Overview of Theory and Modeling in the Heavy Ion Fusion Virtual Laboratory

Presented by

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Overview of Theory and Modeling in the Heavy Ion Fusion Virtual Laboratory

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Presentation Outline

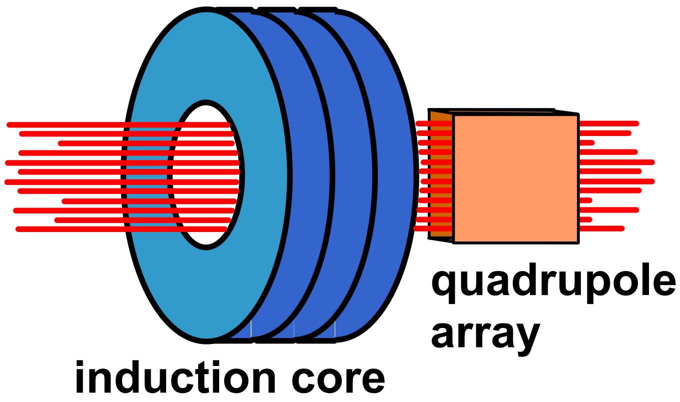
- Nonlinear beam dynamics and collective processes.
- Studies supporting driver-related experiments.
- Beam propagation in fusion chamber plasmas.
- Future experiments and simulation capabilities.

Key Scientific Issues

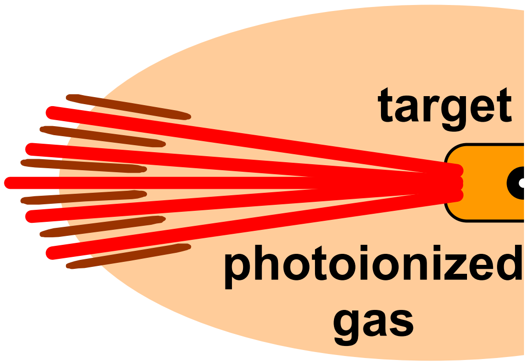
- Develop compact ion sources and injectors with necessary brightness and current (1A).
- Accelerate and transport heavy ion beams quiescently to several GeV at very high space-charge intensities and currents (several kA).
- Focus and transport intense ion beams in the target chamber to small spot size (several mm).
- Optimize fusion targets with necessary gain and hohlrahm symmetry, suitable for mass production, and robust to beam aiming errors.
- Develop attractive fusion chamber concepts (e.g., neutronically thick, liquid flows) that minimize materials development needs.

Key Physics Issues Affecting High-Intensity Ion Beam Propagation

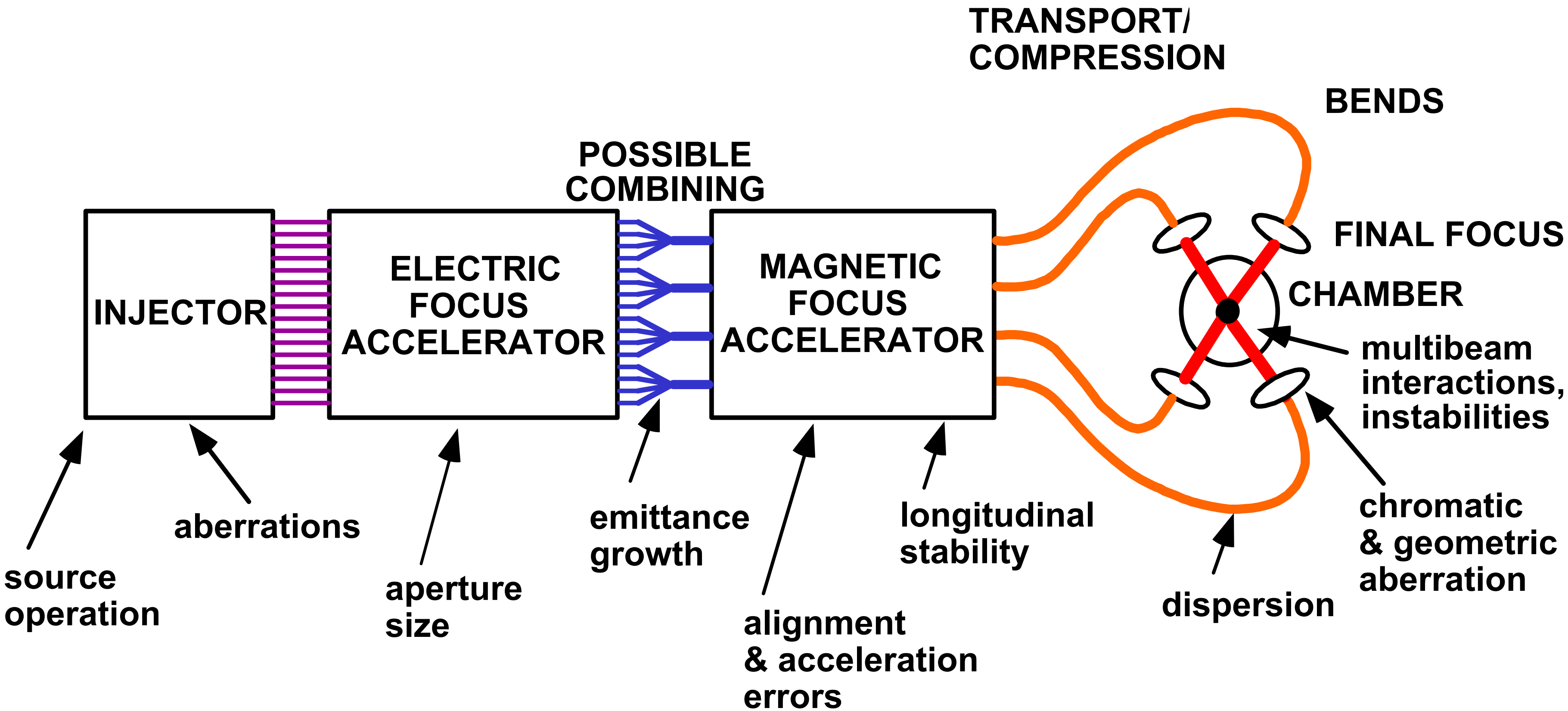
- **In accelerator and transport systems:**
  - Quality of injected beam
  - Emittance growth
  - Halo generation
  - Possible instabilities
  - Stray electrons
  - Multiple beam effects



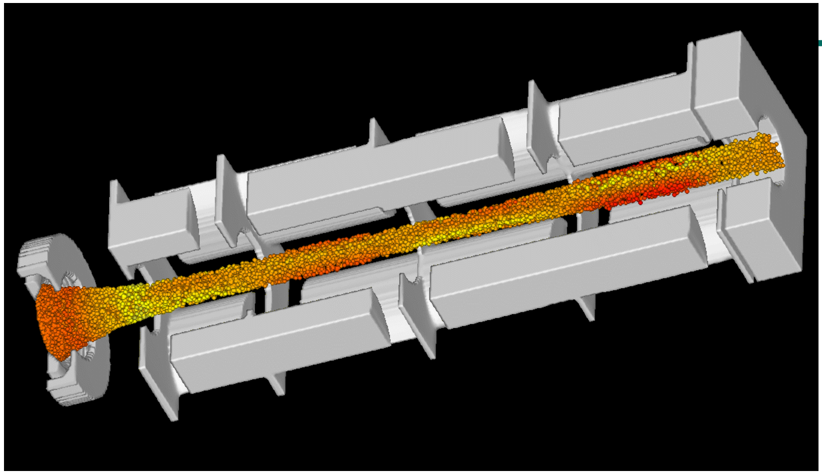
- **In fusion chamber:**
  - Focusing aberrations
  - Ionization of beam and background gas
  - Beam charge neutralization
  - Possible plasma instabilities
  - Self-magnetic and inductive effects
  - Multiple beam effects



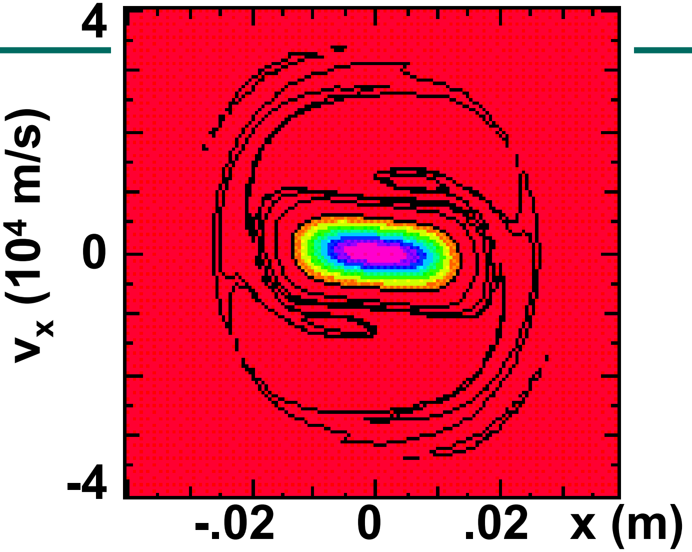
Some of the Technical Issues in a Heavy Ion Fusion System



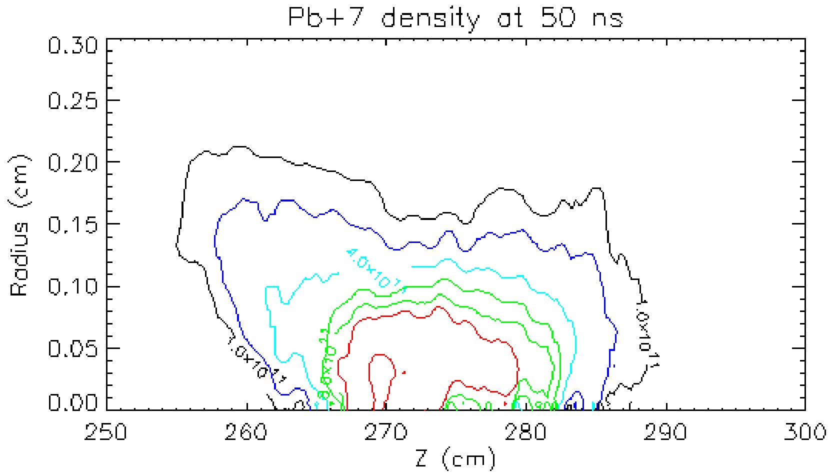
Simulation Tools are Used to Resolve a Wide Range of Scientific Issues



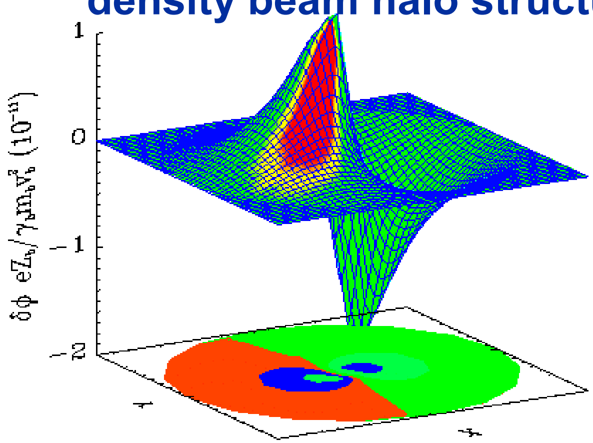
WARP3d PIC simulations quantify nonlinear beam dynamics in electrostatic quadrupole injector



Vlasov code SLV reveals low-density beam halo structure

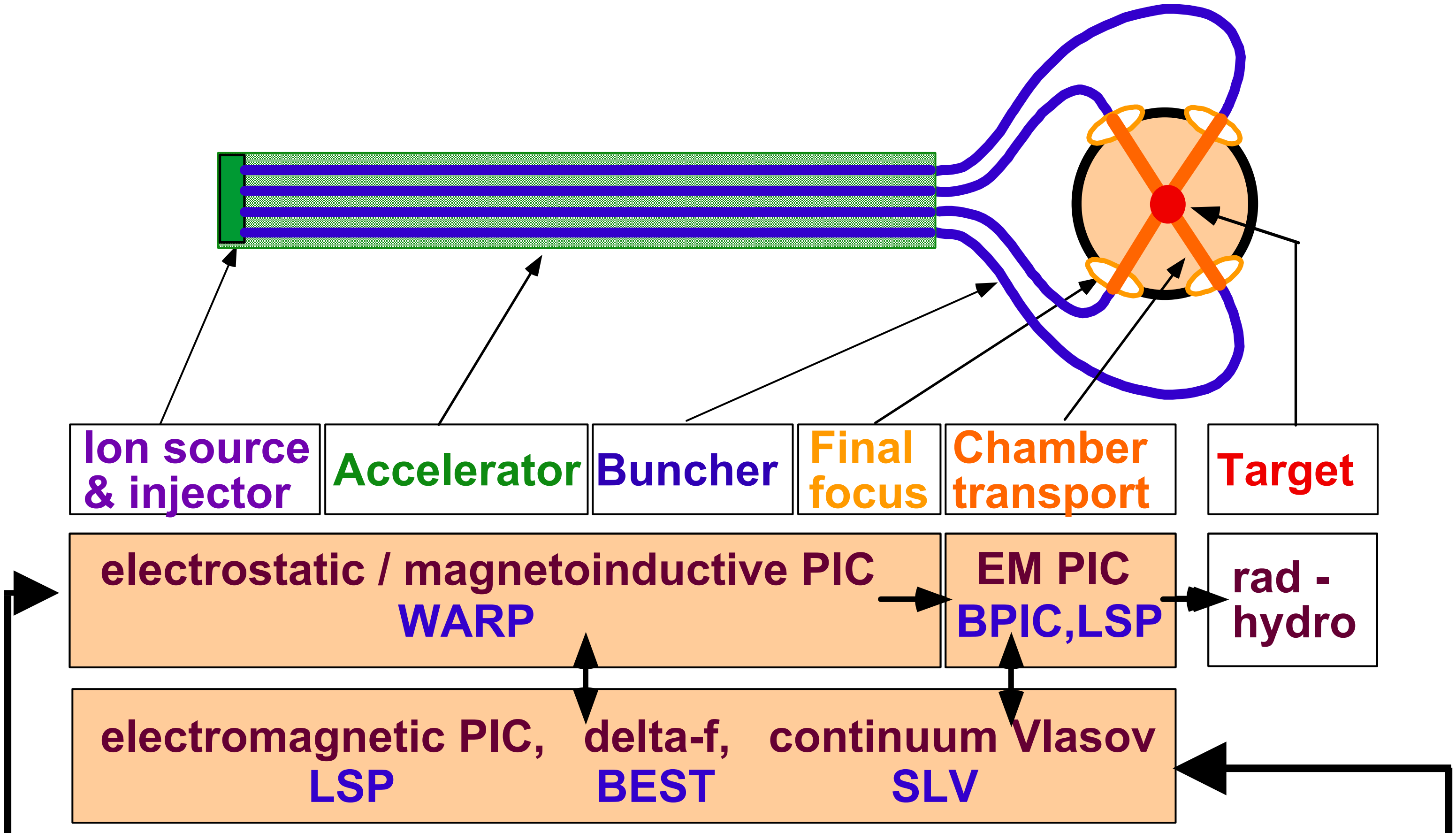


LSP PIC simulation of neutralized ballistic transport shows Pb^{+7} ions focusing to a 2 mm spot



3-D δf code BEST shows structure of two-stream dipole mode

Our goal is an integrated, detailed,and benchmarked source-to-target beam simulation capability

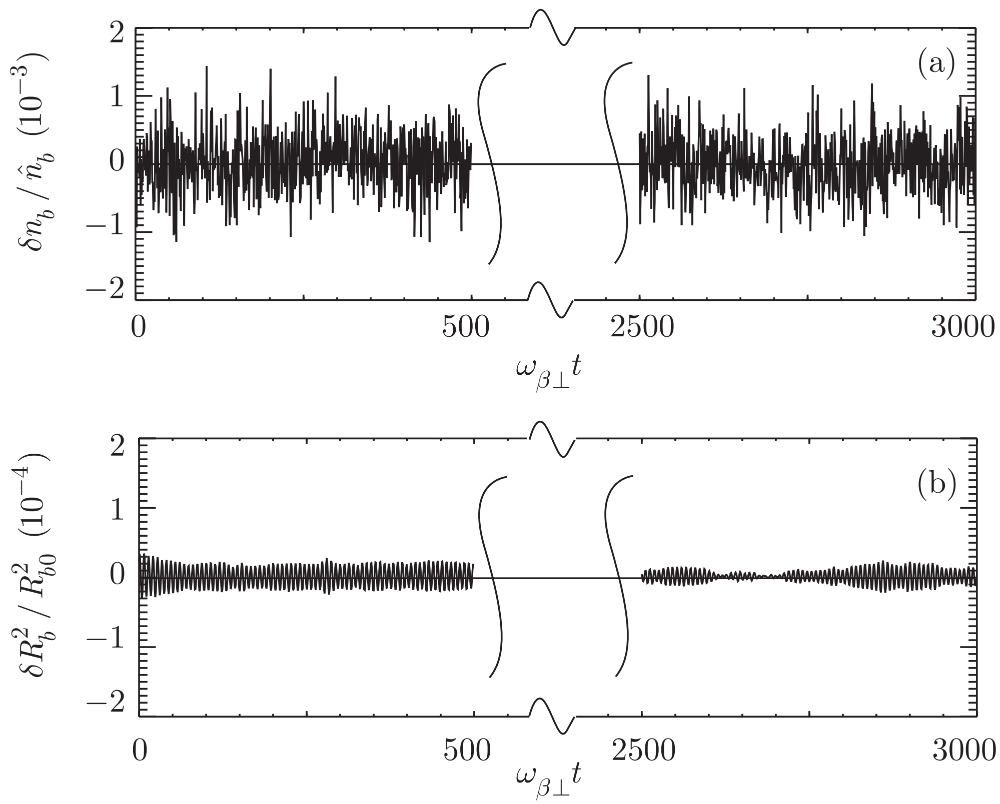


- Track beam ions consistently along entire system.
- Study instabilities, halo, electrons, …, via coupled detail models.

The BEST Code

Application of the 3D multispecies nonlinear δf simulation method to the two-stream instability is carried out using the Beam Equilibrium Stability and Transport (BEST) code.

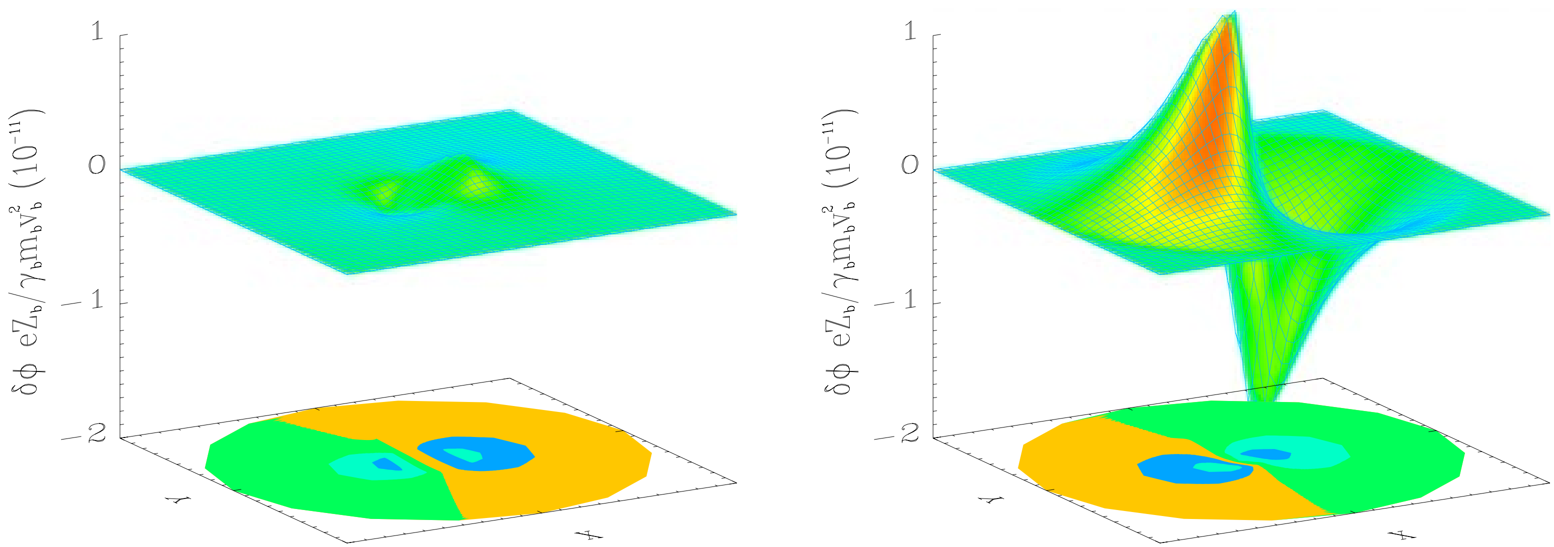
- Adiabatic field pusher for light particles (electrons).
- Solves Maxwell's equations in cylindrical geometry.
- Written in Fortran 90/95 and extensively object-oriented.
- NetCDF data format for large-scale diagnostics and visualization.
- Achieved an average speed of 40μs/(particle$\times$step) on a DEC alpha personal workstation 500au computer.
- The code has been parallelized using OpenMP and MPI.
  - NERSC: IBM-SP2 Processors.
  - PPPL: Dec-α Processors.
- Achieved 2.0×10^{10} ion-steps + 4×10^{11} electron-steps for instability studies.



➪ BEST simulation results show that beam propagates quiescently over large distances, which agrees with the nonlinear stability theorem for the choice of thermal equilibrium distribution function.

BEST Simulation of Two-Stream Instability

➪ When a background electron component is introduced with $\beta_e = V_e/c \simeq 0$, the $l = 1$ dipole mode can be destabilized for a certain range of axial wavenumber and a certain range of electron temperature T_e.



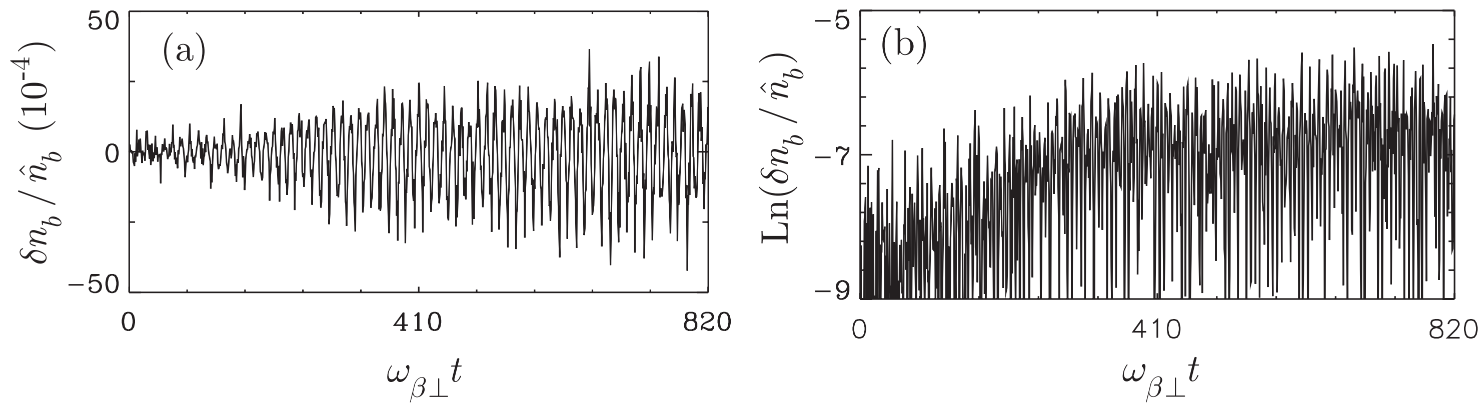
(a) $t = 0$ (b) $t = 200/\omega_{\beta\perp}$

➪ Linear growth phase shows strong dipole mode structure.

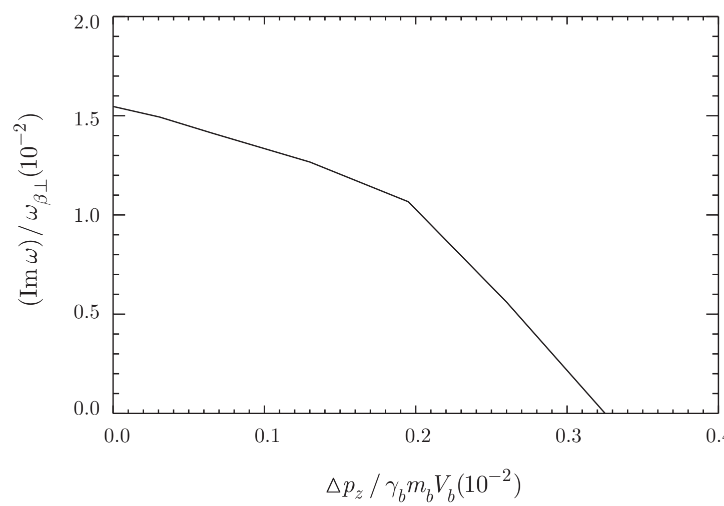
➪ Two-stream instability can be stabilized by modest axial momentum spread of beam ions.

BEST Simulation of Two-Stream Instability

- Nonlinear perturbation saturation level $\delta n_b \sim 3.0 \times 10^{-3} \hat{n}_b$.



- The maximum linear growth rate $(Im\omega)_{max}$ of the electron-proton instability decreases as the axial momentum spread of the beam ions increases.

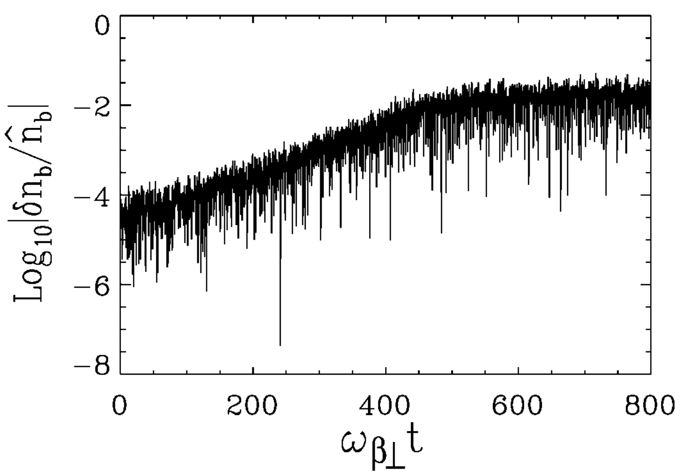


Large Temperature Anisotropies ($T_{\perp b} >> T_{\parallel b}$) Develop Naturally in Accelerators

- For a beam of charged particles with charge q accelerated through a voltage V, the parallel temperature decreases according to

$$T_{\parallel f} = T^2_{\parallel i} / 2qV$$

- The transverse emittance and perpendicular temperature $T_{\perp b}$ can also increase relative to $T_{\parallel b}$ due to nonlinearities and mismatch.
- Free energy is available to drive a Harris-like instability which may lead to a deterioration of beam quality.



Assume axisymmetric perturbations.

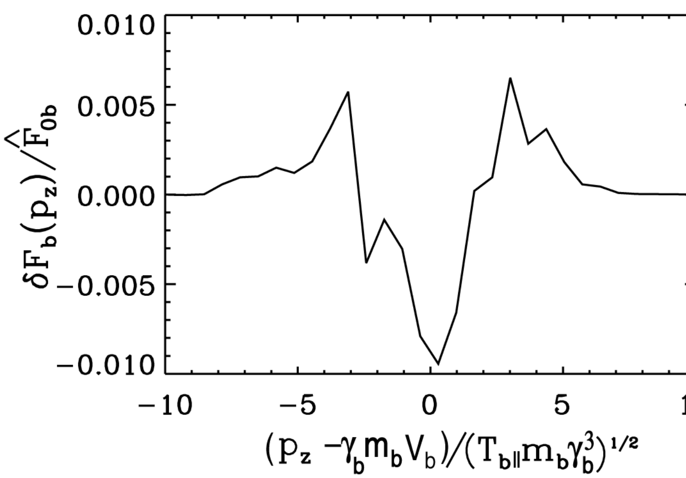
Assume $T_{\parallel b} / T_{\perp b} = 0.04$ and $r_w / r_{beam} = 3$.

Low-noise properties of the BEST code allow one to follow the linear and nonlinear growth through saturation at the level $|\delta n_b^{max} / \hat{n}_b| \cong 0.05$.

Onset and Saturation of the Instability

- Plot shows the net change in the longitudinal momentum distribution $\delta F_b(p_z)/\hat{F}_{0b}$, where

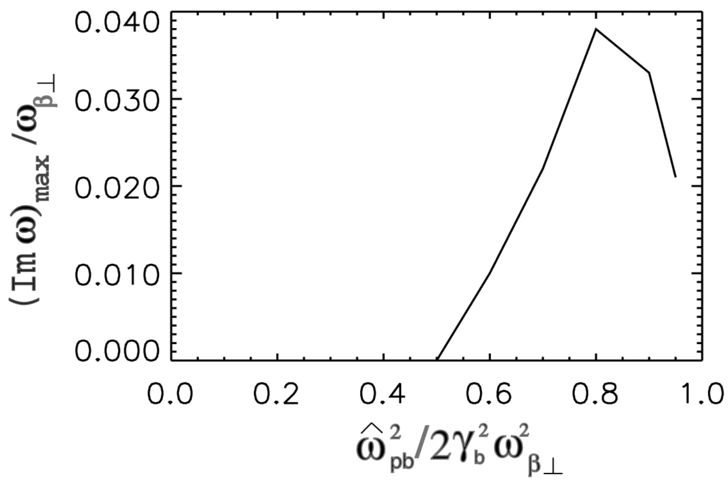
$$\delta F_b(p_z) = \int d^2p_\perp d^3x \delta f_b, \quad \hat{F}_{0b} = \hat{n}_b / (2\pi\gamma_b^3 m_b T_{\parallel b})^{1/2}.$$



- The formation of tails in the axial momentum distribution and the consequent saturation of the instability are attributed to resonant wave-particle interactions.

- The maximum growth rate $(\mathrm{Im}\omega)_{max}/\omega_{\beta\perp} \cong 0.038$ occurs for $s_b = \hat{\omega}_{pb}^2/2\gamma_b^2\omega_{\beta\perp}^2 \cong 0.8$, with no instability in the region $s_b \leq 0.5$.

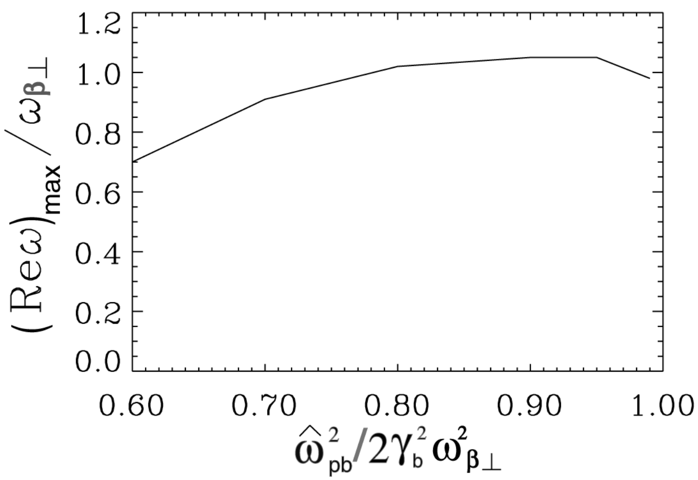
- The instability is found to be absent if $T_{\parallel b}/T_{\perp b} > 0.07$.

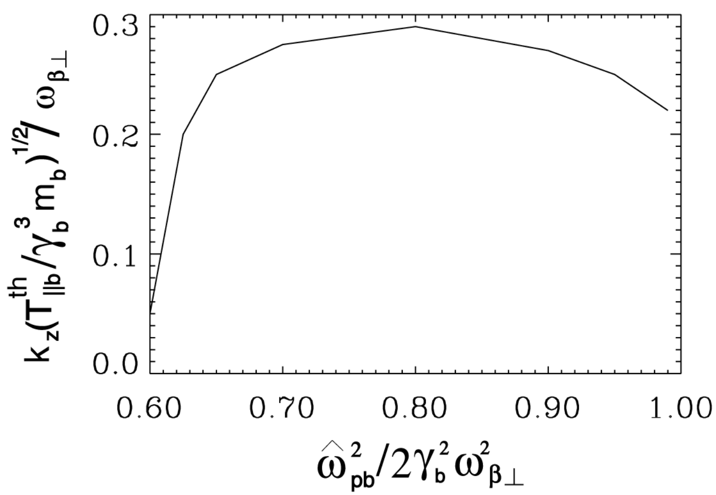


Instability Threshold

- The instability is stabilized by formation of a tail in the longitudinal momentum distribution and the consequent Landau damping of the wave excitations.
- The final width of the longitudinal velocity distribution can be estimated as $\Delta v_{\|} \cong | v_{ph} - V_b |$, where $v_{ph} = \omega / k_z$.
- The growth rate $\gamma(T_{\| b} = 0)$ for $T_{\| b} = 0$ can be estimated as

$\gamma(T_{\| b} = 0) \cong k_z (T_{\| b}^{th} / \gamma_b^3 m_b)^{1/2}$, where $T_{\| b}^{th}$ is the threshold temperature for stabilization.

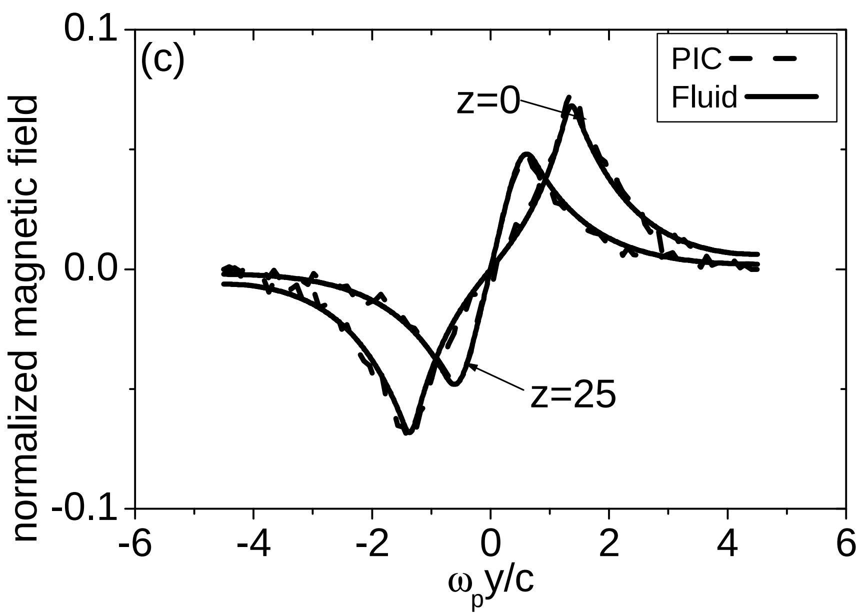




Multiple descriptions of beam propagation in plasma

1. **Fully electromagnetic relativistic PIC code.**
2. **Semi-analytical mode for long beams** $l_b \gg r_b$
   - **Electron fluid description.**
   - **Assumption of conservation of generalized vorticity.**

I. Kaganovich, et. al., Phys. Plasmas **8**, 4180 (2001).

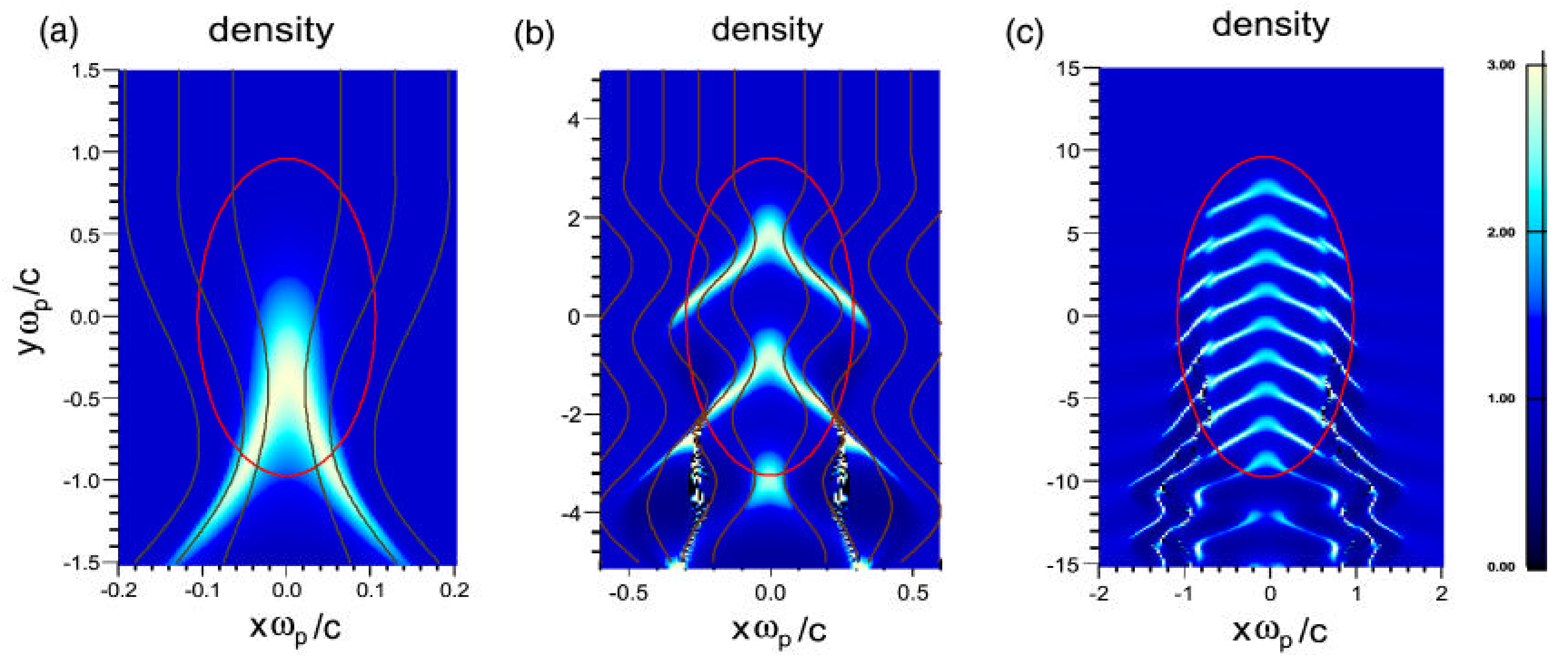


Comparison of models for system parameters:

n_b=n_p , b_b=0.5,

l_b= 30c/w_p , r_b= 1.5c/w_p .

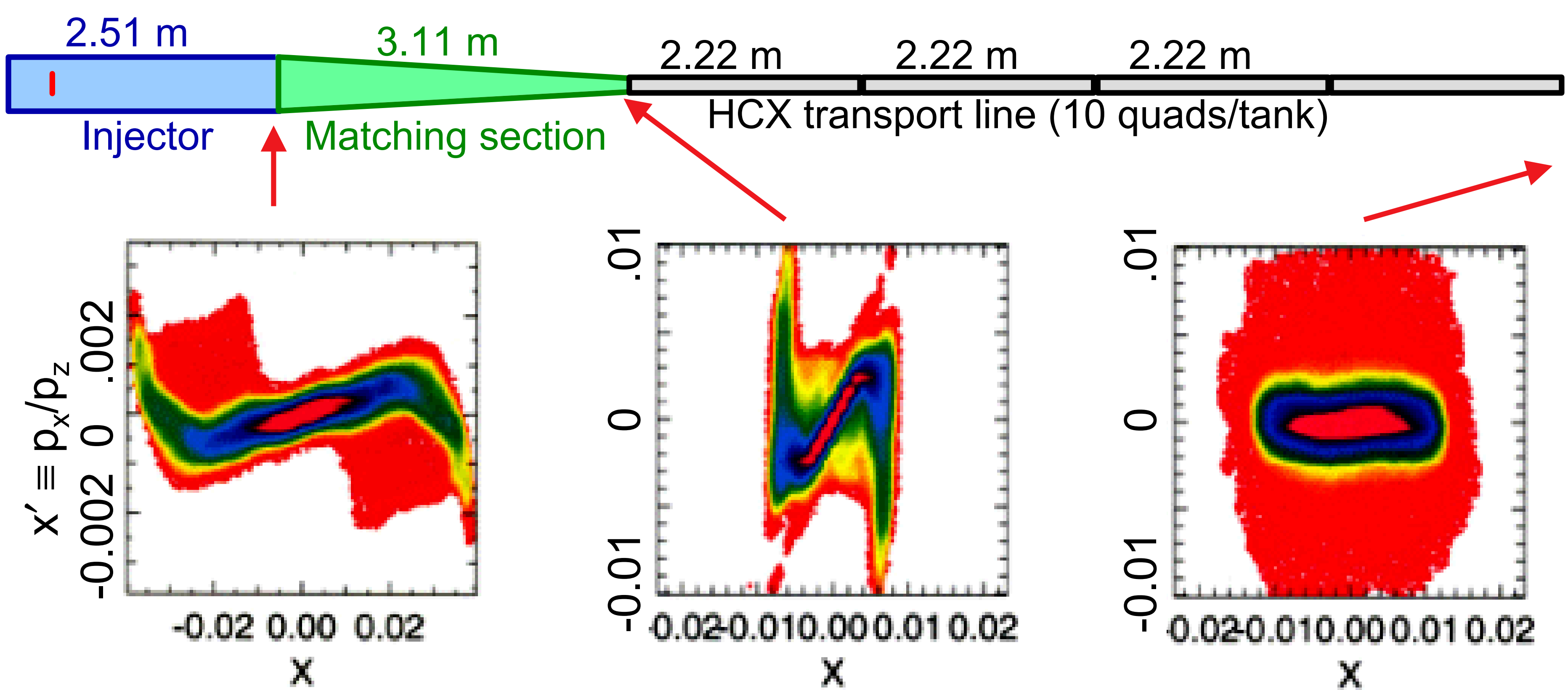
Analytic theory of chamber transport: excitation of plasma waves by beam depends on bunch length



b_b=0.5, l_b/r_b =10, n_b/n_p=0.5 a) l_b= 1c/w_p , b) l_b= 3c/w_p , c) l_b= 10c/w_p .

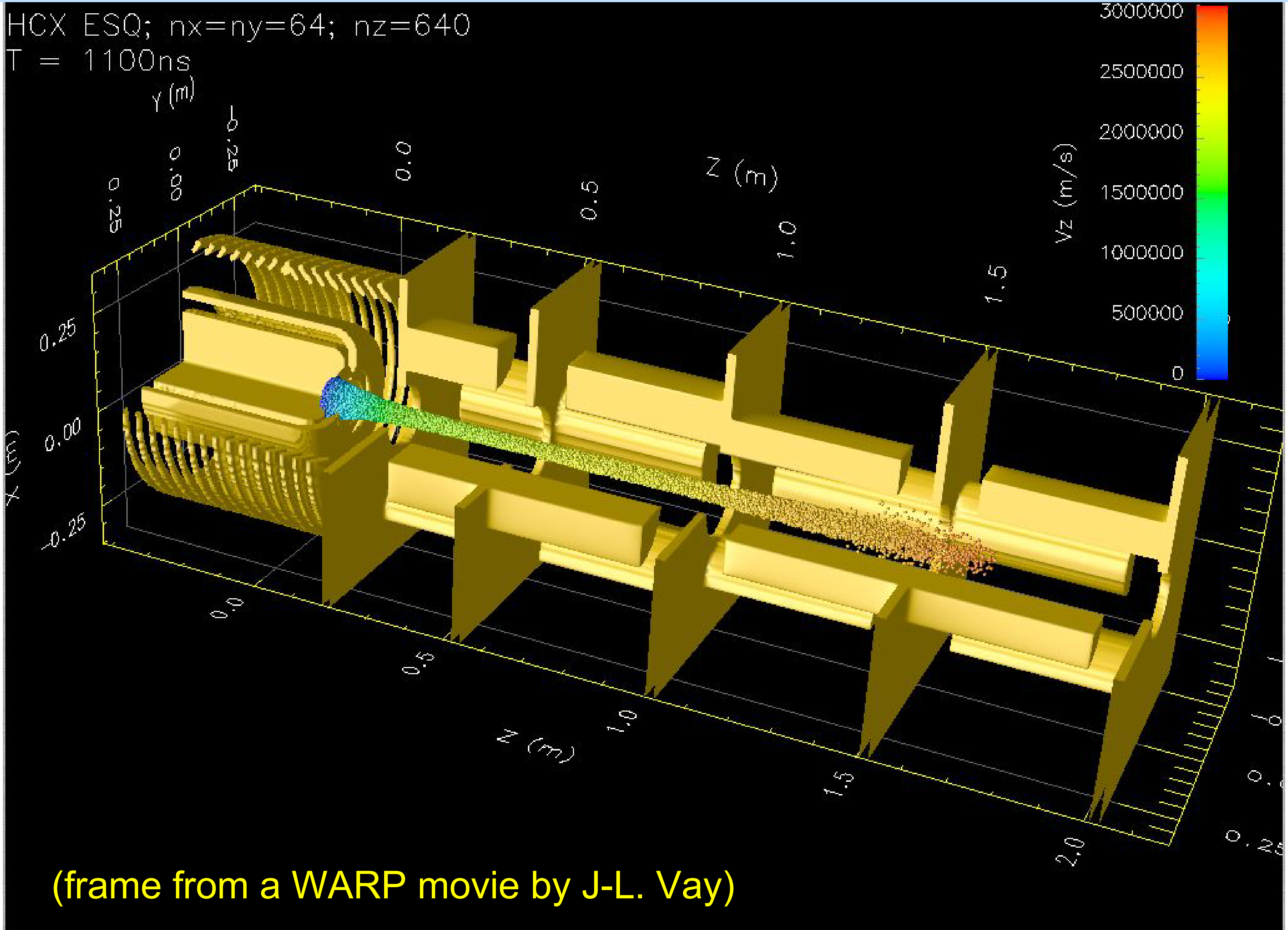
Red line: ion beam size, brown lines: electron trajectory in beam frame

Self-consistent simulations of HCX use WARP3d in injector, and WARPxy in matching section and transport line



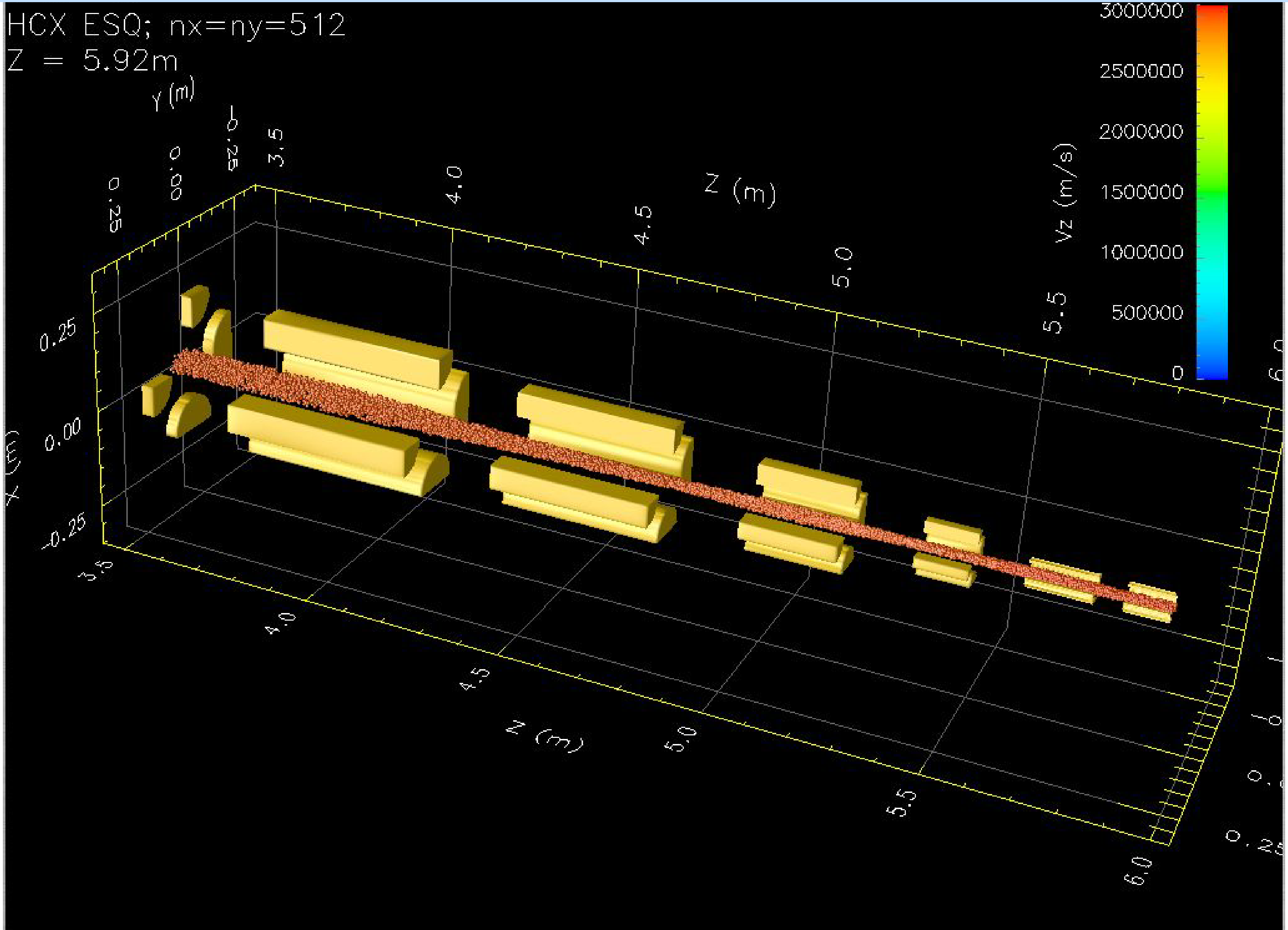
End of injector **End of matching section** **50 lattice periods (100 quads) past matching section**

Time-dependent 3d simulations of ESQ injector show effect of voltage rise-time on beam head

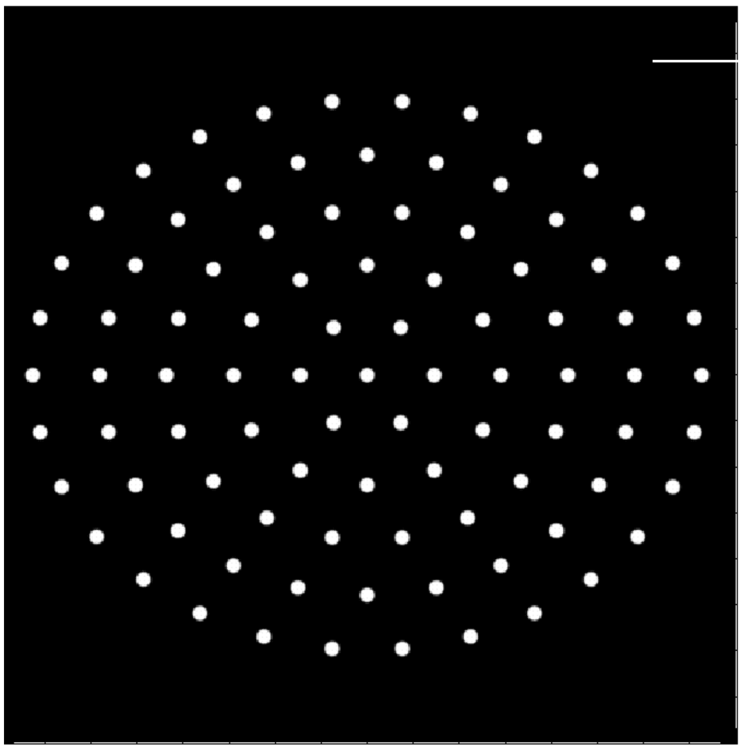


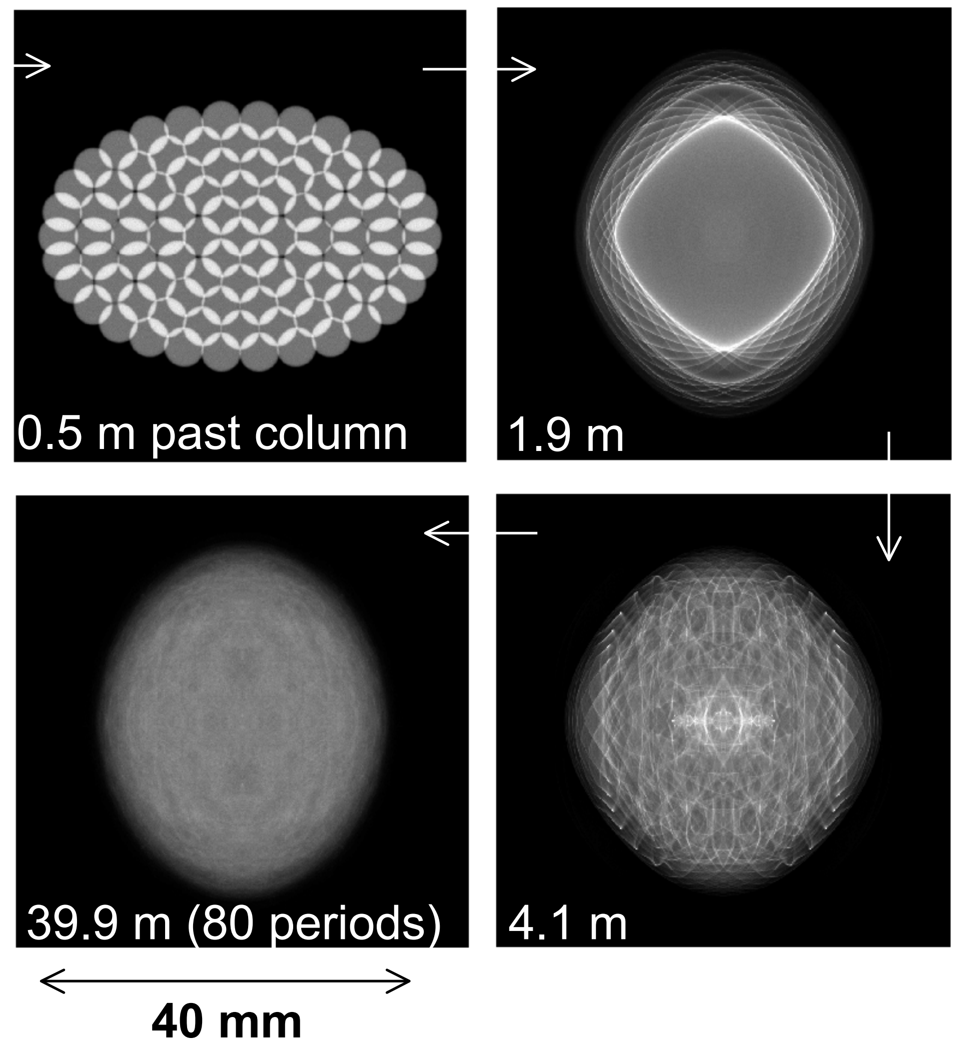
(frame from a WARP movie by J-L. Vay)

Matching section compresses beam significantly before it enters the HCX transport line



Simulation of multi-beamlet merging





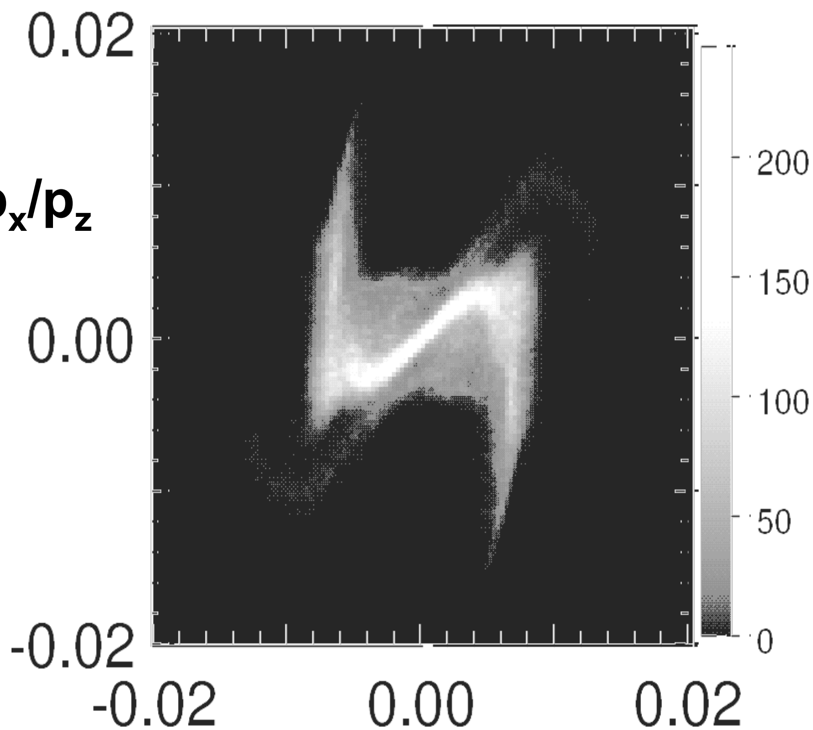
91 semi-Gaussian beamlets (each 0.006 A, 0.003 π-mm-mr), 1.2-1.6 MeV; 29 M particles, 1024x1024 grid, 4000 steps, 18.2 hrs on 64 IBM SP proc's

(frames from a WARP movie)

Simulations of two injector approaches: similar emittances, qualitatively different phase spaces

ESQ injector (555 mA)

(at end of matching section)

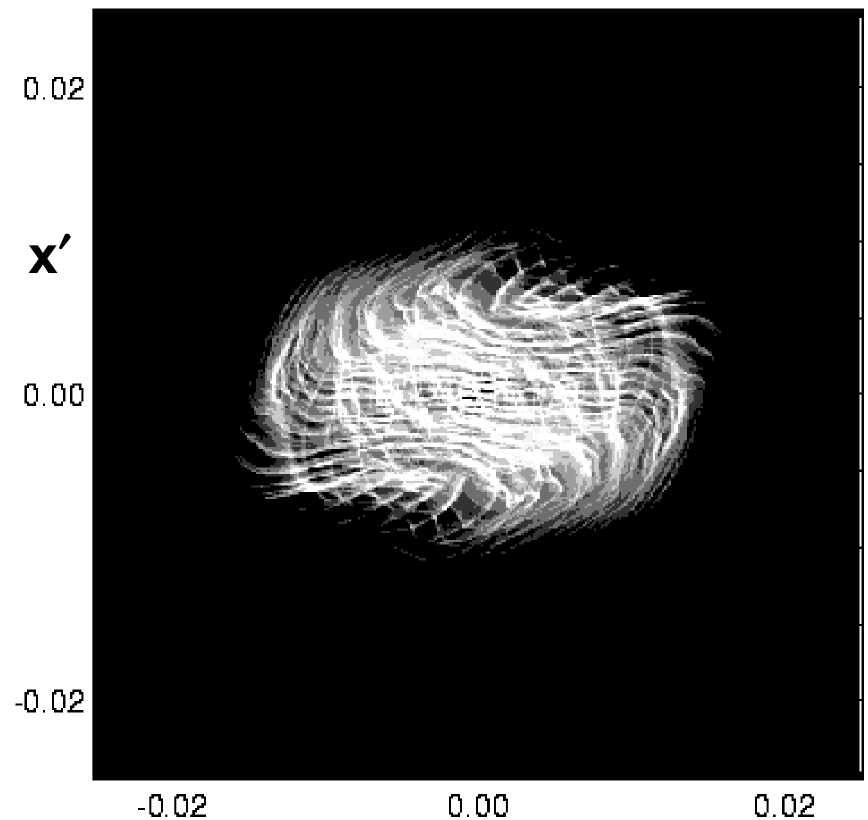


$x' \equiv p_x/p_z$

x (m)

Merging-beamlets (572 mA)

(4.1 m past end of Pierce columns)



x′

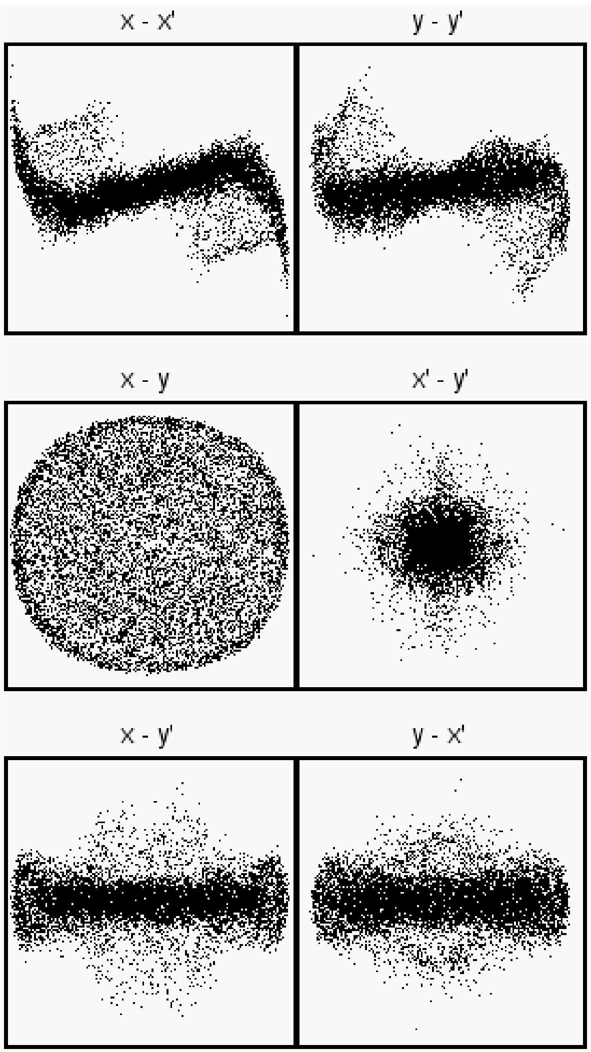
x (m)

We are developing methods for initiating particle simulations using experimental slit-scan data

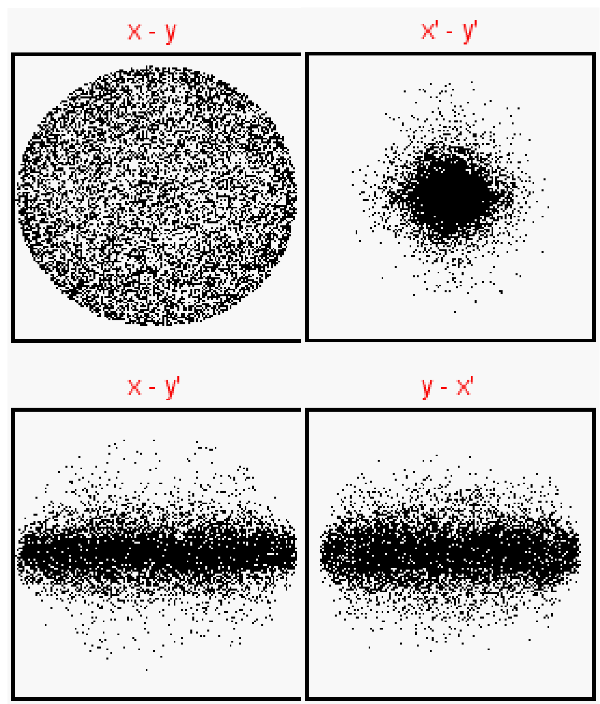
The 4D transverse distribution $f(x,y,p_x,p_y)$ is not uniquely determined by a small number of 2D scans ⇒

must "synthesize" using heuristic methods

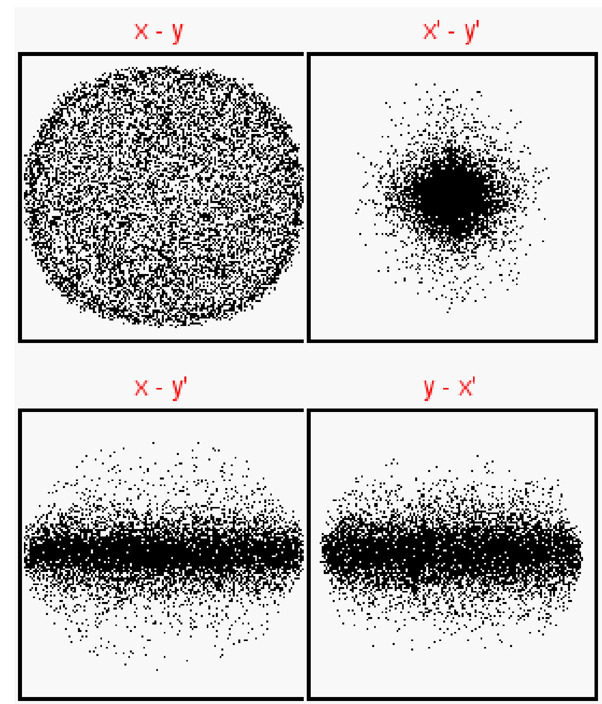
self-consistent 3D simulation, at injector exit



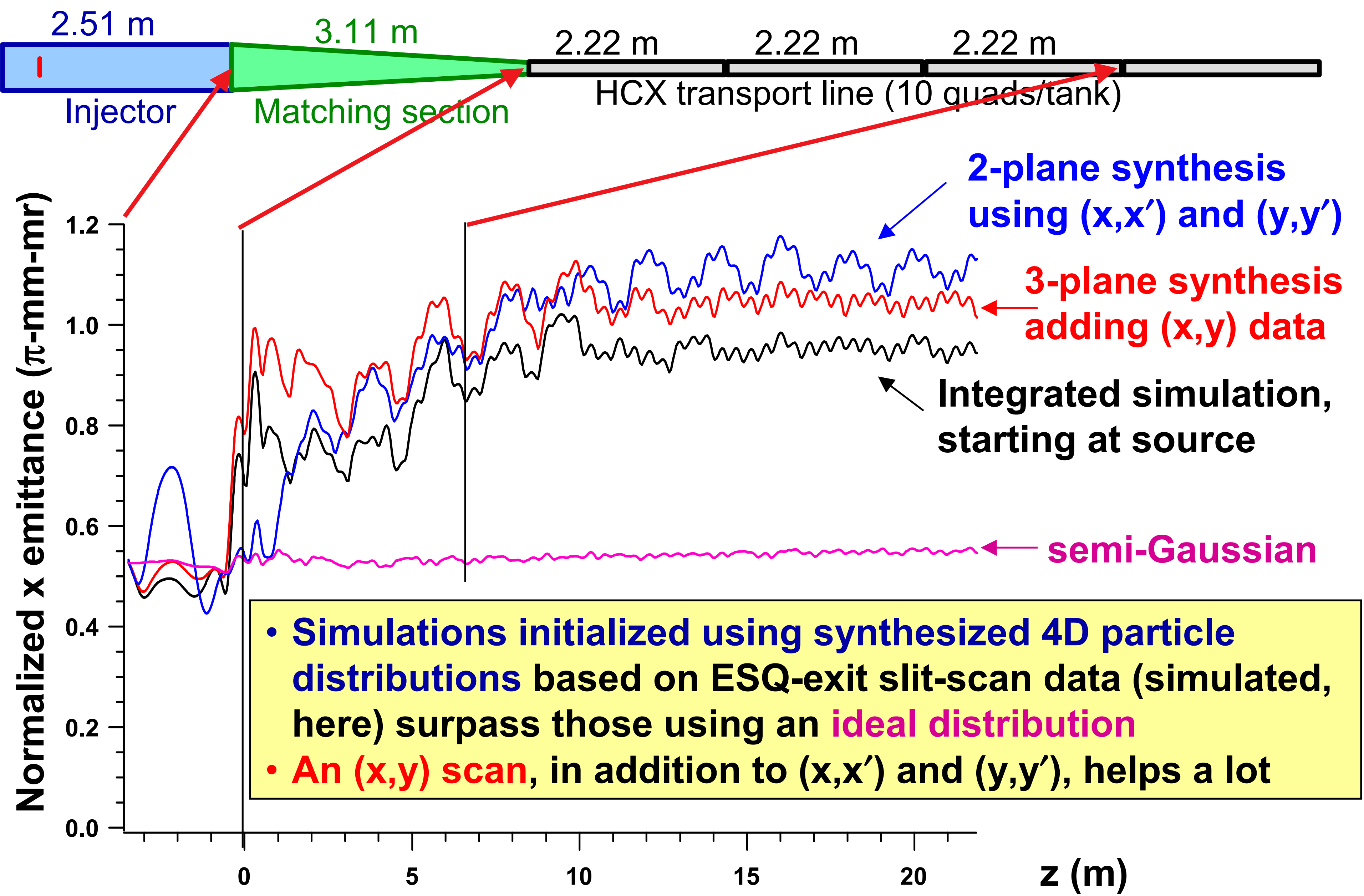
2-plane synthesis using (x,x′) & (y,y′) data



3-plane synthesis using (x,x′), (y,y′), & (x,y) data

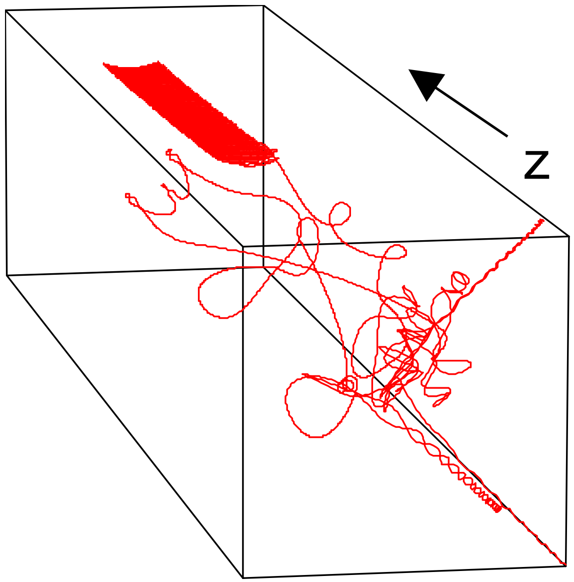


We are using simulations to learn what data we need to take, and how best to use the data we obtain



- **Simulations initialized using synthesized 4D particle distributions based on ESQ-exit slit-scan data (simulated, here) surpass those using an ideal distribution**
- **An (x,y) scan, in addition to (x,x′) and (y,y′), helps a lot**

Studies of stray-electron orbits in HIF accelerators offer guidance to driver design



- Electrons born in magnetic quadrupoles drift out ends
- Acceleration backwards through an induction gap provides enough energy to escape ion beam potential
- Electron lifetime ~ time to drift through a quad

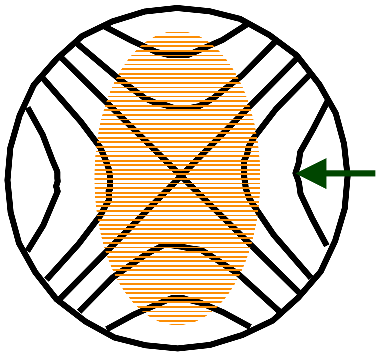
Effects: beam defocusing, deflection, e-i two-stream instability

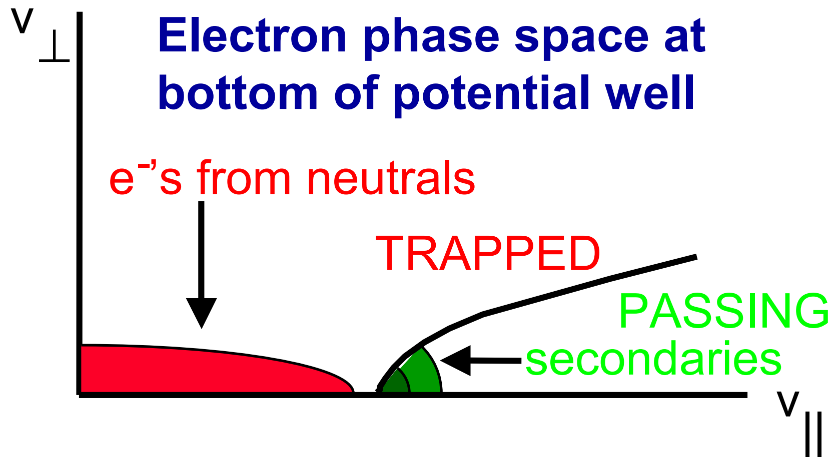
Mitigation approaches:

- avoidance: well-matched beam in good vacuum
- halo limiters / surface sculpting (to force normal incidence)
- surface treating / cleaning
- large apertures
- clearing electrodes or rf fields
- limitation of pulse duration

See presentation by Molvik, et. al.

We are using analytic theory and simulations to study sources, sinks, and dynamics of electrons





$n_e = n_e$(beam-gas) + ion flux to wall $\times$ e^-'s per incident ion $\times$ e^- lifetime

- beam halo
- charge exchange
- scattering

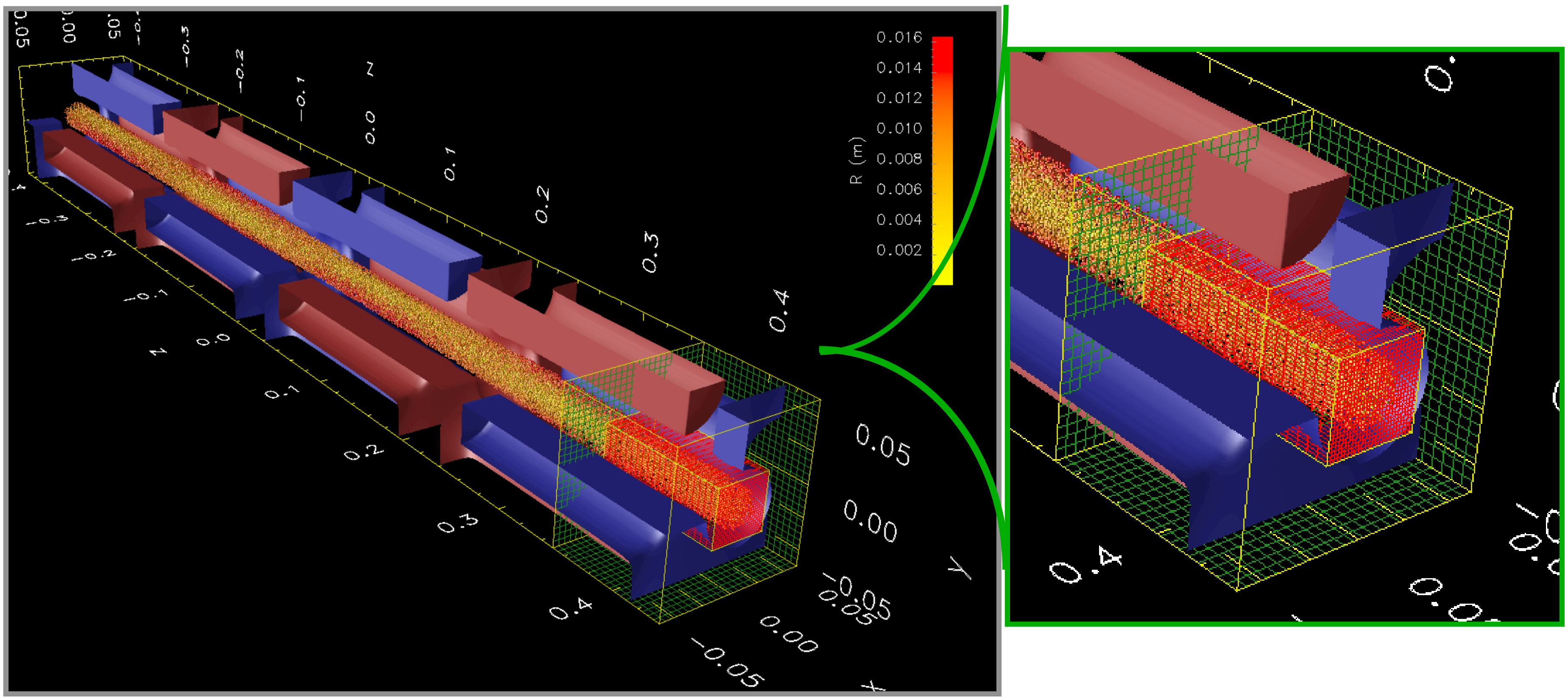
- secondaries
- ionization of neutrals from wall

- trapping
- detrapping
- pulse duration

Experiments on HCX exploring these issues are planned to begin this summer

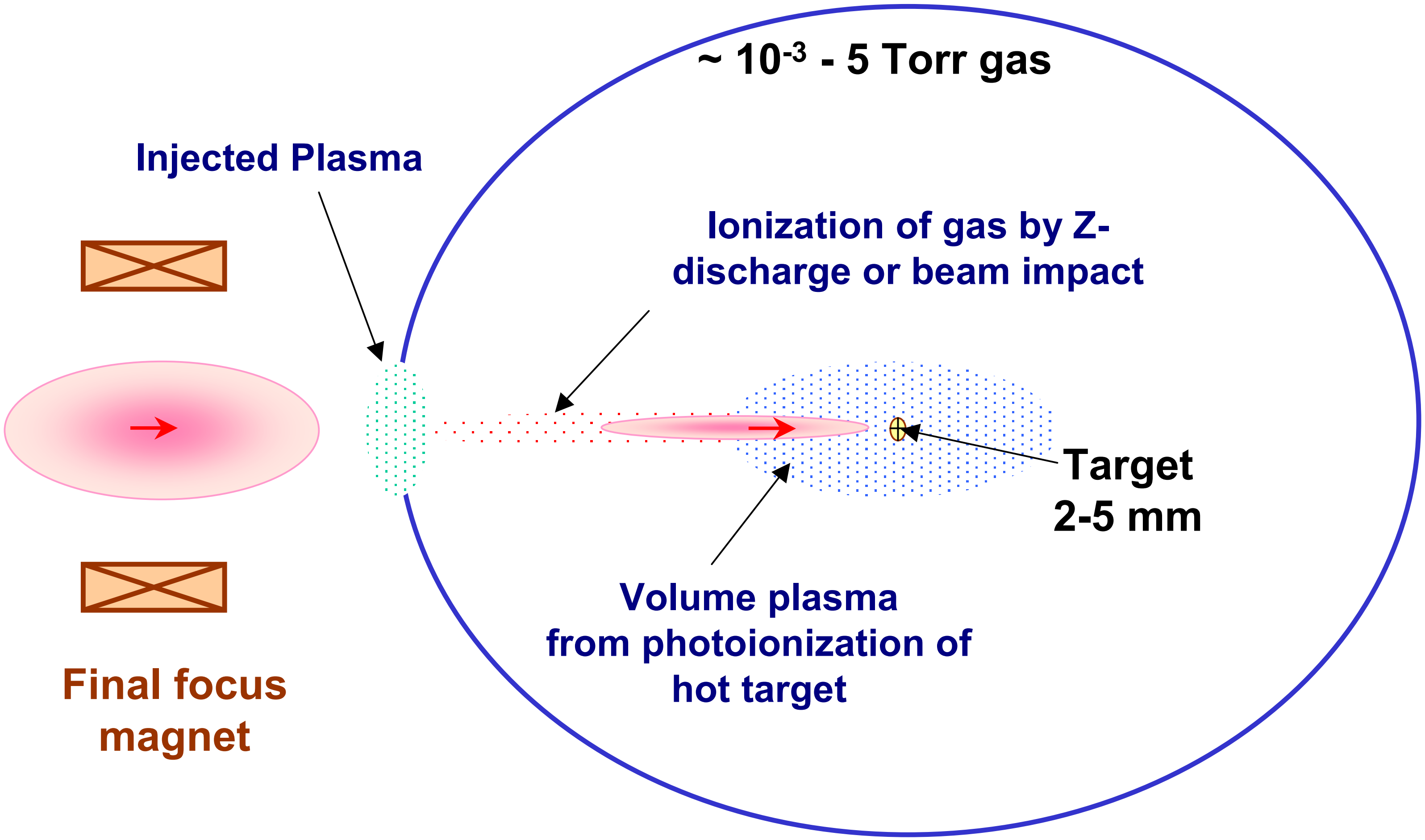
Part of the future: Adaptive Mesh Refinement in WARP

- Must resolve Debye length in beam; mesh refinement offers a “better, cheaper, faster” field solution
- If strong non-uniformities develop, AMR can dynamically resolve them



See presentation by Vay, et. al.

Some neutralization is required in chamber for high perveance beams



LSP code* simulates both neutralized ballistic and self-pinched transport

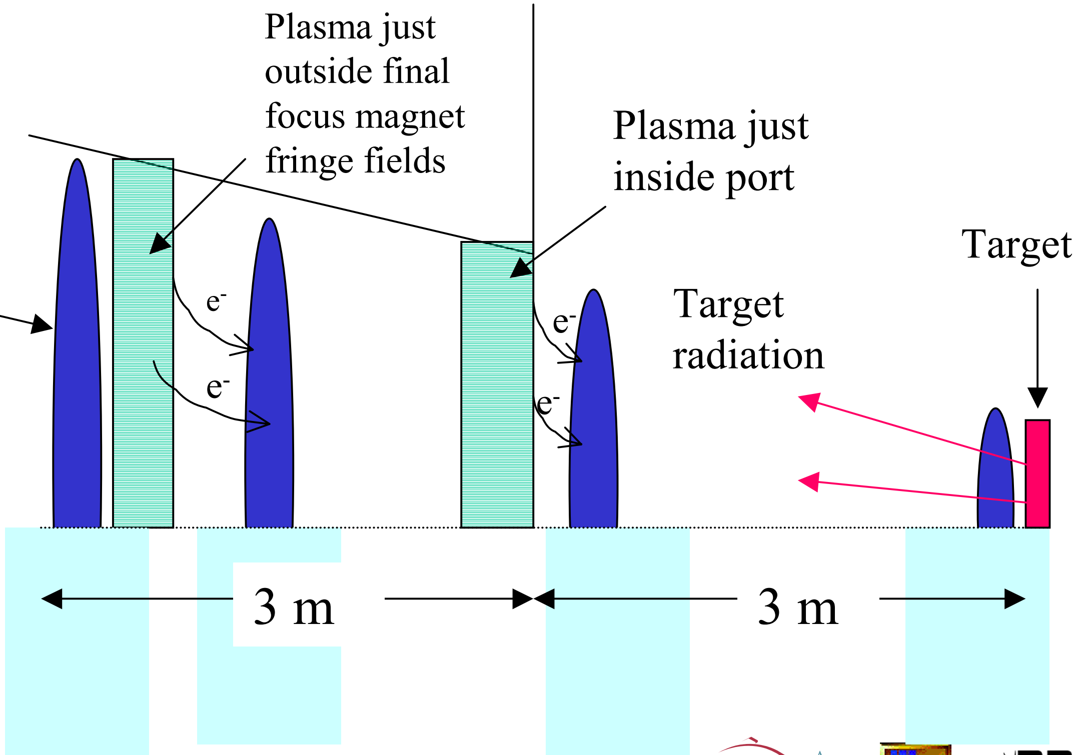
- 1D, 2D and 3D particle-in-cell and cloud-in-cell.
- Energy-conserving electromagnetic and electrostatic algorithms.
- Hybrid fluid-kinetic descriptions for electrons with dynamic reallocation for dense plasma simulation.
- Particle interactions include: scattering, energy transfer, ionization, stripping and charge-exchange.
- Cold plasma initialization; target-photon ionization/stripping.
- Surface physics includes Child-Langmuir emission, surface heating, neutral thermal/simulated desorption.

*See D. R. Welch, et al., Nucl. Instr. and Meth. Phys. Res. A **464**, 134 (2001).

LSP neutralized ballistic transport simulation with plasma pre-neutralization

- 6-m long, 2-plasma foot (in progress) and main pulses
- Including time-dependent photoionization and stripping for main pulse.

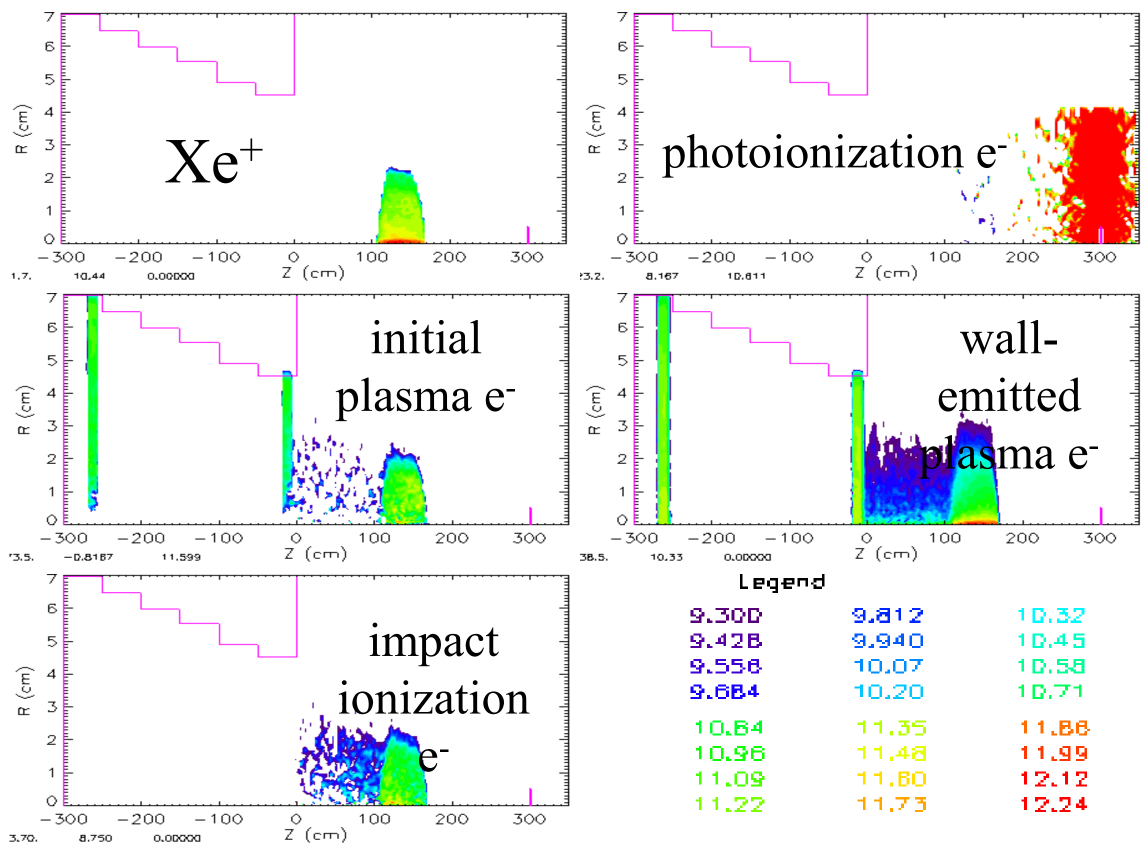
2.5-GeV, 2.8- kA Xe^{+} beam



$7x10^{12}$ cm^{-3} neutral flibe density at t=0 (in chamber) can be ionized and cause beam stripping.

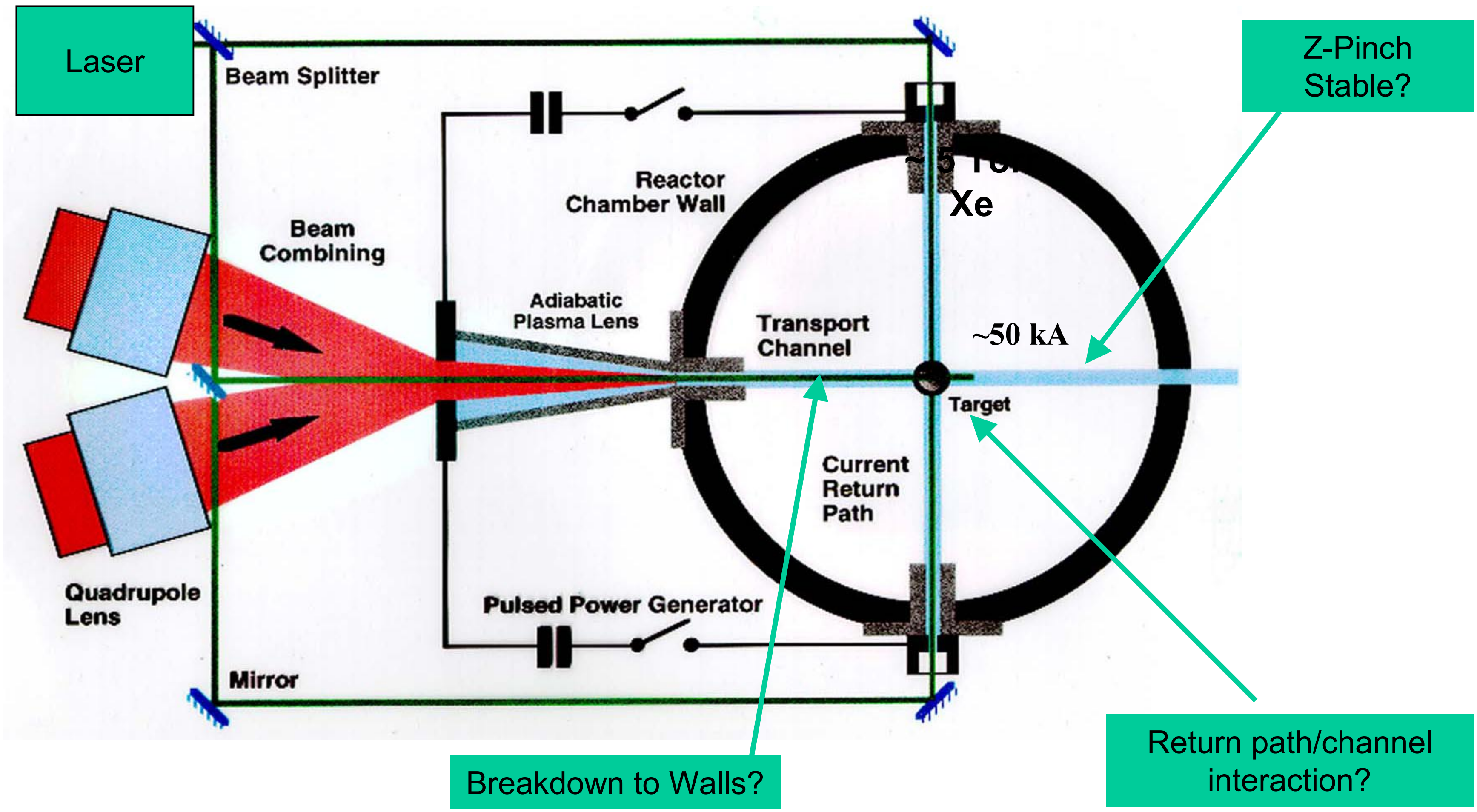
Xe ion beam is neutralized by several electron sources

Log of species density 80 ns into the LSP simulation



< 3-mm focal spot relevant to D.Callahan distributed radiator target.

Assisted pinched transport can reduce chamber focus requirements - backup to neutralized ballistic transport



IPROP simulations have been begun evaluating assisted pinched transport for HIF

- IPROP is a quasi - 3D electromagnetic hybrid code.
  - Code description: D. R. Welch, et al., Phys. Plasmas **1**, 764 (1994).
  - 2 D fluid model for the plasma, PIC beam ions.
  - Ohm's law, $J_e = \sigma_e(\nabla p_e/n_e - \mathbf{v_i}\nu_m + \mathbf{E} + \mathbf{v}\times\mathbf{B})$
  - Initial discharge conditions:
    - D. M. Ponce, Nucl. Instr. and Meth. Phys. Res. A **464**, 331 (2001).

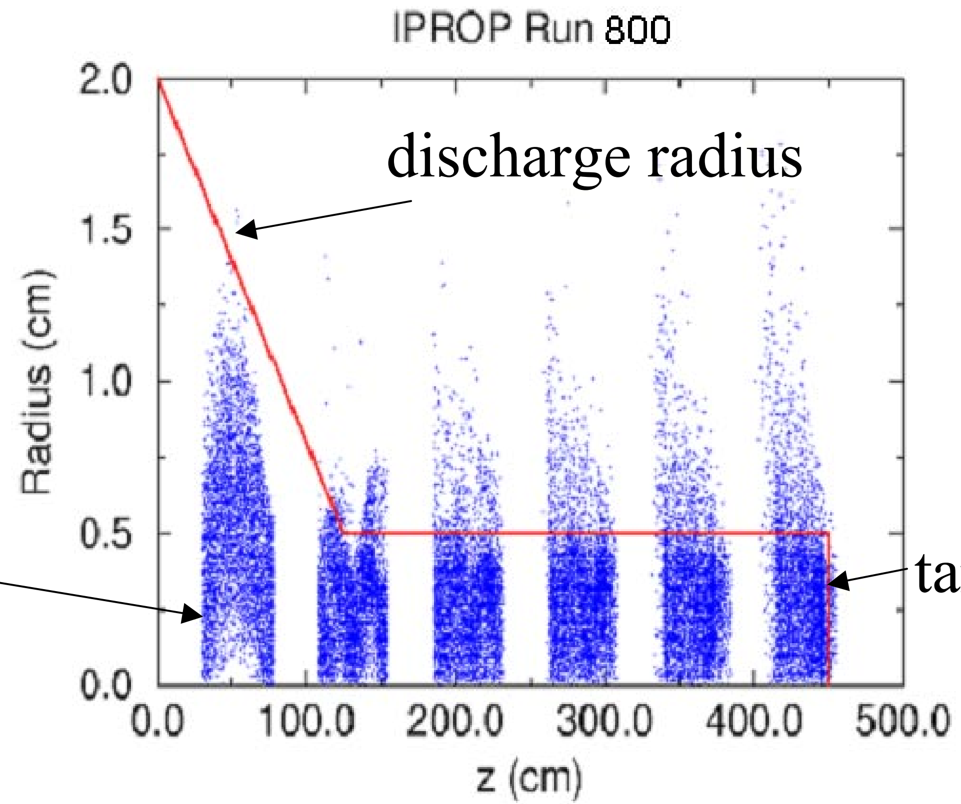
Mission Research Corporation

IPROP calculates 87% energy transport, 3.5mm rms beam radius for assisted pinched transport

Initial discharge conditions.

- 50-kA discharge.
- 5 Torr, 3 eV ambient Xe.
- 0.5 Torr reduced density within discharge.

4-GeV, 6 MA Pb^{+72} ion beam injection

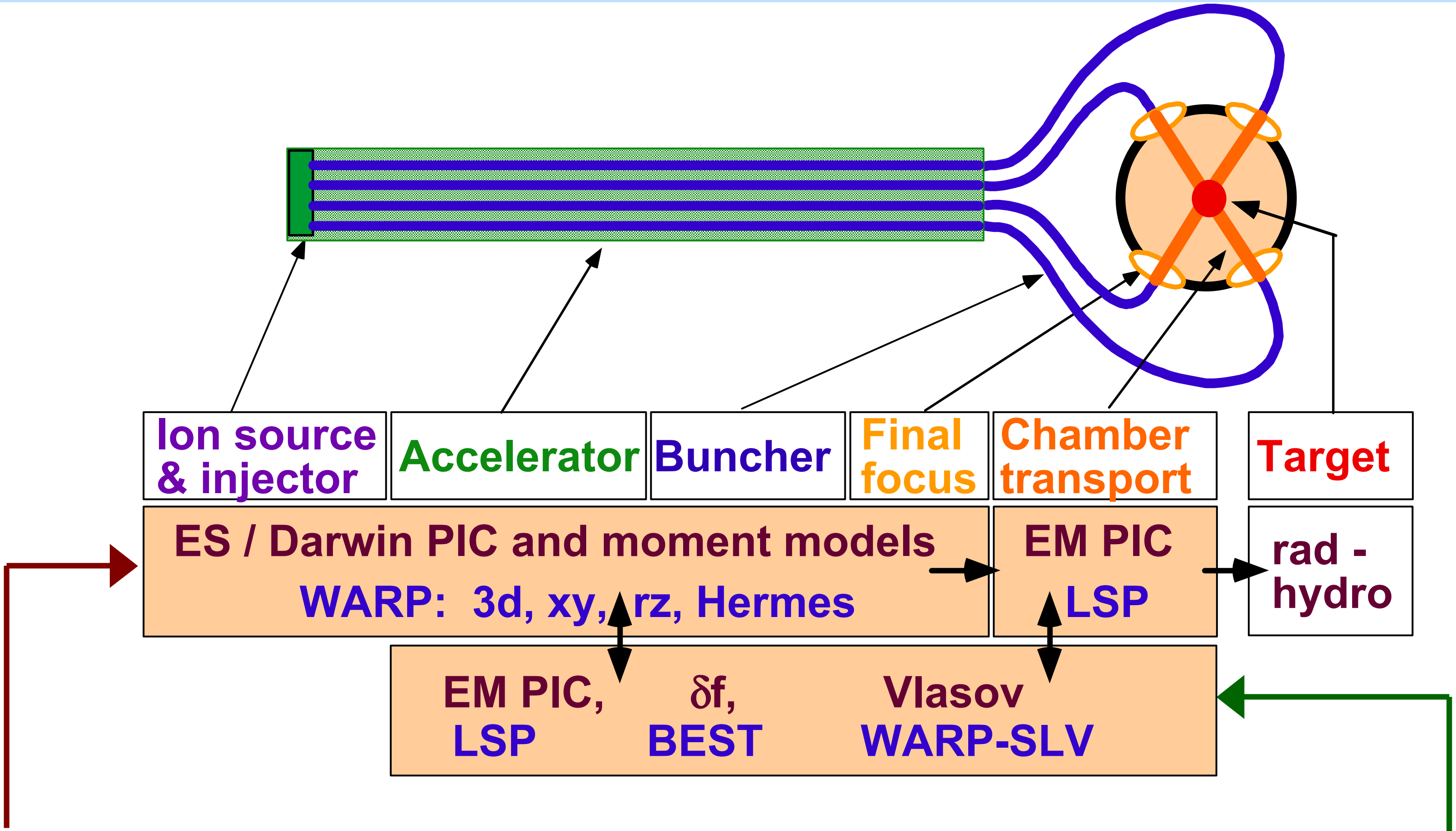


3D simulations show m=1 instability weak

Conclusions

- State of theory for neutralized beam transport is the most mature - LSP simulations suggest plasma produced by photoionization greatly improves transport.
- Assisted pinched transport results are sensitive to gas conductivity:
  - Present IPROP simulations calculate decay length sufficient to suppress deleterious self-field effects.
  - Need better models of gas atomic physics, anomalous resistivity.

We are working toward an *integrated*, *detailed*, and *benchmarked* source-to-target beam simulation capability



Track beam ions consistently along entire system

Study instabilities, halo, electrons, ..., via coupled detailed models

Systems code IBEAM for synthesis, planning

Other Related Symposium Papers

Friedman – Slit-scan tomography

Kaganovich – Plasma neutralization effects

Kwan – Multiple beamlets

Lund – Simulations of HCX

Qin – Two-stream interactions

Startsev – Temperature-anisotropy instability

Vay – Adaptive mesh refinement