Progress in Accelerator R&D for High Energy Density Physics and Warm Dense Matter Applications

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For U.S. Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL)*

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***HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory.**

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Heavy Ion Beam Science for HEDP and Fusion

- **The research objective of the US HIFS-VNL is to address the top-level scientific question central to both High Energy Density Physics (HEDP) and fusion*:**

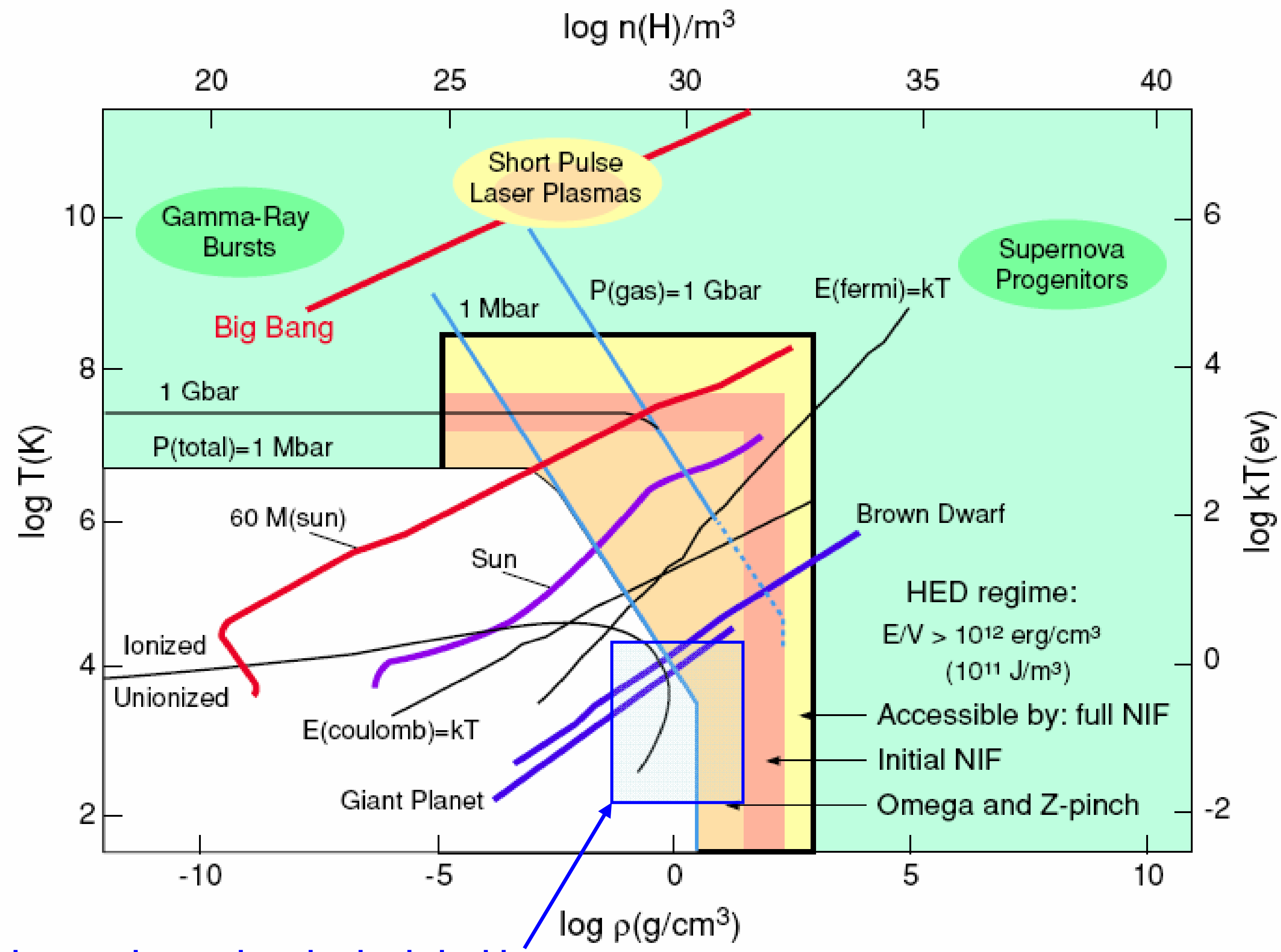
  T7: How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?

- **Principal science thrust areas:**

  – High brightness beam transport
  – Focusing onto targets
  – Longitudinal beam compression
  – Beam-target interaction
  – Advanced theory and simulation tools

* From FESAC Priorities Panel Report (April, 2005).

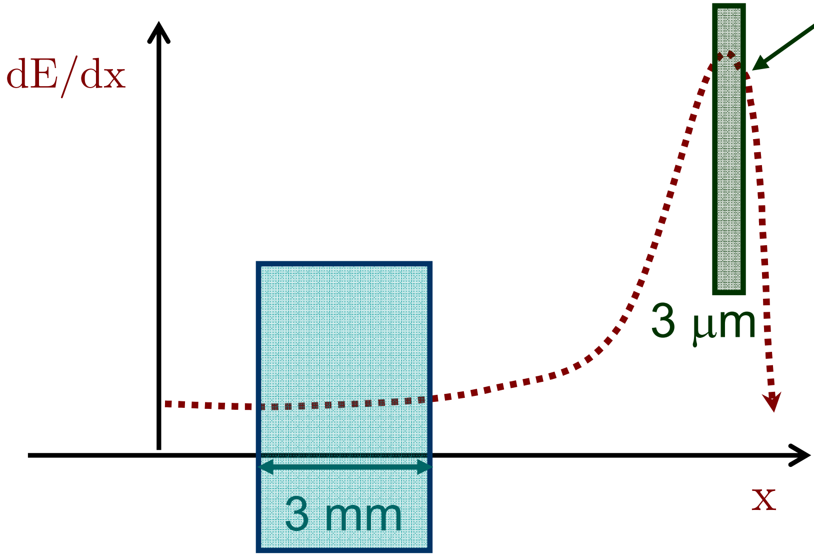
Map of the High Energy Density Physics Universe



Some of the most interesting physics is in this E>kT region accessible to heavy-ion beams

Unique Approach to Ion-Driven HEDP with Short Pulses

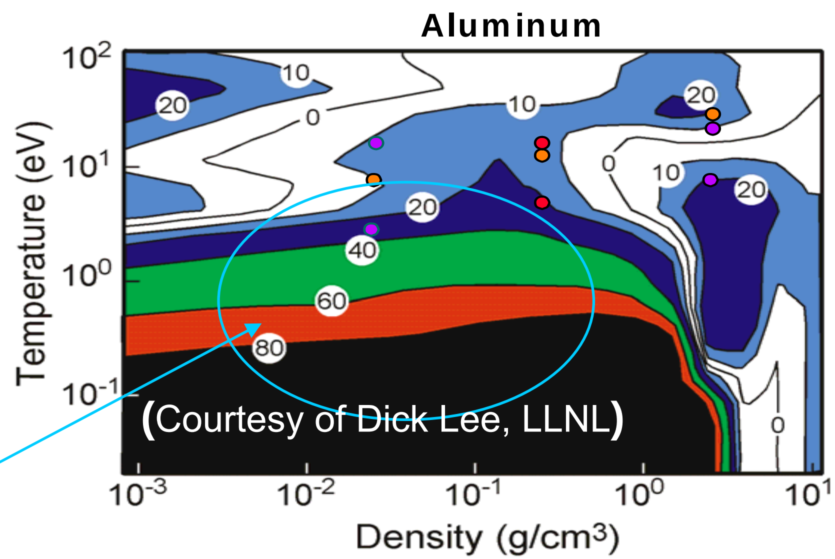
Ion energy loss rate in targets



Maximum dE/dx *and* uniform heating at Bragg peak require short (< few ns) pulses to minimize hydro motion. [L. R. Grisham, PoP, (2004)].
→Te > 10 eV @ 20J, 20 MeV
(Future US accelerator for HEDP)

GSI: 40 GeV heavy Ions→ thick targets→ Te ~ 1 eV per kJ

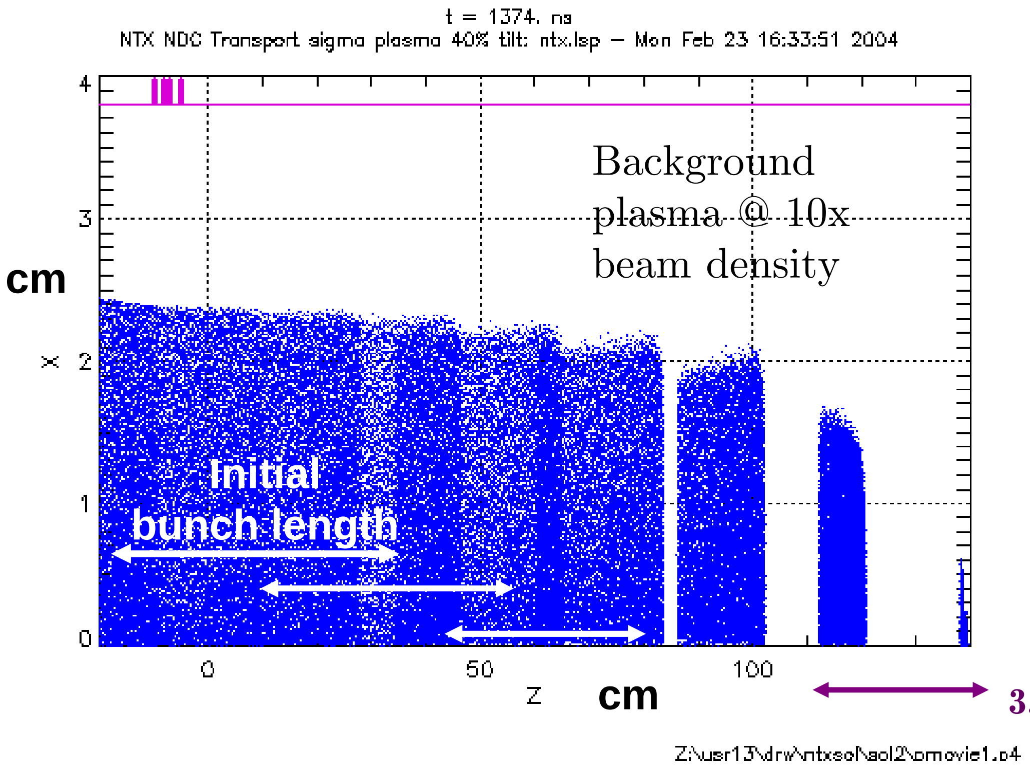
Dense, strongly coupled plasmas 10^{-2} to 10^{-1} *below* solid density are potentially productive areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)



Presentation outline

- **Neutralized Transport Experiment (NTX)**
  - physics of neutralized focusing.
  - achieved 200 fold transverse compression.
- **Neutralized drift compression experiment (NDCX)**
  - achieved 50 fold longitudinal compression.
  - plasma source development.
- **Pulse Line Ion Accelerator (PLIA) for HEDP and IFE.**
- **The High Current Experiment (HCX)**
  - beam transport limits.
  - electron cloud effects.
- **Advanced theory and simulation play an important role.**
  - WARP simulation of electron cloud effects.
  - perturbative particle simulation of collective excitations and instabilities.

Theory and LSP simulations demonstrate the possibility of large compression and focusing of charge neutralized ion beams inside a plasma column



(Welch, Sefkow, et al 2004-2006)

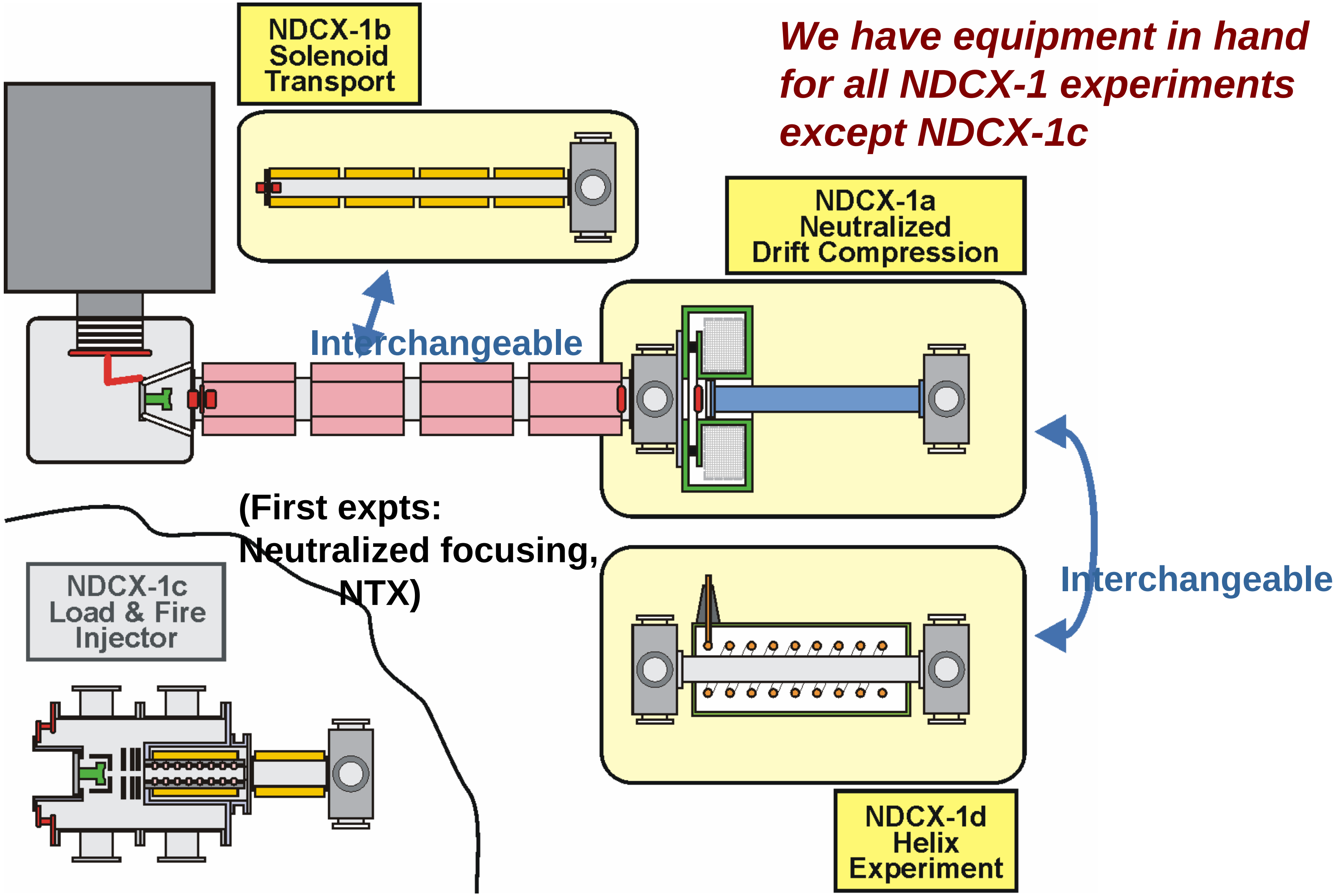
Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

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

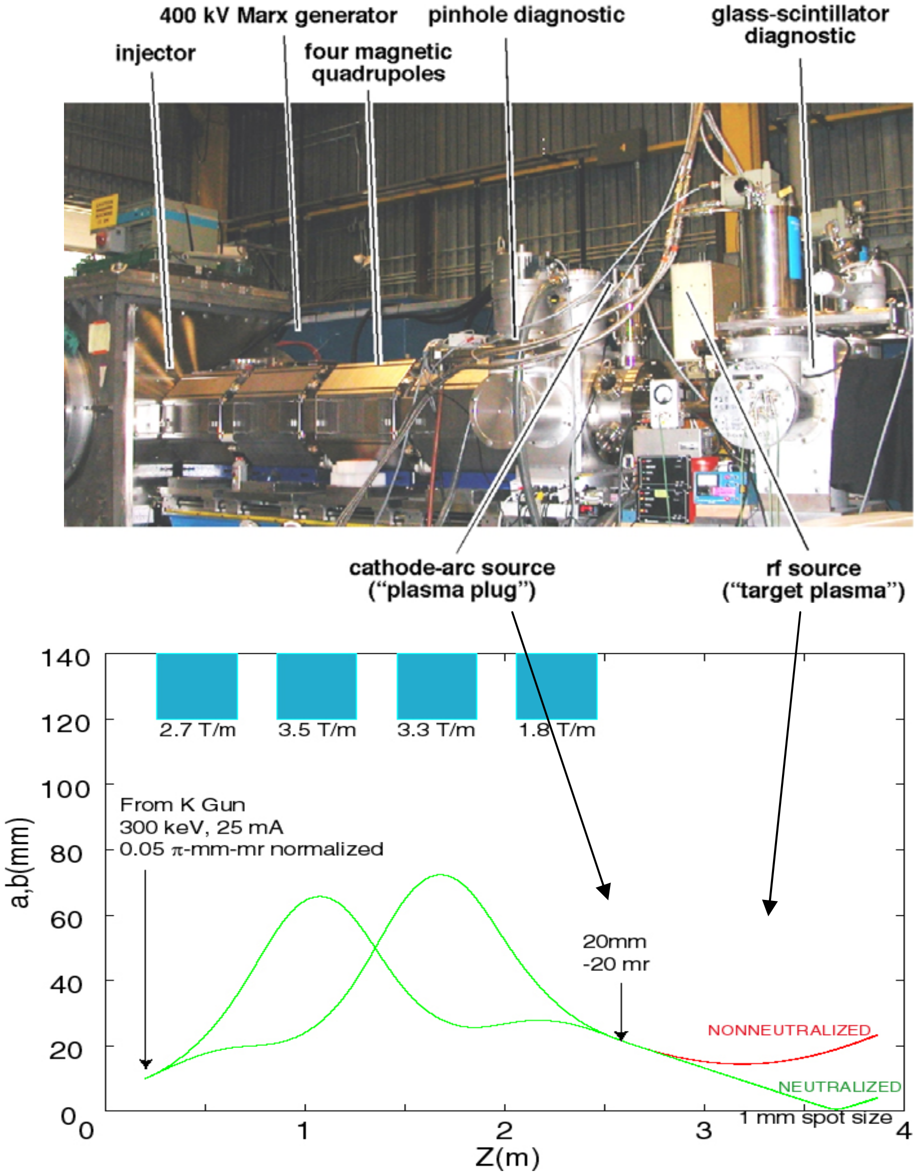
- A three-dimensional kinetic model for longitudinal compression in charge-neutralizing background plasma was developed [Davidson & Qin, 2005].
- Vlasov equation possesses a class of exact solutions describing both transverse and longitudinal compression of the beam pulse.

NDCX-I: A series of experiments towards HEDP (NDCX-II)

We have equipment in hand for all NDCX-1 experiments except NDCX-1c

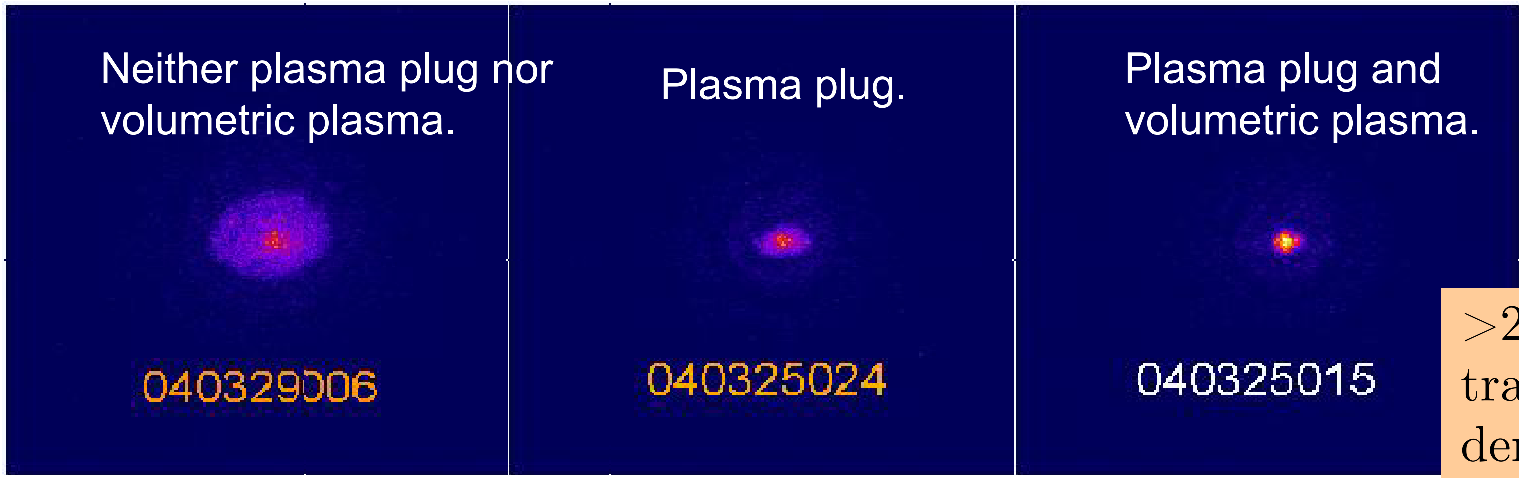


Neutralized Transport Experiment (NTX) investigated physics of neutralized focusing

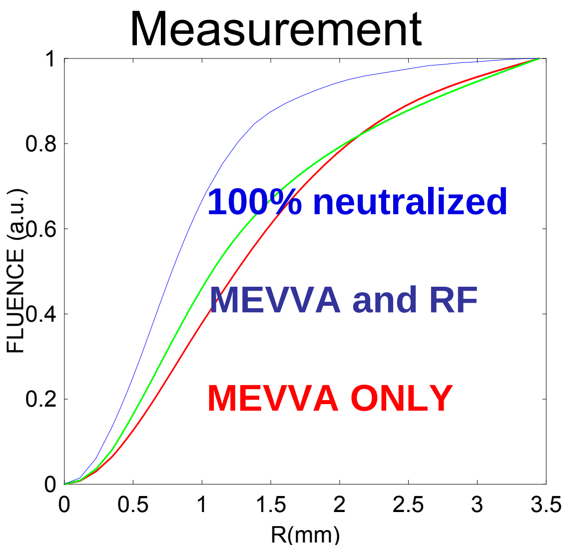


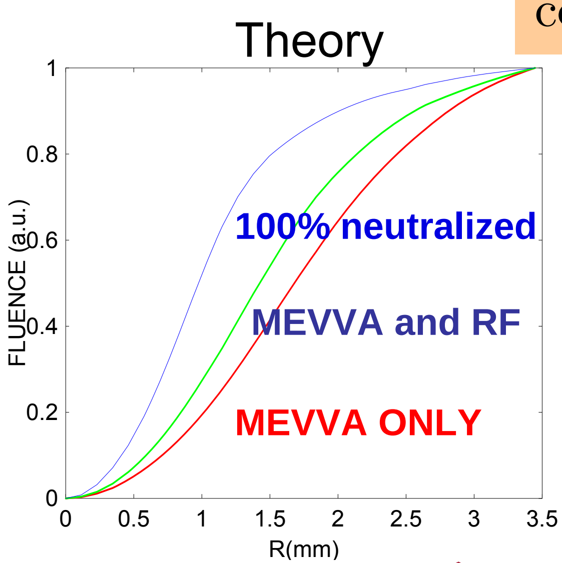
300 keV K+ ions at 25 mA

NTX achieved smaller transverse spot size using volumetric plasma

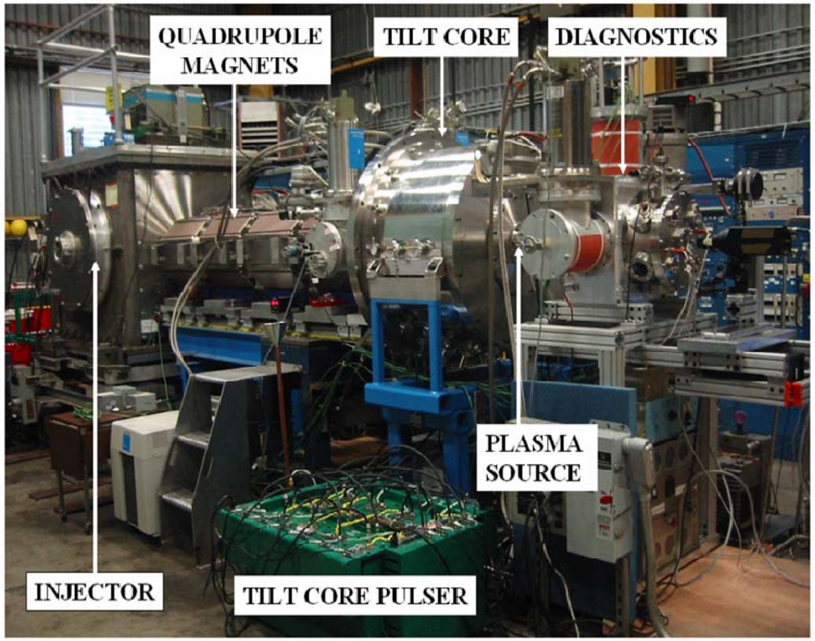


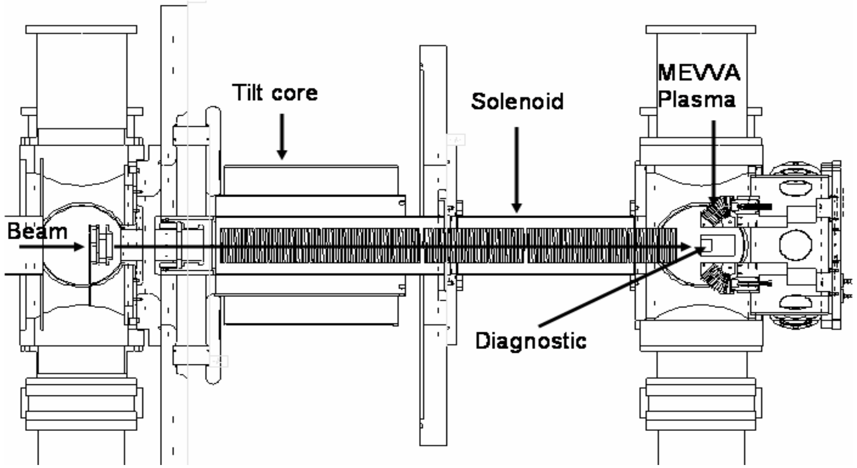
$>$200 times transverse density compression



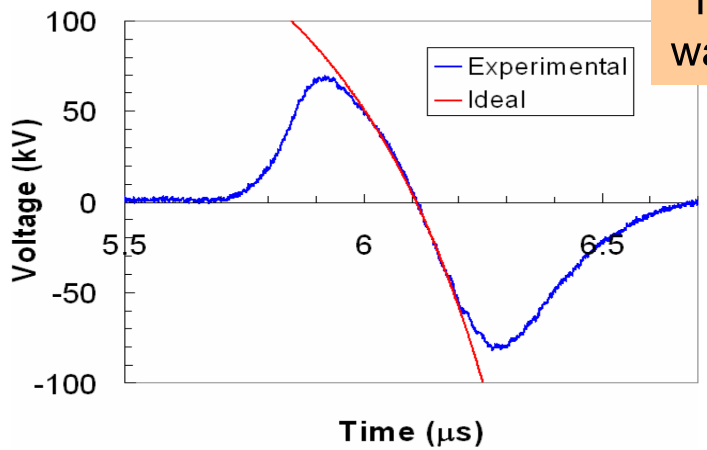


Neutralized drift compression experiment (NDCX)



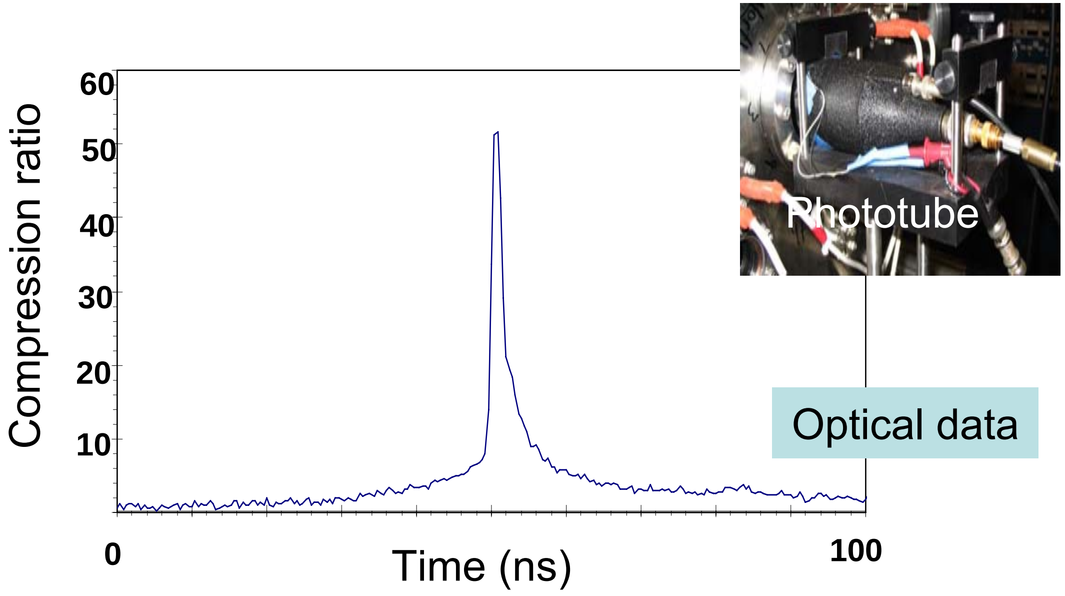


Tiltcore waveform

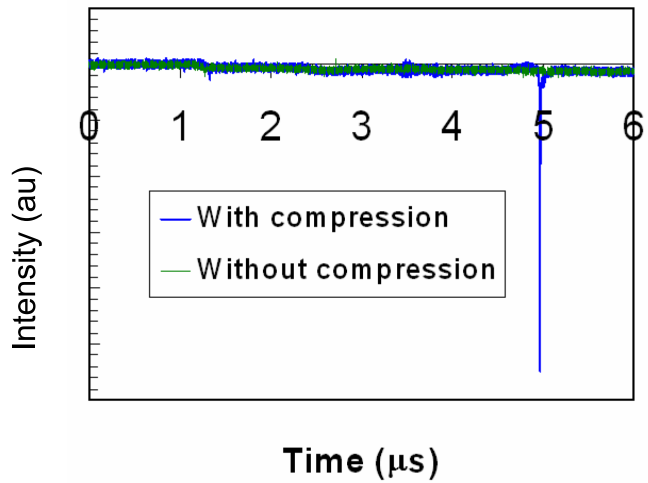


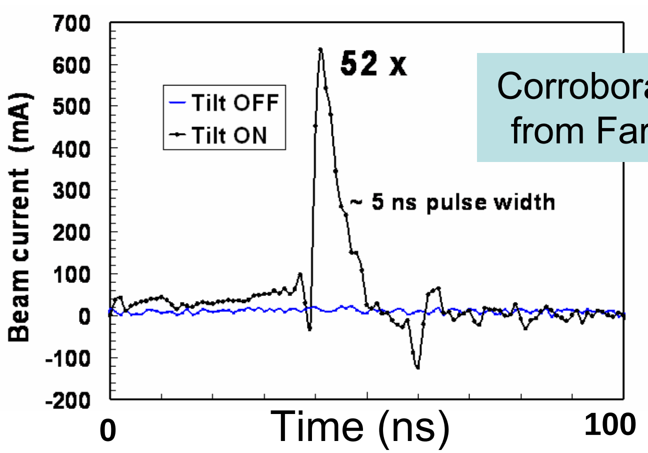
300 keV K+ ions at 25 mA

NDCX achieved 50 fold longitudinal current compression

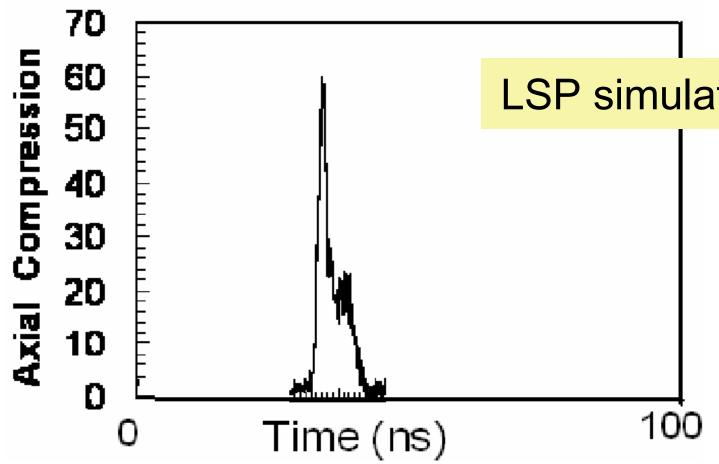


Optical data





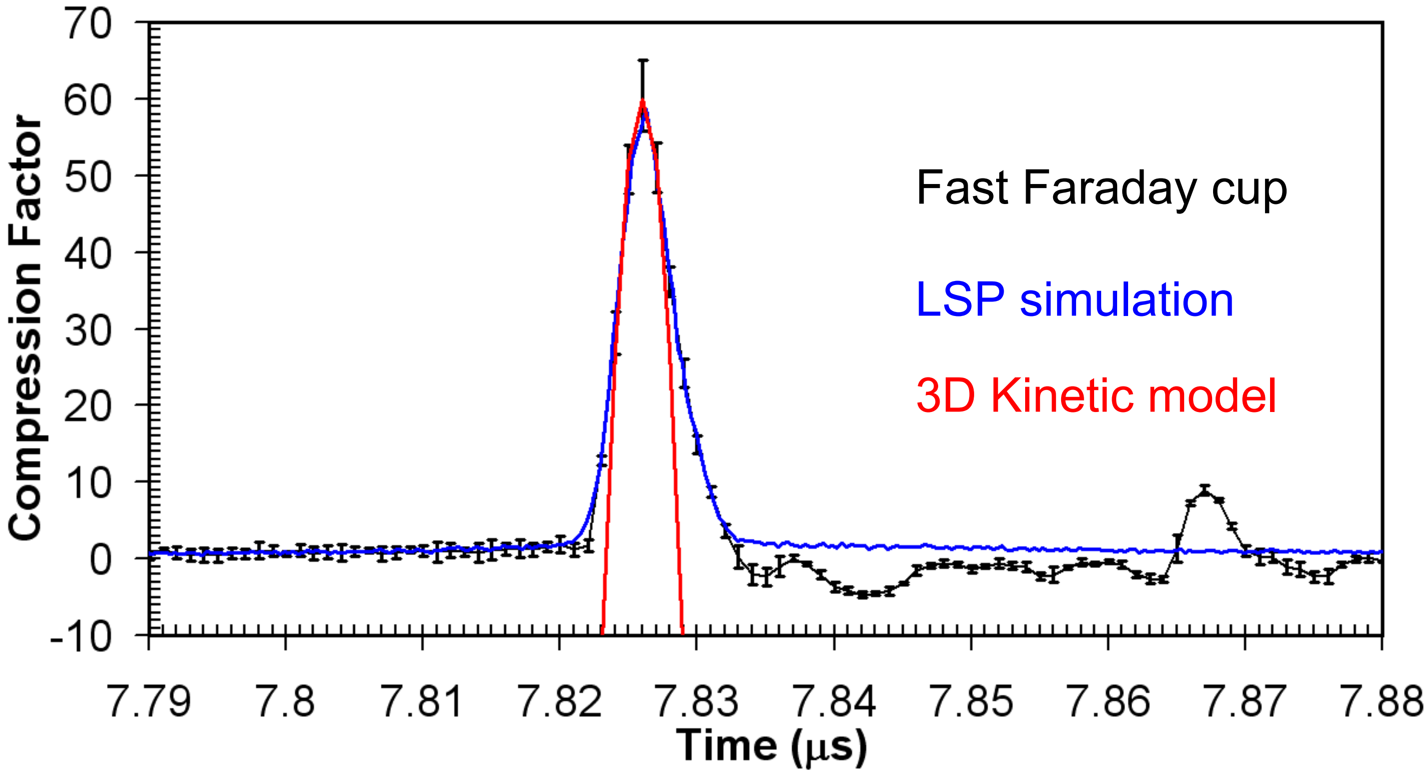
Corroborating data from Faraday cup



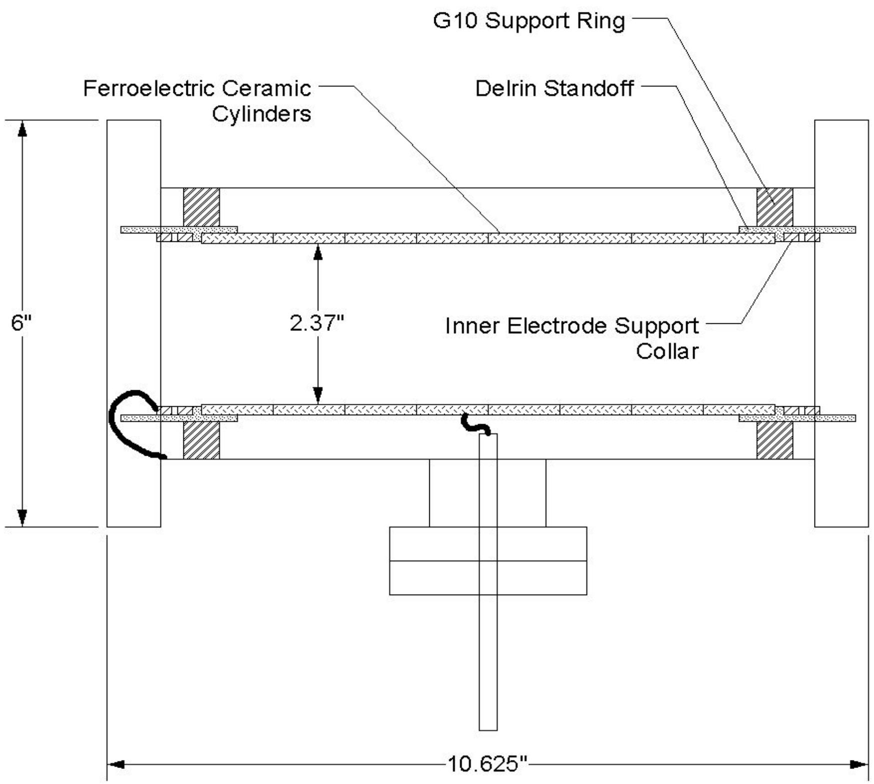
LSP simulation

P.K. Roy et al, PRL, **95**, 234801 (2005)

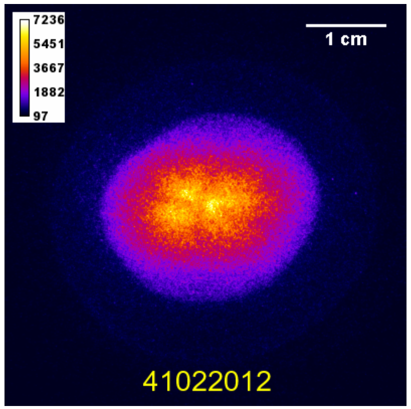
Comparison with longitudinal compression in NDCX at peak compression



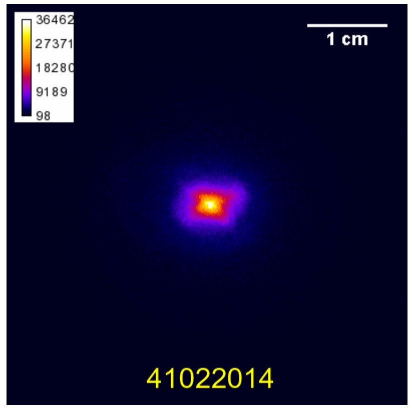
Lead-Zirconium-Titanate (PZT) and Barium Titanate ferroelectric plasma source



A 6~8 kV, 1 ms pulse applied across the inner and outer surfaces of a stack of high-dielectric cylinders produces, on the inner surface. A plasma then fills the interior volume.



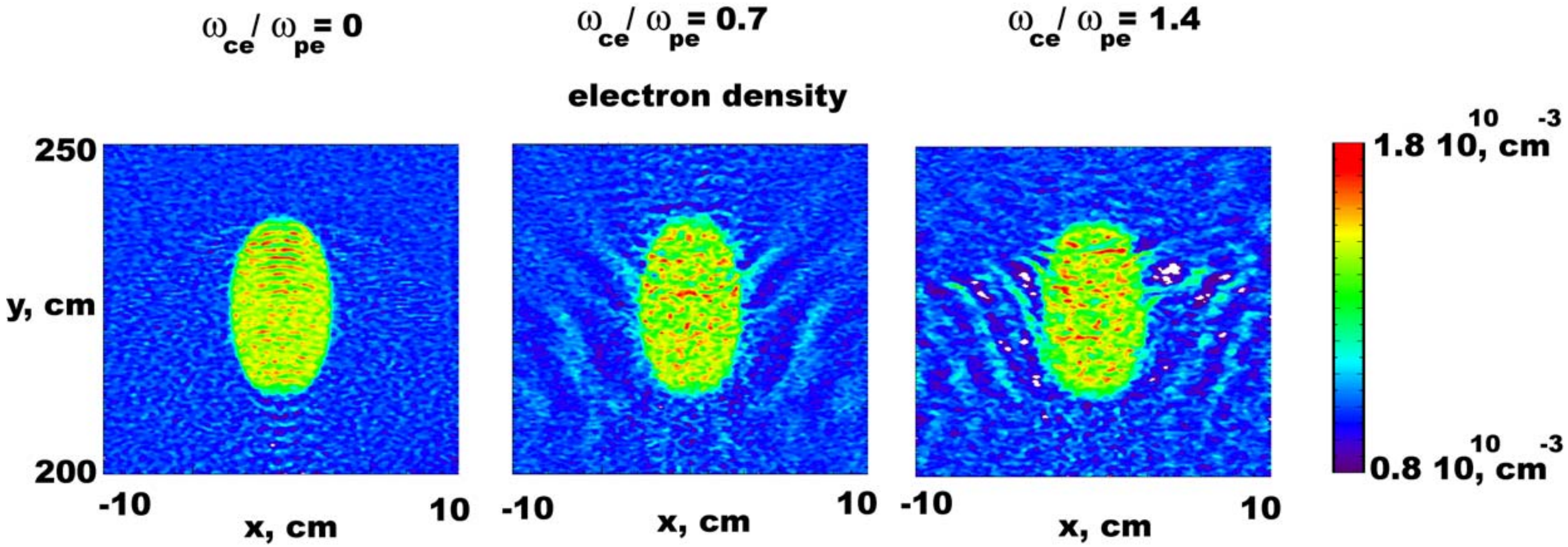
Neither plasma plug nor volumetric plasma



PZT plasma plug

Solenoidal magnetic field reduces neutralization

- Whistler waves excited in a solenoidal magnetic field.
- Perturb the plasma ahead of the beam pulse.
  - Plasma density $n_p = 10^{11} cm^{-3}$; B= 1014 G; $\omega_{ce} = \omega_{pe}$
  - 4.75 ns Beam at $V_b = 0.2c$, I=48.0A, r_b=2.85.



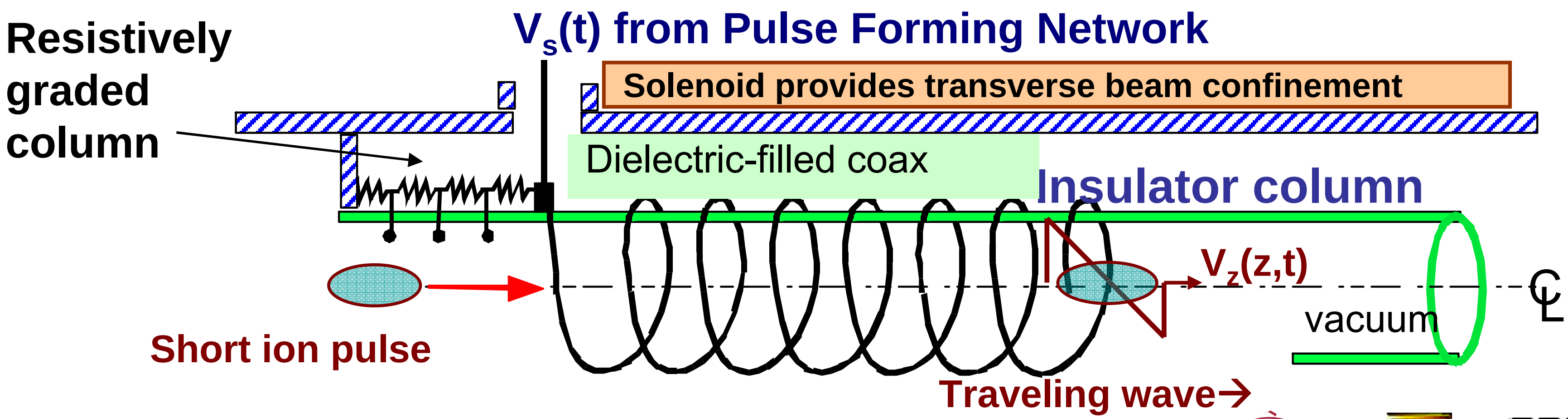
I.D. Kaganovich, E. A. Startsev, R. C. Davidson and D. R. Welch, Nuclear Instruments and Methods in Physics Research **A544**, 383 (2005).

Pulse Line Ion Accelerator (PLIA) for HEDP and IFE

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

- **Pulse Line Ion Accelerator is based on slow-wave structures (helices)**
- **Beam "surfs" on traveling pulse of E_z**
- **E_z (helix) >> E_z (space charge) → Continuous purging of electrons!**

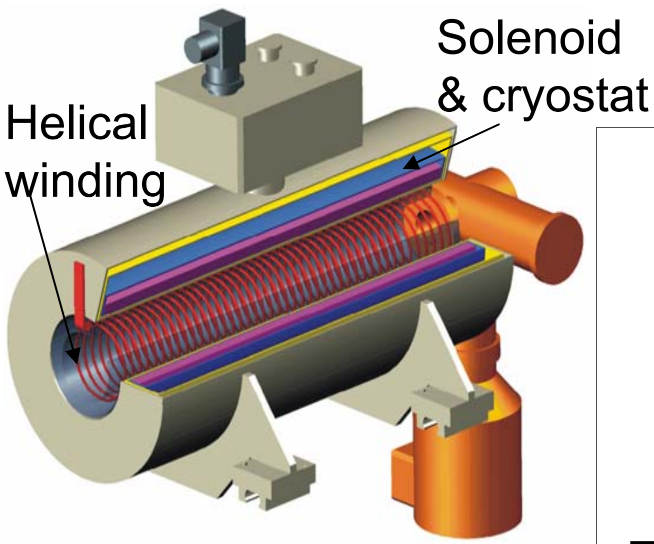
December 2005, demonstrated energy extraction from traveling wave



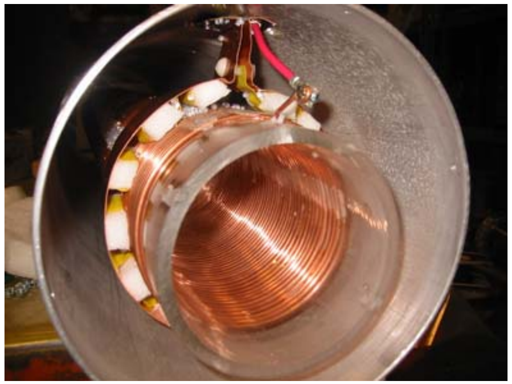
Accelerating fields are those of a “distributed transmission line”

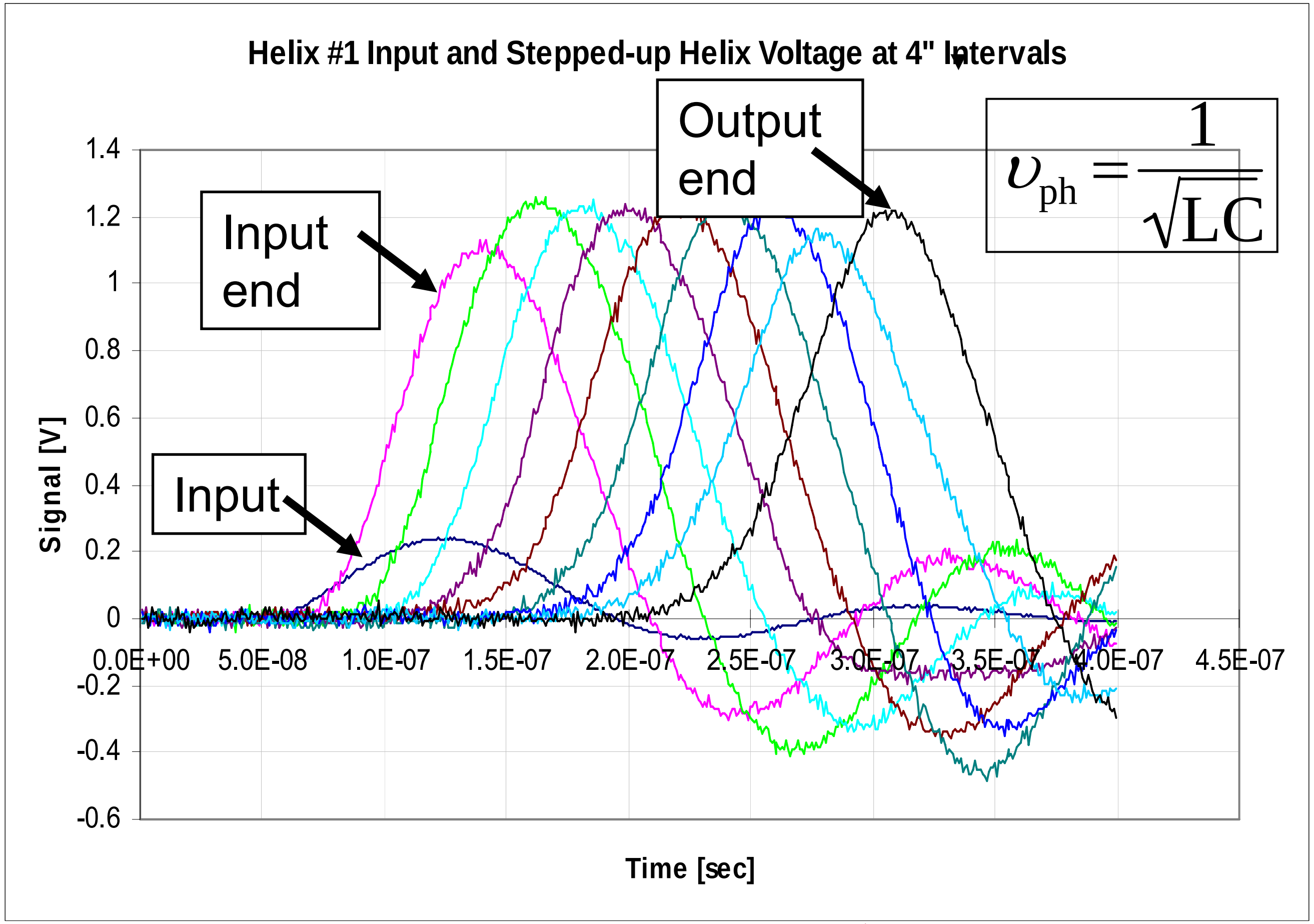
NDCX-II Accelerator Cell

*R.J. Briggs, *et al.* - LBNL Patent, Aug 2004

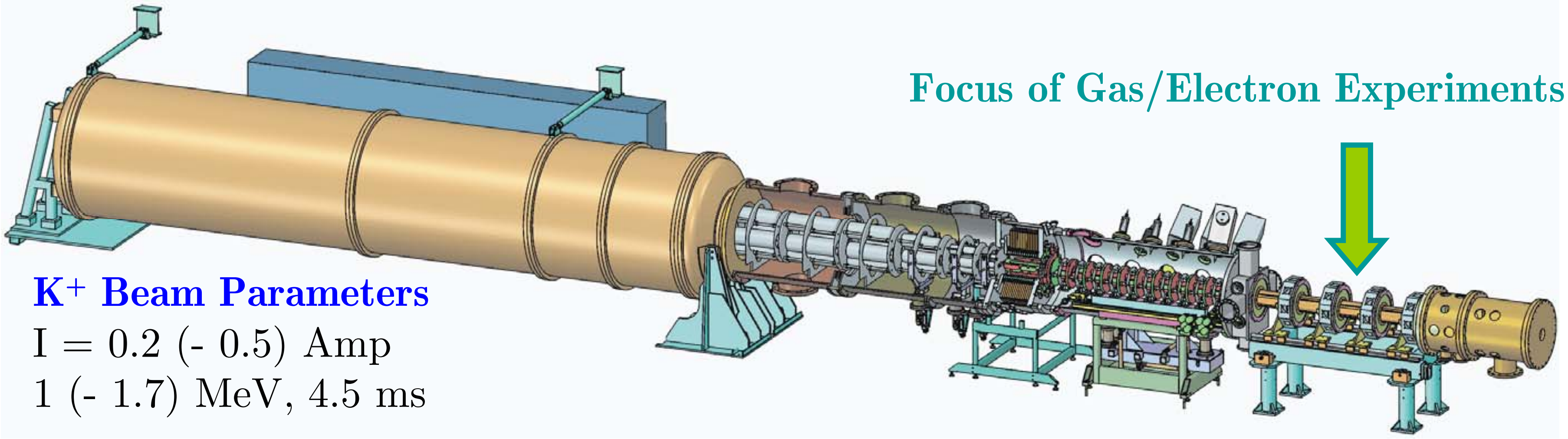


Compact transformer coupling (5:1 step-up)





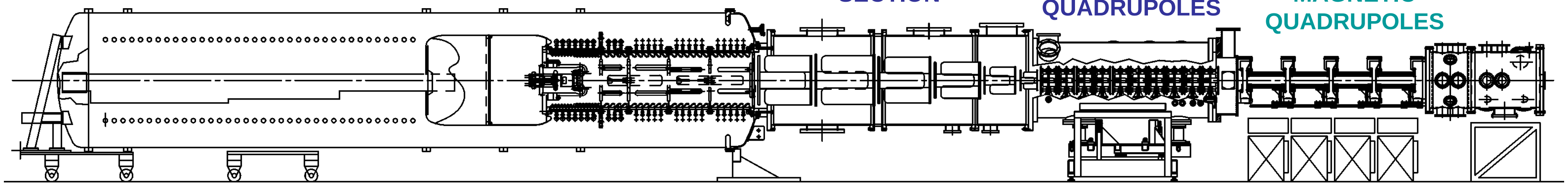
The High Current Experiment (HCX) explores beam transport limits

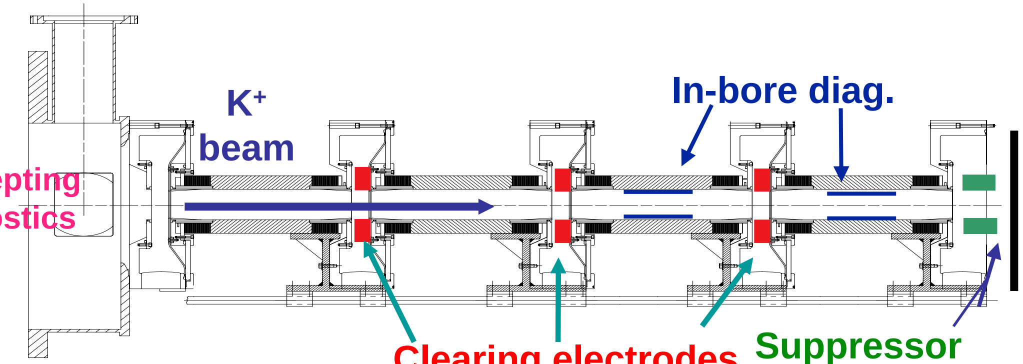


K⁺ Beam Parameters

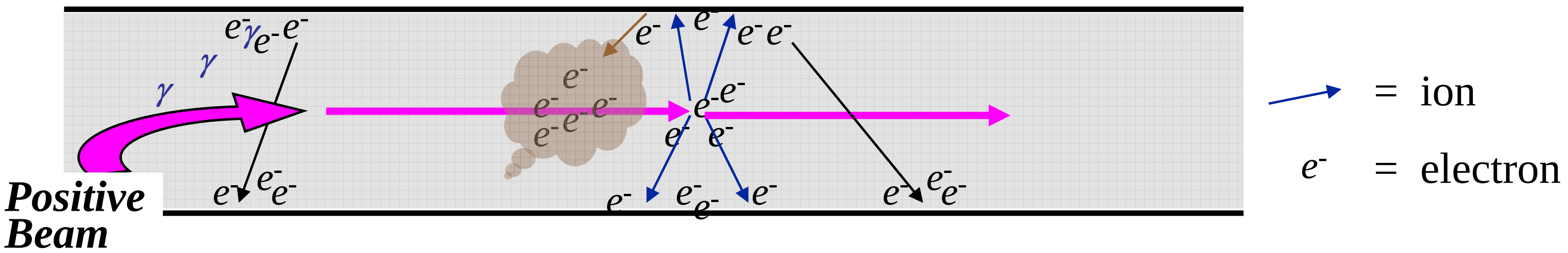
I = 0.2 (- 0.5) Amp

1 (- 1.7) MeV, 4.5 ms





High-brightness beam transport - electron effects on intense ion beams



<u>**Electron cloud caused by:**</u>

Synchrotron radiation

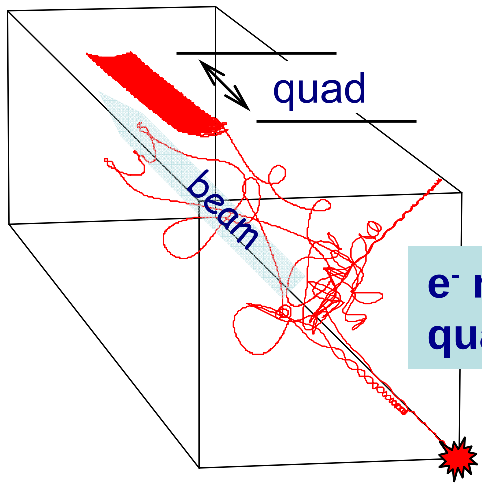
Secondary emission from e⁻ accelerated by beam

Beam halo scraping ⇒ e⁻ emission

Ionization of background gas

Expelled ions hitting vacuum wall

Ionization of desorbed gas

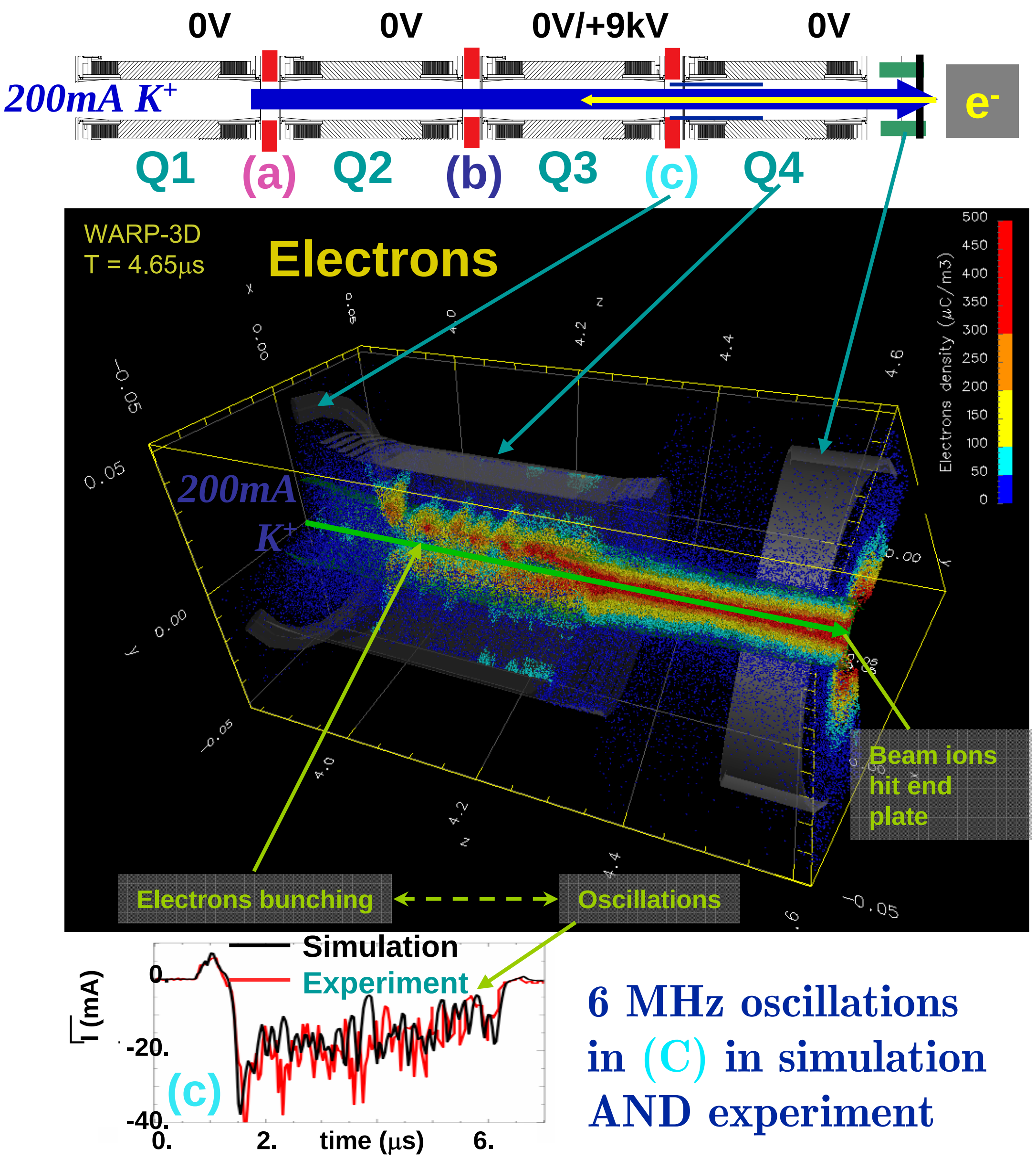


e⁻ motion in a quad

<u>**Goal:**</u> Advance understanding of the physical processes leading to the accumulation of electrons in magnetic quadrupoles in the HCX

A. Molvik, THAW02

WARP simulation of electron/gas cloud effects for HCX



6 MHz oscillations in (C) in simulation AND experiment

Electron and gas cloud modeling critical to all high current accelerators.

J-L. Vay, THAW01

Nonlinear Vlasov-Maxwell equations for high intensity beams

Collective dynamics described by the Vlasov equation

$$\left\{\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{x}} - \left[m_b\left(\omega_{\beta b}^2\mathbf{x}_\perp + \omega_z^2 z\mathbf{e}_z\right) + e_b(\nabla\phi - v_z c\nabla_\perp A_z)\right]\cdot\frac{\partial}{\partial \mathbf{p}}\right\} f(\mathbf{x},\mathbf{p},t) = 0$$

External focusing field:

$$\mathbf{F}_{foc} = -m_b\omega_{\beta b}^2\mathbf{x}_\perp - m_b\omega_z^2 z\,\mathbf{e}_z$$

distribution function on phase space

Self-electric and self-magnetic fields self-consistently determined from Maxwell's equations.

$$\nabla^2\phi = -4\pi e_b\int d^3p f(\mathbf{x},\mathbf{p},t),$$

$$\nabla^2 A_z = -4\pi c e_b\int d^3p v_z f(\mathbf{x},\mathbf{p},t).$$

$f(\mathbf{x},\mathbf{p},t)$ and (ϕ, A_z) nonlinearly coupled

δf particle simulation method reduces noise

$$f = f_0 + \delta f,$$
$$\phi = \phi_0 + \delta\phi,$$
$$A_z = A_{z0} + \delta A_z.$$

(f_0, ϕ_0, A_{z0}) – equilibrium

$(\delta f, \delta\phi, \delta A_z)$ – perturbation

Fully nonlinear

$$\frac{dw_i}{dt} = -(1 - w_i)\frac{1}{f_0}\frac{\partial f_0}{\partial \mathbf{p}} \cdot \delta\left(\frac{d\mathbf{p}_i}{dt}\right),$$
$$\delta\left(\frac{d\mathbf{p}_i}{dt}\right) \equiv -e_b\left(\nabla\delta\phi - \frac{v_{zi}}{c}\nabla_\perp\delta A_z\right),$$

Weight function $w \equiv \frac{\delta f}{f}$ dynamically determines δf

Statistical noise **significantly** reduced by a factor of $\frac{\delta f}{f}$

Beam Equilibrium Stability and Transport (BEST) Code

Physics

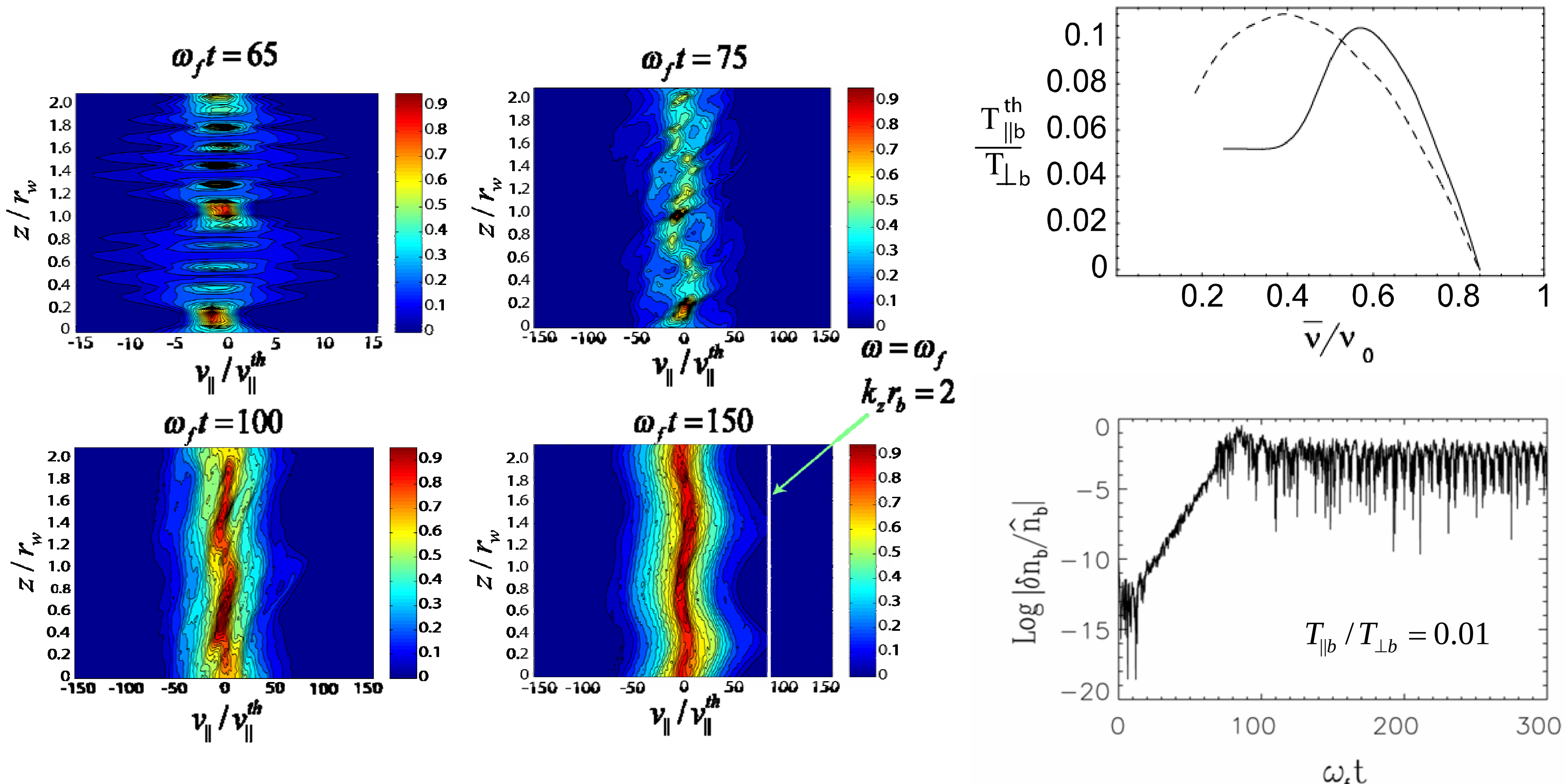
- Perturbative particle simulation method to reduce noise.
- Linear eigenmodes and nonlinear evolution.
- 2D and 3D equilibrium structure.
- Multi-species; electrons and ions; accommodate very large mass ratio.
- Multi-time-scales, frequency span a factor of 10^5.
- 3D nonlinear perturbation.

Computation

- Message Passing Interface
  - Multiple-1D domain decompositon (OpenMP by users).
- Large-scale computing: particle x time-steps ~ 0.5×10^{12}.
- Scales linearly to 512 processors on IBM-SP3 at NERSC.
- NetCDF, HDF5 parallel I/O diagnostics.

Strong Harris instability for beams with large temperature anisotropy

- ❑ Moderate intensity → largest threshold temperature anisotropy.
- ❑ Nonlinear saturation by particle trapping → tail formation.



E. A. Startsev, et al., Nucl. Instr. and Methods in Physics Research A554, 125(2005).

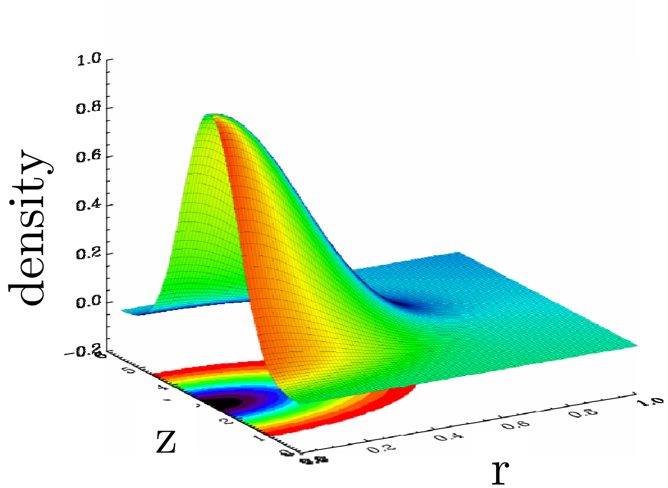
Collective excitation in 3D bunched beams

$$H = \frac{p^2}{2m_b} + e_b\phi + \frac{1}{2} m_b \left(\omega_{\beta b}^2 r^2 + \omega_z^2 z^2\right)$$

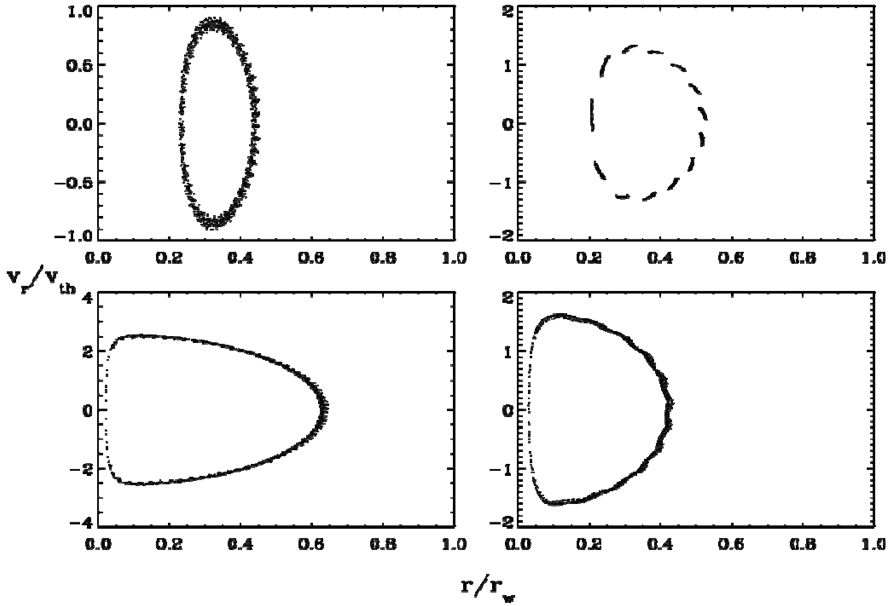
$$f_0 = f_0(H) = \frac{\hat{n}_b}{(2\pi m_b T)^{3/2}} \exp\left(\frac{-H}{T}\right),$$

$$\nabla^2 \phi_0 = -4\pi e_b \hat{n} \exp\left[-\frac{m_b\left(\omega_{\beta b}^2 r^2 + \omega_z^2 z^2\right)}{2T} - \frac{e_b\phi_0}{T}\right],$$

3D anisotropic quasi-equilibrium



Nonlinear space-charge effects reduce integrability of orbits in 3D

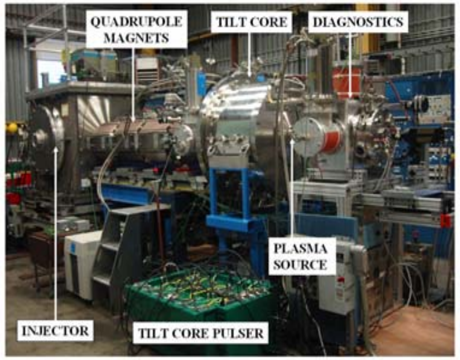


Chaotic particle dynamics

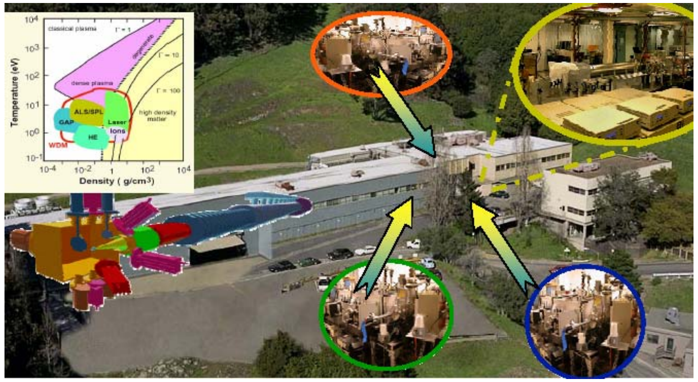
Program vision for next 10 years *(2006 update)*

Challenge 1: (NDCX-I) Understand limits to compression of neutralized beams. *Excellent progress (>50X longitudinal; > 200 transverse). Opportunities for many improvements*

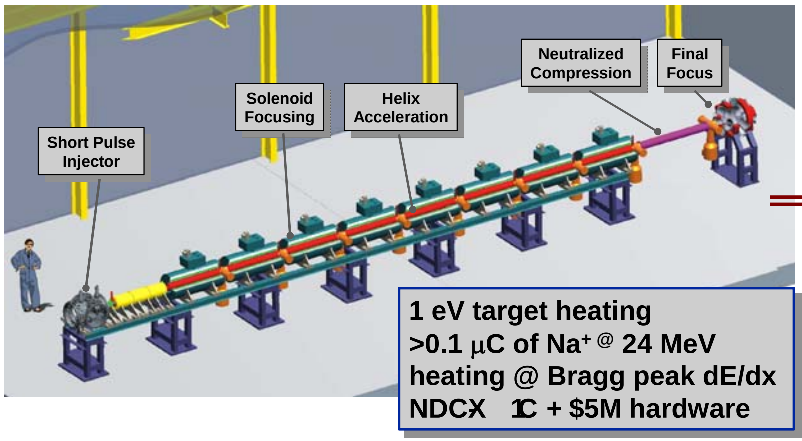
Challenge 3: Ion-HEDP user facility *CD-0 granted 12-1-05. CD-1 requires NDCX-II pre-requisite.*



Challenge 2: Integrated compression, acceleration and focusing sufficient to reach 1 eV in targets: *Assessing backup induction approach with 2 MeV Lithium.*

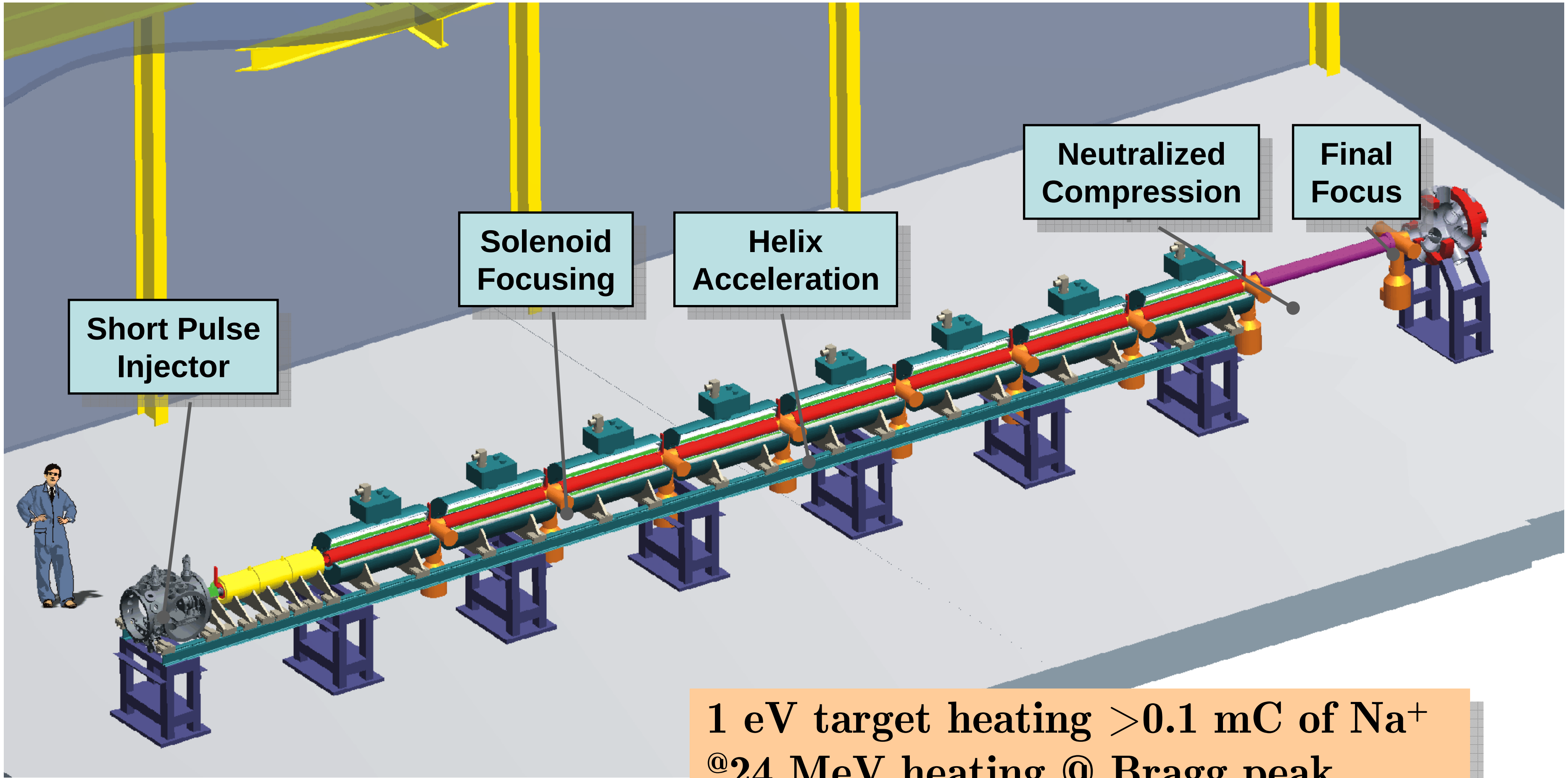


Add acceleration *(either PLIA or induction-TBD)*



Add chambers, targets, HEDP diagnostics

NDCX-I →NDCX-II to validate IB-HEDX (heavy-ion HEDP user facility)



1 eV target heating >0.1 mC of Na^+
@24 MeV heating @ Bragg peak
dE/dx NDCX-1C + $5M hardware

Conclusions

- **Many exciting scientific advances and discoveries that enable:**
  - Demonstration of compression and focusing of ultra-short ion pulses in neutralizing plasma background.
  - Unique contributions to High Energy Density Physics and Heavy Ion Fusion.
  - Contributions to cross-cutting areas of accelerator physics and technology, e.g., electron cloud effects, diagnostics, advanced simulation techniques, beam interaction targets.
- **Heavy ion research on neutralized drift compression and e-cloud effects is of fundamental importance to both HEDP in the near term and to fusion in the longer term.**
- **Theory and modeling play a key role in guiding and interpreting experiments.**
- **There are new tools and knowledge to update studies of heavy ion fusion.**