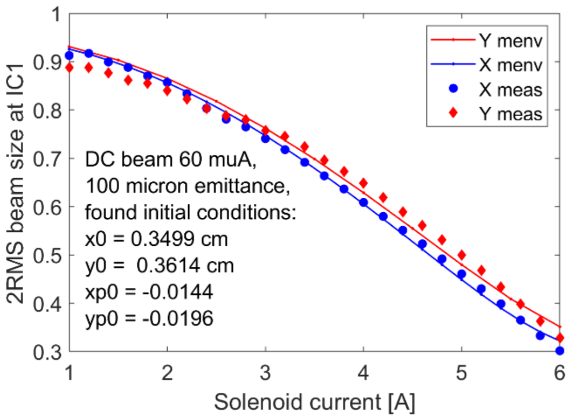
Characterization of low-charge, high-emittance µA beam: emittance and initial conditions

2/3/2016: measurement of DC beam emittance using quad-scan technique (varying QR11, pictures at RC3 fast screen) * see Bernal 2016 AAC paper

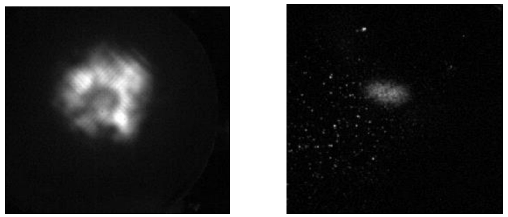
CURRENT	PULSE LENGTH	MEASUREMENT
10 –100 µA	150 ns	40 µA , $\epsilon_{x,y} \approx 300{,}100\ \mu m \pm 20\ \mu m$ 4rms, unnorm.

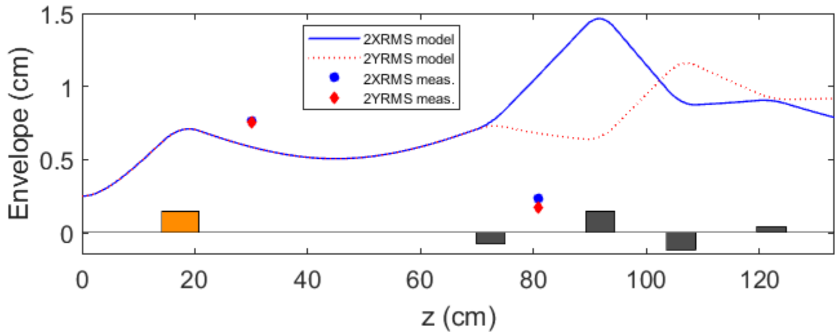


4/24/2018: measurement of beam response to solenoid, assuming 100 μm emittance:

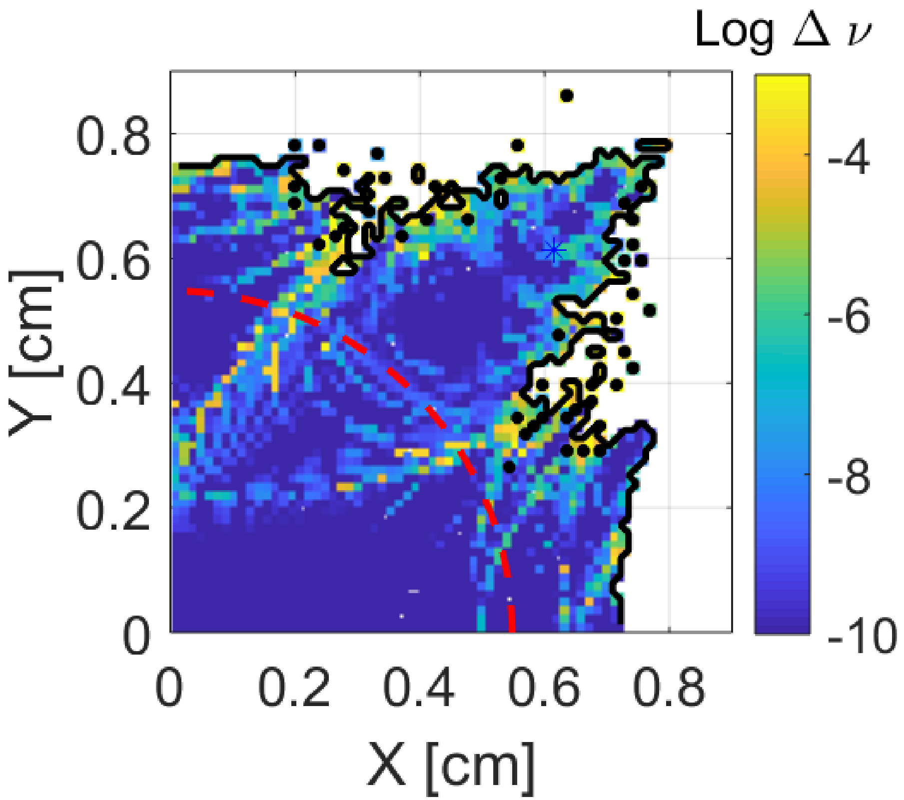


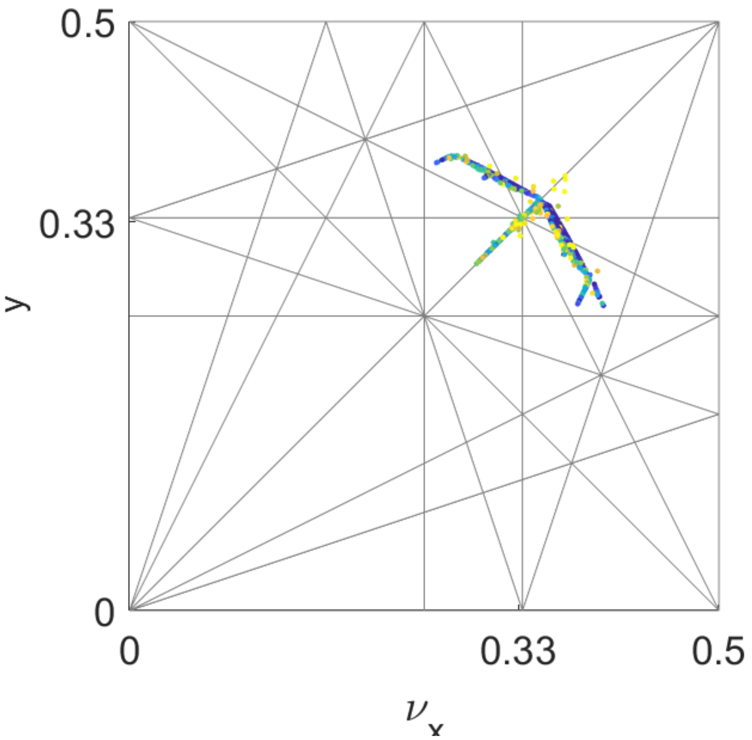
4/24/2018:
Comparison to envelope model





Increasing tune ($\nu = 3.35$) actually works pretty well (despite being off QI condition)

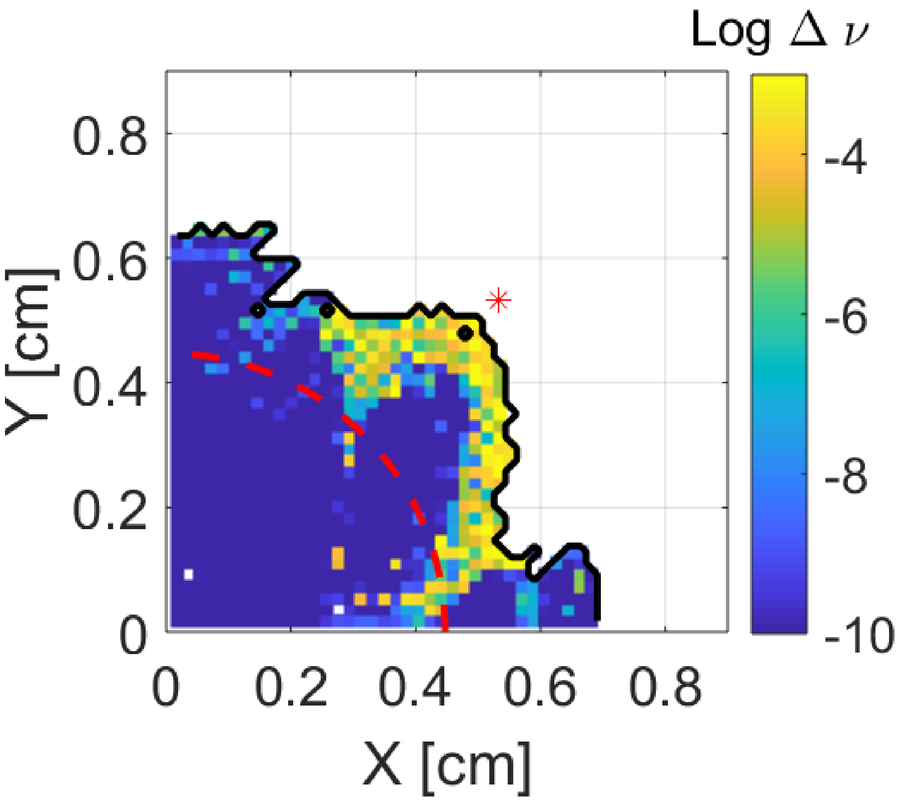


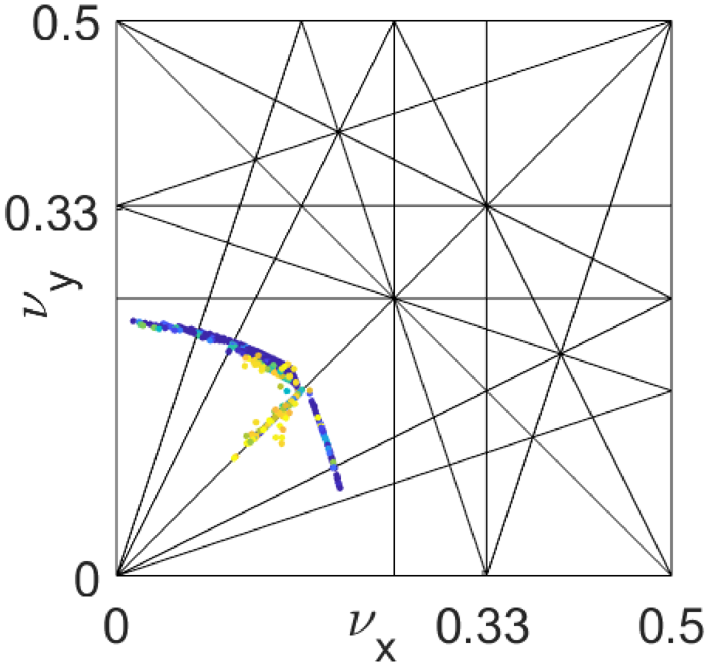


β_*	0.3 m
ν_x	3.357
ν_y	3.344
Peak Oct. Strength	50 T/m^3
I_{beam}	0 A

Max $\Delta\nu$	0.06
$RMS\ \Delta\nu$	0.02
Stable aperture	0.65 cm
$\left\langle \frac{stdH_N}{H_N} \right\rangle$	2.3%

$\beta_* = 0.2\ m, \nu = 3.18$

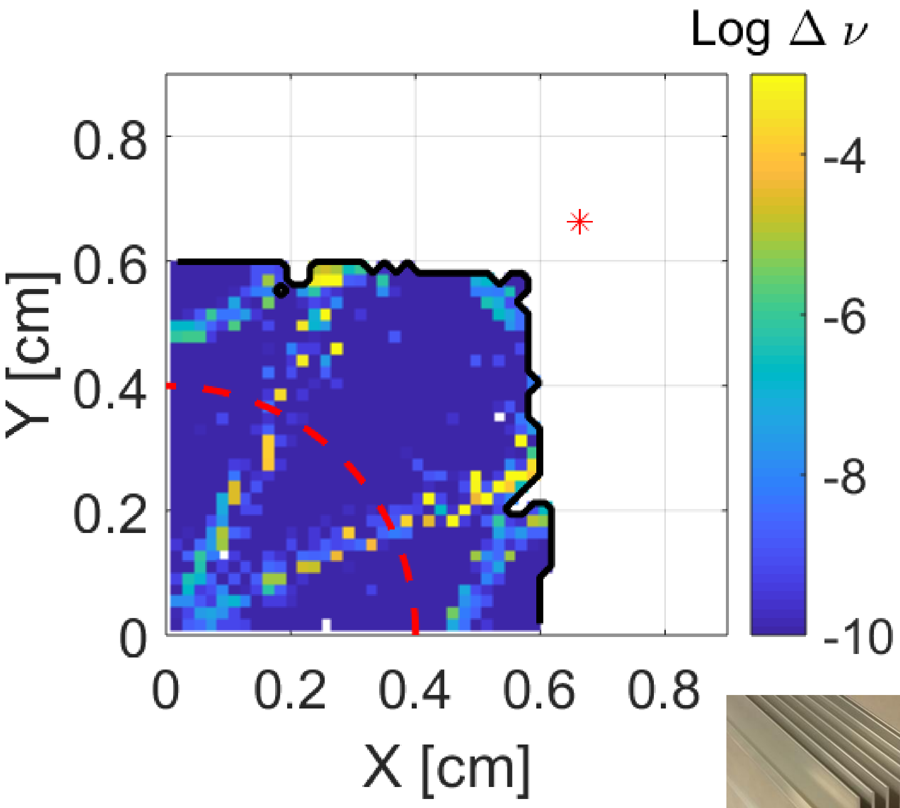


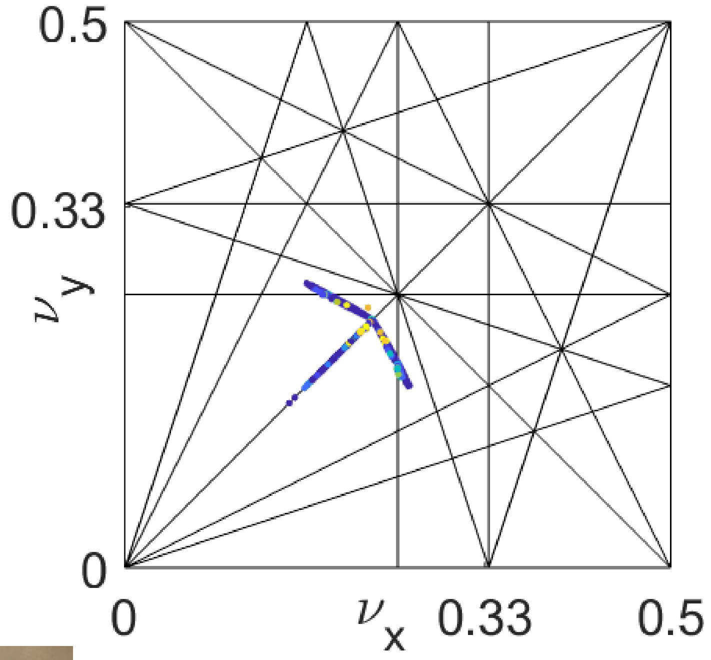


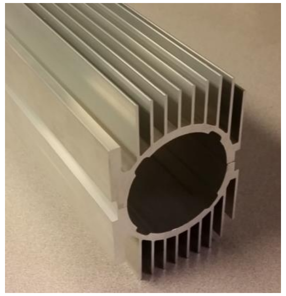
β_*	0.2 m
ν_x	3.159
ν_y	3.189
Peak Oct. Strength	150 T/m^3
I_{beam}	0 A

Max $\Delta\nu$	0.08
$RMS\ \Delta\nu$	0.02
Stable aperture	0.53 cm
$\left\langle \frac{stdH_N}{H_N} \right\rangle$	2.8%

$\beta_* = 0.16\, m, \nu = 3.22$





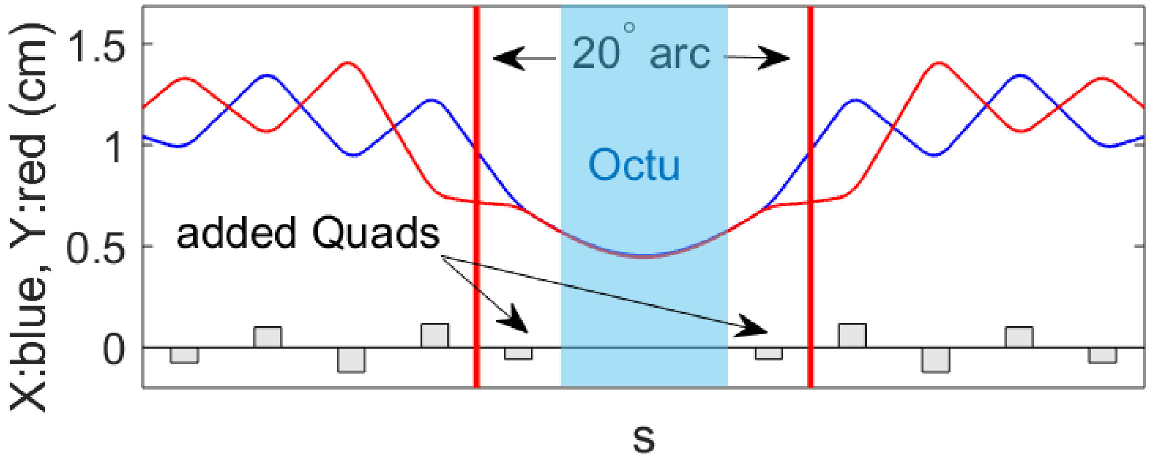


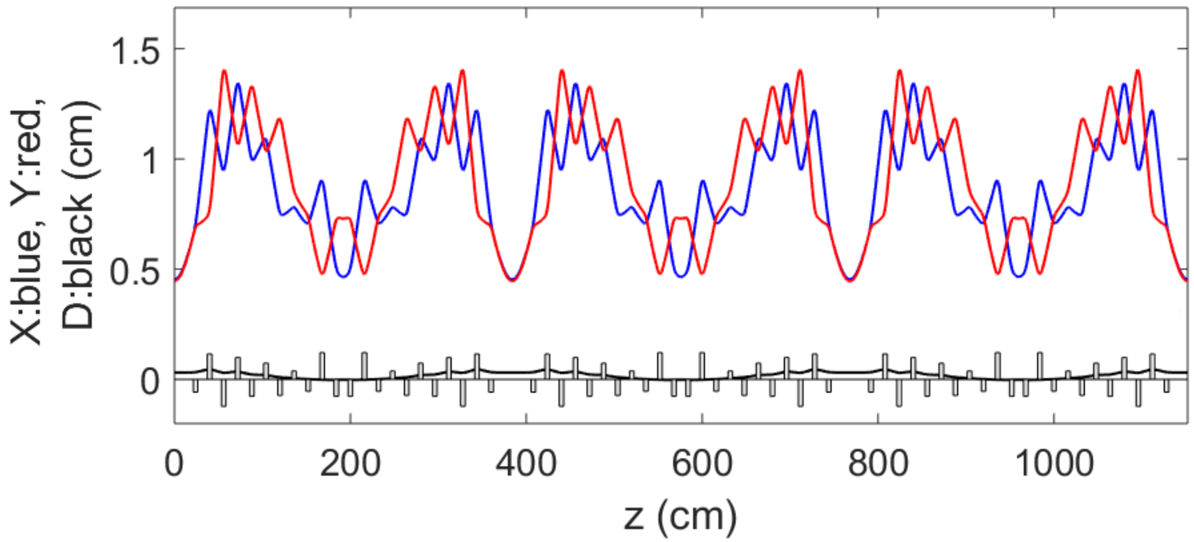
Octupole strength > 150 T/m^3 should be supported with improved heat dissipation design in octupole mount.

β_*	0.16 m
ν_x	3.231
ν_y	3.230
Peak Oct. Strength	150 T/m^3
I_{beam}	0 A

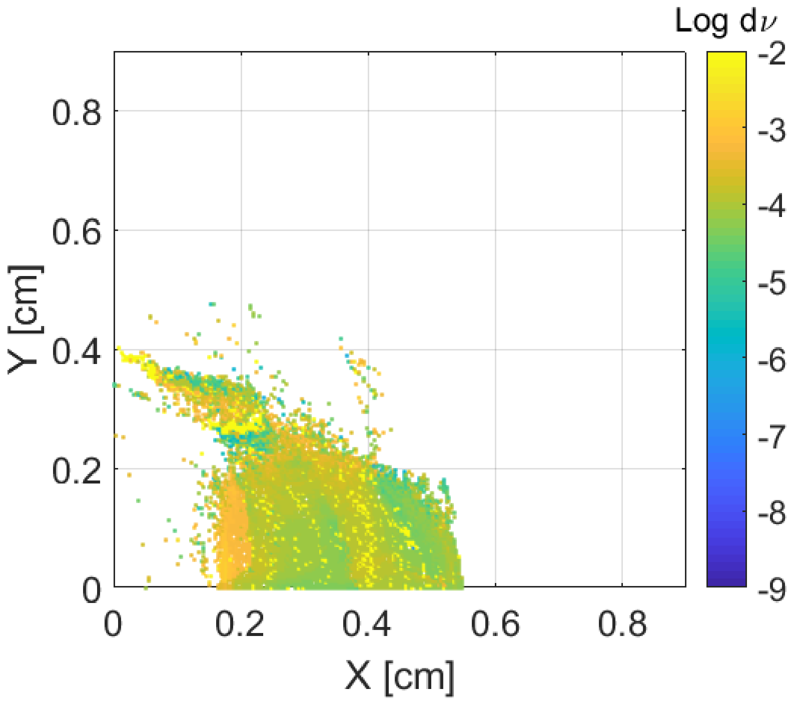
Max $\Delta\nu$	0.06
$RMS\ \Delta\nu$	0.02
Stable aperture	0.58 cm
$\left\langle \frac{std H_N}{H_N} \right\rangle$	3.6%

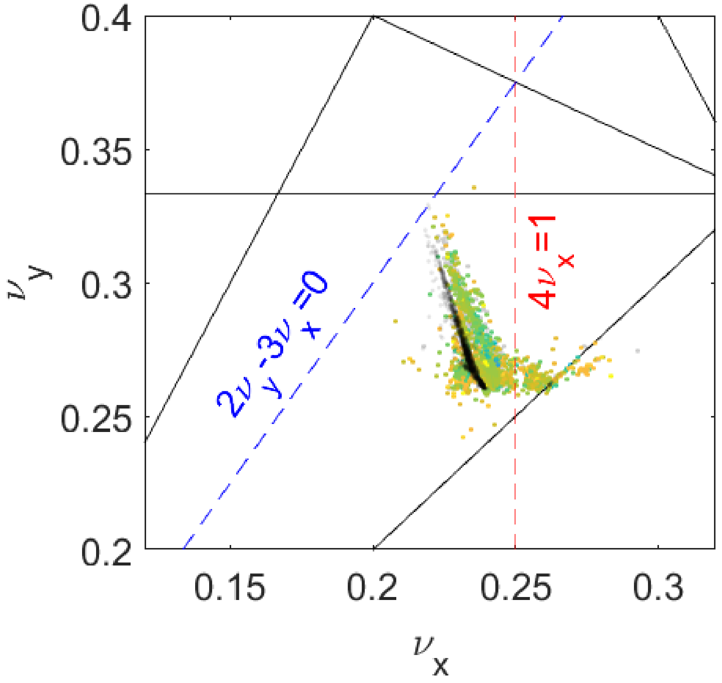
You can gain a little by decreasing size of beam waist

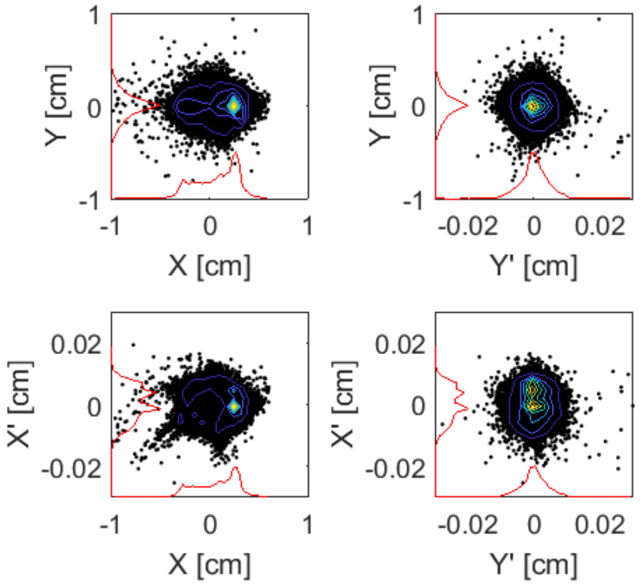




Earlier attempt also showed large losses near $\nu = 0.25$

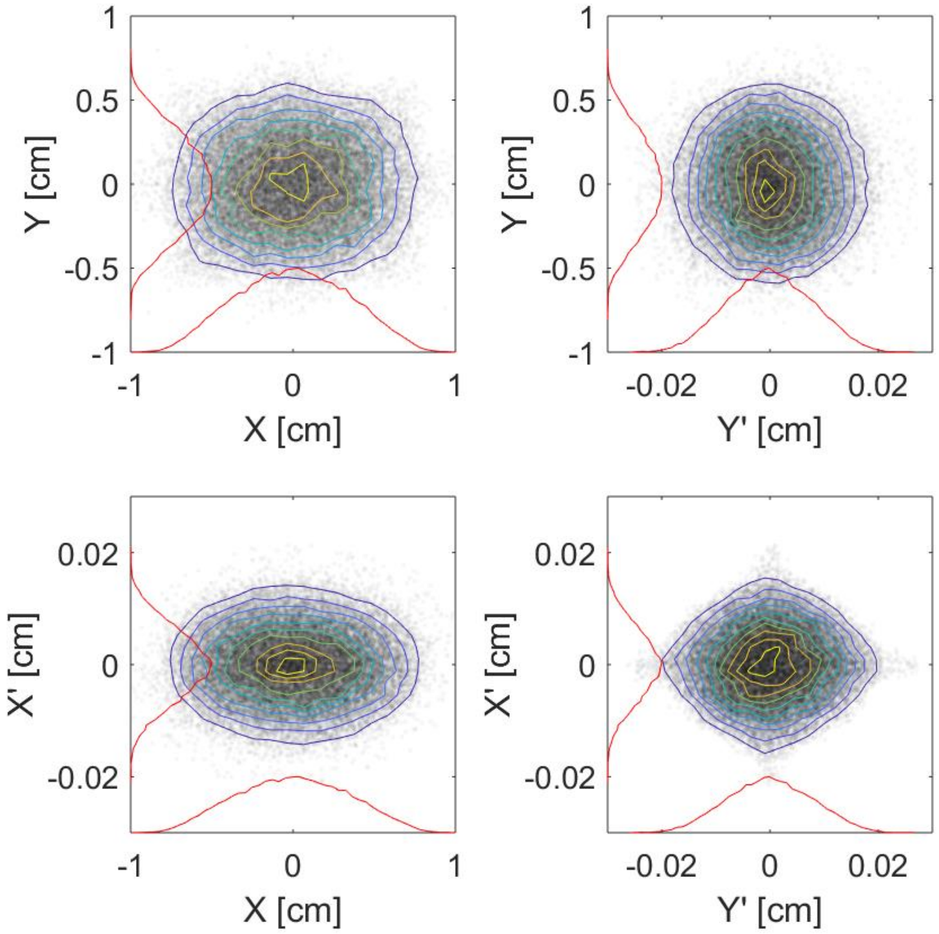


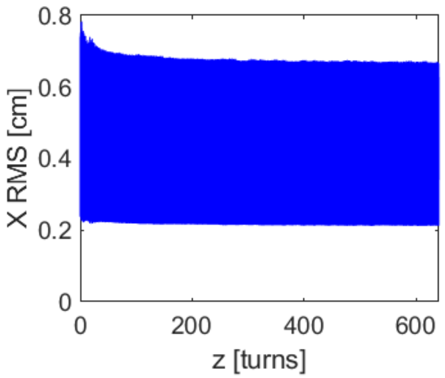


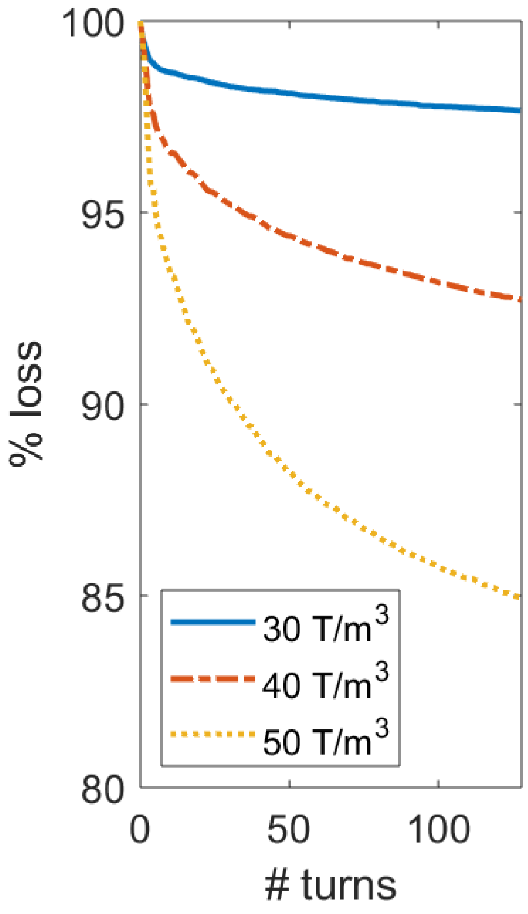


Ruisard, K. (2018). University of Maryland College Park.

Need to operate near stability limit for maximum tune spread

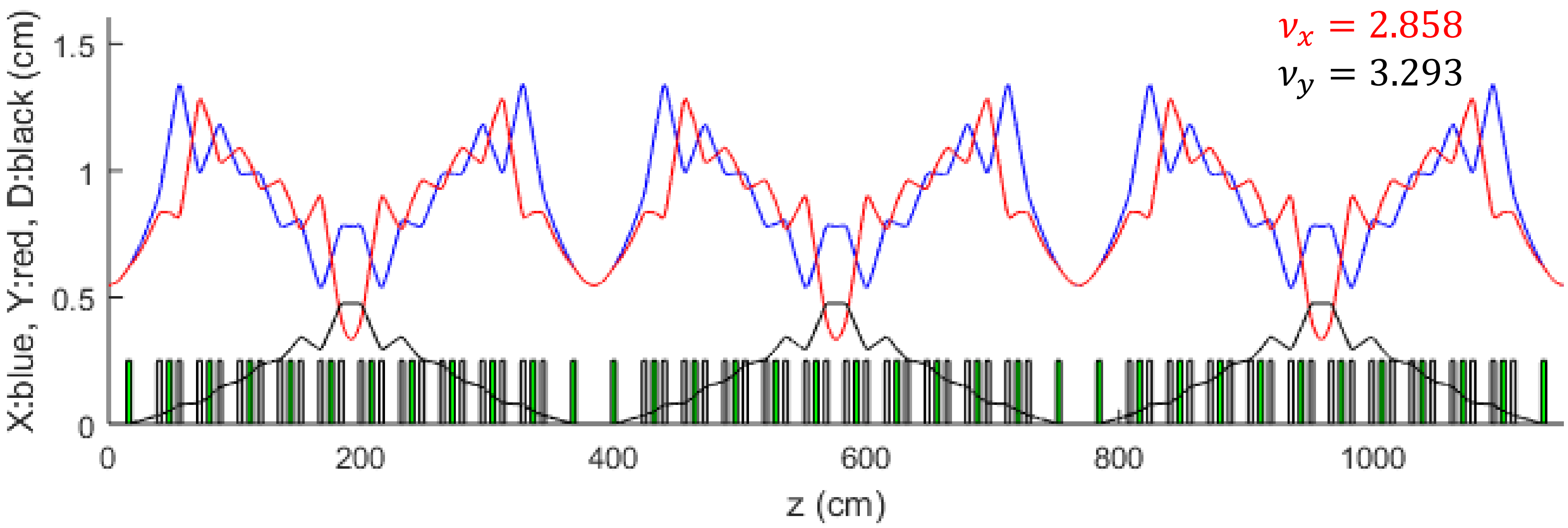




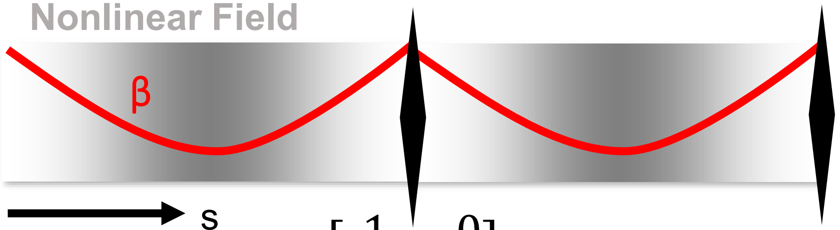


Lattice Solution

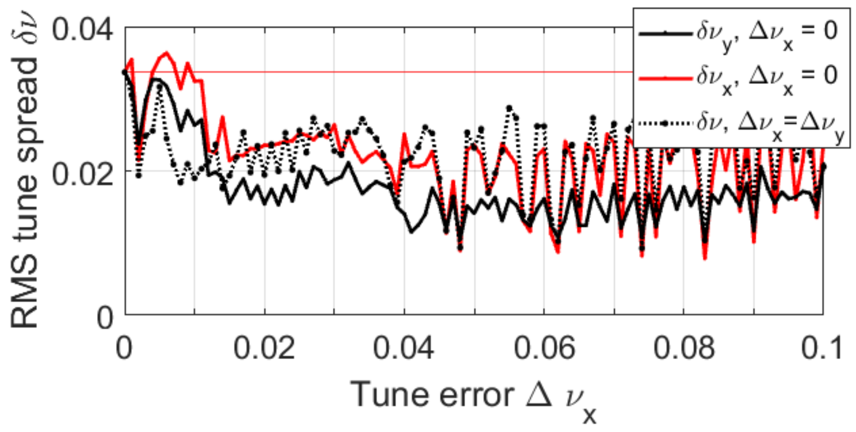
"Low-current" 60 mu-A beam: $\epsilon \approx 100\ \mu m$

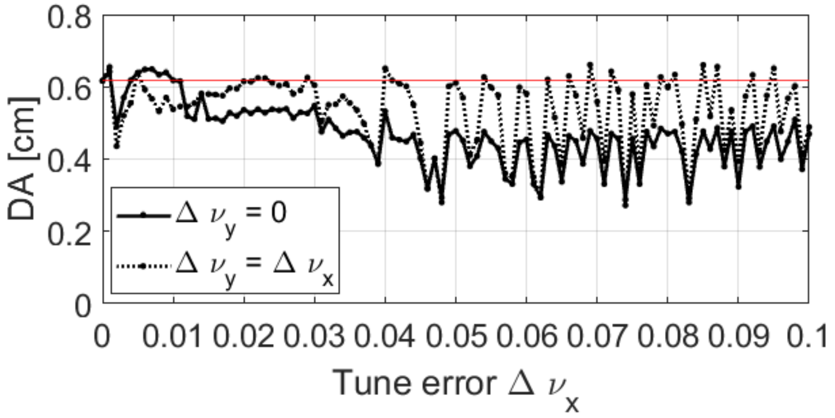


Dynamics relatively insensitive to errors in linear lattice tune



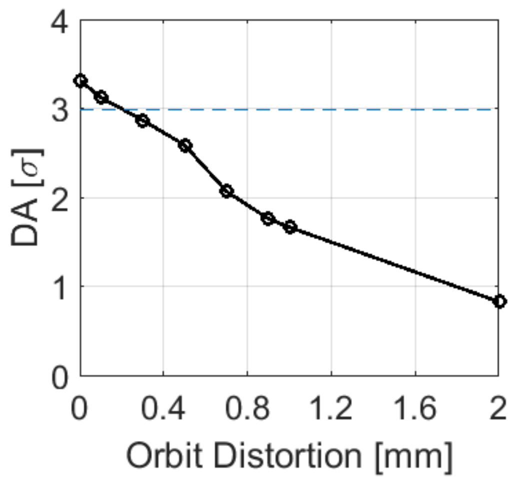
$$\begin{bmatrix} 1 & 0 \\ -k & 1 \end{bmatrix}$$ + phase shift



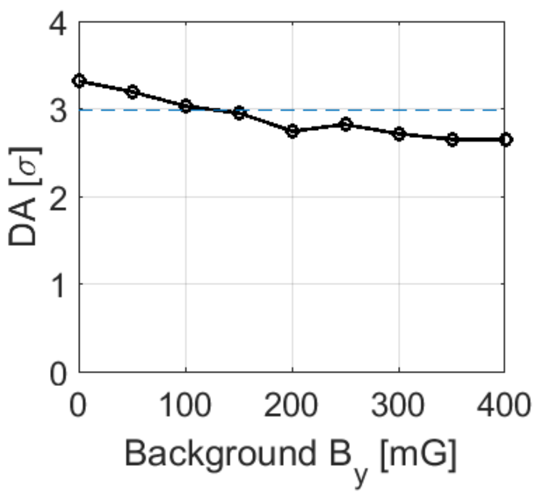


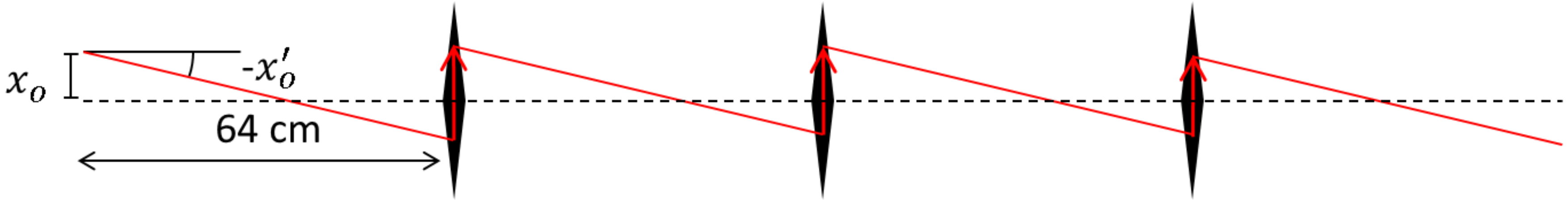
Dynamic aperture suffers when beam centroid is off-axis

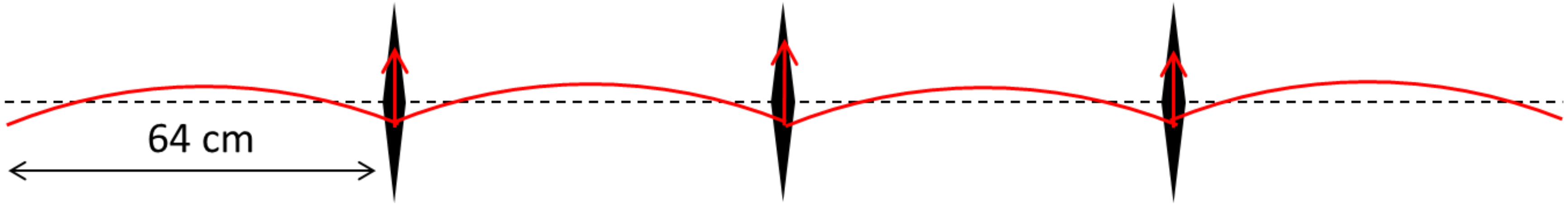
$\bar{x}, \bar{y} < 0.2$ mm distortion



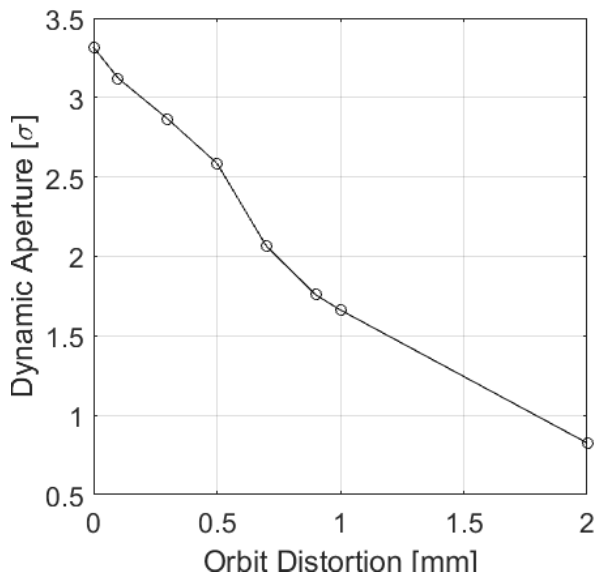
$B_y < 100$ mG







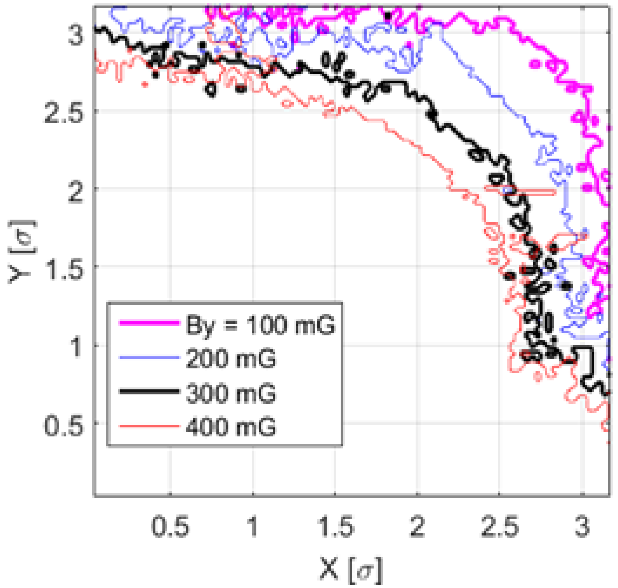
Steering tolerances for beam through long octupole channel

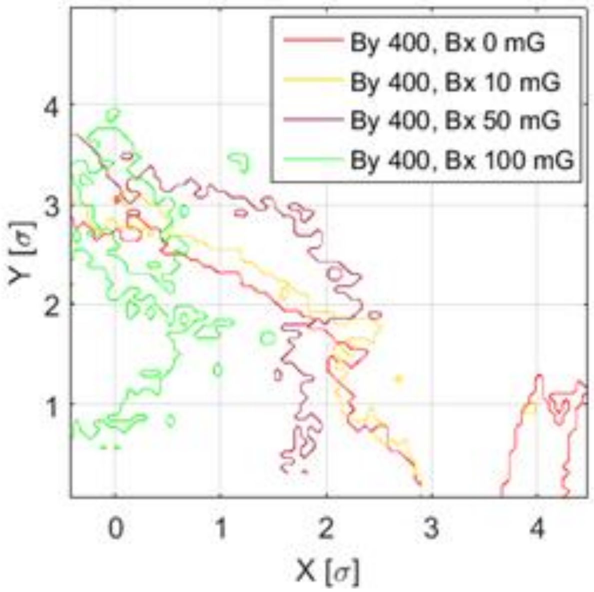


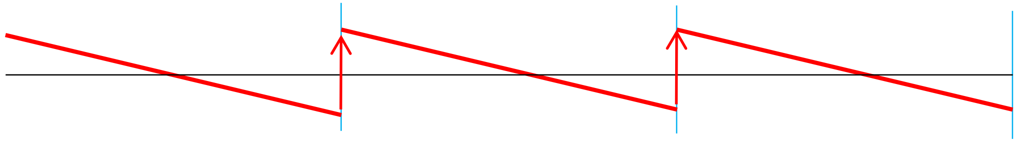
“Toy model” WARP simulations with steering error;

Left: dependence on orbit distortion

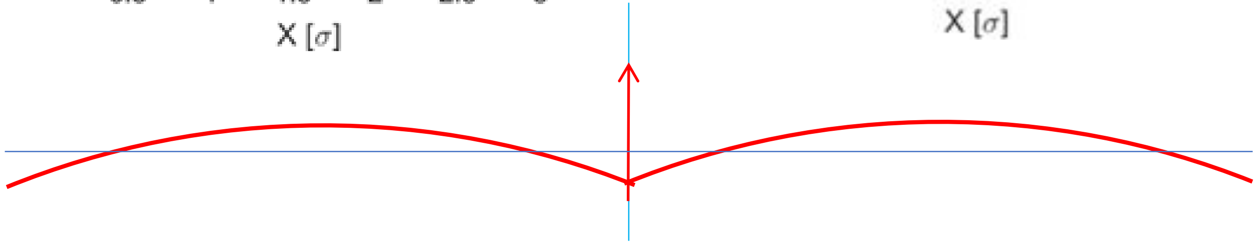
Right: immersed in background field







Beam with closed orbit distortion



Beam immersed in background field