Simulation of intense beams for Heavy Ion Fusion*

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(for the Heavy Ion Fusion Virtual National Laboratory)

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Outline: Beam simulations by HIF-VNL and collaborators (and some new capabilities)

- Present-day Experiments
  - Injectors (Adaptive Mesh Refinement)
  - HCX (high current experiment)
  - NTX (neutralized transport experiment)
- Fundamental Beam Science
  - Electron Cloud (models and e-mover)
  - Quad Strength Errors
  - Instabilities
  - Halo (new Vlasov methods)
- Future Experiments
  - IBX (integrated beam experiment) & RPD (robust point design)
  - NDCX's (neutralized drift compression experiments) & Modular Driver
- Discussion

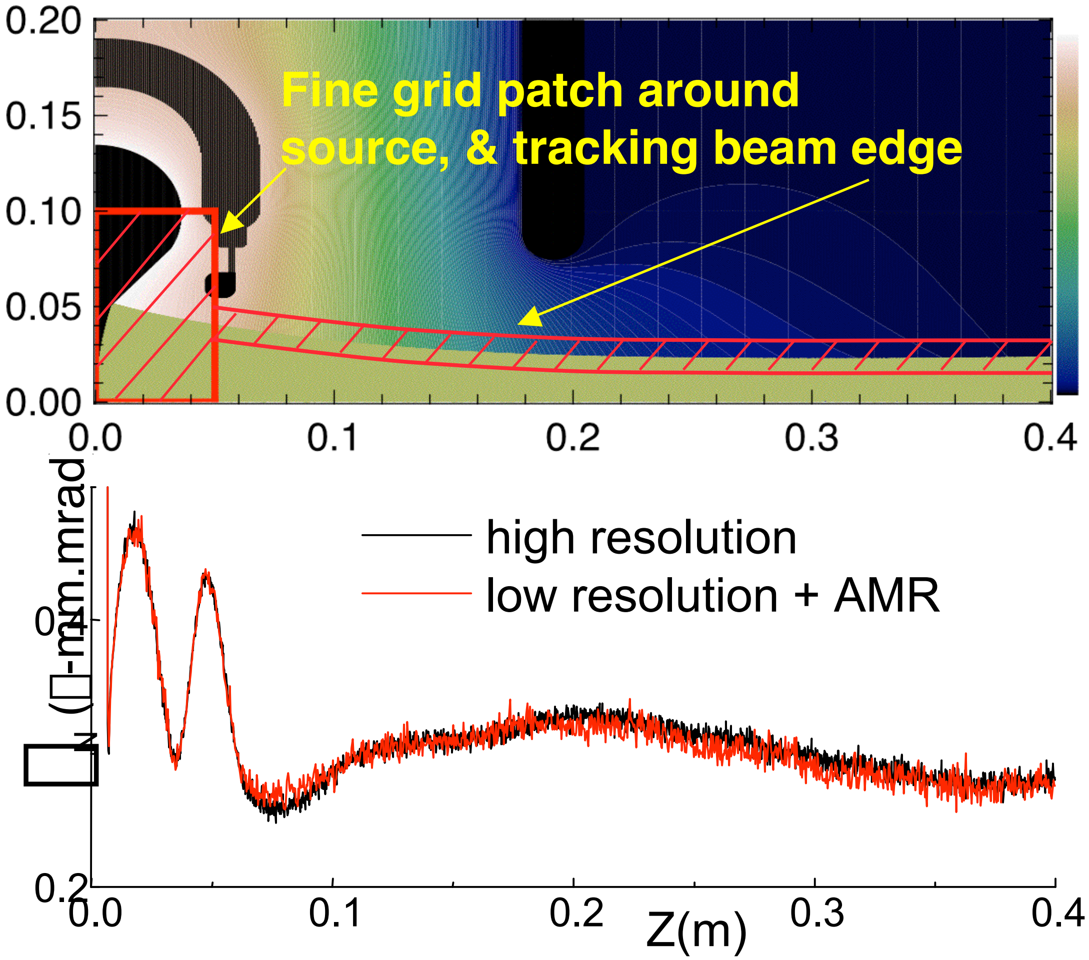
Present-day Experiments

Injectors

Kwan Tu.I-13
Kishek W.I-11
Vay W.P-08 (oral talk Tues. aft'n)
Kwan Th.P-11
Westenskow Th.P-12
Haber Th.P-14

Particle-In-Cell & Adaptive Mesh Refinement: married at last!

Application to HCX triode in axisymmetric (r,z) geometry



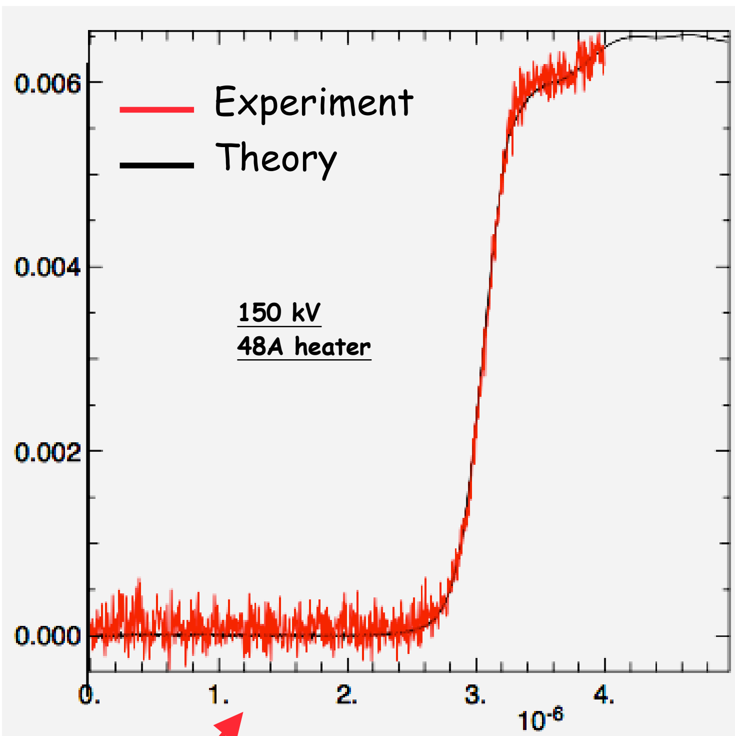
This example:
~ 4x savings in computational cost
(in other cases, far greater savings)

(simulations by J-L. Vay)

WARP simulations model STS-500 experiments using 10-cm-diameter K^+ alumino-silicate source

Rise time

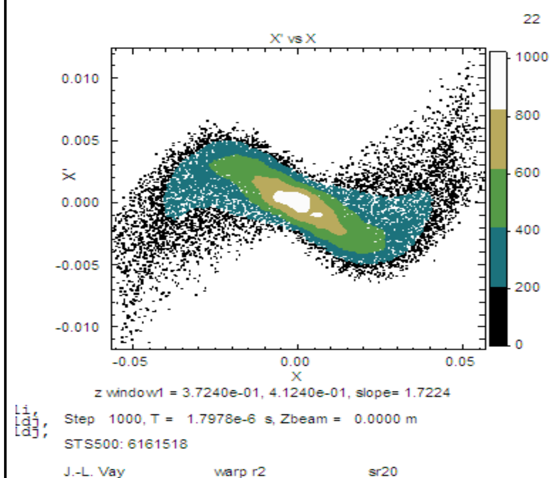
Current at Faraday cup



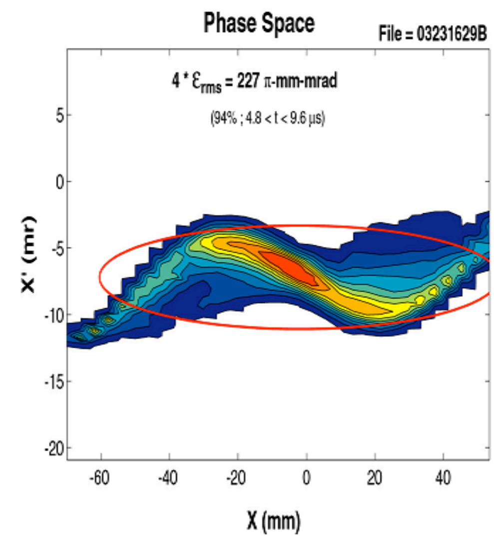
Result depends critically on Mesh Refinement

Phase Space at End of Diode

Warp simulations

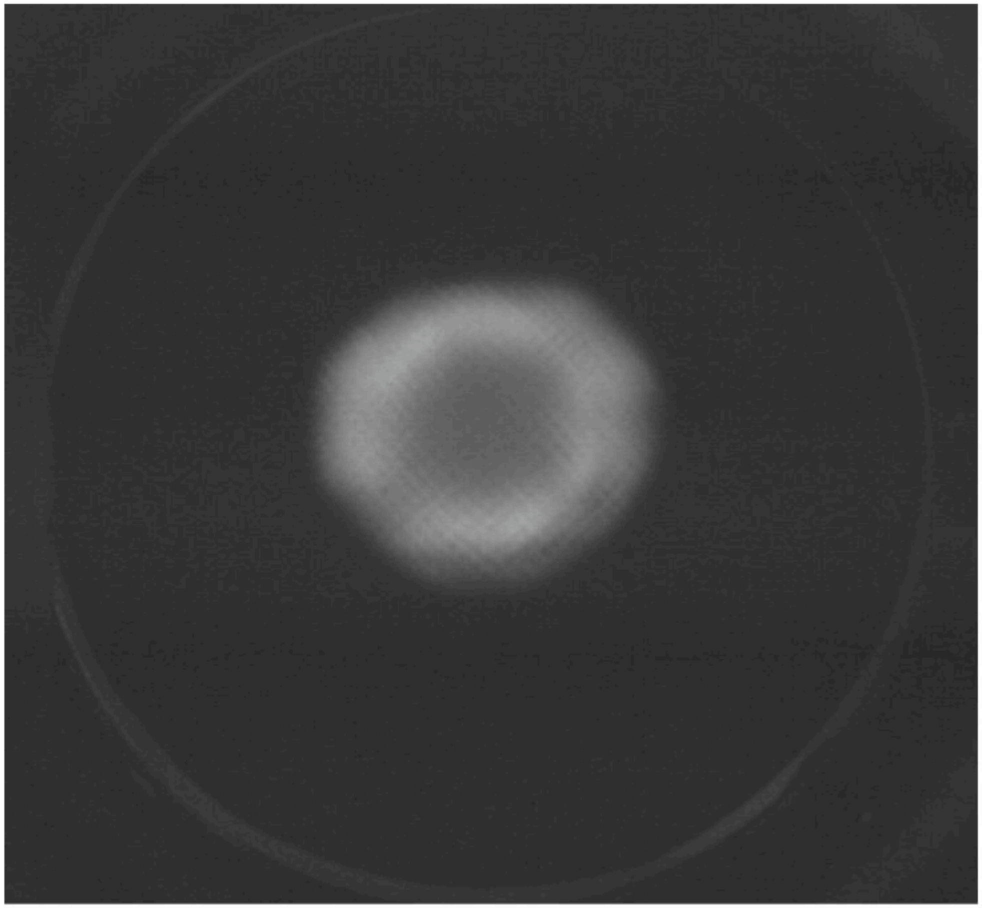


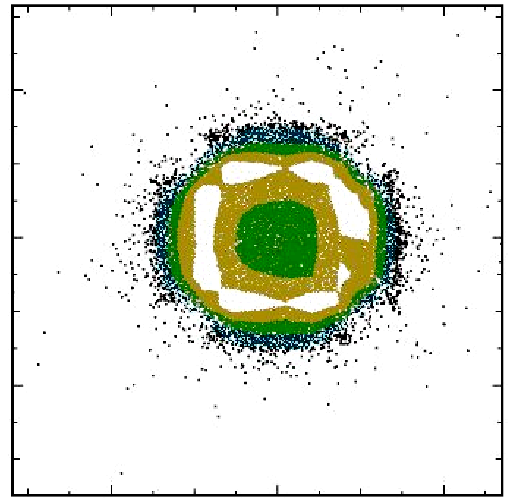
Experimental results



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

WARP simulations of the UMER electron gun reproduce some features of the observed velocity space

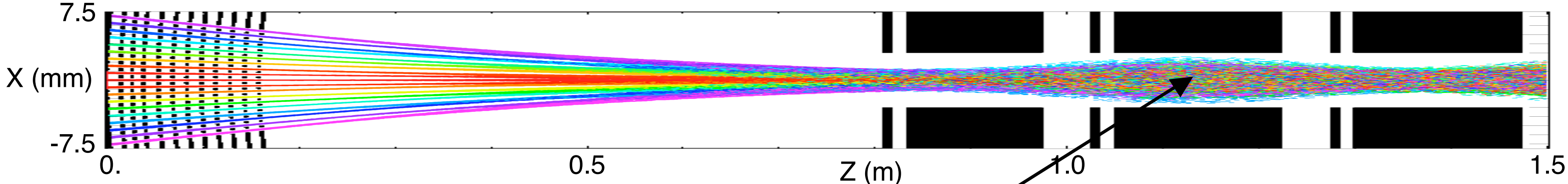




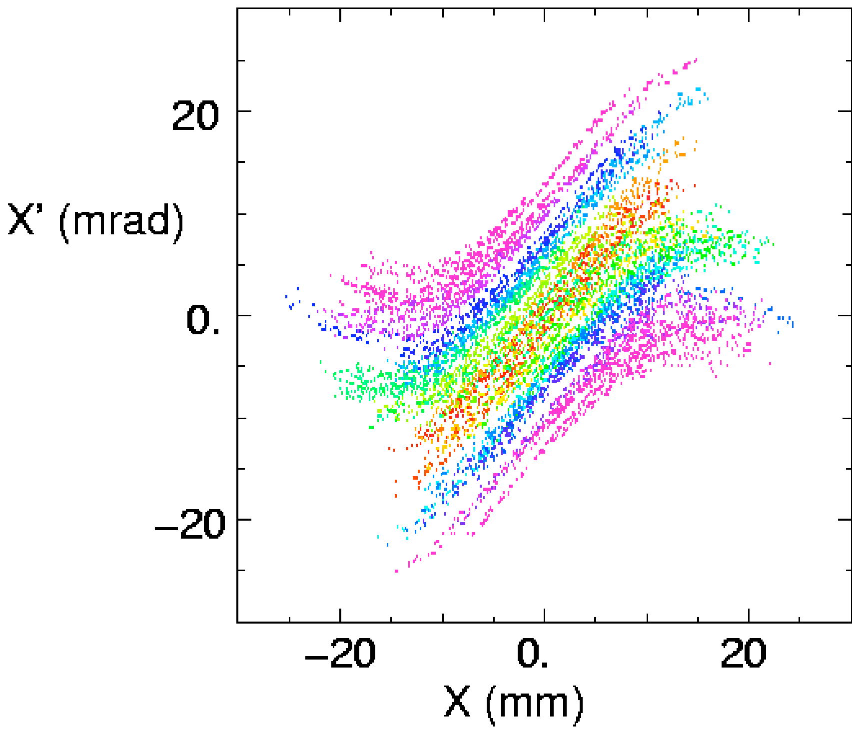
Beam velocity distribution emerging from the gun, measured as a phosphor screen image of the beam after passage through a small hole

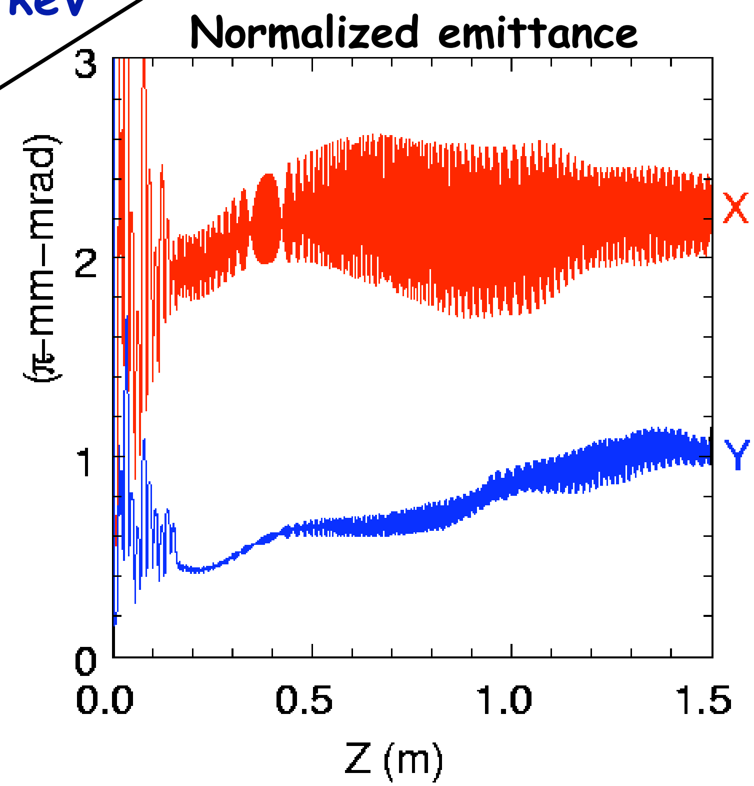
(simulations by I. Haber / R. Kishek)

Physics design of beamlet-merging experiment on STS-500 is complete



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





WARP RZ and XY runs were used for synthesis, 3D for validation

(simulations by D. Grote)

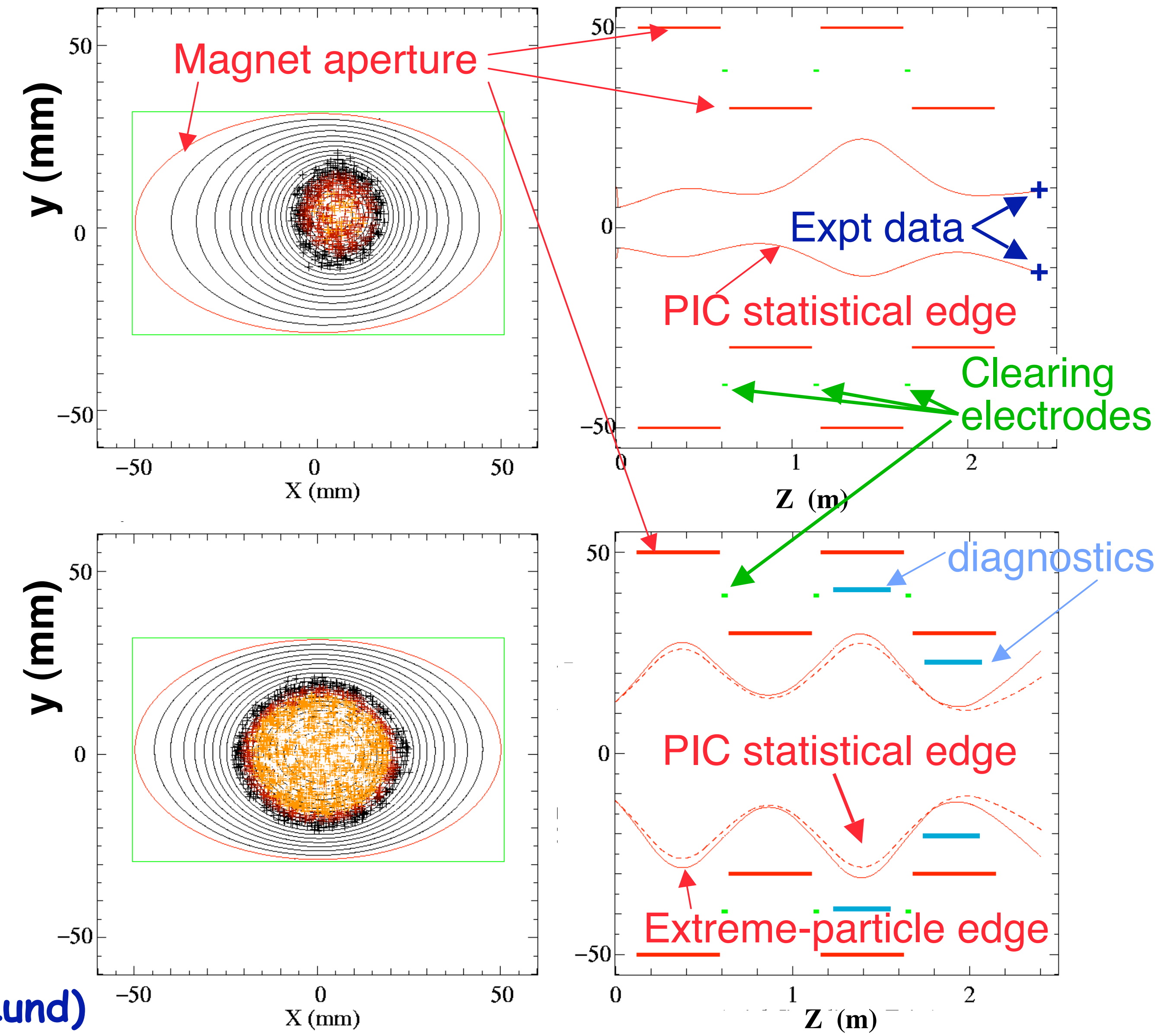
HCX

Prost W.I-07

WARPxy 2D simulations initialized with measured (a,a',b,b') have been "workhorses" for HCX

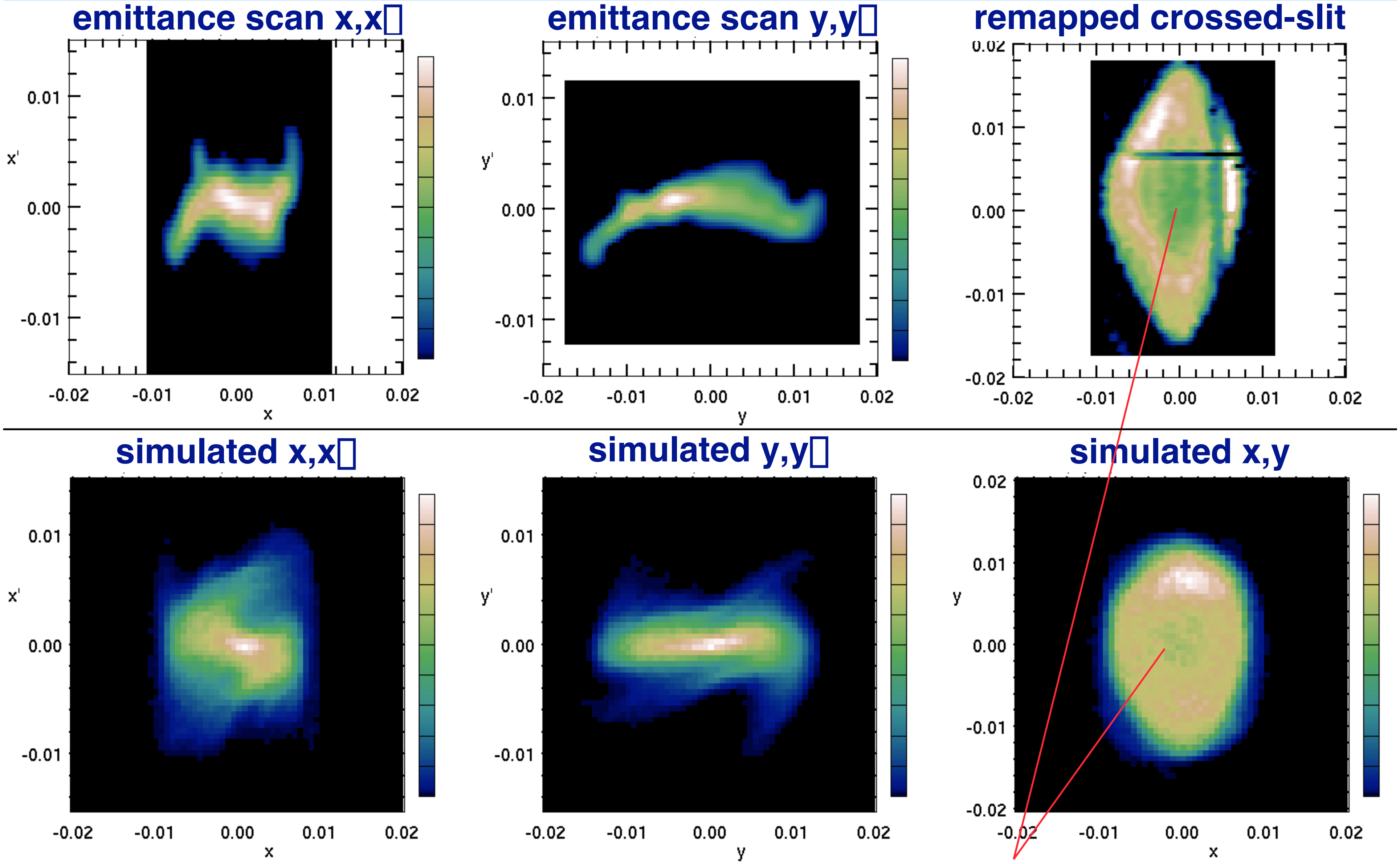
32 mA beam:
53% fill factor; good transport consistent with simulations

175 mA beam:
67% fill factor; recent experiments & simulations have been aimed at achieving clearance for diagnostics insertion



(Simulations by S. Lund)

Simulations initialized tomographically from measured (x,x′), (y,y′), and (x,y) views are only in coarse agreement with data at "D-end"



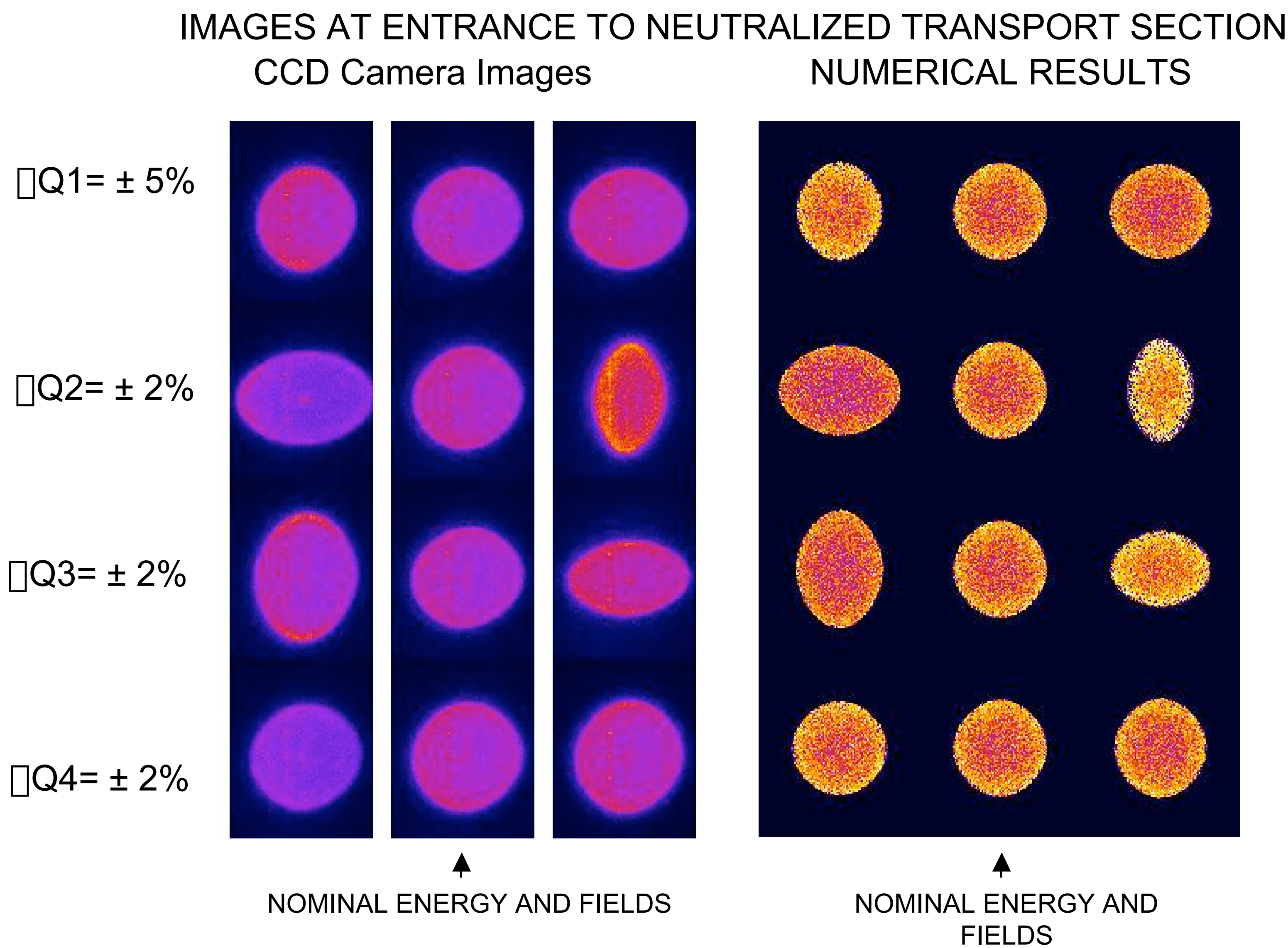
Suspect: observed correlations in "other" planes, *e.g.* (y,x′) - see Bieniosek talk

Spatial hollowing is a common feature

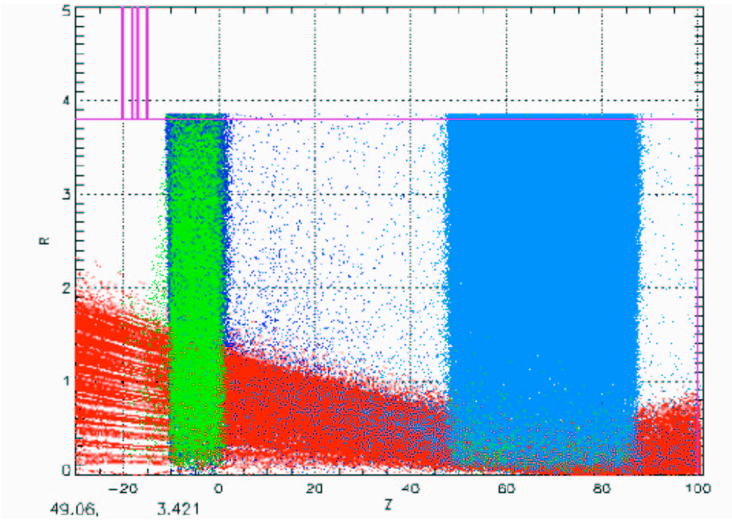
NTX

Welch Th.I-06
Eylon Th.P-26

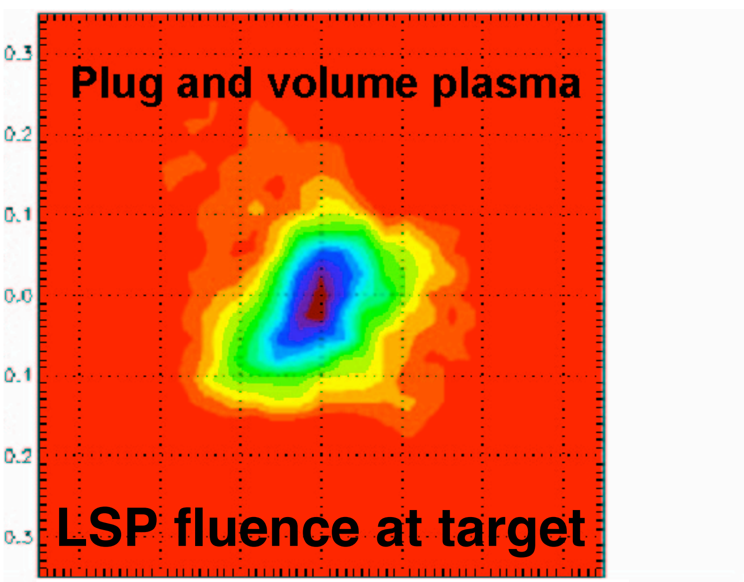
Variation of NTX beam images vs. quadrupole strengths show good agreement with WARP simulation



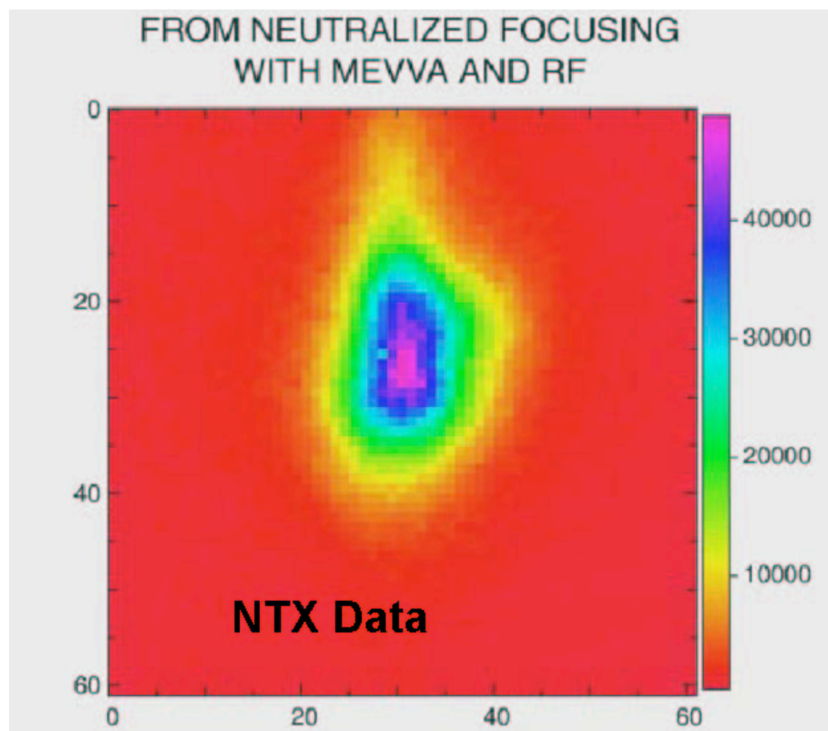
LSP simulations of NTX transport are now being initialized with the measured 4D particle distribution



- EM, 3D cylindrical geom., 8 azimuthal spokes
- 3 eV plug 3×10^9 cm^{-3}, volume plasma 10^{10} cm^{-3}
- 2 days run time on 4 processors



Carsten Thoma, et. al.



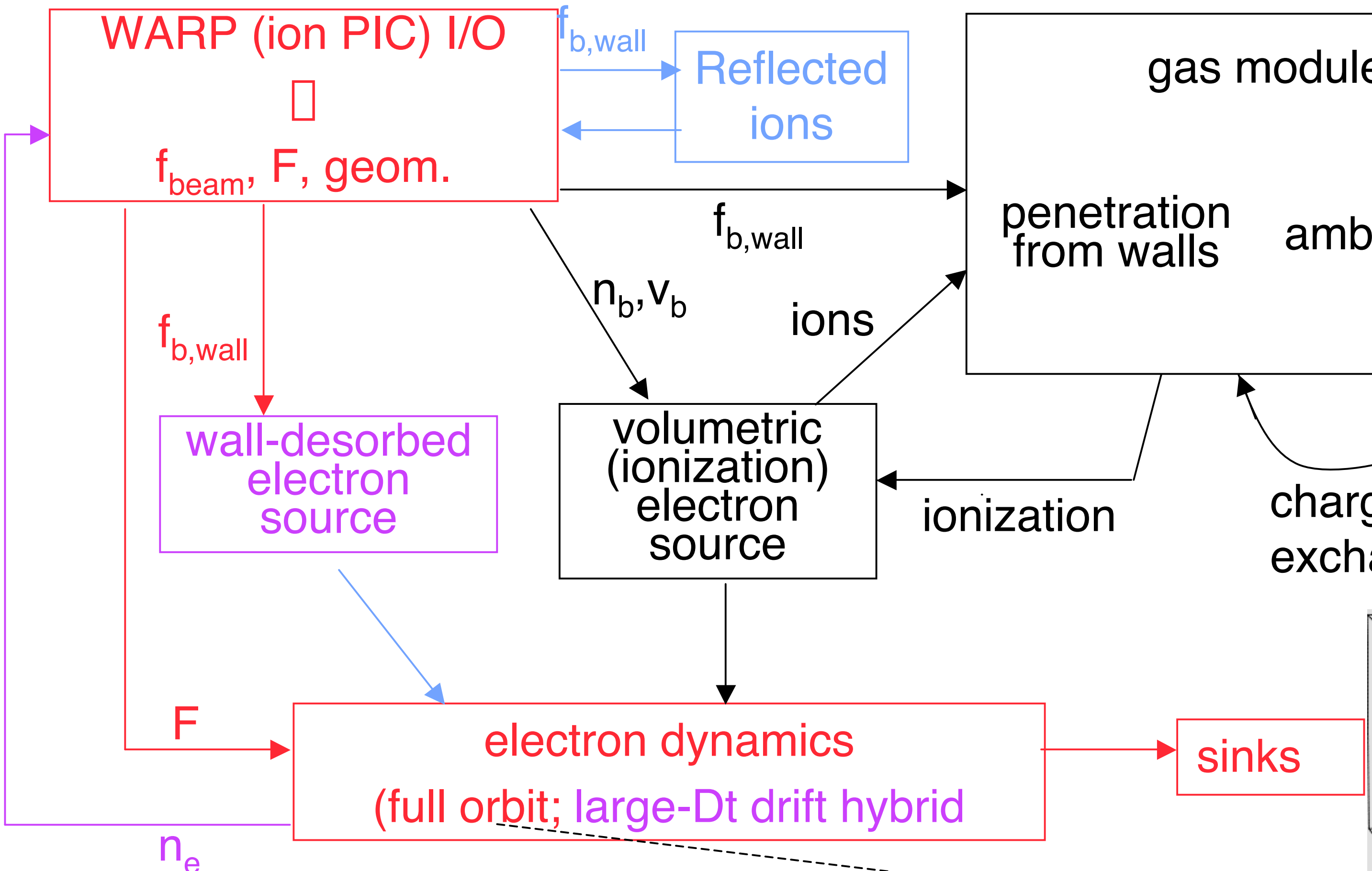
Fundamental Beam Science

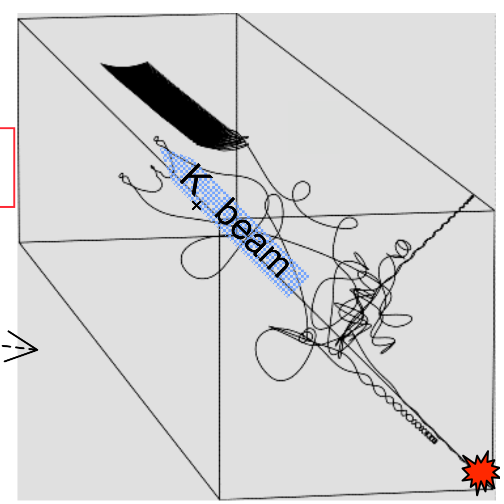
(Afflictions and their Avoidance)

e-Cloud
(new models and e-mover)

Cohen Th.I-03
Stoltz Th.P-25

We are following a road map toward toward self-consistent e-clouds and gas modeling in WARP



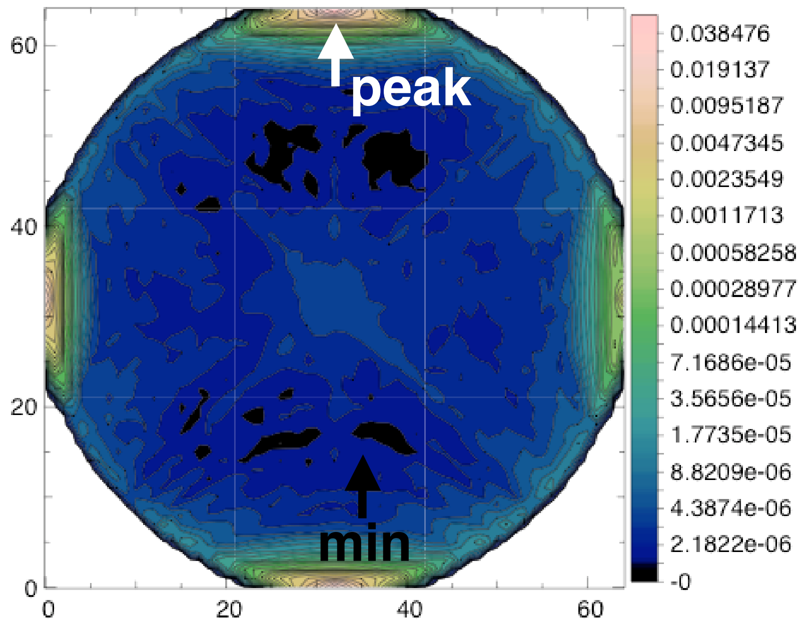


operational; implemented / testing;
partially implemented; offline development

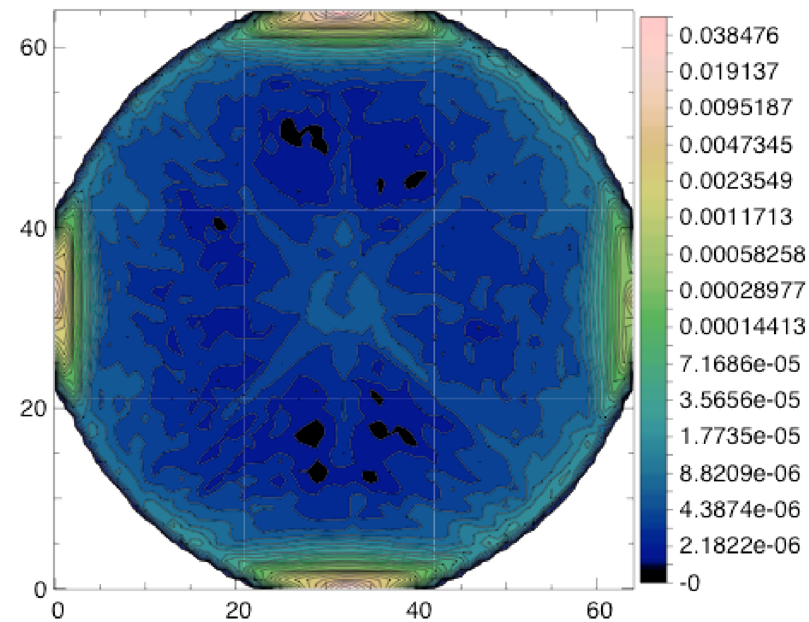
New large time-step electron mover reduces computational effort by factor of 25

Simulated wall-desorbed electron density distributions (log scale)

Full-orbit , $\Delta t=.25/f_{ce}$



Large time-step interpolated



electrons in 45° regions caused by first-flight reflected ions

Tests of new mover are encouraging; we imagine application to other fields, including MFE, astrophysics, near-space

Quad Strength Errors & relaxation of nonuniformities

S. Lund work; for latter topic see Th.P-20

Driver-like random quad strength errors of 0.1% induce only small emittance growth over 200 lattice periods

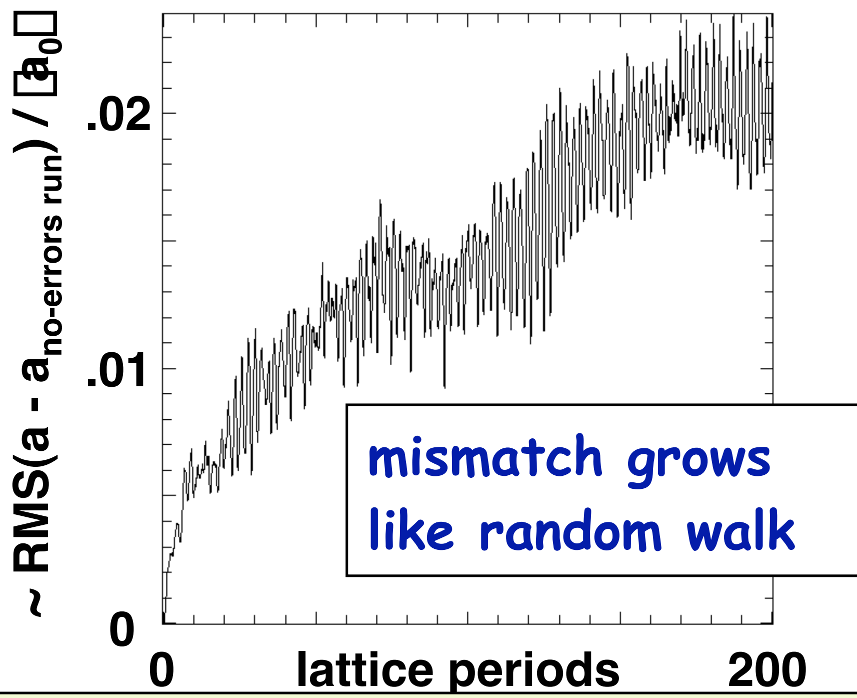
- Scaling rules that bound the emittance growth were derived by Lee & Barnard, assuming continuous thermalization; IBEAM sys. code uses:

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\sqrt{2}}{\sigma/\sigma_0}\sqrt{\left\langle\left(\frac{\Delta B}{B}\right)^2\right\rangle}\sqrt{N}$$

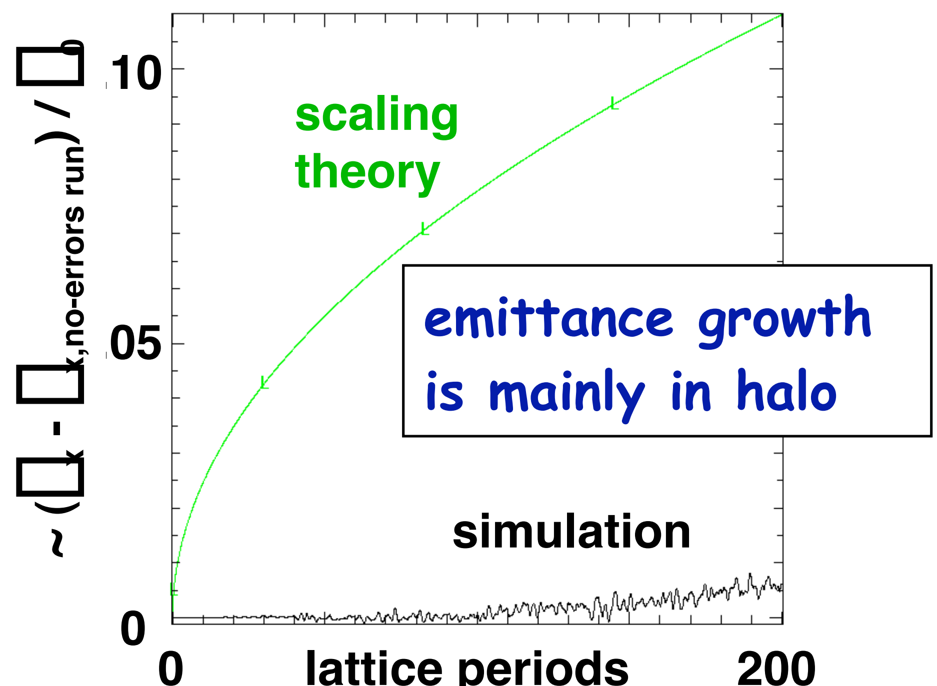
N = Number of lattice periods

- Ensemble of 14 WARPxy runs, errors ± 0.1% (uniform); σ/σ_0= 0.1:

Relative RMS mismatch amplitude



Relative growth in emittance



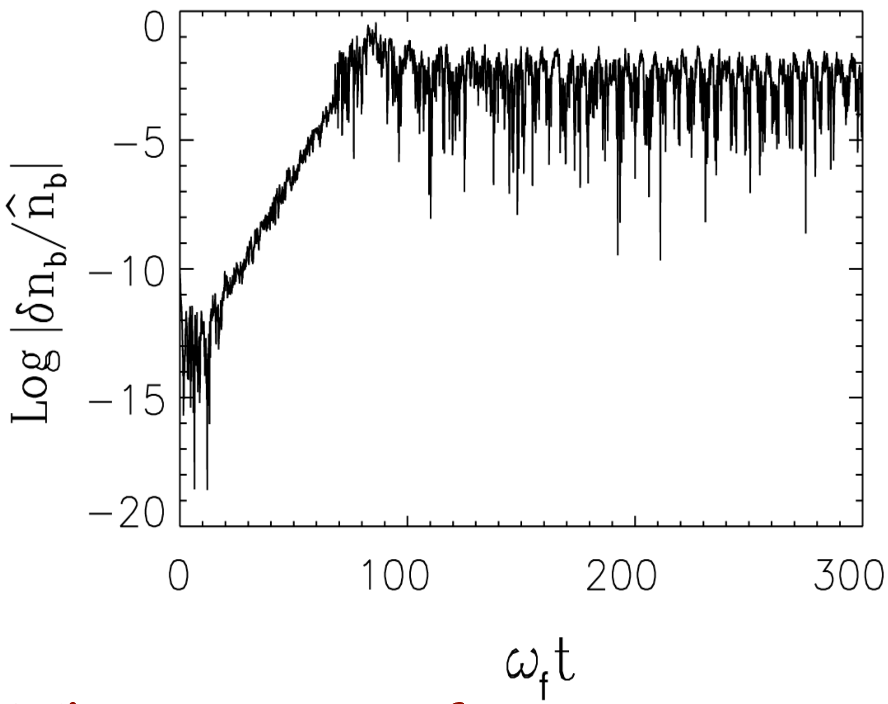
Scaling seems pessimistic; need to extend runs to 1000 LP's

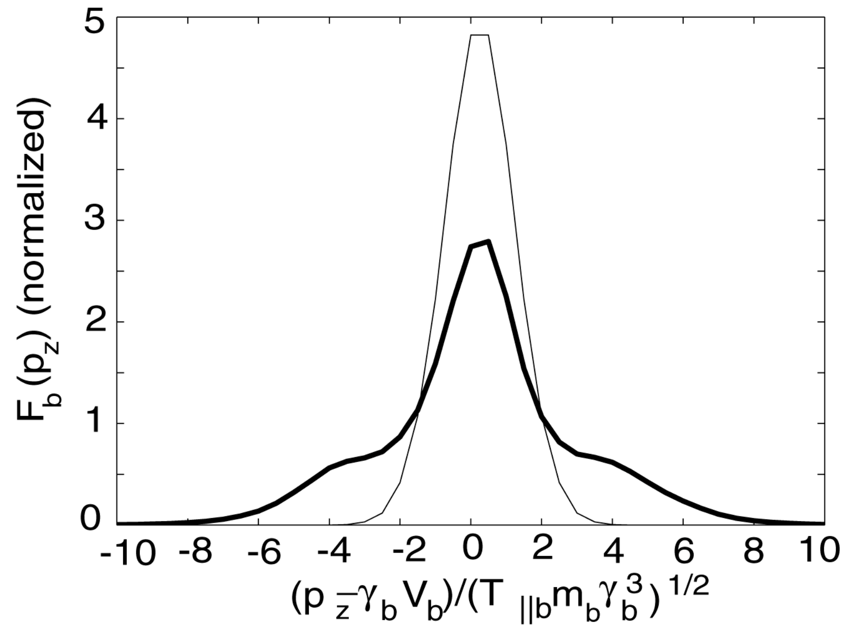
(S. Lund)

Instabilities

Davidson Tu.I-11
Startsev Tu.I-12
W. Lee W.P-09
Rose W.P-15

Studies of electrostatic anisotropy-driven mode show that driver designs must take this effect into account



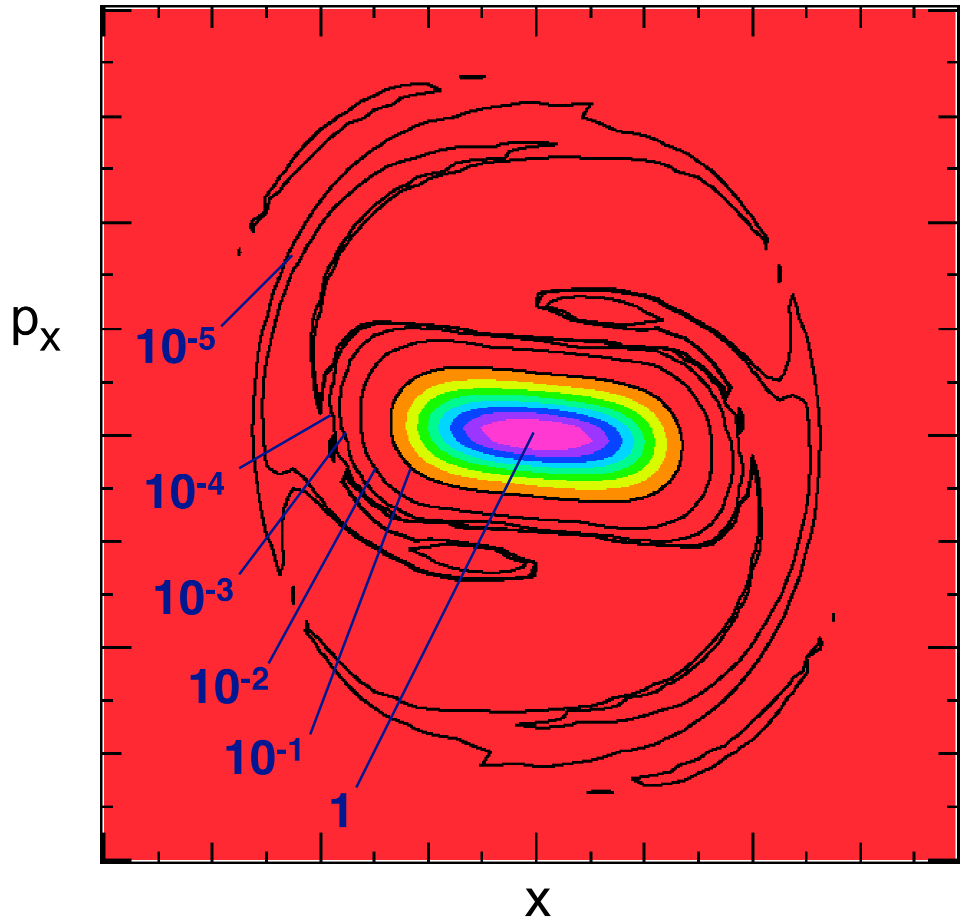


- **When $T_\perp > T_{||}$, free energy is available for a Harris-like instability**
- **Earlier work (1990 …) used WARP**
- **Simulations using BEST δf model (above) show that the mode saturates quasilinearly before equipartitioning; final $\Delta v_{||} \approx \Delta v_\perp / 3$**
- **BEST was also applied to Weibel; that mode appears unimportant for energy isotropization**
- **BEST, LSP, and soon WARP are being applied to 2-stream**

Halo
(new Vlasov methods)

Sonnendrucker W.I-09

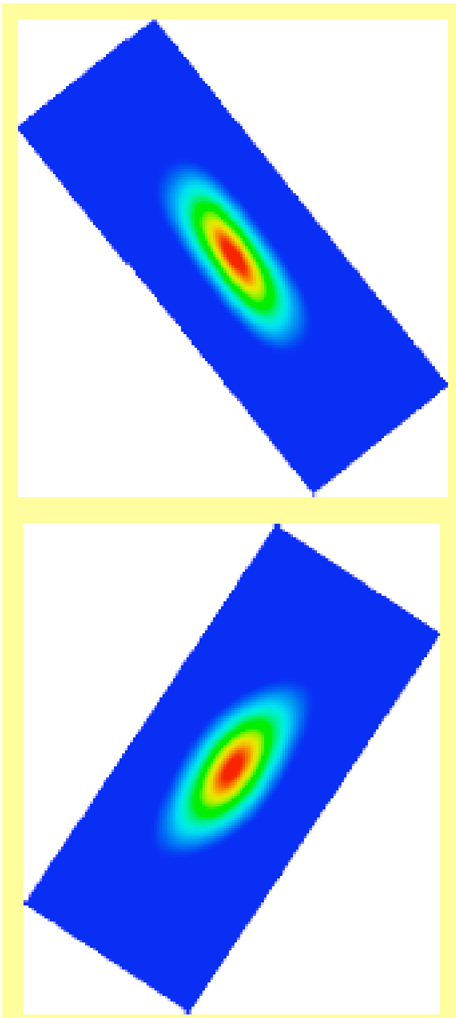
Solution of Vlasov equation on a grid in phase space offers low noise, large dynamic range



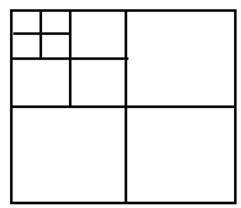
Evolved state of density-mismatched axisymmetric thermal beam with tune depression 0.5, showing halo

- **4D Vlasov testbed (with constant focusing) showed halo structure down to extremely low densities**

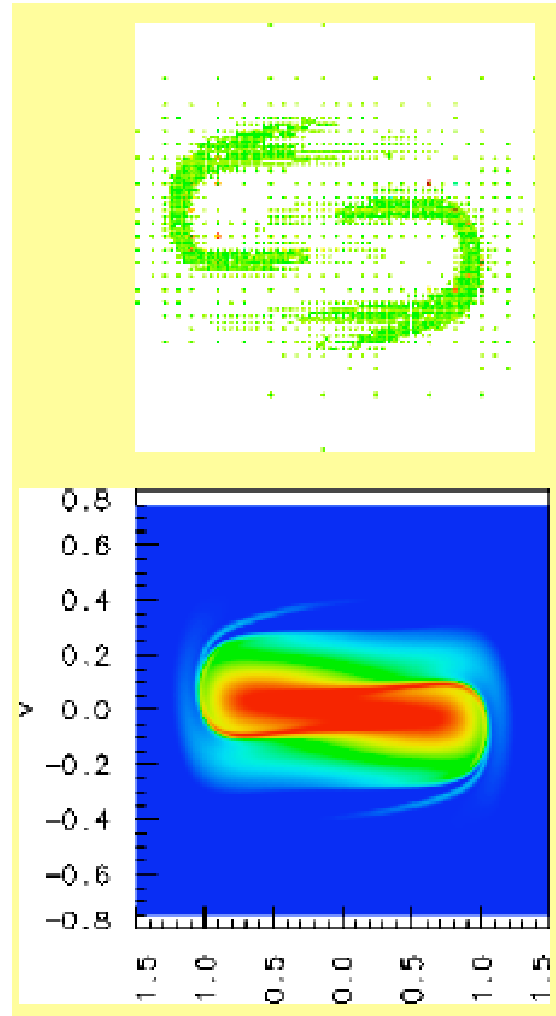
Latest work uses moving grid in phase space to handle A-G focusing, and adaptive mesh to resolve fine structures



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



adaptive mesh in phase space



Future Experiments

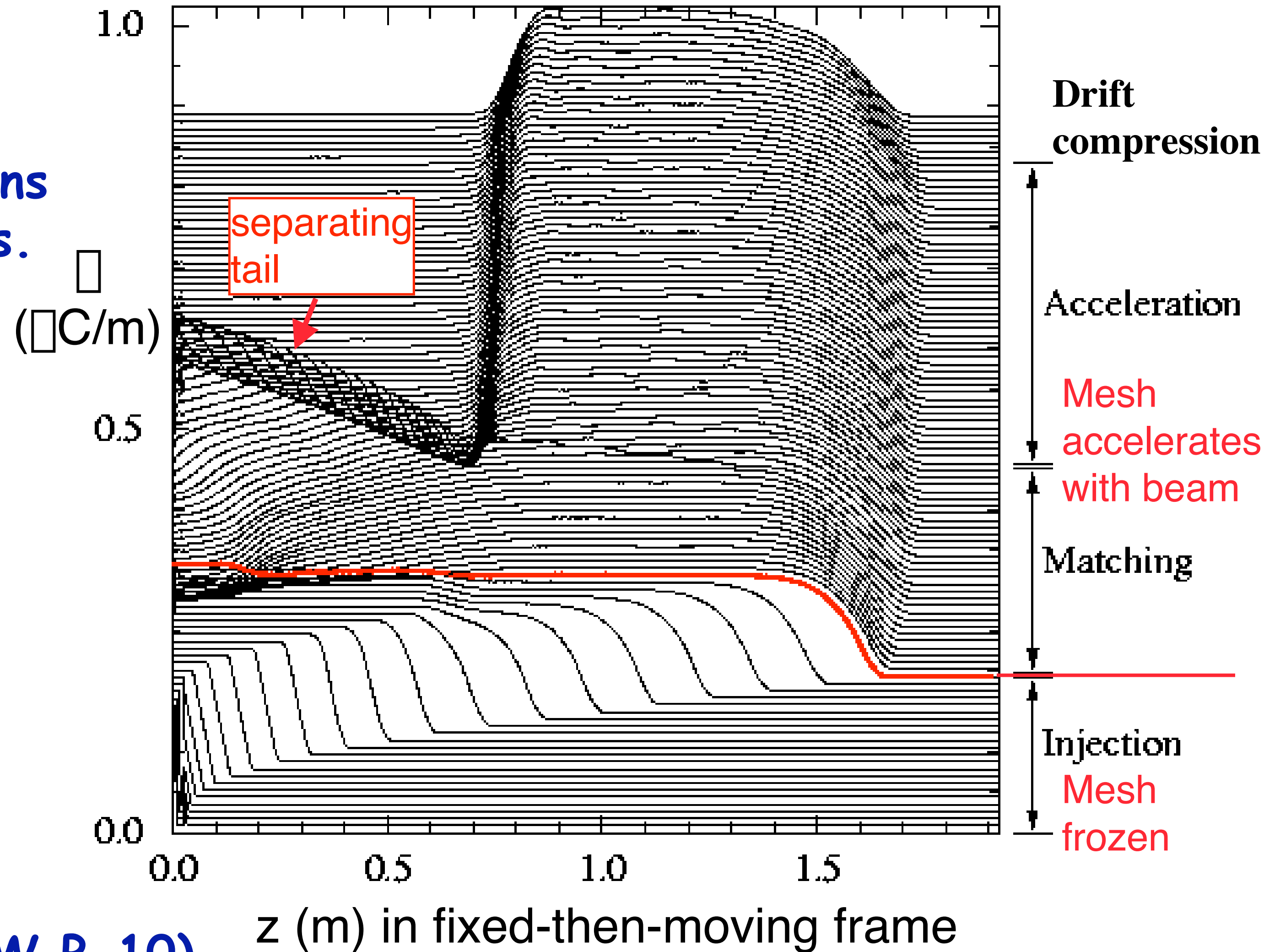
IBX and RPD

Grote W.P-10
Sharp W.P-19
Barnard Th.I-07
Yu F.I-01
Leitner F.I-06

3D WARP simulations of an "ideal" IBX show quiescent behavior

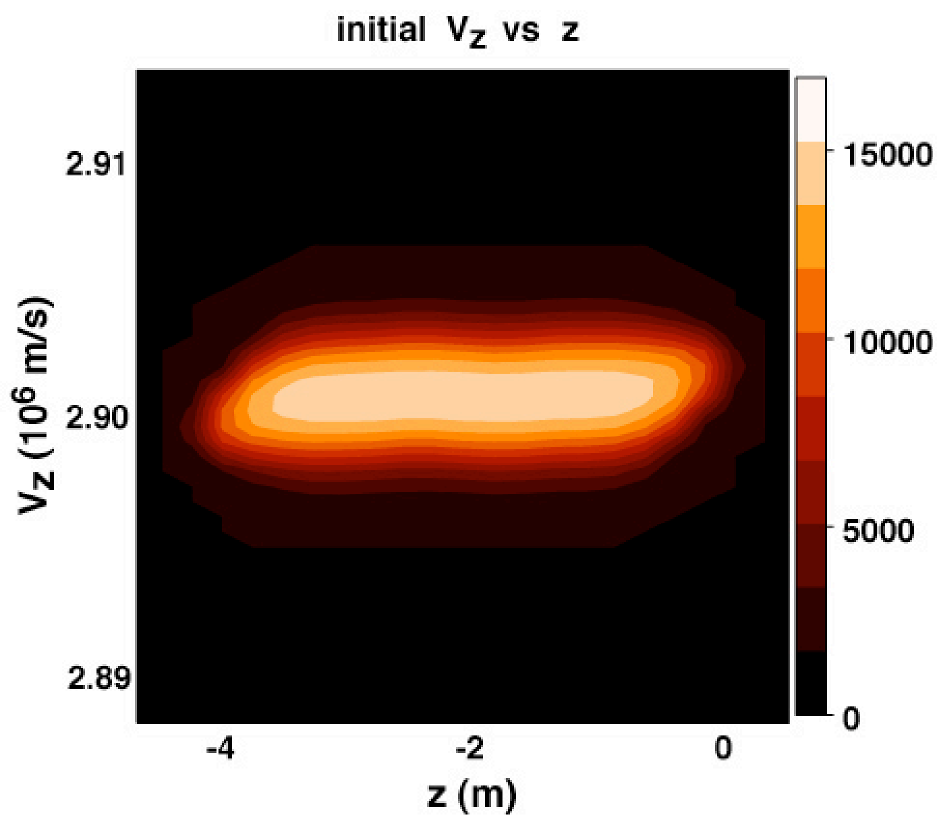
- **Beam created at source, matched, accelerated, begins to drift-compress.**
- **Parameters:**
  - 1.7 ⇒ 6.0 MeV
  - 200 ⇒ 100 ns
  - 0.36 ⇒ 0.68 A
  - 4.6 μs of beamtime

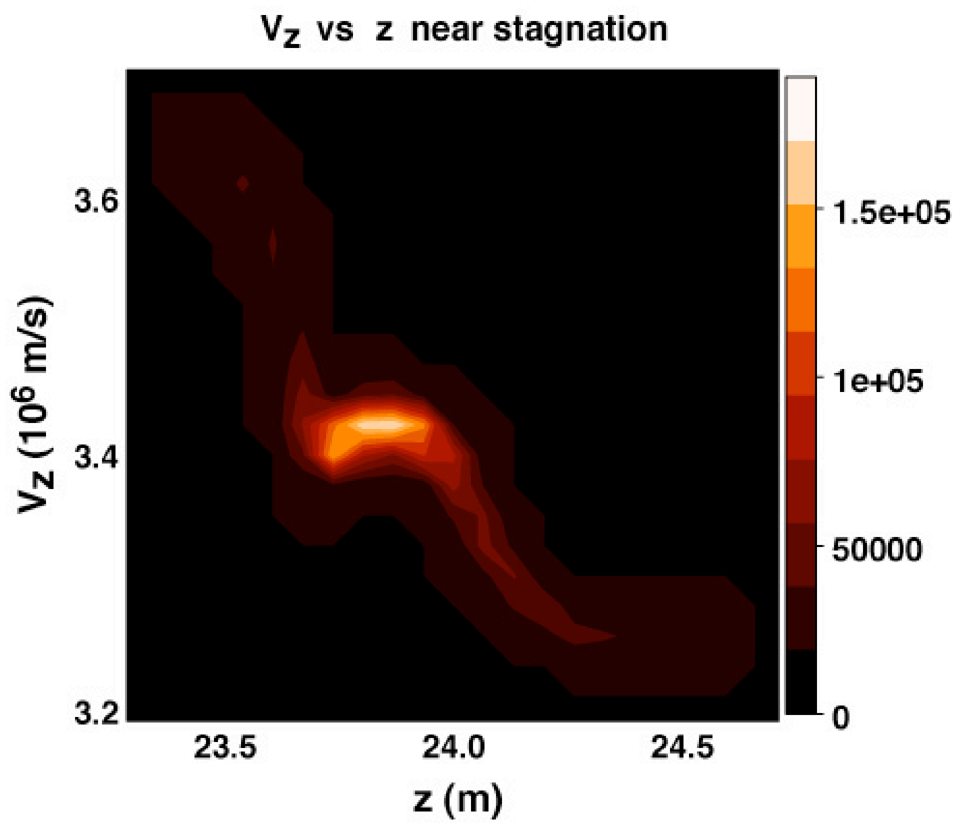
Line-charge at 100 successive times (vertically offset)



(See D. Grote, W.P-10)

Simulations of unneutralized drift compression are in progress





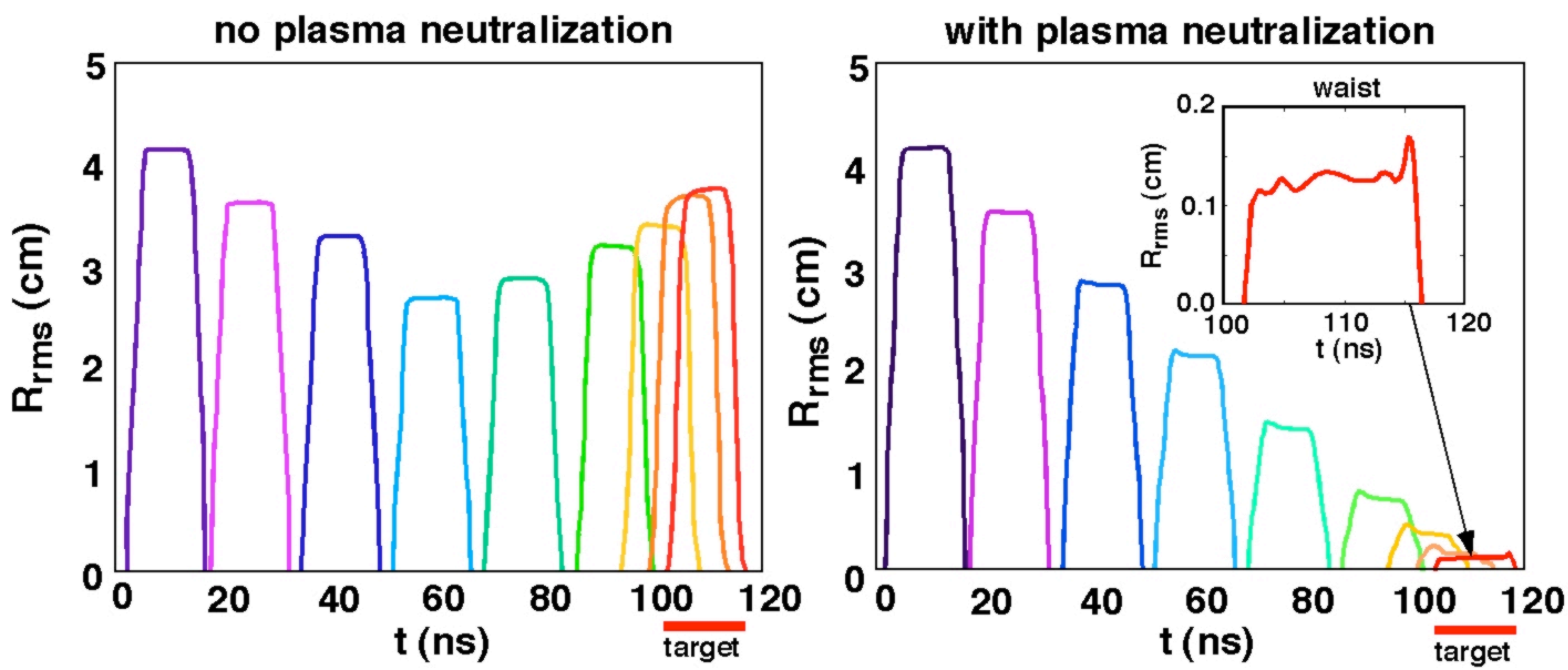
Simulations of IBX beam at 10:1 compression show some loss to halo

- improved pulse-shaping is expected to reduce beam loss
- transverse emittance growth is typically less than a factor of two

(See W. Sharp, W.P-19)

Neutralization of an "RPD" main pulse in fusion chamber yields a focal spot with 1.2 mm RMS radius

Beam radius vs. time at selected points over a 6-m focal length:



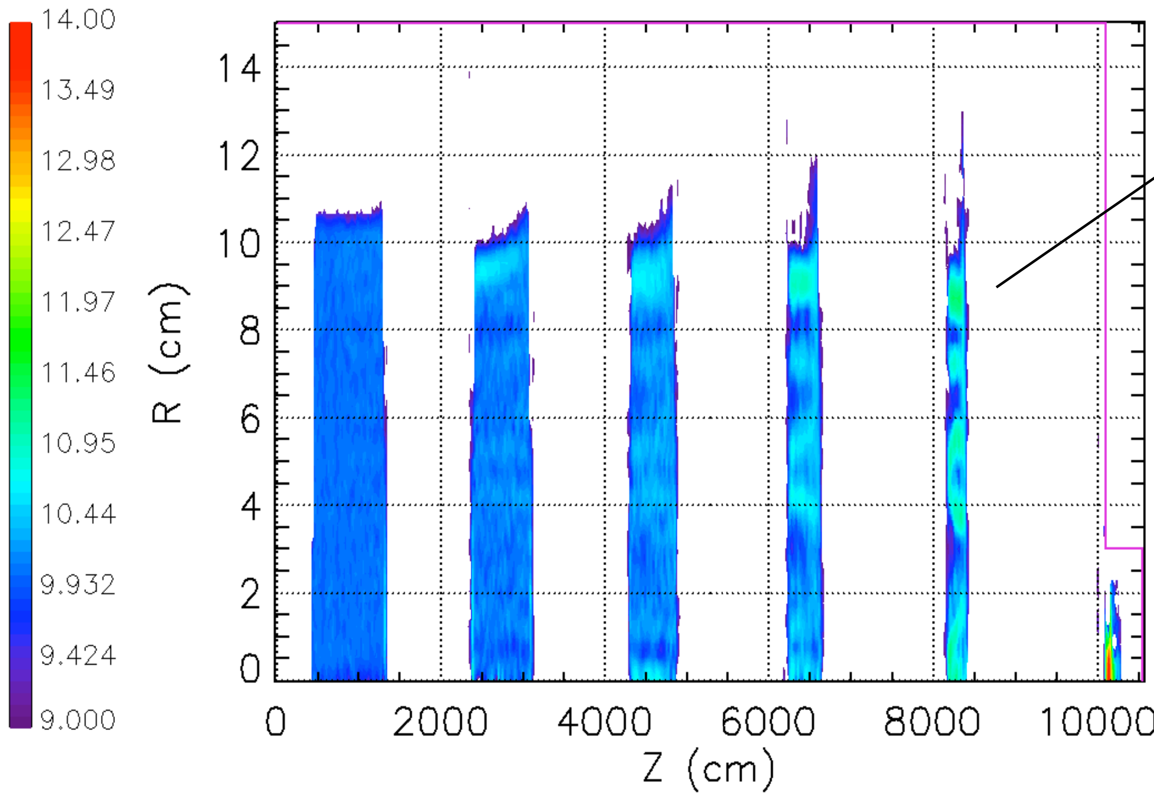
2 kA, 4 GeV, Bi^+

(LSP simulations by W. Sharp)

Neutralized Drift Compression eXperiments & Modular Driver

E. Lee W.I-12
Kaganovich W.P-14
Welch Th.I-06
Henestroza Th.P-13 - **Accel/decel injector**
Meier F.I-05

Preliminary LSP simulations for a modular IFE driver show neutralized compression and focusing in a 100-m plasma column



Run shows filamentation, but 92% of beam still falls within the 5 mm spot needed for a hybrid distributed radiator target

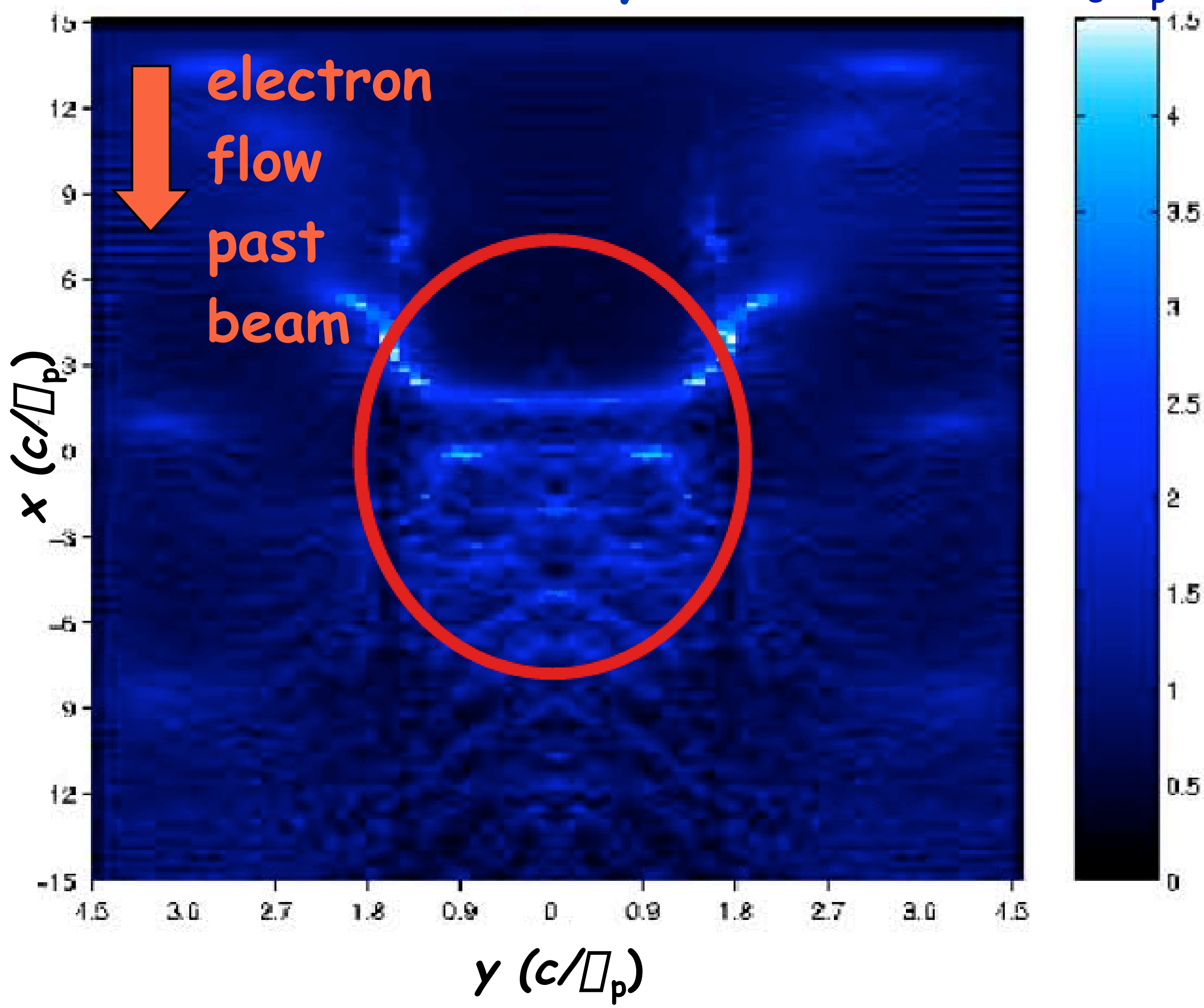
Ne+ beam
Pulse energy: 140 kJ
Energy ramp: 200 - 240 MeV
Current: 3 → 140 kA
Beam radius: 10 cm → < 5 mm
Pulse duration: 210 → 5 ns

Other LSP simulations are playing a major role in scoping out the "NDCX" experiments to begin in the near future

(Simulations by D.Welch & D. Rose)

Simulation of ion pulse neutralization: waves induced in plasma are modified by a uniform axial magnetic field

electron density contours



2D EM PIC code "EDPIC" in XY slab geometry, comoving frame, beam & plasma ions fixed

$v_b = c/2$; $l_b = 7.5\ c/\omega_p$;
$\omega_c = 5\omega_p$; $r_b = 1.5\ c/\omega_p$;
$n_b = n_p/2$
(I. Kaganovich poster)

Discussion

Discussion … simulation effort is evolving toward "multiphysics, multiscale" modeling

- e-Cloud and Gas:
  - merging capabilities of WARP and POSINST (e-cloud sources for high-energy physics), and adding new models
  - implementing method for bridging disparate e & i timescales
- Plasma interactions:
  - LSP already implicit, hybrid, with collisions, ionization, … now with improved "one-pass" implicit EM solver
  - Darwin model development (W. Lee et. al.; earlier Sonnendrucker work)
- Injectors
  - Merging beamlet approach is "multiscale"
  - Plasma-based sources (FAR-Tech SBIR)
- New "HEDP" mission changes path to IFE; models must evolve too
  - Non-stagnating pulse compression
  - Plasmas early and often
  - Modular approach a complement

End

& thanks to all whose work formed the basis for this talk!