UMER 2.0: Adapting the University of Maryland Electron Ring to explore intermediate space-charge and nonlinear optics for Hadron and ion beam facilities

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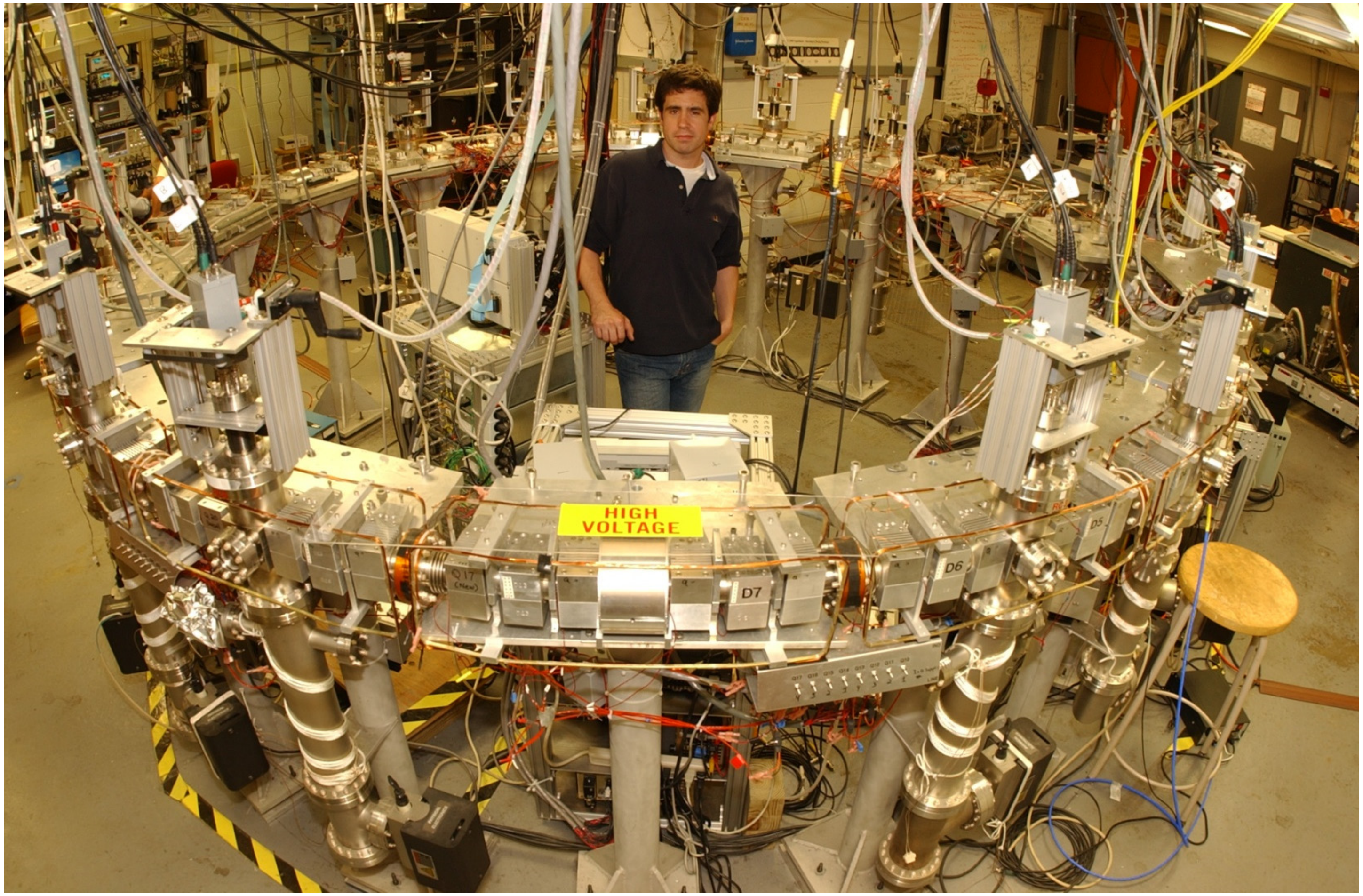
Outline

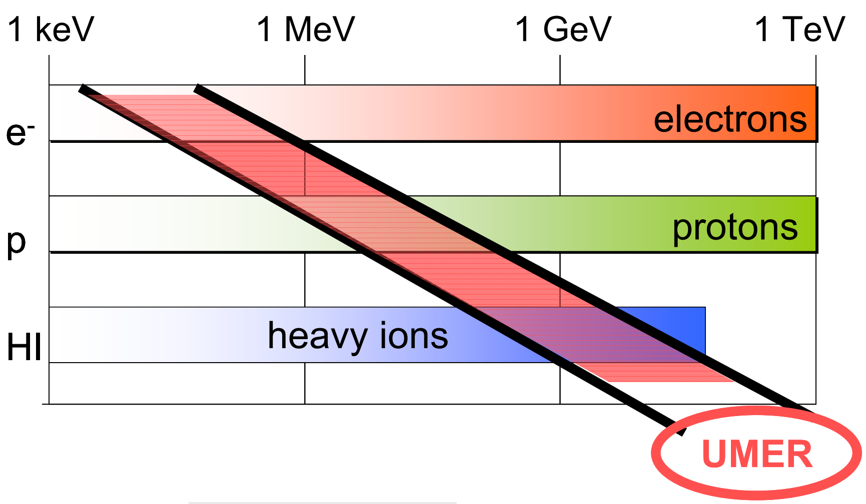
1. Introduction to UMER
2. Brief overview of recent accomplishments (last 2 years)
   - Solitons
   - Barrier Shock compression
   - Resonances, Halo, and beam loss mechanism
3. Proposed upgrades open door to new physics
   - Nonlinear optics testbed
4. Conclusions

University of Maryland Electron Ring (UMER)

Flexible, Low-cost testbed for high-intensity beam dynamics



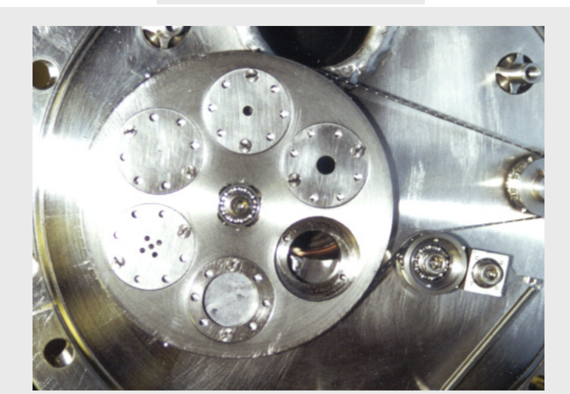
Why Low Energy Electrons?

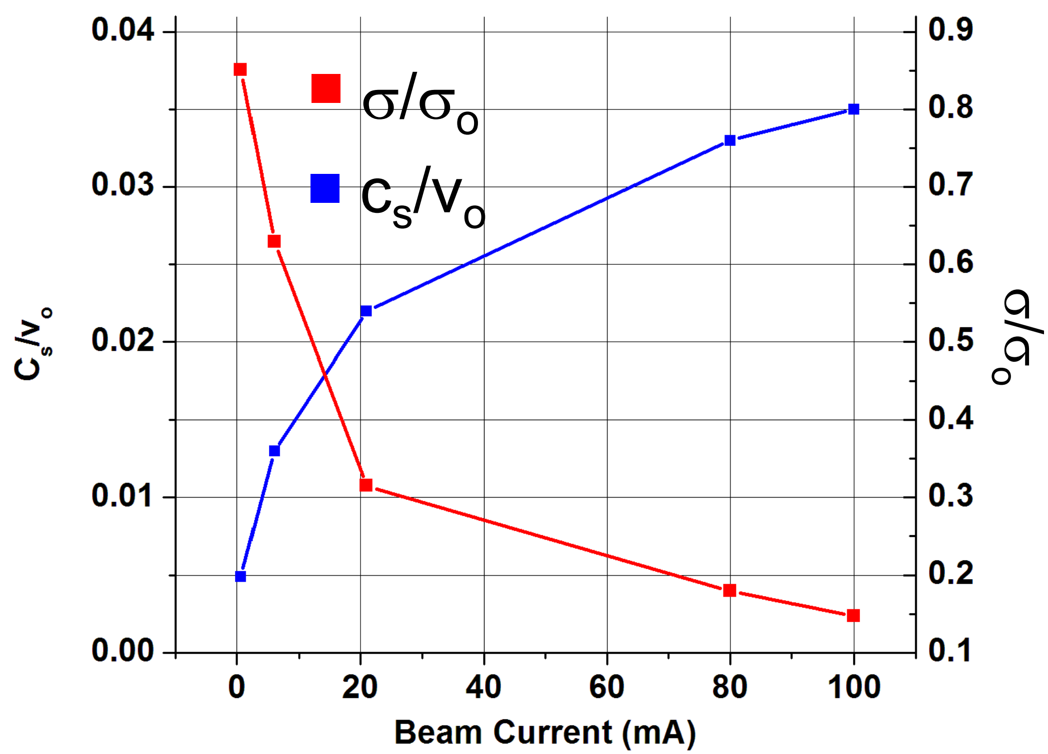


10-50 keV electrons
~ 20-100 MeV / nucleon

UMER spans a broad range of intensities through the use of an aperture plate

APERTURE PLATE





Tune shift

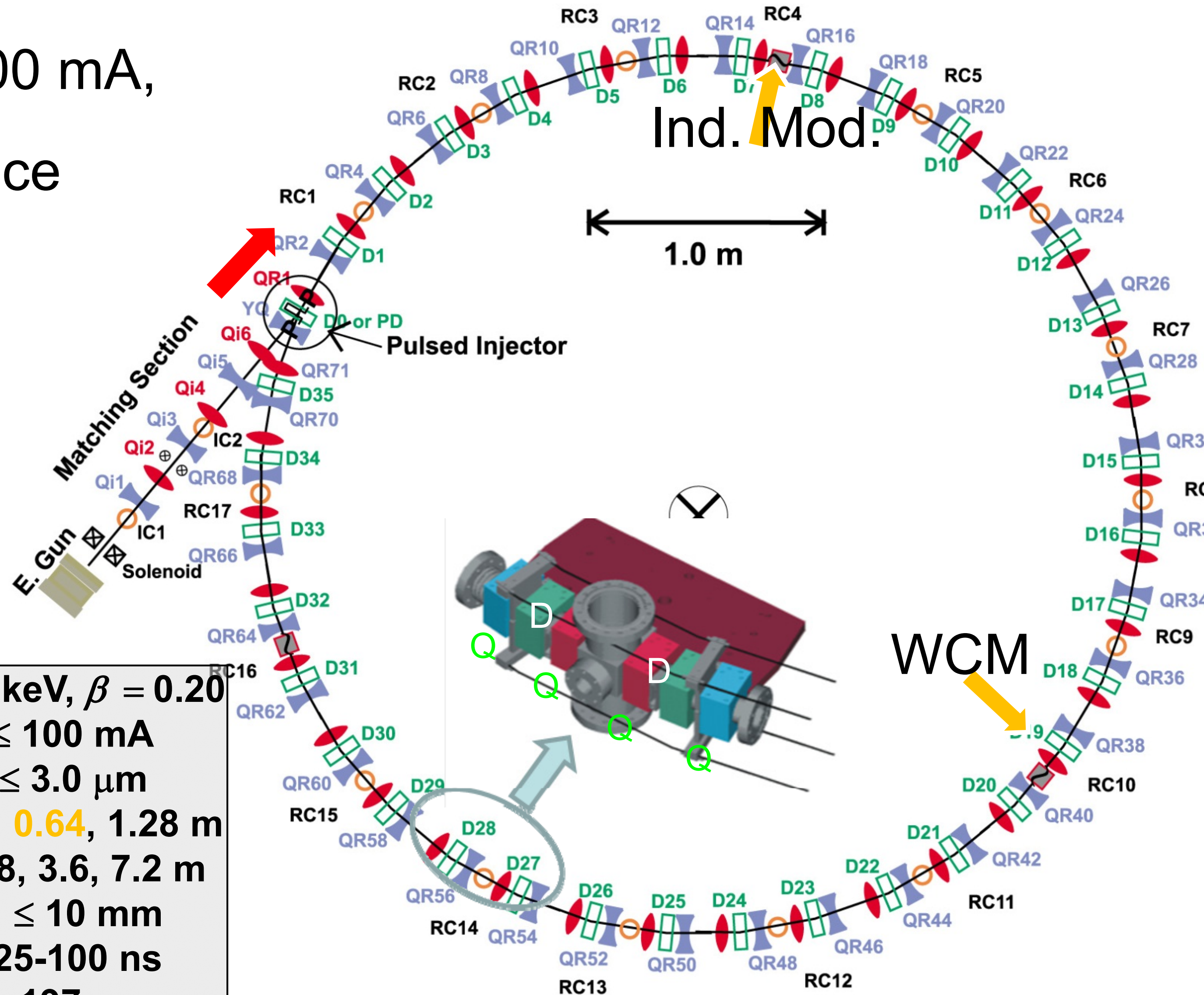
$$\Delta Q = Q_o \left(1 - \frac{\sigma}{\sigma_o} \right)$$

UMER Layout

10 keV e-, 0.5-100 mA,

0.3-3 μm emittance

~10^{10} particles



Energy:	**$\leq$ 10 keV, $\beta = 0.20$**
Current, *I*:	**$\leq$ 100 mA**
Emittance*, ε:	**$\leq$ 3.0 μm**
Lattice period, *S*:	**0.32, 0.64, 1.28 m**
Zero-current λ_0:	**≈ 1.8, 3.6, 7.2 m**
Av. beam radius, *a*:	**$\leq$ 10 mm**
Pulse length:	**25-100 ns**
Lap time:	**197 ns**

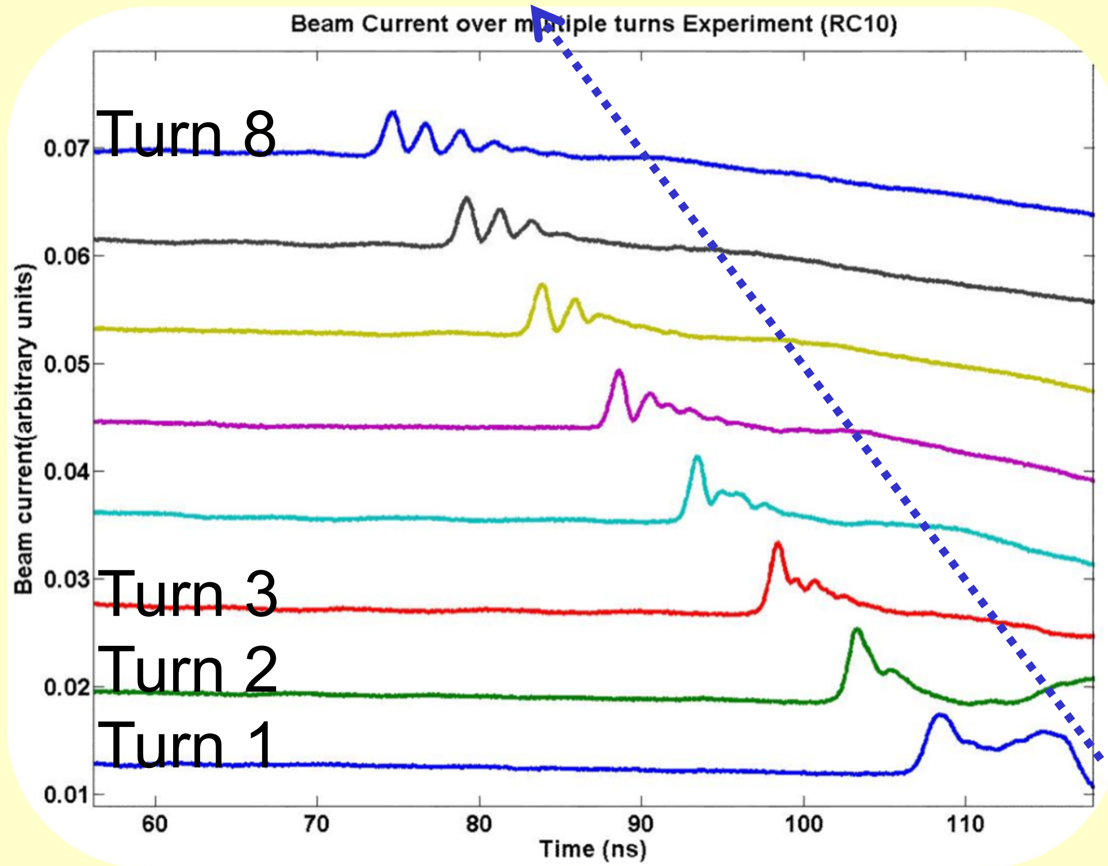
***norm., rms**

First Experimental Observation of Soliton Wave Trains in Electron Beams

Persistent large-amplitude waves that retain their shape

Nonlinear steepening balances wave dispersion

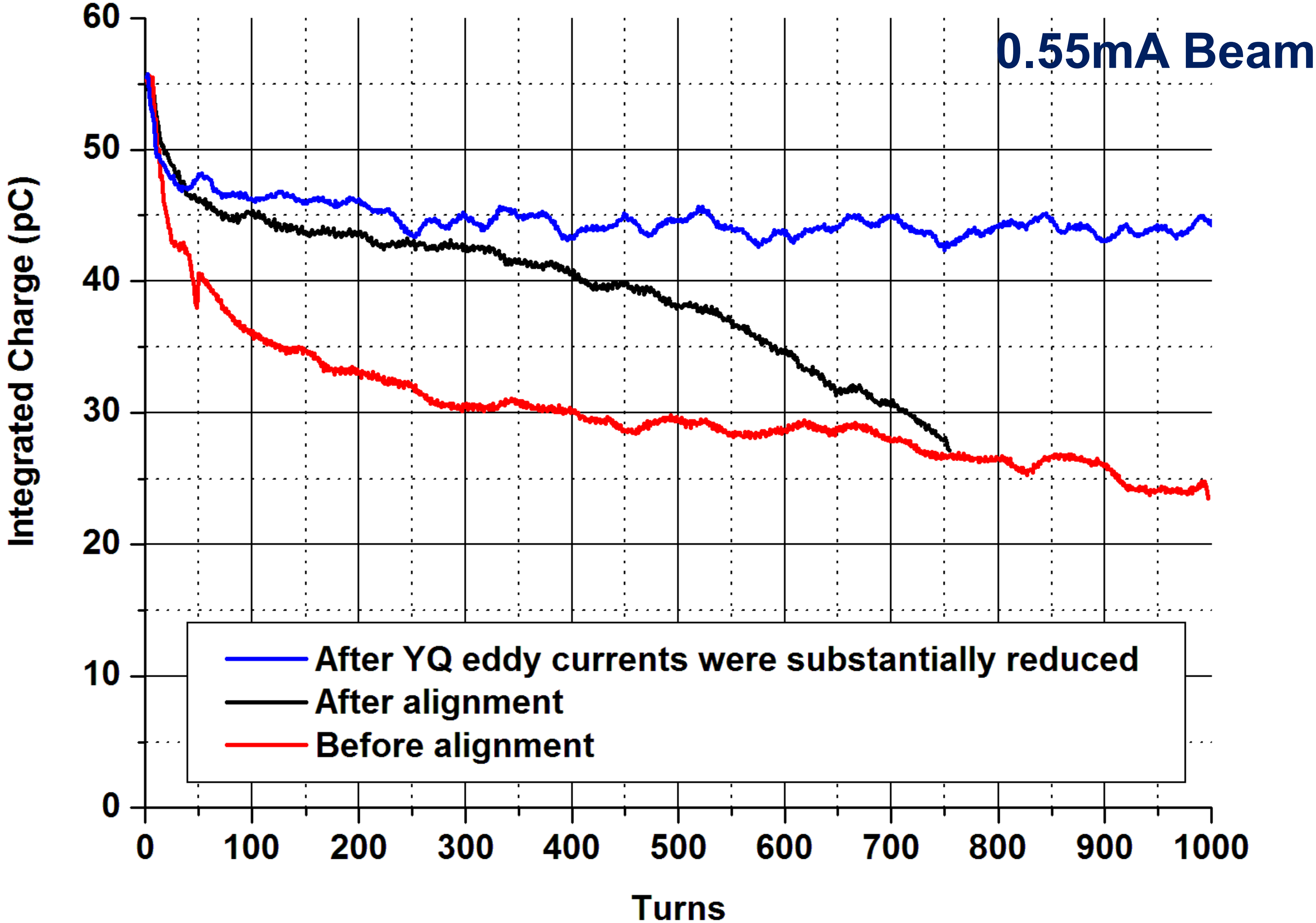
Evolution of Large-Amplitude Perturbation



J. Charles T. Thangaraj, Ph.D. Thesis, (2009) and

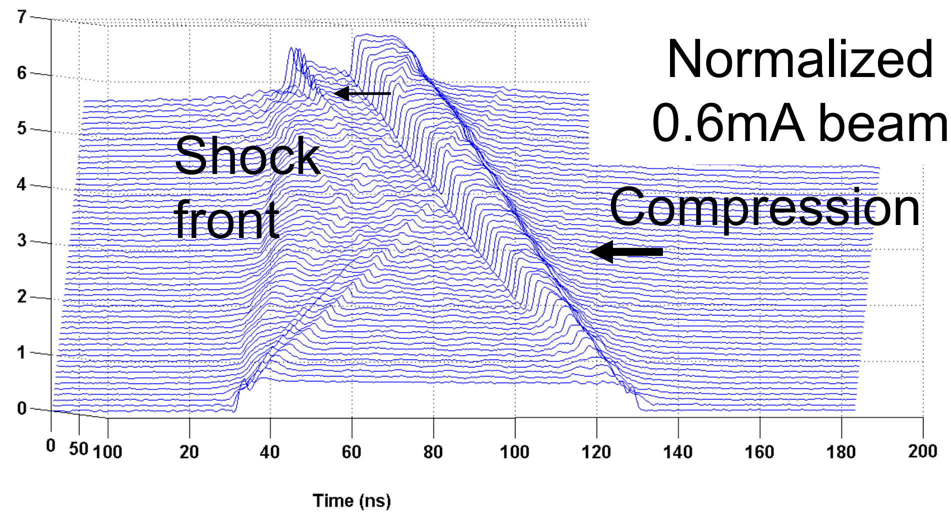
Y. C. Mo et al, Phys. Rev. Lett. 110, 084802 (2013)

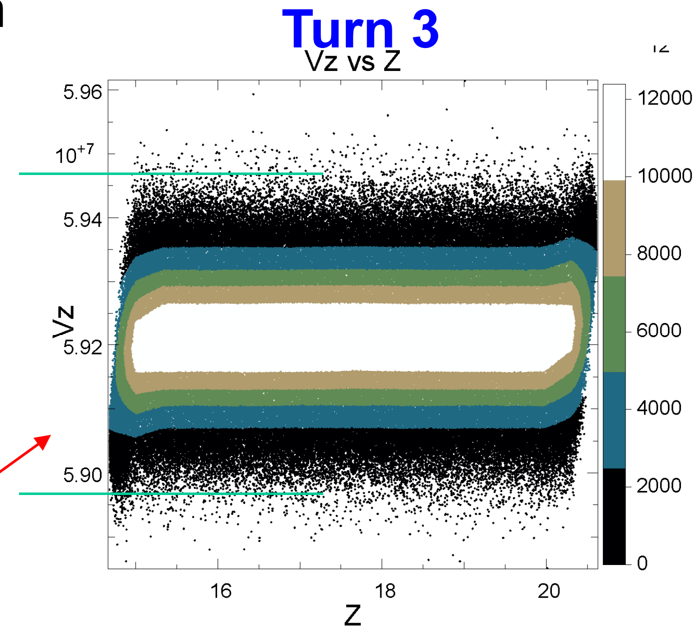
Barrier Bucket Longitudinal Focusing – Far Exceeded 100-turn design spec



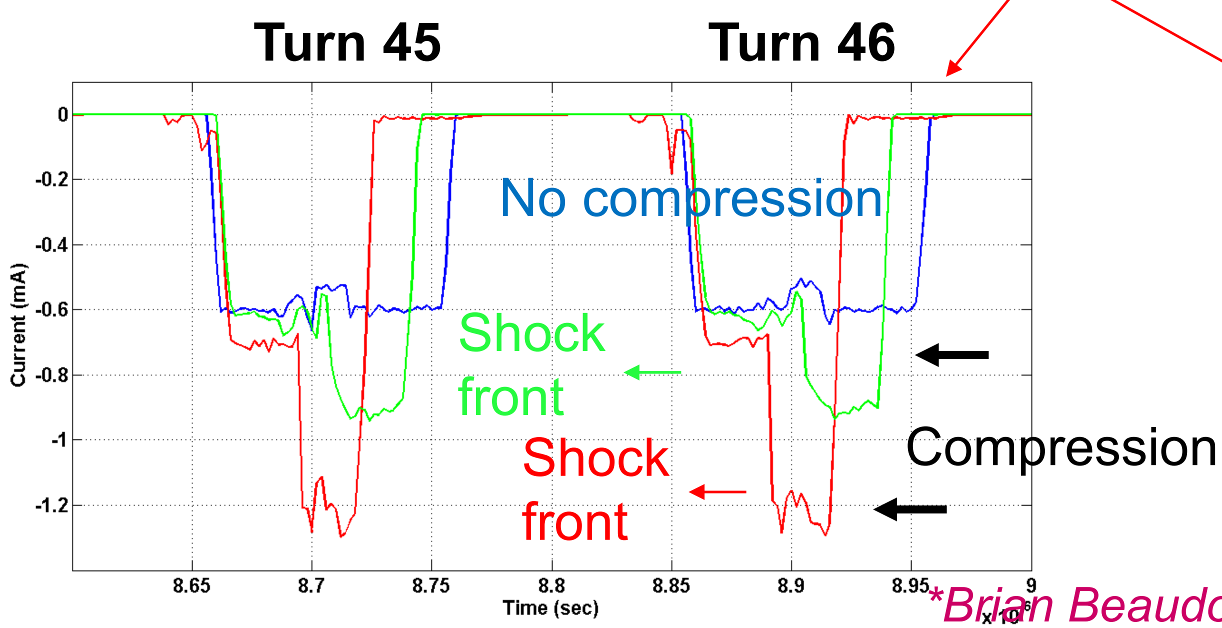
Barrier Shock Compression with Longitudinal Space-Charge

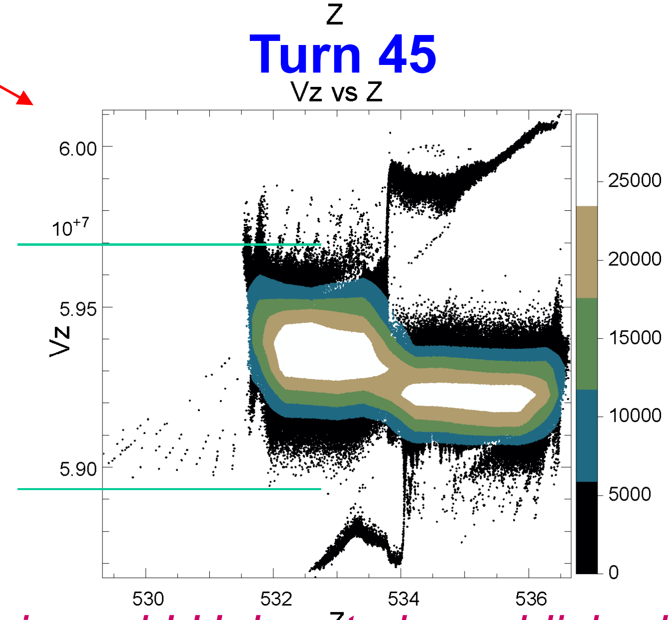
Measurements illustrating shock compression





WARP simulations

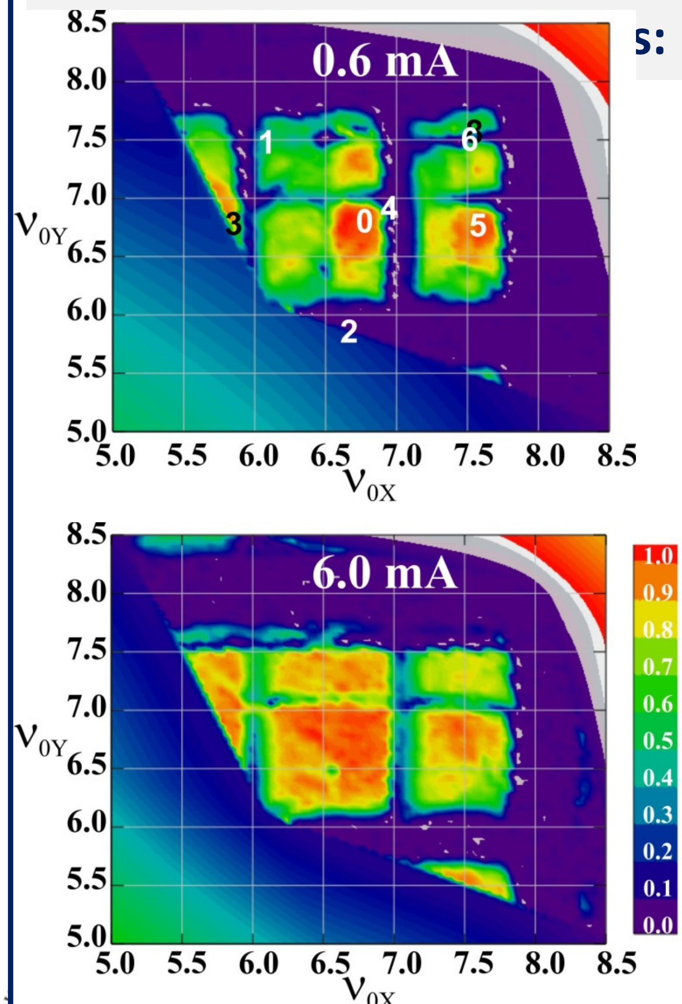




**Brian Beaudoin and I Haber, to be published*

BETATRON RESONANCES AND BEAM CURRENT*:
0.6 mA beam behaves more coherently than 6.0 mA

Transmitted peak beam current



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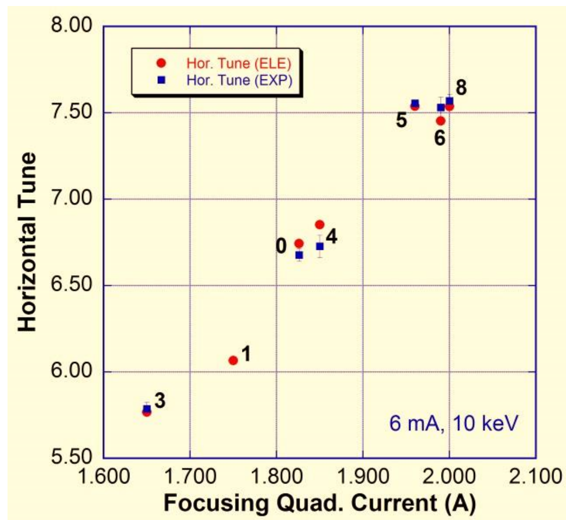
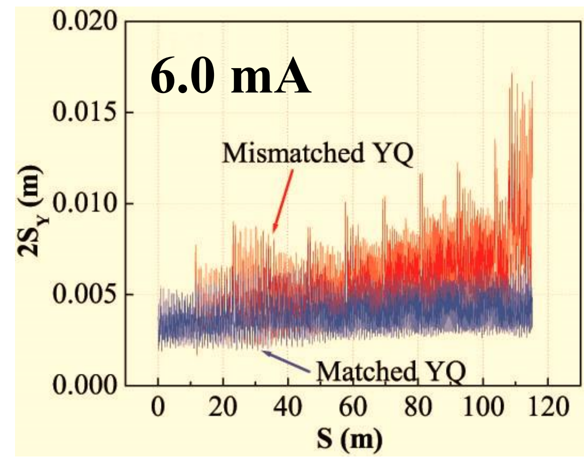
Measured vs. Calculated (ELEGANT) Tunes



Calculated (ELEGANT) Beam Envelope with space charge

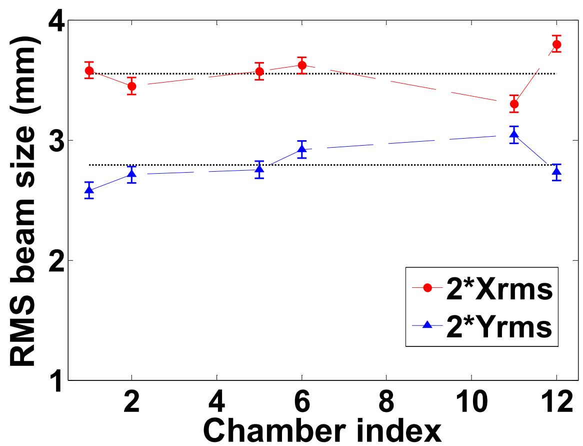


*S. Bernal et al, Proc. NA-PAC 2013, Pasadena, CA, Sep. 2013

IREAP

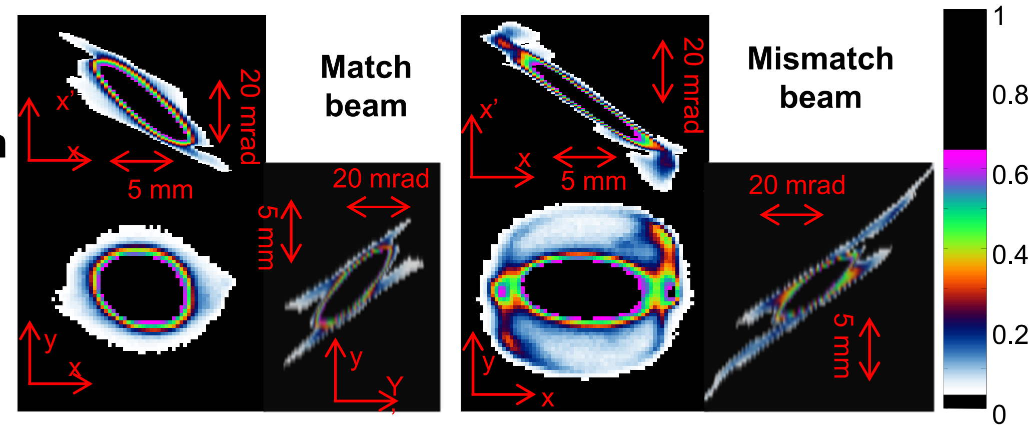
Halo Formation from mismatch in Experiment

First turn Beam Match result



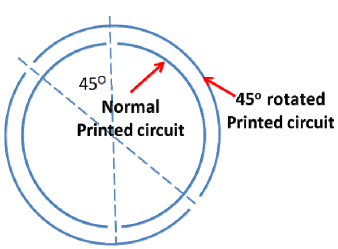
Halo from envelope mismatch

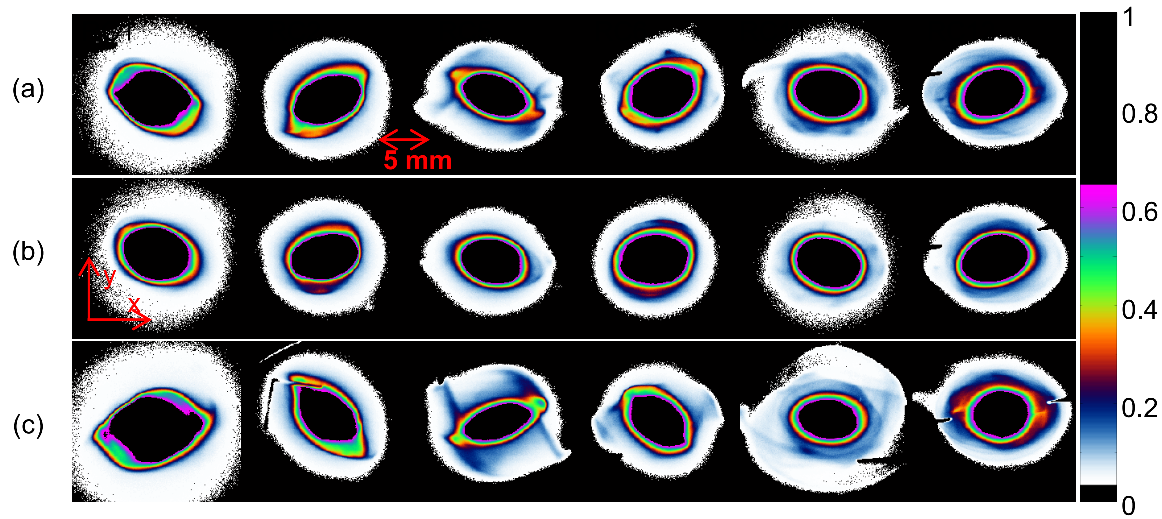
Reduce Injection Q5 by 20%



Halo from rotational error

Set skew quad at Q6:
(a) 0.5, (b) 0.1 and (c) -0.4

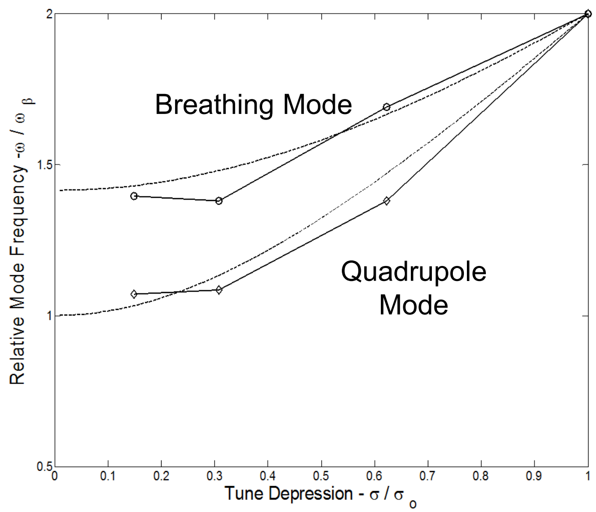




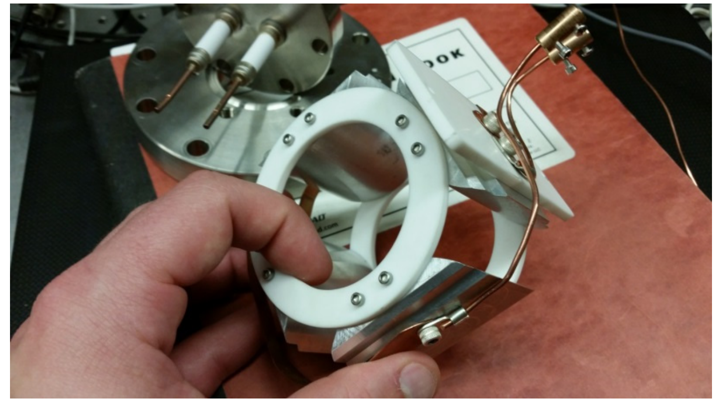
H. D. Zhang, B. L. Beaudoin, and R. A. Kishek, N-PAC 2013

Envelope Mode Characterization

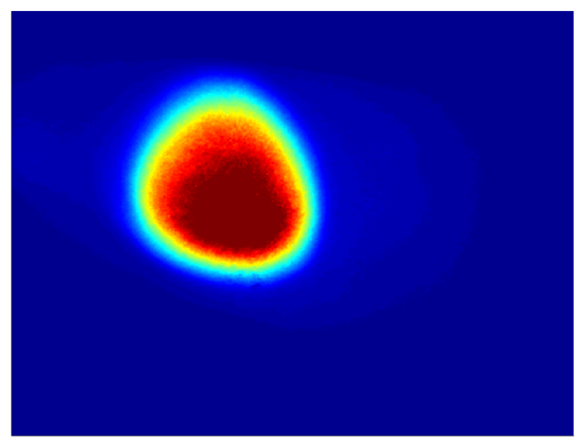
- Two modes ("breathing" and "quadrupole") with different nonlinear, intensity-dependent frequencies



- Image excited beam slice using fast phosphor screens and 3 ns gated camera to find location/ bandwidth of resonance modes



- Independently excite modes using tunable resonant circuit and electric quadrupole



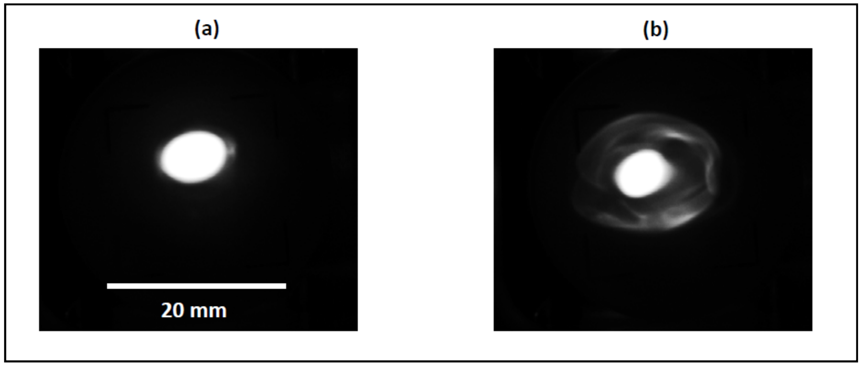
Will Stem, to be published

UMER as nonlinear optics testbed

- Nonlinear integrable optics theory is compelling for single particle dynamics (Danilov and Nagaitsev, Phys. Rev. ST Accel. Beams, 2010)
- UMER and ideal testing ground for nonlinear optics with space charge
  - Well bench-marked simulations
  - Inexpensive printed circuit magnets
  - UMER flexibility
    - Independently powered quadrupoles
    - Variable space charge
    - Tune-in halo

GOALS:

- Design and implement a nonlinear lattice in the UMER framework
- Experimentally verify lattice properties (stability, halo suppression)
- Investigate consequences of space charge through experiment and simulation



Beam halo through quadrupole mismatch
Phosphor screen images

Following slides courtesy of Kiersten Ruisard

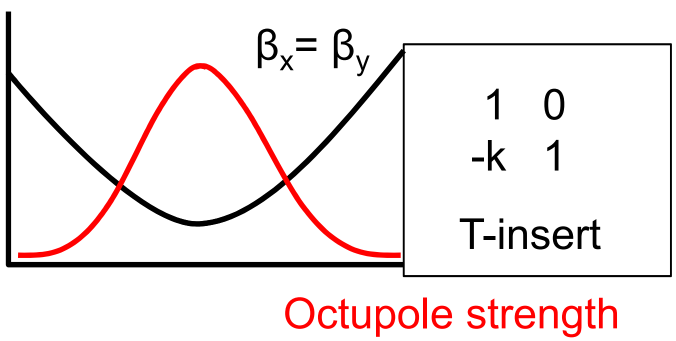
"Quasi-integrable" octupole lattice

- 1 invariant of motion if octupole potential is scaled longitudinally:

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

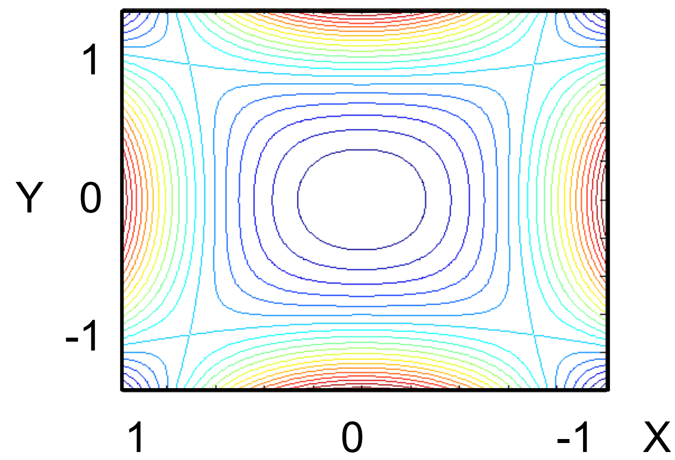
Danilov and Nagaitsev, Phys. Rev. ST Accel. Beams, 2010

- Implementing octupole lattice

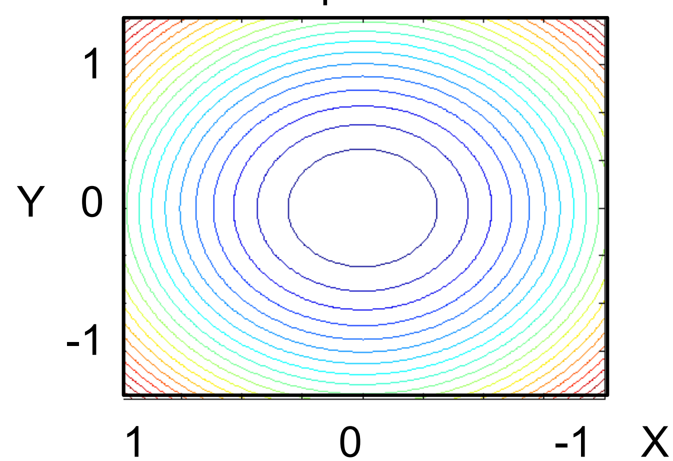


- Shown to suppress halo (S.D. Webb and D. Bruhwiler, to be published)

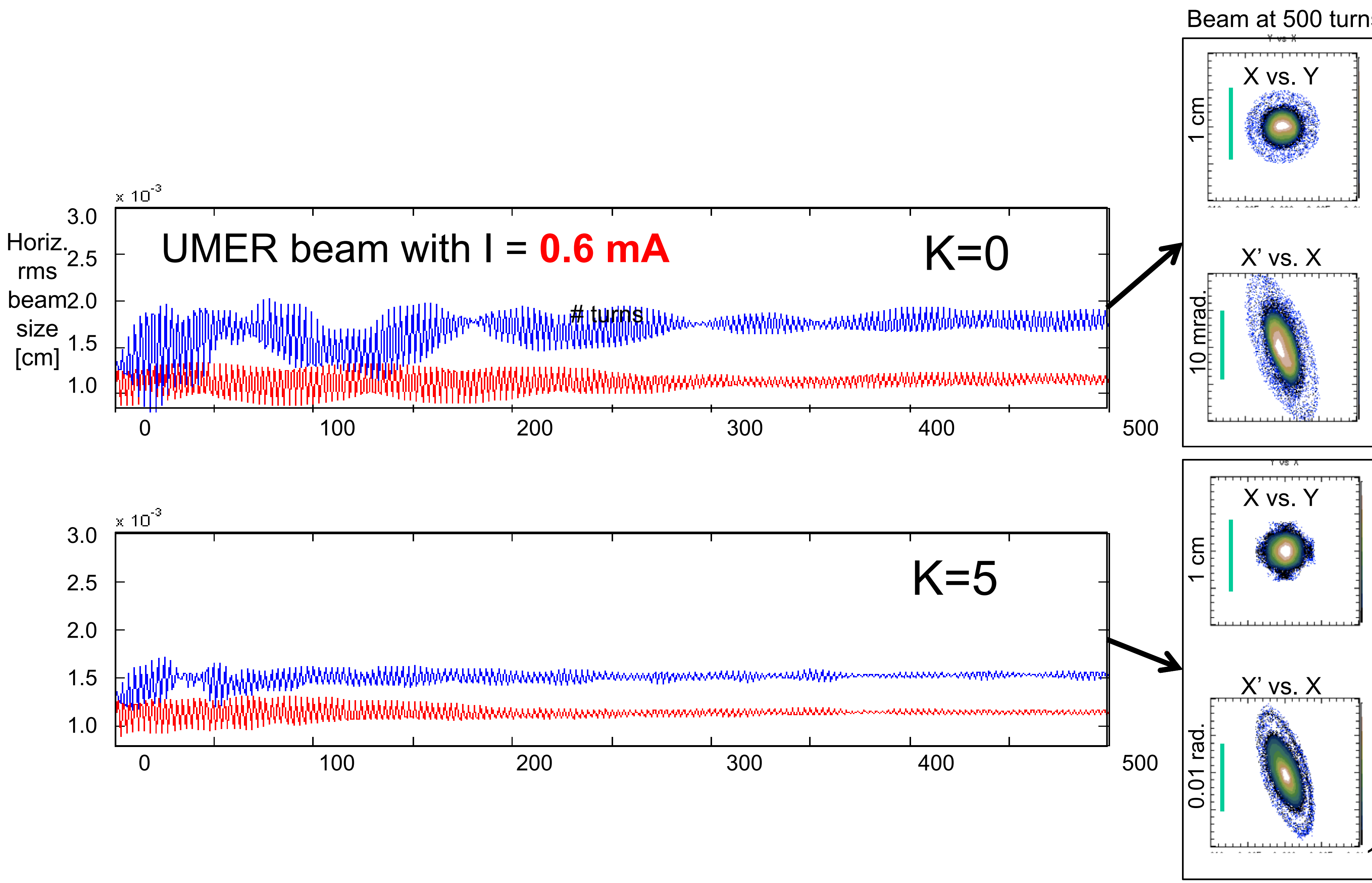
Potential in linear lattice with octupole



Normalized potential in linear lattice



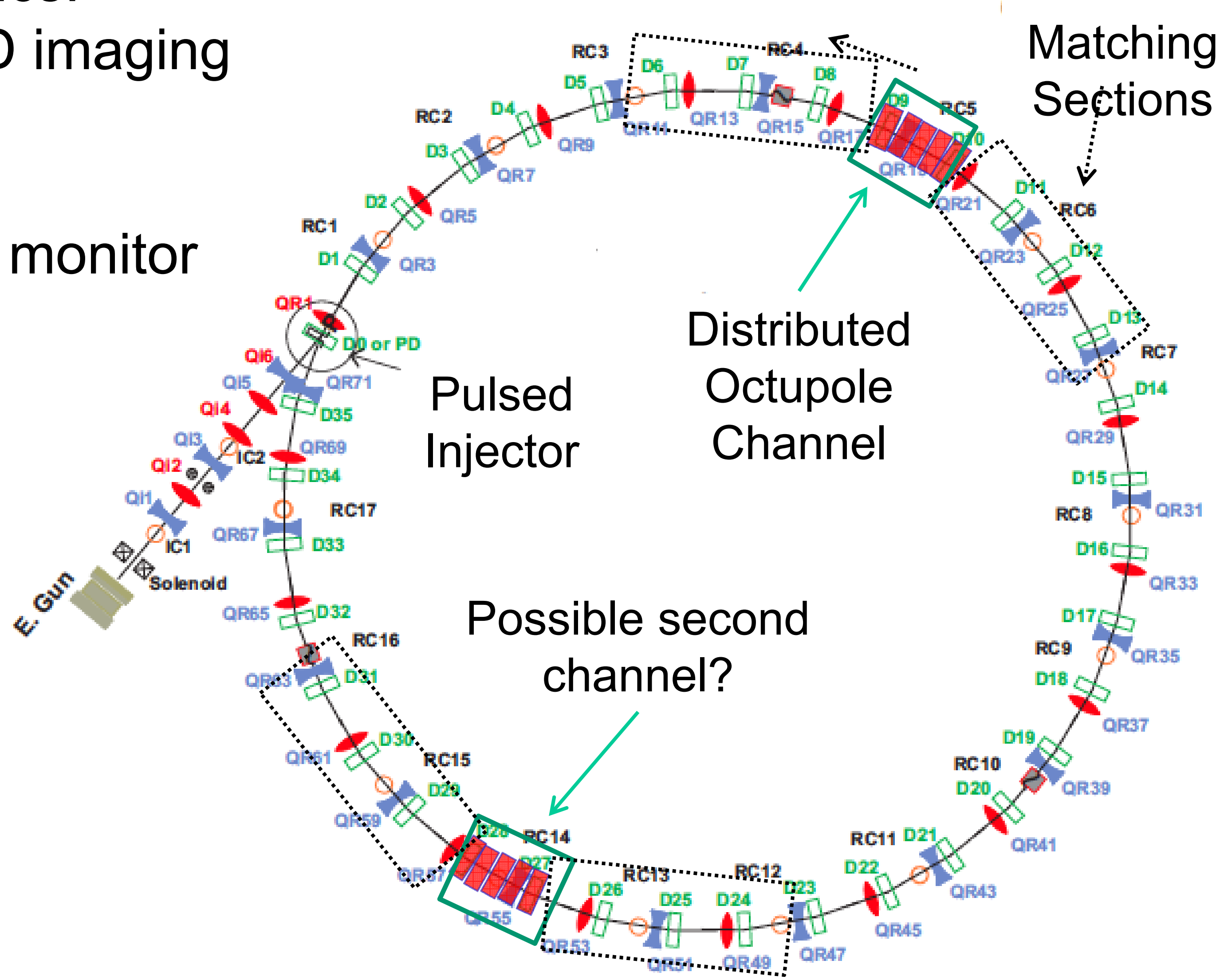
PIC simulations: halo suppression in quasi-integrable lattice



What will an experiment look like?

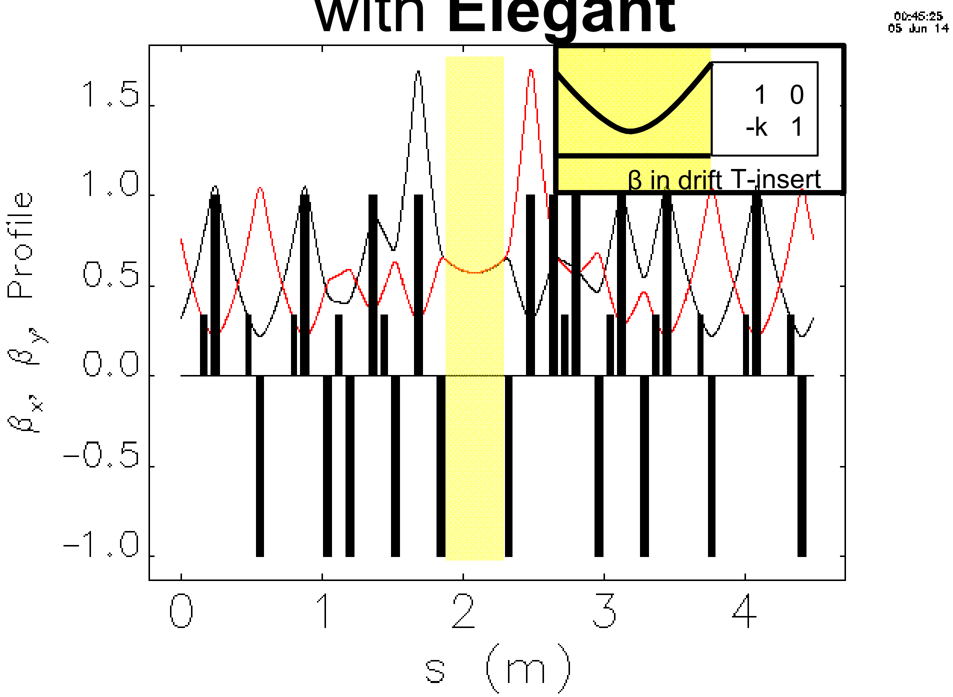
Ring Diagnostics:

- Multi-turn 3D imaging "knock-out"
- 14 BPM's
- Wall current monitor



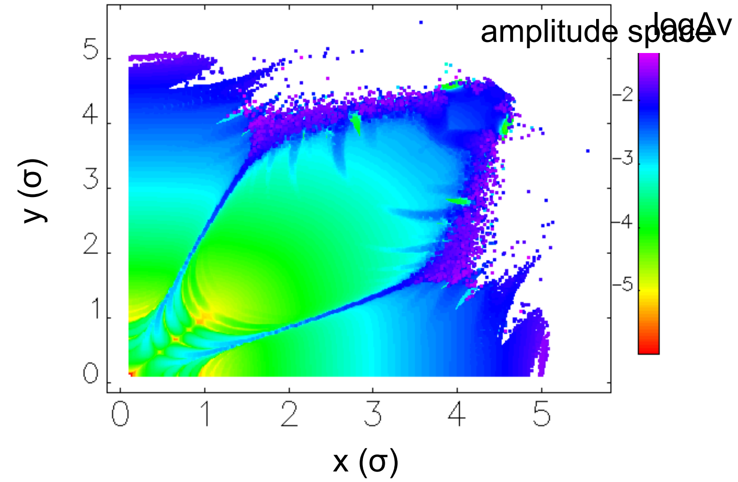
IOTA-like lattice at UMER

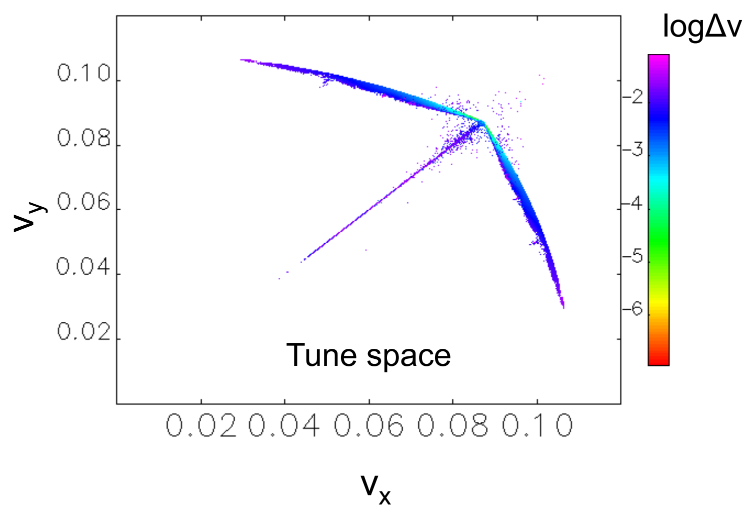
“0-current” Lattice Functions with **Elegant**



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

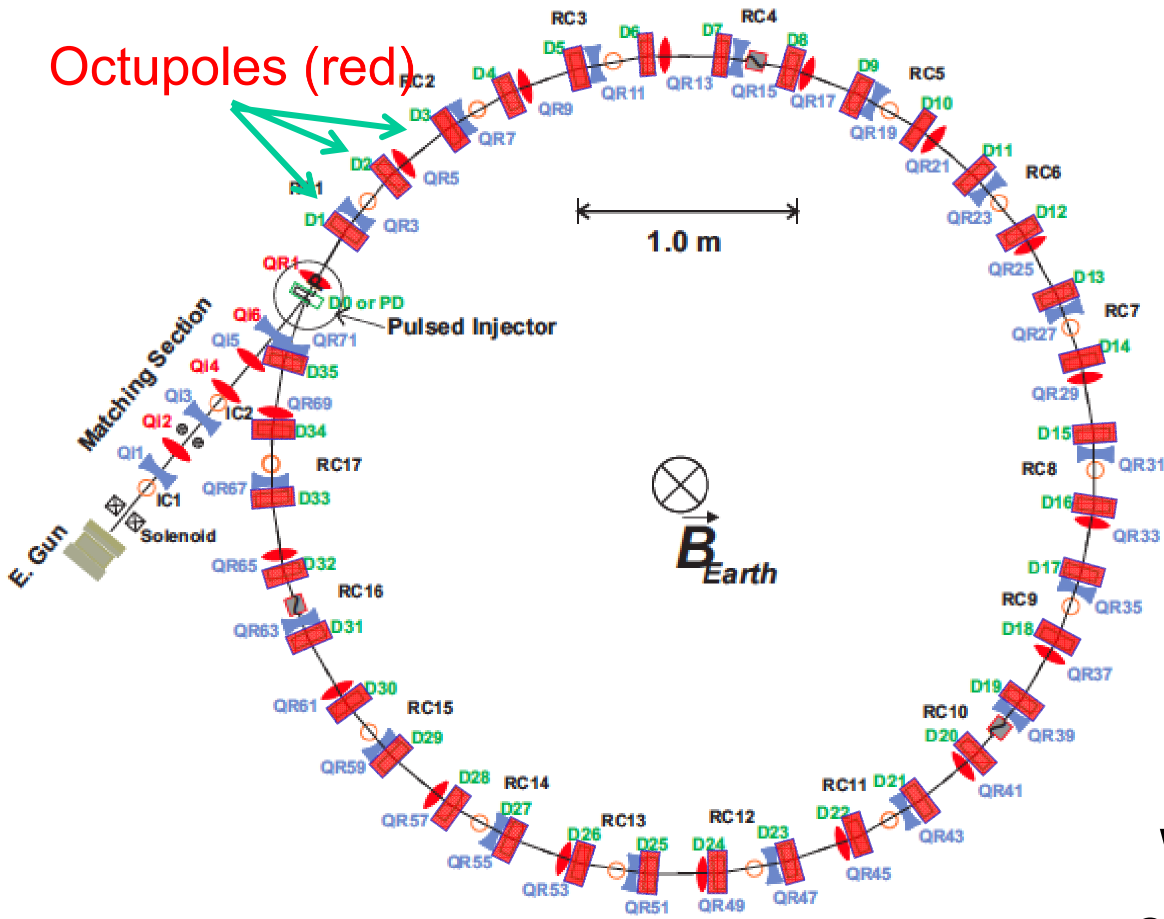
Frequency analysis of IOTA-like UMER (toy model)



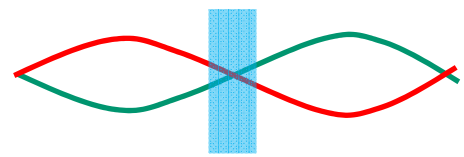


Distributed Octupole lattice

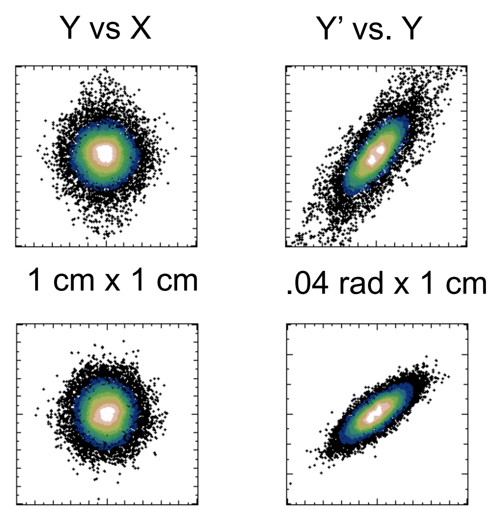
Octupoles (red)



Placement of octupoles:

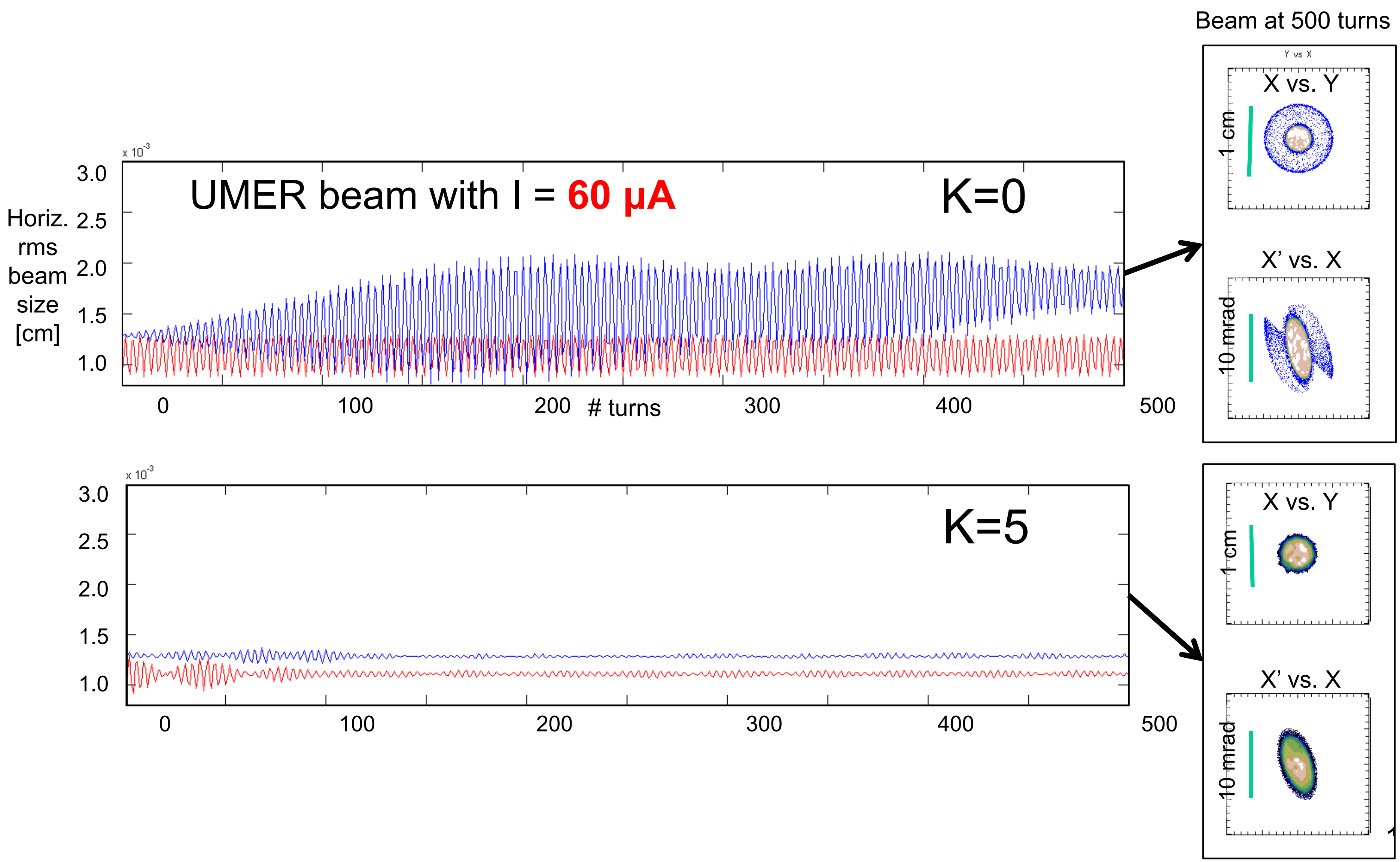


$\beta_x \approx \beta_x$ in dipole x



WARP PIC simulations of 0.6 mA beam with 200 T/m^3 octupoles

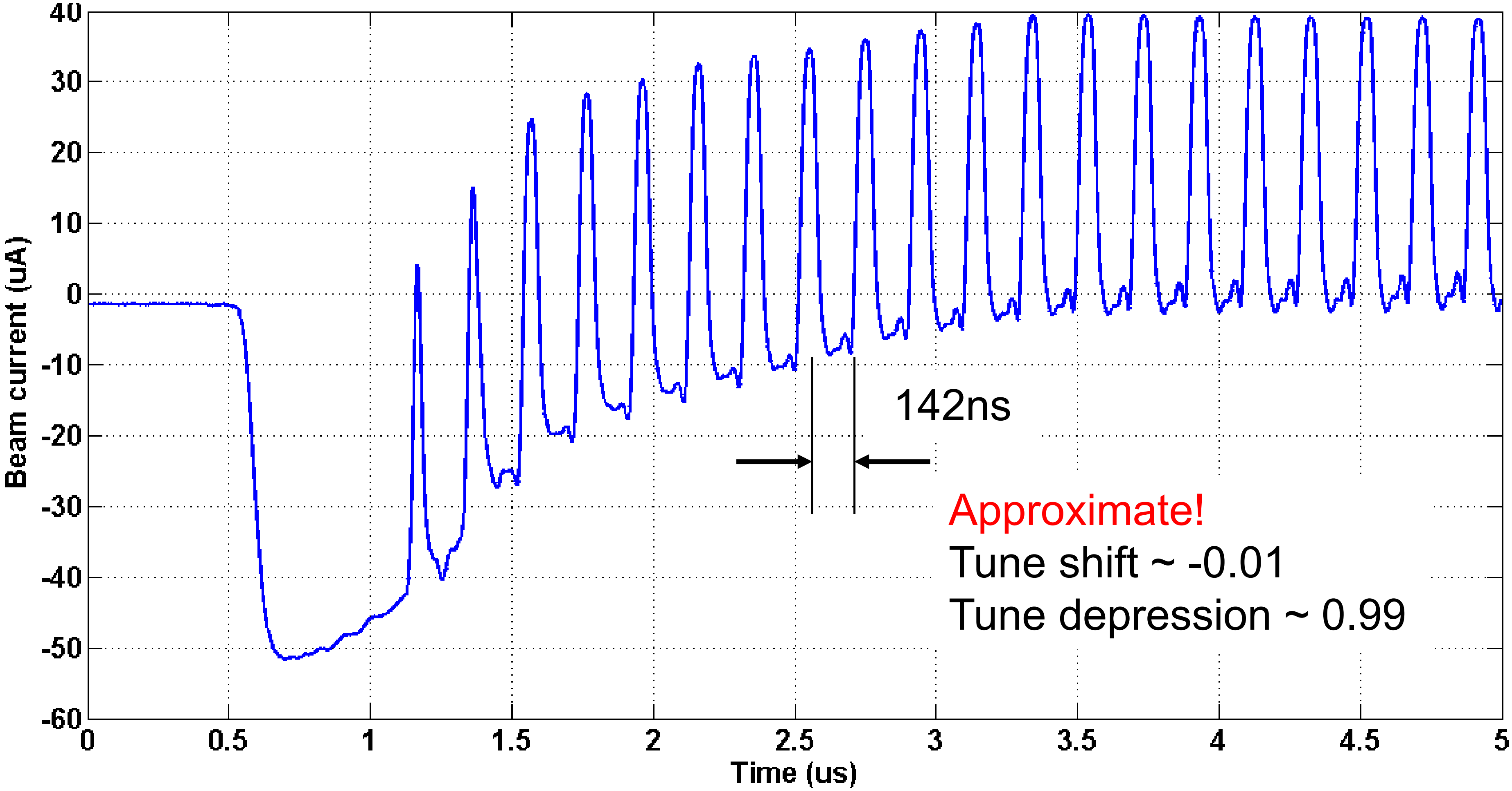
PIC simulations: halo suppression in quasi-integrable lattice



Low Current Beam Development

Preliminary

Ongoing work on generating and detecting a negligible space charge beam paves the way for more controlled tests of space charge effects in nonlinear lattices.



Brian Beaudoin, Irving Haber, and Santiago Bernal

Summary and Conclusions

- UMER a flexible machine, demonstrated accomplishments in understanding space charge dynamics.
- Designs and studies underway for extending UMER's range of operation and accessible physics.
- Proposed nonlinear optics studies at UMER complement FNAL's IOTA research program by looking at quasi-integrable and distributed octupole configurations, with space charge.
- Longitudinal experiments on shock-wave compression (in collaboration with GSI) and soliton wave train compression (at FNAL's ASTA facility) are underway.