The University of Maryland Electron Ring Program – Recent Developments

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B.L. Beaudoin, S. Bernal, M. Cornacchia, D. Feldman, R. Fiorito, I. Haber, T. Koeth, Y.C. Mo, K. Poor Rezaei, K.J. Ruisard, W. Stem, D. Sutter, and H.D. Zhang

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Research sponsored by US DOE & DOD

Outline

1. Introduction to the U. Maryland Accelerator Research Group
2. Facilities description
3. A glimpse of current research
   - Beam halo
   - Resonant excitation of envelope modes
   - Nonlinear optics
   - New emittance measurement technique
   - Soliton Formation
   - Design of an extraction section
4. Summary

Beam Physics Facilities at the University of Maryland

- Laboratory for Photocathode Research:
  Advanced facility for preparation and testing of self-healing photocathodes.
  TUPMA17, TUPMA18, TUPMA21
- Beam Diagnostics Development Laboratory:
  Development of advanced intercepting and non-intercepting diagnostics in support of UMER and collaborative experiments at other national and international accelerator labs (JLAB, SLAC, ANL, LANL, FERMI@Trieste).
  WEPBA20
- The University of Maryland Electron Ring (UMER):
  Beam dynamics experimental studies relevant to hadron and ion machines, over long path lengths, using low-energy electrons in a compact ring geometry.

Hallmarks of the Maryland program

- Education in accelerator and beam physics, with emphasis on hands-on experience.
  - 18 Ph.D. degrees awarded since 2000.
    4 more expected by end of this year.
  - Dozens of masters and undergraduate students.
  - Internships for high school students.

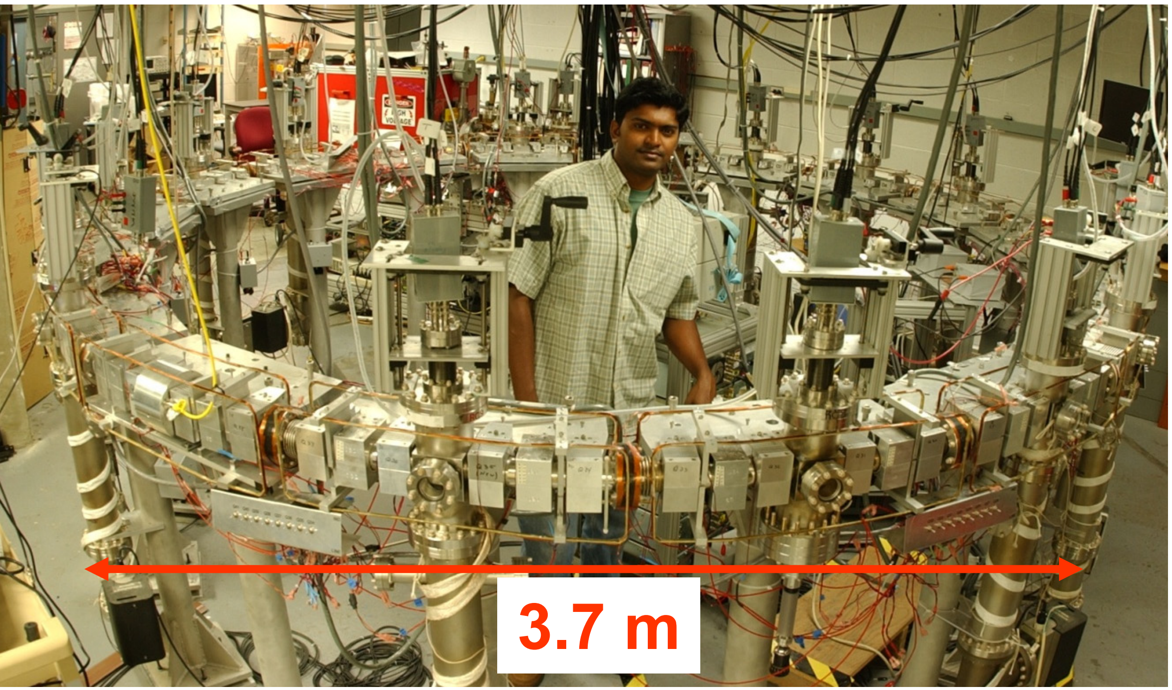
- Close-coupling with theory and simulation.
  - ELEGANT[1]: tracking code commonly used in the community.
  - WARP[2]: self-consistent 3-D PIC code for space charge modeling.

[1] Elegant developed by M. Borland, ANL
[2] WARP developed by A Friedman, D. Grote, and J.-L. Vay, LLNL and LBNL

UMER – A Scale Model of a High-Intensity Ring

Original Mission: Study Space Charge Dynamics

low energy	high current	low-emittance
10 keV	0.5-100 mA	0.3-3 μm



~10^{10} particles
or up to 14 nC

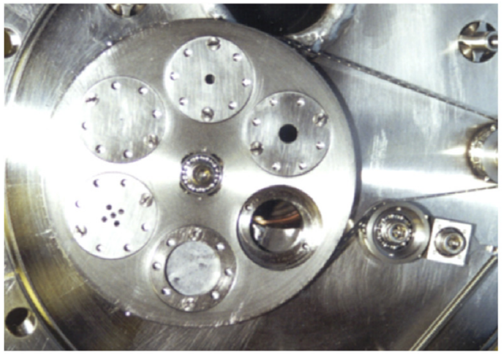
- Safe
- Reproducible results
- Available: accelerator and beam physicists are the users
- Flexible: lattice, magnets, apertures

Lap time	=	197 ns, (5.08 MHz)
Pulse Length	=	15 to 145 ns,
Full-Lattice Period	=	0.32 m (std. lattice)
Vacuum Pipe radius	=	25.4 mm

Shown: UMD graduate Charles Thangaraj (2009), now at FNAL

UMER Beam Parameters

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



Calculated for operating tune $\nu_{ox} = \nu_{oy} = 6.6 = k_0 R$

I	$\varepsilon_{n,rms}$	a_{ave}	ν_i / ν_o	$\Delta\nu_{coh}$	$\Delta\nu$
[mA]	[μm]	[mm]			
0.6	0.4	1.6	0.85	−0.005	−0.94
6.0	1.3	3.4	0.62	−0.05	−2.4
21	1.5	5.2	0.31	−0.17	−4.5
78	3.0	9.6	0.18	−0.67	−5.4
104	3.2	11.1	0.14	−0.91	−5.6

$$\frac{\nu_i}{\nu_0} = \sqrt{1 - \chi},$$

$$\chi = \frac{K}{k_0^2 a^2}$$

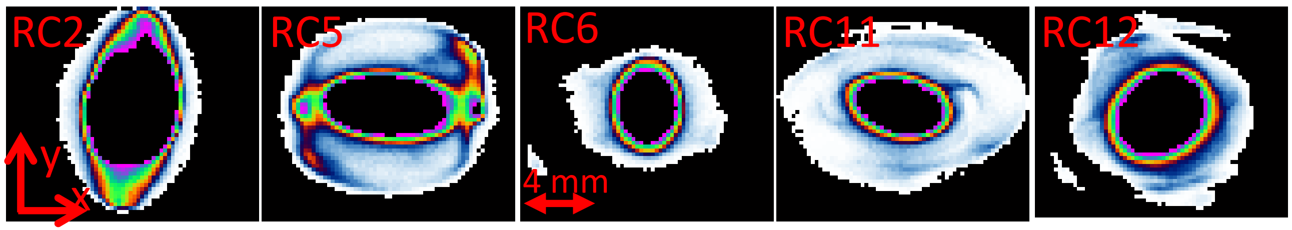
Enables beam lifetime studies and stability as a function of space charge

See Santiago Bernal TUPAC31

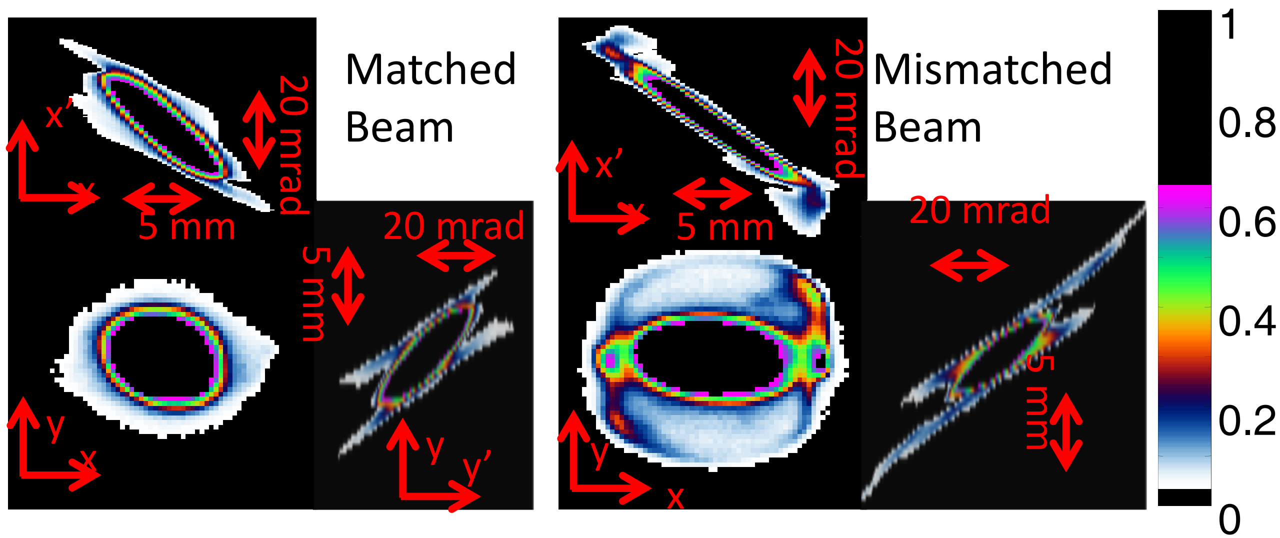
Halo formation from a Mismatch

Goal: to induce controlled mismatches and observe effect on halo, comparing to theoretical models

Experiment – induced mismatch



Phase Space from Tomography



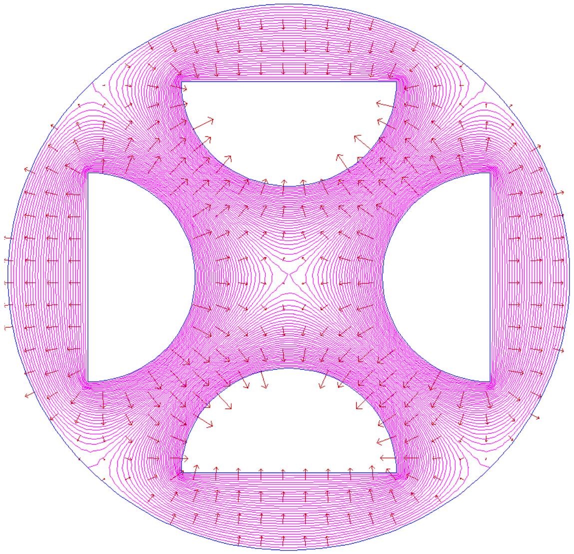
See Hao Zhang's talk: FR0AA6, Friday 9:45 am

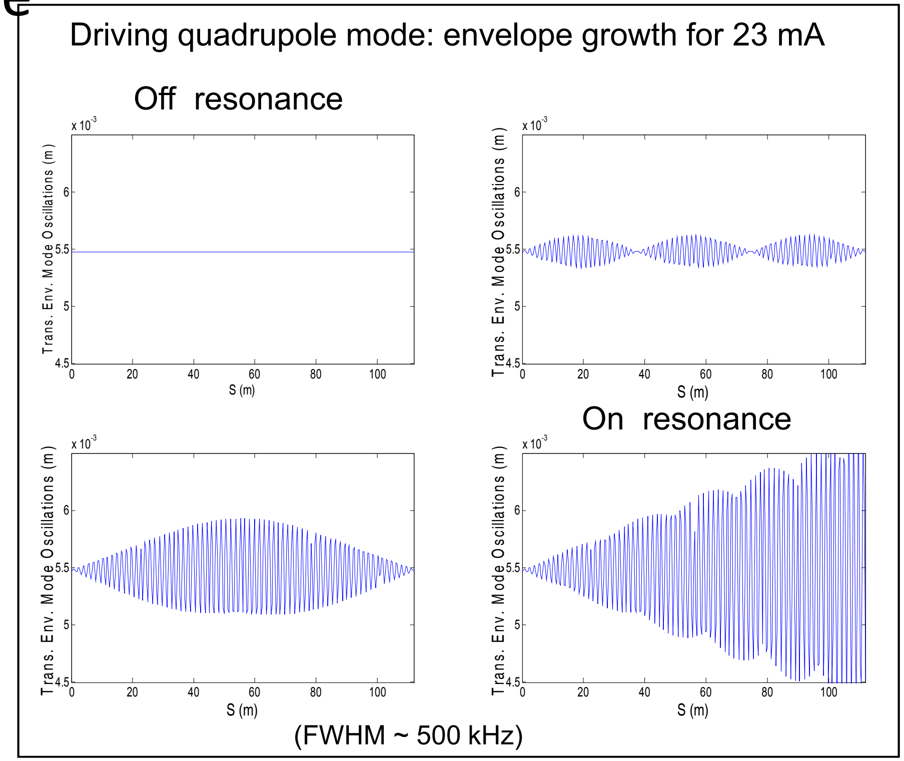
Envelope Resonance Excitations

Goal: to resonantly excite quadrupole and breathing envelope modes using a fast esq. Use excitation as an emittance diagnostic, as well as a way to seed instabilities.

Will Stem, TUPAC32

Status: We have designed, simulated, and built an electrostatic quadrupole to observe and manipulate these resonances at UMER.





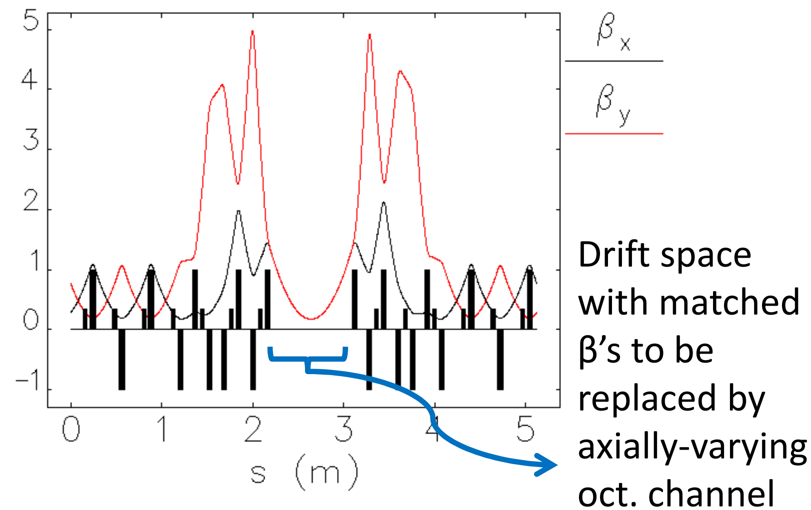
Lund, S.M. and Bukh, B. *Physical Review Special Topics: Accelerators and Beams*, 7 (2004), p. 024801-14

Nonlinear Optics at UMD

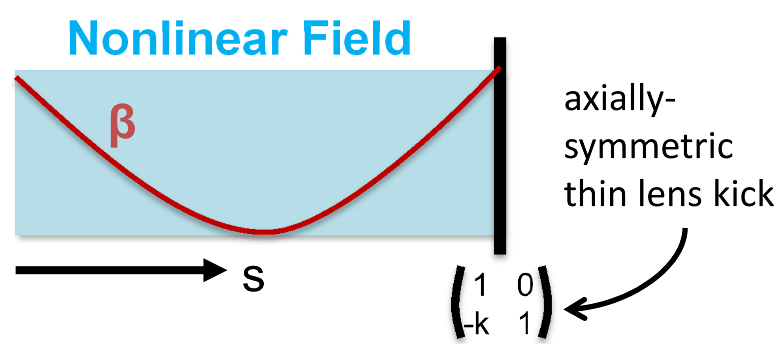
Goal: reconfigure UMER to test concepts of nonlinear optics

- Nonlinear Integrable Optics proposal: **Danilov and Nagaitsev (Phys. Rev. ST Accel. Beams, 2010)**
- Further work on pure octupole lattice: **S.D. Webb et. al (submitted to PRL)**
- Nonlinear Optics at UMD
  - Synergy with Integrable Optics Test Accelerator (IOTA) at Fermilab
  - **Simulation**: Predict IOTA and nonlinear UMER performance for intense beams (WARP code)
  - **Experiment**: Modify UMER lattice to include octupole channel
    - map nonlinear phase space
    - observe halo suppression
    - stability near beam resonance

Possible configuration of UMER lattice for NO experiment.



Schematic of WARP simulation.



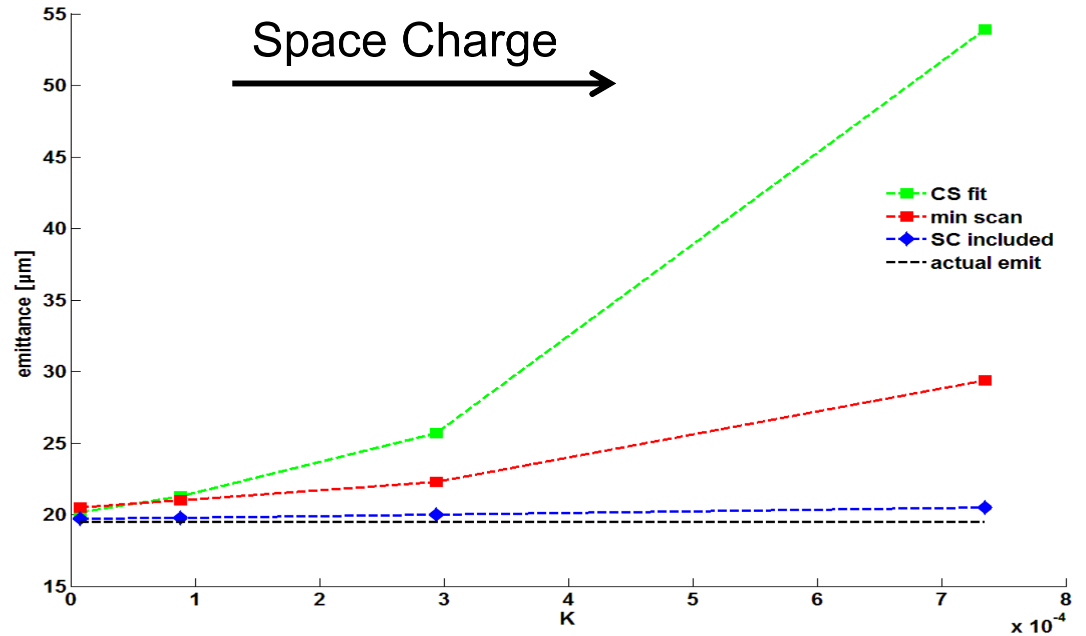
New Emittance Diagnostic for Beams with Space Charge

Goal: Take advantage of the insensitivity of divergence to space charge to make a quad-scan type emittance diagnostic

- Emittance is calculated from 2 radius & divergence measurements obtained from OTR near and far field images. (No need do complete quad or solenoid scan)
- For negligible space charge, a formula is given for the emittance.
- A procedure is developed for beams with linear space charge.

Simulation Test: emittance measured using different methods

Kamal Poor Rezaei, WEPBA20



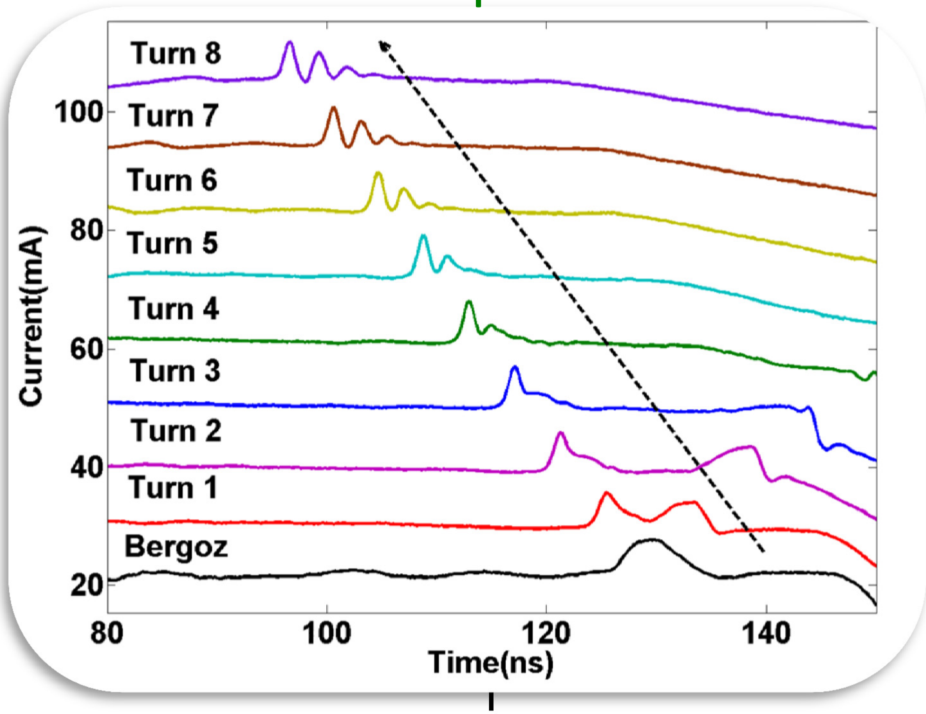
K. Poorrezaei, R.B. Fiorito, R.A. Kishek, and B. Beaudoin, PRSTAB **16**, 082801 (2013).

Experimental Observation of Soliton Wave Train in UMER

Goal: understand the behavior of large-amplitude perturbations

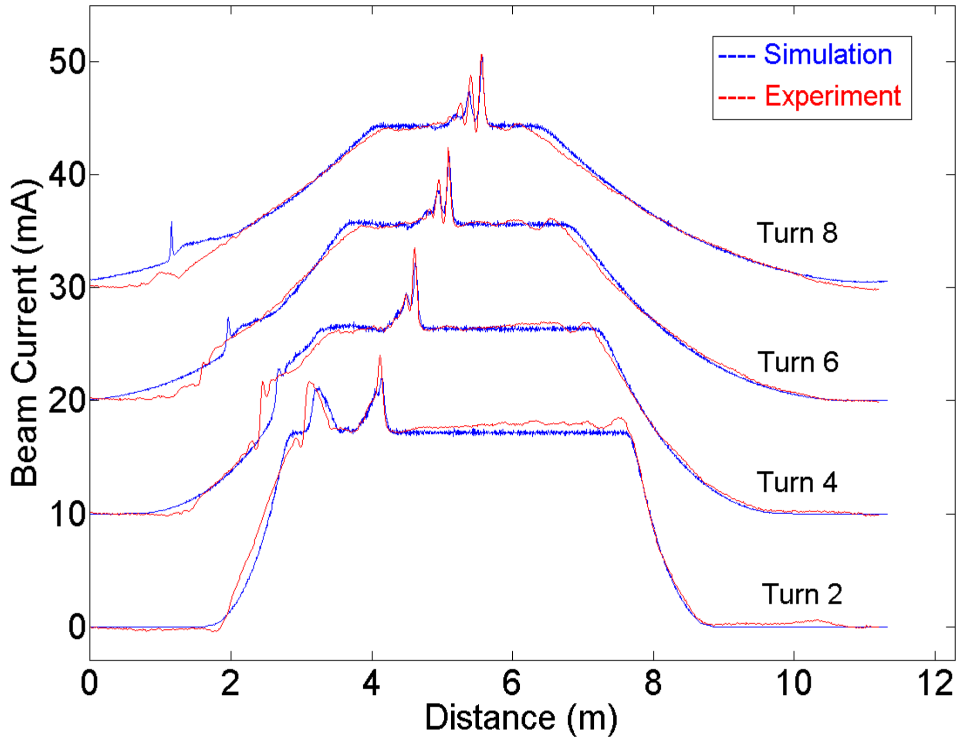
Observation: formation of KdV-type solitary waves when nonlinear steepening balances wave dispersion.

UMER Experiment



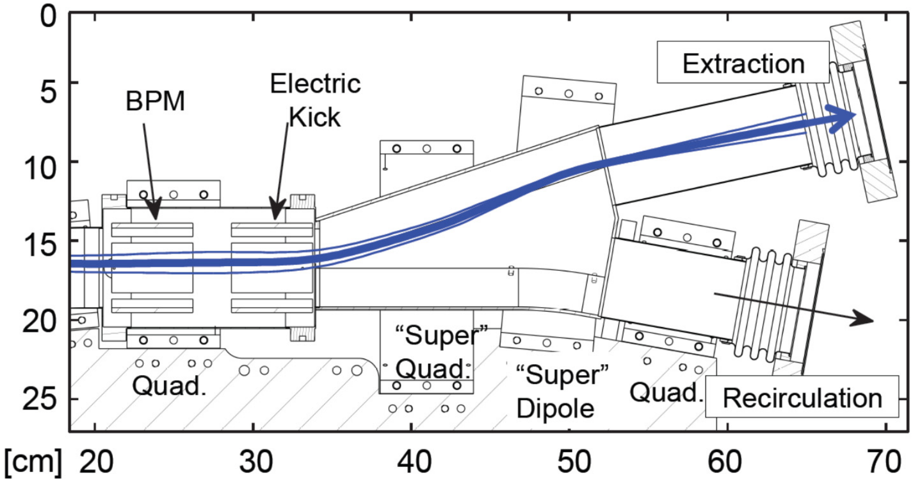
22 mA beam, 25% density perturbation

WARP Simulation



Y.C. Mo, R.A. Kishek, D. Feldman, et al., Phys. Rev. Lett., ***110,*** *084802 (2013).*

UMER Extraction Section

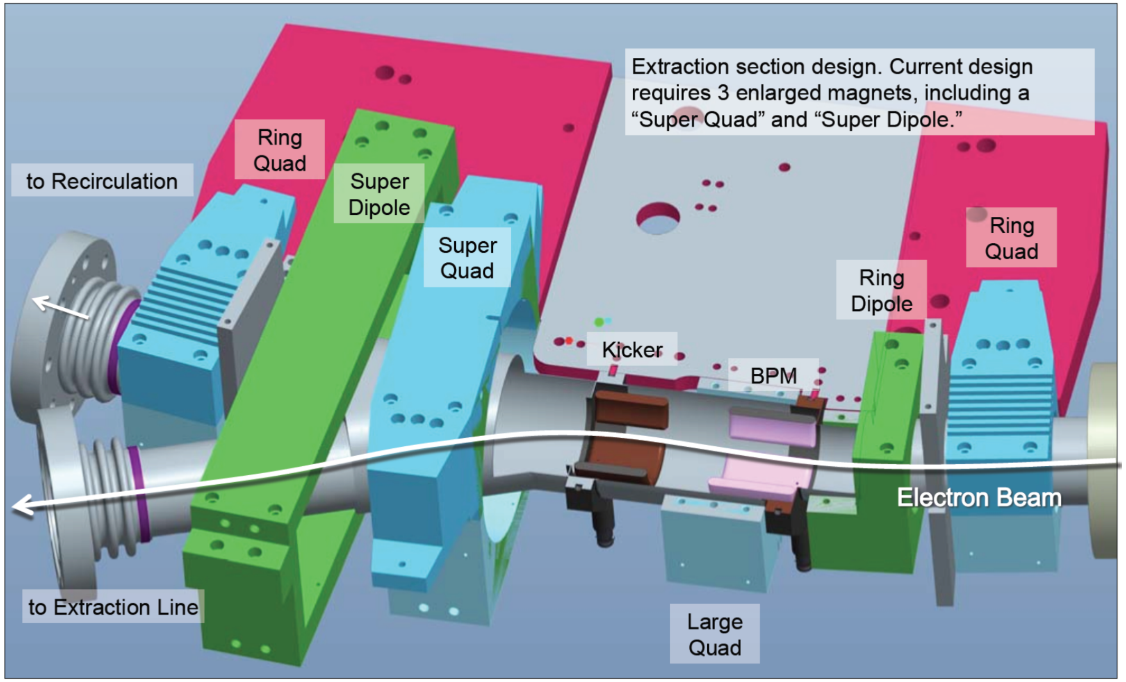


Goals:

- Minimize perturbation to recirculation
- Exceed rings admittance
- Transport full range of UMER beams

Status:

- WARP space charge model finished
- Mechanical design complete
- Ready to cut metal…



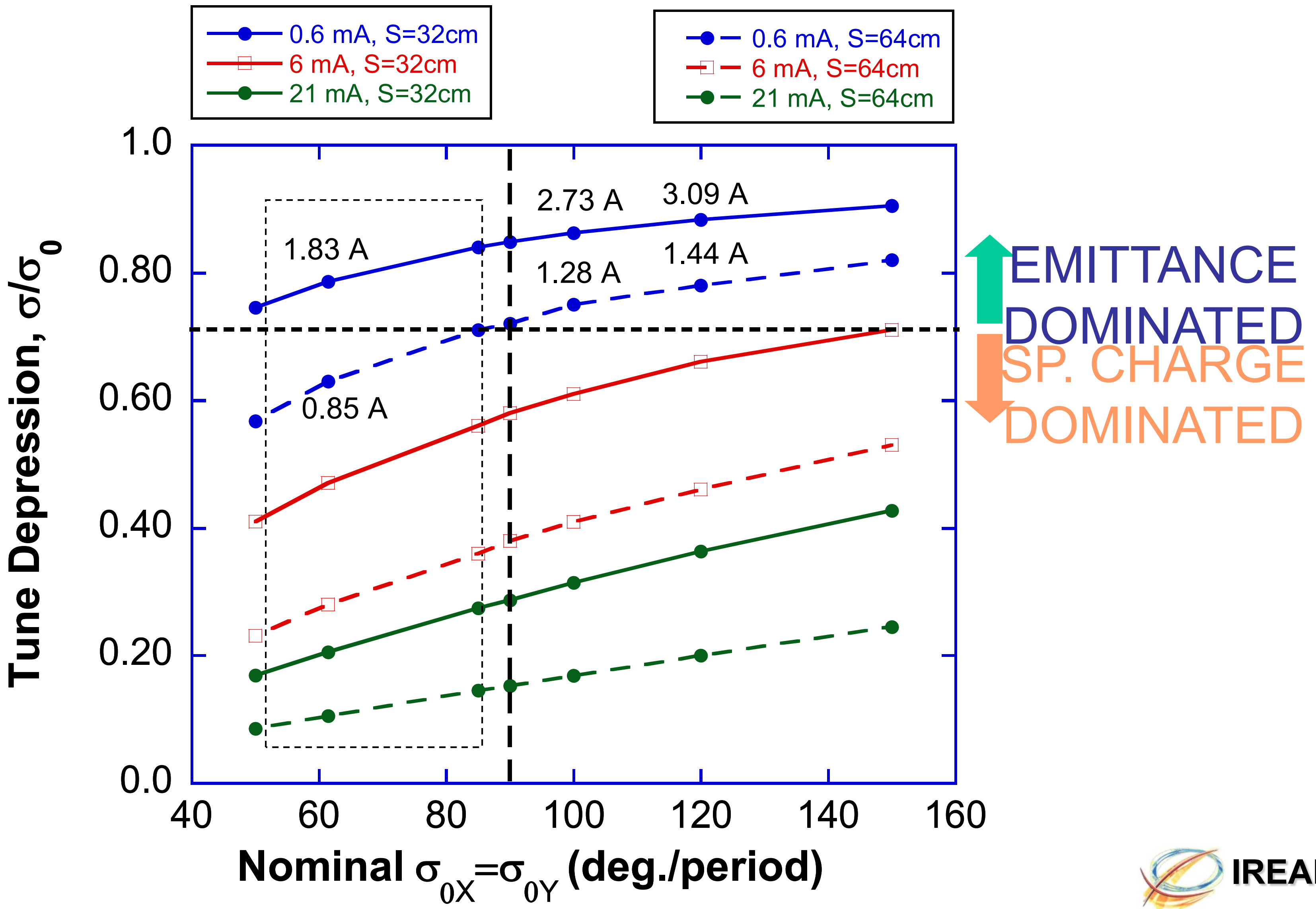
Kiersten Ruisard's Master's research, IPAC 13

Conclusions

- The UMD accelerator research program is geared towards study of key challenges in beam dynamics at the Intensity Frontier.
- In the past year, the group has branched into exciting new directions.
- We are interested in collaborations with the accelerator community.
- UMER is available for experiments and for code benchmarking

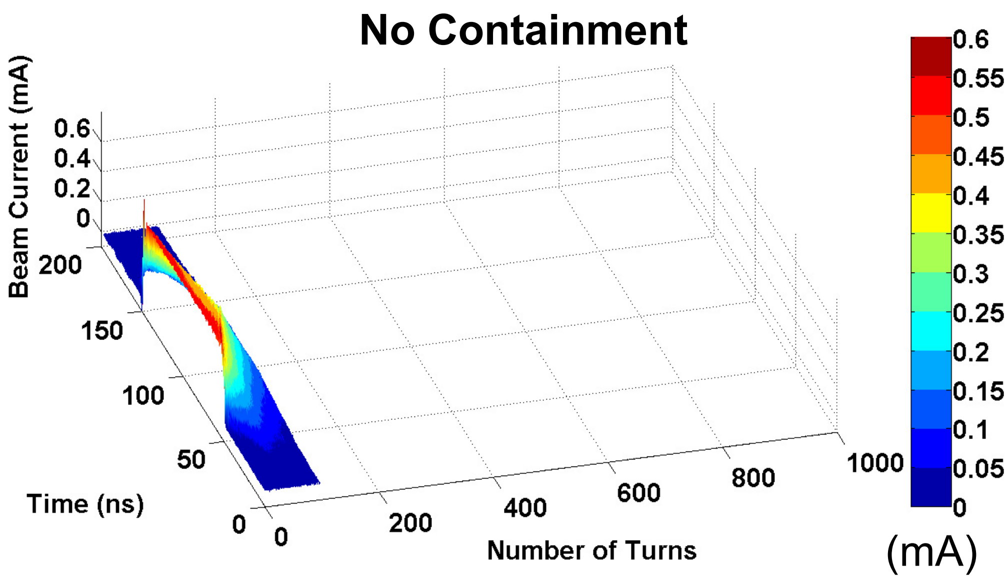
Backup Slides

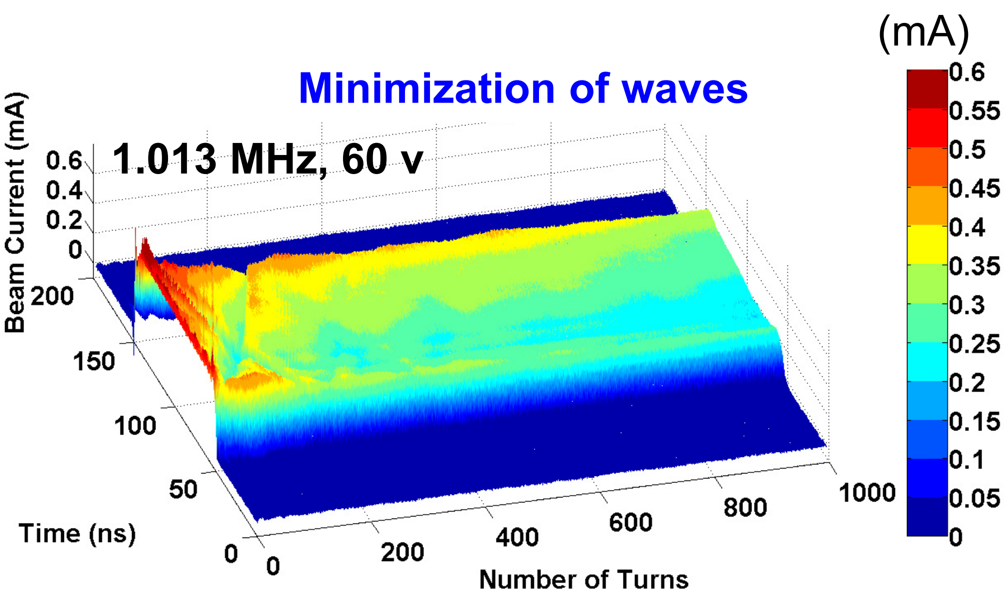
IDEAL TUNE DEPRESSION VS. FOCUSING:
3 BEAMS AND TWO LATTICES

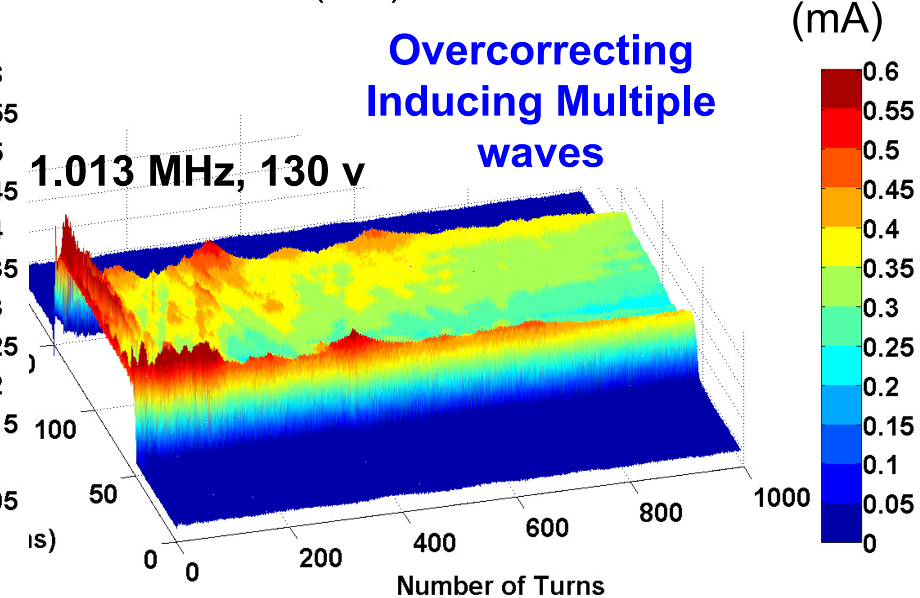


IREAP

Containment of Long Bunches







-B. Beaudoin, I. Haber, R.A. Kishek, S. Bernal, T. Koeth, D. Sutter, P.G. O'Shea, and M. Reiser, Physics of Plasma, 18, 013104 (2011).

Education/Training: Recent PhD Graduates

Student	PhD year	Placement	Currently @
Yun Zou	2000	Industry	GE Global Research
Yupeng Cui	2004	KLA-Tencor	Velodyne Acoustics
Hui Li	2004	Microsoft	Embarcadero Technologies
John Harris	2005	NRL	Colorado State University
Jon Neumann*	2005	NRL	Naval Research Laboratory
Nathan Moody*	2006	LANL	Los Alamos National Laboratory
David Gillingham	2007	NRL	Institute for Defense Analysis
Kai Tian	2008	J-Lab	Stanford Linear Accelerator
Diktys Stratakis*	2008	BNL	Brookhaven National Laboratory
J. Charles Tobin*	2009	FNAL	Fermi National Accelerator Laboratory
Chao Wu	2009	FDA	Hillcrest Labs
Chris Papadopoulos	2009	LBNL	Lawrence Berkeley National Laboratory
Eric Montgomery*	2009	UMD	U. Maryland
Mike Holloway	2010	LANL	Los Alamos National Laboratory
Matt Virgo	2010	ANL	Argonne National Laboratory
Brian Beaudoin	2011	UMD	U. Maryland
Daniela Moody	2012	LANL	Los Alamos National Laboratory
Zhigang Pan *	2013	(NRL)	Naval Research Laboratory

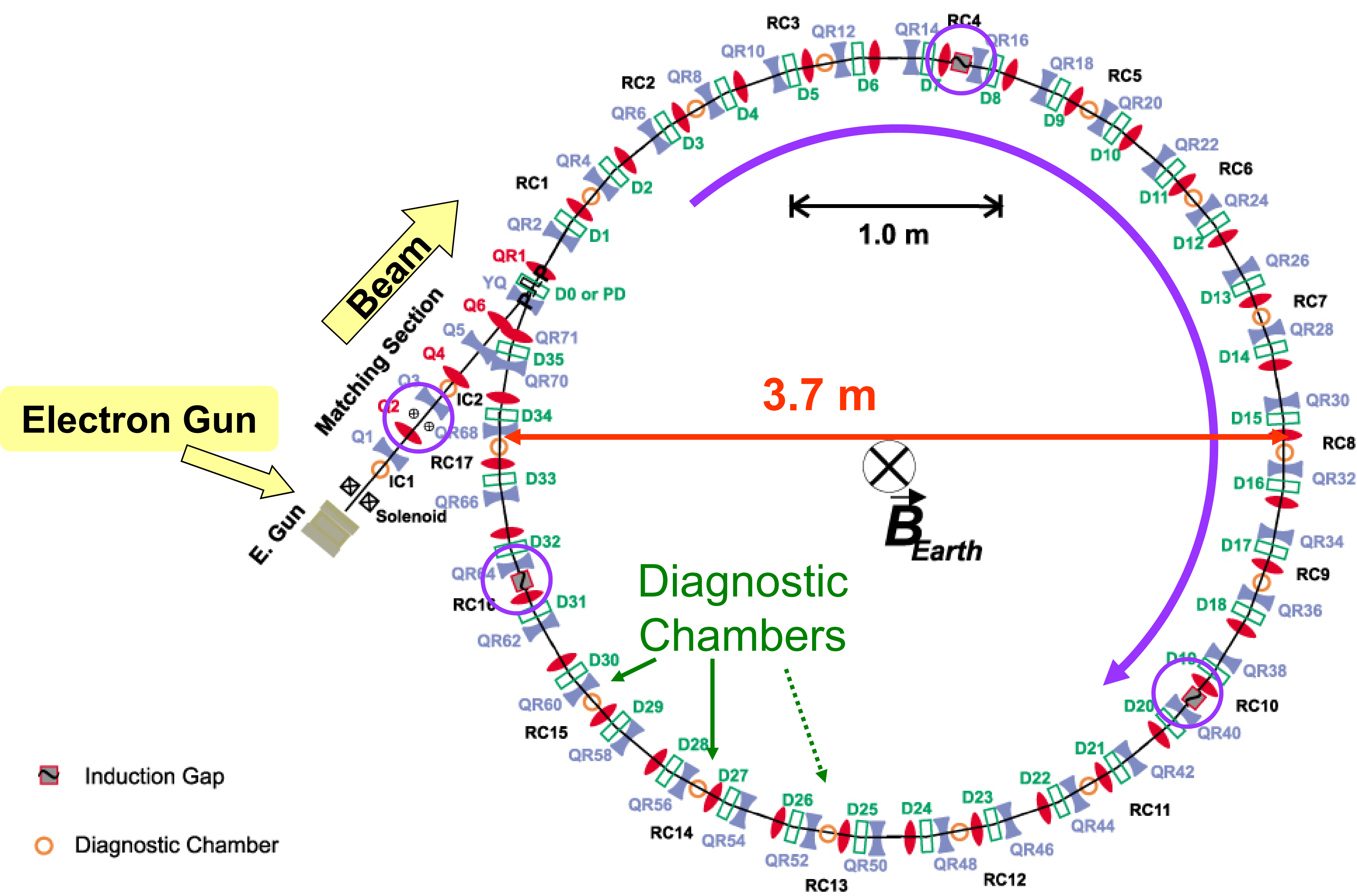
** Received prestigious awards*

Includes both ONR-funded and DOE-funded students

Ongoing Collaborations

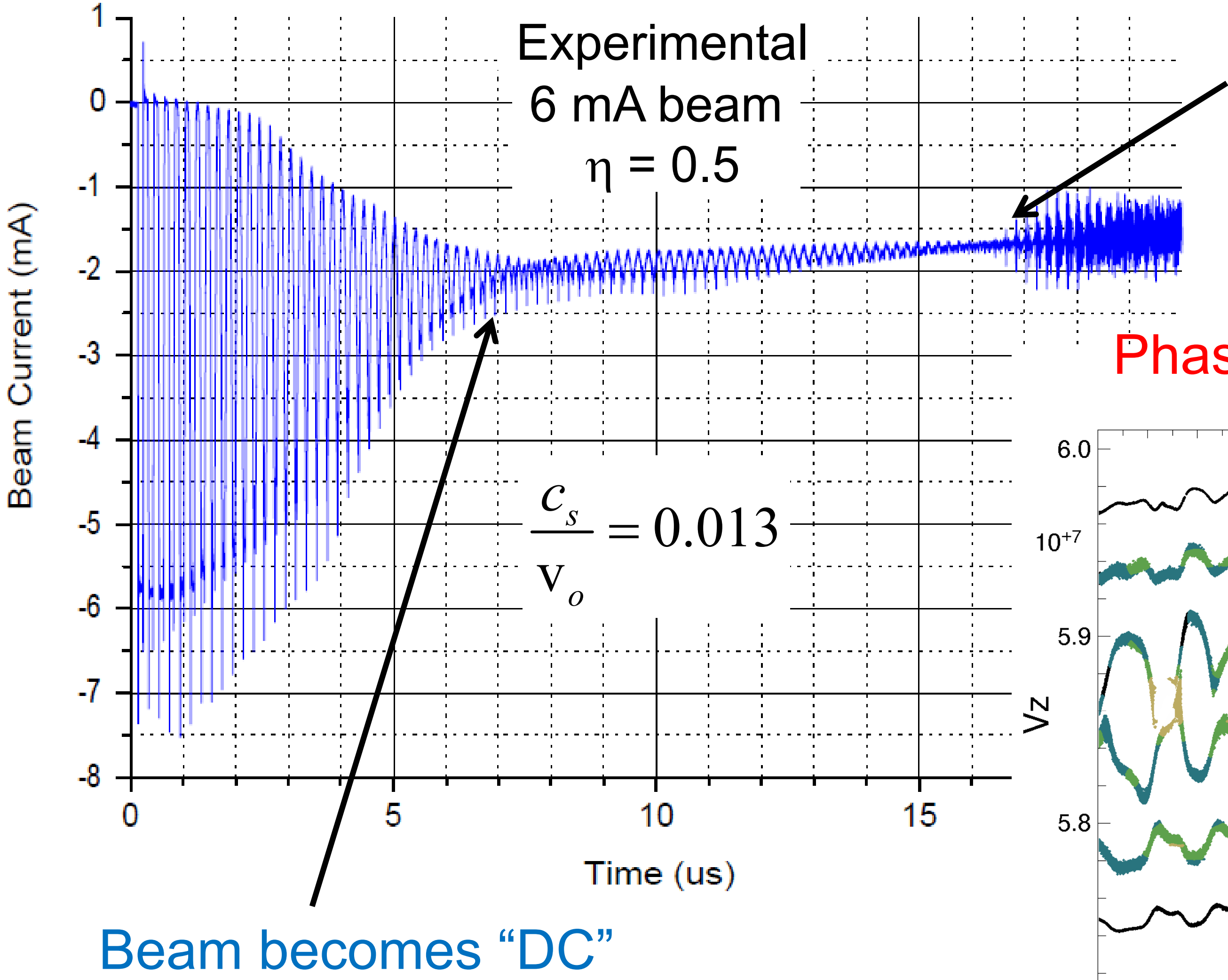
Institution	Point of Contact	Area of Common Interest
Lawrence Berkeley / Livermore National Laboratories	Alex Friedman, Dave Grote, Jean-Luc Vay	Development, benchmarking, and use of the WARP code.
Princeton Plasma Physics Laboratory	Ron Davidson, Ed Startsev	Study of solitons in electron beams
Los Alamos National Laboratory	Bruce Carlsten, Nathan Moody	Development of a 100 kW-class FEL
Thomas Jefferson National Accelerator Facility (FEL)	Dave Douglas, Shukui Zhang	Non-interceptive diagnostics
Fermi National Accelerator Laboratory	Gustavo Cancelo	Use of ESECON boards for fast beam control
Argonne National Laboratory, Advanced Wakefield Accelerator	John Power, Manoel Conde	Development of advanced accelerator diagnostics for space-charge-dom. beams
SLAC National Accelerator Laboratory (SPEAR3 and LARP/CERN)	Jeff Corbett, Alan Fisher Kai Tian	Development of high dynamic range beam imaging diagnostics, THz measurements
Naval Research Laboratory	Kevin Jensen, Phillip Sprangle	Cathode theory and simulation; rf thermionic injector development
FERMI@Elettra	Simone DiMitri, Marco Veronese	Development of advanced emittance and phase-space diagnostics
Calabazas Creek Research, Inc.	Lawrence Ives, Lou Falce	Precision machining of controlled-porosity reservoir cathodes

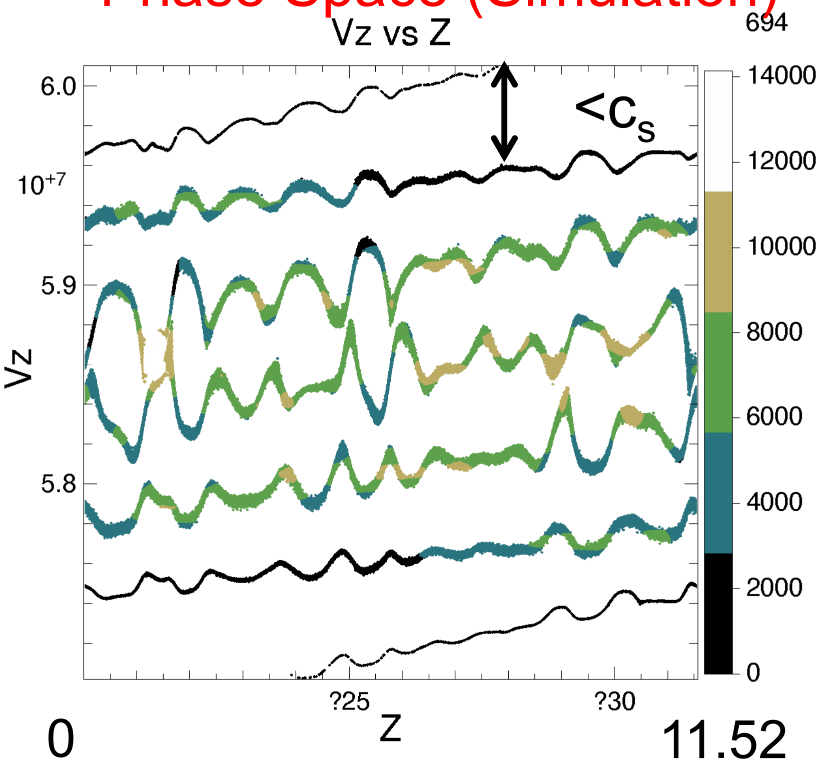
UMER – A Research Machine for Space-Charge Dynamics



Observation of a Multi-stream instability

No longitudinal focusing – Beam expands and wraps around ring





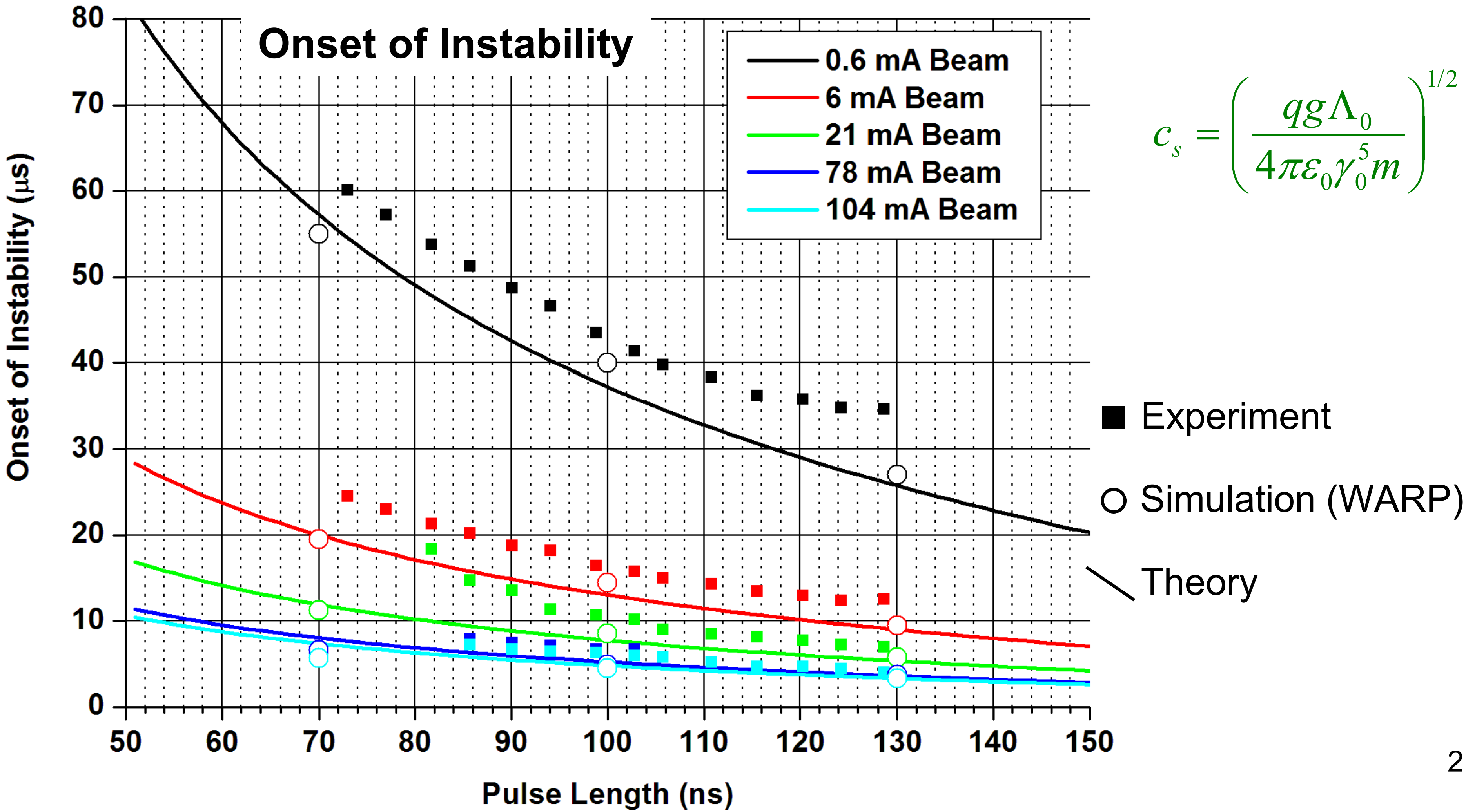
B.L. Beaudoin, R.A. Kishek, I. Haber, T.W. Koeth, submitted (2012).

Comparison between Theory, Simulation and Experiment

$$t_{onset} = \frac{C}{4c_s}\left(\frac{2}{\eta} - \eta\right)$$

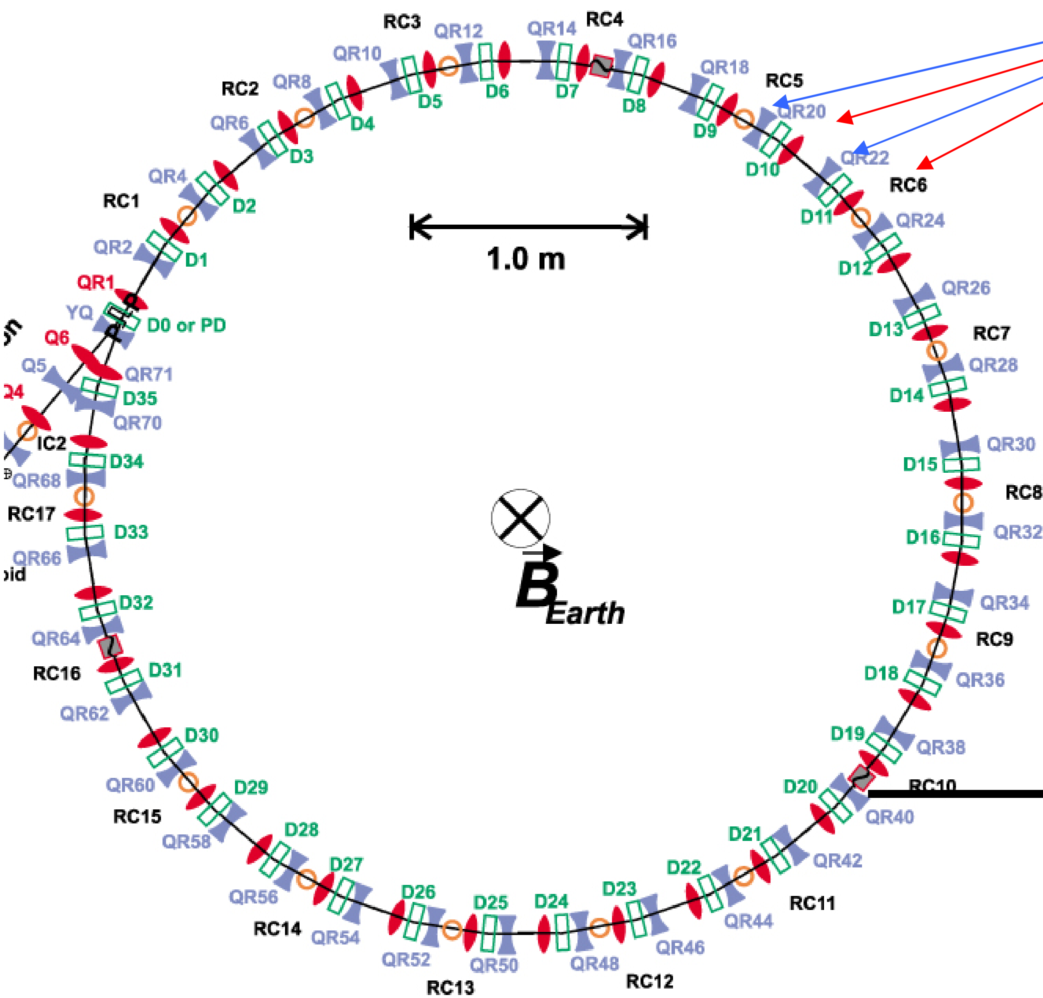
η = fill factor
= injected pulse length / ring lap-time

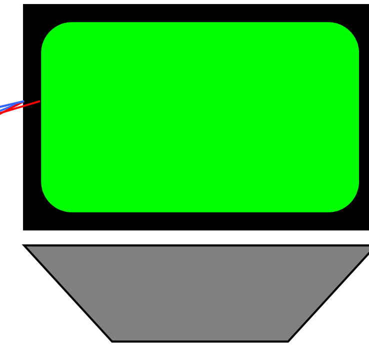
$$c_s = \left(\frac{qg\Lambda_0}{4\pi\varepsilon_0\gamma_0^5 m}\right)^{1/2}$$



Beam Lifetime and Losses (No Longitudinal Focusing)

Automated Scans ~ 24 hours





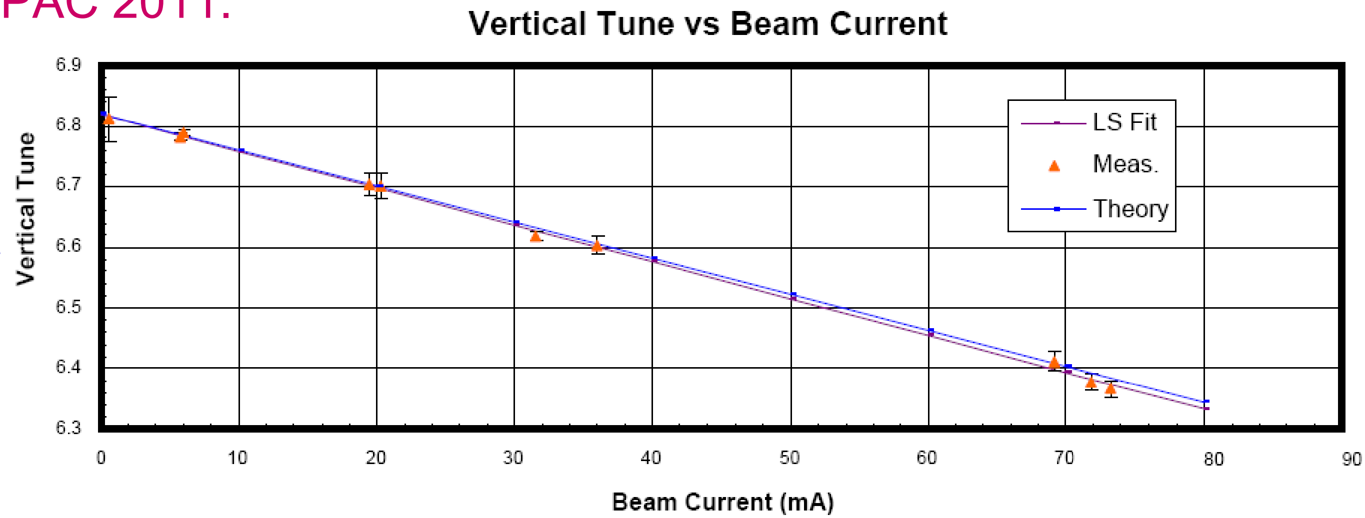
Quad Scan

1. Set even quads (D)
2. Set odd quads (F)
3. Measure beam intensity every turn (norm to 1st turn)
4. Repeat at new D,F Quad values

Current Dependence of Tune Diagrams

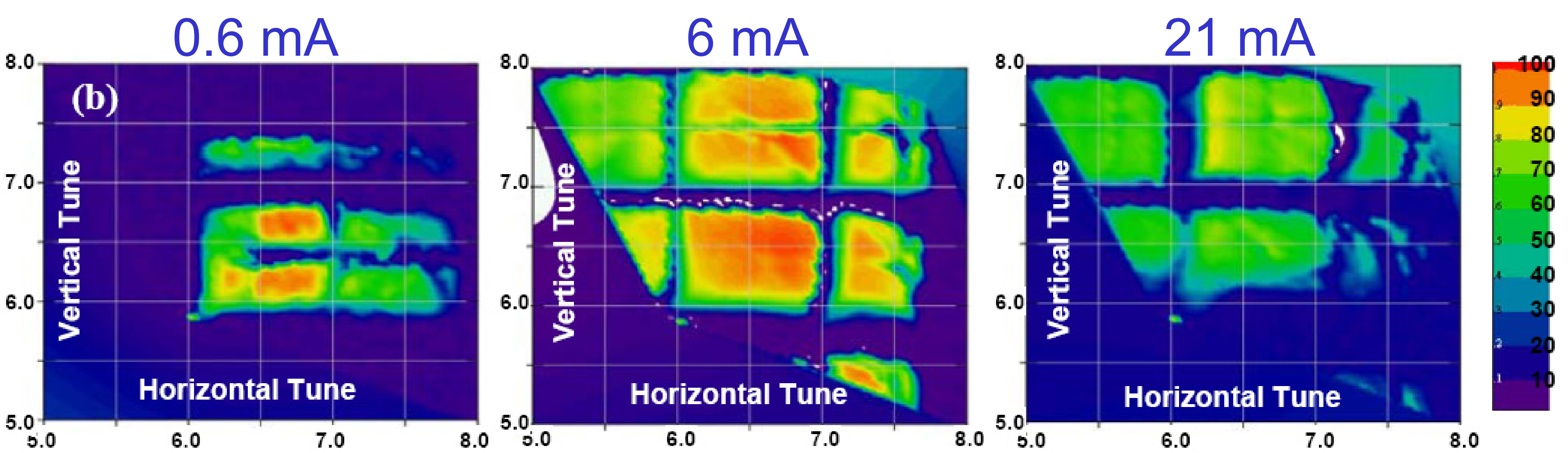
Dave Sutter, *et al.*, Proc. PAC 2011.

Coherent Tune Shift Measurement



S. Bernal, *et al.*, Proc. AAC 2010, (New York: AIP Press **1299**, 2010), p. 580.

survival after 20th turn (before the alignment, and with some defective magnets)



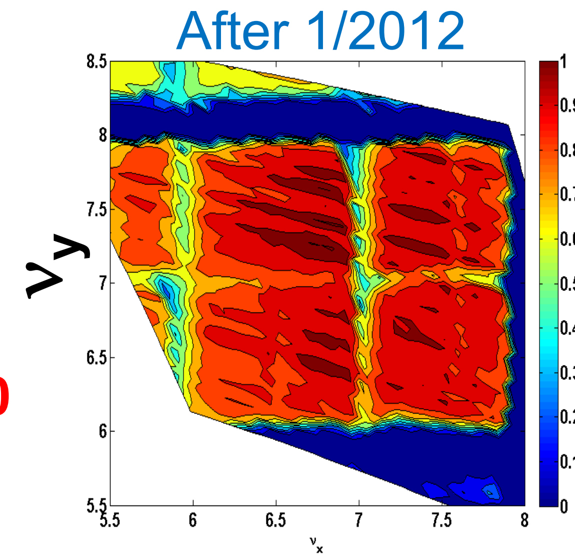
Mapping of Resonances over Wide Range of Tunes

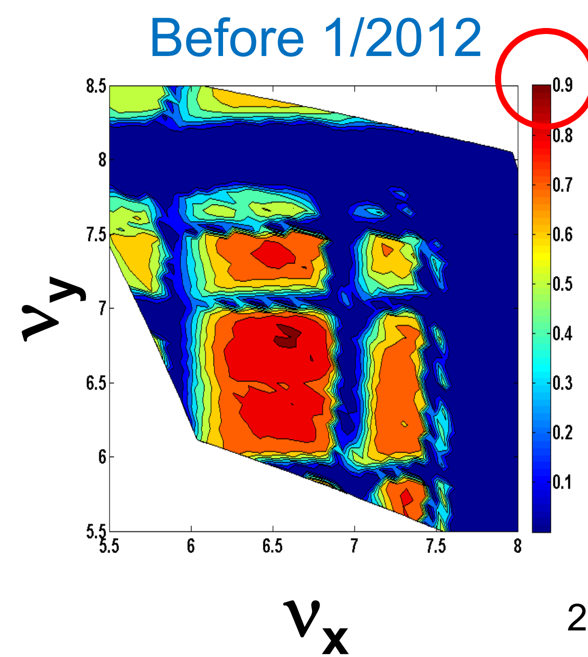
Work in Progress

Shown: fraction of transmitted current after **10 turns**
For each of 2000 operating tunes

6 mA beam: $\chi \sim 0.8$, $\sigma/\sigma_o \sim 0.45$
Injected incoherent tune shift from space charge **> 3.0**

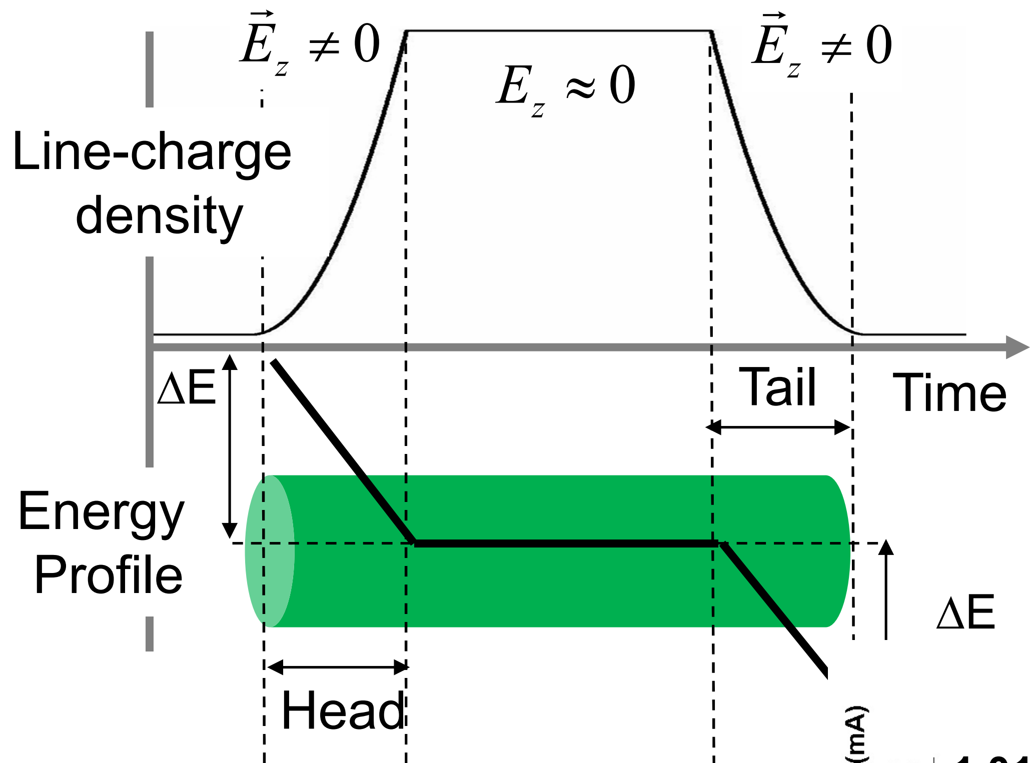
Stop bands narrowed and growth rates reduced after detailed mechanical survey and alignment in 1/2012





Sutter, Beaudoin, Bernal, Koeth 2012

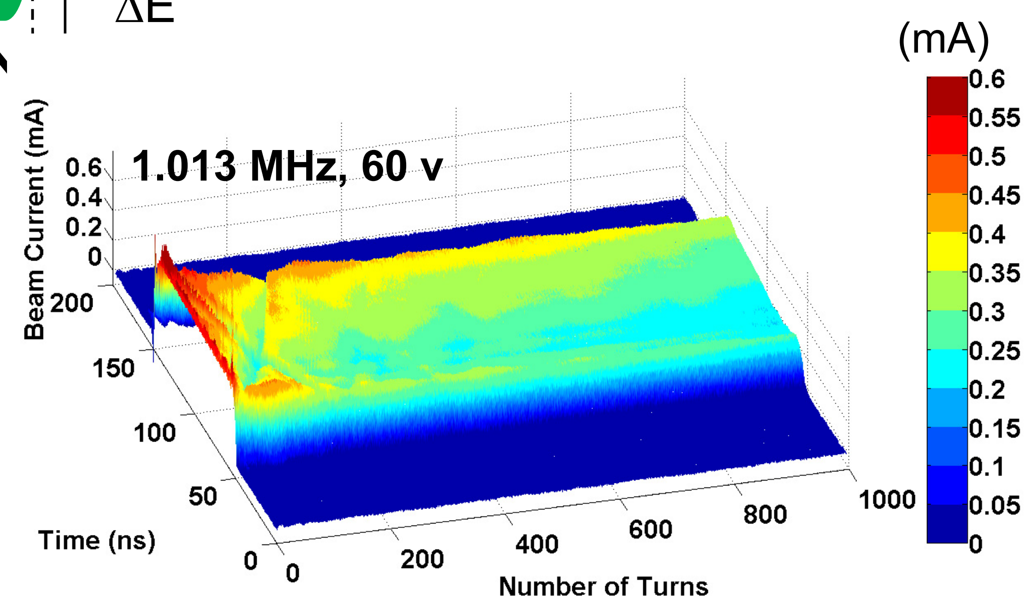
Longitudinal Confinement with Induction Cells



Long Wavelength Limit

$$E_z \propto -\frac{d\lambda}{dz}$$

0.6 mA beam

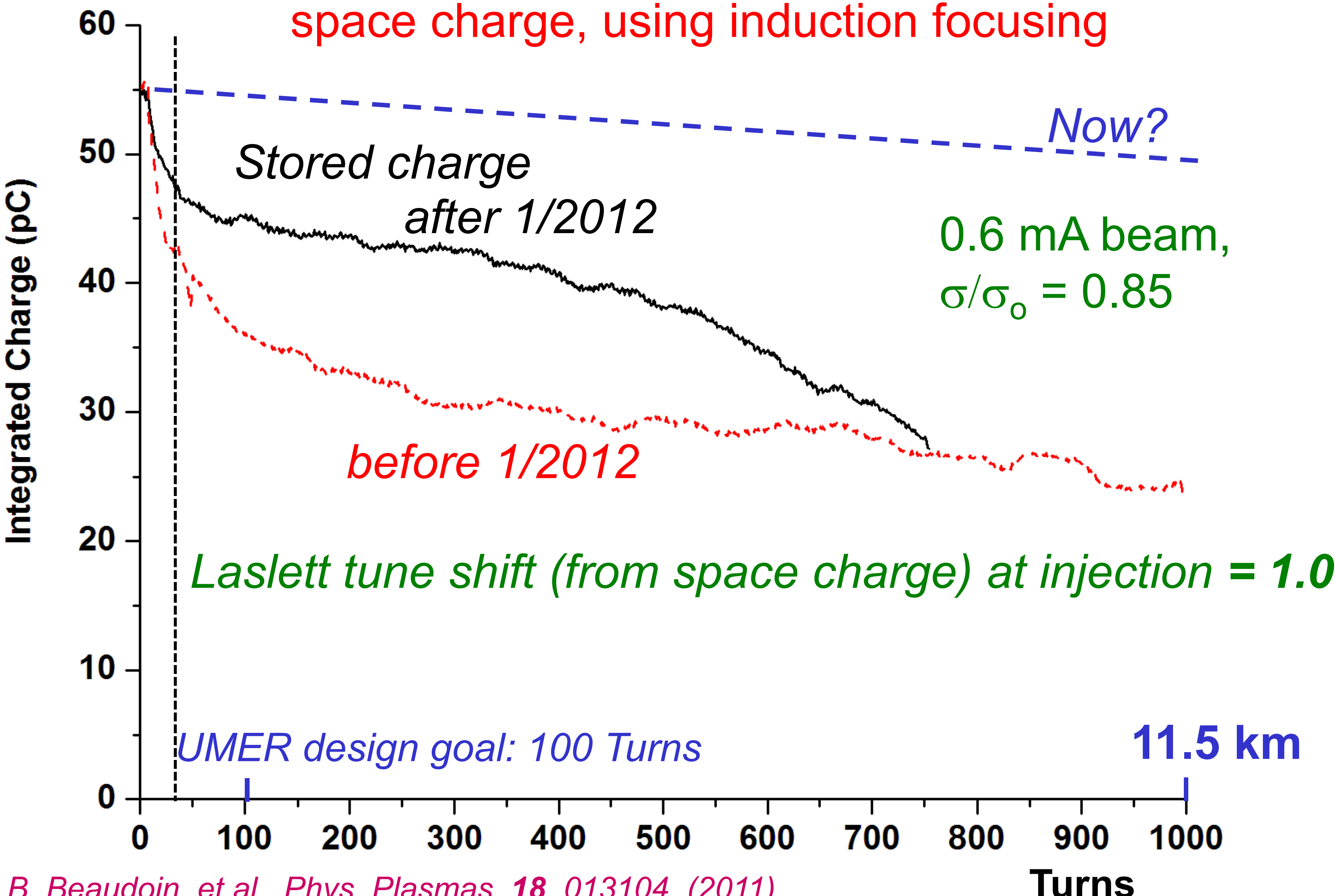


Application of Induction cell Ear fields keeps beam confined for > 1000 turns

*B. Beaudoin, I. Haber, R.A. Kishek, et al., Physics of Plasma, **18**, 013104 (2011).*

Beam Losses with Longitudinal Containment

Demonstrated long-distance recirculation of a beam with high space charge, using induction focusing



*B. Beaudoin, et al., Phys. Plasmas, **18**, 013104 (2011)*