Longitudinal Space Charge Phenomena in an Intense Beam in a Ring

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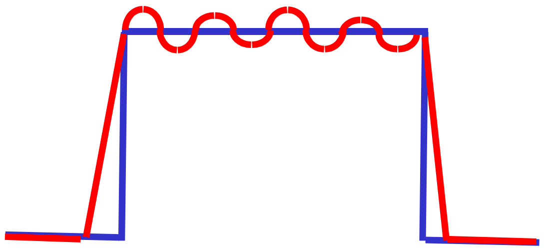
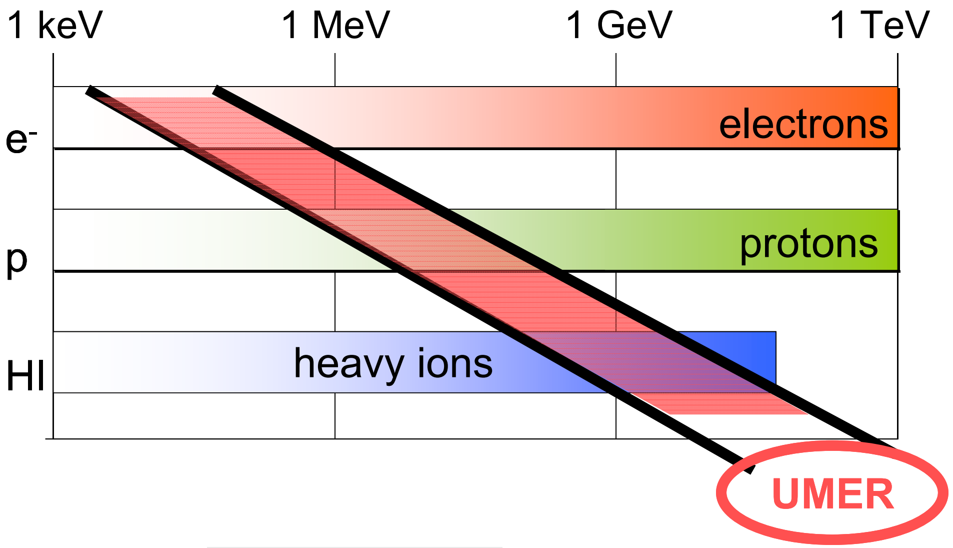
Outline

1. Motivation: Noisy Beams



2. Experimental Setup and UMER update
3. Results of Two Recent Longitudinal Studies
   – Space-charge Induced Multi-Stream Instability
   – Solitons in Space-charge-dominated beams
4. Conclusion
5. Discussion:
   – Transverse Physics at UMER

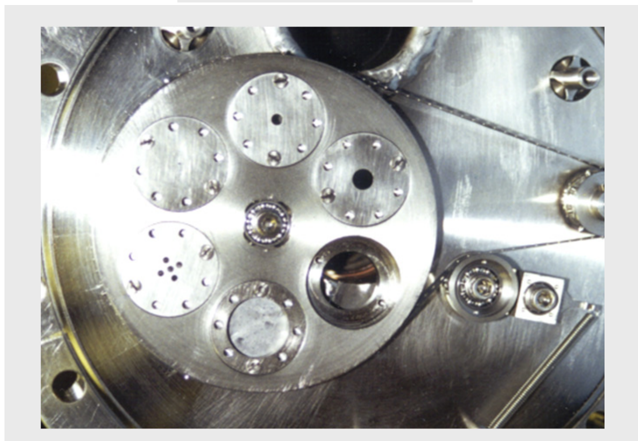
Why Low Energy Electrons?

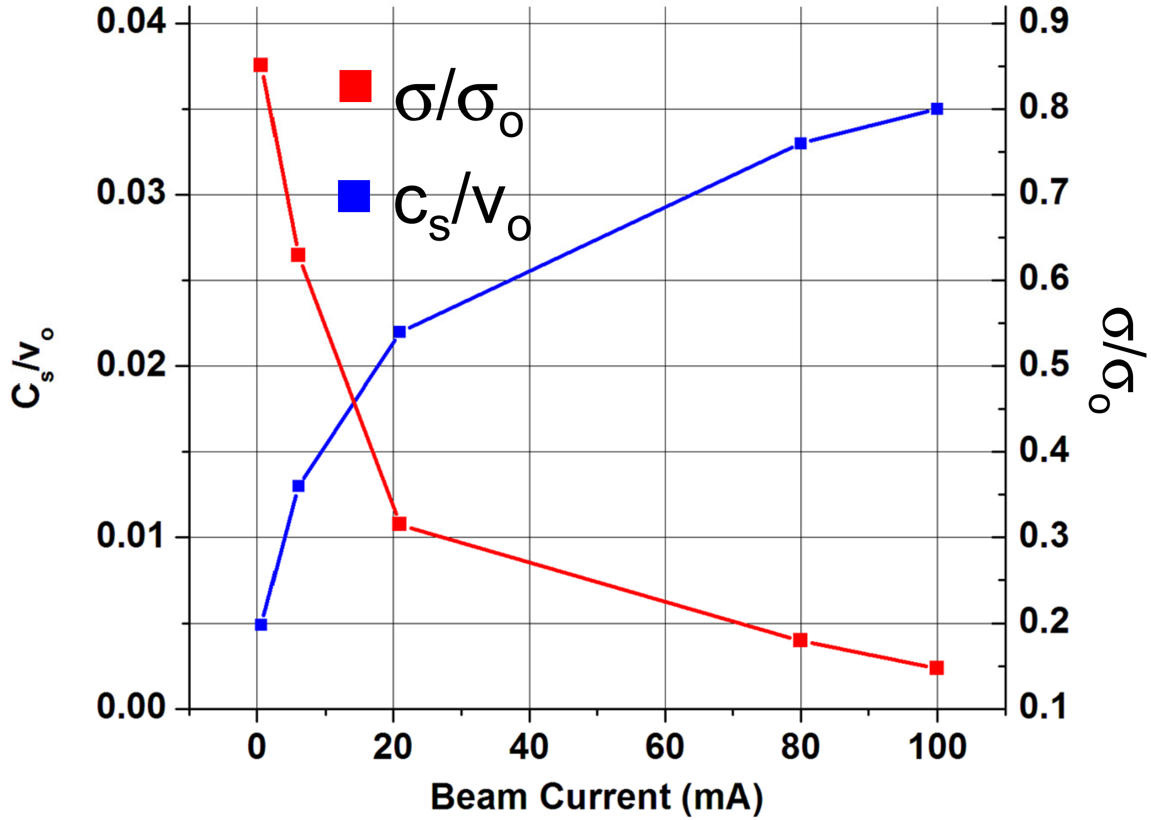


10-50 keV electrons
~ 20-100 MeV / nucleon

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

APERTURE PLATE





Tune shift

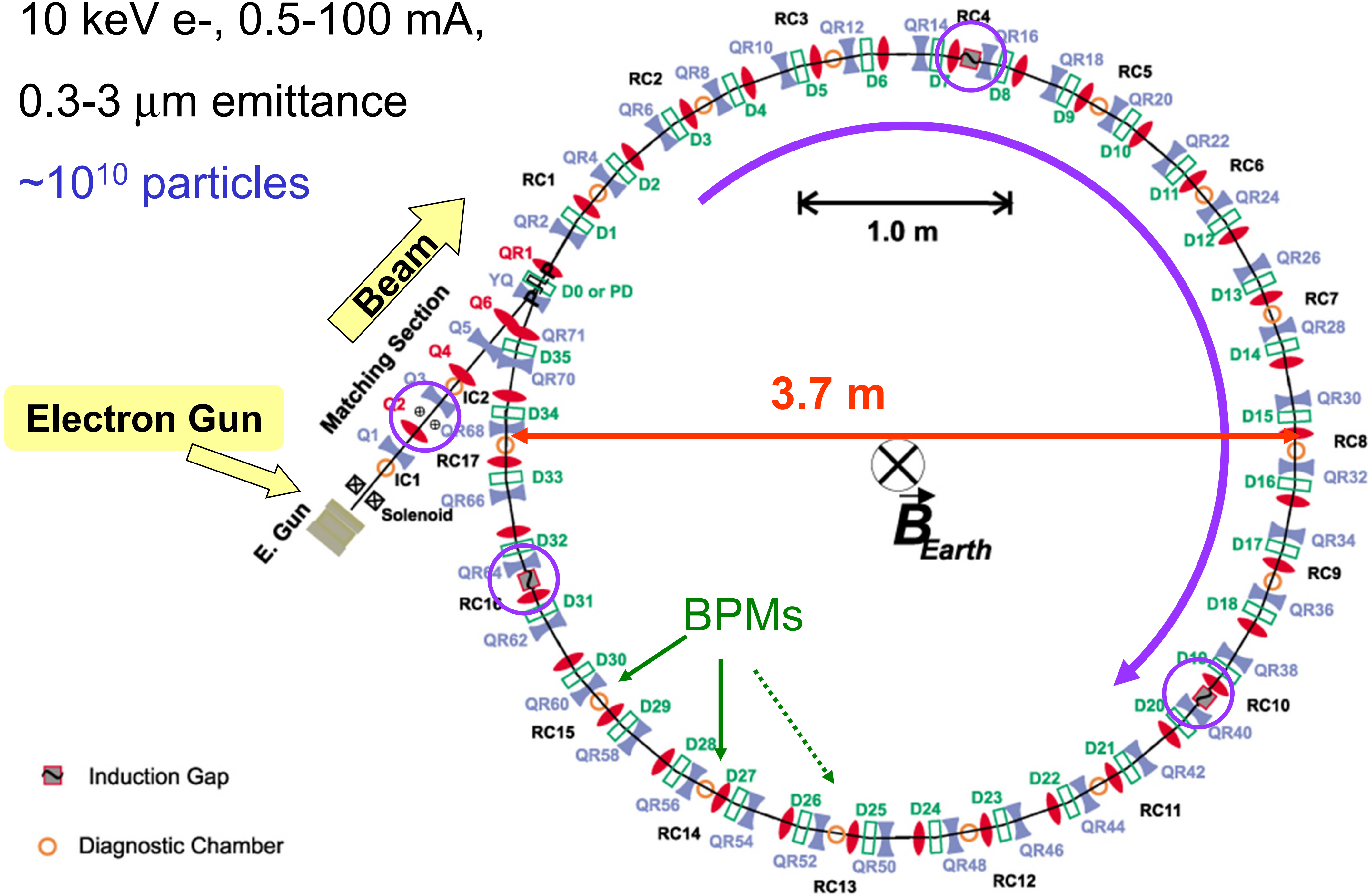
$$\Delta Q = Q_o\left(1 - \frac{\sigma}{\sigma_o}\right)$$

UMER – A Research Machine for Space-Charge Dynamics

10 keV e-, 0.5-100 mA,

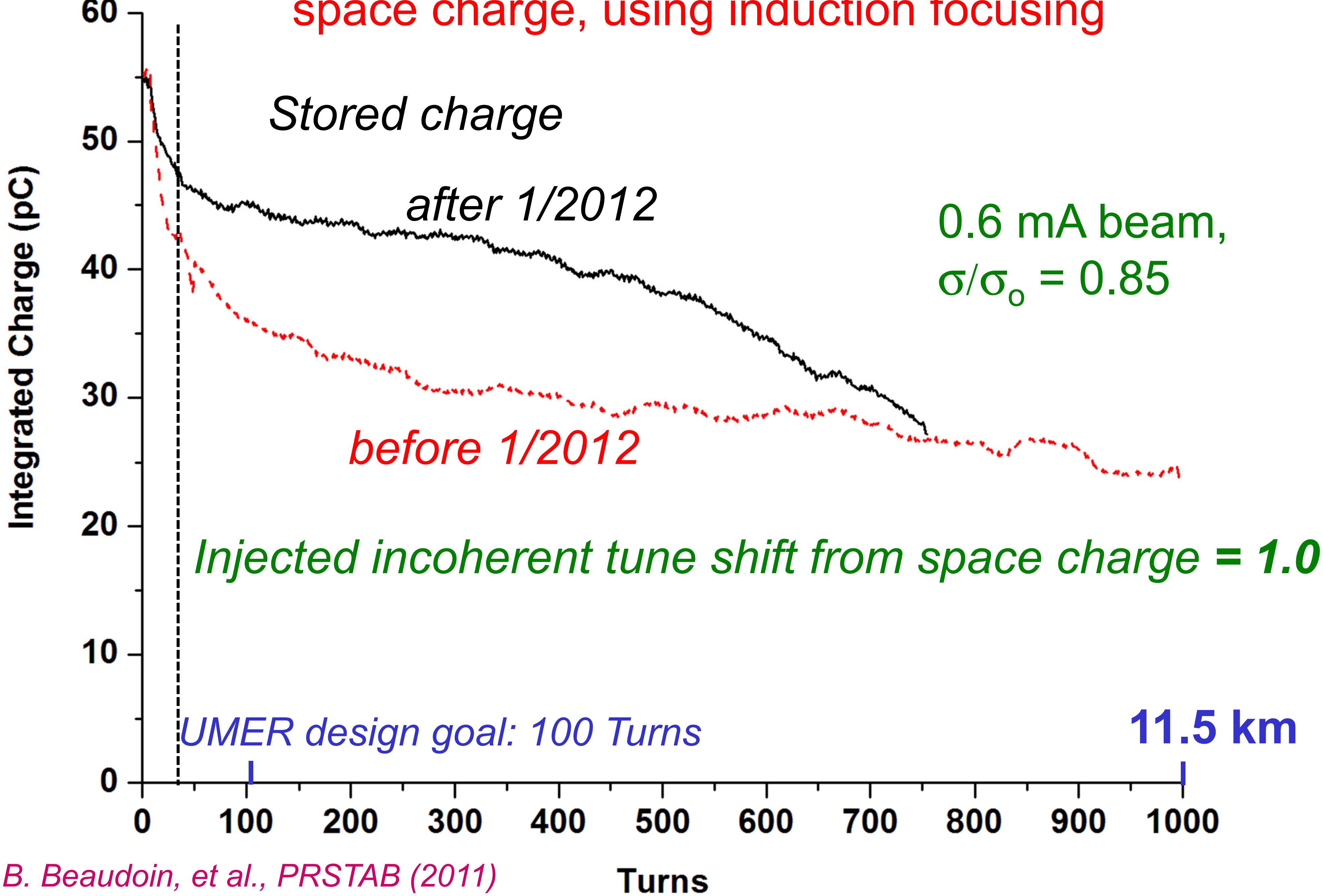
0.3-3 μm emittance

~10^{10} particles



Key Results from UMER

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



B. Beaudoin, et al., PRSTAB (2011)

Mapping of Resonances over Wide Range of Tunes

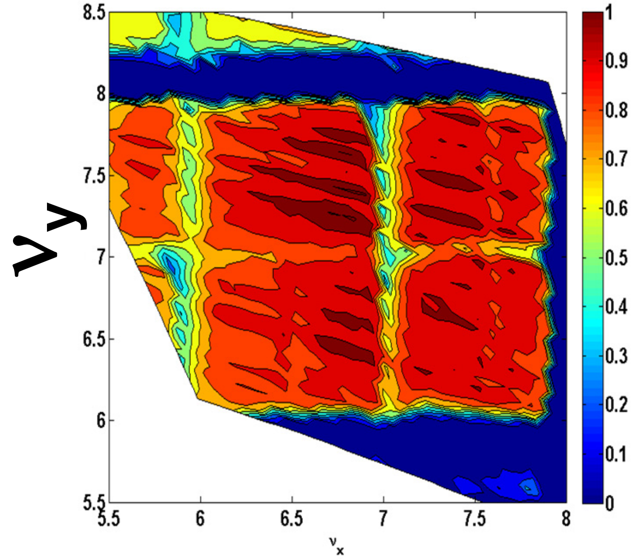
Work in Progress

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

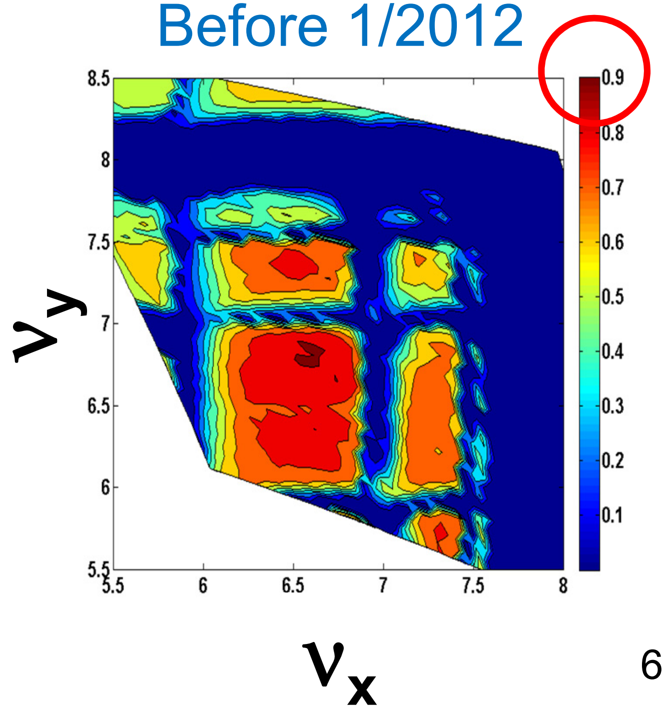
6 mA beam: $\sigma/\sigma_o \sim 0.45$
Injected incoherent tune shift from space charge **> 3.0**

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

After 1/2012



Before 1/2012



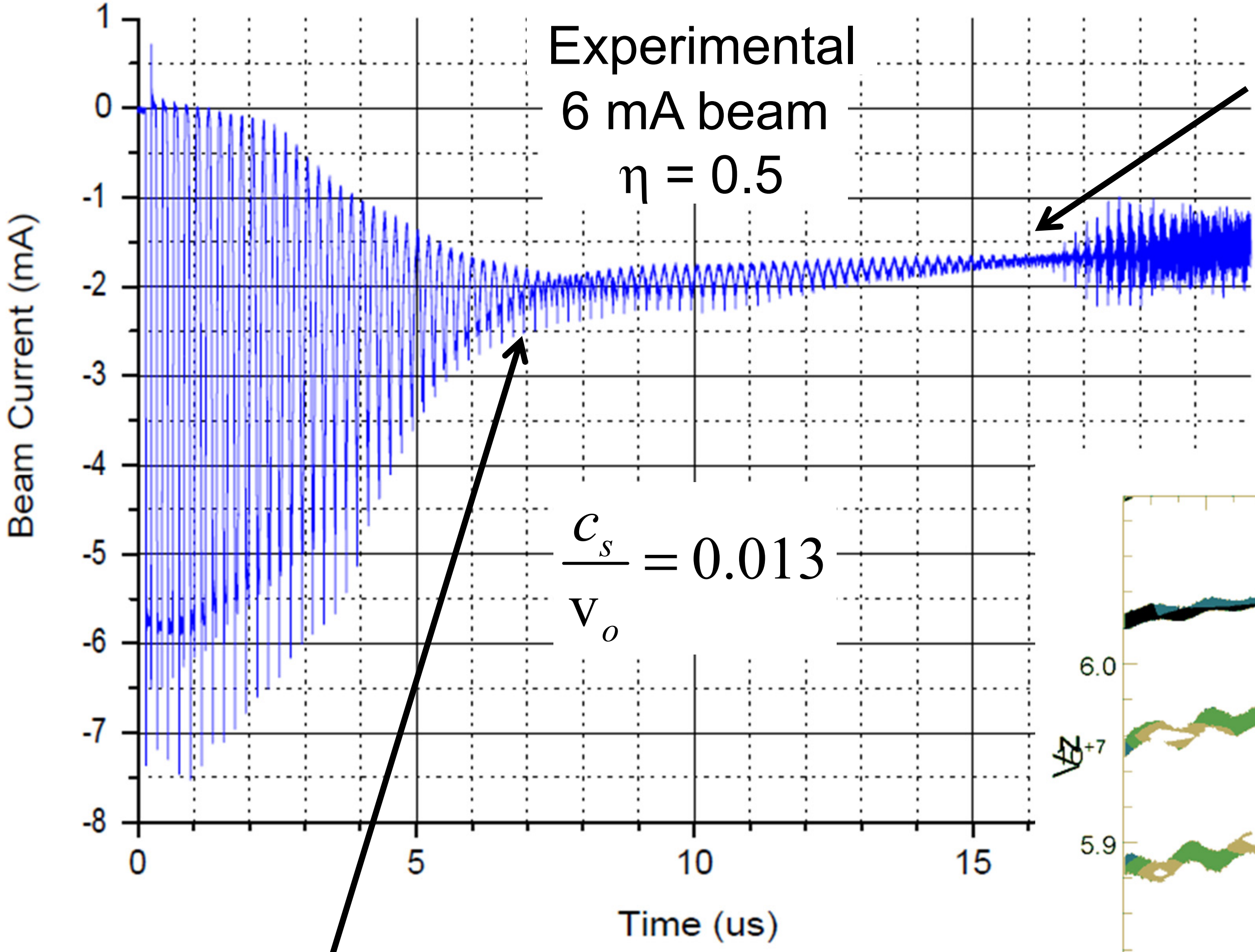
Sutter, Beaudoin, Bernal, Koeth 2012

Space Charge Induced Multi-Stream Instability

- Motivation: Multi-bunch injection in a ring or longitudinal stacking
- Predicted:
  - Ingo Hofmann, Particle Accel. **34**, 211 (1990).
- Experimental observation for short bunches:
  - S. Appel and O. Boine-Frankenheim, PRSTAB **15**, 054201 (2012).
- Will show experimental observation for long bunches in UMER

Observation of Multi-stream instability

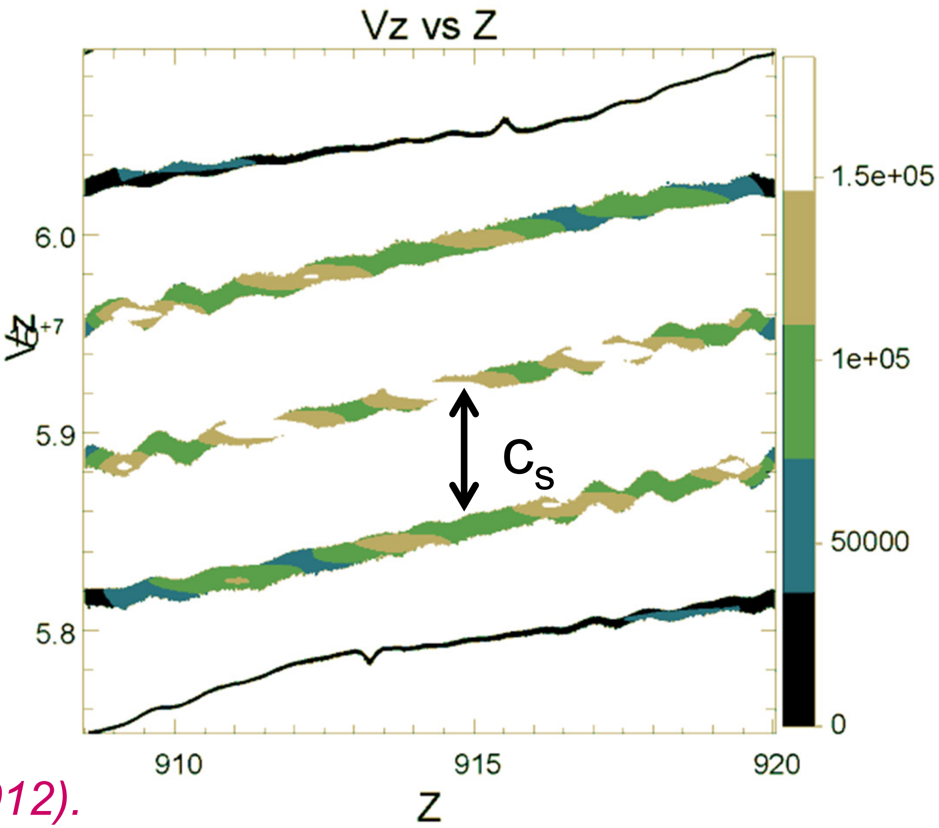
No longitudinal focusing – Beam expands and wraps around ring



Onset of instability
$t_{onset} = 16.5\ \mu s$

Beam becomes "DC"

Phase Space



B. Beaudoin, R.A. Kishek, I. Haber, et al., submitted (2012).

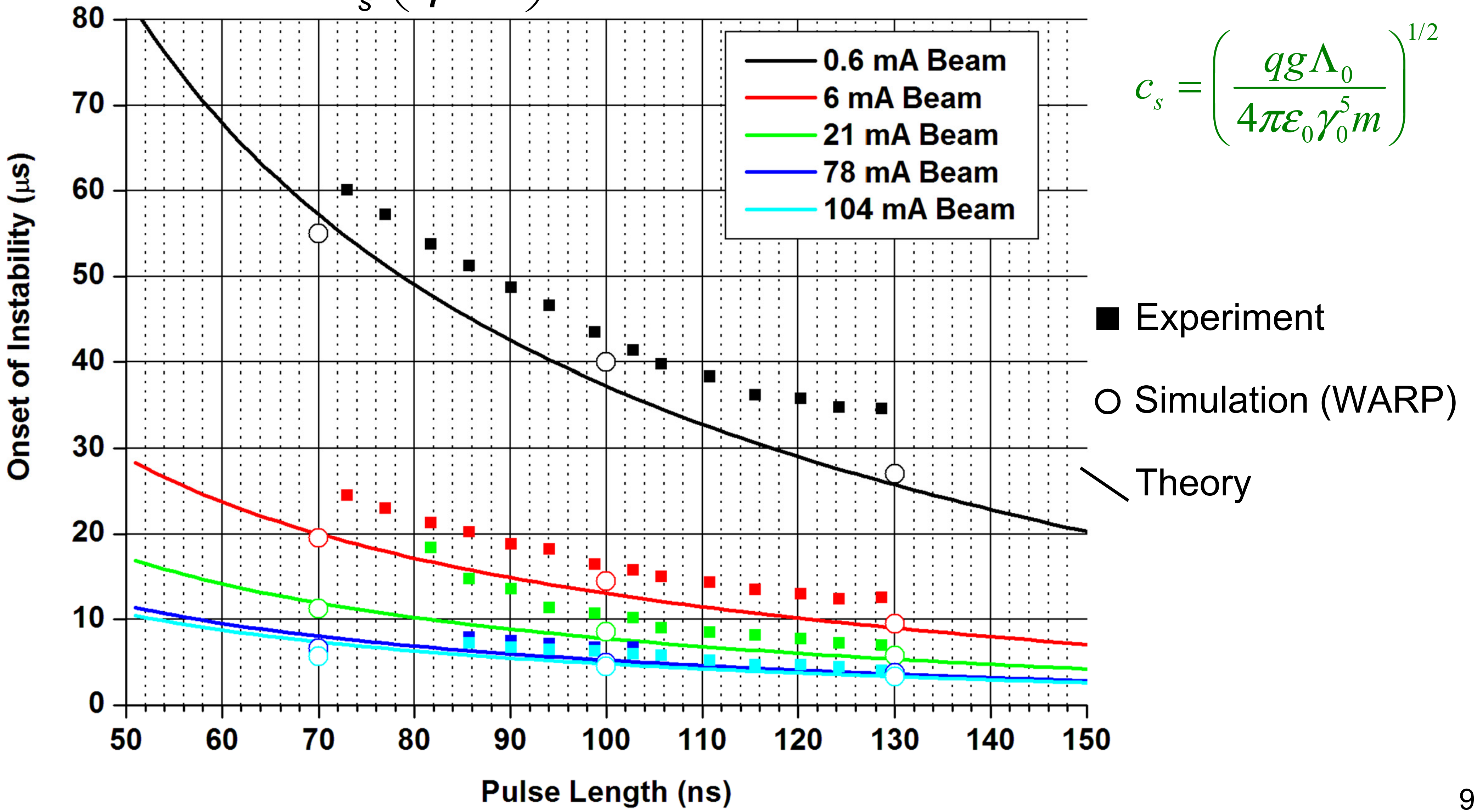
Test of Theory Against Experiment and Simulation

Onset of Instability

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

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

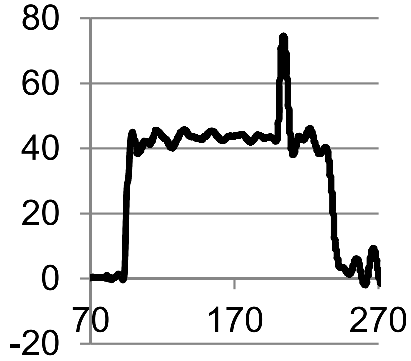
$$c_s = \left(\frac{qg\Lambda_0}{4\pi\varepsilon_0\gamma_0^5 m}\right)^{1/2}$$



Study of Large-Amplitude Perturbations

- Solitary waves: large-amplitude waves that persist and retain their shape for long distances. Discovered by J. Scott Russell (1834).
- Korteweg and deVries wrote equation to describe them

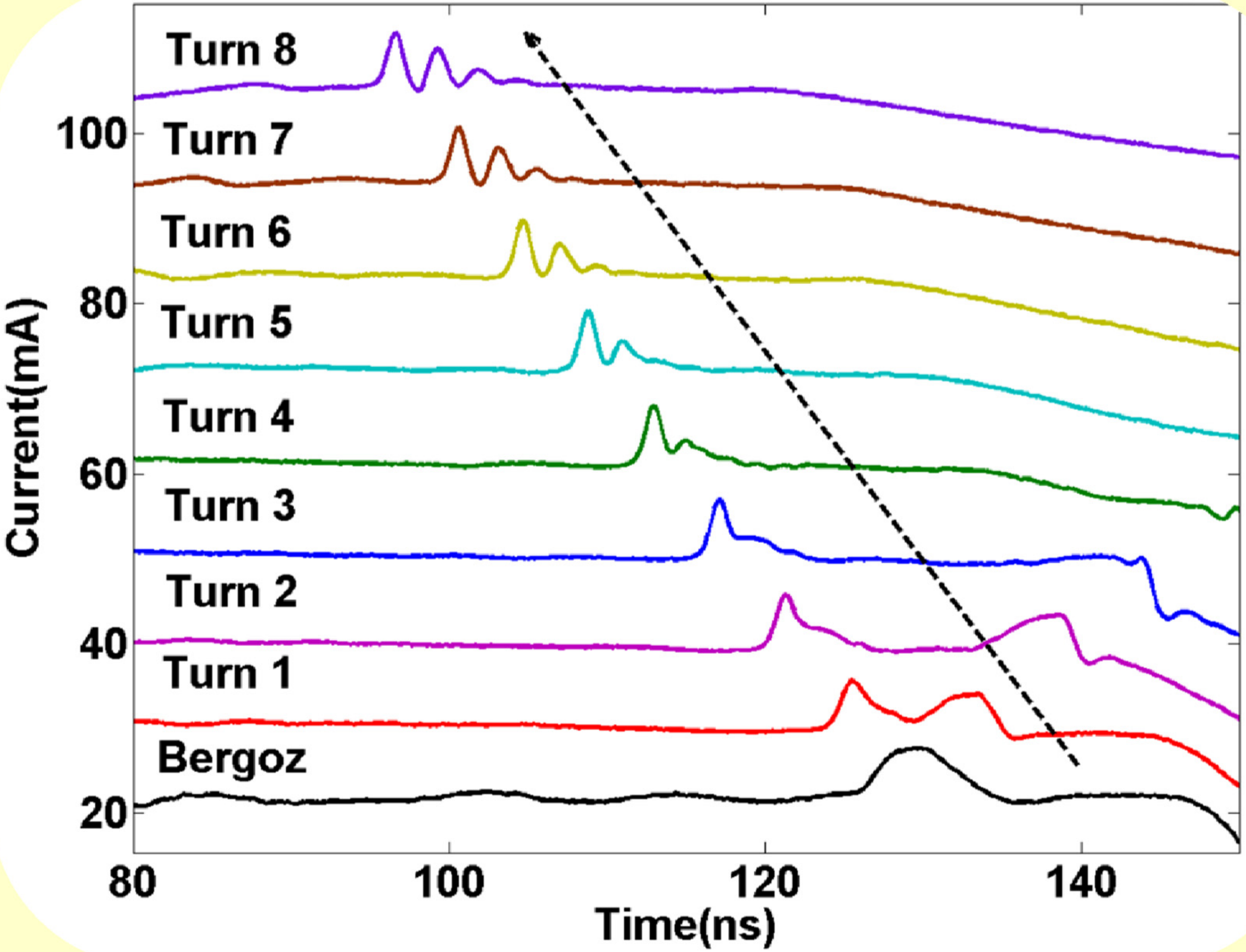
$$\frac{\partial u}{\partial t} + u * \frac{\partial u}{\partial x} + \frac{\partial^3 u}{\partial x^3} = 0$$



- KdV Equation solved in 1965 by Zabusky and Kruskall, “solitons” - particle properties
- Predicted for charged particle beams by Bisognano and Haber (1981), Suk (1996), and Davidson (2004).
- Experimental observations of stationary perturbations: Koscielniak (2001, CERN) and Blaskiewicz (2004, BNL).

Experimental Observation of Soliton Wave Train in UMER

Nonlinear steepening balances wave dispersion

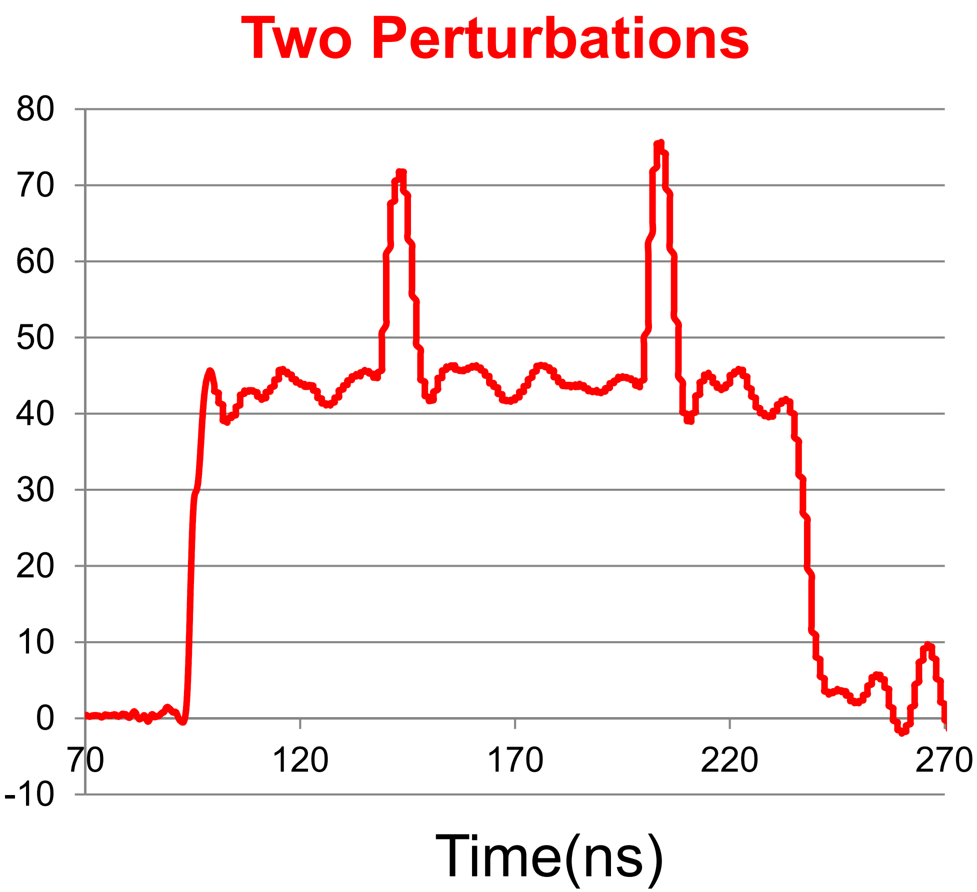


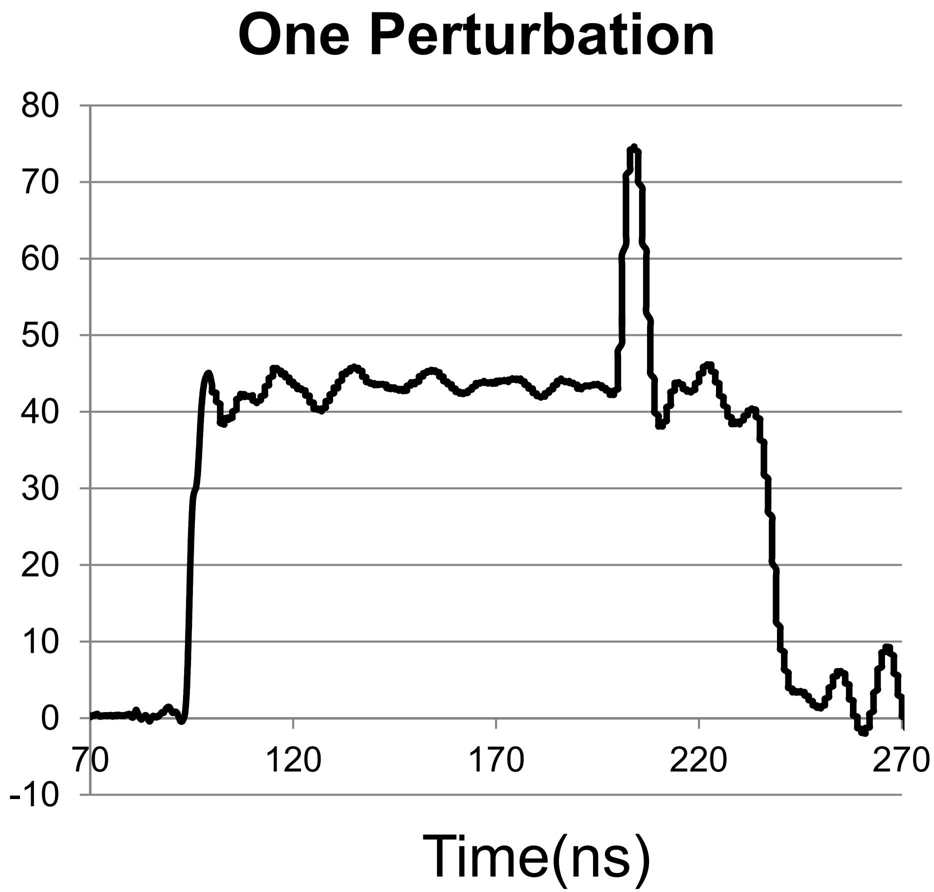
22 mA beam, 25% density perturbation

Y. Mo, B. Beaudoin, R.A. Kishek, I. Haber, J. Charles T. Thangaraj, et al., submitted, (2012)

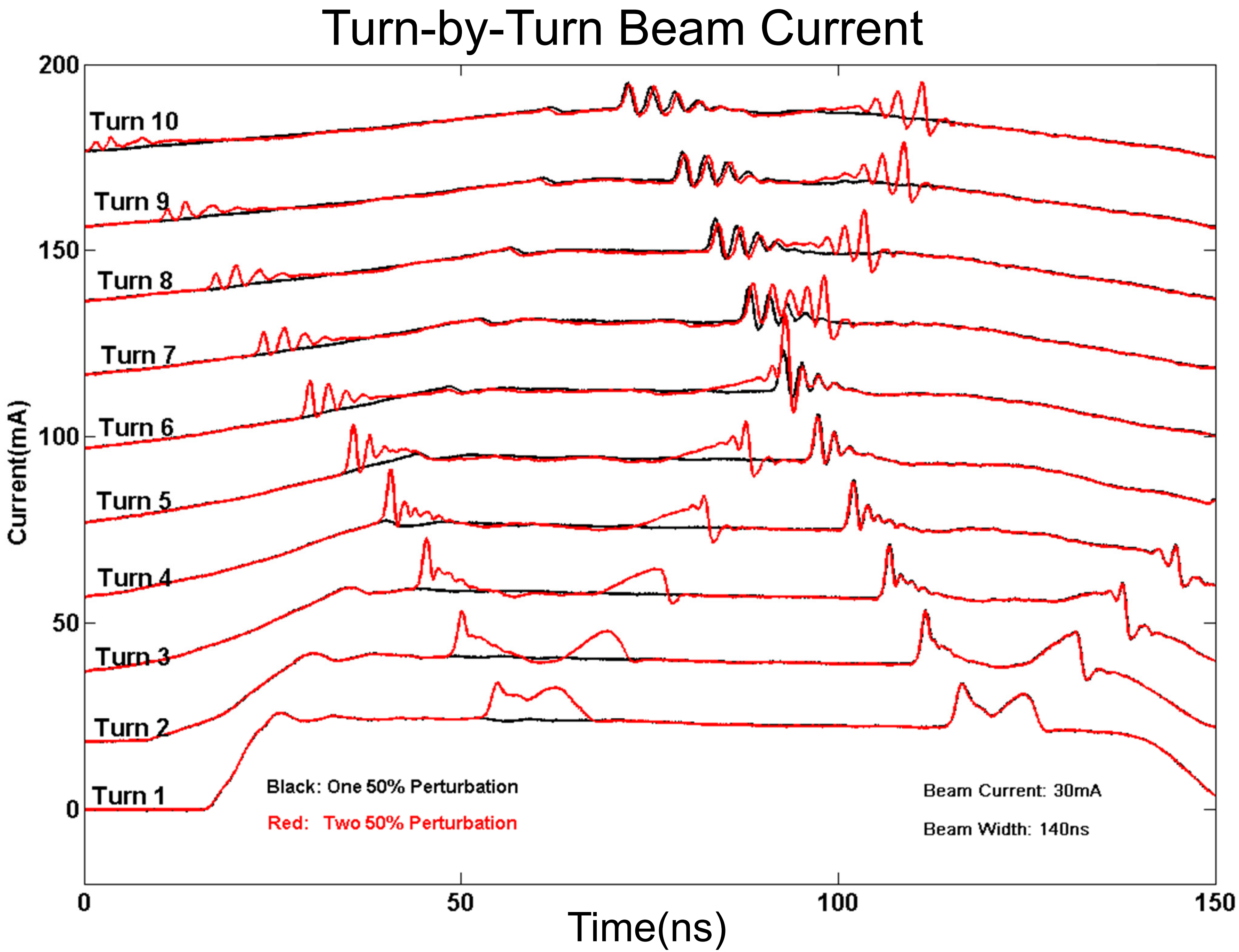
Soliton-Soliton Interaction Experiment

Initial Beam Current Traces

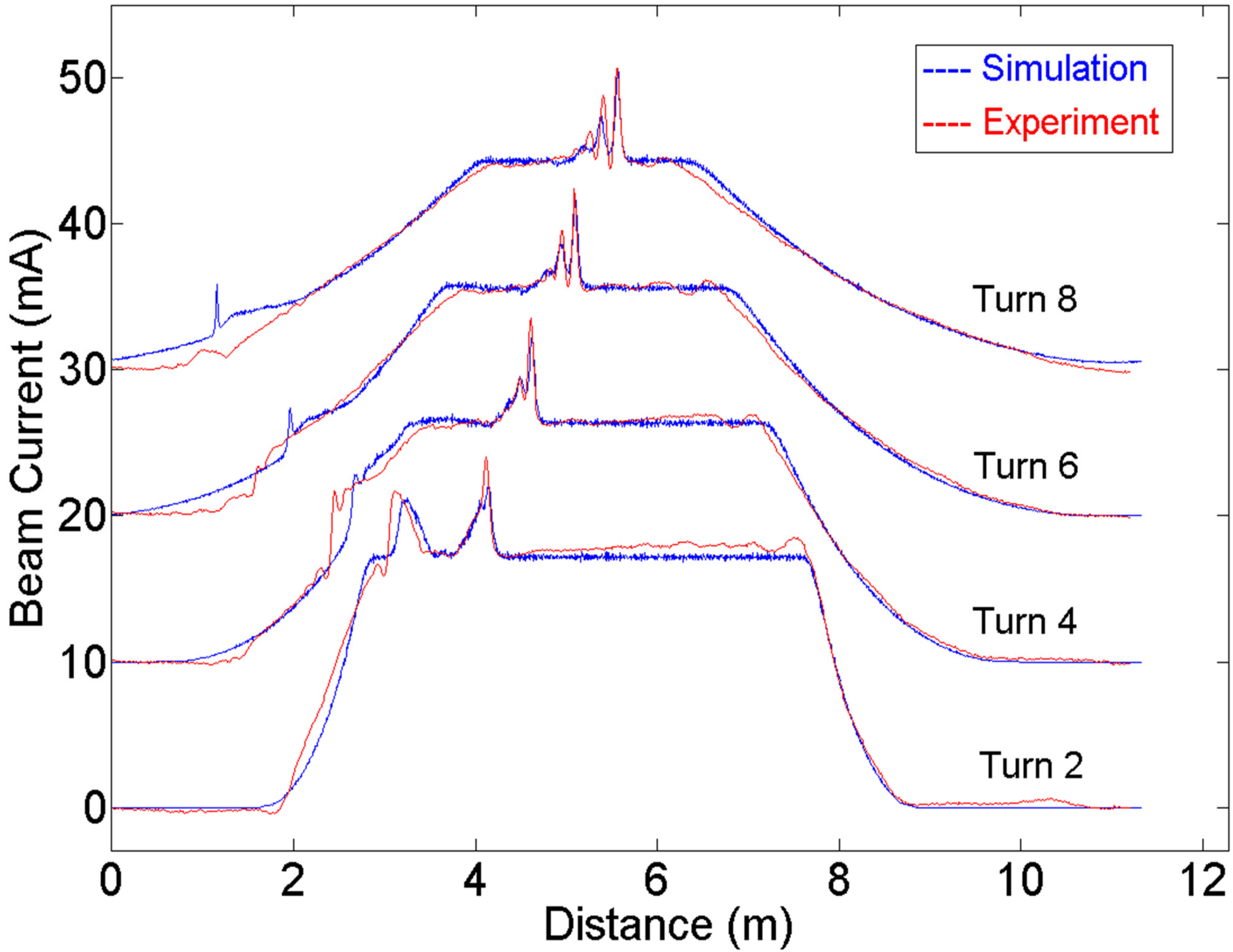




Soliton-Soliton Interaction Experiment



Simulation of Soliton Experiment



Y. Mo, B. Beaudoin, R.A. Kishek, I. Haber, J. Charles T. Thangaraj, submitted, (2012)

Summary and Recent Accomplishments

- UMER is a dedicated machine for studying space charge dynamics, at a wide range of intensities, over long path lengths
- Observed a space-charge induced multi-stream instability
- Observed solitary waves predicted by theory
- Good agreement with theory and simulation
- Resonance scans and halo studies in progress

Continuing and Future Research

- Longitudinal Instabilities
  - Prototyped new gun pulser that injects multiple short bunches
  - Study of impedance/resistive-wall instabilities
- Soliton excitation and propagation
  - Excitation from velocity perturbations (using induction cell)
- Resonances and resonance crossing
  - Prototyped acceleration 10 → 11 keV
  - Investigating envelope mode excitation
- Beam halo and Emittance Growth
  (see Poster by colleague Hao Zhang)

Dispersion leads to transverse split of head and tail

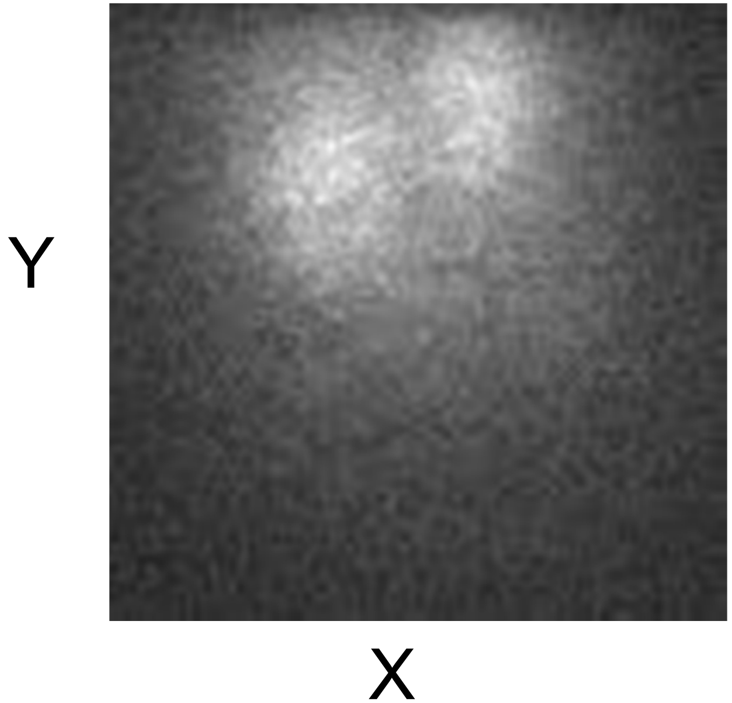


Image of 0.6 mA beam during turn 46