Status and new physics directions for heavy-ion-driven high energy density physics and fusion*

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U.S. Institutions Participating in Heavy Ion Fusion Research

UC Berkeley
UC Los Angeles
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Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Princeton Plasma Physics Laboratory
Mission Research Corporation
Los Alamos National Laboratory
Sandia National Laboratories
University of Maryland
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Tech-X
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Outline of talk

1. **Research progress over the last year on selected key issues affecting high intensity heavy-ion beam propagation.**

2. **New research beginning on neutralized beam compression and focusing relevant to high energy density physics and fusion.**

3. **Conclusions**

Heavy Ion Beam Research

An important scientific question fundamental to future applications of heavy ion beams to both high energy density physics and fusion:

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

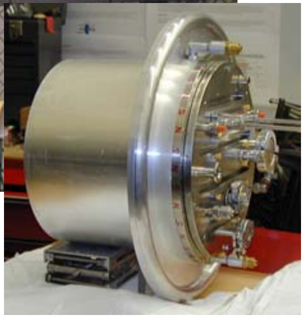
Subsidiary science thrusts needed to address this top-level question:

- **Determine the technical requirements for preserving high beam brightness during the acceleration, transport and focusing of intense high-current ion beams.**
- **Develop a basic understanding of how beam-plasma interactions can be used to optimize the focusing of intense ion beams to a small spot.**
- **Determine the conditions under which the shortest pulses are achievable with longitudinal drift compression.**
- **Determine how uniformly warm dense matter can be heated with tailored short-pulse ion beams.**
- **Develop integrated source-to-target simulation capability for robust modeling of intense heavy ion beam propagation from the source through final focus onto the target.**

We have completed key experiments important to the quality of large, high current injected beams (LLNL)

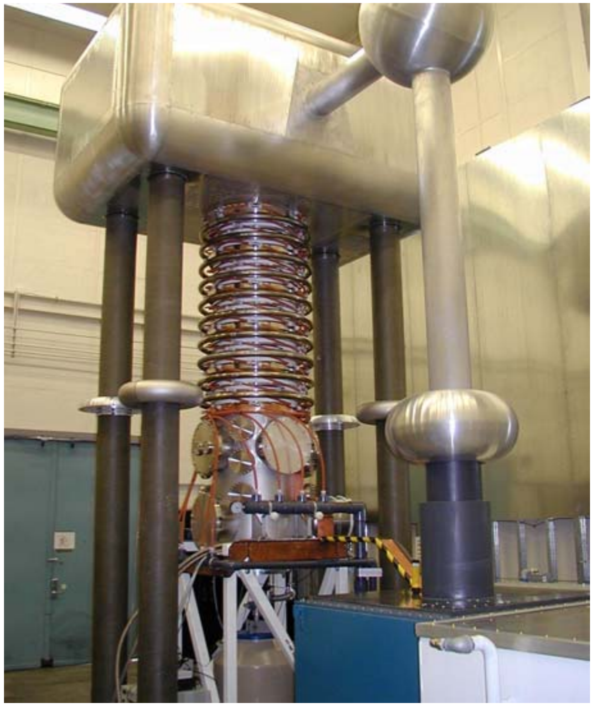
→ We measured and modeled beam optics of a large surface ionization source, successfully bench- marking simulations

→ We have tested new high current density, high brightness multiple beamlet sources needed for the next experiment test merging beamlets for compact driver-scale injectors.



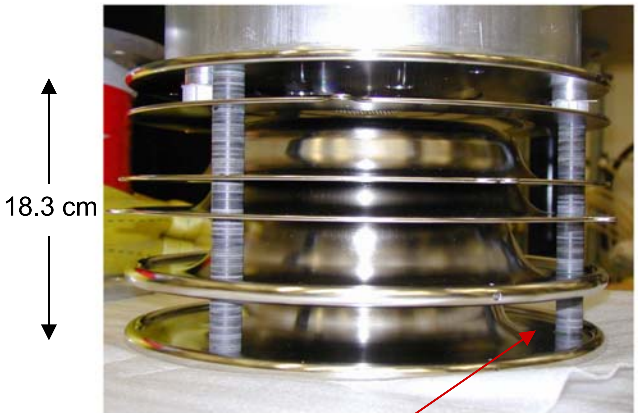
STS-100 Source test stand

Two LLNL injector test stands



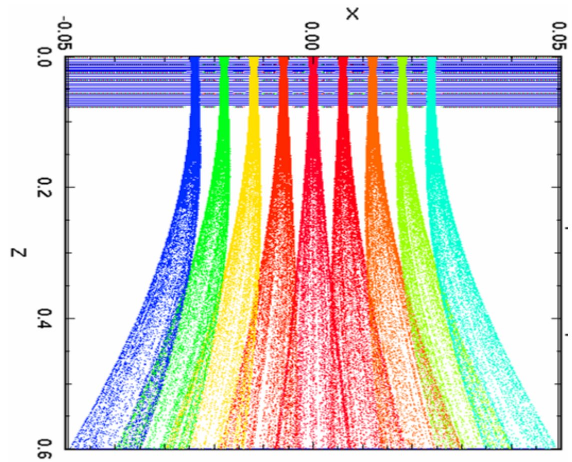
STS-500 Injector test stand

1stQTR-FY05: First step towards merging-beamlets in STS: extraction and merging of 61 beamlets at high current density >100 mA/cm^2 and full gradient > 100 kV/cm (not yet in converging geometry)

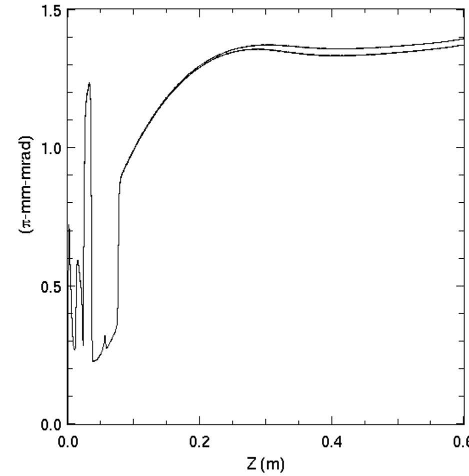


High Gradient Insulators held 30 kV/cm

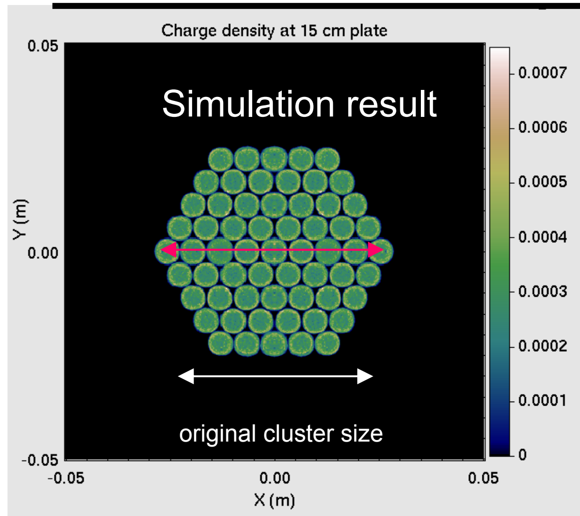
Warp 3D simulation of beamlets expand and merge downstream

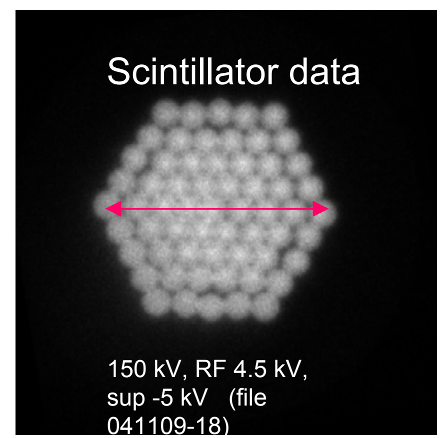


Normalized emittance (x and y) reaches steady state value



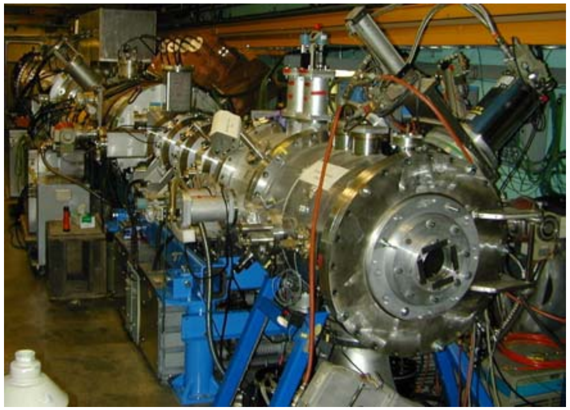
Excellent agreement between experimental data and simulation



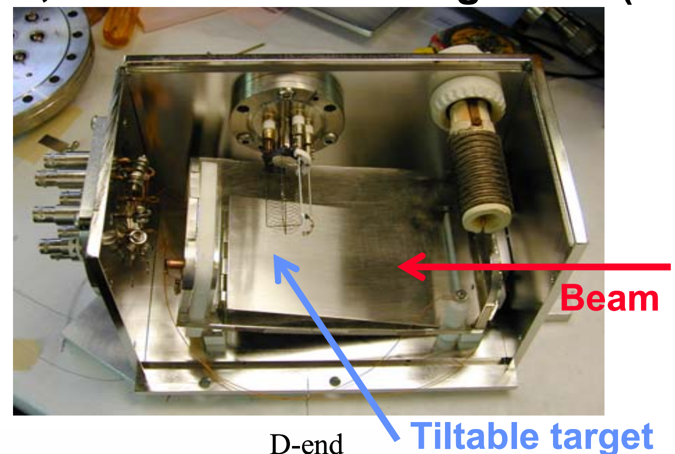


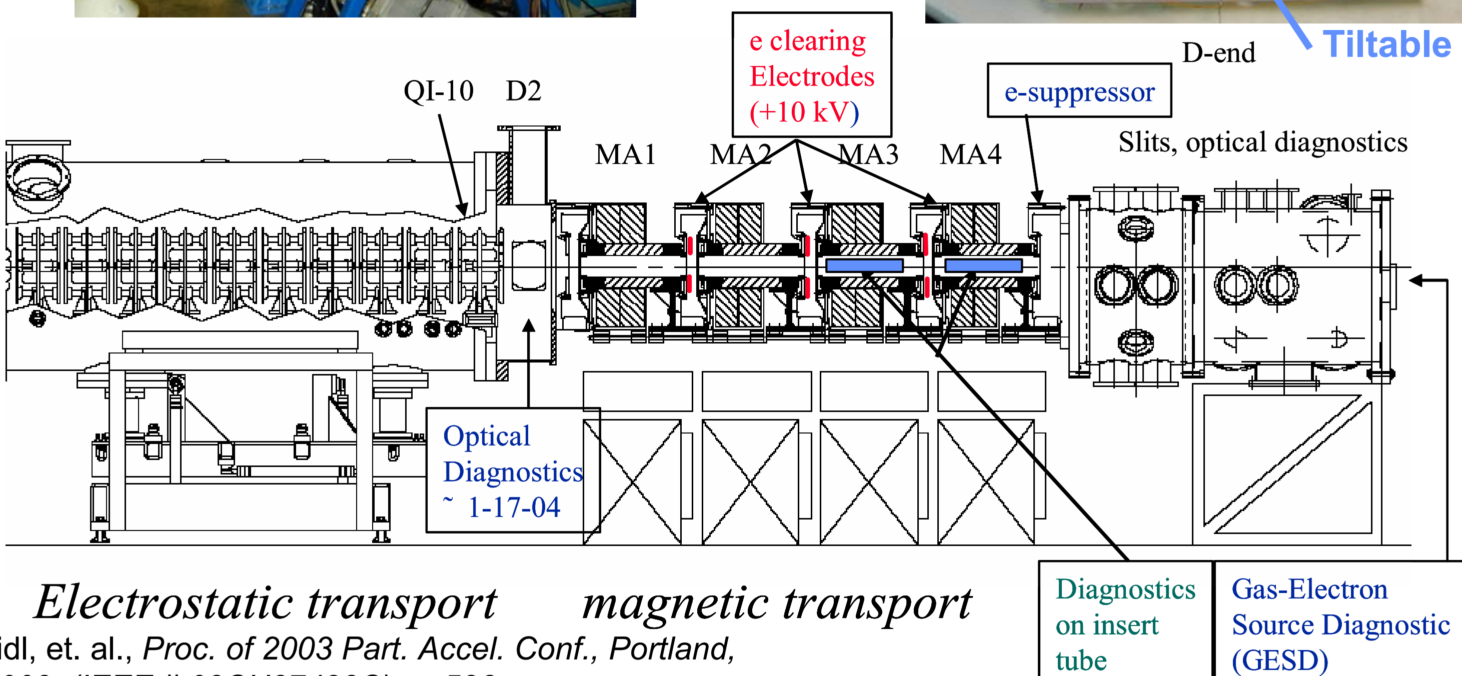
Since 2002, HCX (LBNL) has explored transport to high fill factors in ten electric quads*, and gas/electron cloud effects in four magnetic quads.

The HCX with magnetic quad section (2003)



Gas, electron source diagnostic (GESD)



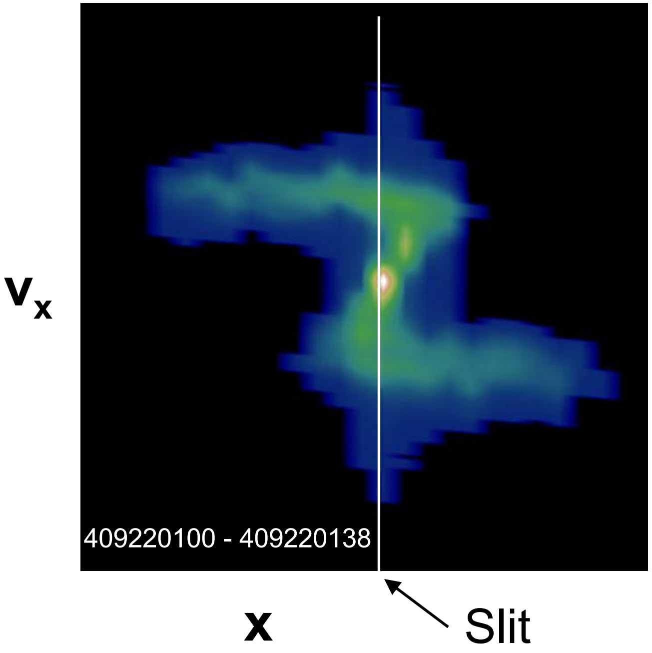


*P. Seidl, et. al., *Proc. of 2003 Part. Accel. Conf., Portland, USA 2003, (IEEE # 03CH37423C)*, p. 536

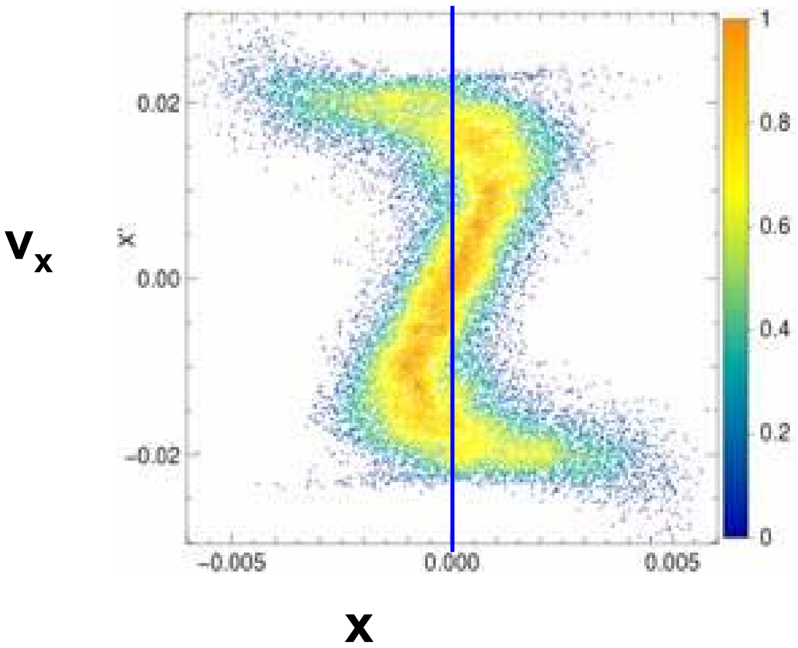
We have successfully simulated electron cloud effects on *ion beam dynamics in HCX* with WARP in 3D using models of electron emission and reflection, and a new electron mover algorithm (Ron Cohen).

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

Measured v_x vs x.



3-D simulation of electron cloud affecting ion beam v_x vs x



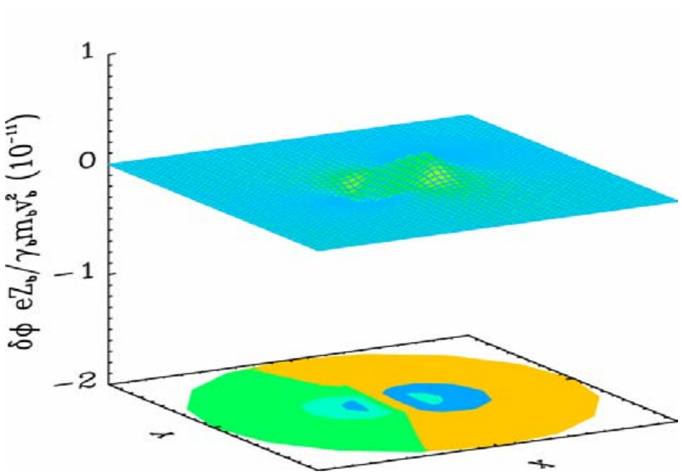
→This multi-species modeling capability is key to a predictive capability for electron cloud effects in any high intensity accelerator.

Electron-Ion Two-Stream (Electron Cloud) Instability*

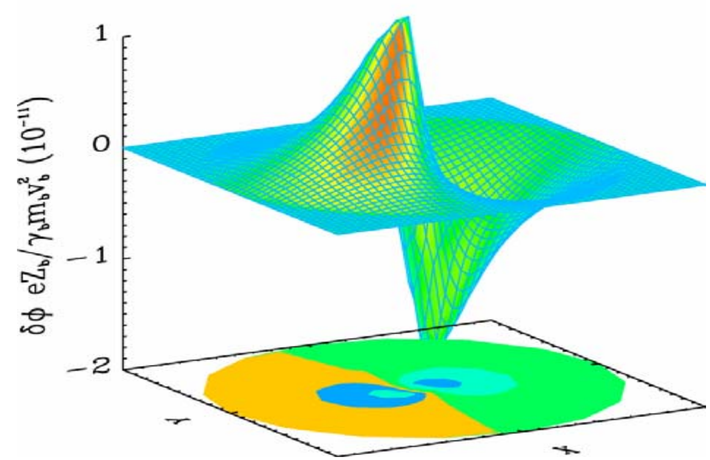
Proton storage ring (PSR) experiment at Los Alamos observes strong electron-proton (e-p) two-stream instability.

Electron-proton instability could also limit the achievable beam intensities for the Spallation Neutron Source and other high intensity accelerators.

δf simulations show that the l=1 dipole mode is destabilized by a background electron population. Mode characteristics and excitation frequencies are consistent with the BEST simulations.



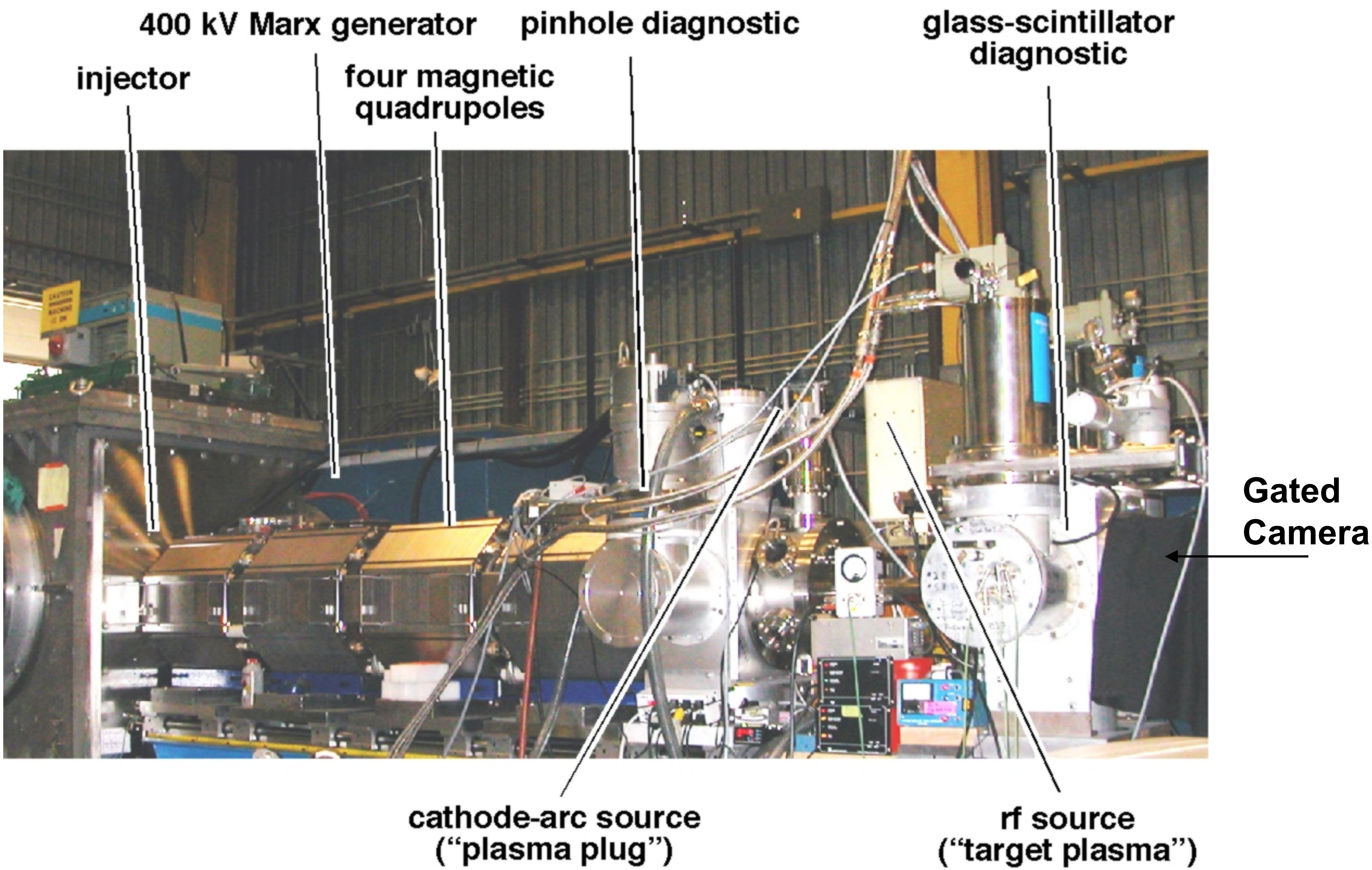
t=0



$t=200/\omega_{\beta b}$

*H. Qin, E. A. Startsev and R. C. Davidson, Phys. Rev. Special Topics on Accelerators and Beams **6**, 014401 (2003)..

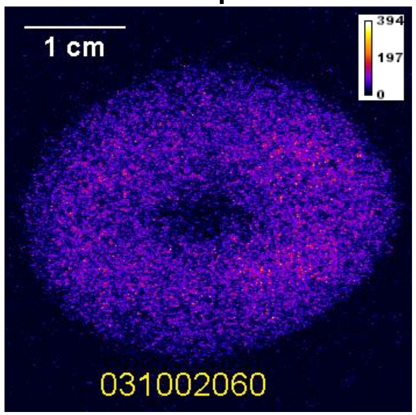
The Neutralized Transport Experiment gave us confidence that plasma could neutralize intense heavy-ion beam space charge for ballistic focusing without strong beam-plasma instabilities



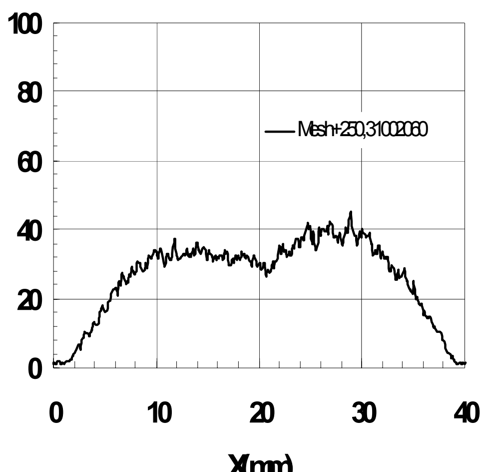
Plasma neutralization of space charge for a high perveance (6 x10^{-4}) 25 mA, 300 keV K^+ beam reduces beam focal spot size by 10 x, consistent with particle simulations*

After magnetic focus, data and calculated beam density profiles agree well, except for halo.

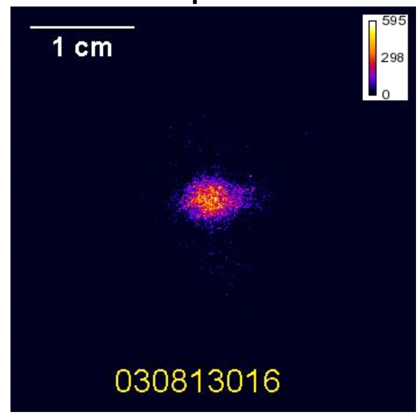
Non-neutralized transport



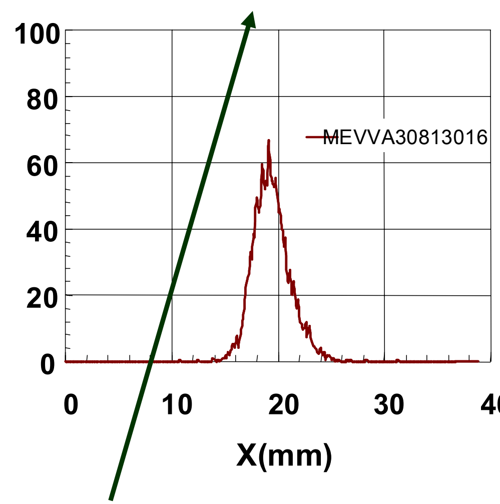
FWHM: 2.7 cm



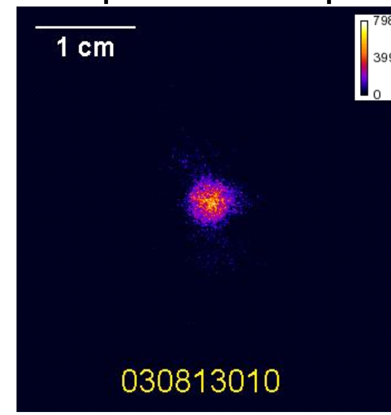
Effect of plasma plug on spot size



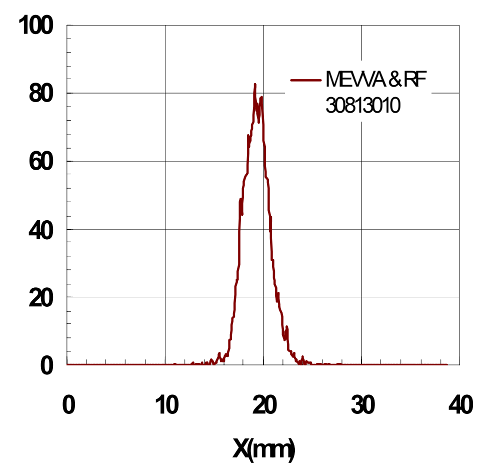
FWHM: 2.83 mm



Effect of plasma plug and volume plasma on spot size



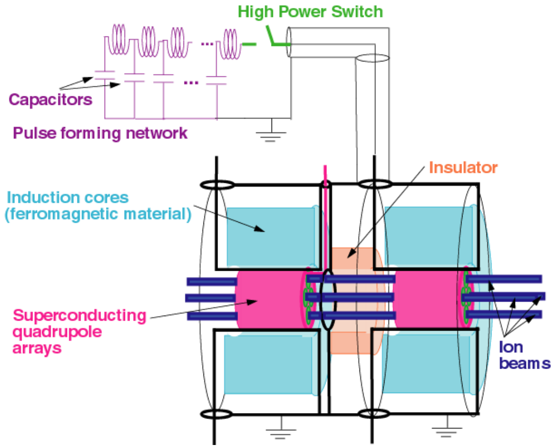
FWHM: 2.14 mm



***Simulations (C. Thoma, D.R. Welch, S.S. Yu, P.K. Roy, S. Eylon, and E.P. Gilson, submitted to Physics of Plasmas, September 2004) predict 1.4 mm rms spot radius for plug plasma case**

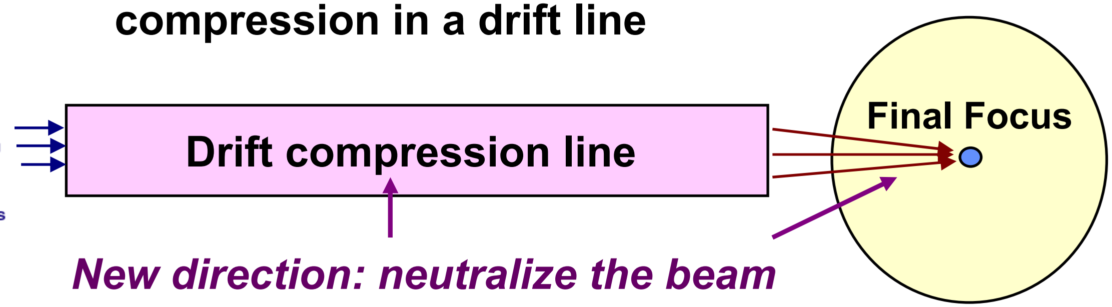
Creating warm dense matter and fusion ignition conditions requires *longitudinal* as well as *transverse* beam compression

Induction acceleration is most efficient at τ_{pulse} ~100 to 200 ns



Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

Near term High Energy Density targets require ~ 1 ns pulses; Fusion requires ~ 10 ns

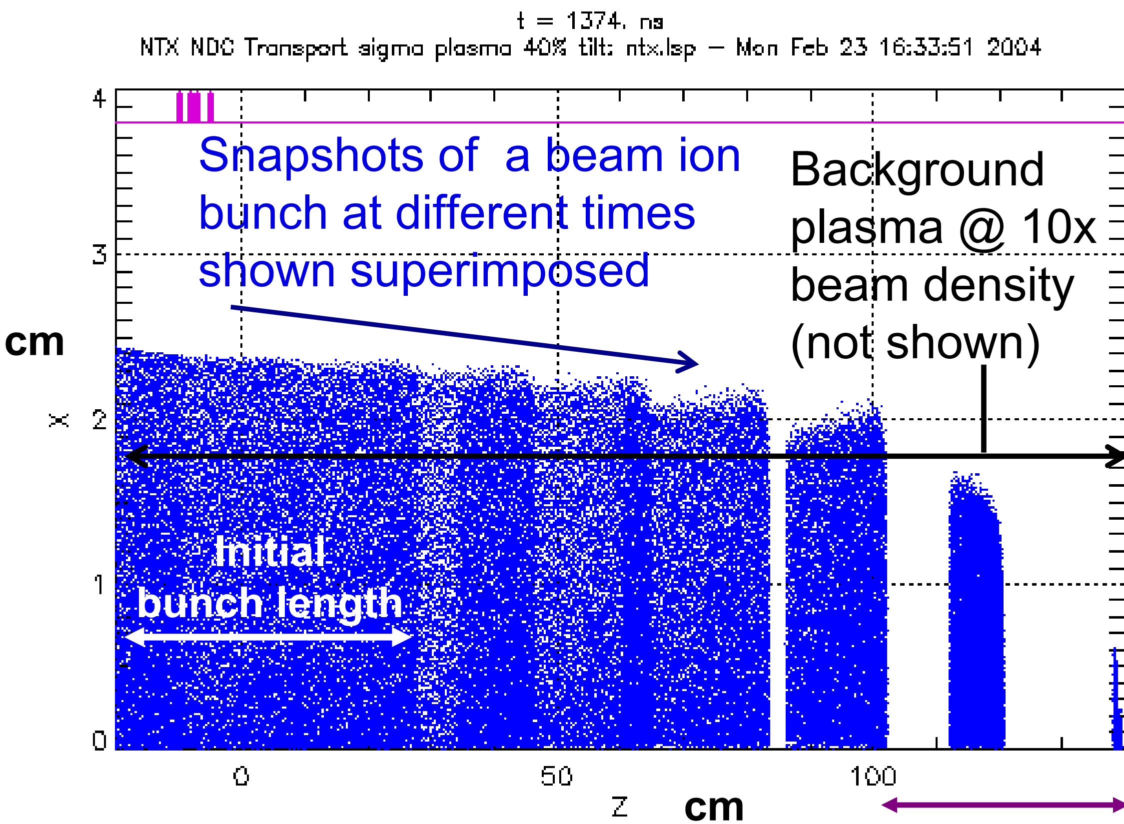


New direction: neutralize the beam space charge both in longitudinal drift compression as well as in final focus

Issues that need more study and experiments:

1. **Beam-plasma instabilities during compression.**
2. **Beam heating due to compression (conservation of longitudinal invariant)**
3. **Chromatic focus aberrations due to velocity spread**

We are assembling an experiment to test neutralized beam compression: LSP-PIC simulations of proposed experiment show dramatically larger compressions of tailored-velocity ion beams *inside a plasma column*



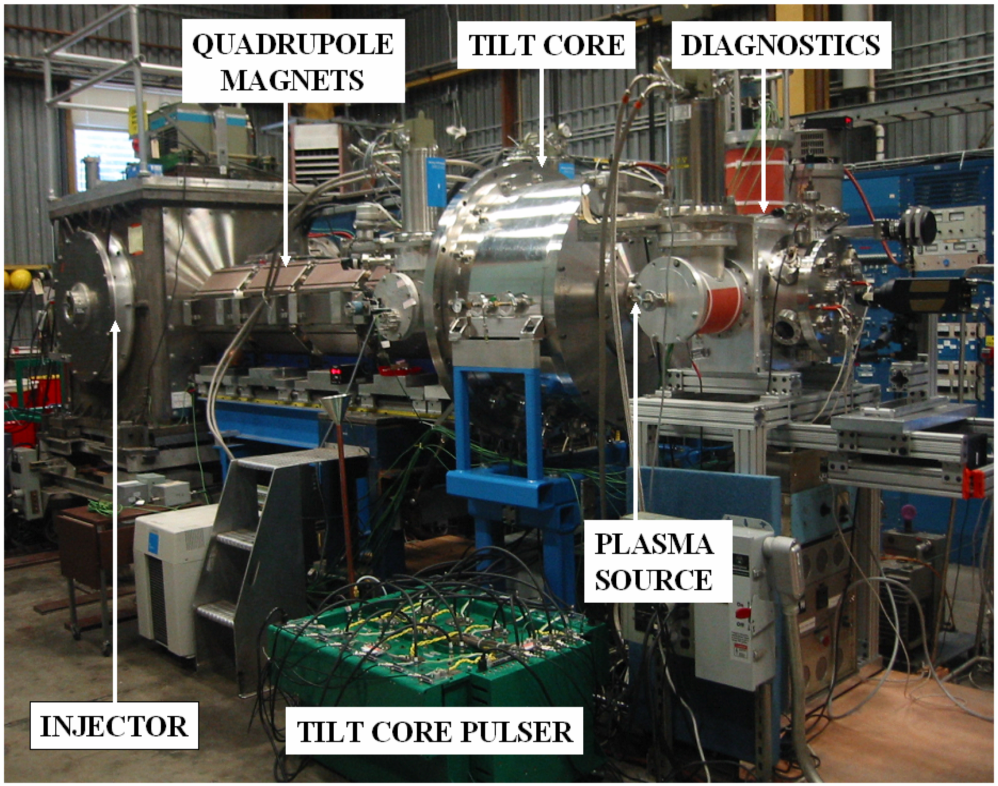
←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

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

Existing 3.9T solenoid focuses beam

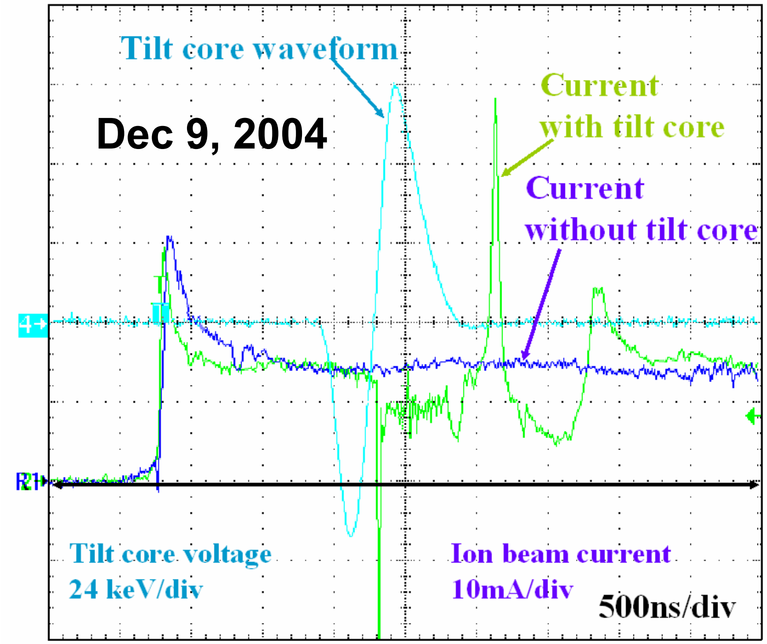
- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with n_p>>n_b, and B_z field [D. Welch, D. Rose (MRC), , I. Kaganovich (PPPL)]**

First Demonstration of Longitudinal Compression in NDCX

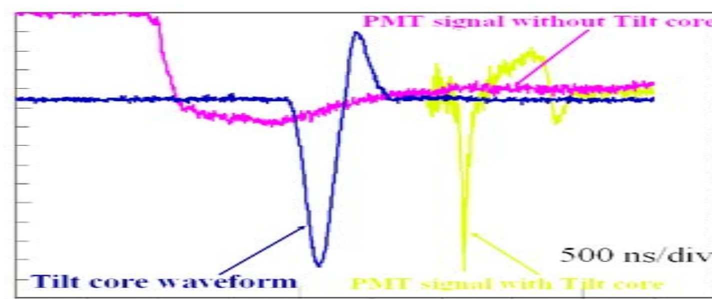


NDCX Beamline

(December 1, 2004)



Beam current (Faraday cup)



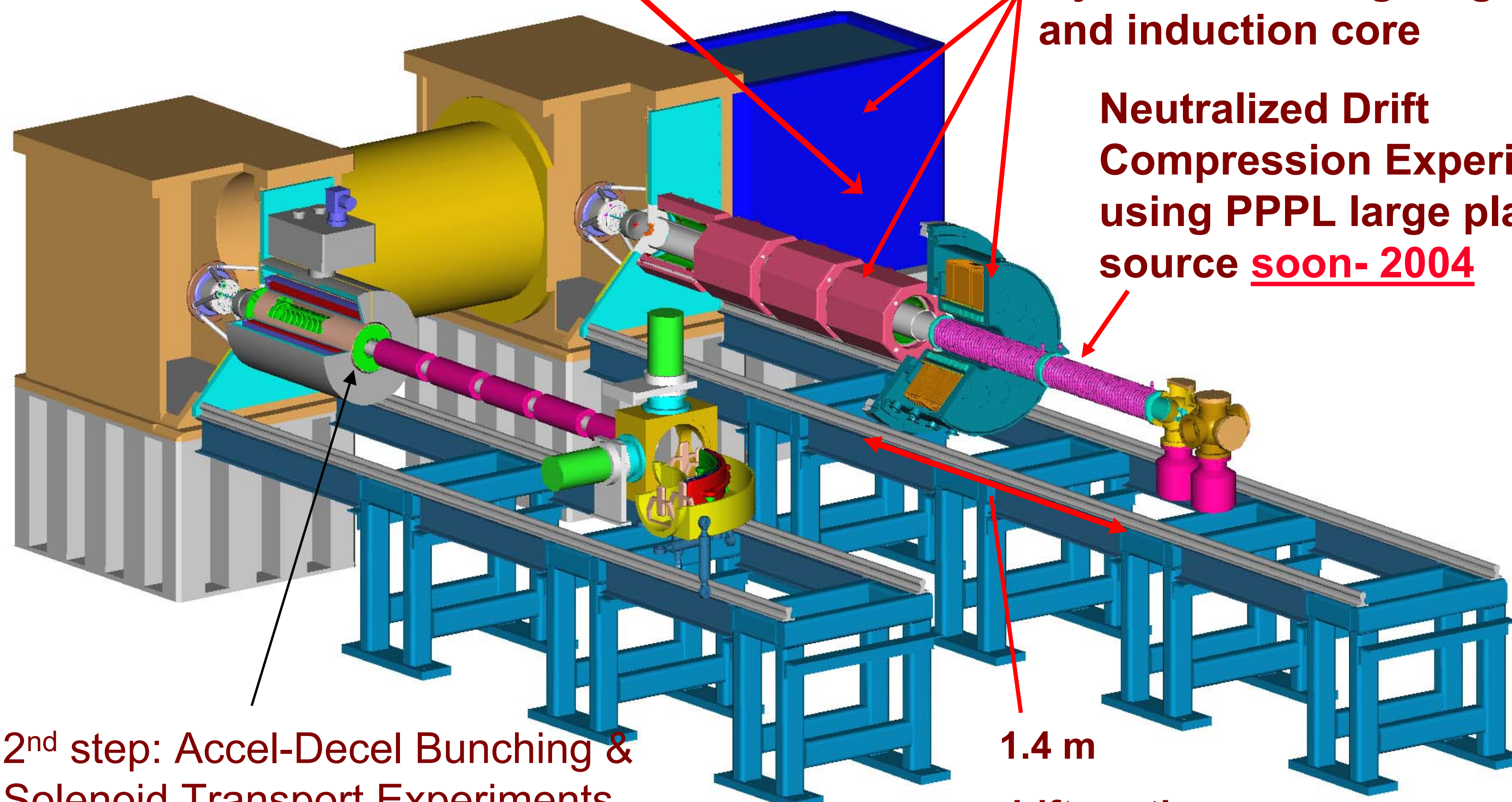
Corroborating optical diagnostic (PMT)

First experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (NDCX-I, before upgrade to NDCX-II)

First neutralized drift experiment using existing equipment

Existing LBNL 400 kV injector, focusing magnets and induction core

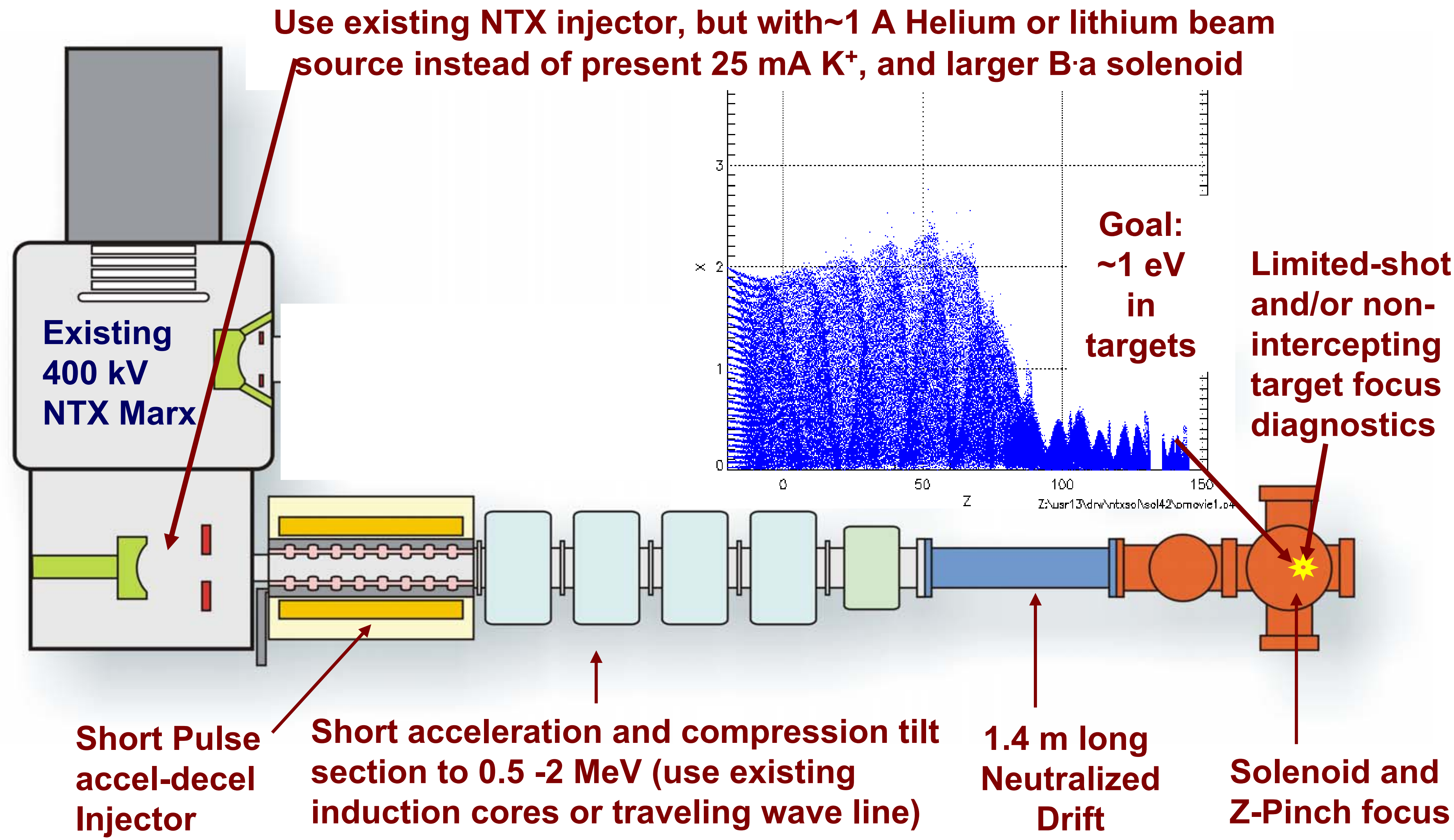
Neutralized Drift Compression Experiment using PPPL large plasma source soon- 2004



2nd step: Accel-Decel Bunching & Solenoid Transport Experiments using existing solenoids and pulsers

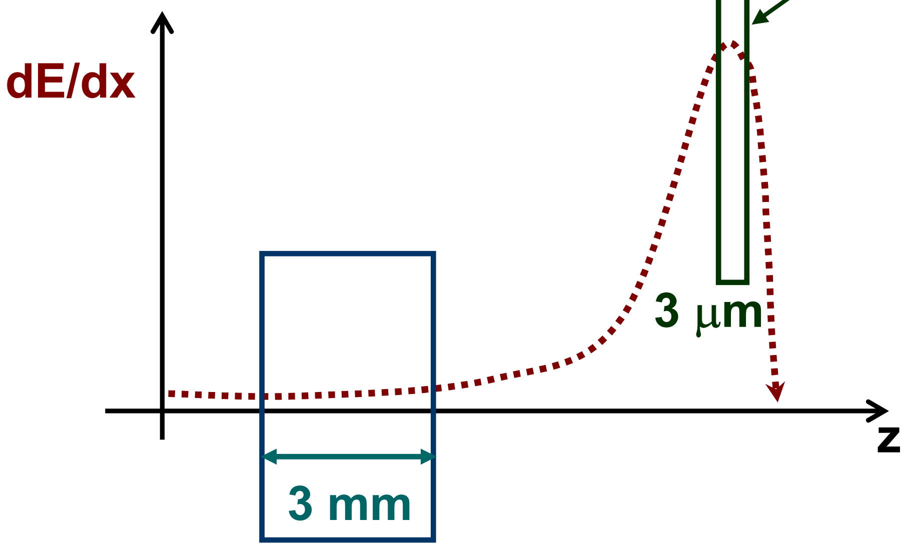
1.4 m drift section

Five-year goal: Integrated beam and target experiments at nominal solid target temperatures of 1 eV (NDCX-II)



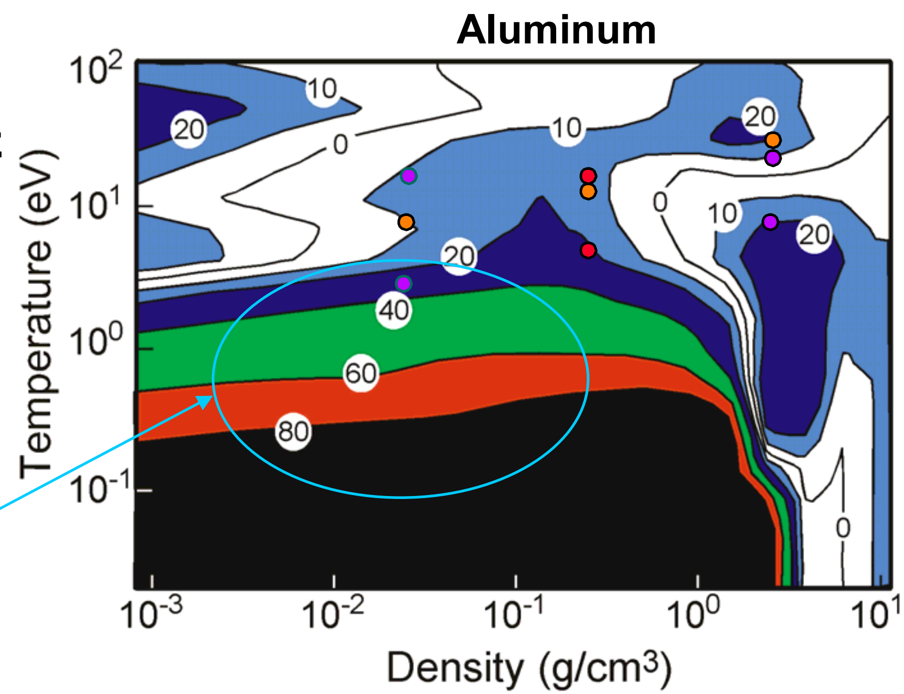
New research examines using short pulses with neutralized compression for high energy density physics experiments.

Ion energy loss rate in targets



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

Maximum dE/dx *and* uniform heating at Bragg peak require short (< 1 ns) pulses to minimize hydro motion. [L. R. Grisham, Physics of Plasmas, in press (2004)].
→Te > 10 eV @ 30J, 30 MeV (Future US accelerator for HEDP)



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)

Key areas for further research in neutralized beam drift compression and focusing for high energy density physics and fusion:

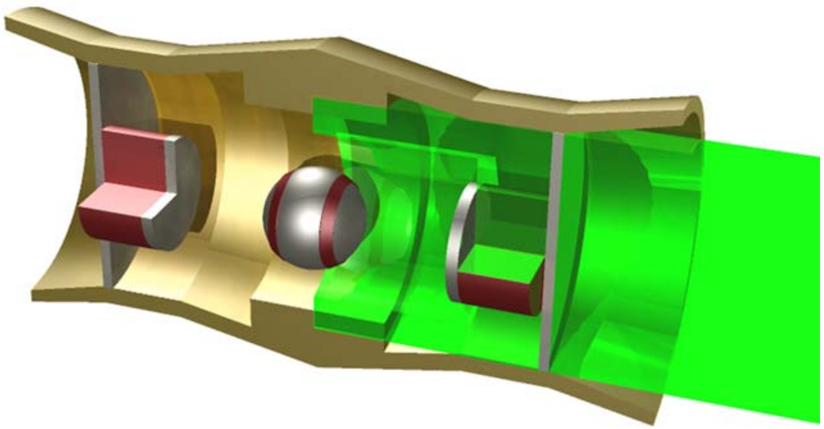
- Injection/acceleration/bunching to high beam space charge (perveance > 10^{-2}) with sufficiently low parallel and transverse emittances before plasma neutralization.

- Beam transitions at high line-charge densities from Brillouin flow into neutralizing plasma columns with tolerable emittance increases.

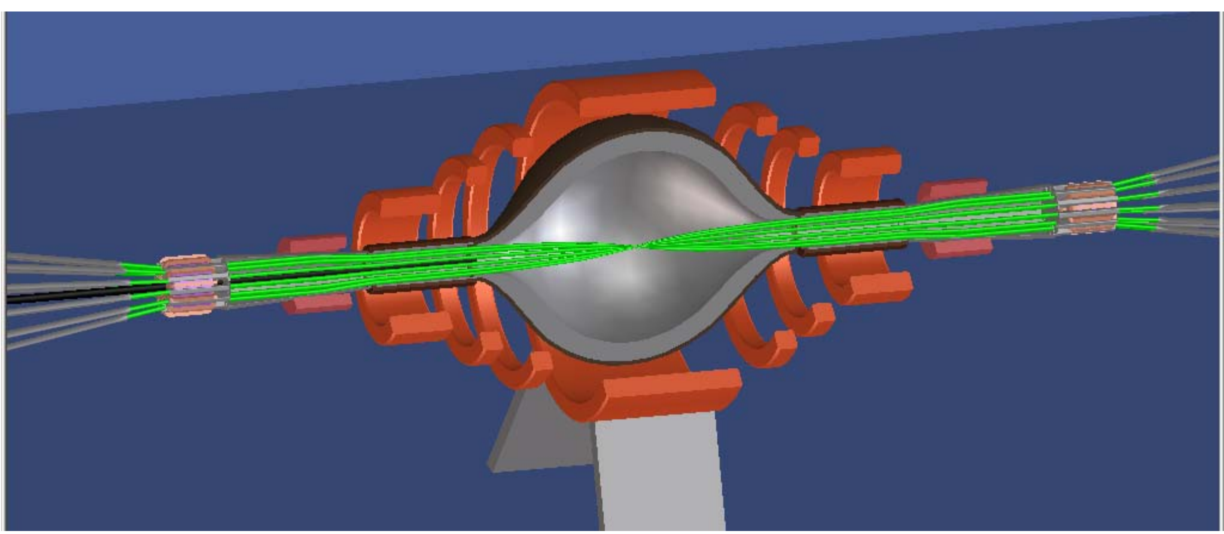
- Control of beam plasma instabilities over long regions of drift compression in background plasma, and controlled stripping.

- For fusion, validation of symmetry control techniques in large-focal-spot hybrid targets (LLNL and SNL joint experiments on Z)

Research on neutralized rift compression and focusing of velocity "chirped" beams for HEDP could lead to improved concepts for heavy ion fusion



"Hybrid" target allows large 5 mm radius focal spots (D. Callahan). Uses low cost manufacturing methods for hohlraums with foam x-ray converters (D. Goodin).



Neutralized ballistic, solenoid-focused, plasma-filled liquid Flibe-wall vortex chamber concept (Per Perterson, UCB)

SUMMARY

- With advanced theory and simulation tools, we have made excellent progress over the last three years understanding limits to high intensity heavy-ion beam propagation at higher currents (25-180 mA) in the STS, HCX, and NTX heavy ion beam experiments.

- With NTX experiments and advanced theory and simulation tools, we have learned how to apply plasma neutralization to improve intense beam focusing and to apply that knowledge to new experiments for neutralized beam longitudinal compression.

- Over the next 5 years we hope to show the feasibility of delivering 1 ns heavy-ion pulses for high energy density physics applications.

- Neutralized beam compression and focusing may also lead to future improved heavy-ion fusion.

The new heavy-ion research is directed to address the scientific question central to both high energy density physics and IFE:

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

Backup slides

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

In simplest example, target is a foil of solid or "foam" material

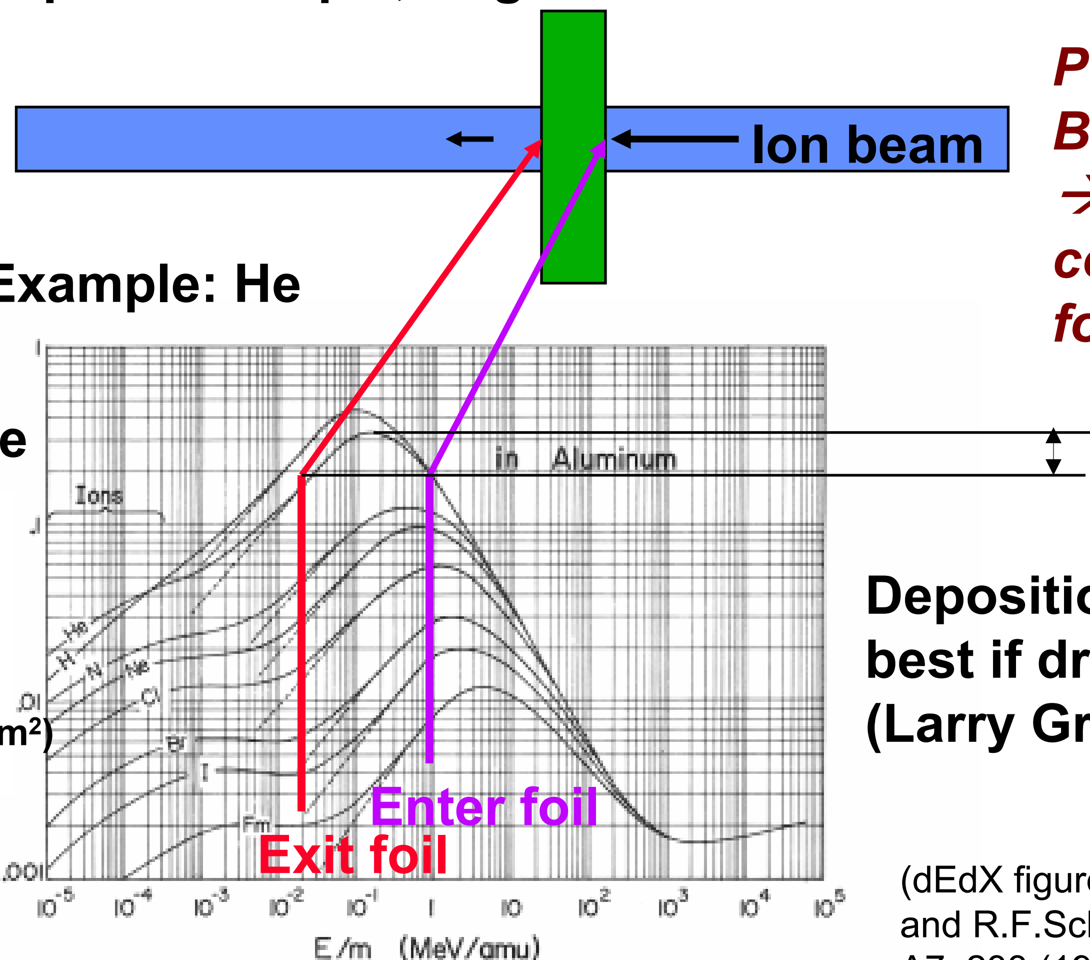
Perveance of beams at Bragg peak are high →require neutralized compression and focusing.

Example: He

Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm²)



ΔdE/dX ∝ ΔT

Energy/Ion mass **(MeV/amu)**

Deposition rate and uniformity best if driven at Bragg peak (Larry Grisham, PPPL).

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))

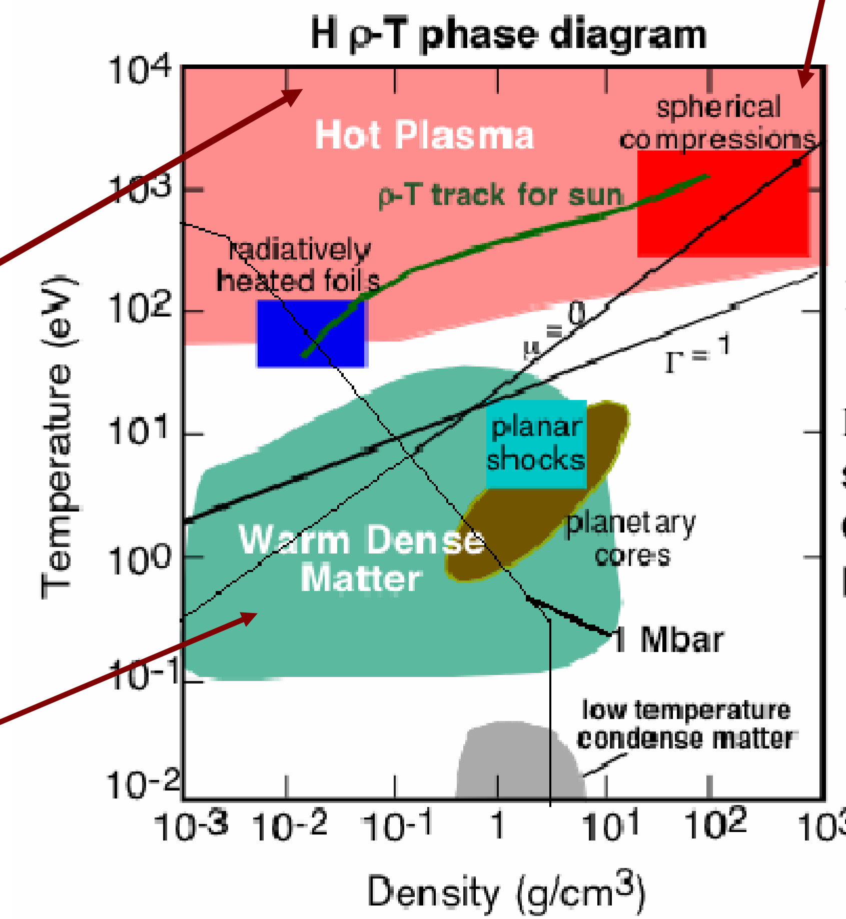
HEDP has rich discovery potential

Fusion: ***Effects of 3-D RT instabilities on burn propagation (NIF)***

Quark-gluon plasmas ***in heavy-ion nuclear collisions (way off scale in this chart)***

Fast igniter physics:
fast electron dissipation enhancement via collective instabilities

Strongly-coupled plasmas:
Many ab-initio theories of strongly coupled plasmas remain un-resolved by existing laser data



$$\Gamma = \frac{q^2 n^{1/3}}{kT}$$

$\Gamma > 1 \Rightarrow$ strongly coupled plasmas

HEDP definition: $U > 10^{11}$ J/m^3; $P > 1$ Mbar; $kT > 1$eV

Uniform isochoric heating is desirable to enable EOS measurements accurate enough to distinguish different *ab initio* WDM theories

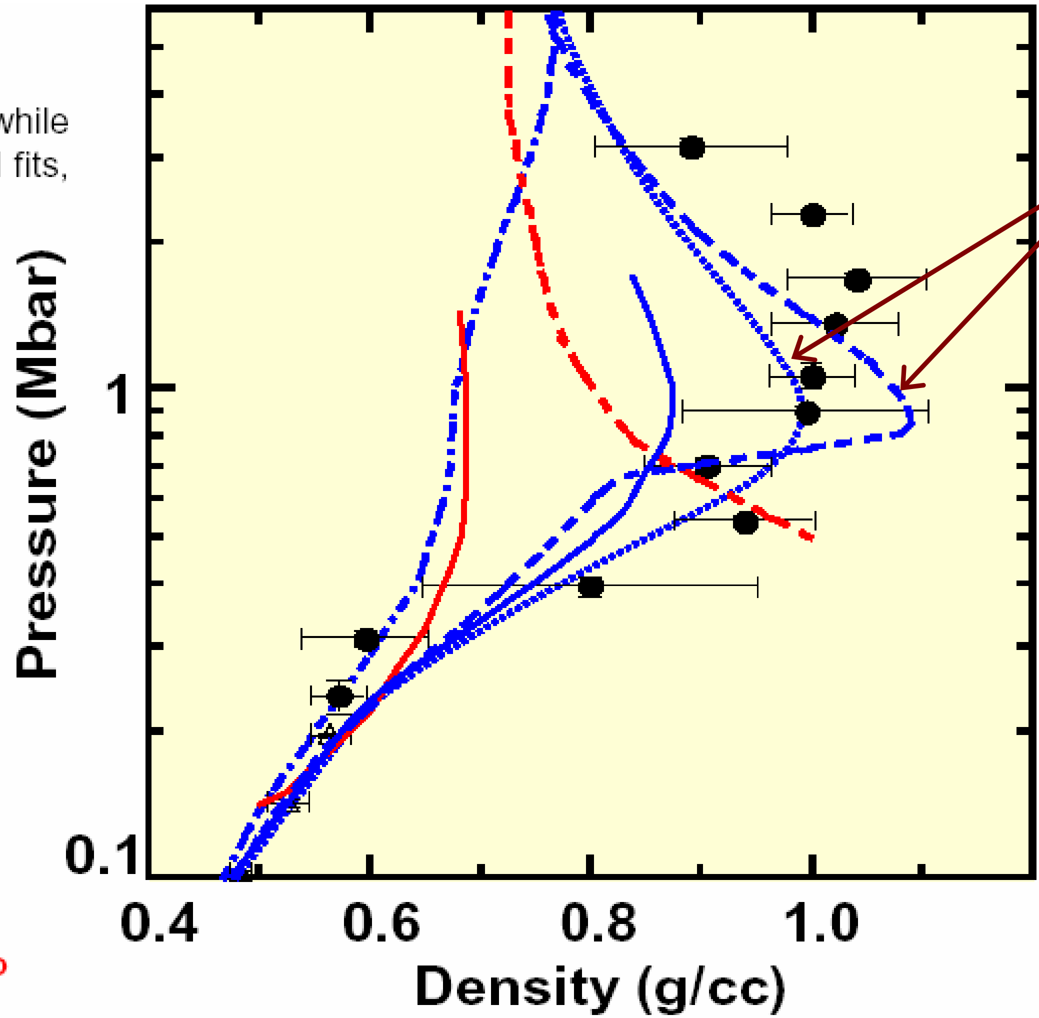
- High pressure H data shows that no theory provides agreement; while models, with empirical fits, are better

-·- Kerley/Sesame
— Redmer-Beule
- - - Saumon-Chabrier
······· Ross

● Data

Simulation

— Tight-binding MD
-·— Quantum Monte Carlo



Variations in temperature or density *<u>less than a few percent over diagnostic resolution volumes</u>* needed to distinguish various theories

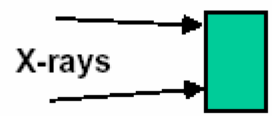
HEDP science would benefit from a variety of facilities offering different tools, shots on demand, and different convenient locations for students

WDM regimes are presently accessed by heating a solid (most useful) or by compressing/ shock heating a gas. Volume and uniformity set limits to accuracy of EOS measurements.

- Foils preheated by hard x-rays

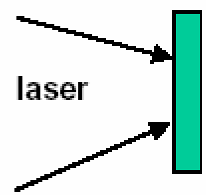
XFEL heating uniform but small volumes (10's of millijoules). High range electrons can heat < 1 mm spots –but too small for diagnostics

- Supersonically heated foams or low Z materials (thermal x-rays)



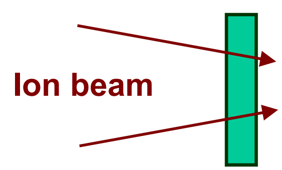
MJ of soft-x-rays available on Z but limited number of shots

- Shock compressed and heated thin foils



Lasers absorb at critical density << solid density→ large density/ pressure gradients

- Ion heated thin foils

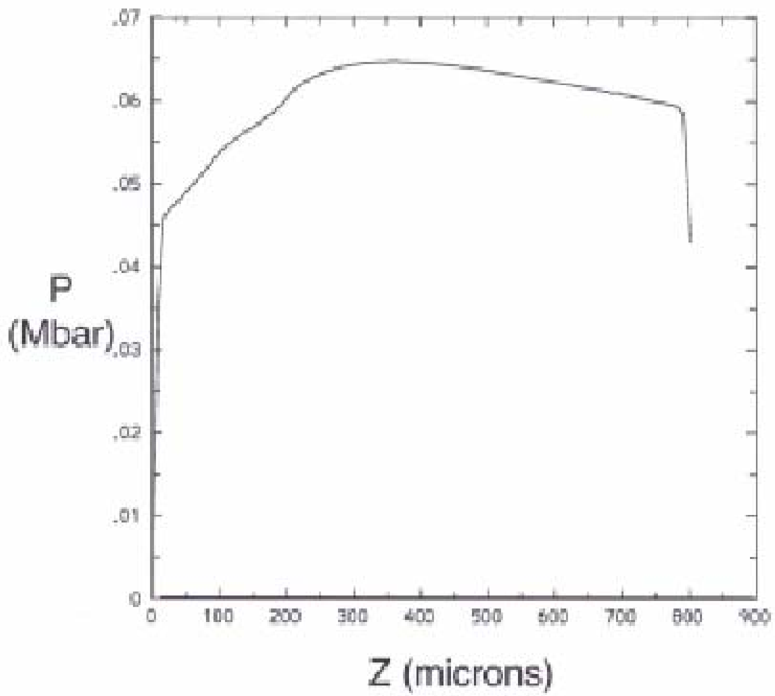


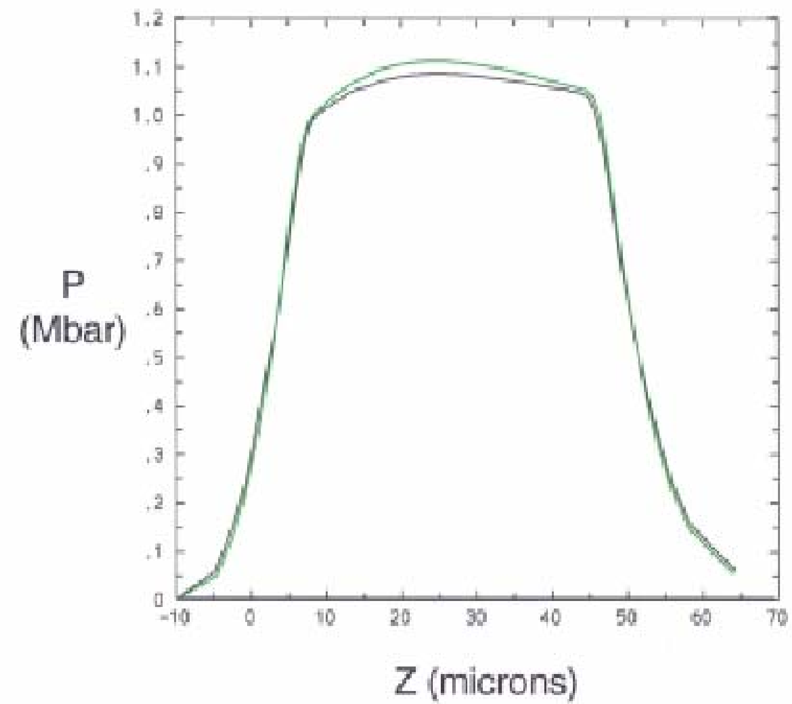
Fast heating of a solid with penetrating ions →lower gradients→ more accurate EOS

- 100TW lasers →10-50 mJ, ps ion bunches →large energy spreads, non-uniform deposition
- GSI-SIS-100 plans 10-40 kJ of ions @100GeV,100 ns→ large volumes but limited T < 1 eV

1-D hydro calculations of aluminum foam target examples driven by "Ten-yr goal machine" parameters. (Slide courtesy of D. Callahan and M. Tabak, LLNL)

Ne+1 ions, 30 J total beam energy, 30 MeV kinetic energy, 20 - 40 MeV energy spread, 1 mm radius at best focus, 3.8 TW/cm^2 center of beam, 0.5 ns pulse duration





1% solid density
800 microns thick

15% solid density
53 microns thick

Combining low Bragg peak energy, target energy densities >10^{11} J/m^3, and pulses shorter than target expansion times (<1 ns) leads to >10^{13} ions/cm incident on target →needs beam compression experiments

- →Requires focusing in neutralizing plasma (otherwise high perveance > 0.1 !)
- →Requires perveance x longitudinal compression ratios > 0.1 upstream

ρ(g/cm^3)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (μ)	480			48			4.8		
kT (eV)	3.1	4.8	15	4.2	7.3	18	5.9	12	22
Z^*	1.1	2.1	2.7	0.56	1.7	2.6	0.56	1.2	2.5
$\Gamma_{ii}=Z^{*2}e^2n_i^{1/3}/kT$	0.45	1.1	0.95	0.30	0.63	1.4	0.30	0.70	1.6
$N_{ions}/(r_{spot}/1mm)^2/10^{12}$	1	3	10	1	3	10	1	3	10
Δt (ns)	84	48	27	3.8	2.2	1.2	0.04	0.03	.014
U (J/m^3)/10^{11}	.015	.045	0.15	0.15	0.45	1.5	1.5	4.5	15

Example: Neon Z=10, A=20.17, E_{min}=7.7 MeV, E_{center}=12.1 MeV, E_{max}=20.1 MeV Δz_{min} = 40 m

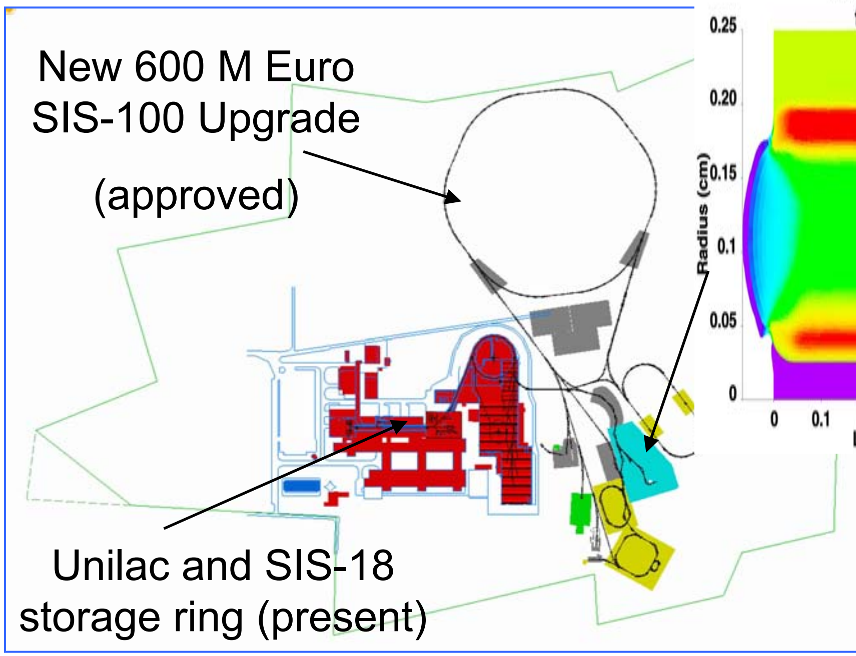
(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)

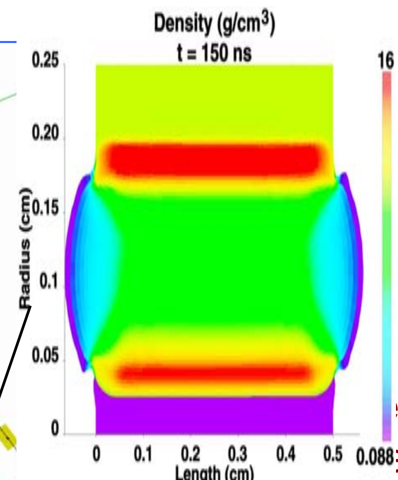
A US-DOE and German Government agreement* supports cooperation in dense plasma physics

- Beam loss/vacuum issues and accelerator activation
- Petawatt laser for ion-driven HEDP diagnostics
- beam physics basis for high intensity ion drivers
  - space charge effect on resonances
  - models of beam halo generation
  - longitudinal instabilities
  - compression schemes for short pulses

GSI and HIF-VNL have agreed to the technical content of a new proposed annex on gas desorption and electron cloud effects in accelerators.

Technical Coordinators:
Arthur Molvik LLNL
Hartmut Reich-Sprenger GSI

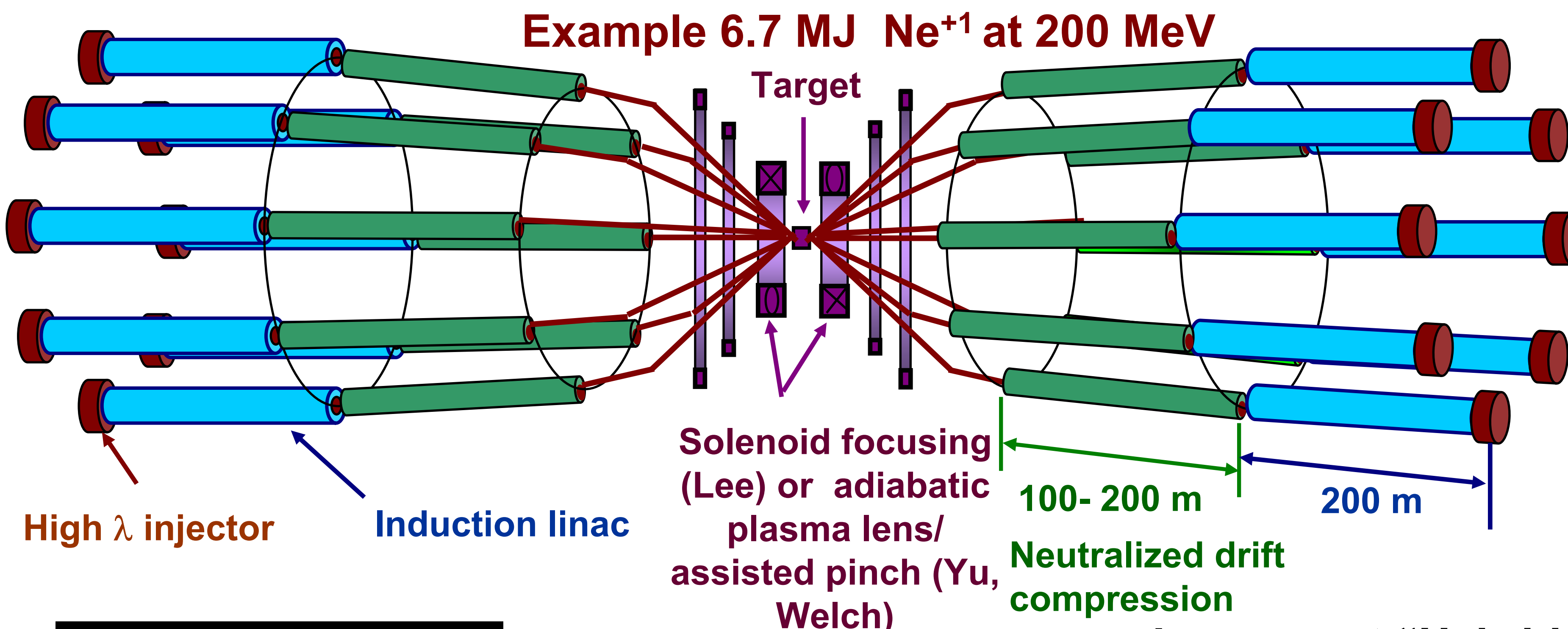


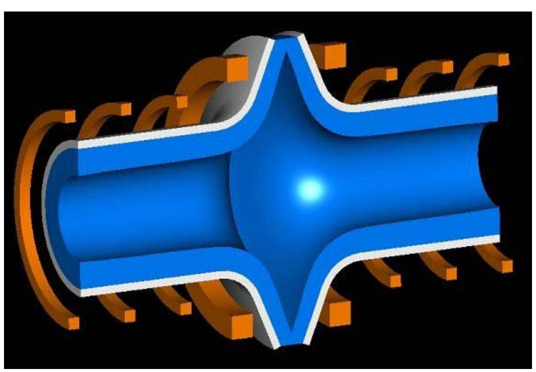


Simulation of a cylindrical target driven by GSI heavy ion beam

*...nting Agreement between the ...nt of Energy of the United States of America and the Federal Ministry of Education and Research of the Federal Republic of Germany on Collaboration in the Field of Dense Plasma Physics (2001)

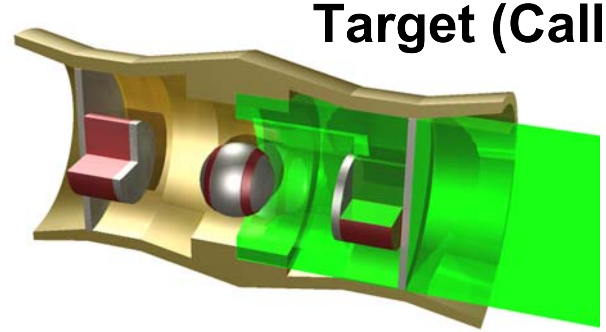
Neutralized compression might lead to an improved IFE driver with a modular development path



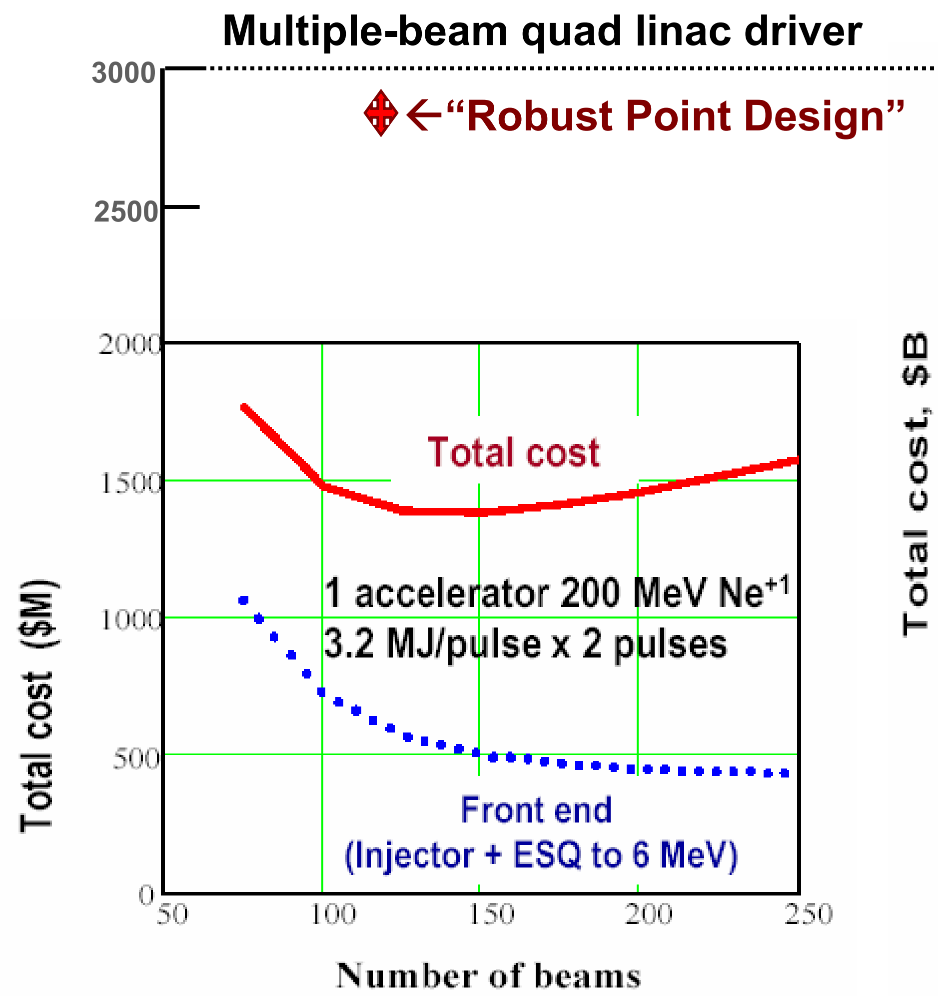


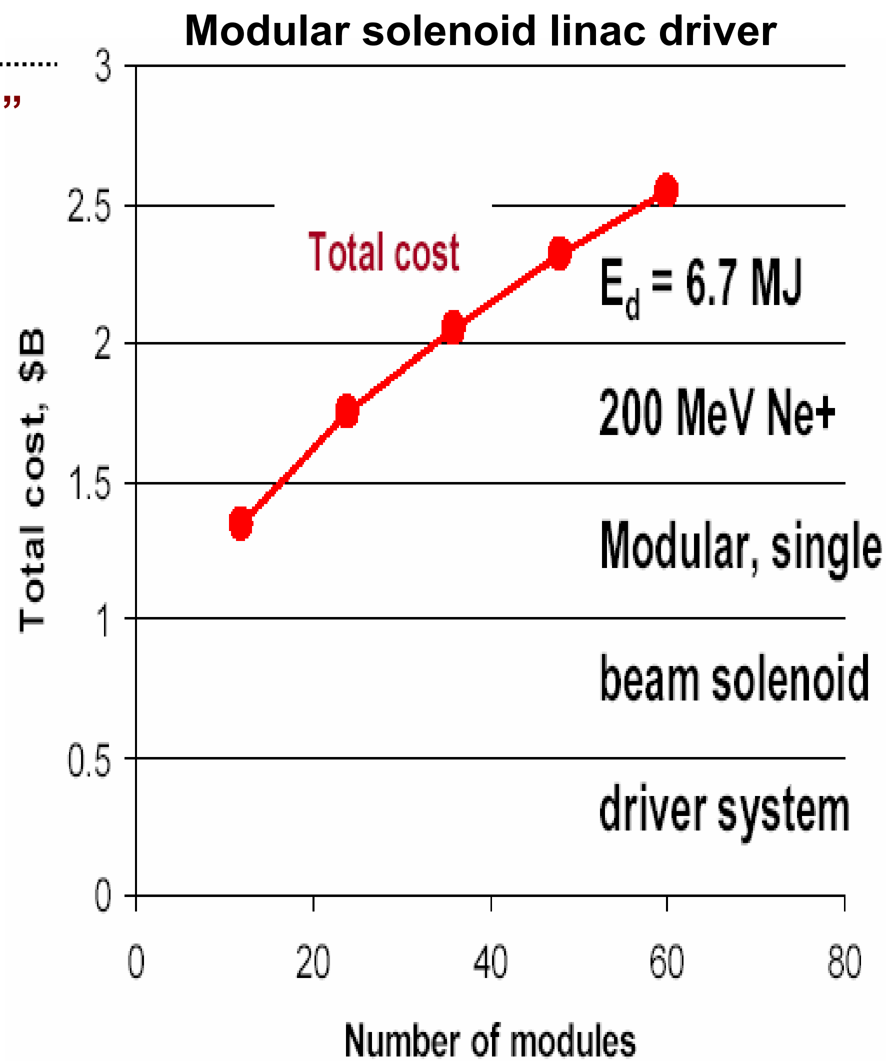
Liquid vortex chamber Concept (Peterson)

Large spot "Hybrid Target (Callahan)



Neutralized drift compression/focusing + hybrid targets may reduce costs ~ 50% for both conventional multiple-beam quadrupole and modular solenoid driver options for IFE (See talk by Meier F.I-05)





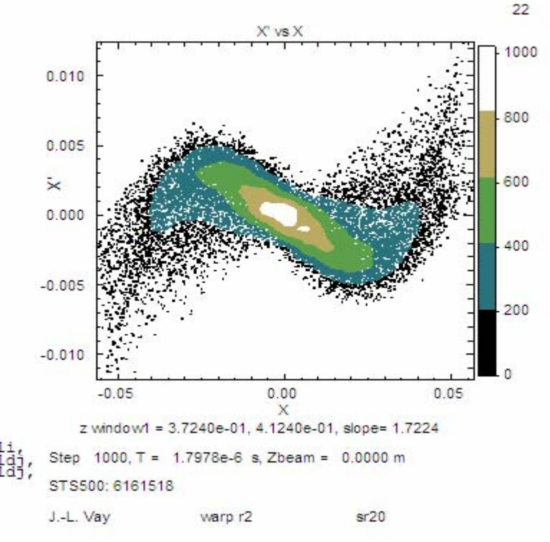
We find good agreement between measured and simulated large-aperture diode dynamics*

$X^{/}$-X phase Space at the end of diode

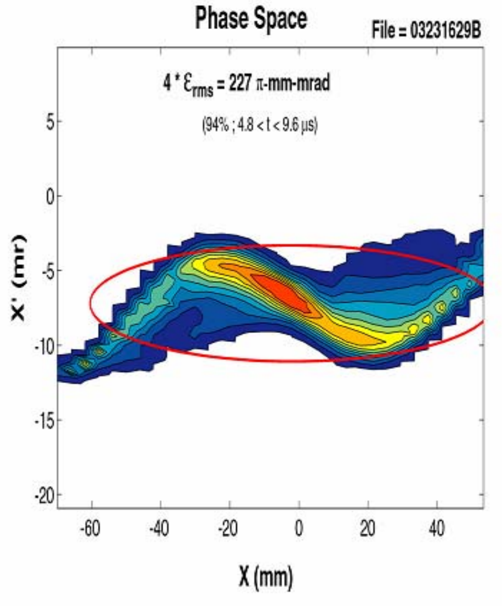
10-cm diameter K+ Alumino-silicate source

Risetime

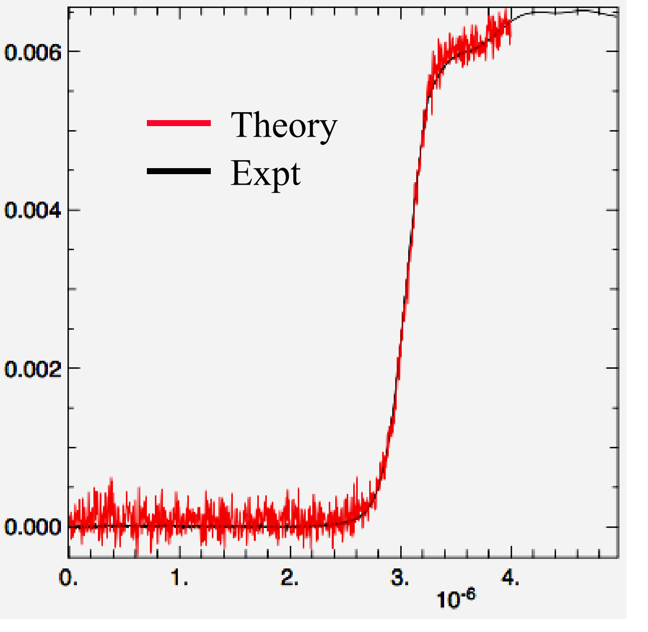
Warp simulations



Experimental results



Current at Faraday cup



Results on risetime benefited from a novel simulation method (based on Adaptive Mesh Refinement), that has moved the state-of-the-art.

*J. Kwan, Rev. Sci. Instr. Vol. 75, No. 5, pg 1838 May 2004