

# WARP - Simulation/Experiment Comparisons

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*BLAST Workshop 2018*

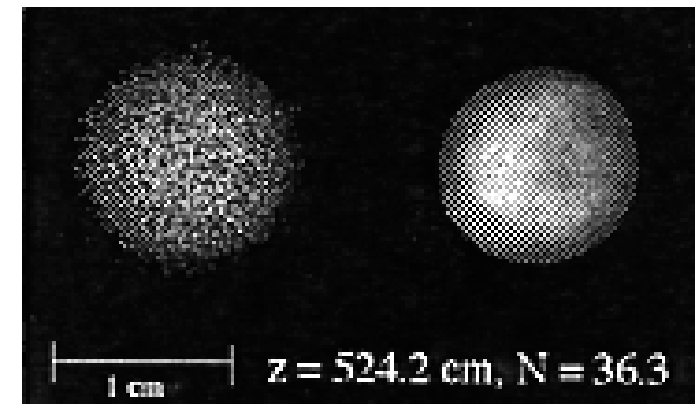
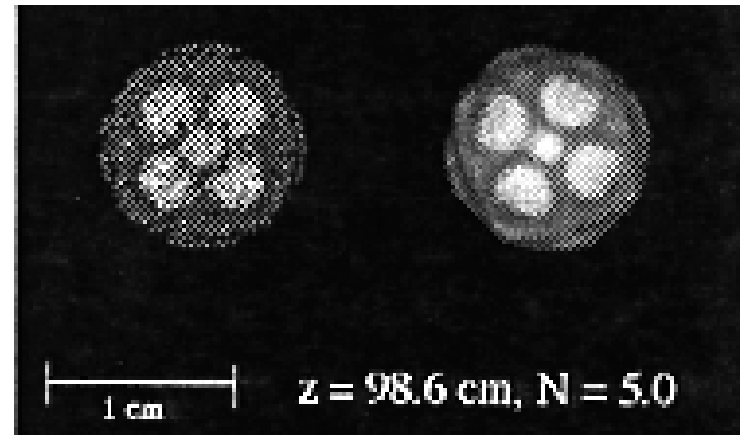
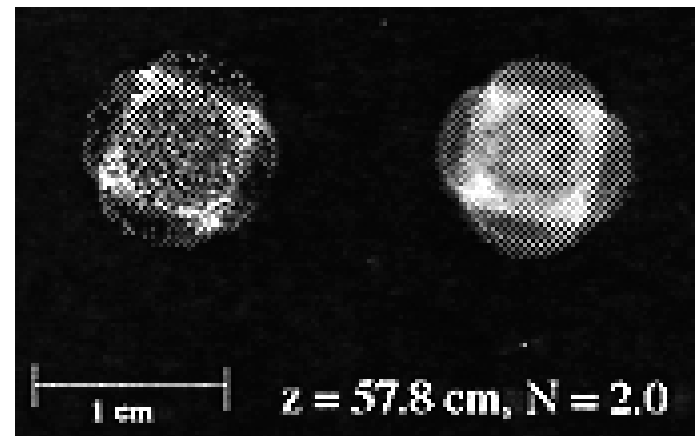
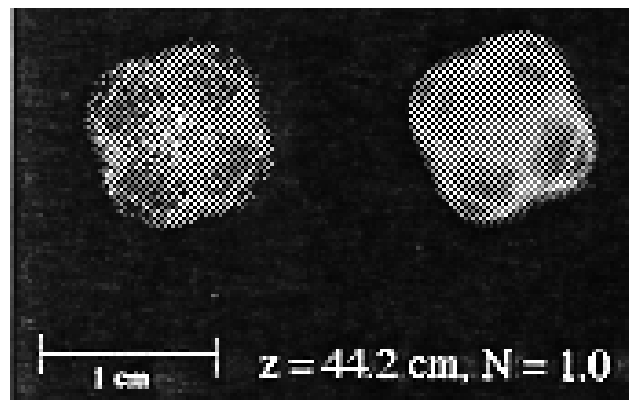
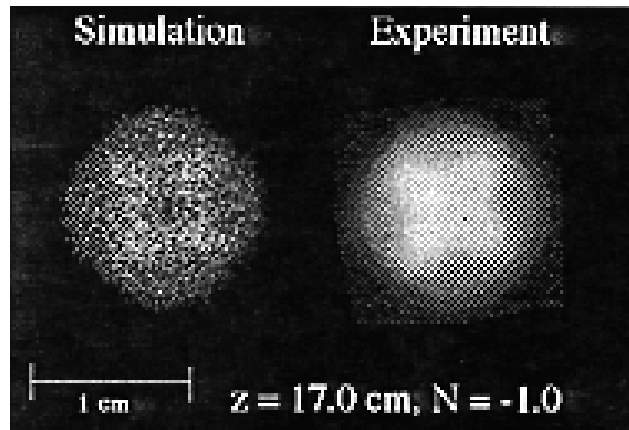
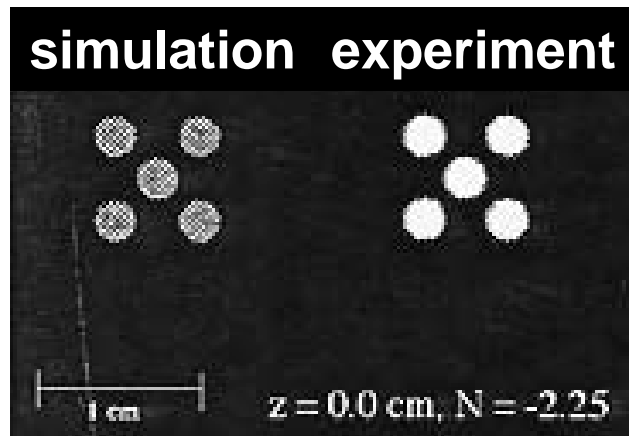
# Introduction

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- **“Low Hanging Fruit – Space-Charge-Dominated Beam”**
  - Only a few Debye lengths for a few plasma periods.
  - Convergence “relatively” easy to achieve.
  - Detailed experiment/simulation agreement should be possible.
- **Motivation: to see what we can infer that we don't expect**
- **Limits even when numerics are converged**
  - Detailed agreement requires detailed knowledge of experiment.
  - Inadequate diagnostics can limit this knowledge
- **Examples:**
  - Transverse: Five Beamlet
  - Longitudinal: Bunch-end interpenetration
  - Three-dimensional: Gridded-source Dynamics

# Five Beamlet Experiment

# RMS Matched Beam $\sim 1989$



# Five-Beamlet Experiment

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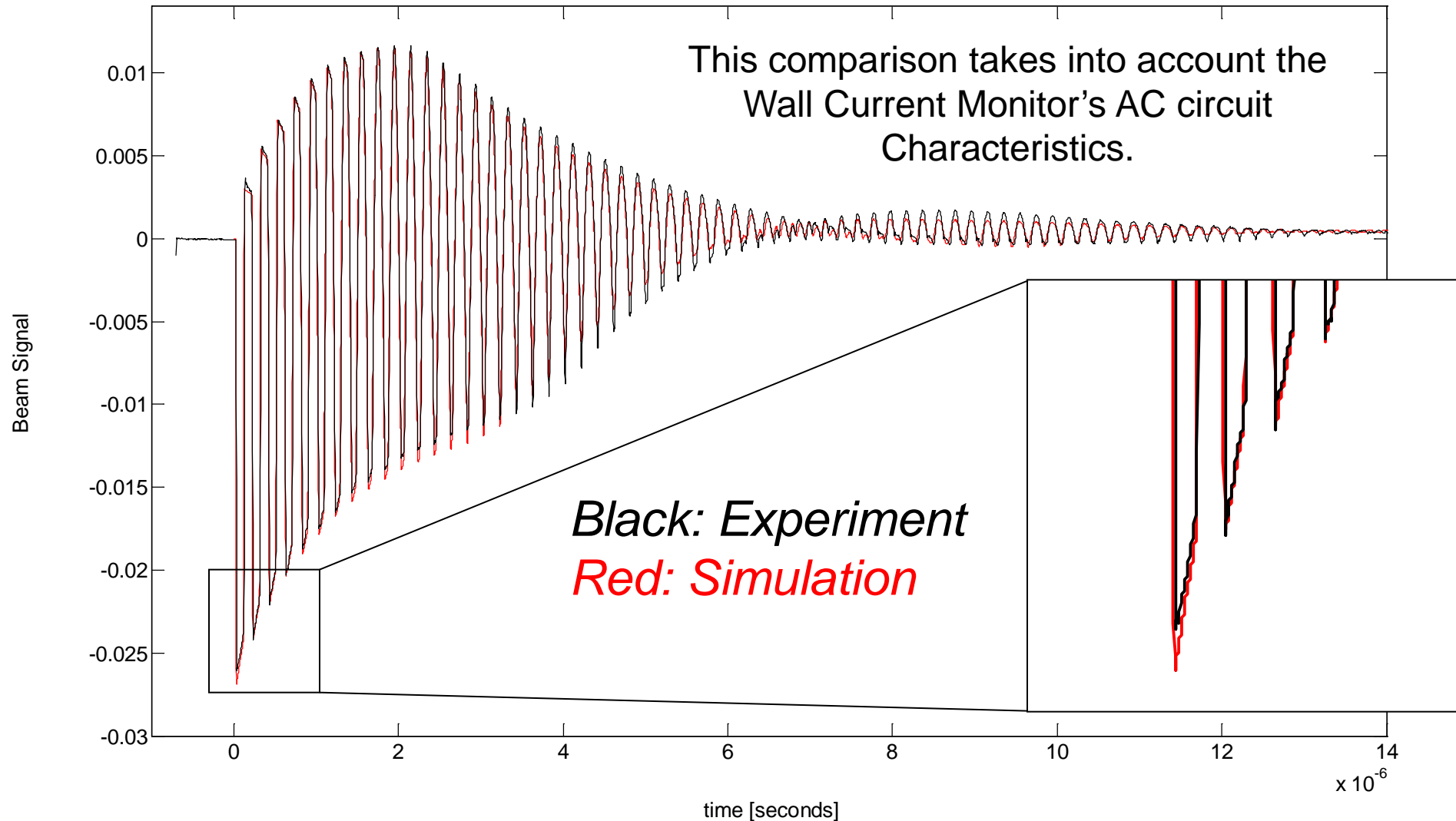
- Performed to test theory of emittance growth from homogenization of an initially nonuniform beam
- Simulation and experiment agreed with theory, (image formation was not expected).
- No free parameters in simulation.
- Results are sensitive to initial emittance, could be used to estimate emittance.
- Biggest surprise was level of detailed agreement, (able to 'fix' expt) probably due to knowledge of initial distribution.
- No halo for matched beam. **Simulations of mismatched beam led to discovery of halo formation, verified by experiment.**

I. Haber, D. Kehne, M. Reiser, and H. Rudd, , Phys. Rev. A15, 44, 5194 (Oct. 15, 1991).

# Bunch-End Interpenetration

# Simulation/Code Comparison

## *Bunch-lengthening without Longitudinal Focusing*



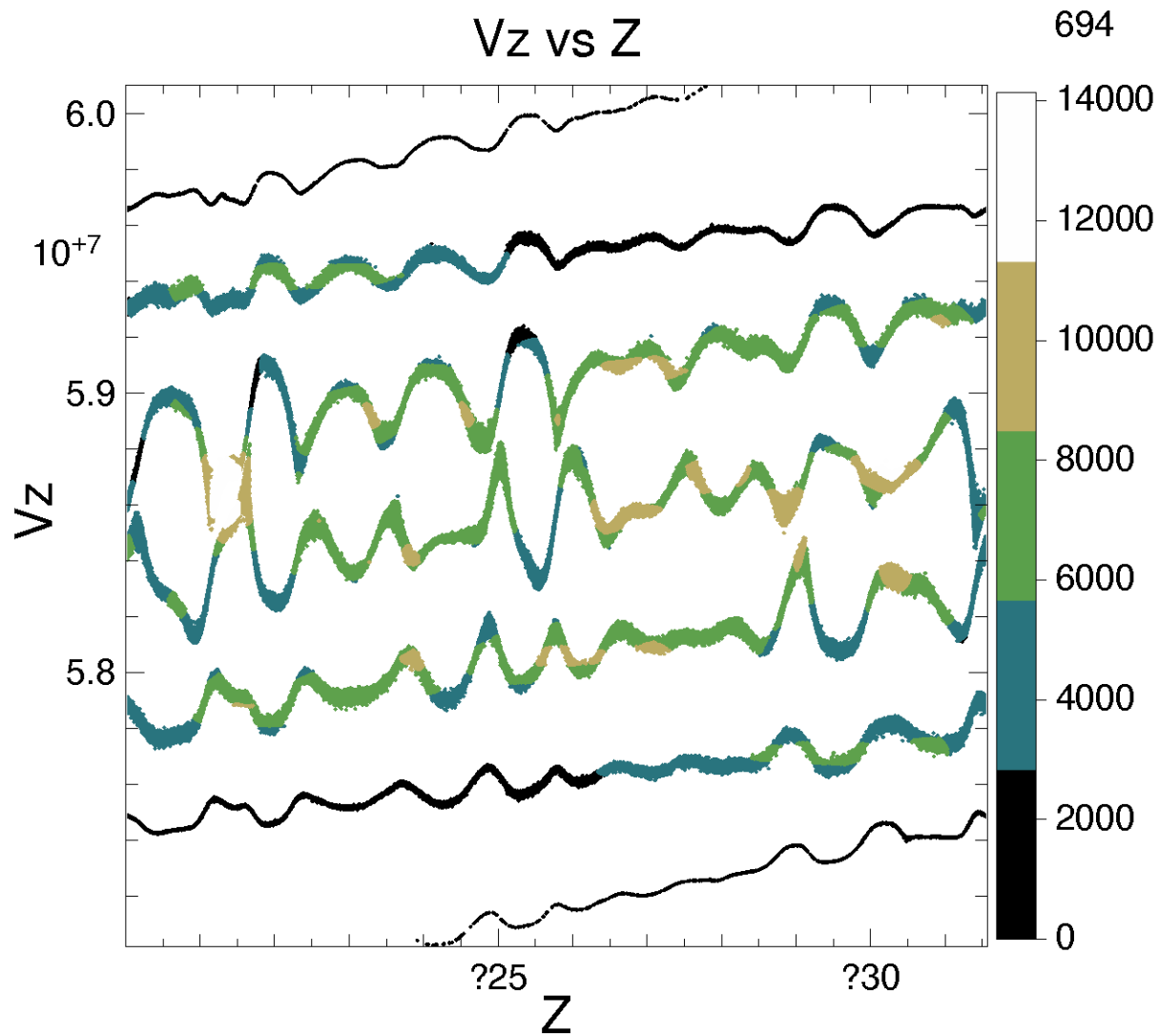
# Bunch-End Interpenetration

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- R-Z simulation geometry – straightened ring with periodicity.
- As bunch lengthens, bunch-ends (repeatedly) pass through each other.
- Measurement circuit (primarily inductance in parallel with resistance) distorts time response so that DC component of signal is lost.
- Transverse current loss (as measured by knock-out) approximated by simple bi-linear model in simulation
- Multi-streamed phase space implied by simulations goes unstable.
- **Instability subsequently seen in experiment.**

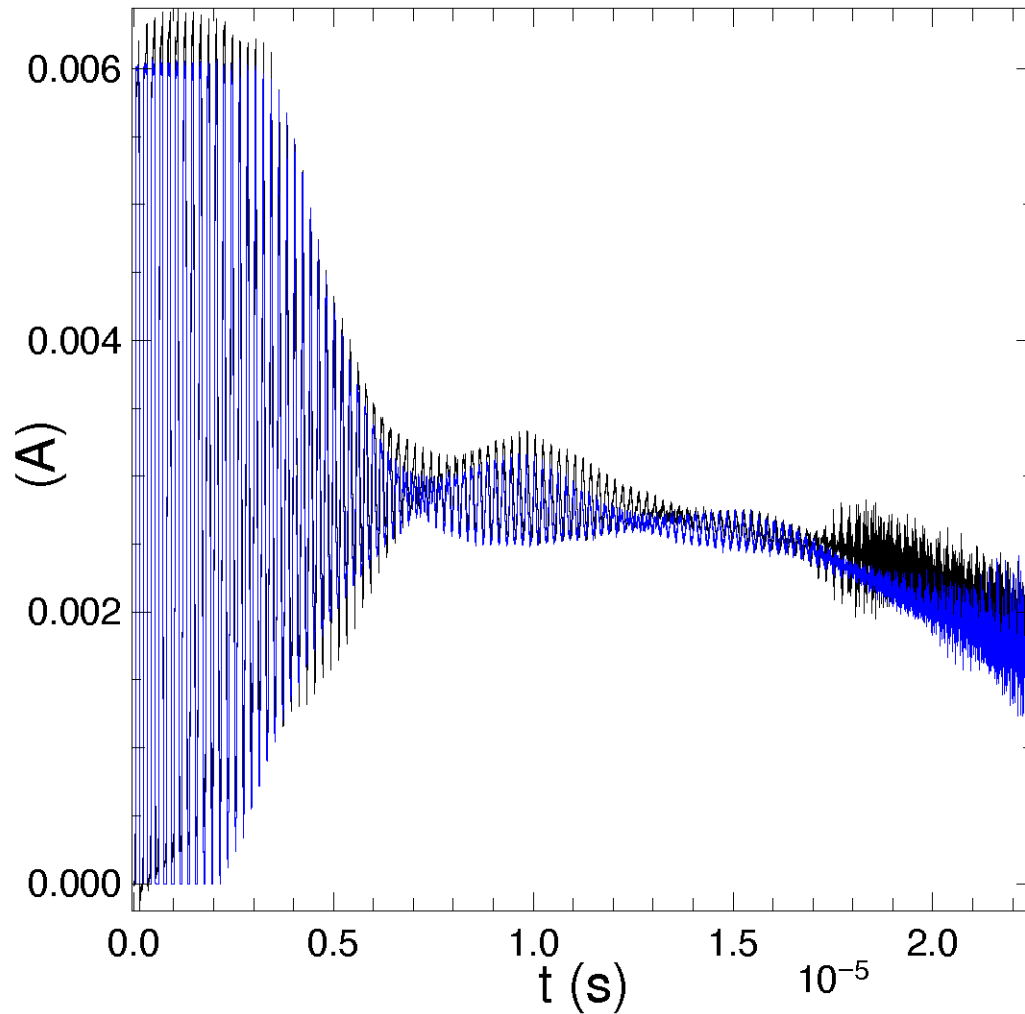
Koeth T. Koeth, B. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, and P.G. O'Shea,  
[Proceedings of the 2011 IEEE Particle Accelerator Conference, New York, NY, 22 \(2011\)](#)





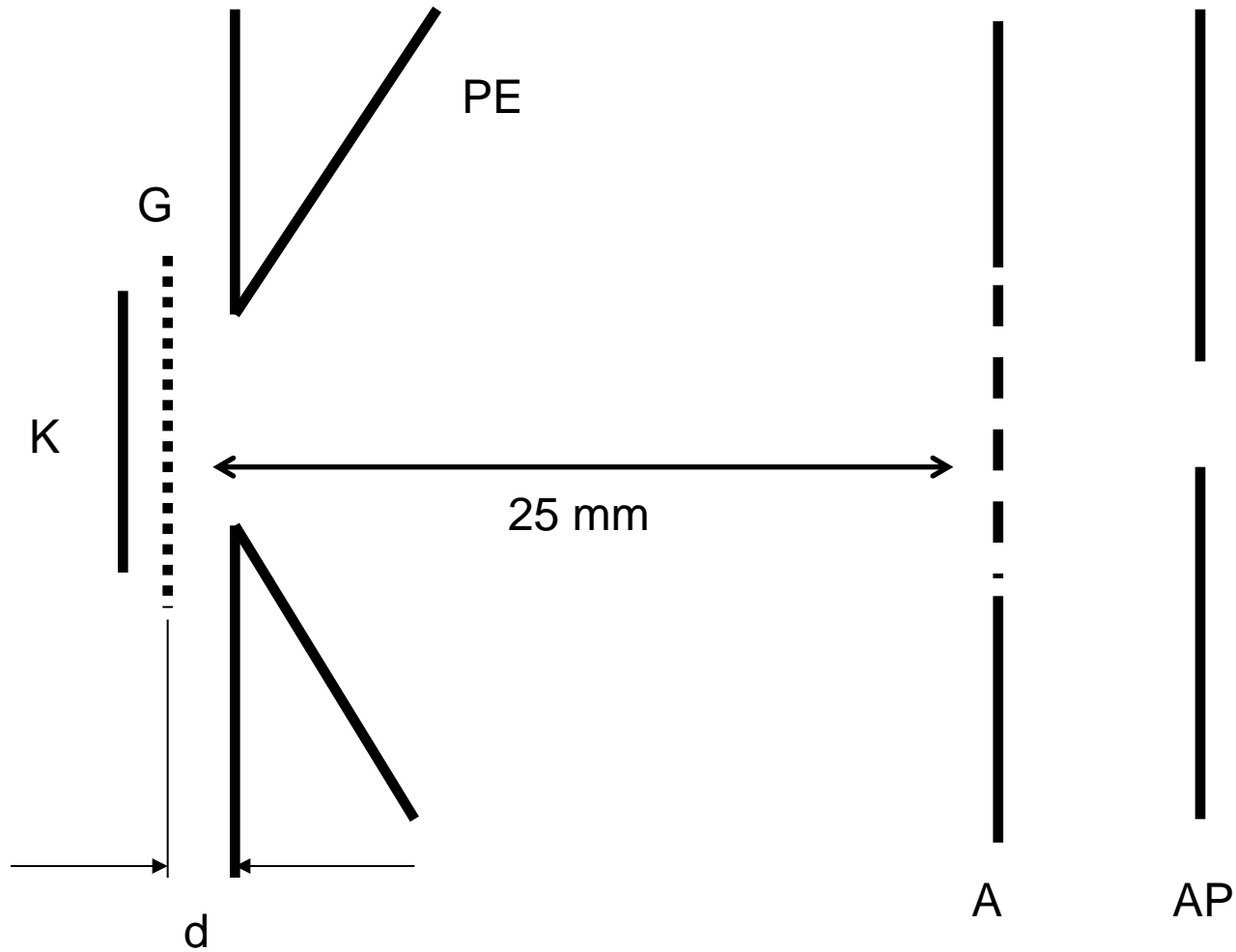
$z$ - $V_z$  phase space from the simulation after the instability is well developed. Unstable wavelength is  $\sim 1$ m, compared to  $\sim 0.05$ m pipe diameter.

## current versus time

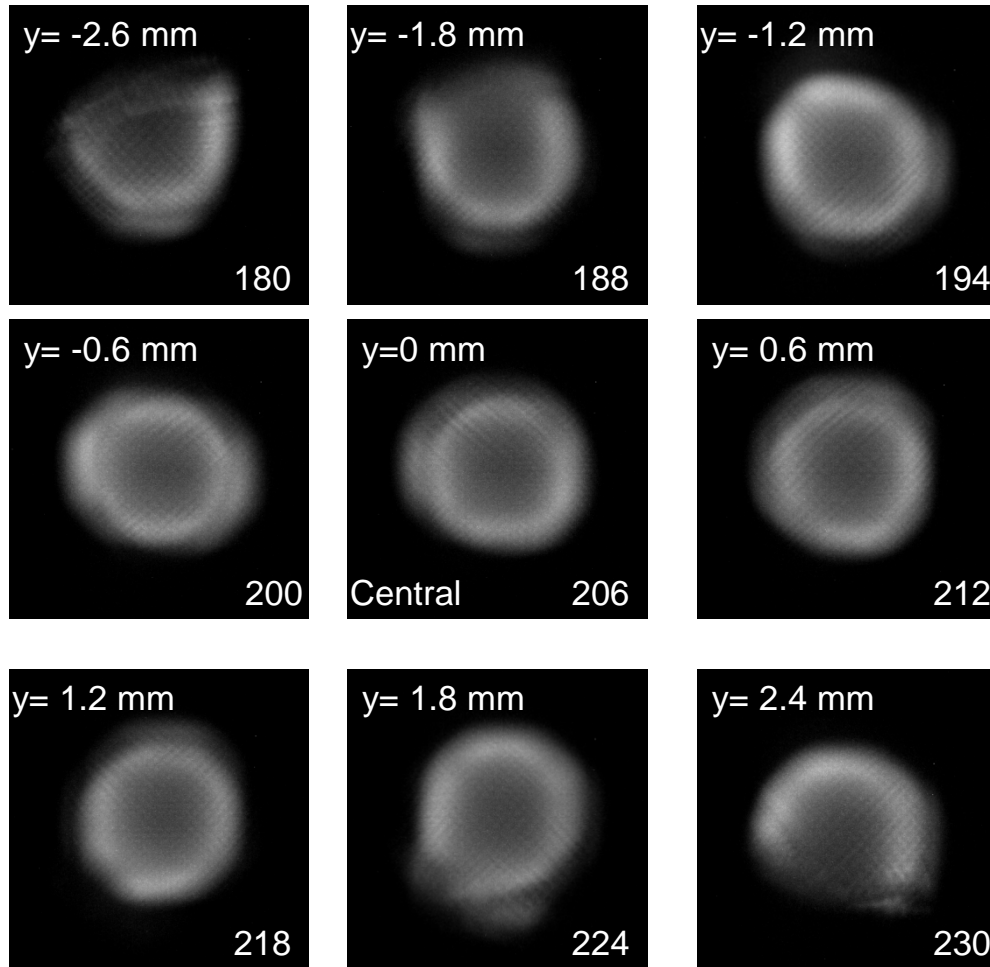


Comparison of current from experiment (black) and simulation (blue). Onset of instability in experiment is observed earlier than in simulation.

# Gridded Gun Behavior



Cartoon of UMER gun showing cathode (K), cathode grid (G), Pierce electrode (PE), gridded anode (A), and aperture plate (AP).



Pinhole-measured transverse velocity distribution  
hollow and relatively constant across across the beam

# Simulations of One Grid Cell with Four-Fold Symmetry

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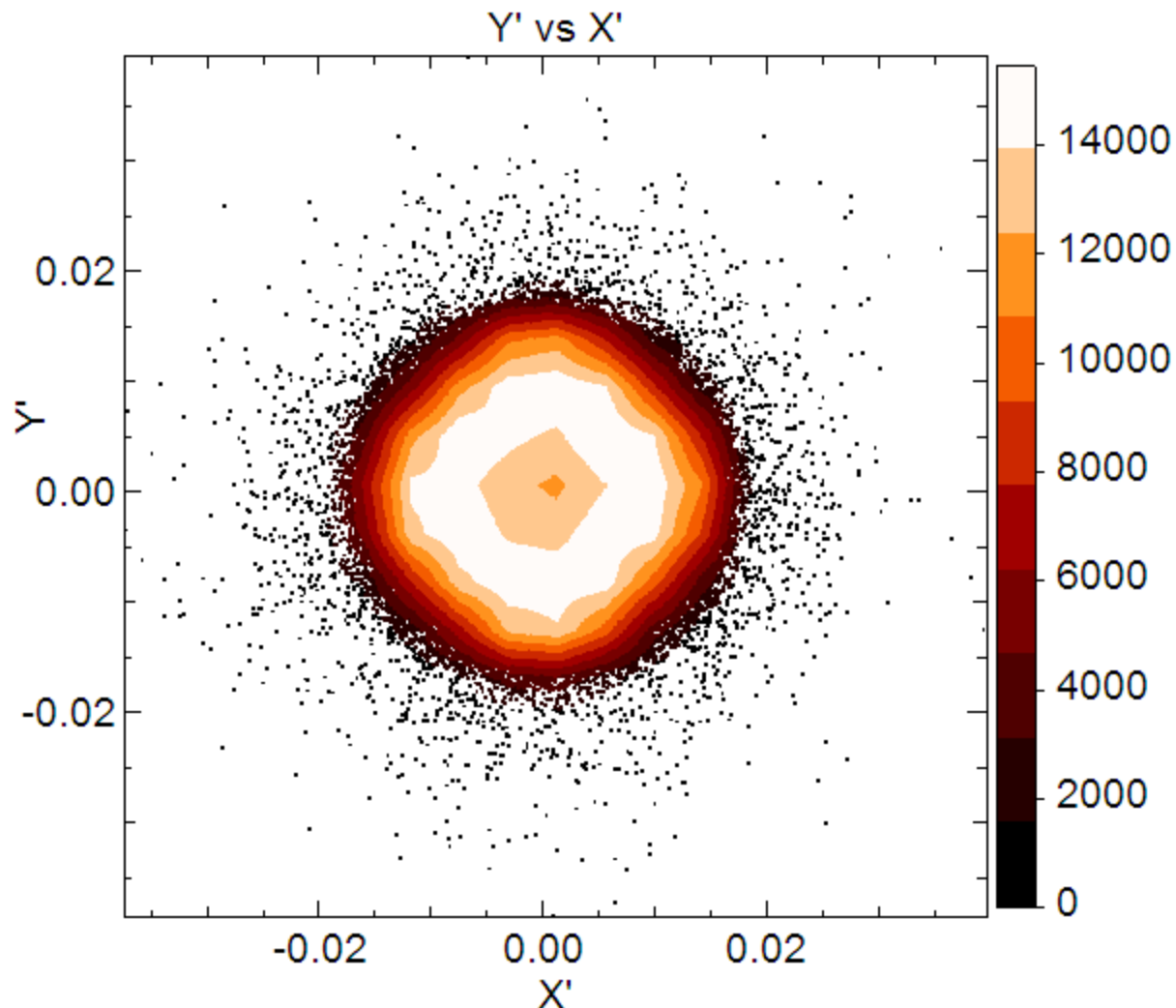
- 3-D simulation region
  - 75x75 $\mu\text{m}$  transverse
  - 35 mm longitudinal
- $\sim 10^7$  particles.
- Hollow velocity distribution observed experimentally, reproduced in simulations.
- Unexpected virtual cathode oscillations observed in the simulations were observed in experiment.

I. Haber, D. Feldman, R. Fiorito, R. A. Kishek, B. Quinn, M. Reiser, J. Rodgers, P. G. O'Shea, K. Tian, M. Walter, A. Friedman, D. P. Grote, J. -L. Vay, [Nuclear Instruments and Methods A](#) **577**, 157-160 (2007).

# Simulations of One Grid Cell with Four-Fold Symmetry

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- 3D Simulation system transversely  $75 \times 75 \mu\text{m}$
- Longitudinal grid  $\sim 25\text{mm}$  with mesh refinement near grid.
- $\sim 10^7$  particles
- Hollowed velocity distribution reproduced in simulations.
- Virtual Cathode oscillations predicted and measured.

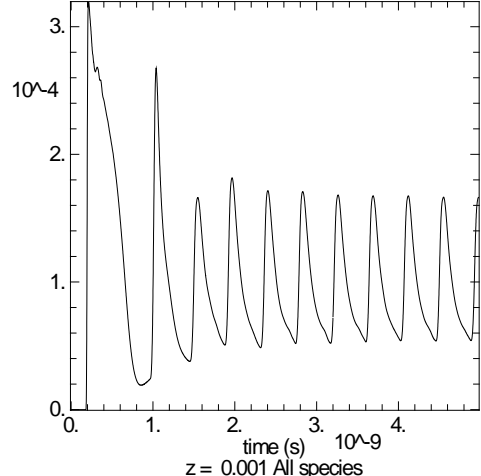
**30V**

iz = 254 (z = 0.023892 m)

pli,  
pldj, Step 32700, T = 0.0052e-6 s, Zbeam = 0.0000 m  
pldj, Simulation of full diode length  
16x16x256 with MR

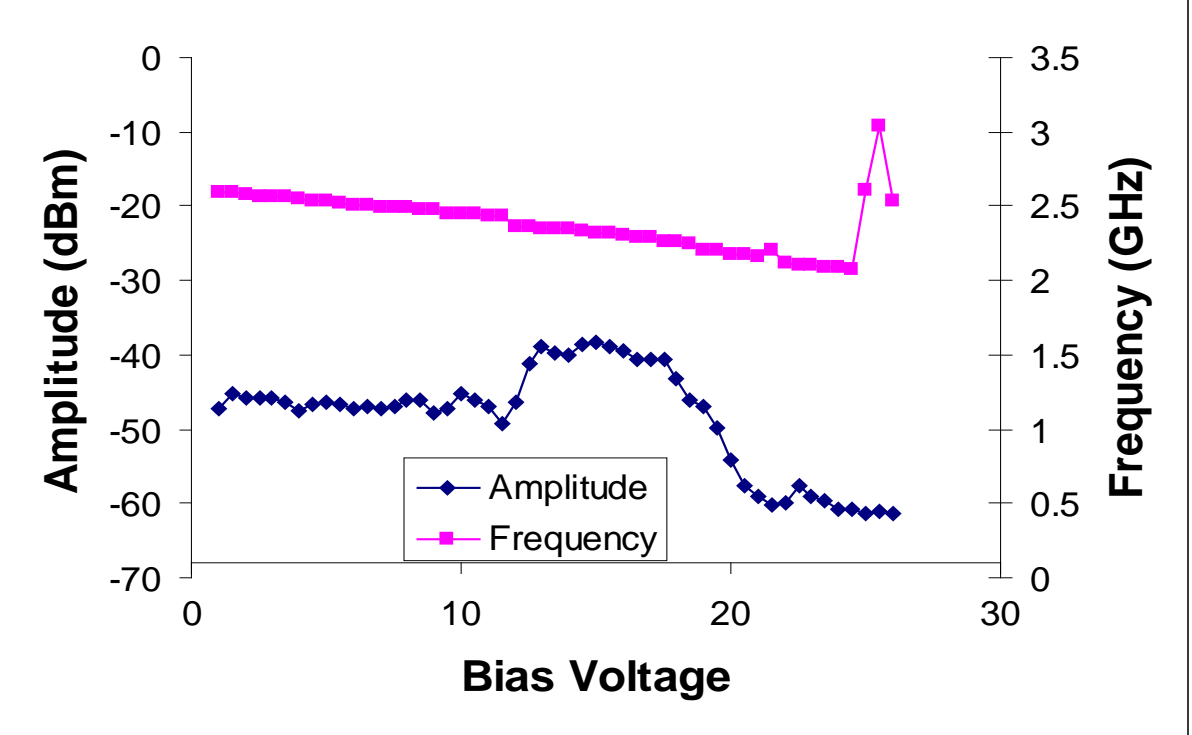


Virtual cathode oscillations predicted by simulation were measured by spectrum analyzer near predicted frequency.



Simulated current waveform

Step 31500, T = 0.0050e-6 s, Zbeam = 0.0000 m  
Simulation of full diode length  
16x16x256 with M/R  
I. Haber, D. P. Grote    warp r2    me42



Peak of measured spectrum

# Conclusions

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- Detailed experiment/simulation agreement can allow reliable discovery of unanticipated physics. (If you trust the simulations).
- Skeptics abound.