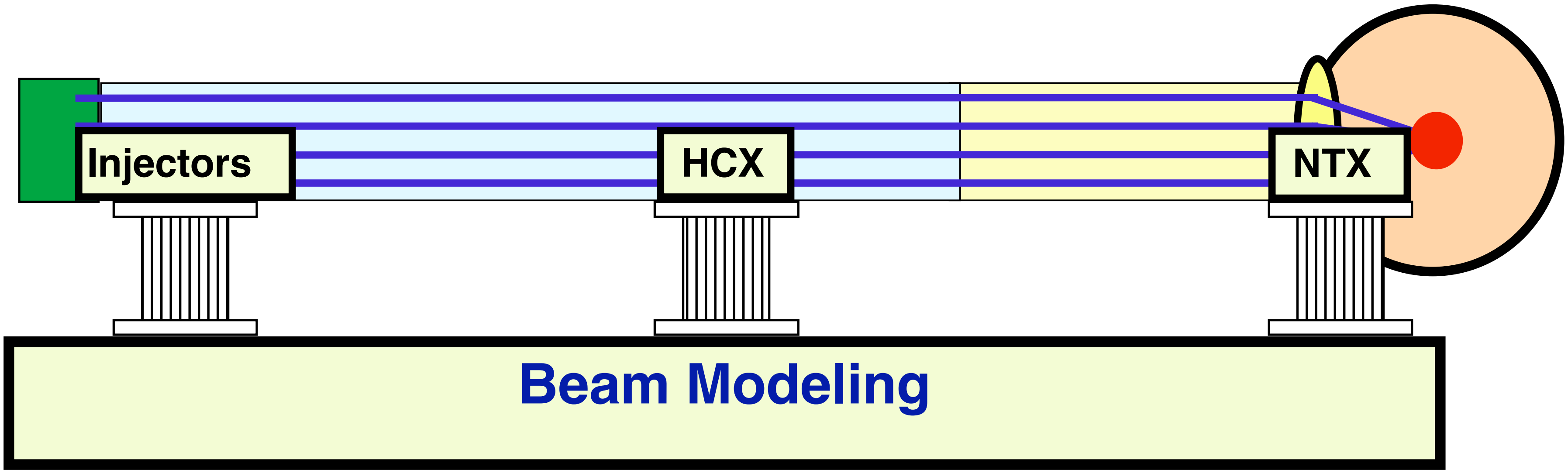
Beam Modeling Progress



Alex Friedman
Beam Modeling Task Area Leader
HIF-VNL Q4 Progress Report Meeting
September 29, 2004

Heavy Ion Fusion
Virtual National Laboratory

Outline

I. Modeling in support of experimental milestones
   a) Injector research
   b) High-current transport: HCX & electron clouds
   c) Neutralized transport & focusing: NTX
II. Preparations for future experiments
III. Other developments & closing thoughts

Embedded: computational physics innovations

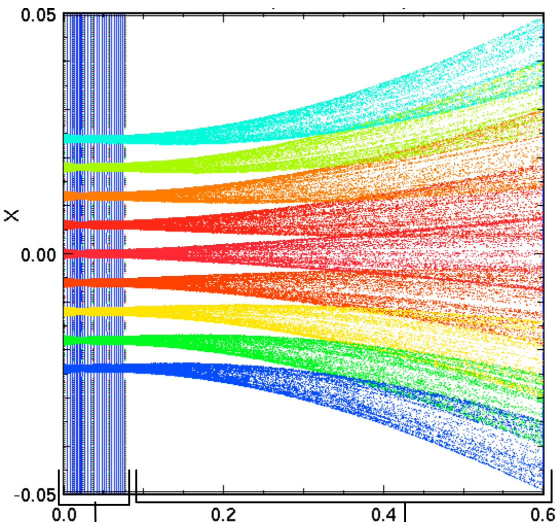
I. Modeling in support of experimental milestones

a) Injector research

Goal: Carry out full voltage beamlet acceleration and determine beamlet characteristics (multibeamlet source configured in FY 2003) for heavy ion beam inertial fusion.

High-gradient beamlet merging experiment (with initially parallel beamlets) is in progress on STS-500

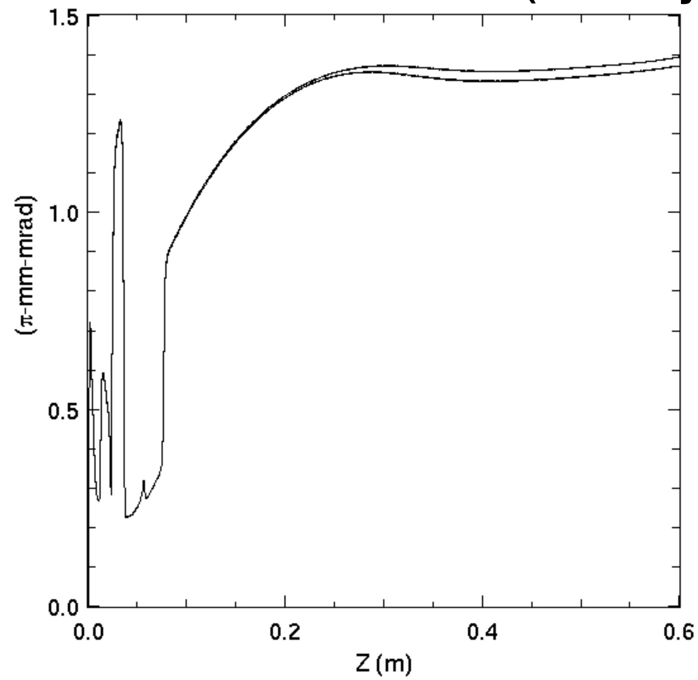
WARP simulations show that the beamlets expand as they merge



Einzel lens plates

Free drift

Normalized emittance (x and y)

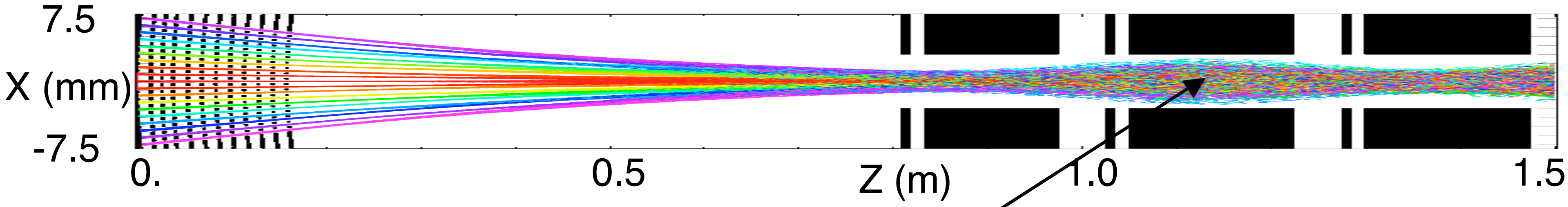


The emittance growth saturates as the beamlets begin to touch each other

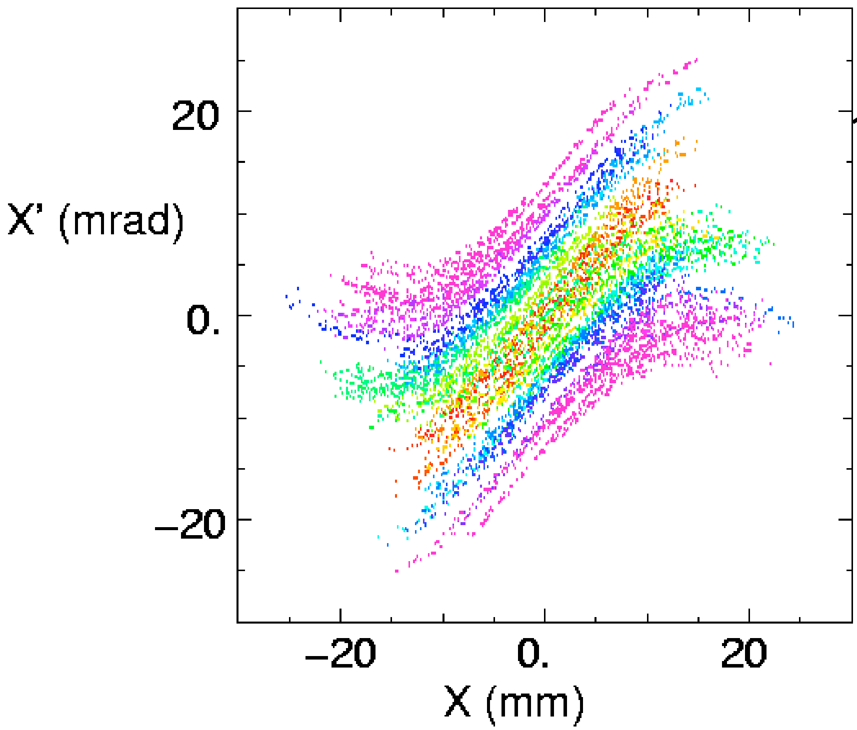
(Simulations by D. Grote)

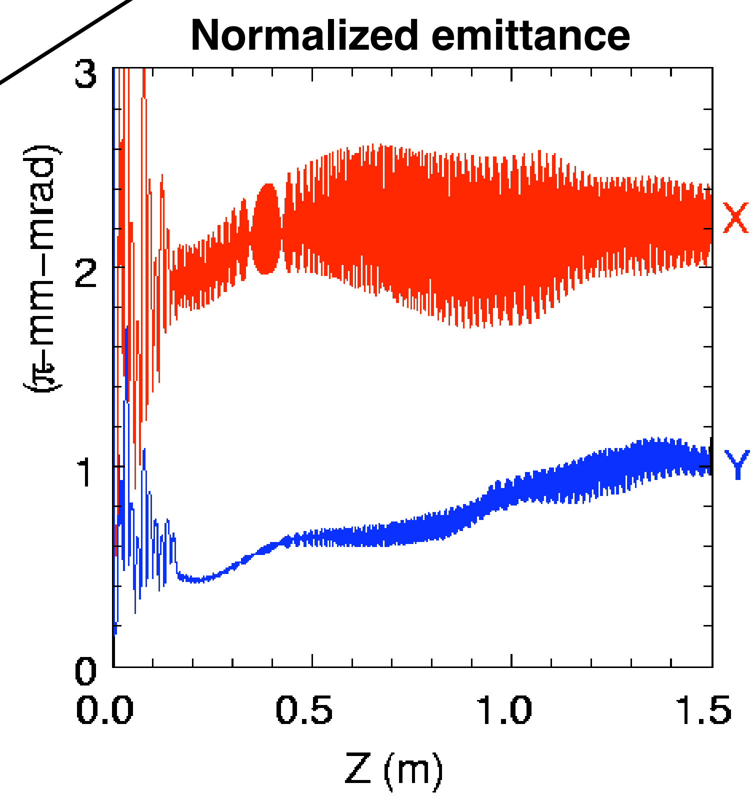
Comparisons of data with simulations will be carried out

WARP guided the design of the "curved-plate" beamlet-merging experiment that is planned for FY05 on STS-500



119 beamlets, I_{Total} = 0.07 A, E_{final} = 400 keV

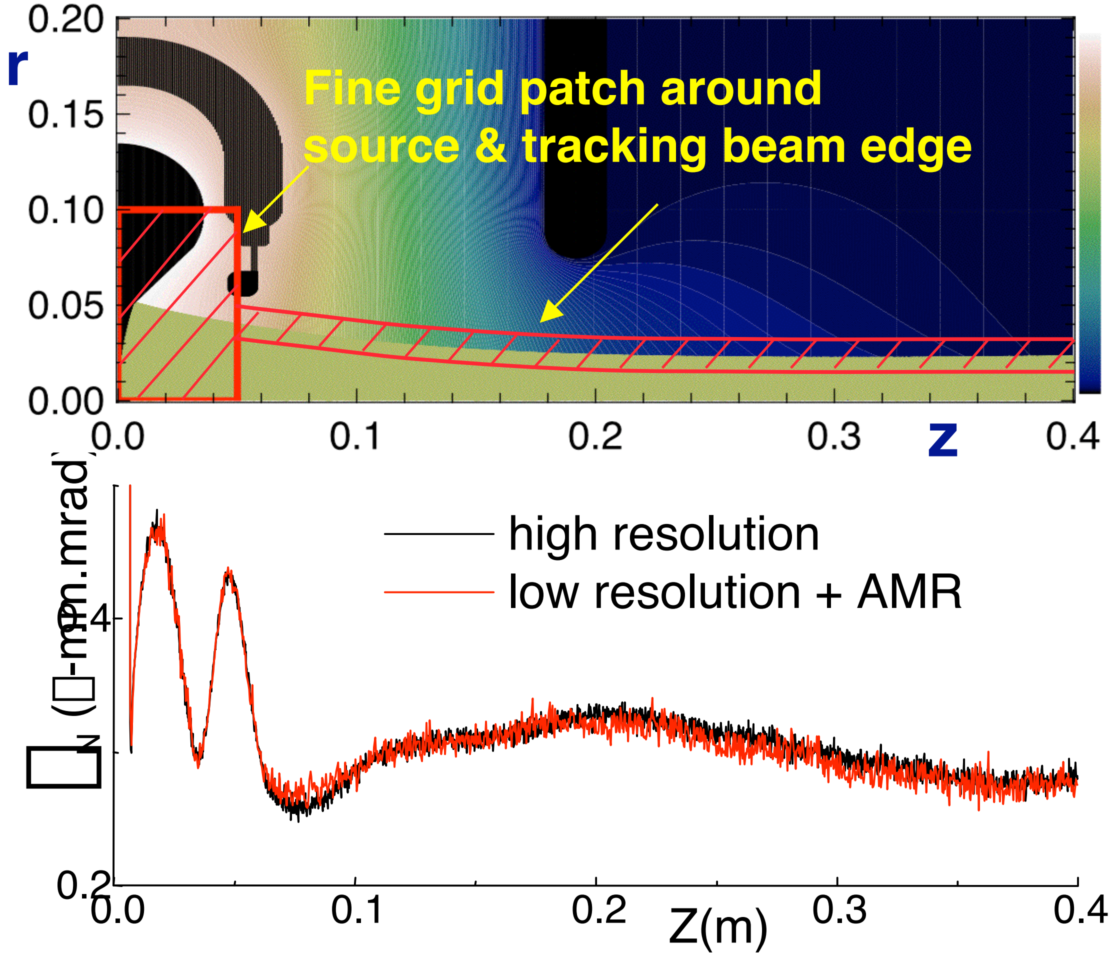




RZ and XY for synthesis; 3D for validation

(Simulations by D. Grote)

WARP simulations of HCX triode illustrate a new capability: the merger of particle-in-cell (PIC) & adaptive mesh refinement (AMR)

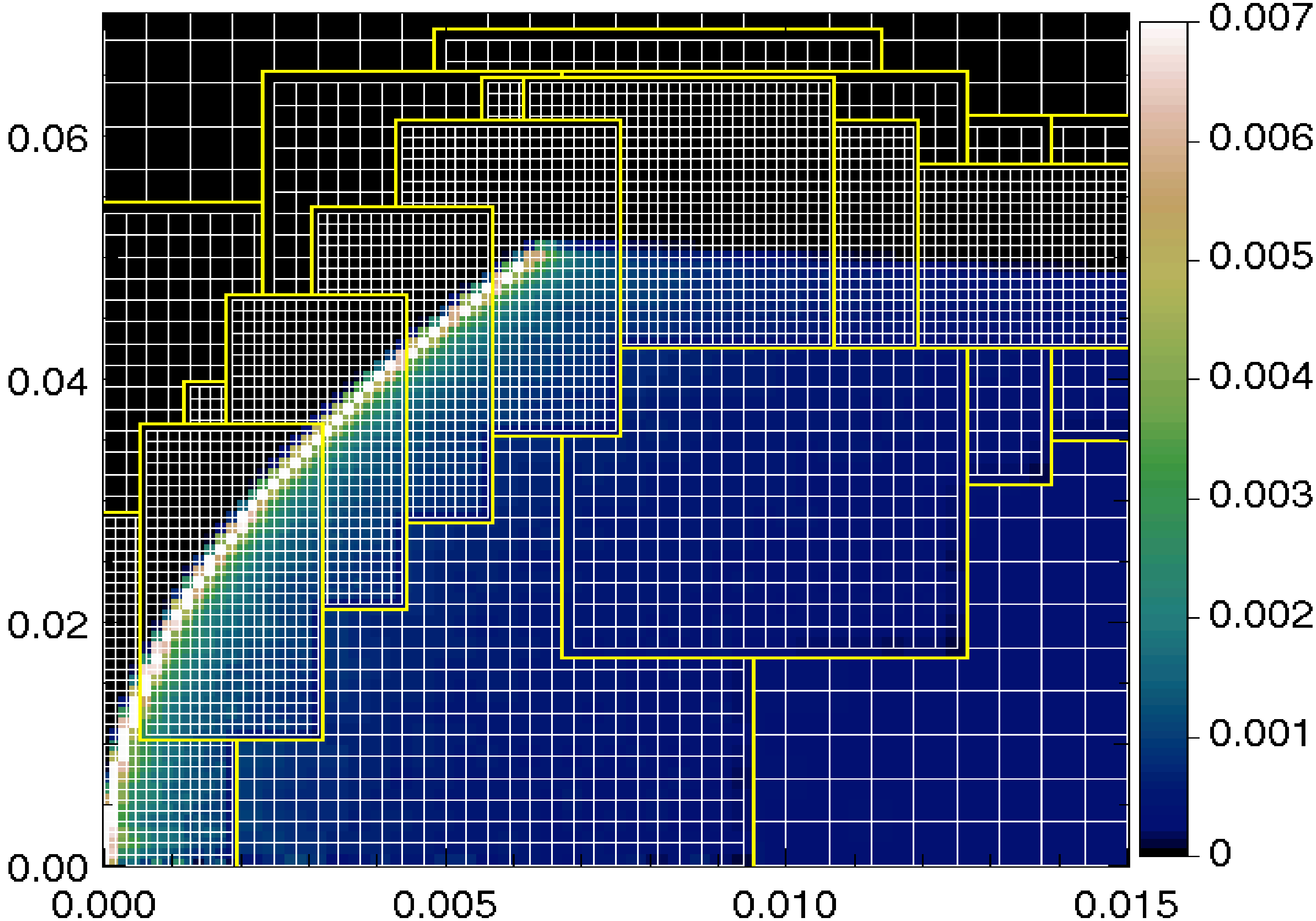


This example:
~ 4x savings in computational cost
(in other cases, far greater savings)

(Simulations by J-L. Vay)

The VNL's development of AMR/PIC is a significant contribution to computational physics

Adaptive Mesh Refinement requires automatic generation of nested meshes with "guard" regions

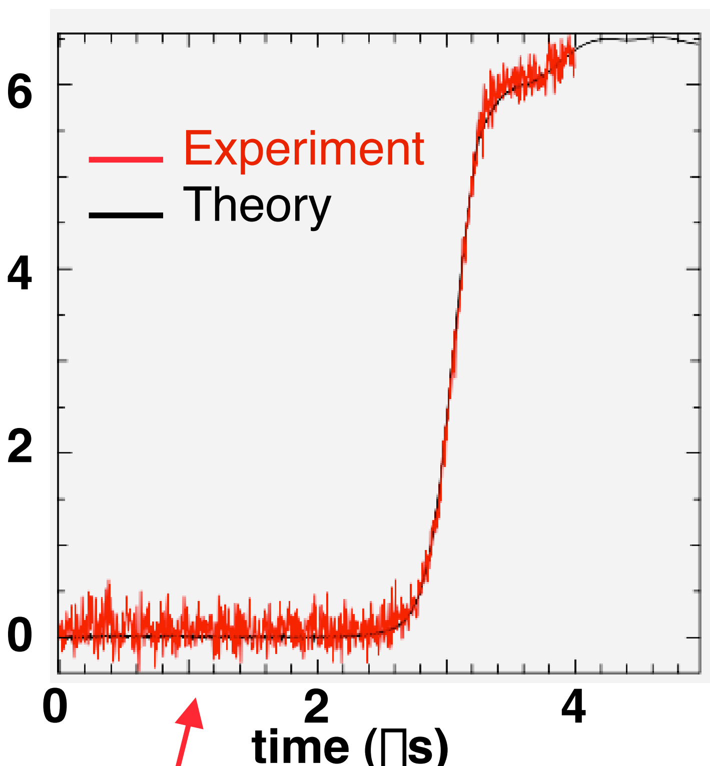


Simulation of diode using merged Adaptive Mesh Refinement & PIC

WARP simulations of STS-500 experiments clarify our understanding of short-rise-time beam generation

Rise time

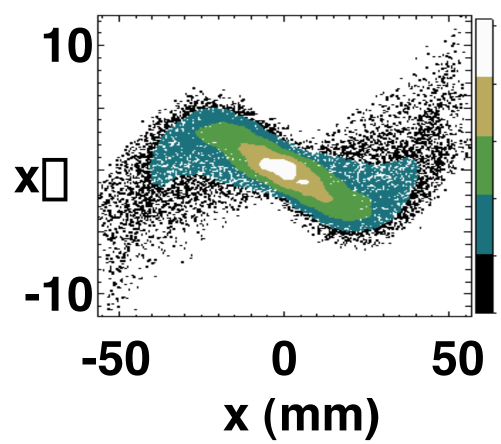
Current (mA) at Faraday cup



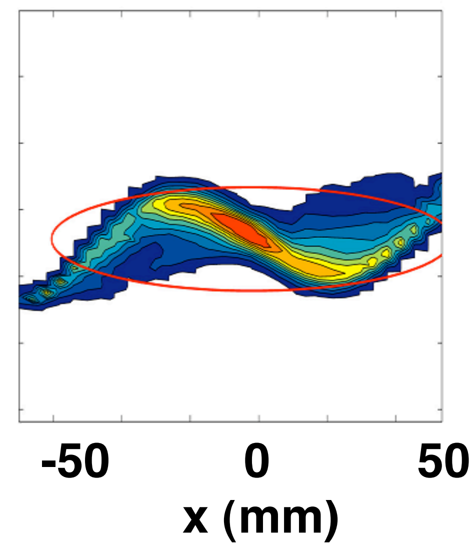
Result depends critically on mesh refinement

Mid-pulse phase space at end of diode

Warp simulation



Experimental data



5-cm-radius K^+ alumino-silicate source

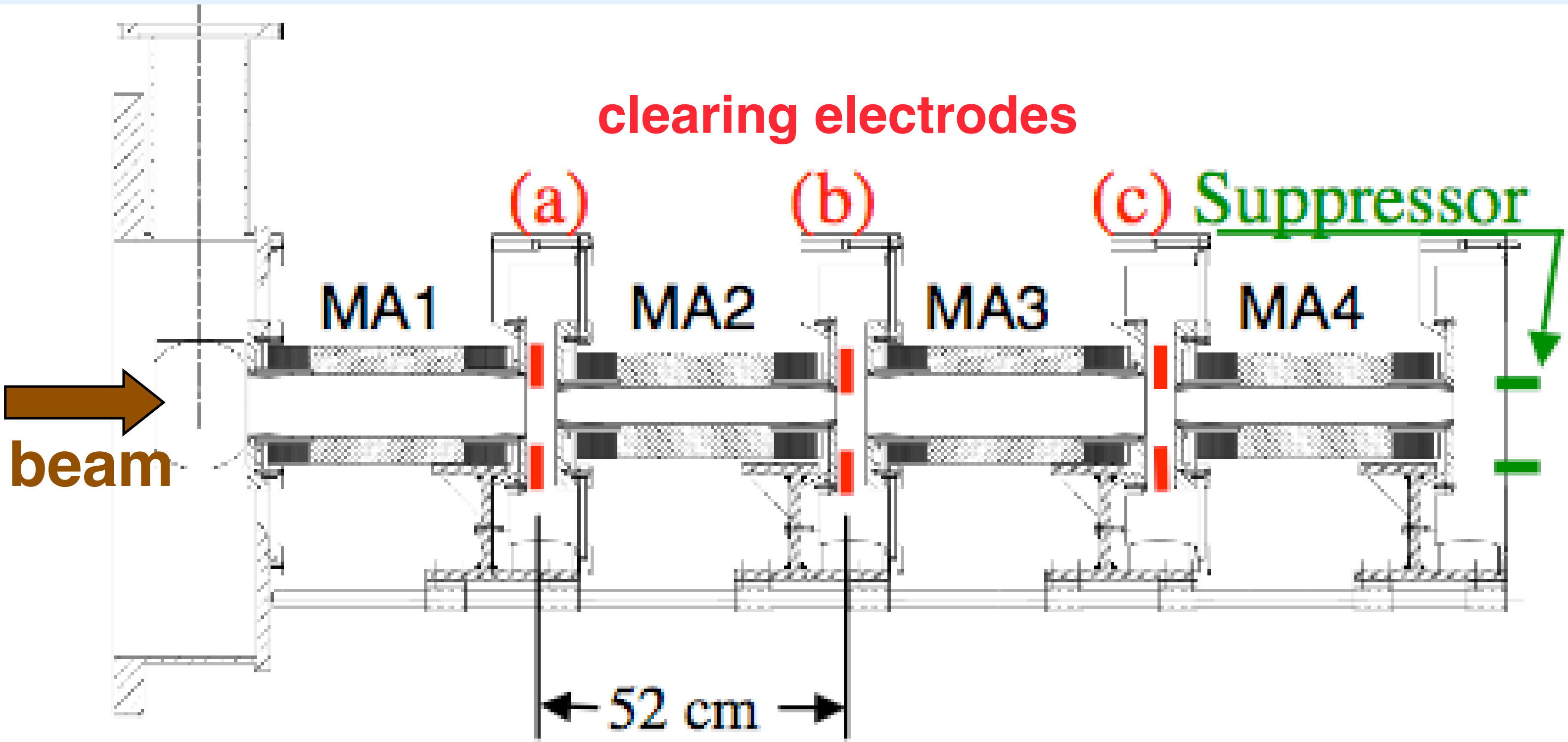
(Simulations by I. Haber, J-L. Vay, D. P. Grote)

I. Modeling in support of experimental milestones

b) High-current transport: HCX & electron clouds

Goal: Evaluate the effects of stray electrons on heavy ion beams by comparing results from the high current experiment (HCX) with calculations of beam transport through HCX

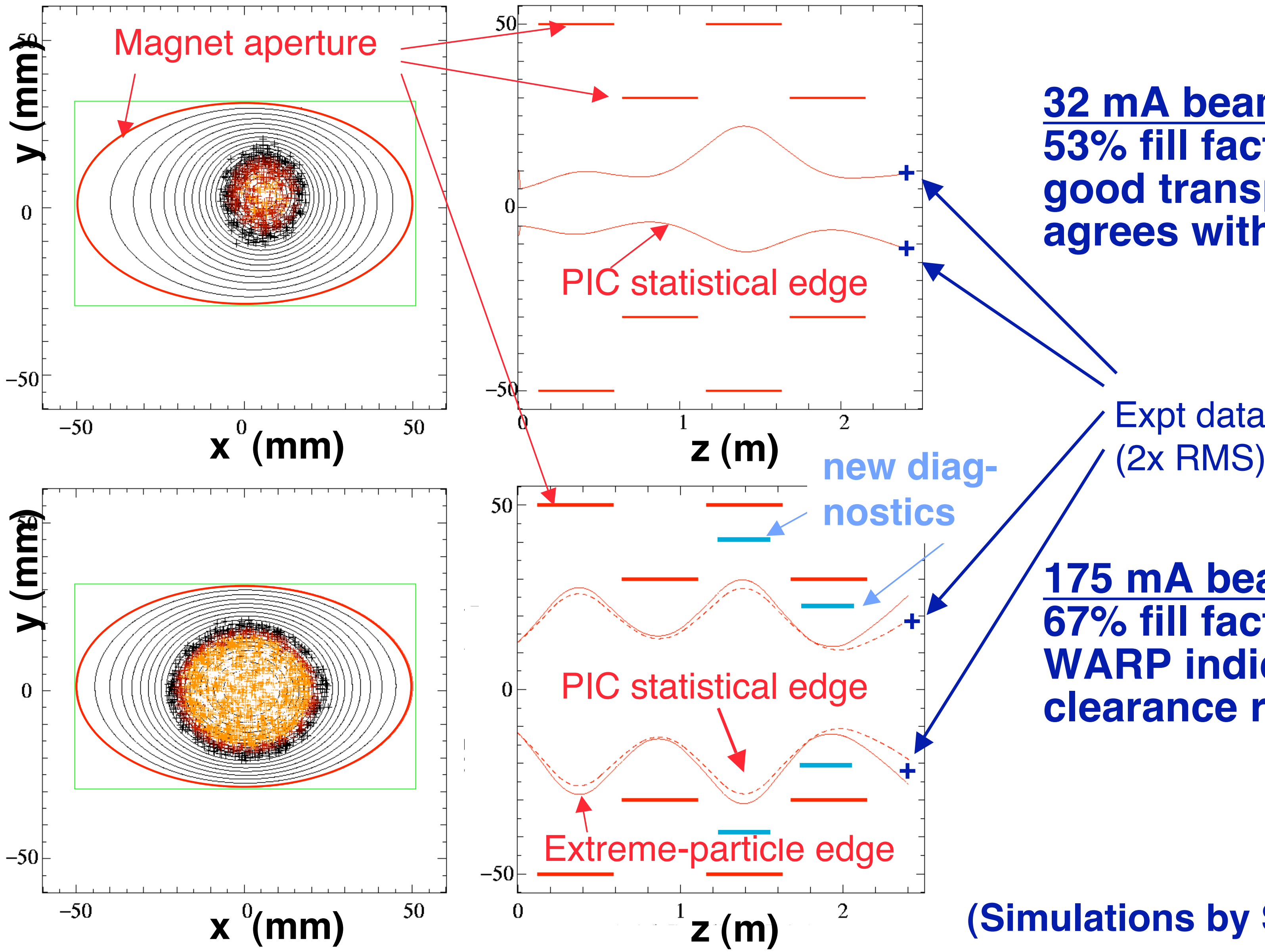
HCX experimental configuration includes magnetic quadrupoles, with clearing and suppressor electrodes



Quadrupole magnets (MA1-MA4) have elliptical bores (6 and 10 cm major axes)

HCX ion dynamics

WARPxy 2D simulations initiated with measured (a,a′,b,b′) yielded new beam “tune” for HCX



32 mA beam:
53% fill factor; good transport agrees with WARP

175 mA beam:
67% fill factor; WARP indicates clearance required

(Simulations by S. Lund)

electron cloud

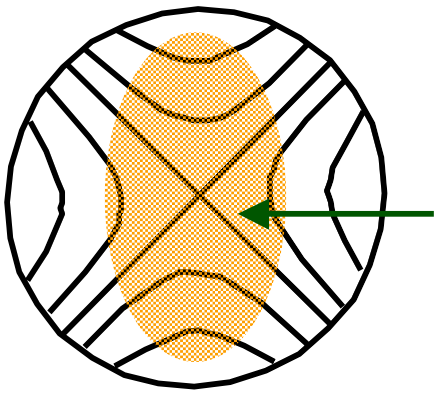
HIF-VNL's research into "electron clouds" & gas is addressing a major issue for ion accelerators

- Electron cloud effects (ECEs) impact:
  - HIF accelerators (for HEDP and/or IFE)
  - present electron-positron colliders and ion rings (e.g. PSR)
  - next generation colliders and ion rings (NLC, LHC, SNS, GSI)

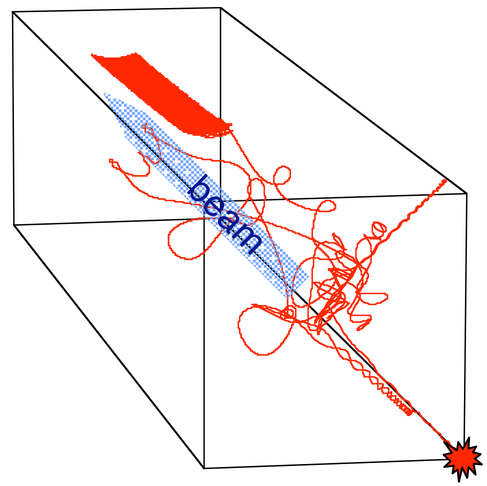
- Collaboration with Tech-X (2 SBIR's), U.C. Berkeley, LBNL/HEP

- Invited papers:
  - 3 at ECloud04
  - 3 at other conferences
  - Future: 1 at APS-DPP & 1 at PAC
- Computational advances have broad applicability
- Expect at least 5 refereed publications from FY04 work

Experiments and simulations explore sources, sinks, and dynamics of stray electrons

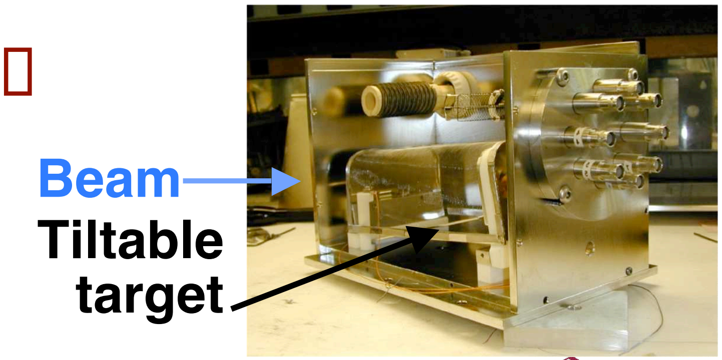


Electrons can trap into beam space-charge and quadrupole magnetic fields



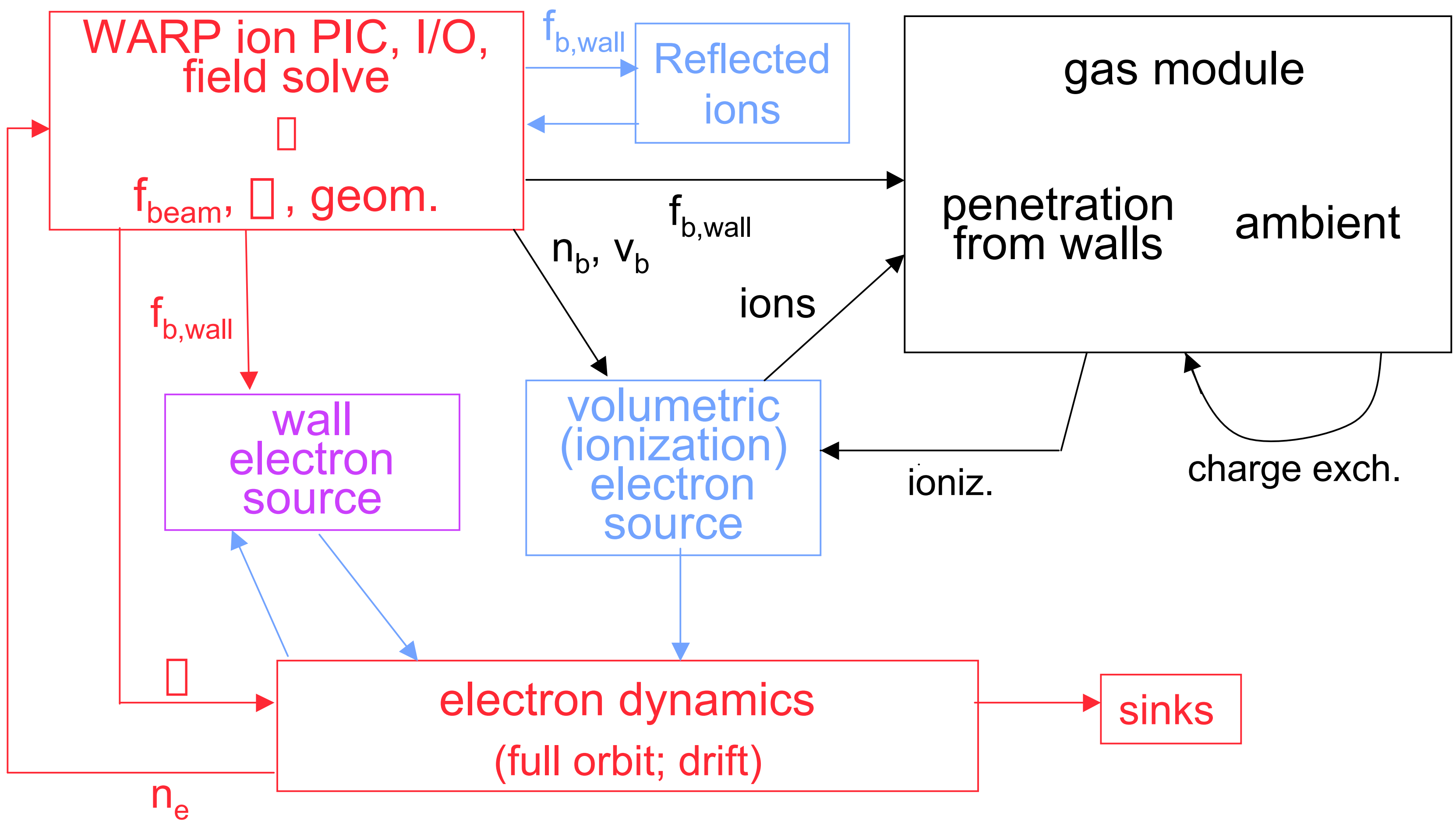
Electron lifetime ~ time to drift out the end of a magnetic quadrupole

Gas, electron source diagnostic for number and energy of electrons and gas molecules produced per incident ion



Toward a self-consistent model of electron effects

- **Roadmap for self-consistent electron physics modules for WARP**

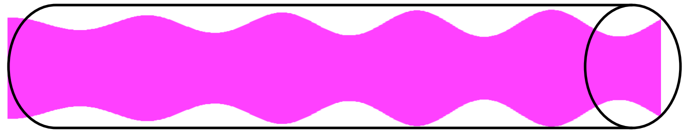


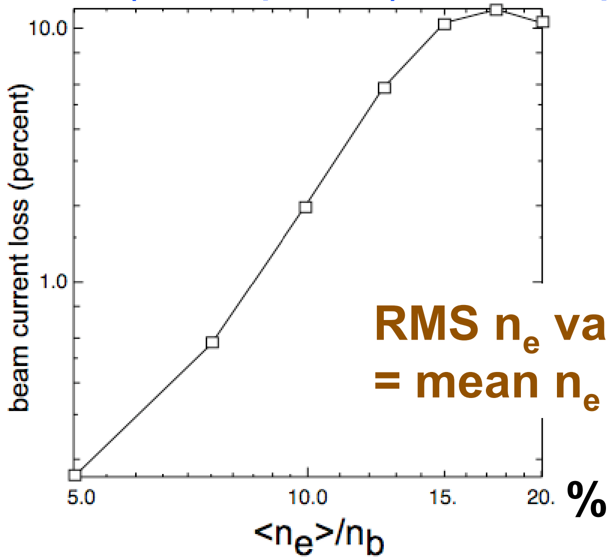
- **Key: operational; implemented, testing; partially implemented; active offline development (as of 9/04)**

Simulation using imposed (frozen) electron distributions show that the beam is surprisingly robust; but resonant behavior may be important

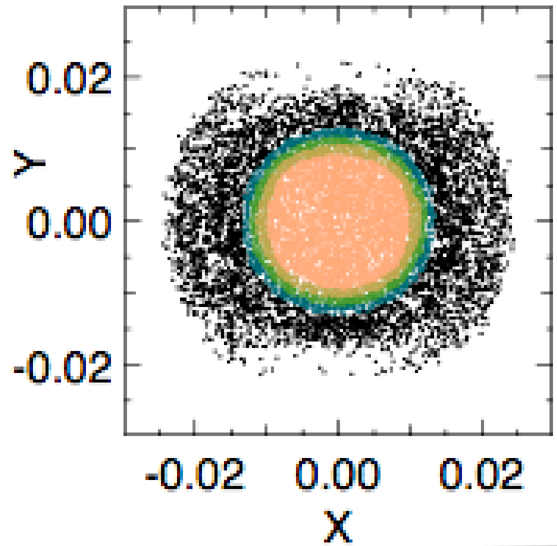
WARP ion beam simulations

450 m (200 quads) of transport



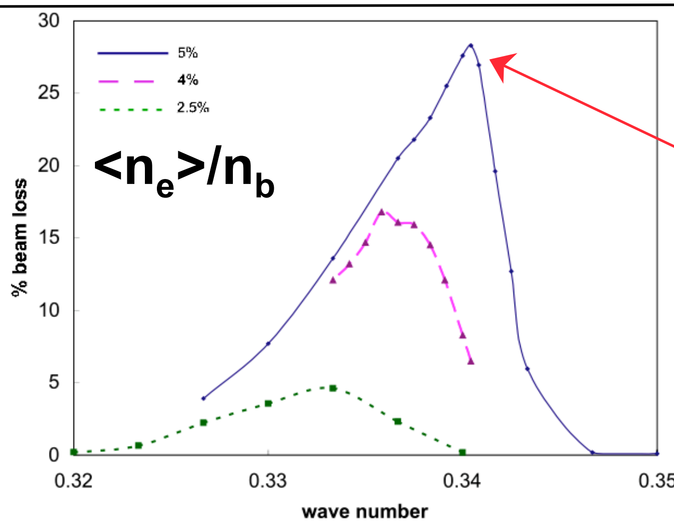


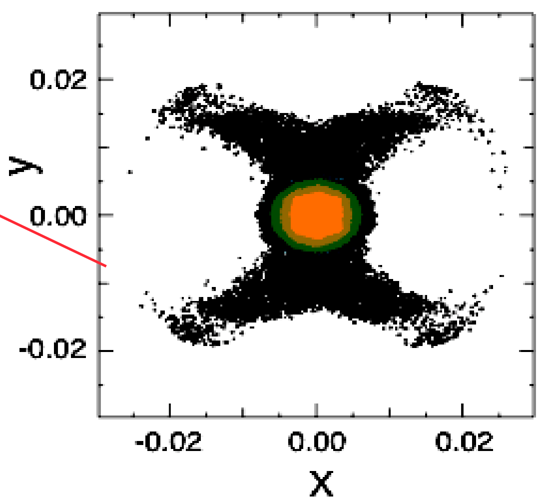
RMS n_e variation = mean n_e



Random amplitude variation:

2.1% beam loss



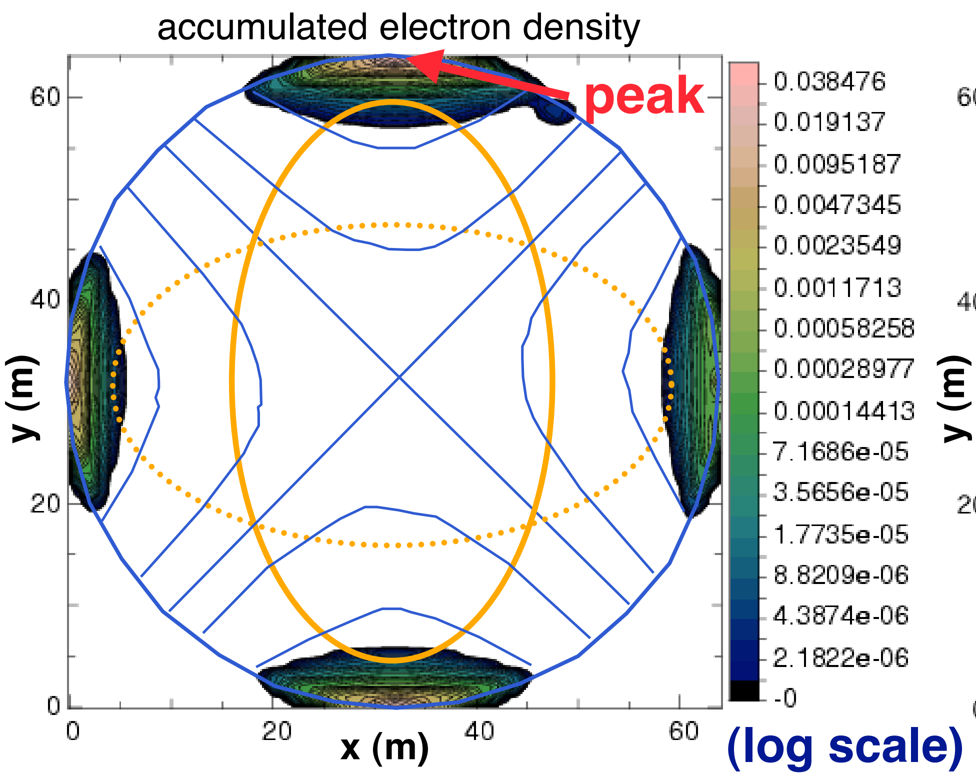


Sinusoidal shape variation

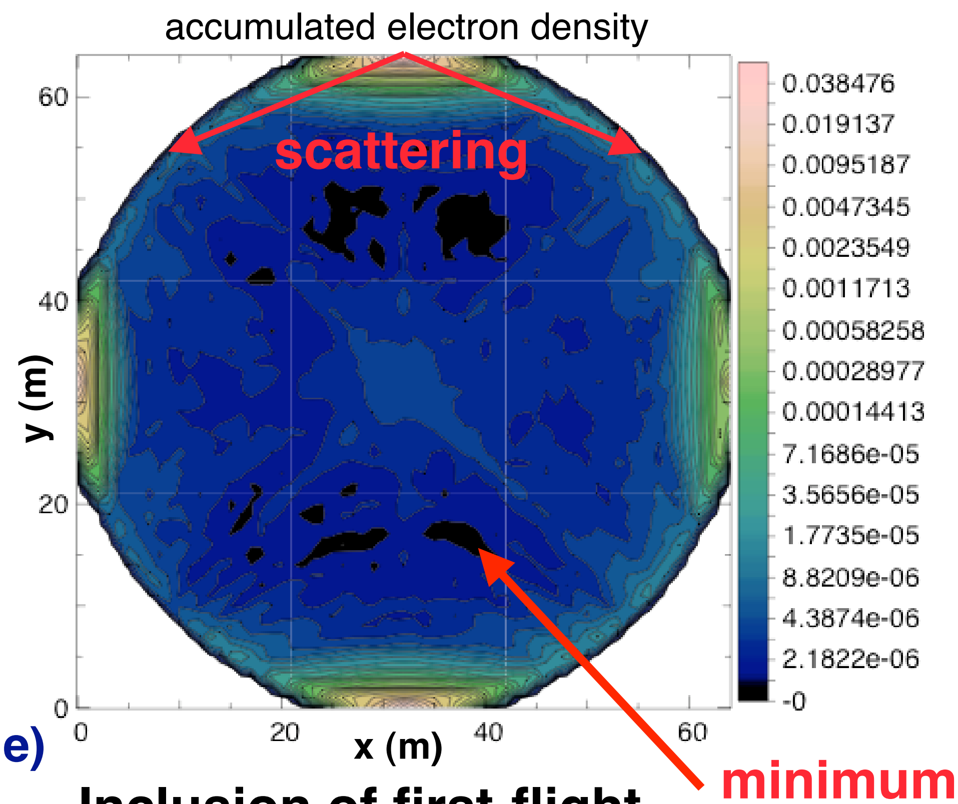
28% beam loss

A sequence of simulations gave us a first picture of wall-desorbed electron density distributions in quads

- **Ran WARP with mismatch; noted where ions hit walls**
- **Then launched electrons at wall using prescription derived from exp'ts**



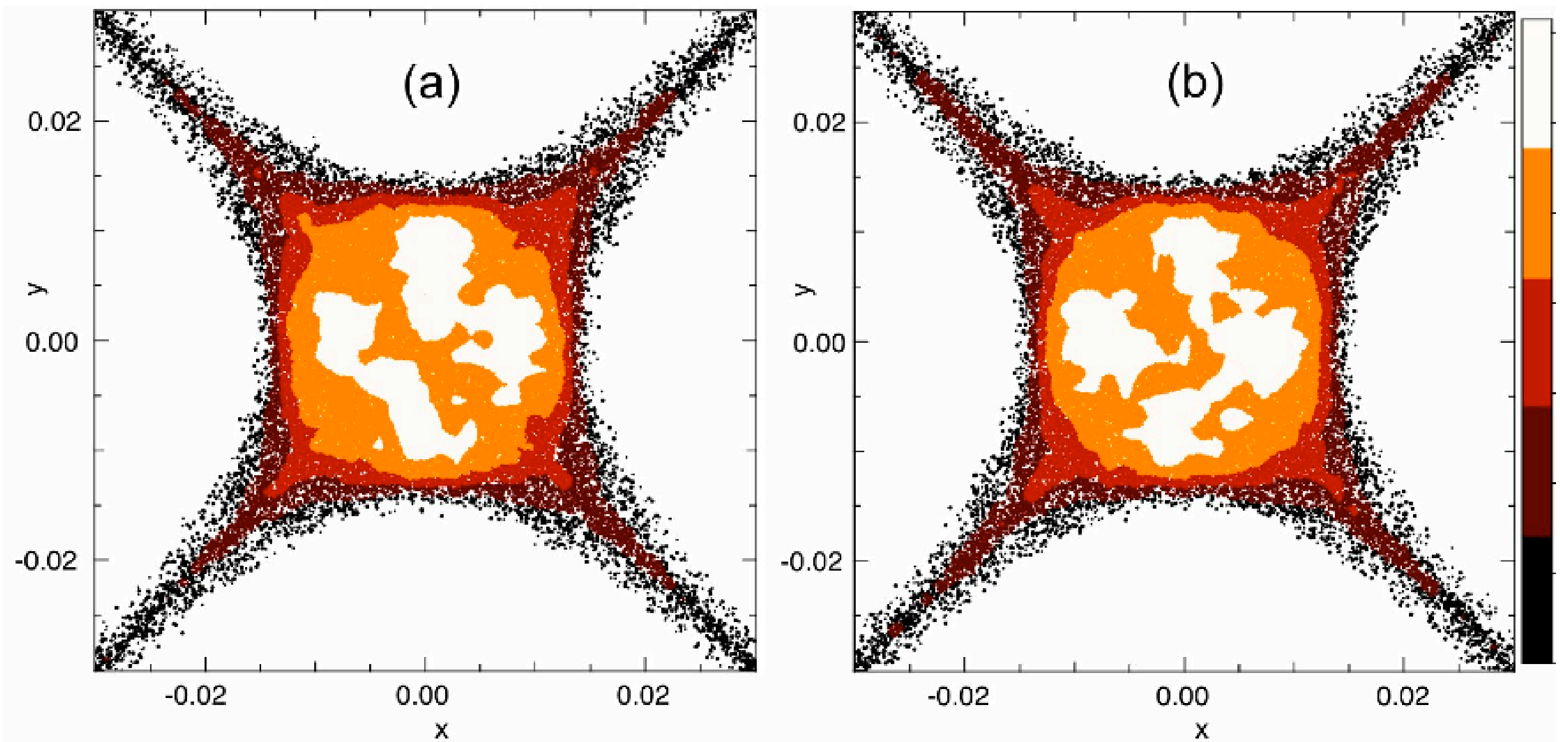
Electrons confined close to birth positions on non-penetrating field lines



Inclusion of first-flight reflected ions yields electrons at ~ 45°

Large time-step “interpolated” electron mover should have applications in MFE, astrophysics, space physics, …

Spatial distribution of electrons from a source uniform out to nominal r_b (an approximate model for electrons produced by ionization of gas)



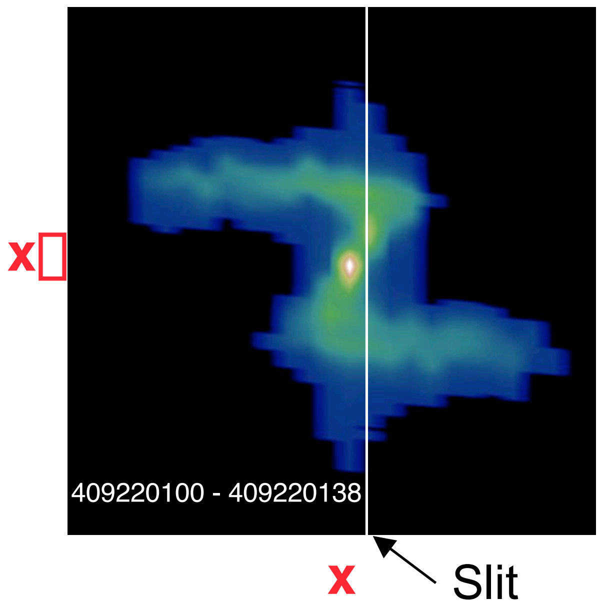
Full-orbit, $\Delta t = 0.25 / f_{ce}$ **New mover, Δt 25x larger**

Ron Cohen will present this work in an invited talk at APS-DPP 2004

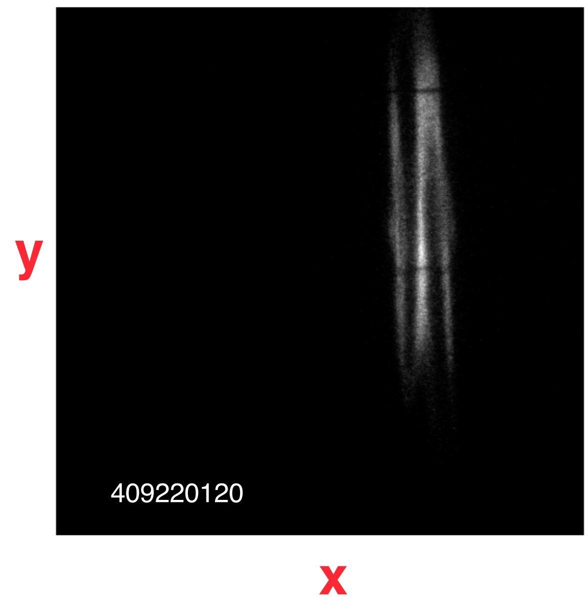
Experimental (HCX) observations: without suppressor or clearing electrodes, electrons distort phase space (“Z-ing”)

1 MeV, 0.18 A K^+ ion beam after 4 quadrupole magnets

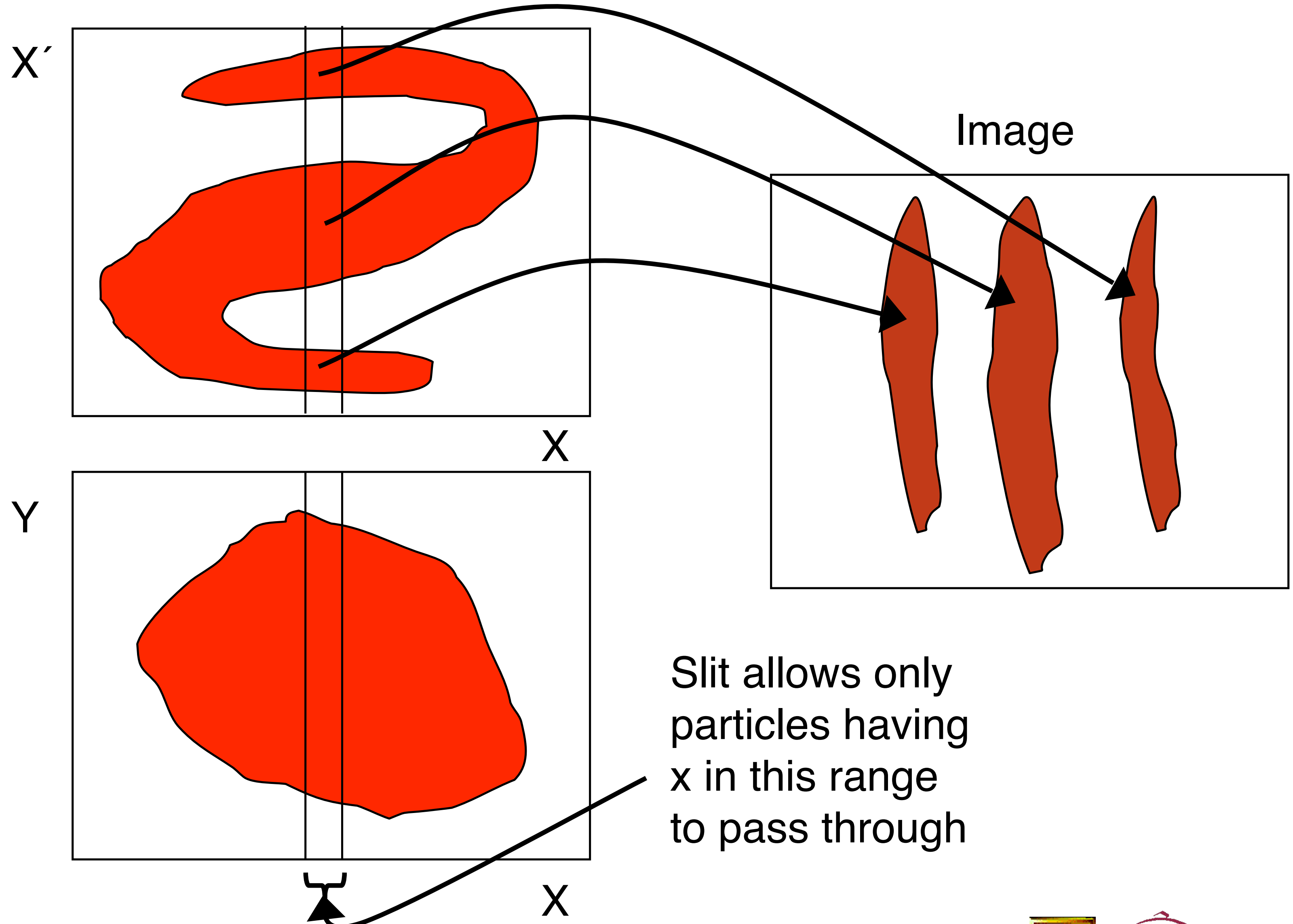
Measured x vs. x′



Beam emerging from slit (see diagram on left) shows 3 components of v_x



A "z" or "s" distortion of phase space can result in multiple stripes in the image of a beam that has passed through a slit



When the electron backflow from the end plate in HCX is suppressed, the beam is observed to be well-behaved

f(x,x´) derived from multiple slit positions

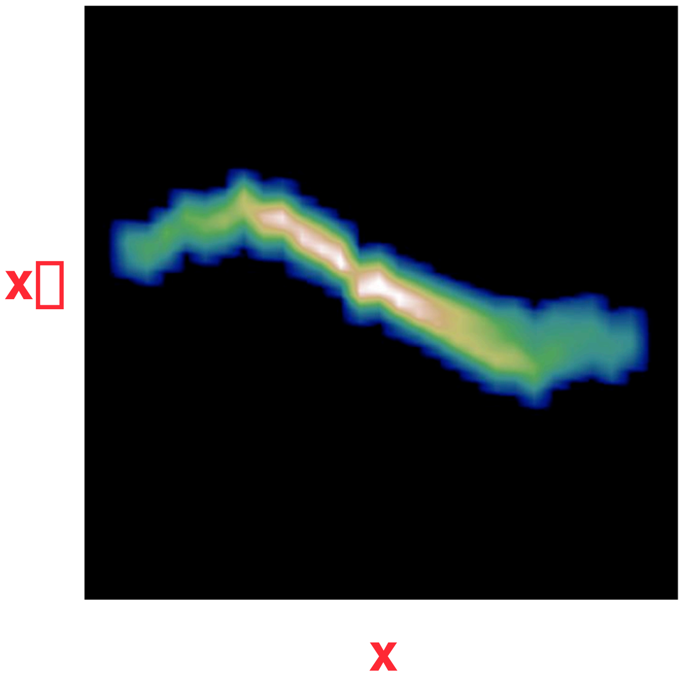
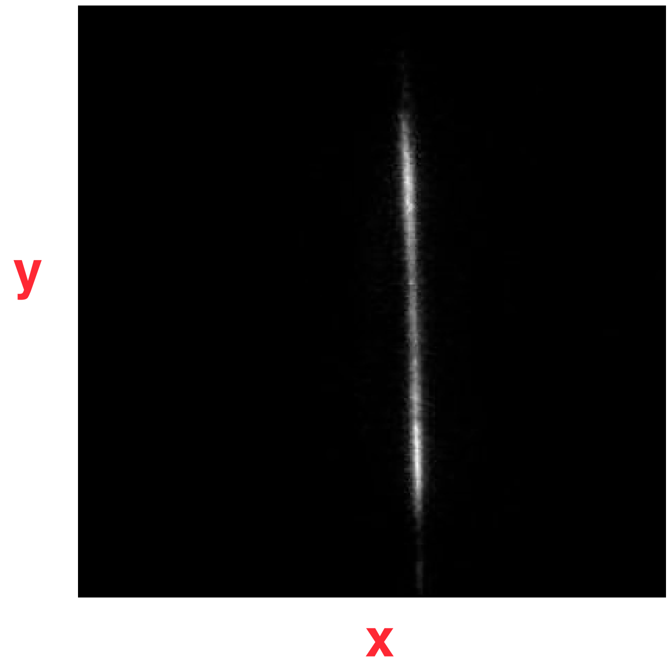
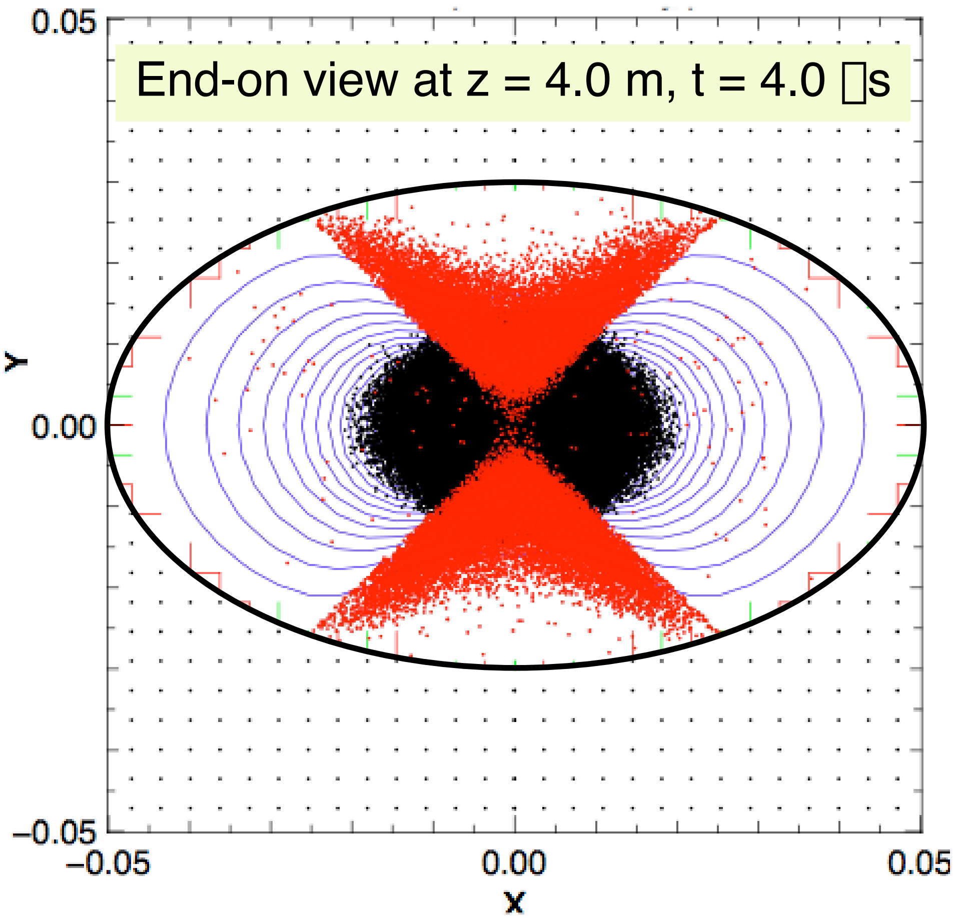


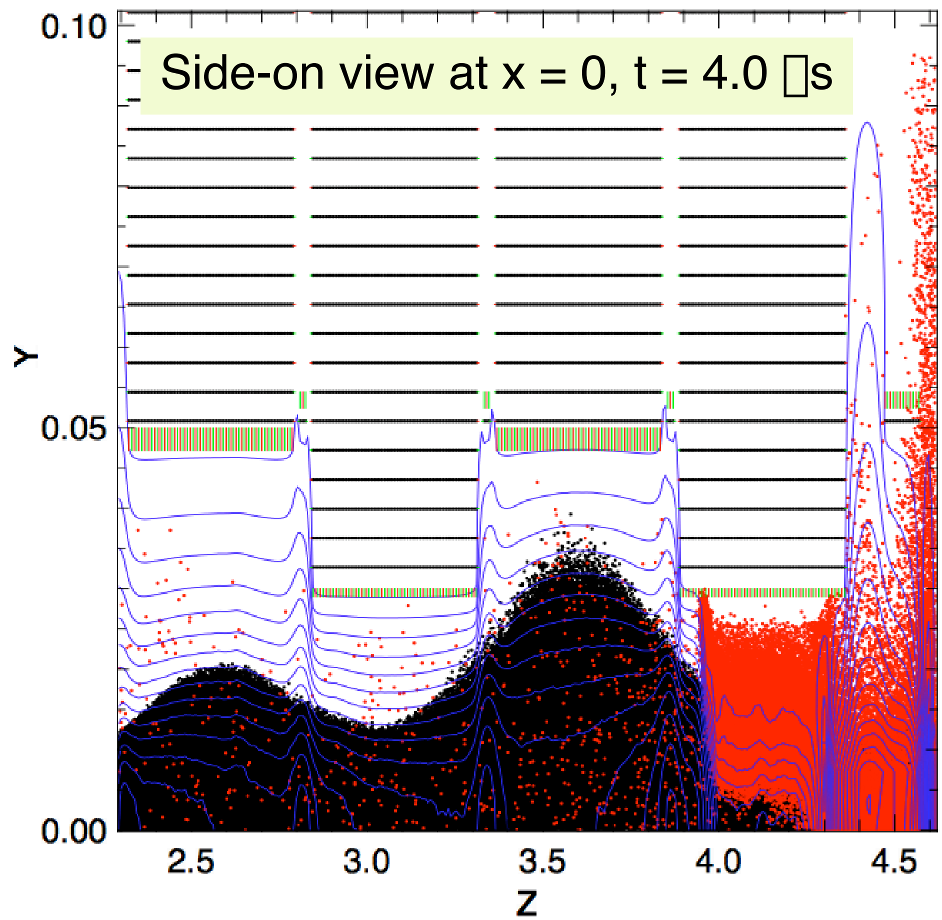
image after passage thru slit



3-D WARP simulations treat (for the first time) electrons self-consistently, using new large-timestep mover



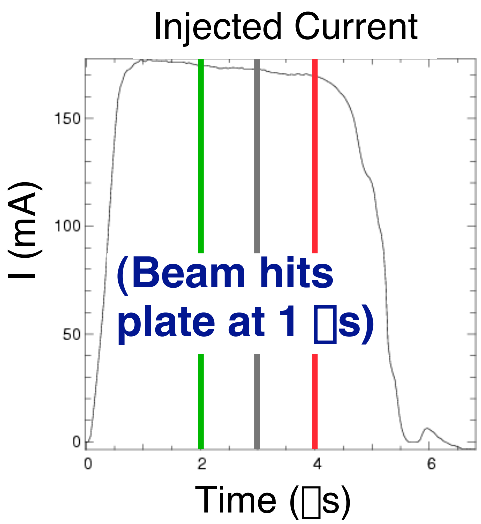
Electrons (shown in red) can only enter two quadrants of the final quadrupole



Their flow tracks equipotentials (blue) until they strike the wall (reemission not used in this run)

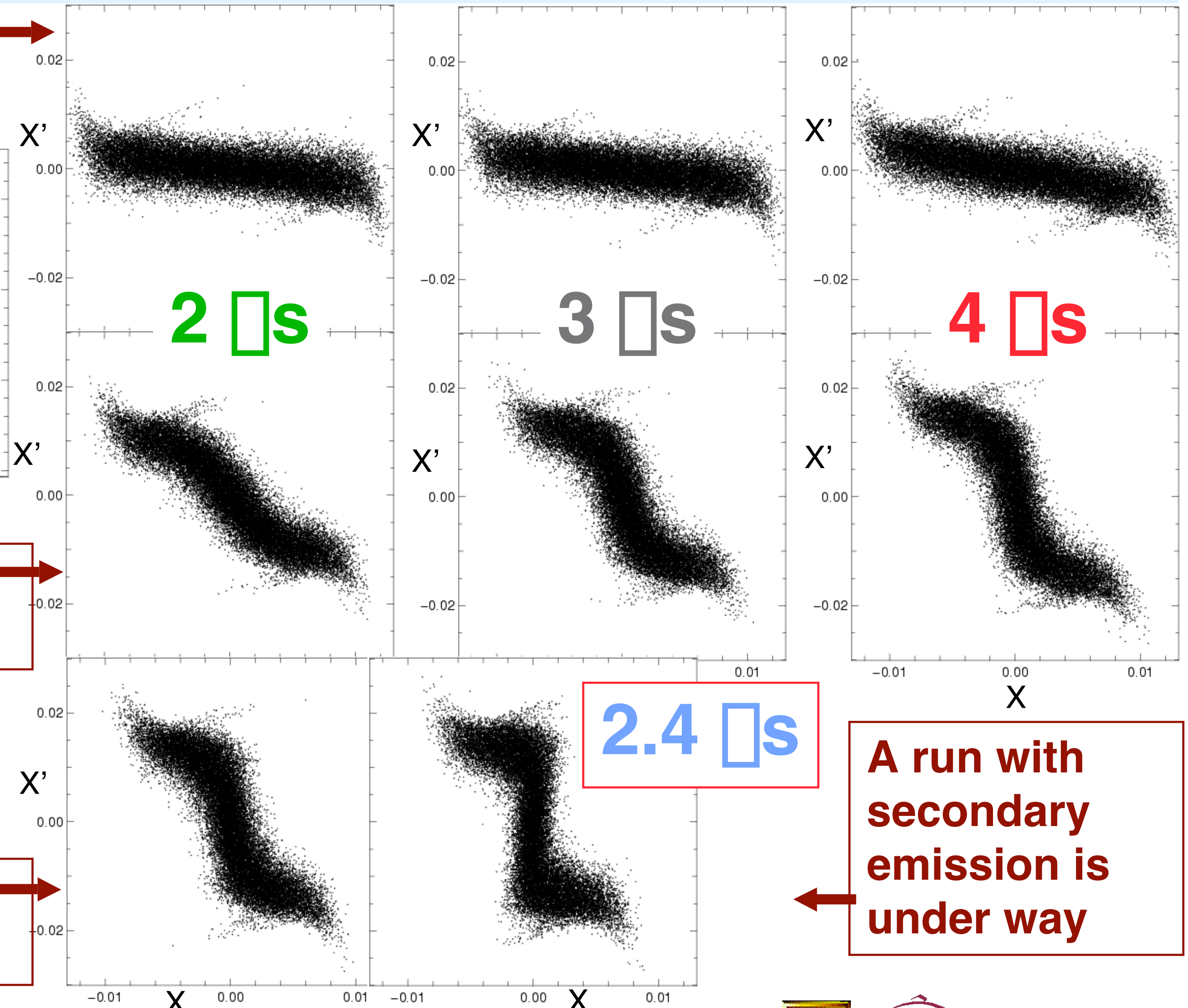
3-D simulation w/o e⁻ re-emission results in electrons confined to the 4th magnet. Reemission reinforces Z-ing.

***No* electrons**



***With* electrons (no reemission)**

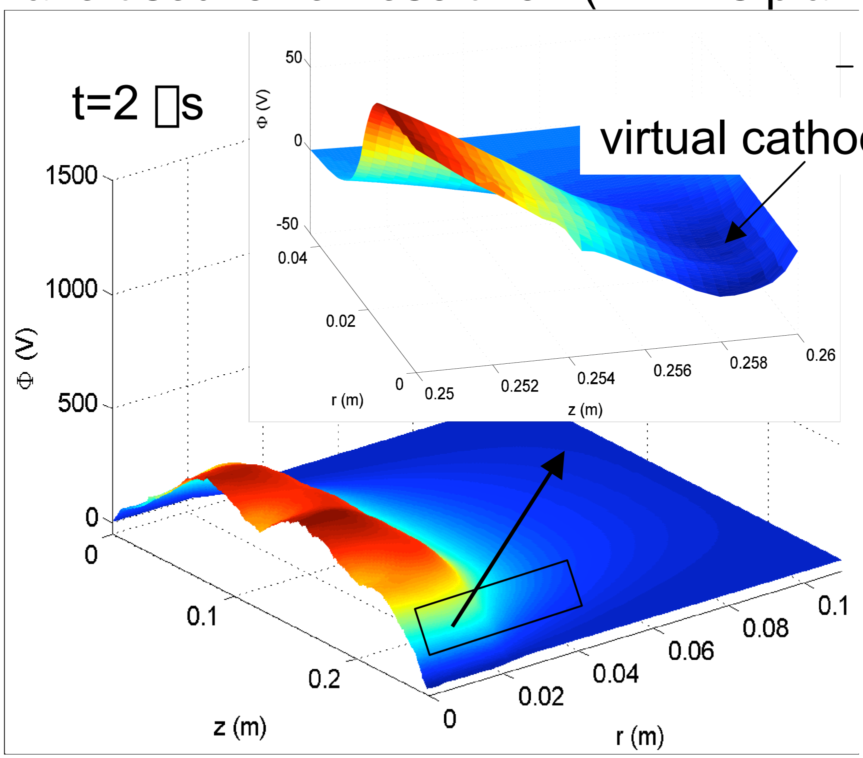
***With* electrons & reemission**

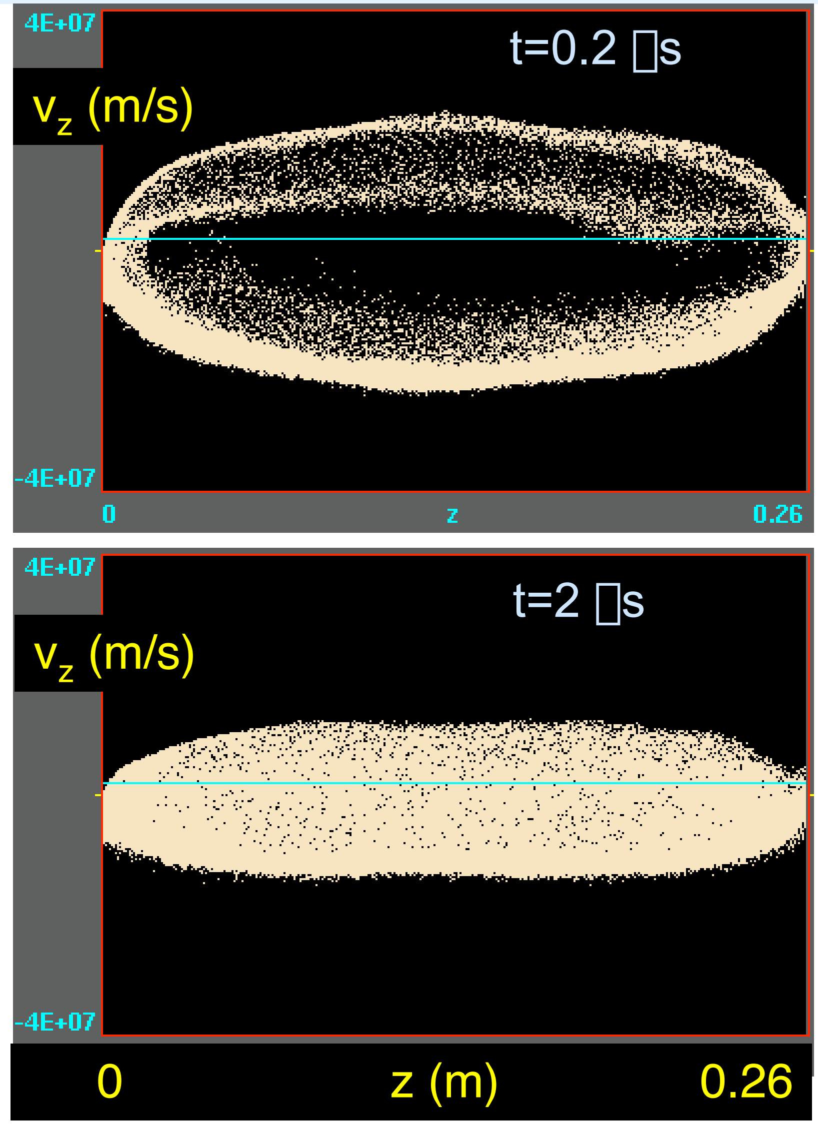


A run with secondary emission is under way

Hi-resolution 2D (r,z) XOOPIC runs were carried out at UCB, studying the region between the final quad and the end

- Six electrons / ion desorbed from end wall
- Virtual cathode forms near emitting surface; energetic electrons make it through
- Over time, the phase space hole fills in and the virtual cathode grows deeper
- These runs inform WARP 3D runs, which have used lower resolution (AMR is planned)



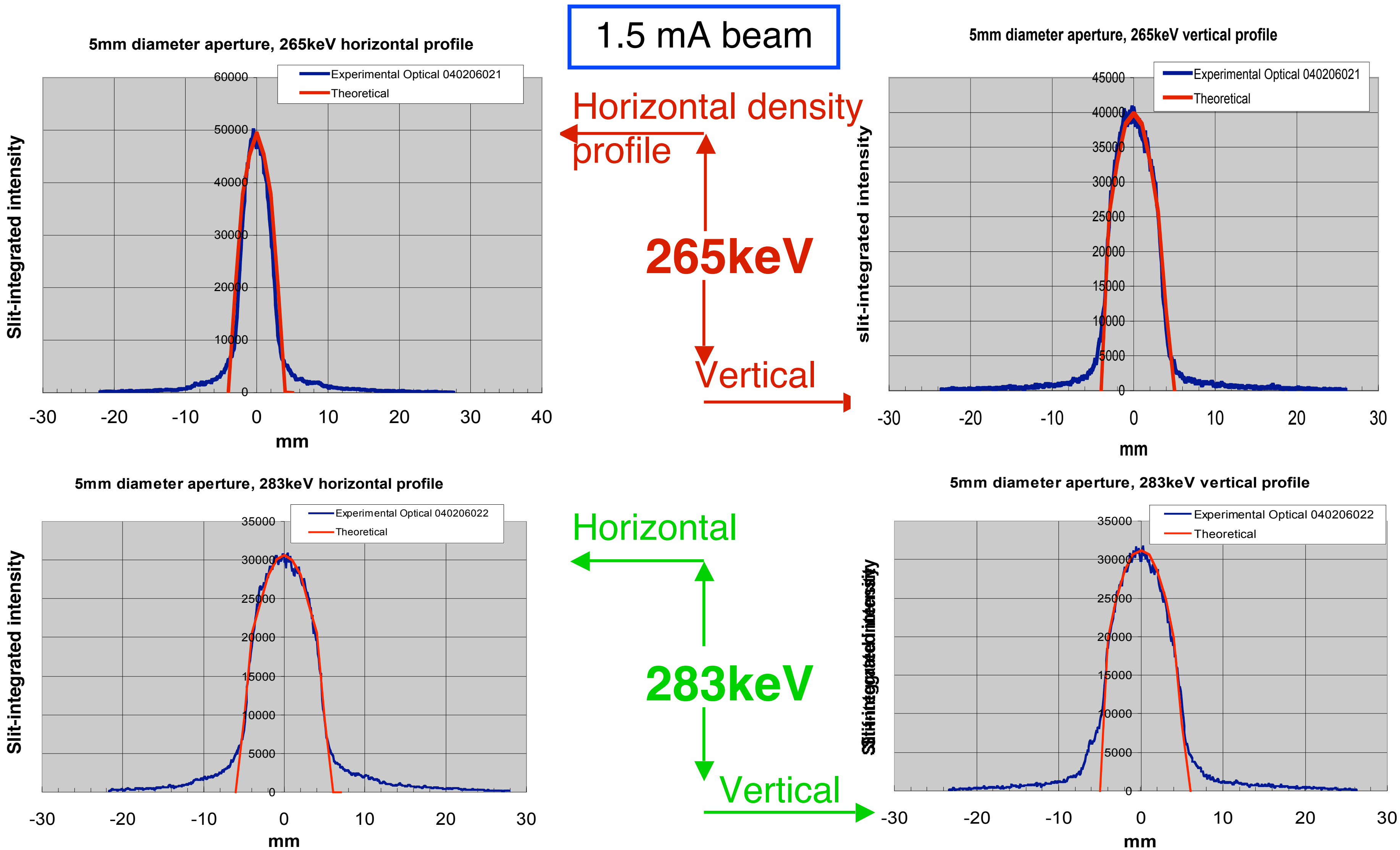


I. Modeling in support of experimental milestones

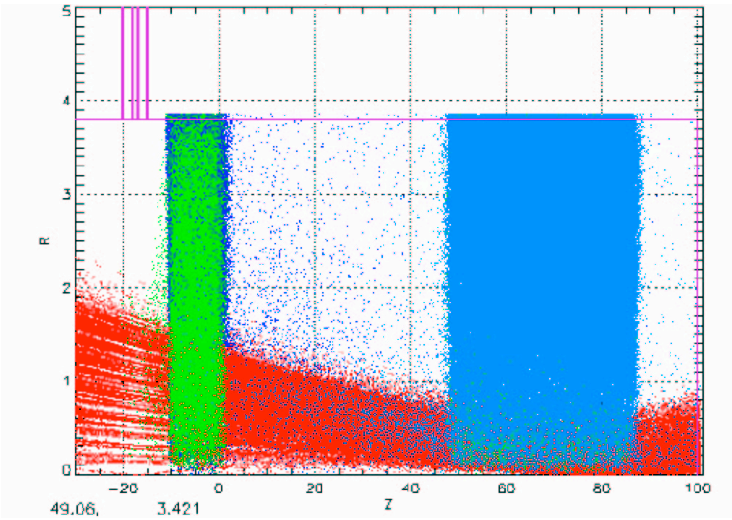
c) Neutralized transport & focusing: NTX

Goal: Integrate elements of initial plasma neutralized beam focus and carry out initial experiments in support of heavy ion beam inertial fusion

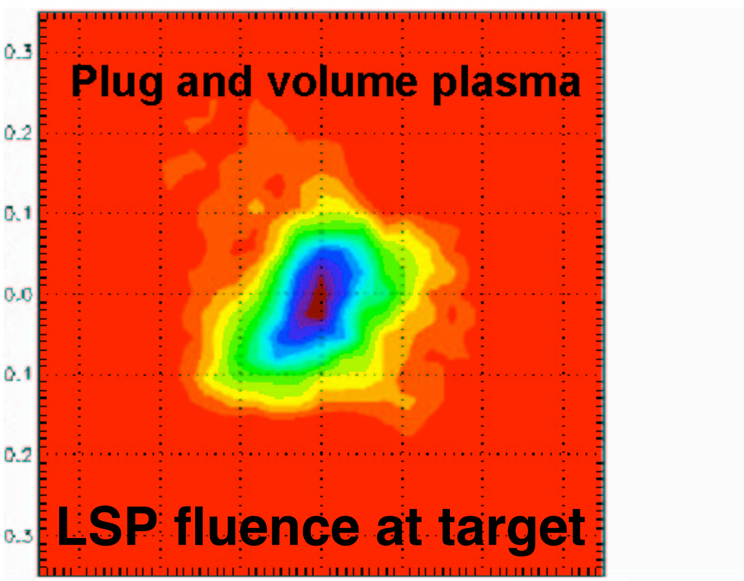
After 4 magnetic focusing quads, data & WARP-generated density profiles agree well, except for halo; still +/- 3% uncertainty in B′/energy ratio



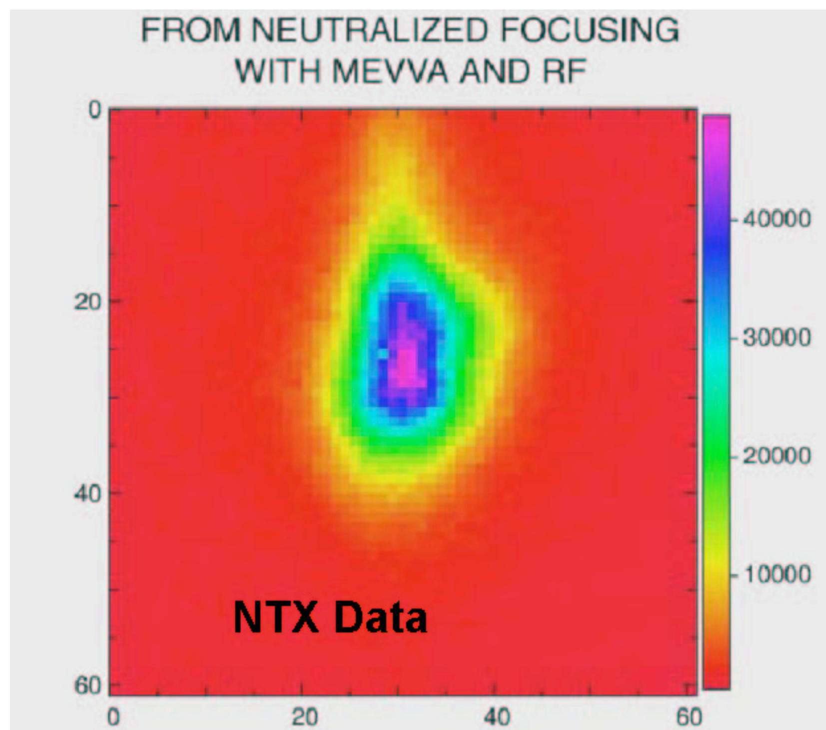
LSP simulations of NTX transport are now being initialized with the measured 4D particle distribution



- EM, 3D cylindrical geom., 8 azimuthal spokes
- 3 eV plug 3×10^{9} cm^{-3}, volume plasma 10^{10} cm^{-3}



Carsten Thoma, et. al.



LSP simulations agree with experimental data at focal plane for different neutralization methods (within error bars)

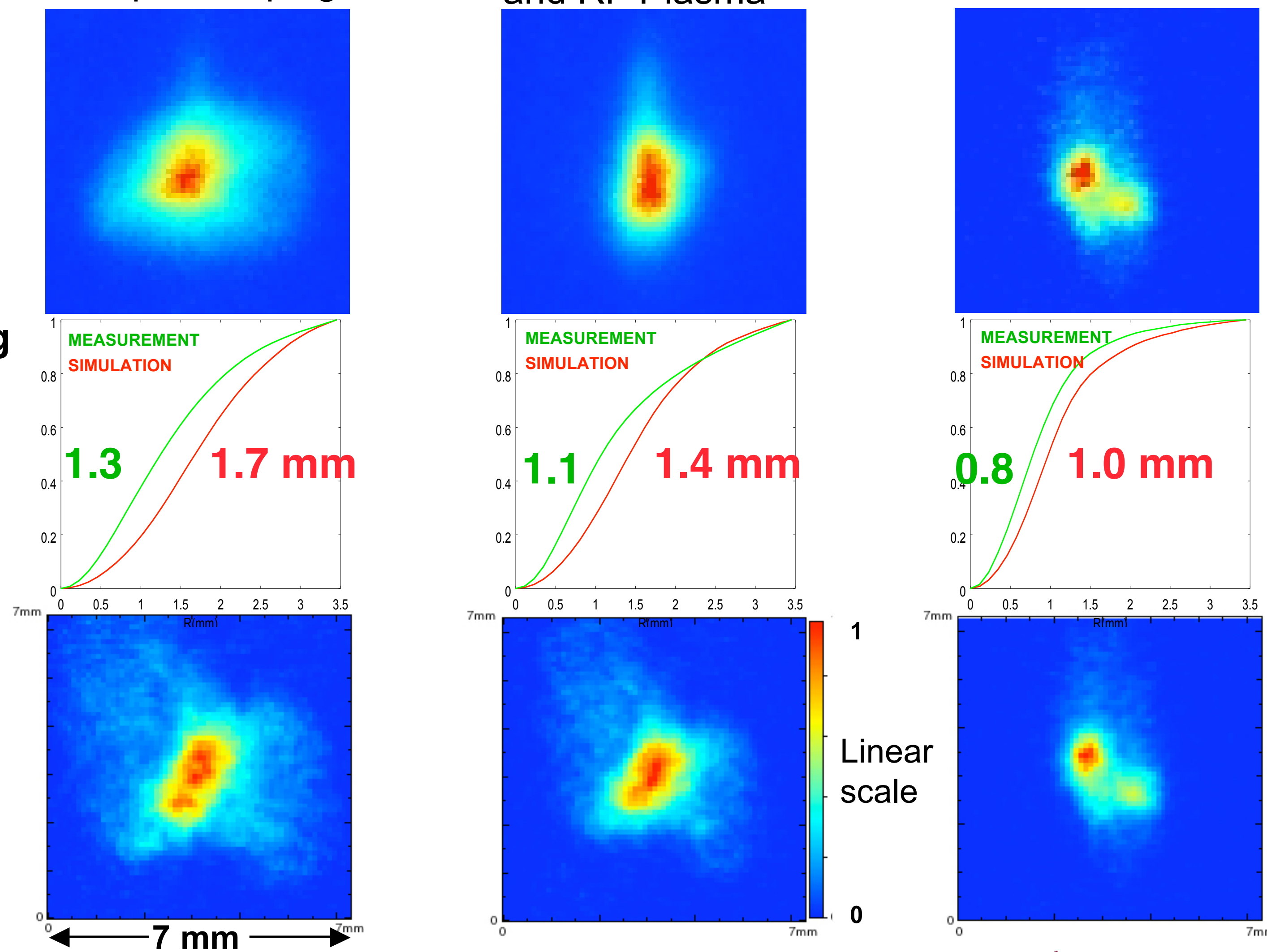
6 mA
10 mm initial radius

With plasma plug | With plasma plug and RF Plasma | "No space charge"

MEASUREMENT

Radius containing 1/2 the integrated current is given →

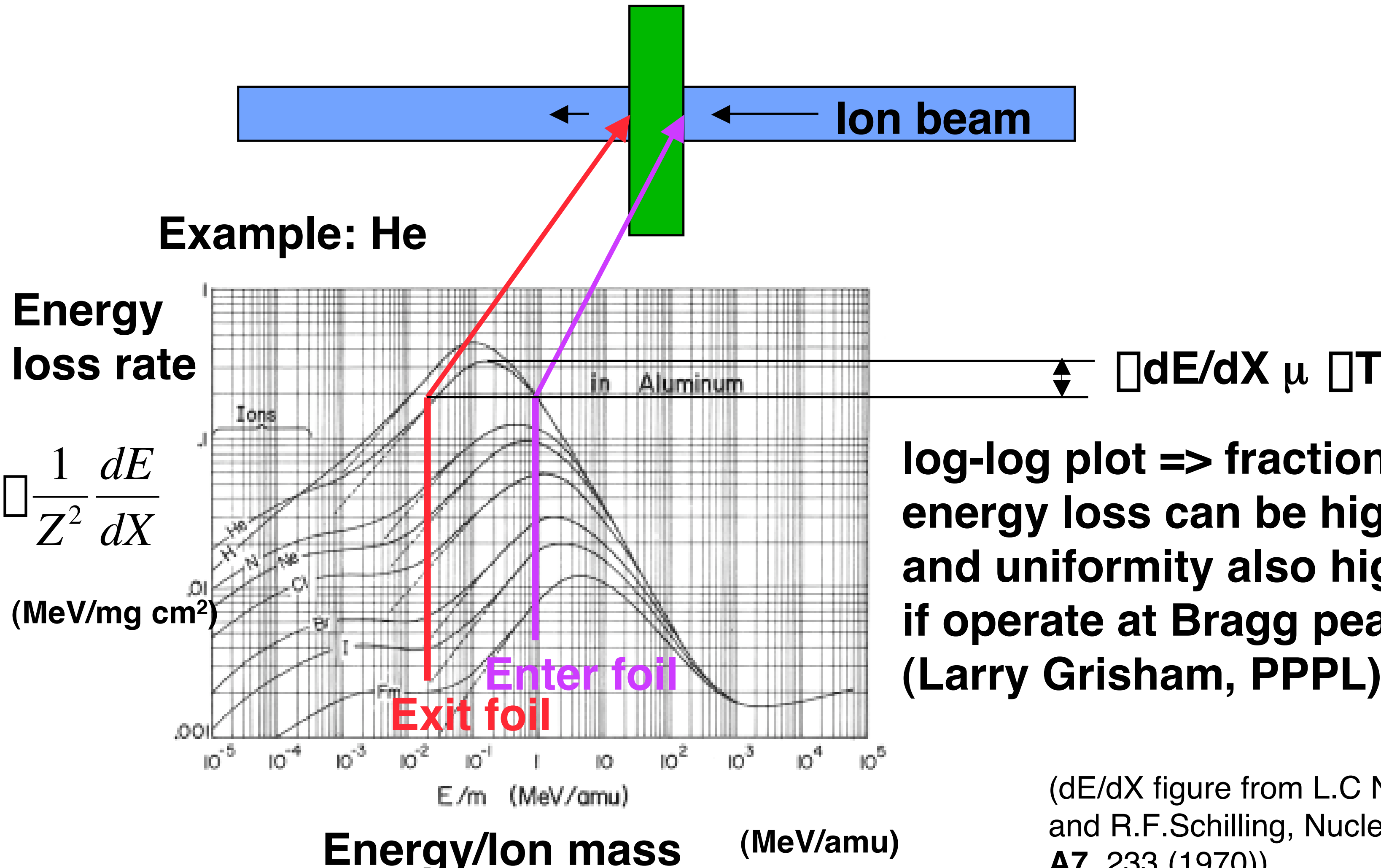
SIMULATIONS



II. Preparations for future experiments

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

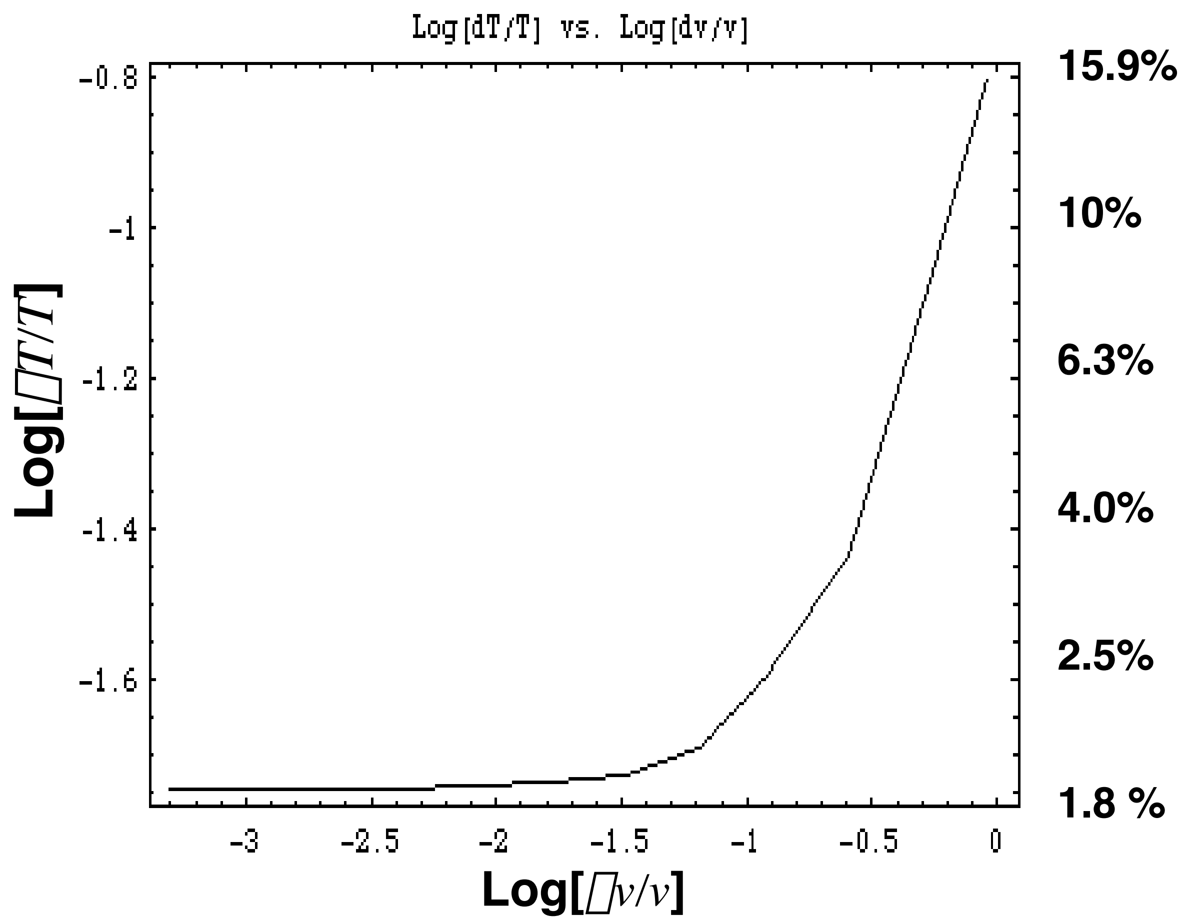
In simplest example, target is a foil of solid or “foam” metal



log-log plot => fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

(dE/dX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

We have looked at the effect of a velocity spread on temperature uniformity on target



October workshop will further develop new concepts for achieving ion-driven HEDP

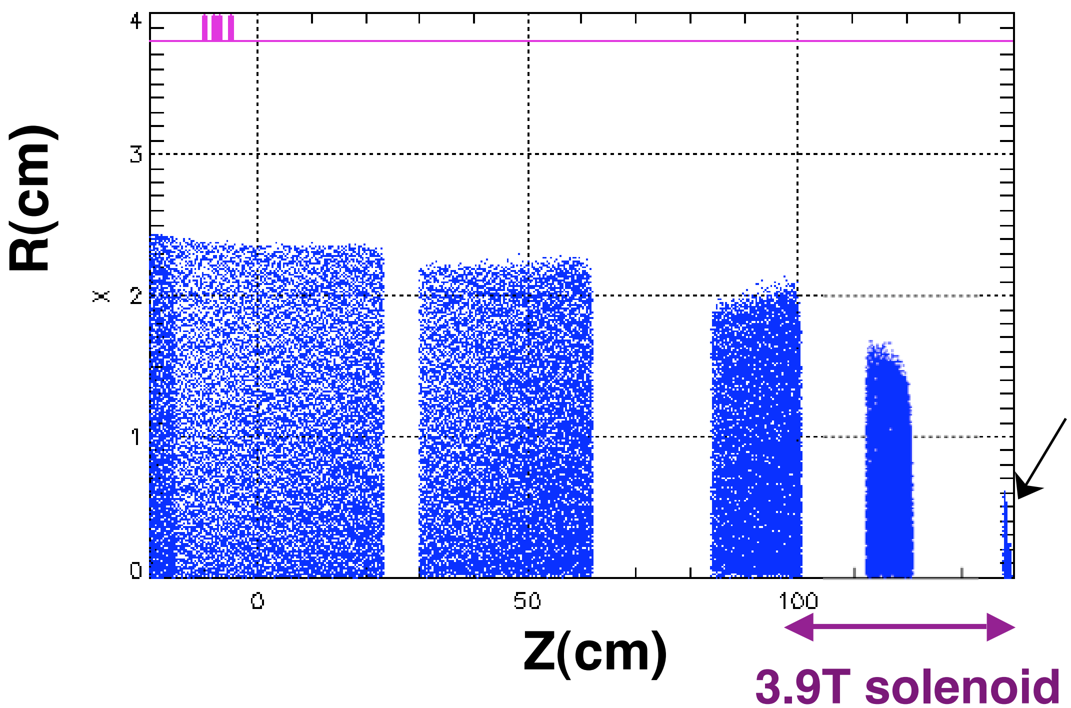
- **First step is to derive requirements on accelerator**
  - Stopping power as function of ion mass and energy
  - Range over which variation in stopping power is tolerable
  - Ionization state of target, allowing calculation of energy density, pressure, and temperature

    Simple Zeldovich and Raizer model used for equation of state
  - Velocity spread for which combined ion stopping power is within tolerable limits
- **Objects of workshop:**
  - Develop target and diagnostic concepts

    Requirements depend on suite of diagnostics envisioned.
  - Develop accelerator concepts

    Experiments may optimize differently for different accelerators

LSP simulations of neutralized drift and focusing show possibility of strong compression in NDCX-1



As simulated:

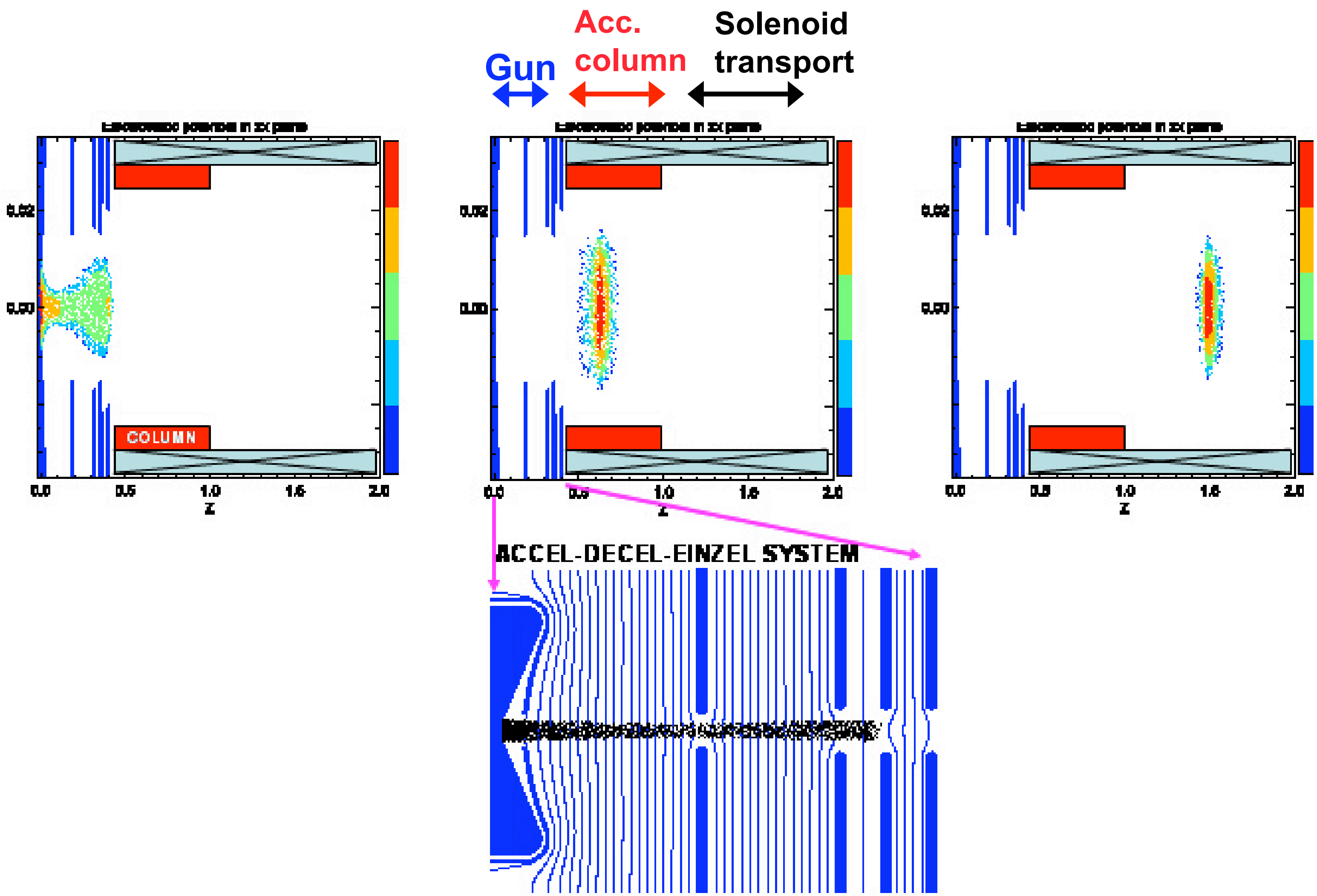
- **Axial compression 120 X**
- **Radial compression to 1/e focal spot radius < 1 mm**
- ***Beam intensity on target increases by 50,000 X.***

Ramped 220-390 keV, K^+, 24 mA ion beam injected into a 1.4-m long plasma column with density 10 x beam density.

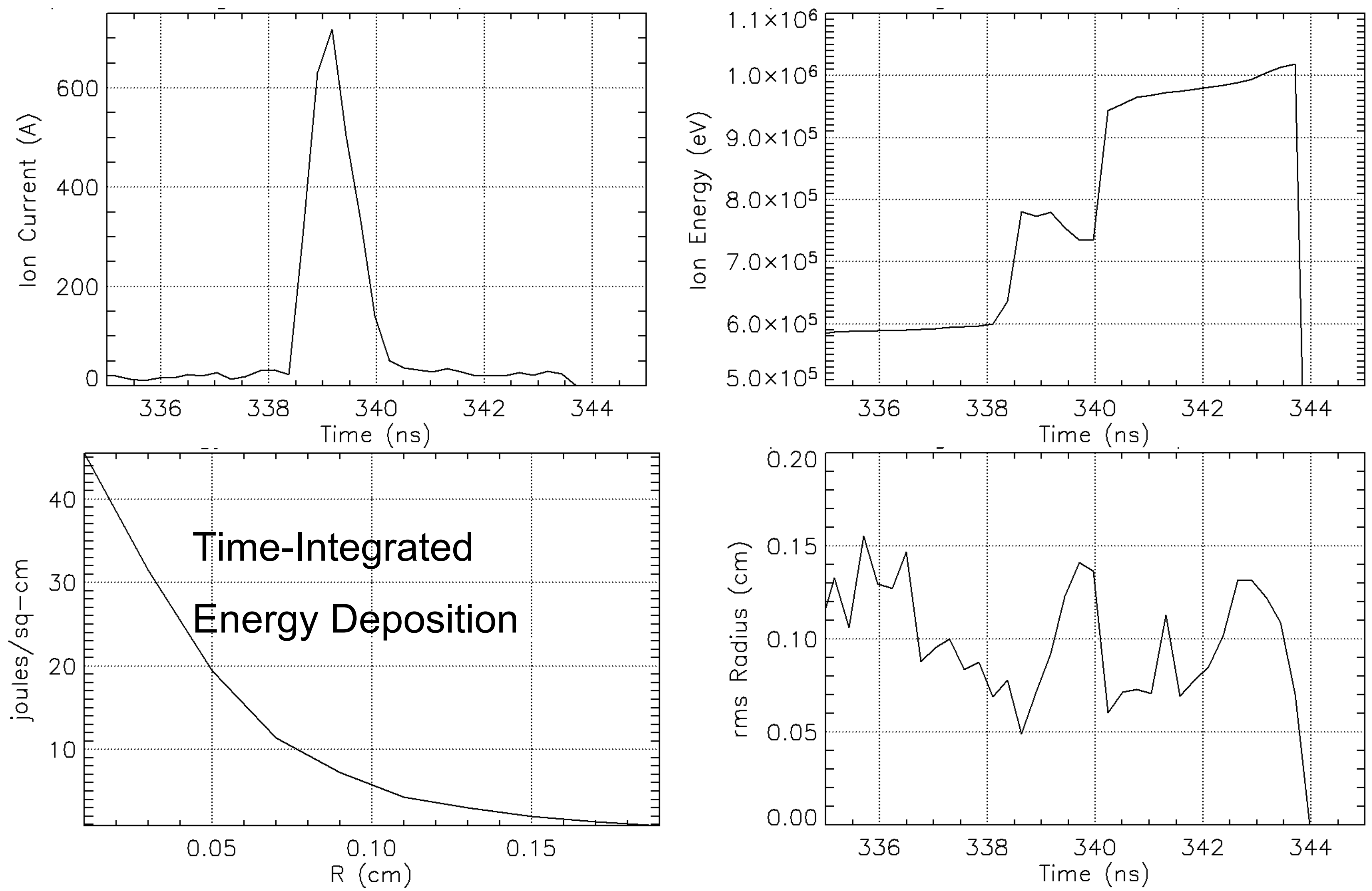
(simulations by Welch, Rose, Henestroza, Yu)

Simulation of a scaled experiment: novel High Line Charge Density Injector (NDCX-1c)

(Fully self-consistent WARP3D calculation of an ACCEL-DECEL-LOAD-AND-FIRE SYSTEM)



NDCX-2 beam compresses to conditions of interest for HEDP



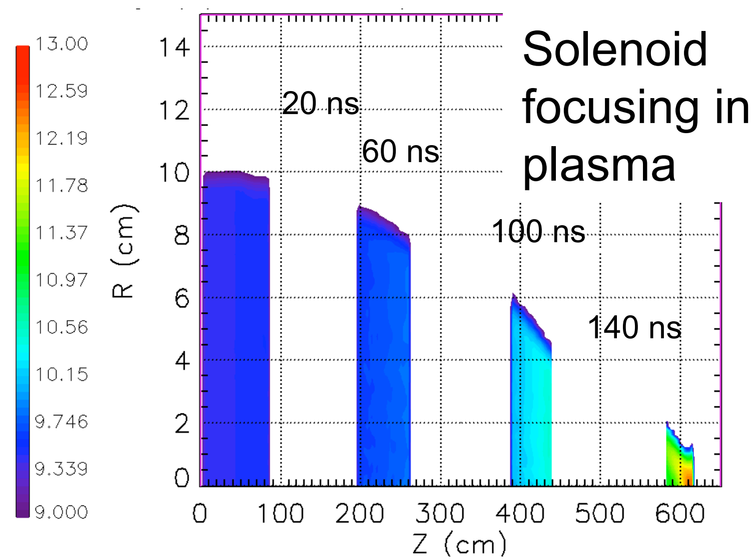
< 1 ns, < 1 mm pulse "on target" at z = 152 cm

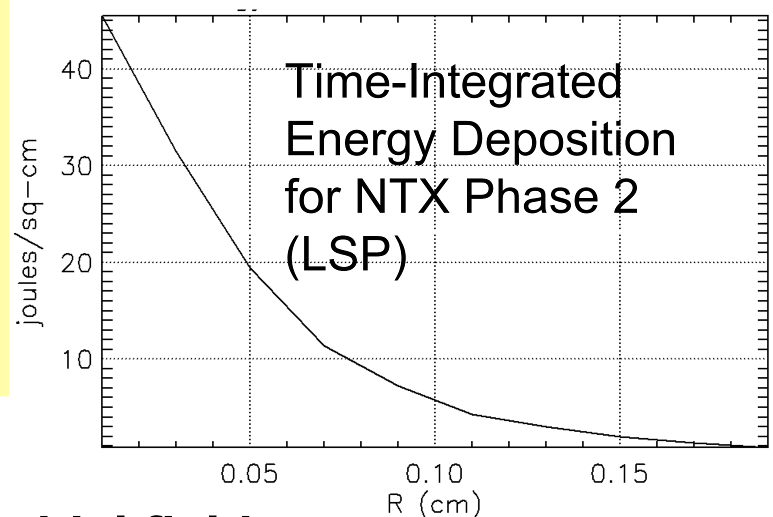
Compressed to .75 kA, 75x

(Simulations by C. Thoma, MRC)

Several Neutralized Drift Compression issues addressed

- Plasma neutralization allows 50-100x compression with applied velocity tilt
- Two-stream impact on beam is small
- Filamentation minimized for $r_c/\square_{sd} << 1$, $n_p >> n_b$
- Transition from Brillouin flow to NDC is feasible with dipole B
- 2-stage focusing with solenoid and discharge channel transversely focuses a beam with large energy tilt
- NDC can be tested on proposed NTX experiment w; large energy tilt; runs show condition approaching HEDP possible given 0.1% velocity accuracy



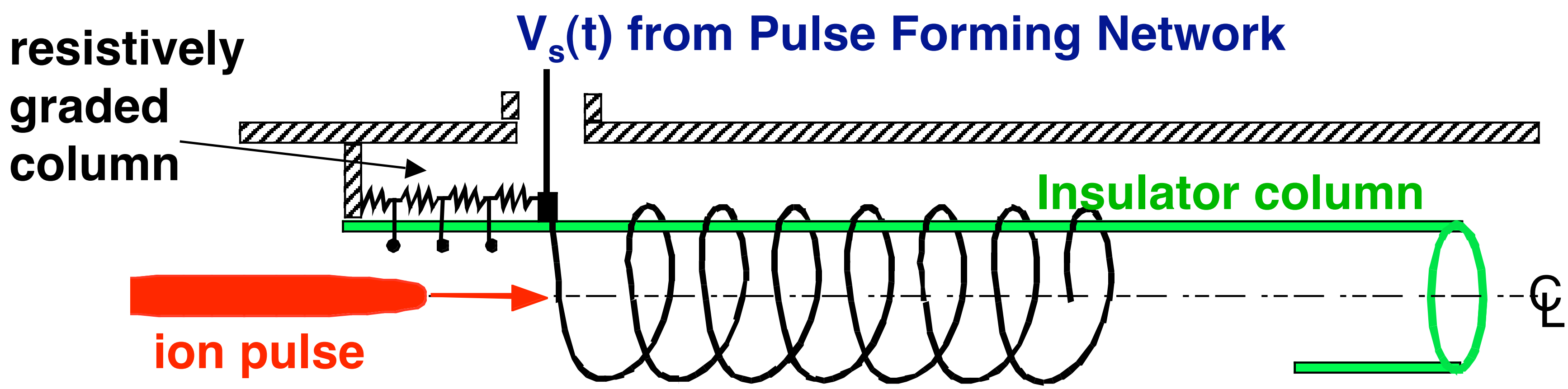


Key unaddressed issues:
Plasma must be created in varying solenoidal fields
Beam stripping by plasma limits NDC length
Multiple beam combining for driver

NDCX-3 experiments may employ a novel accelerating method based on a Traveling Wave Accelerator

Accel-decel injector with "load-and-fire" column →	Pulsed resistive column →	Broadband Traveling Wave Accelerator →	Energy ramping →	Neutralized Drift Compression

- Traveling Wave Accelerator is based on slow-wave structures (helices)
- Beam "surfs" on traveling pulse of E_z (moving at ~ 0.01 c in first stage)
- *One possible configuration:*



A. Friedman to present an invited talk on accelerators for HEDP at PAC '05

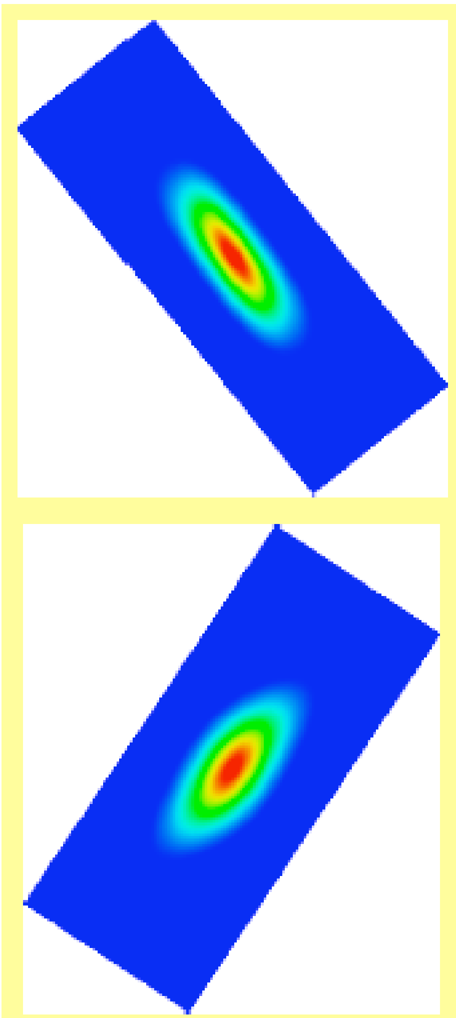
III. Other developments and closing thoughts

Fundamental simulation progress

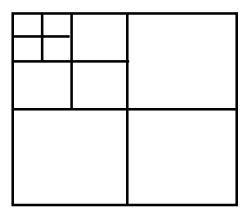
Challenges are being addressed by new computational capabilities

- **resolution challenges** (Adaptive Mesh Refinement-PIC)
- **dense plasmas** (implicit, hybrid PIC+fluid - LSP)
- **short electron timescales** (large-□t advance)
- **electron-cloud & gas interactions** (a "roadmap")
- **slowly growing instabilities** (□f for beams - BEST)
- **beam halo** (advanced Vlasov)

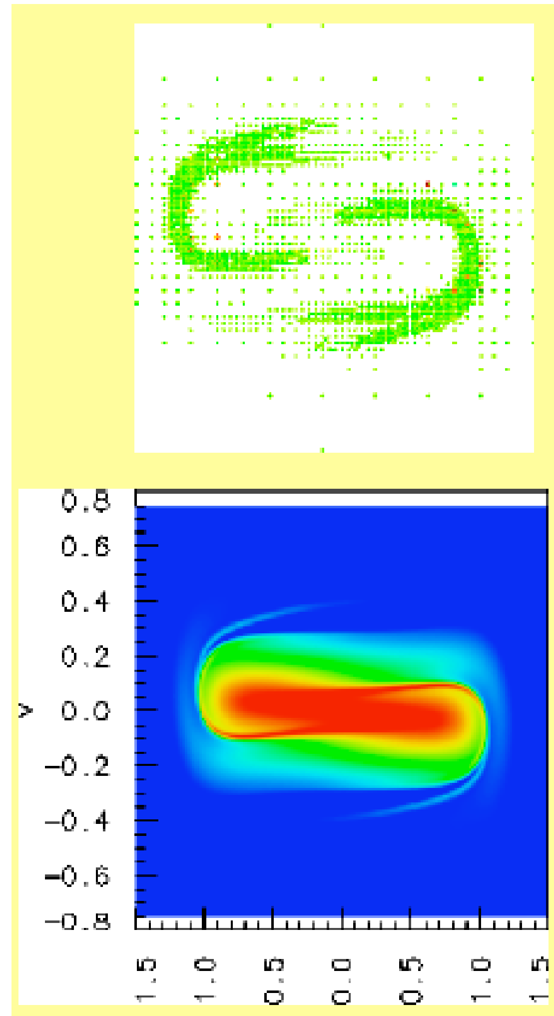
Vlasov innovations promise a route to efficient simulation of low-density “halo” regions of phase space



- moving phase-space grid, based on non-split semi-Lagrangian advance



- adaptive mesh in phase space



Active collaboration with E. Sonnendrucker, Univ. Strasbourg

Closing thoughts …

Beam modeling played a major role in the HIF-VNL's experimental program in FY04

Improvements in simulation capabilities over the past year were very significant, and offer benefits for a range of applications

These advanced tools are being employed in planning for the future, and are especially valuable in light of the new HEDP mission