Scientific Issues and Opportunities in Heavy Ion Fusion

Ronald Davidson
Professor of Astrophysical Sciences
Plasma Physics Laboratory
Princeton University, Princeton, New Jersey
and
Deputy Director
Heavy Ion Fusion Virtual National Laboratory

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Dr. Michael Holland
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U.S. Institutions Participating in Heavy Ion Fusion Research

UC Berkeley
UC Los Angeles
UC San Diego
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Princeton Plasma Physics Laboratory
Naval Research Laboratory
Los Alamos National Laboratory
Sandia National Laboratories
University of Maryland
University of Missouri
Stanford Linear Accelerator Center
Advanced Magnet Laboratory
Idaho National Environmental and
Engineering Laboratory

Massachusetts Institute of
Technology
Advanced Ceramics
Allied Signal
National Arnold
Hitachi
Mission Research Corporation
Georgia Institute of Technology
General Atomics
MRTI

Heavy Ion Fusion Has Important Synergisms With Other Scientific Areas

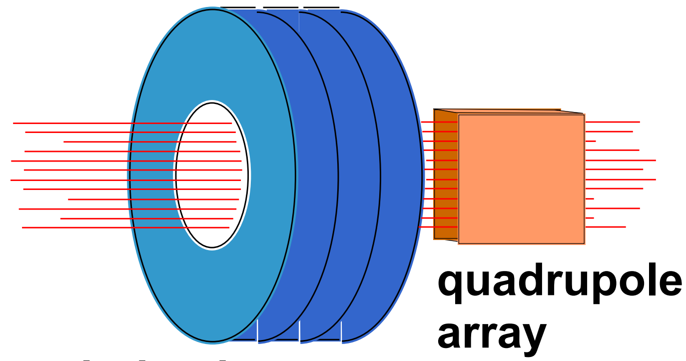
- Nonneutral plasma physics
  - Theoretical techniques; space-charge effects
- High energy and nuclear physics
  - Accelerator physics and technology
- High energy density plasma physics
  - Target physics/inertial confinement fusion (DP)
- Magnetic fusion plasma physics
  - Beam-plasma interaction (target chamber); diagnostic techniques
- Advanced nonlinear dynamics
  - Chaos; collective processes
- Atomic physics
  - Ionization and stripping cross sections
- Advanced computing
  - Algorithms; massively parallel computations
- Plasma processing
  - RF source technologies

Key Scientific Issues

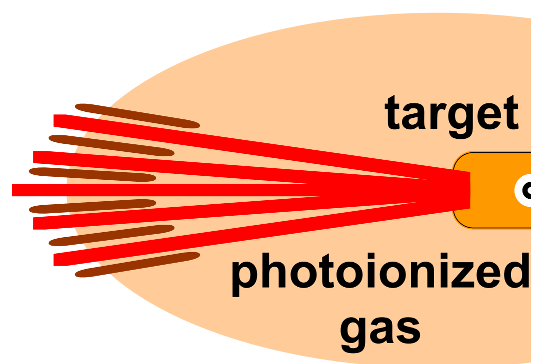
- Develop compact ion sources and injectors with necessary brightness and current (1A).
- Accelerate and transport heavy ion beams quiescently to several GeV at very high space-charge intensities and currents (several kA).
- Focus and transport intense ion beams in the target chamber to small spot size (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

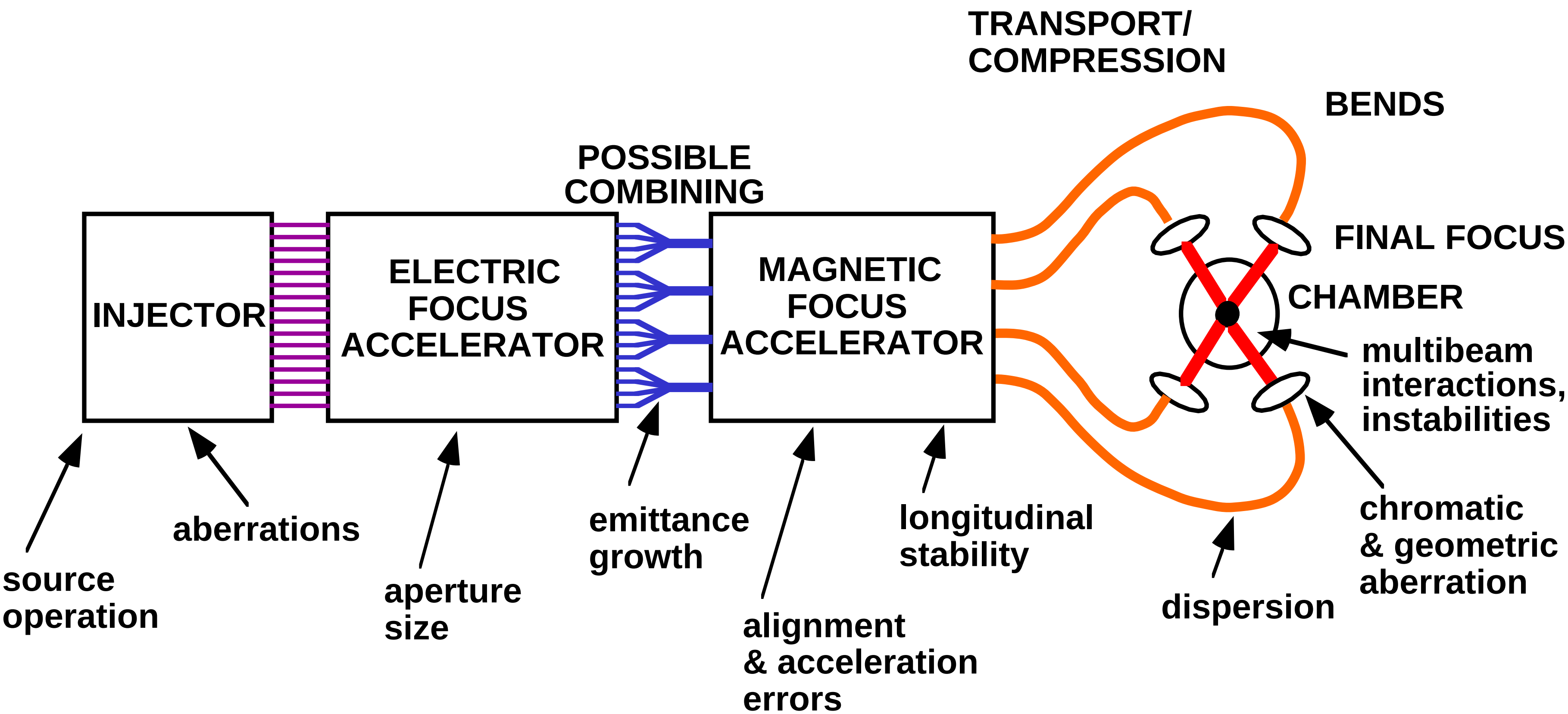
- **In accelerator and transport systems:**
  - Quality of injected beam
  - Emittance growth
  - Halo generation
  - Possible instabilities
  - Stray electrons
  - Multiple beam effects



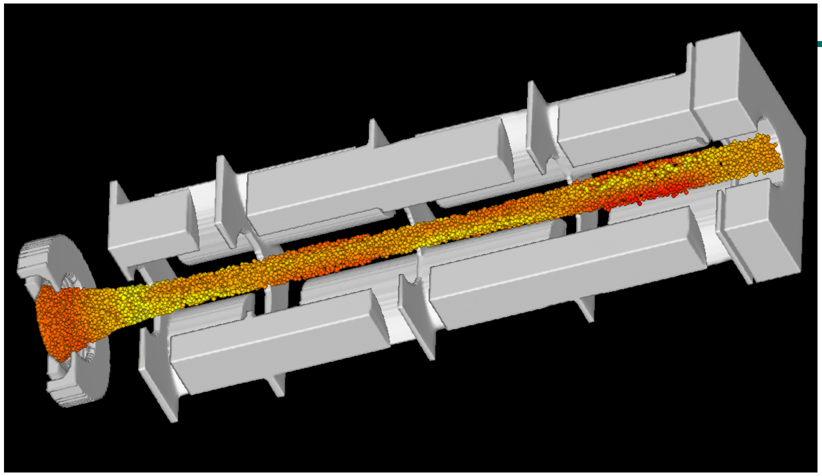
- **In fusion chamber:**
  - Focusing aberrations
  - Ionization of beam and background gas
  - Beam charge neutralization
  - Possible plasma instabilities
  - Self-magnetic and inductive effects
  - Multiple beam effects



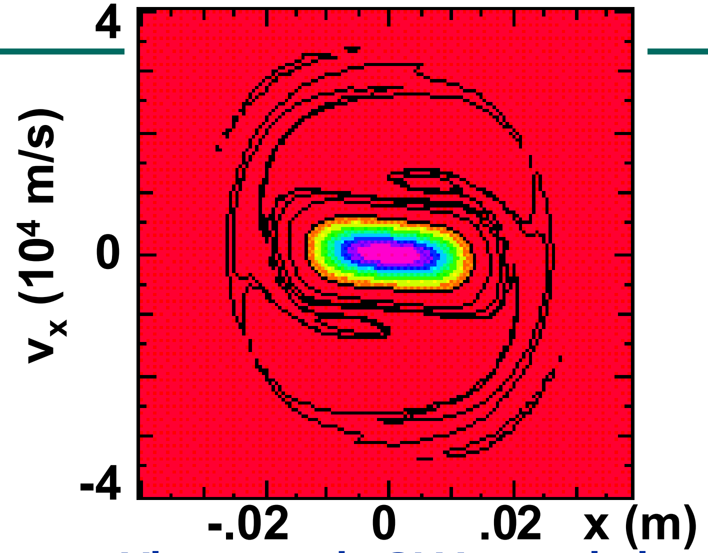
Some of the Technical Issues in a Heavy Ion Fusion System



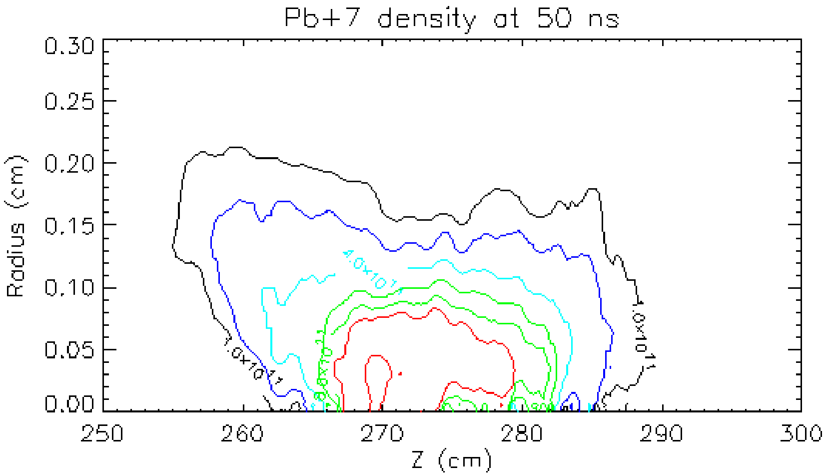
Simulation Tools are Used to Resolve a Wide Range of Scientific Issues



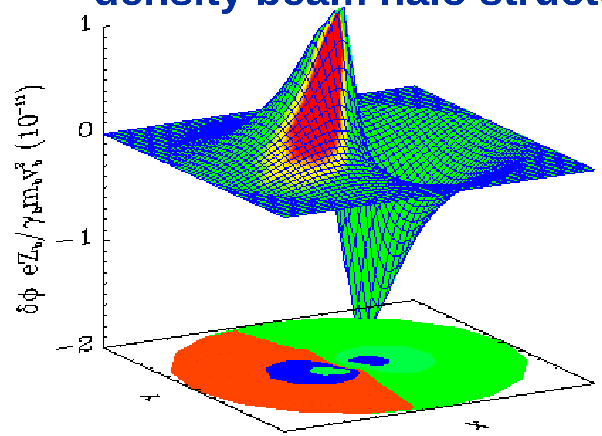
WARP3d PIC simulations quantify nonlinear beam dynamics in electrostatic quadrupole injector



Vlasov code SLV reveals low-density beam halo structure

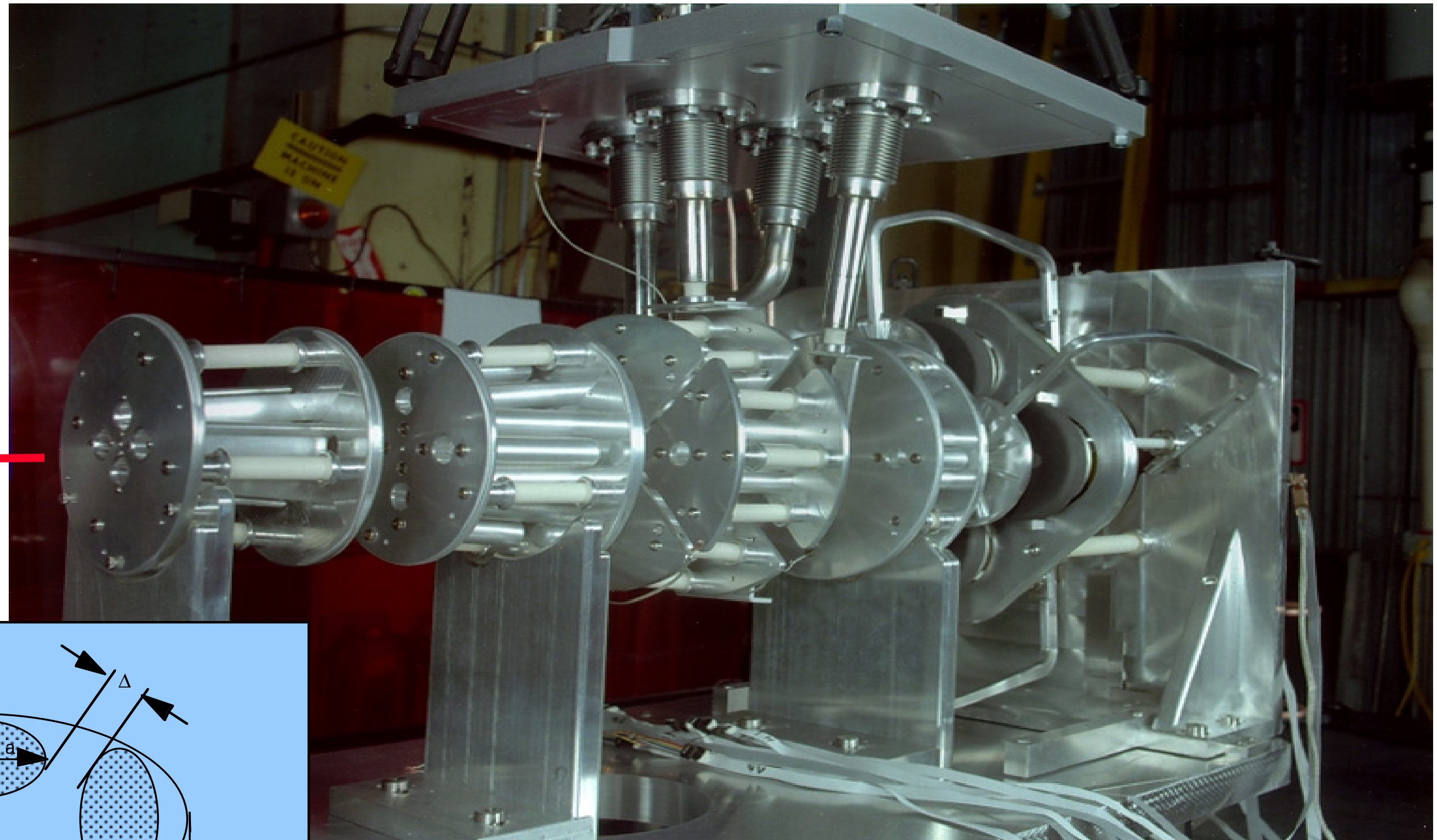


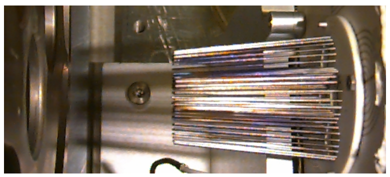
LSP PIC simulation of neutralized ballistic transport shows Pb^{+7} ions focusing to a 2 mm spot

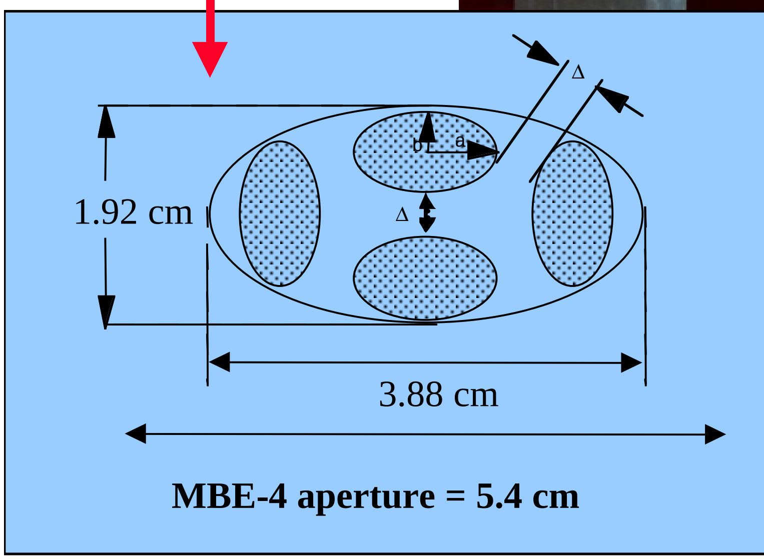


3-D δf code BEST shows structure of two-stream dipole mode

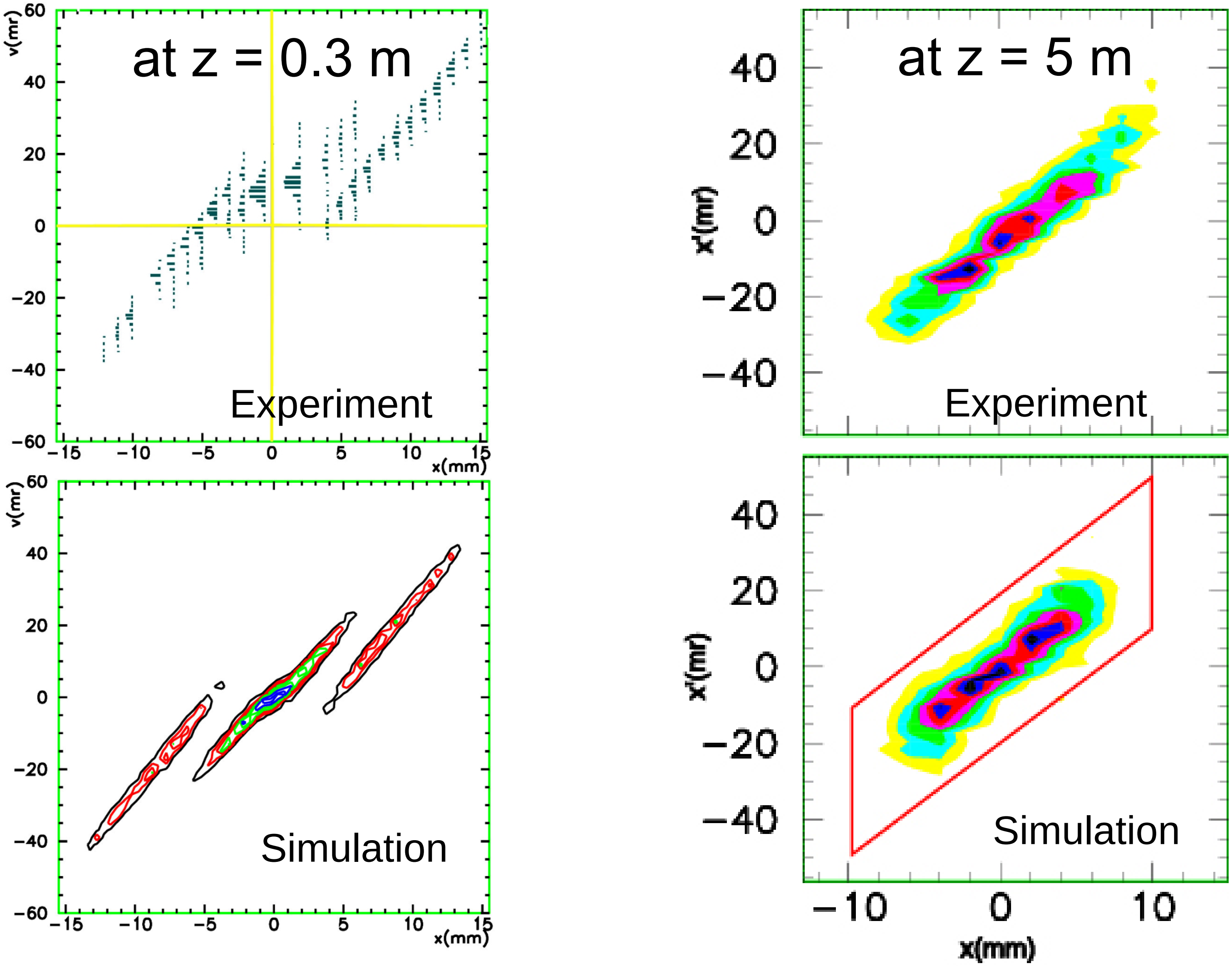
Scaled Beam Combining Experiment



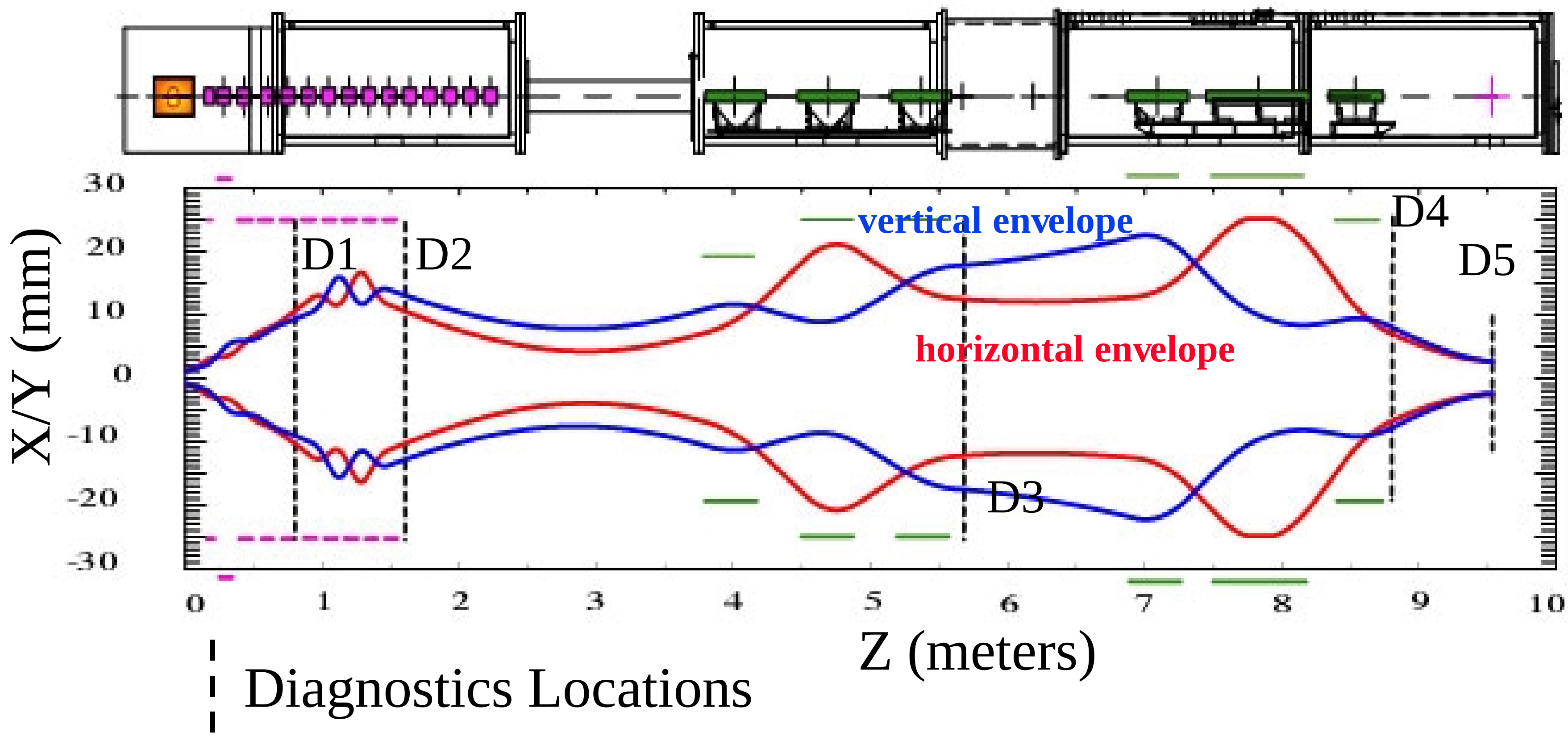




Combiner Phase Space: Near-Equilibration After Two Plasma Periods, in Good Agreement with Simulations

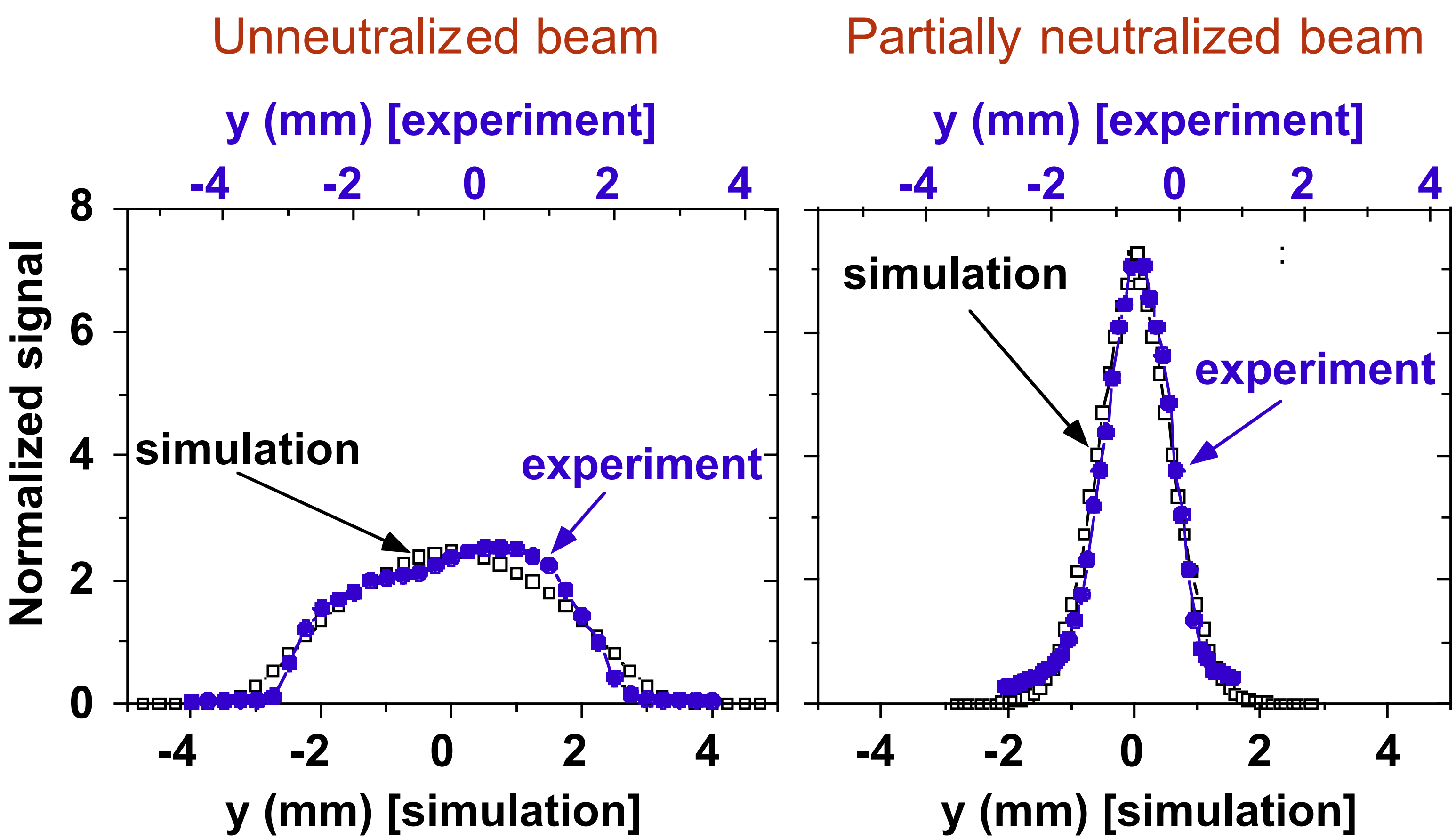


Final Focus Scaled Experiment



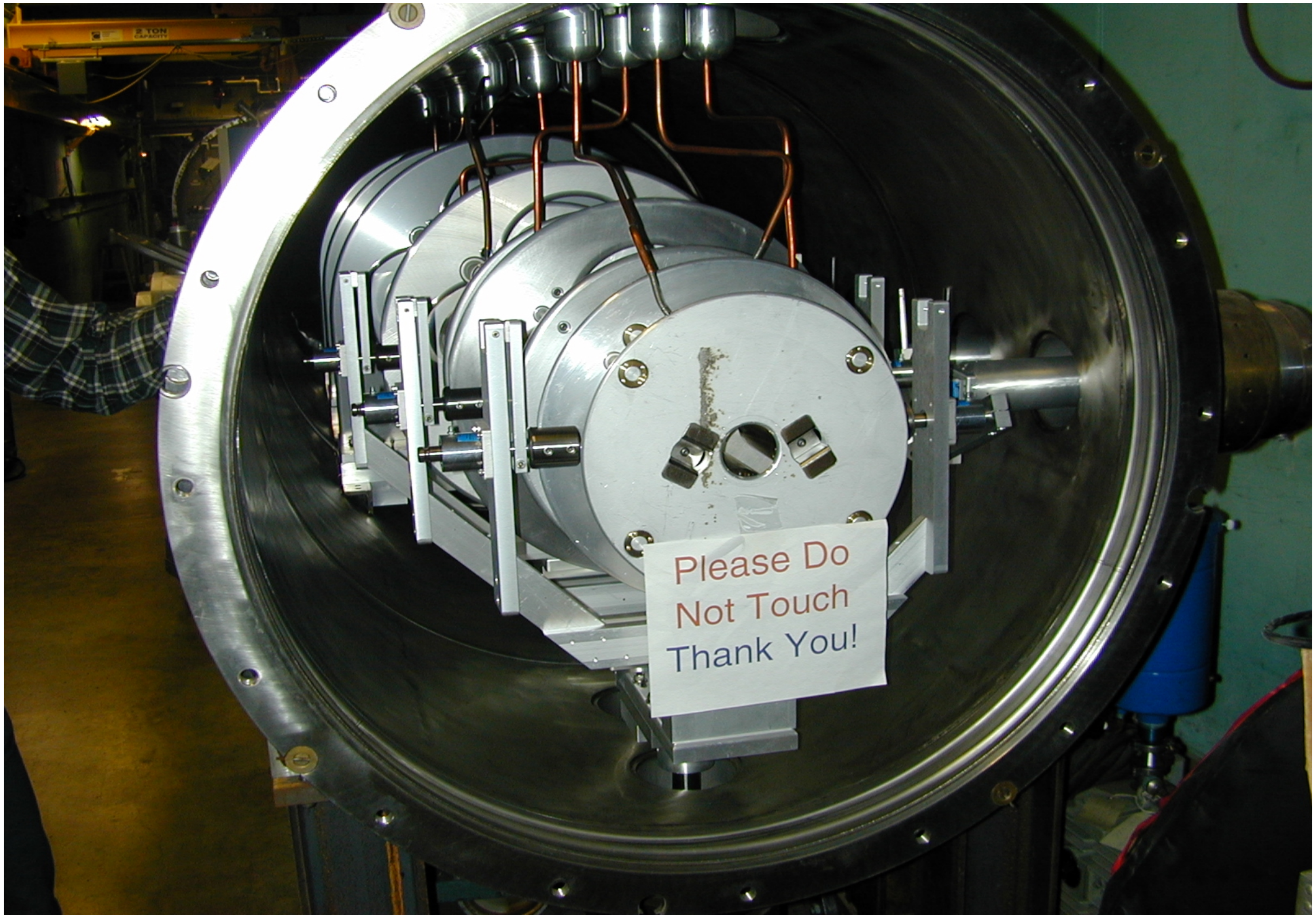
400μA, 160 keV, Cs^{+} — but dimensionless parameters match

LSP Simulations Capture Neutralizing Effect of Hot-Filament Source



400μA, 160 keV, Cs^+

High Current Experiment (HCX) to Address Transport Issues for Space-Charge-Dominated Heavy Ion Beams at ~1 Ampere Current



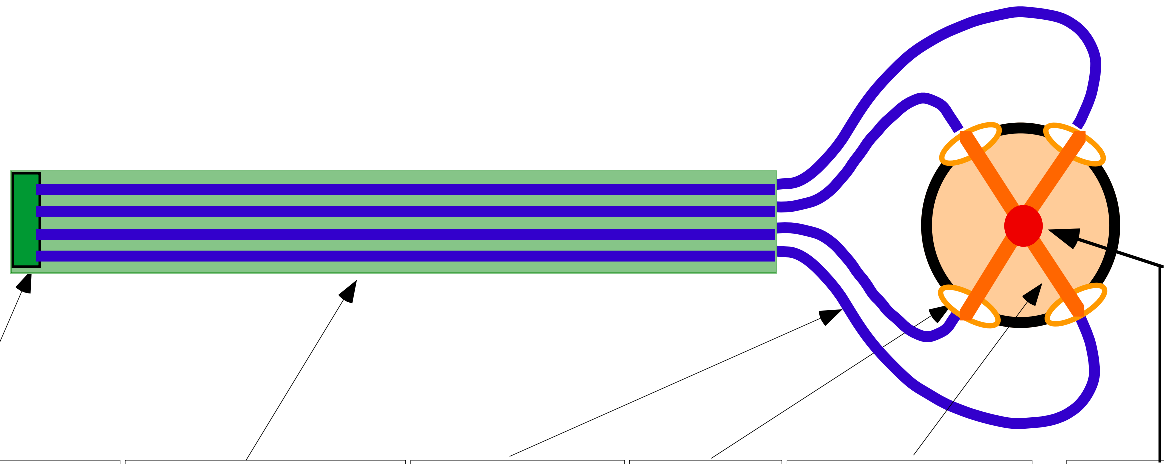
2 MeV, 810 mA, K^+ ion; phase advance per quad $\sigma_0 = 80^o$

Physics Issues to be Addressed in HCX

The High Current Transport Experiment will investigate key physics issues related to beam transport at high intensities.

- Limits on beam transport at high aperture fill factors.
- Effects of imperfections in alignment and focusing fields.
- Image charge effects from beam proximity to conducting wall.
- Collective oscillations and instabilities at high current.
- Beam halo particles
  - Production rates
  - Effects on beam quality
  - Electron production
- Electron effects
  - Two-stream interactions
  - Secondary emission

Future Simulations: Source-to-Target Simulations Using Coupled Models



Ion source & injector	Accelerator	Buncher	Final focus	Chamber transport	Target

electrostatic / magnetoinductive PIC
WARP

EM PIC
BPIC,LSP

rad - hydro

electromagnetic PIC, LSP — delta-f, BEST — continuum Vlasov SLV

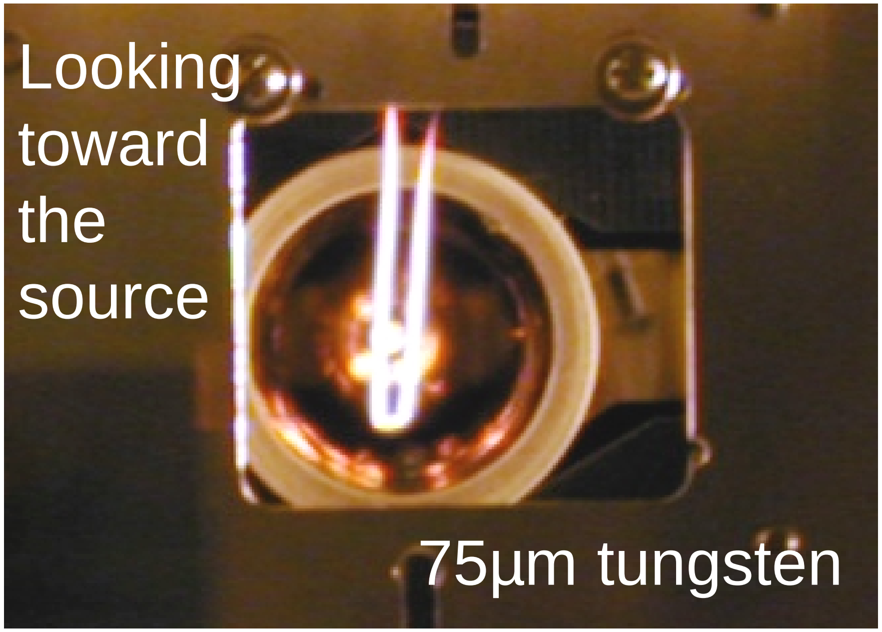
Conclusions

- Heavy ion fusion research benefits from:
  - Increased institutional participation.
  - Strong synergisms with other scientific areas.
  - Advances in technology.
- While significant scientific issues remain to be addressed, there is excellent technical progress in the generation, acceleration, transport and focusing of heavy ion beams.
- Advanced numerical simulations are playing an increasingly important role in the planning and interpretation of experiments, and in advancing scientific understanding.
- Integrated experiments (source to target) are essential to establishing the underlying scientific basis for heavy ion fusion.

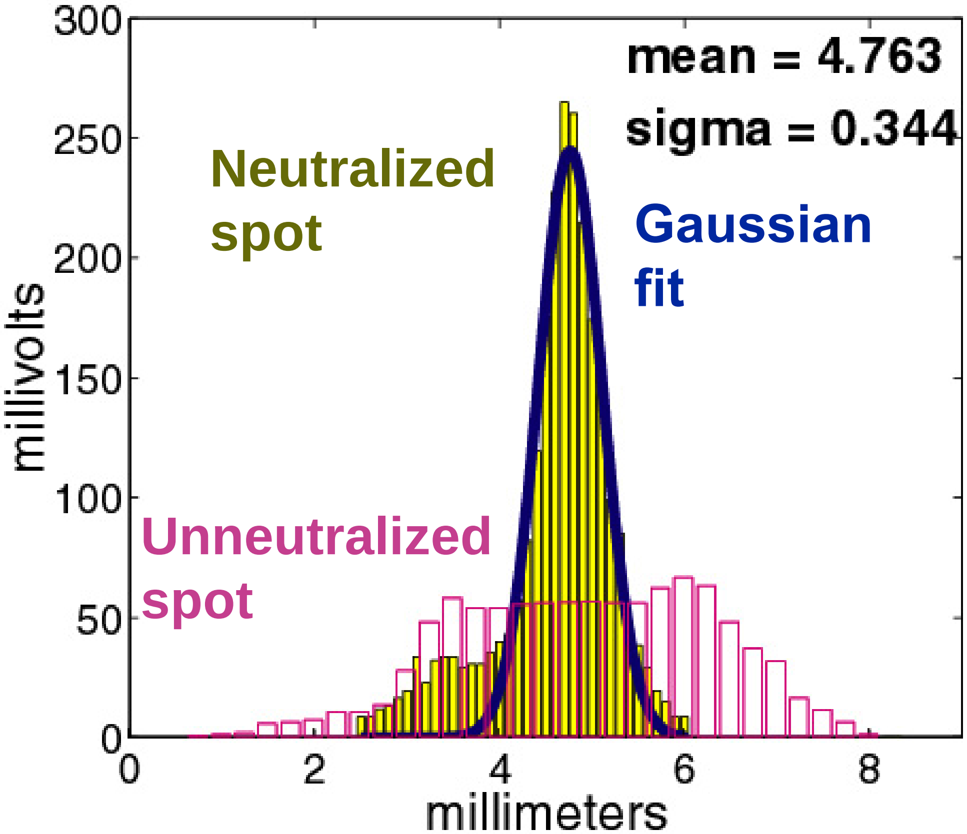
Backup

Focusing a Heavy Ion Beam Onto a Small Spot Requires Neutralization in the Fusion Chamber

- A hot (~2100K) tungsten filament is inserted into the beam after the last magnet
- Filament voltage is switched off immediately prior to beam pulse

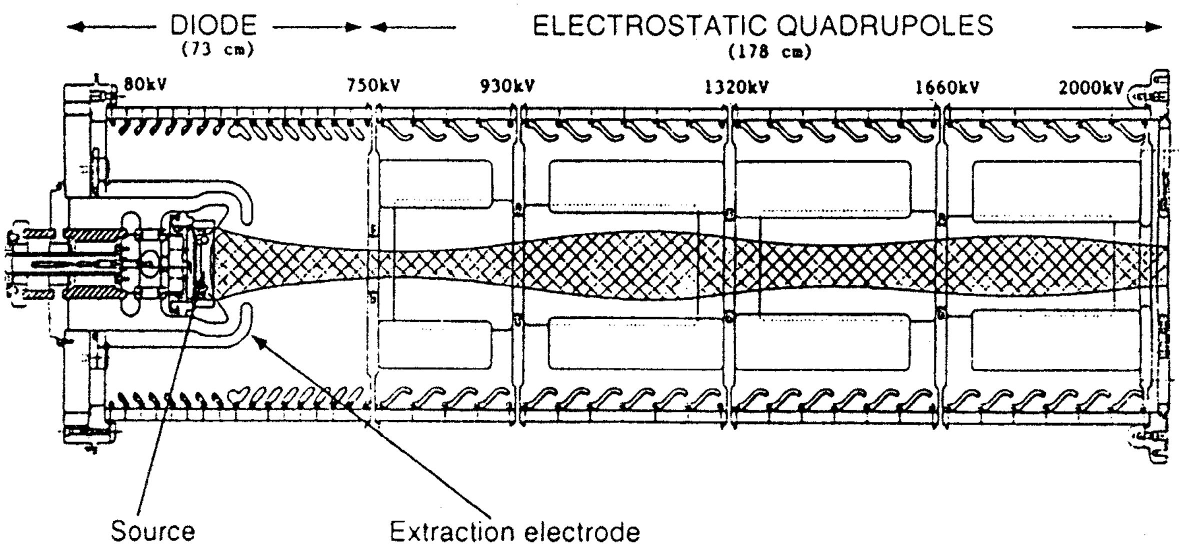


Single-slit scans in horizontal (x) plane with 100µm step size



Existing 2MV Injector will be Used for the High Current Transport Experiment (HCX)

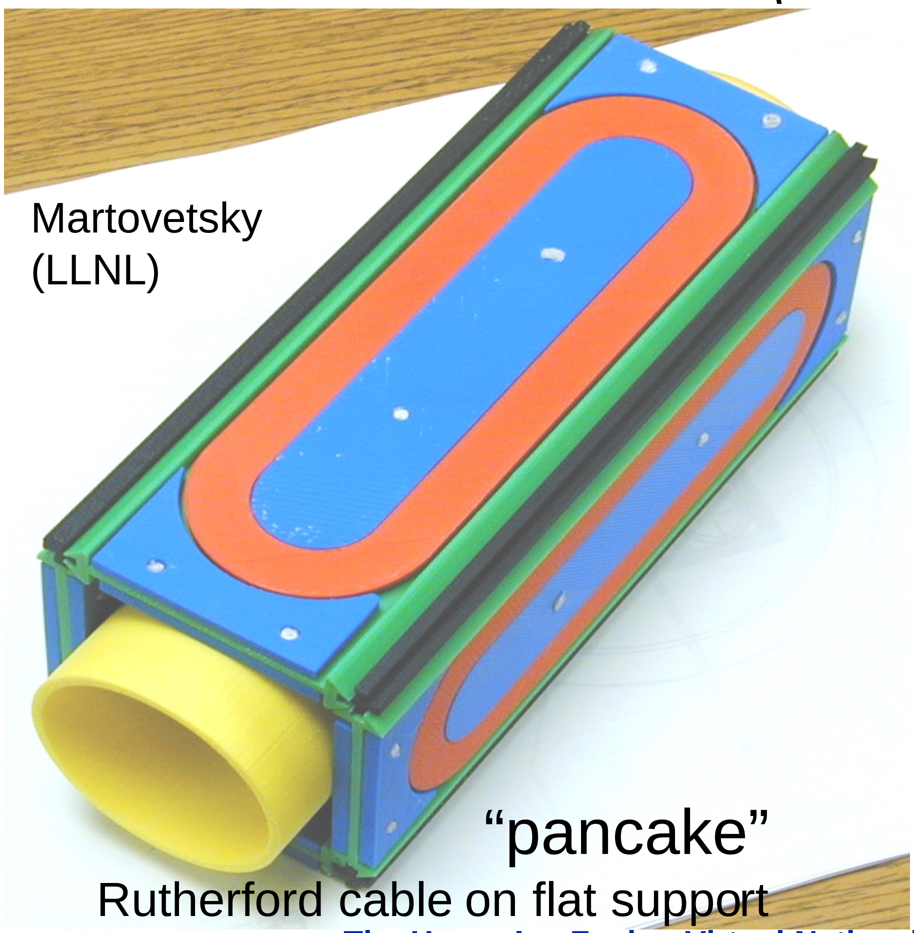
- Beam brightness and current are adequate for HCX.
- Injector beam uniformity is being improved for the HCX transport experiment.

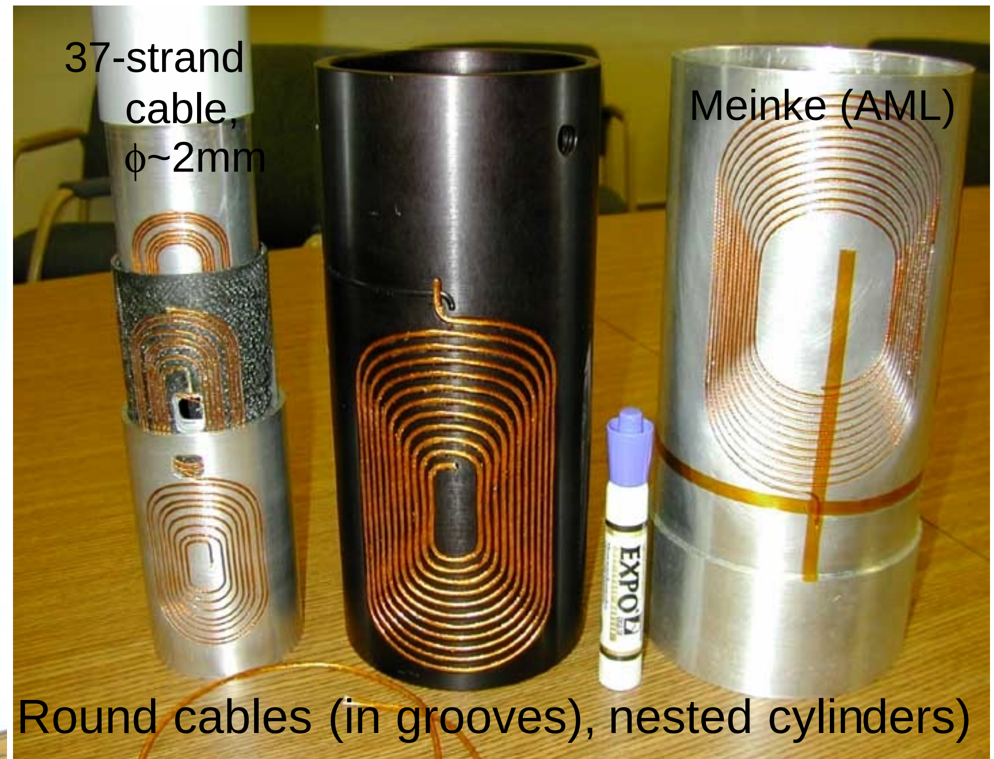


Same profile with K^+ (Al-Si) source, or Cs^+ contact ionization source.

Advances in Superconducting Magnet Technology will Enable Investigation of Beam Transport Physics at High Current in HCX

$L < 20$ cm, $\eta \approx 0.5$, $r_w \approx 3$ cm, $B_w = 3\text{-}4$ T.





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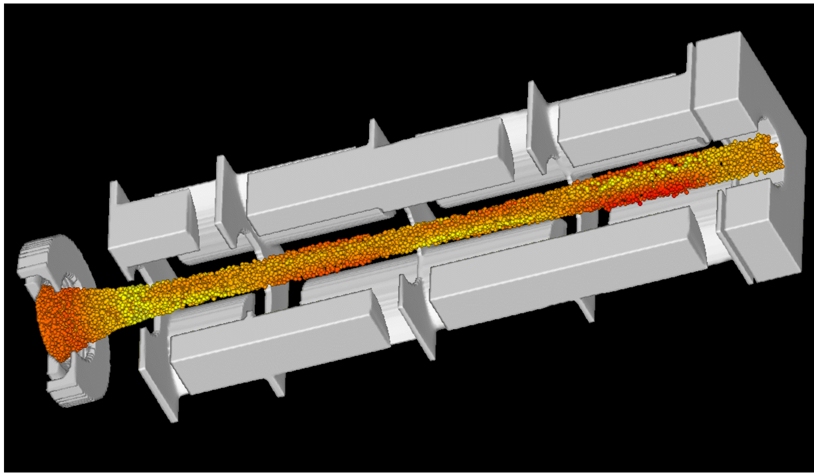

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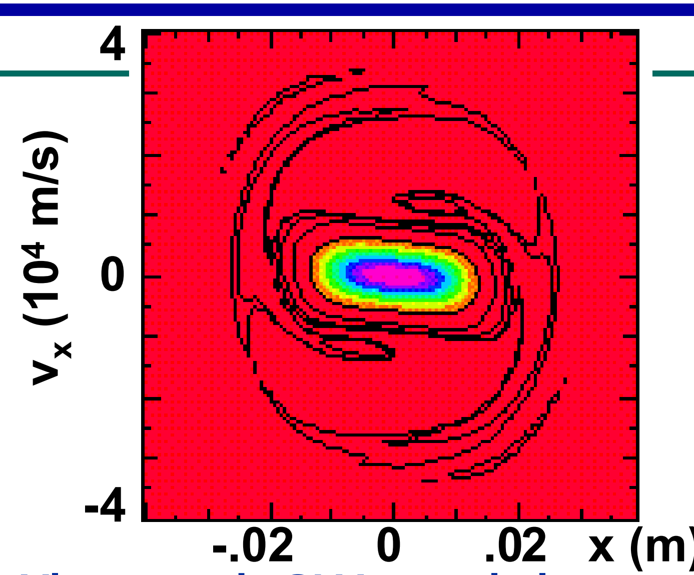

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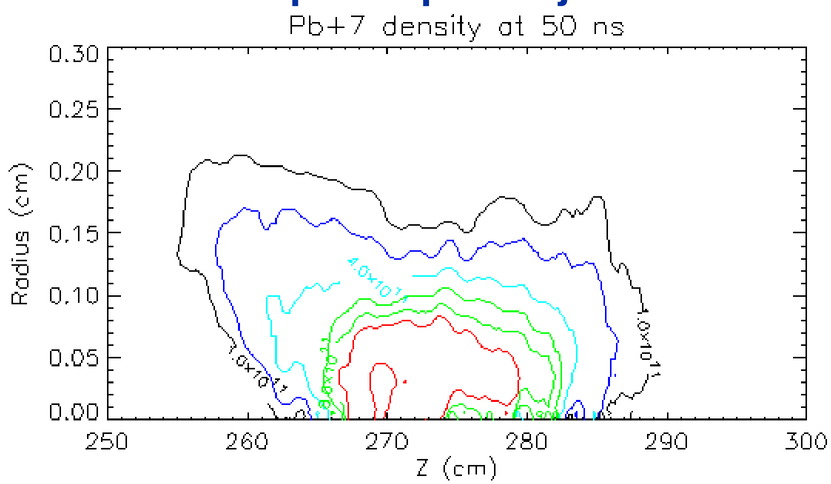

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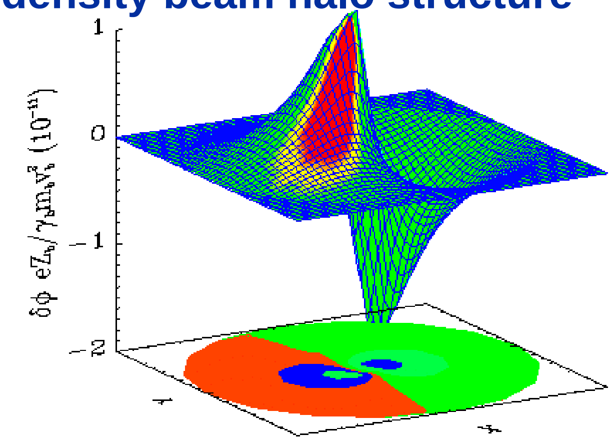

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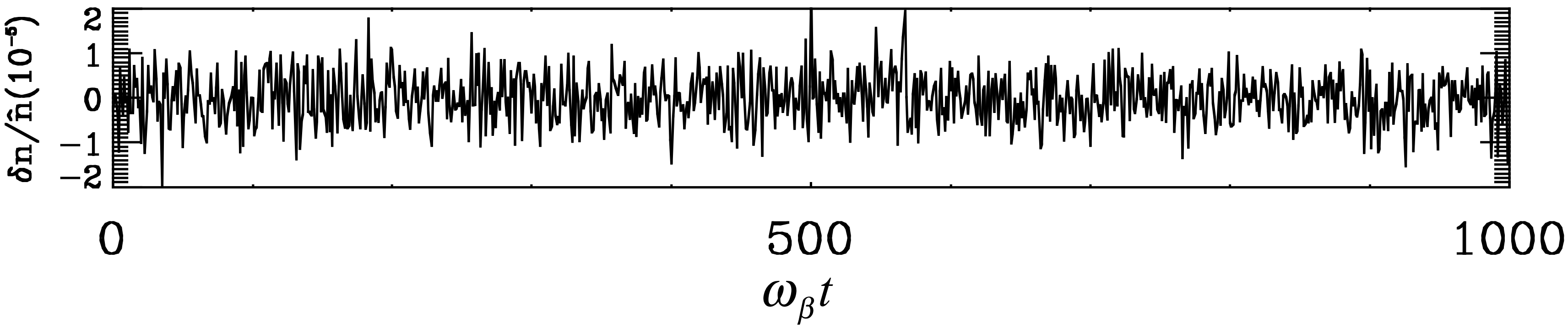
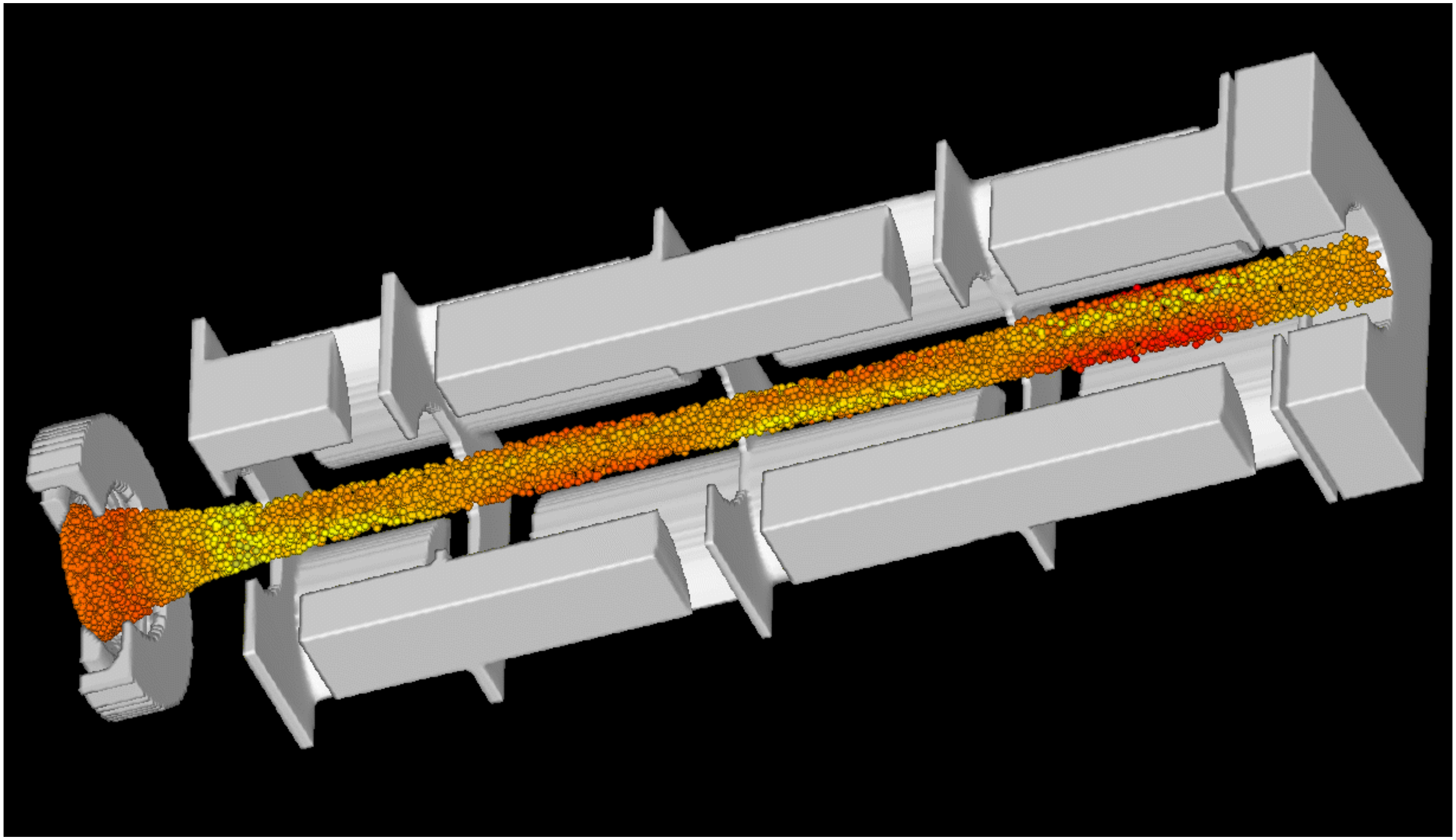
BEST Simulation of Intense Beam Propagation over Large Distances



- Random initial perturbations with normalized density amplitudes of 10^{-5} are introduced into the system.
- The beam is propagated from t=0 to t=1000/ω_β.
- BEST simulation results show that the perturbations do not grow and the beam propagates quiescently over large distances which agrees with the nonlinear stability theorem for the choice of thermal equilibrium distribution function [PRL **81**, 991 (1998)].

WARP3d Simulation of 2 MV, 0.8 A Electrostatic Quadrupole Injector Experiment



“Energy effect”: focusing potentials approaching ± 200 kV are not small relative to beam energy