Overview of U.S. Heavy Ion Fusion Research*

G. Logan, F. Bieniosek, C. Celata, E. Henestroza, J. Kwan, E. P. Lee, M. Leitner, L. Prost, P. Roy, P.A. Seidl, S. Eylon, J-L. Vay, W. Waldron, S. Yu
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

J. Barnard, D. Callahan, R. Cohen, A. Friedman, D. Grote, M. Kireeff Covo,
W. R. Meier, A. Molvik, S. Lund
Lawrence Livermore National Laboratory, Livermore, CA, USA

R. Davidson, P. Efthimion, E. Gilson, L. Grisham, I. Kaganovich, H. Qin, E. Startsev,
Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA

D. Rose, D. Welch, Mission Research Corporation, Albuquerque, NM, USA

C. Olson, Sandia National Laboratories, USA

R. Kishek, P. O'Shea, I. Haber, University of Maryland, College Park, MD, USA

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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
Mission Research Corporation
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
General Atomics
Georgia Institute of Technology
First Point Scientific
Tech-X
FAR-Tech

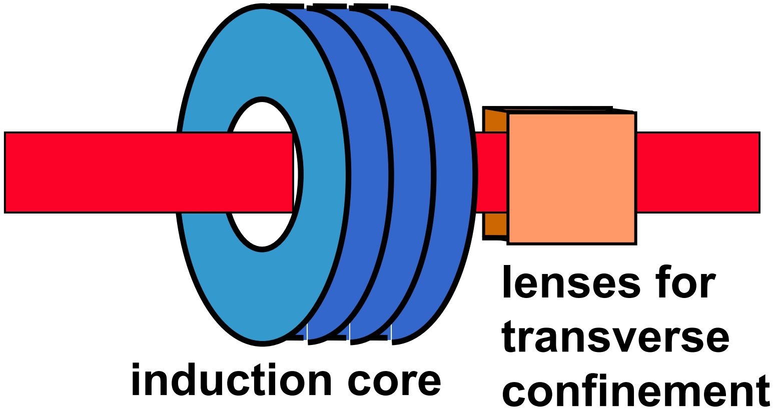
Outline of talk

1. **Research progress over the last two years 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.**

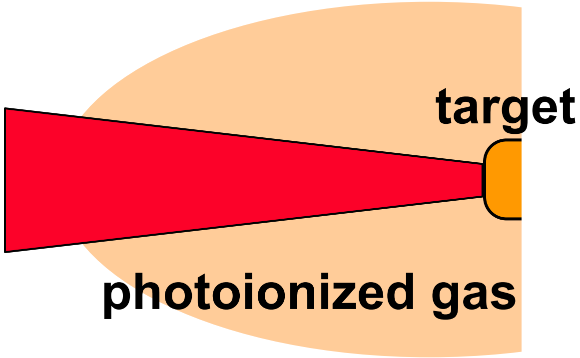
3. **Conclusions**

Research over the last two years has focused on selected key issues affecting high intensity heavy-ion beam propagation



In accelerator and transport systems:

- Quality of injected beam
- Emittance growth
- Halo generation
- Possible instabilities
- Gas and electron cloud effects

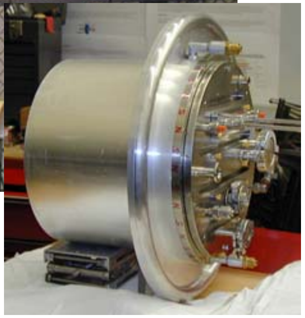


In neutralization and chamber systems

- Ionization of beam and background gas
- Beam charge neutralization
- Possible beam-plasma instabilities
- Focusing aberrations
- Self-magnetic and inductive effects

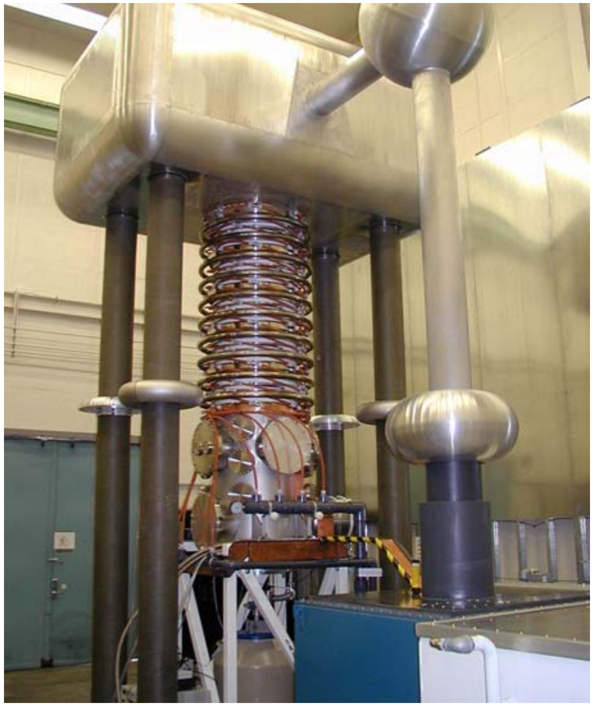
We have completed key experiments important to the quality of large, high current injected beams (LLNL)

- → 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

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

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

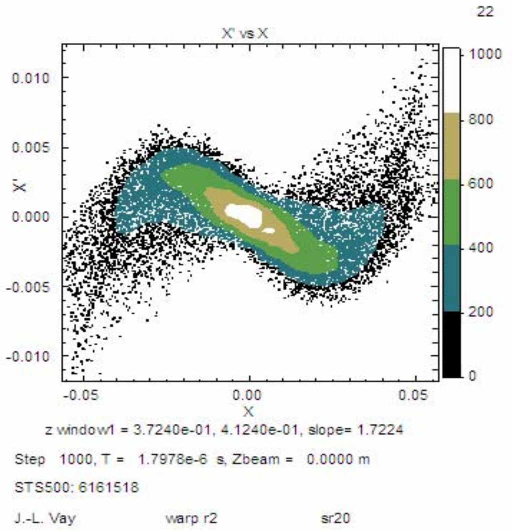
10-cm diameter K+
Alumino-silicate source

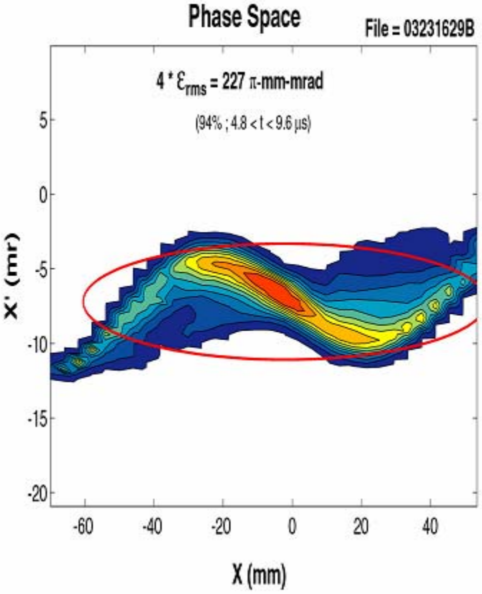
Risetime

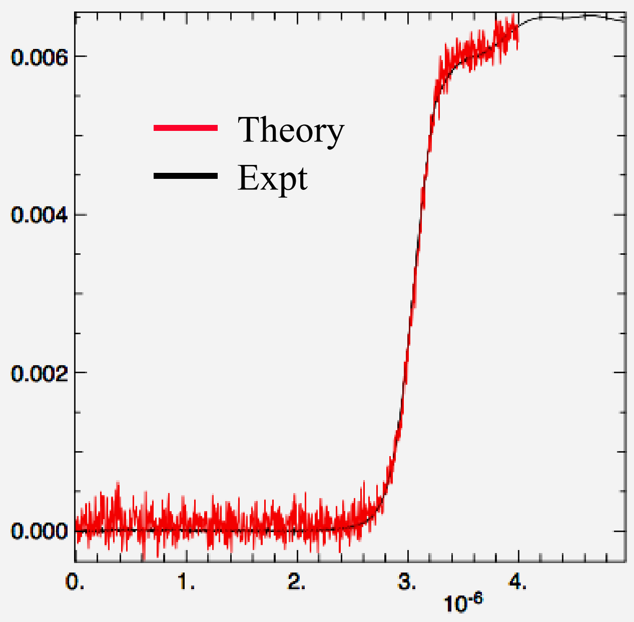
Warp simulations

Experimental results

Current at Faraday cup





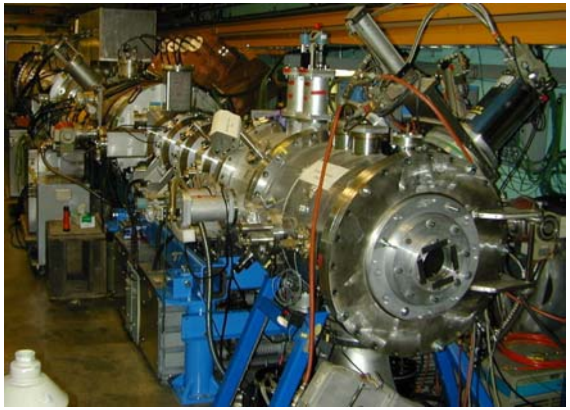


Results on risetime benefited from a novel simulation method (based on Adaptive Mesh Refinement), that has moved the state-of-the-art.

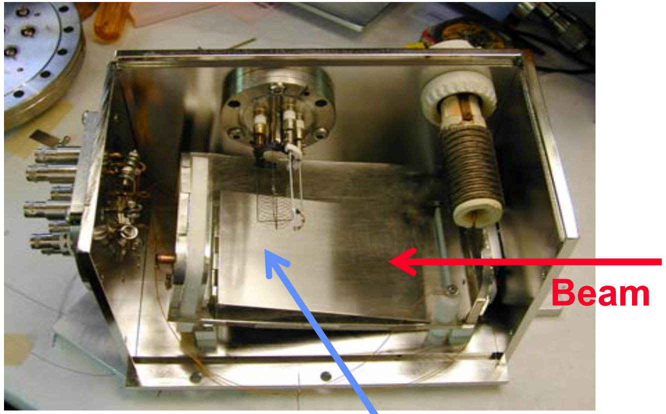
*J. Kwan, Rev. Sci. Instr. Vol. 75, No. 5, pg 1838 May 2004

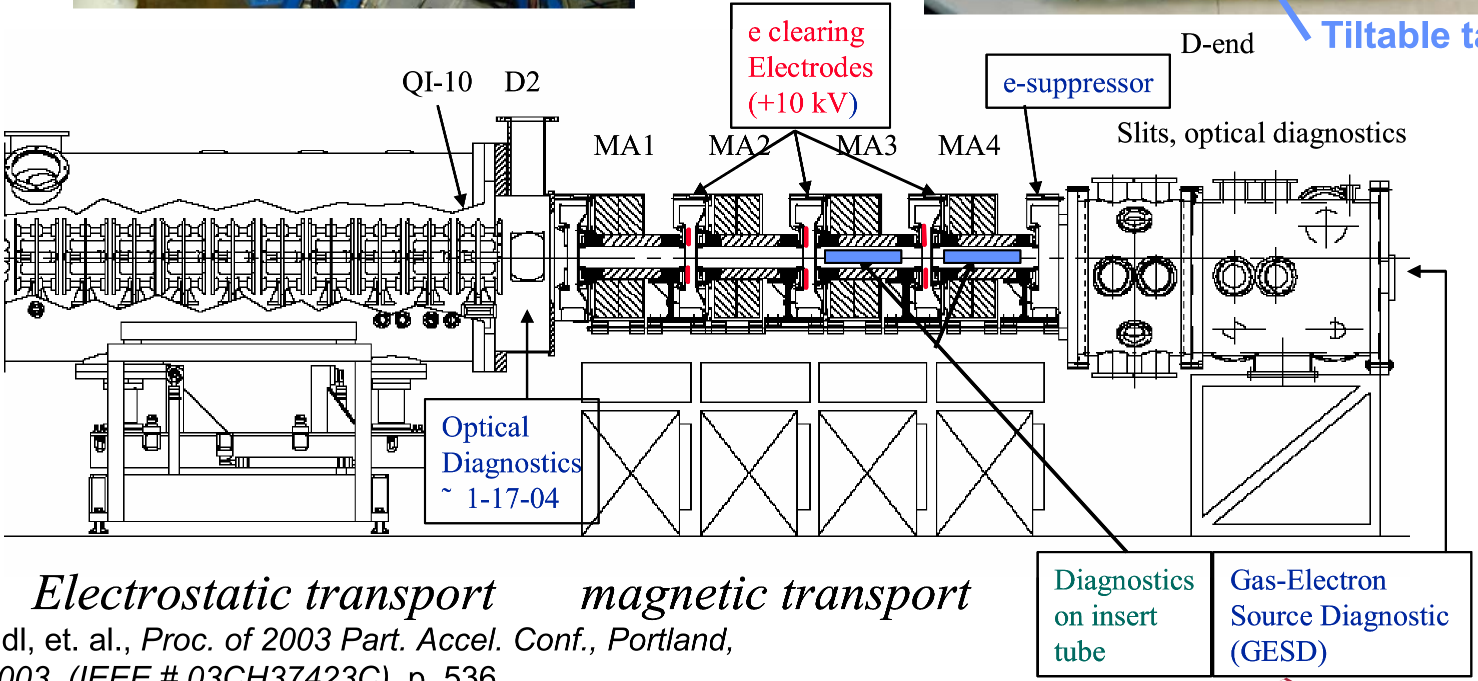
Since 2002, HCX (LBNL) has explored transport to high fill factors in ten electric quads*, and gas/electron cloud effects in four magnetic quads.

The HCX with magnetic quad section (2003)



Gas, electron source diagnostic (GESD)



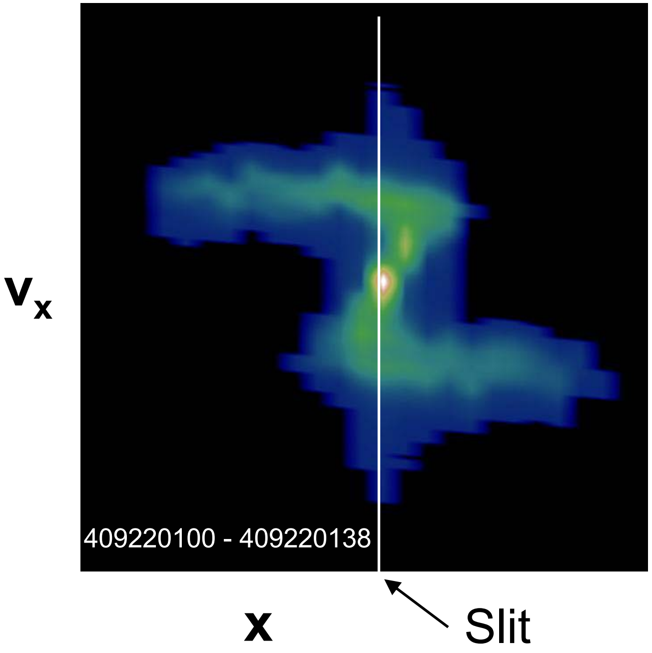


*P. Seidl, et. al., *Proc. of 2003 Part. Accel. Conf., Portland, USA 2003, (IEEE # 03CH37423C)*, p. 536

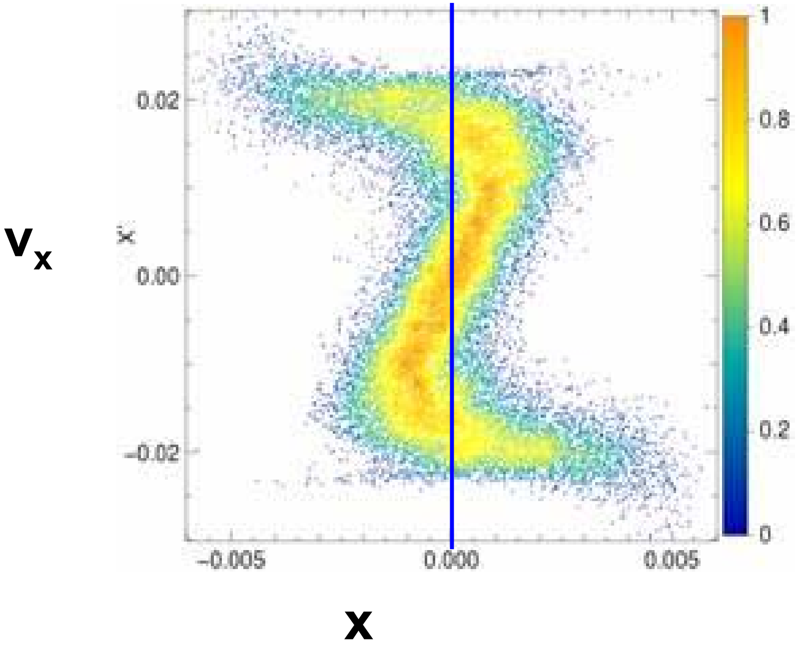
Experimental observations: Without suppressor or clearing electrodes, electrons cause distorted (“Z-ing”) of ion beam (v_x-x) phase space.

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



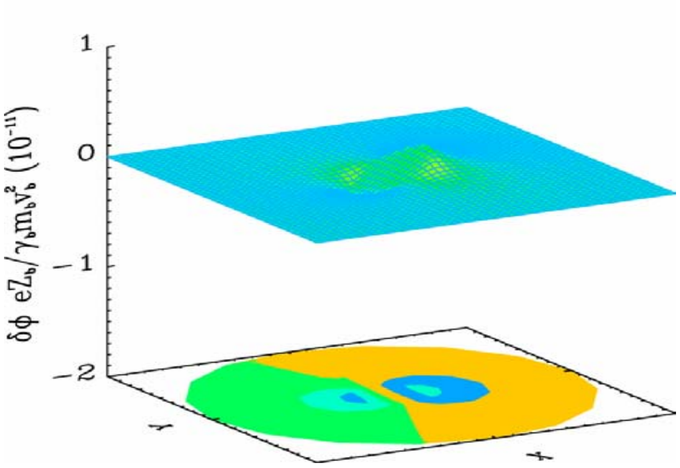
→Simulations with WARP in 3D using models of electron emission and reflection, and a new electron mover algorithm (Ron Cohen), show this “Z” effect of electron clouds. This multi-species modeling capability is key to a predictive capability for electron cloud effects in any high intensity accelerator.

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

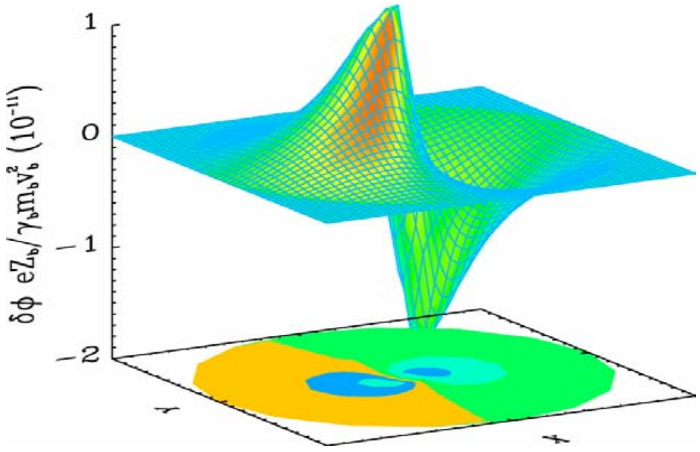
Proton storage ring (PSR) experiment at Los Alamos observes strong electron-proton (e-p) two-stream instability.

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.



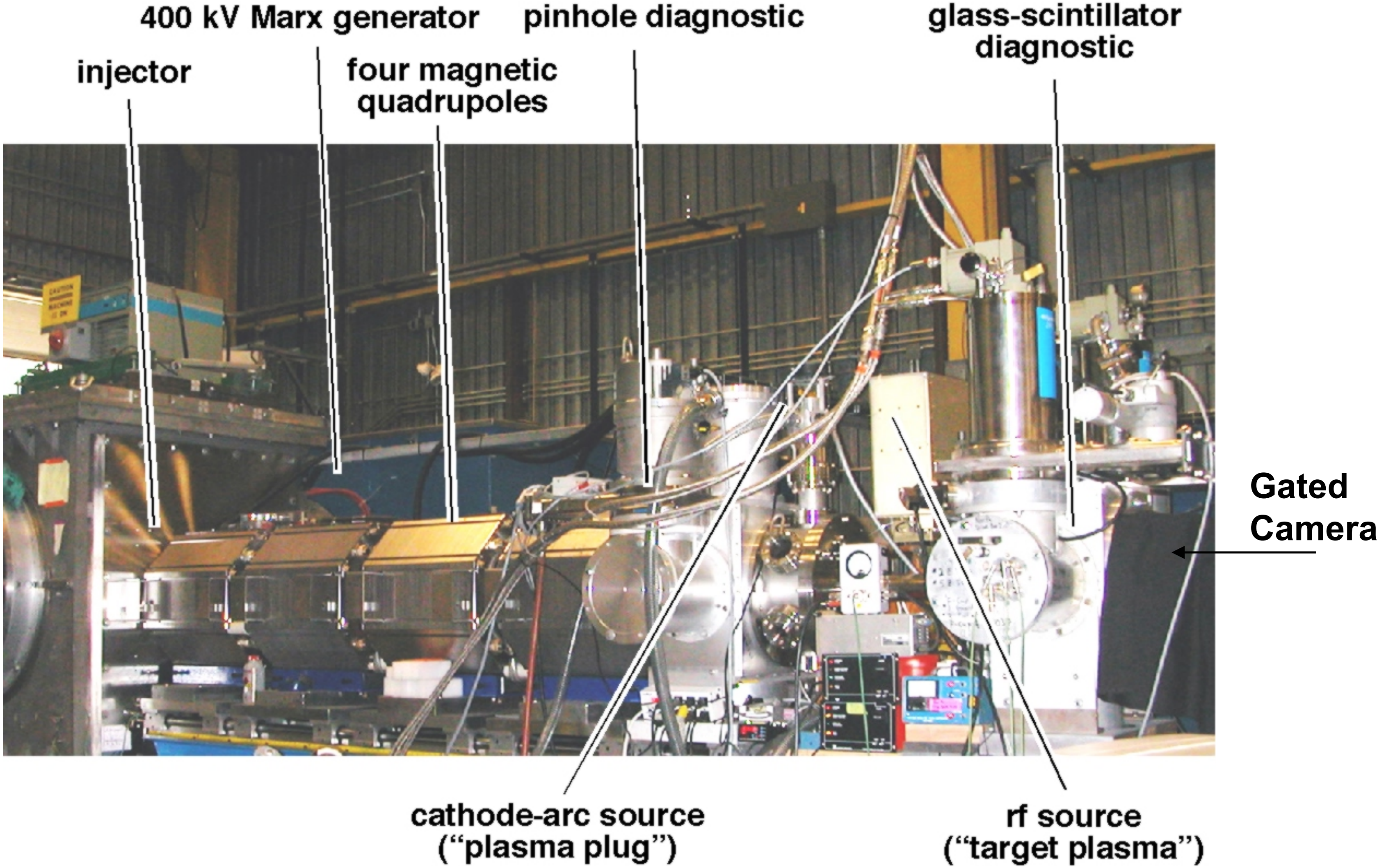
t=0



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

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

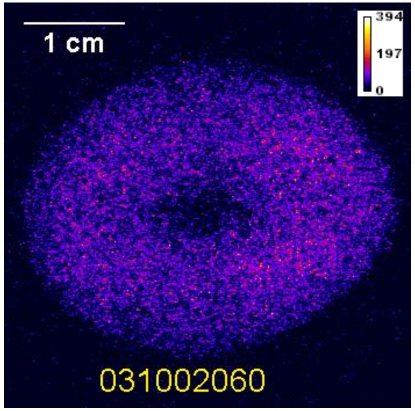
The Neutralized Transport Experiment (LBNL)



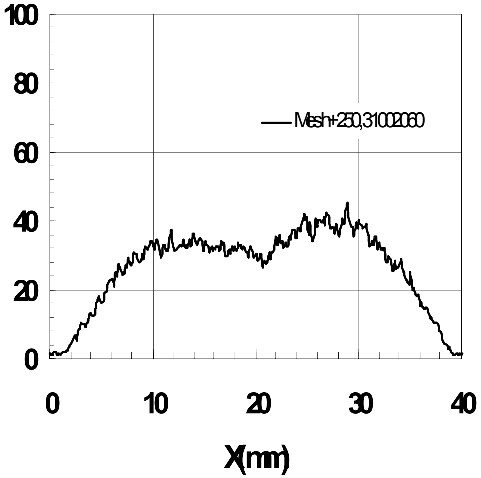
Plasma neutralization of space charge for a high perveance (6 x10^{-4}) 25 mA, 300 keV K$^+$ beam reduces beam focal spot size by 10 x, consistent with particle simulations*

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

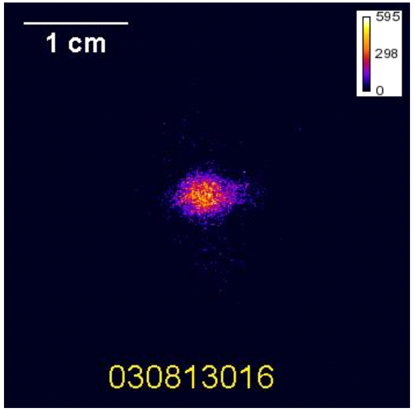
Non-neutralized transport



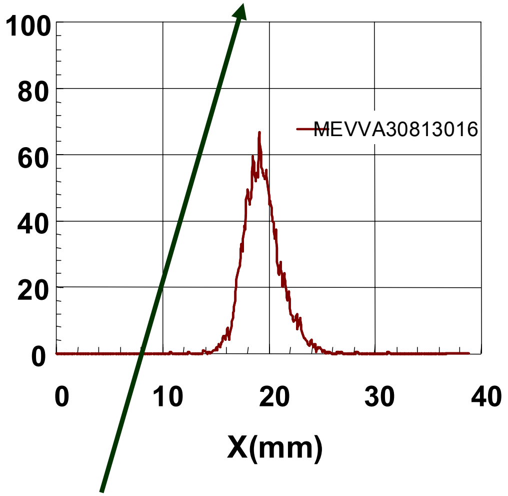
FWHM: 2.7 cm



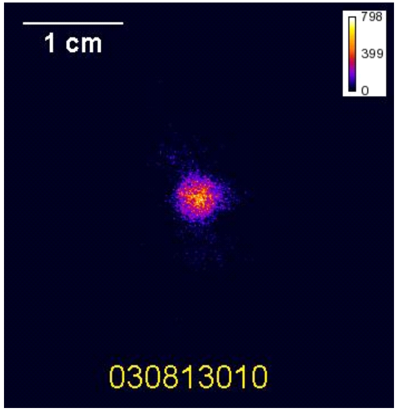
Effect of plasma plug on spot size



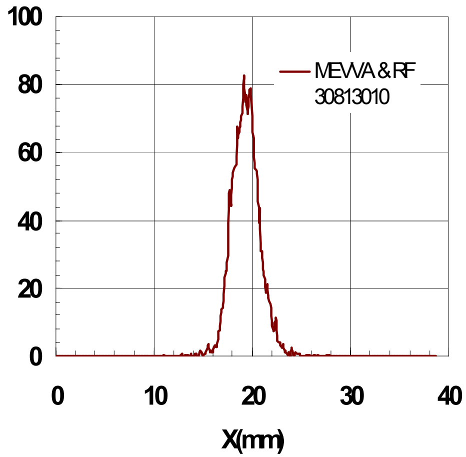
FWHM: 2.83 mm



Effect of plasma plug and volume plasma on spot size

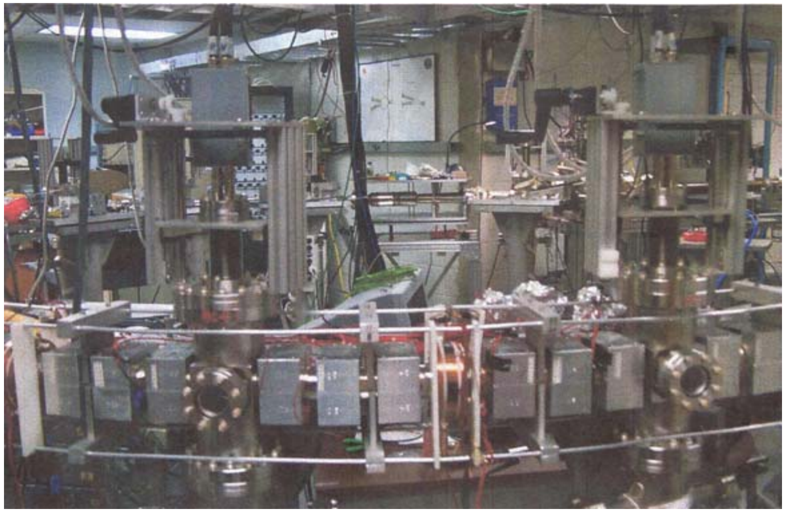


FWHM: 2.14 mm

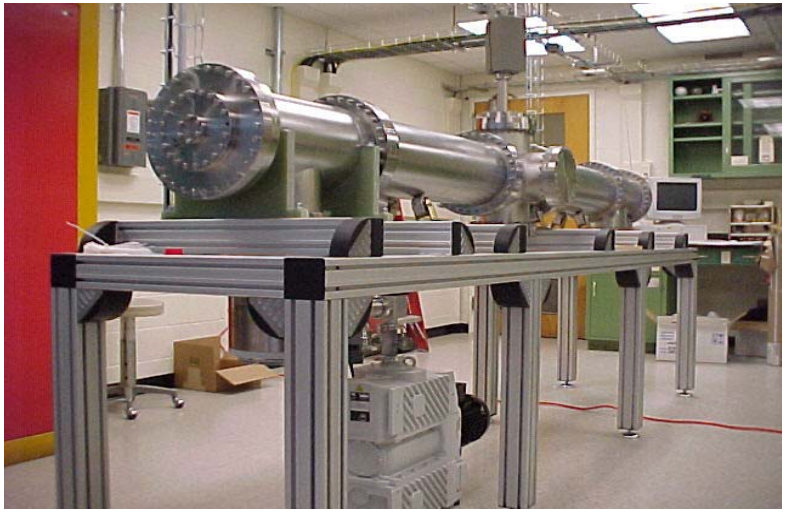


***Simulations (C. Thoma, D.R. Welch, S.S. Yu, P.K. Roy, S. Eylon, and E.P. Gilson, submitted to Physics of Plasmas, September 2004) predict 1.4 mm rms spot radius for plug plasma case**

Small-scale experiments have begun to study long-path transport physics such as slow emittance growth



Construction of the University of Maryland Electron Ring experiment (UMER) is nearing completion. UMER uses electrons to study HIF-beam physics with relevant dimensionless space charge intensity. (R. Kishek, submitted to Nuc Instr & Method A, 2004)



The Paul Trap Simulator Experiment at PPPL uses oscillating electric quadrupole fields to confine ion bunches for 1000s of equivalent lattice periods (E. P. Gilson, R.C. Davidson, P. Efthimion and R. Majeski, Phys. Rev. Lett. 92, 155002 (2004).)

Noteworthy U.S. progress in beam theory, simulation and modeling

Simulation studies in support of experiments:

- Injectors: large-aperture aberrations; short rise-time tests; multi-beamlet merging
- HCX: WARP studies of transport & matching into magnetic quads; analysis of optical-slit and other data
- NTX: WARP and LSP studies of beam transport and focusing

Studies of future experiments

- Neutralized Drift Compression Experiments studying compression in space and time
- simulation and analysis of HEDP-relevant beam experiments and modular driver approaches
- time-dependent 3D simulations of a model IBX
- scoping of scaled multi-beam experiment using electrons (with U. Md.)

Fundamental beam science studies

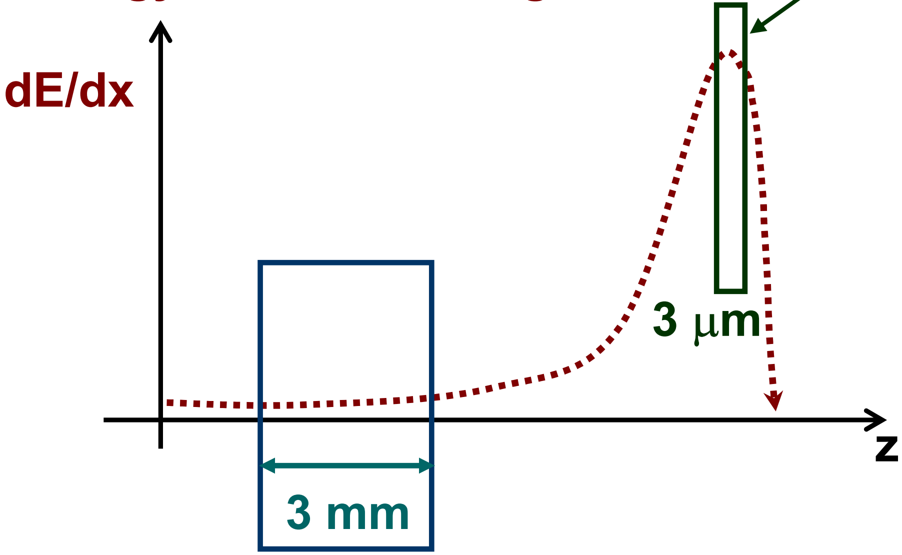
- electron cloud effects, and roadmap for comprehensive electron/gas modeling
- quantitative assessment of effects of quadrupole magnet strength errors
- “Harris” and “Weibel” anisotropy modes, and two-stream instability
- drift compression and final focus (both non-neutral and neutralized), including solenoid focusing; time-dependent focusing; and chromatic aberration studies
- beam aperturing and effects of beamline transitions
- parametric limits to stable transport set by both envelope and kinetic effects

Development of advanced simulation capabilities

- Mesh refinement capability in WARP (application to injector triode, rise time study)
- New Vlasov modeling methods for halo, including moving-mesh and “non-split” advance (with U. Strasbourg)

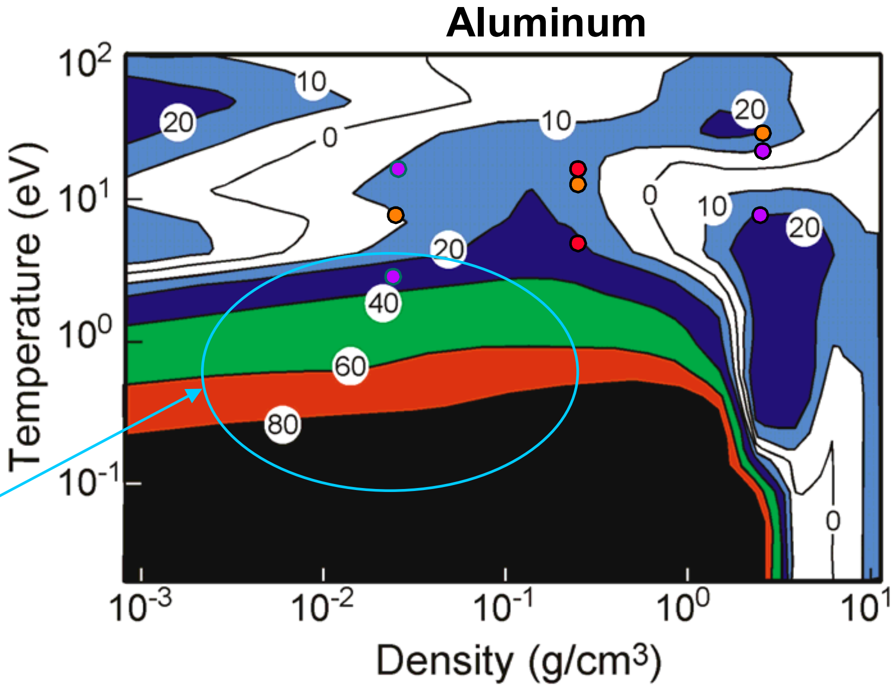
New research is beginning on neutralized beam compression to short pulses needed for high energy density physics and applicable to fusion.

Ion energy loss rate in targets



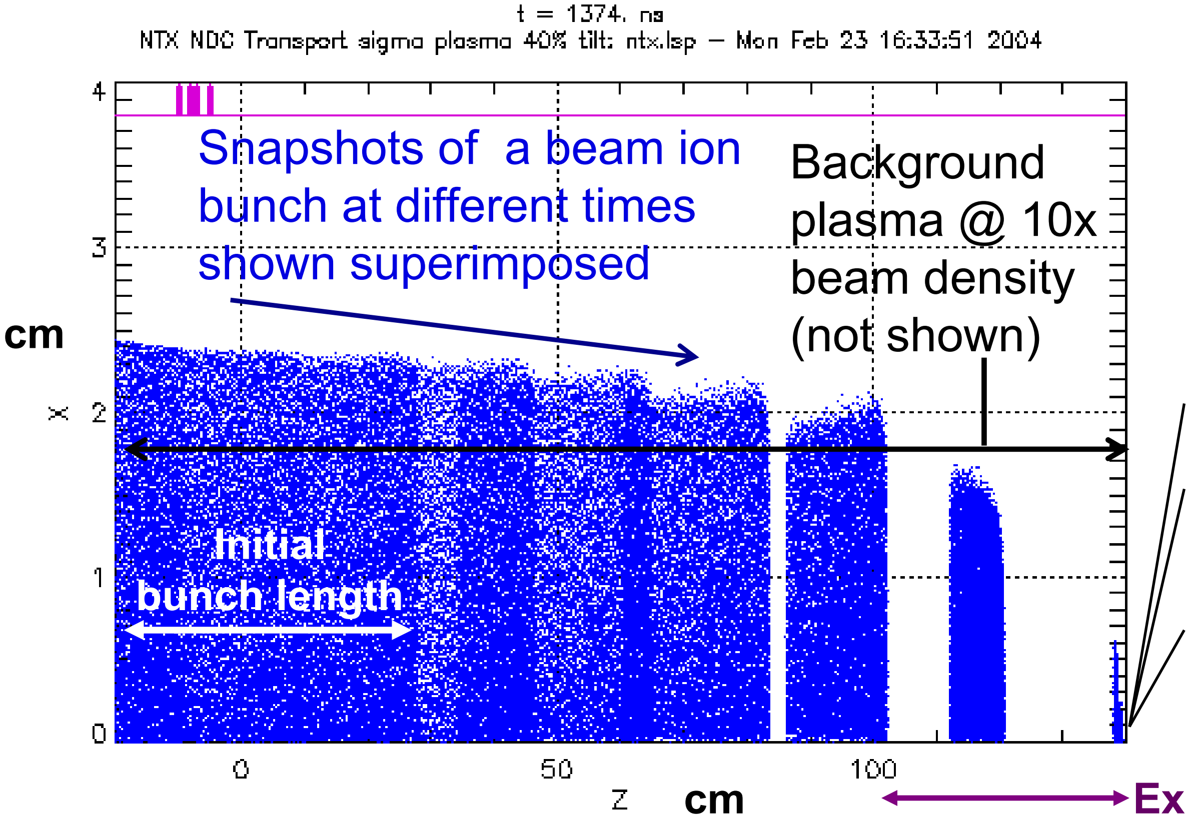
Maximum dE/dx *and* uniform heating at Bragg peak require short (< 1 ns) pulses to minimize hydro motion. [L. R. Grisham, Physics of Plasmas, in press (2004)].
→Te > 10 eV @ 30J, 30 MeV
(Future US accelerator for HEDP)

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)

We are building 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*



Snapshots of a beam ion bunch at different times shown superimposed

Background plasma @ 10x beam density (not shown)

←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)]**

Key areas for further research in neutralized beam drift compression and focusing for near-term application to high energy density physics:

- 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 IFE, extension of neutralized final focus to longer standoff distances.

- For IFE, validation of symmetry control in large-focal-spot hybrid targets.

SUMMARY

With advanced theory and simulation tools, we have made excellent progress over the last two 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.

Over the next 10 years we plan to continue high brightness beam transport, with a new area in neutralized drift compression and focusing. Both address a 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

Heavy Ion Beam Research

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

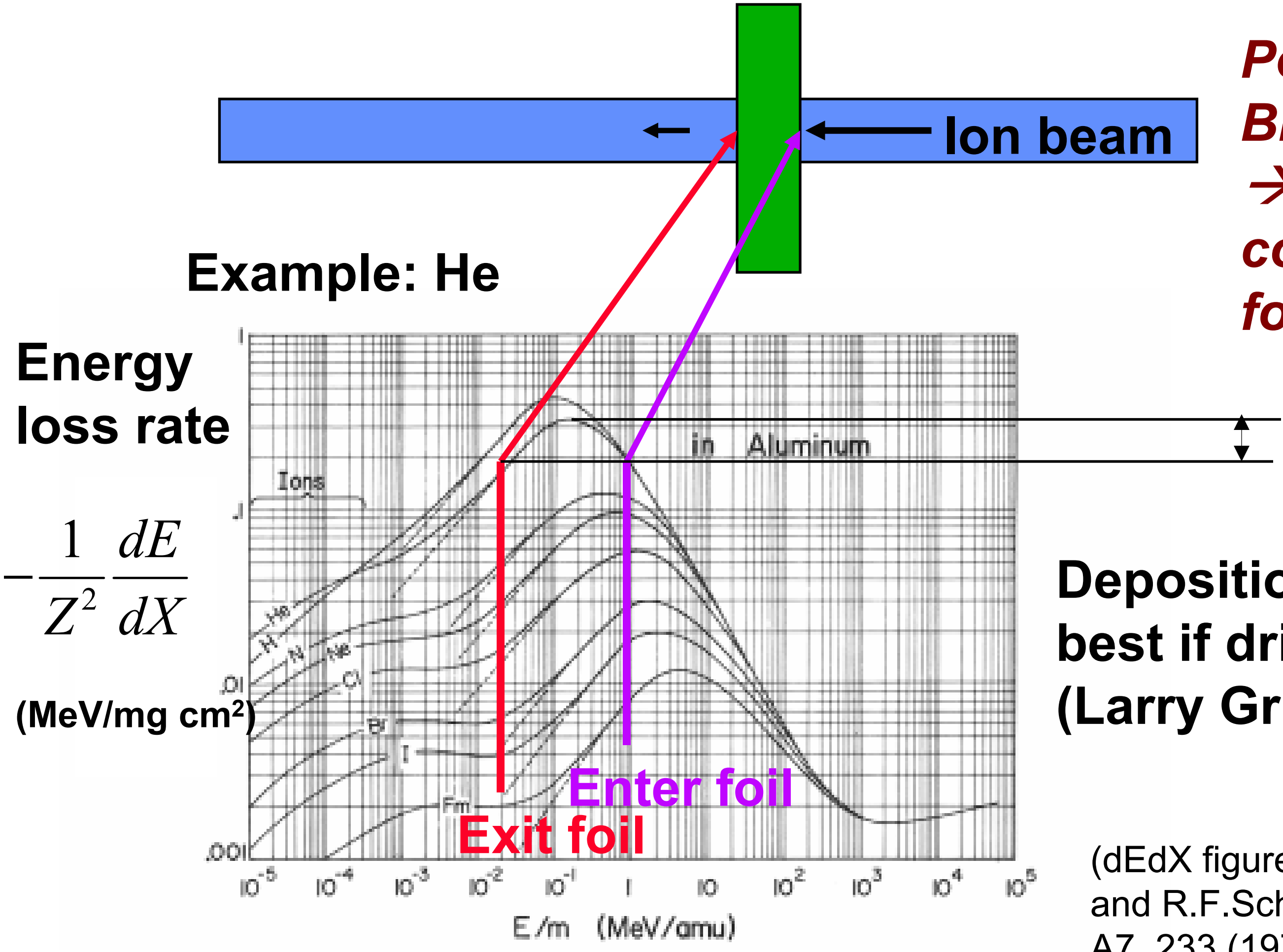
How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Subsidiary science campaigns needed to address this top-level question are:

- **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 size.**
- **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.**

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



Ion beam

Example: He

Energy loss rate

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

(MeV/mg cm^2)

Enter foil

Exit foil

$\Delta dE/dX \propto \Delta T$

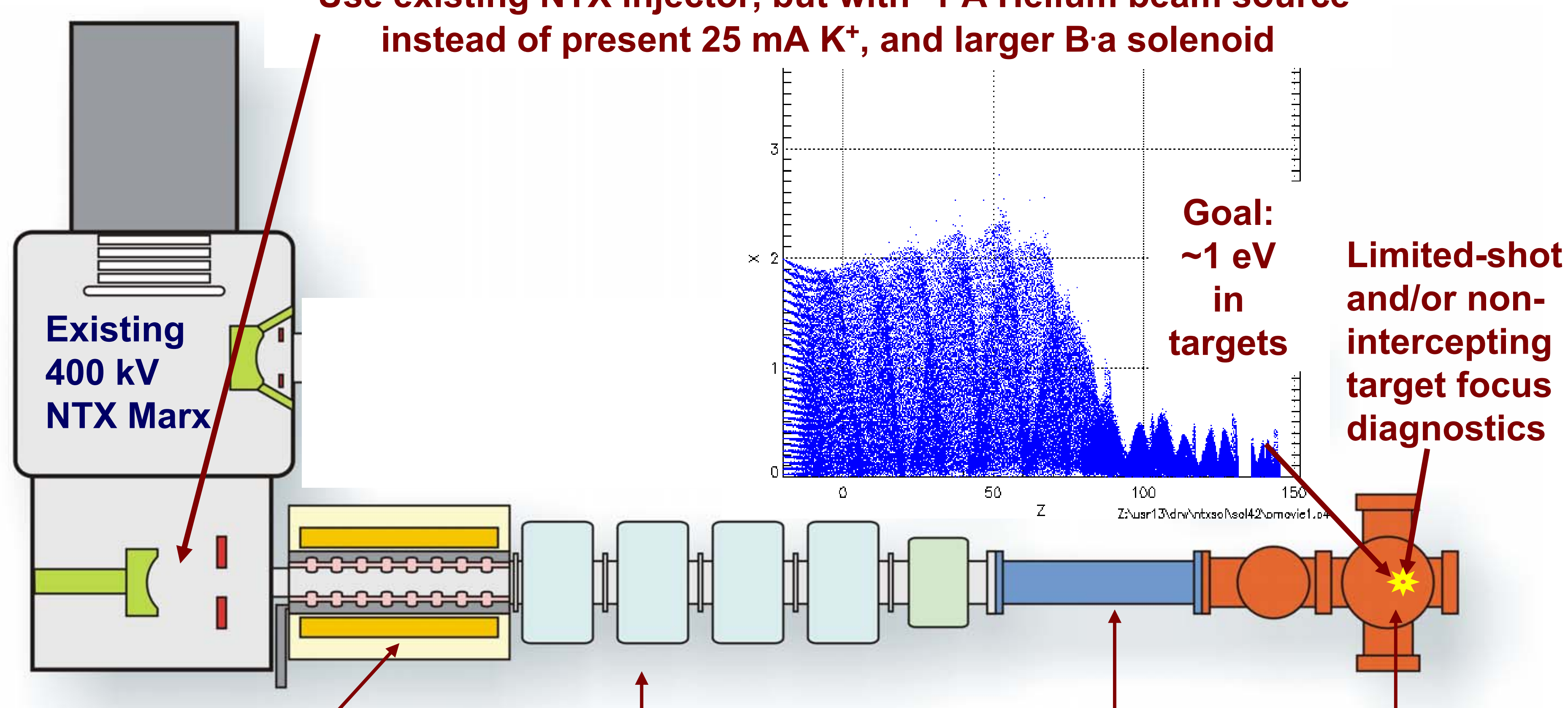
Energy/Ion mass **(MeV/amu)**

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

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))

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



Use existing NTX injector, but with~1 A Helium beam source instead of present 25 mA K^+, and larger B·a solenoid

Existing 400 kV NTX Marx

Goal: ~1 eV in targets

Limited-shot and/or non-intercepting target focus diagnostics

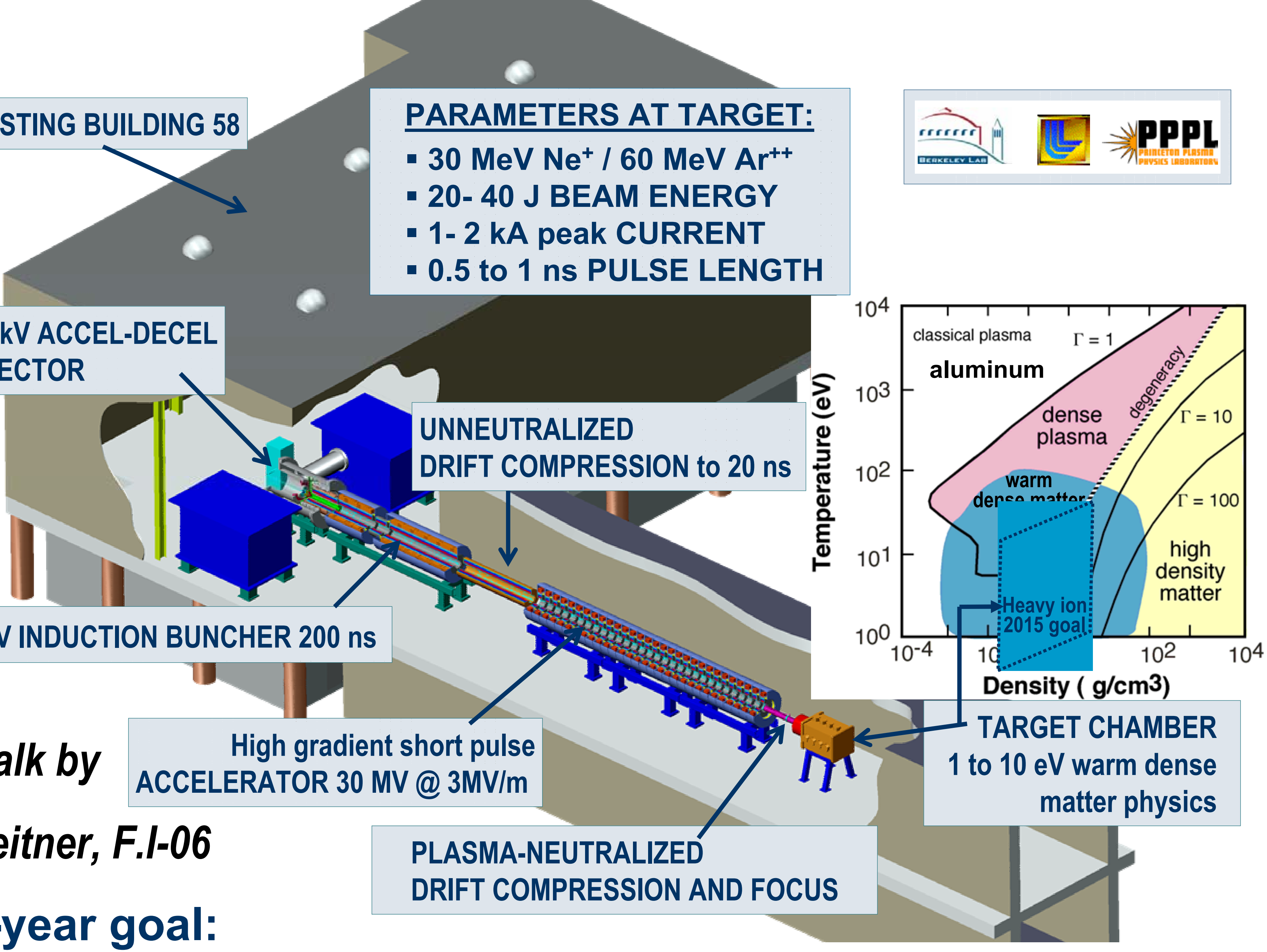
Short Pulse accel-decel Injector

Short acceleration and compression tilt section to 700 keV (use existing ETA and DARHT Cores)

1.4 m long Neutralized Drift

Solenoid and Z-Pinch focus

Ten-year goal:
Conceptual NDCX-III High Energy Density User Facility



EXISTING BUILDING 58

PARAMETERS AT TARGET:

- 30 MeV Ne^+ / 60 MeV Ar^{++}
- 20- 40 J BEAM ENERGY
- 1- 2 kA peak CURRENT
- 0.5 to 1 ns PULSE LENGTH

600kV ACCEL-DECEL INJECTOR

UNNEUTRALIZED
DRIFT COMPRESSION to 20 ns

2-3 MV INDUCTION BUNCHER 200 ns

High gradient short pulse
ACCELERATOR 30 MV @ 3MV/m

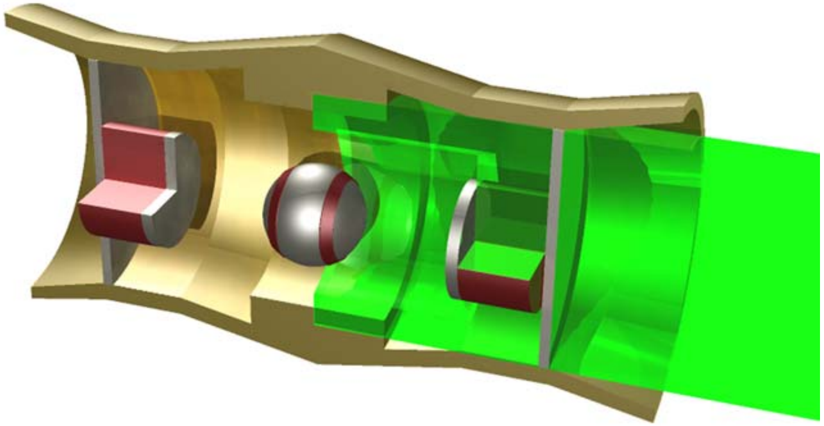
TARGET CHAMBER
1 to 10 eV warm dense
matter physics

PLASMA-NEUTRALIZED
DRIFT COMPRESSION AND FOCUS

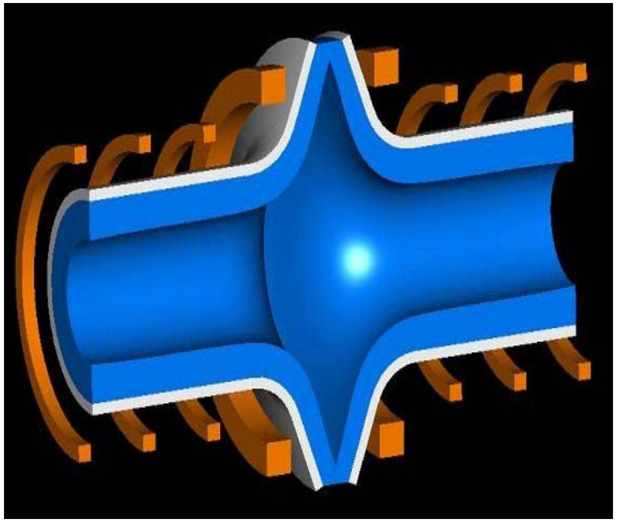
See talk by

M. Leitner, F.I-06

Chromatic focus aberrations with neutralized beam drift compression with velocity “tilts” $\delta v/v < 10\ \%$ may be tolerable with larger spot hybrid targets, together with focusing using solenoids and/or adiabatic plasma lens.



“Hybrid” target allows large 5 mm radius focal spots (D. Callahan M.I-06). See also low cost manufacturing methods for hohlraums with foam x-ray converters (D. Goodin M.I-09).



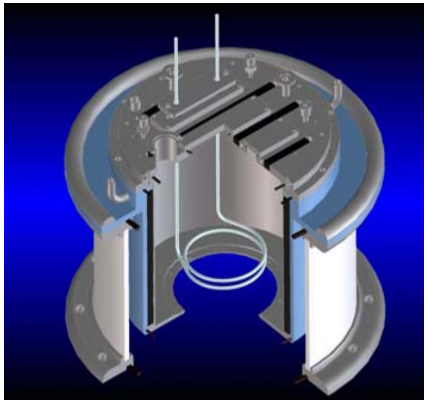
Solenoid-focused, plasma-filled liquid vortex chamber. (See related talks by P. Peterson, W.I-01, E. Lee W.I-12, Welch Th.I-06, S. Yu F.I-01, and W. Meier F.I-05)

Beamlets from Argon RF Plasma Source meet Heavy Ion Fusion requirements

Single Beamlet:

Parameters	Results	Status
Current density	100 mA/cm^2 (5 mA)	met goal
Emittance	$T_{eff} < 2$ eV	met goal
Charge states	> 90% in Ar$^+$	met goal
Energy spread	< a few % beam suffers CX	met goal?

RF Source:



Multiple Beamlet:

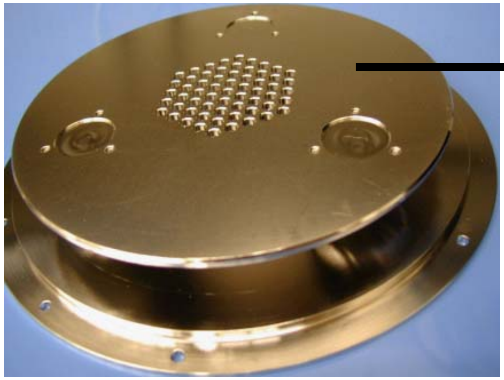
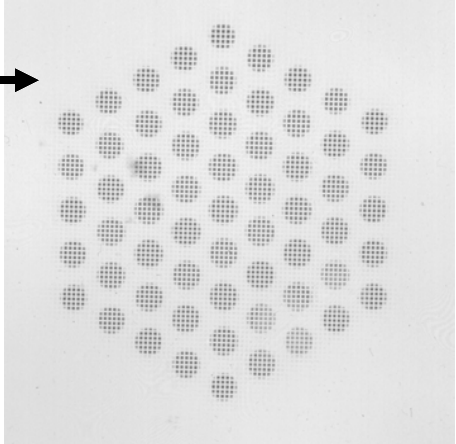
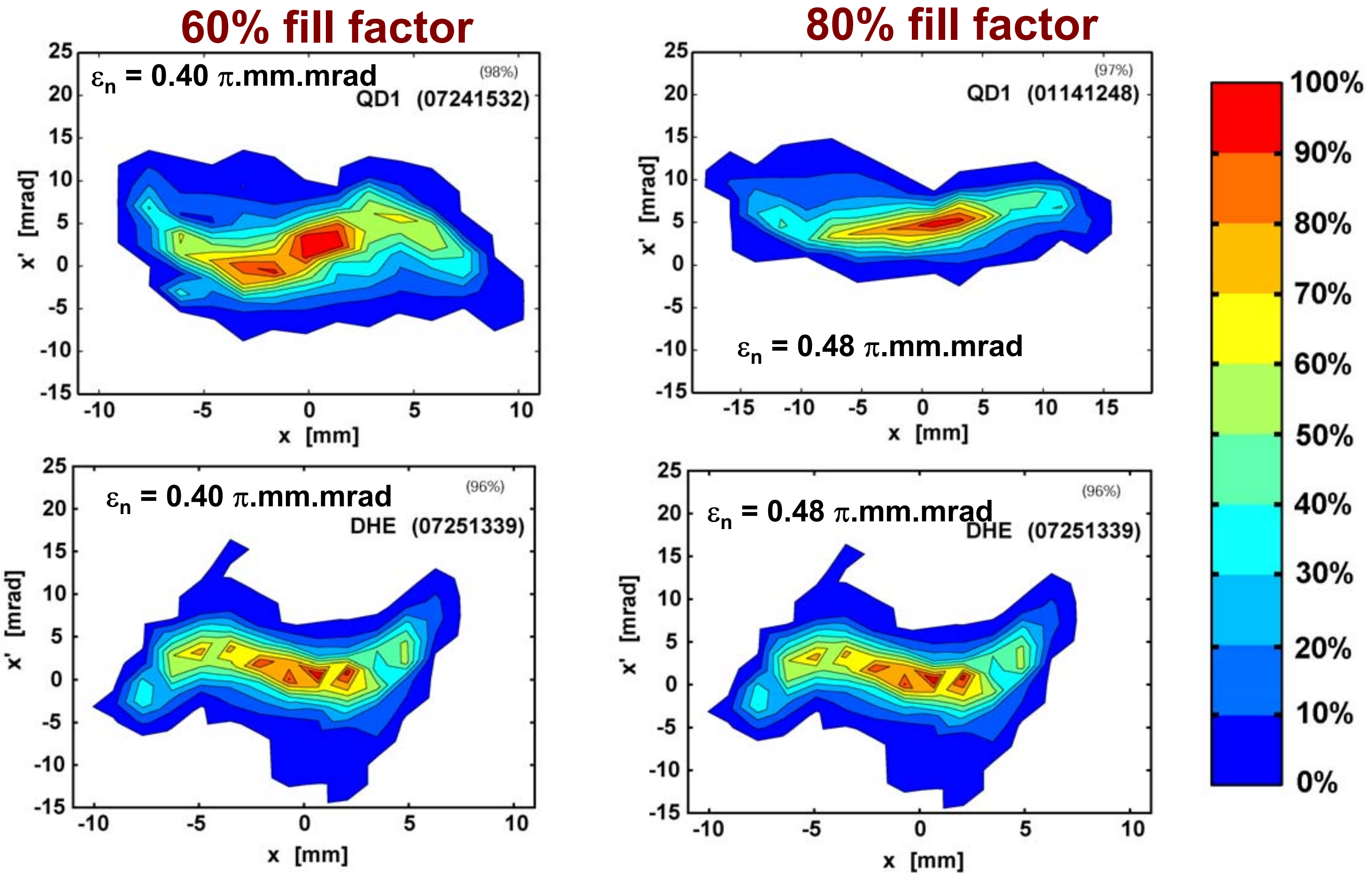


Image on Kapton:



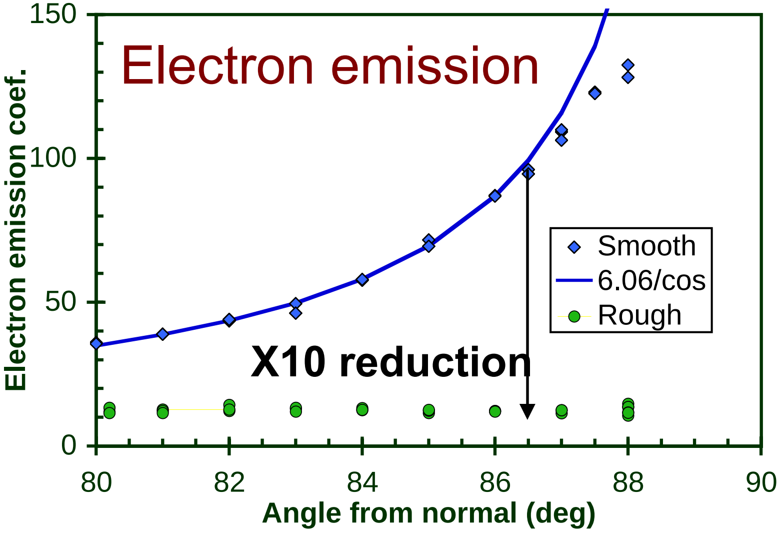
In both 60% and 80% fill-factor cases measured, no evidence of emittance growth, within diagnostic sensitivity.

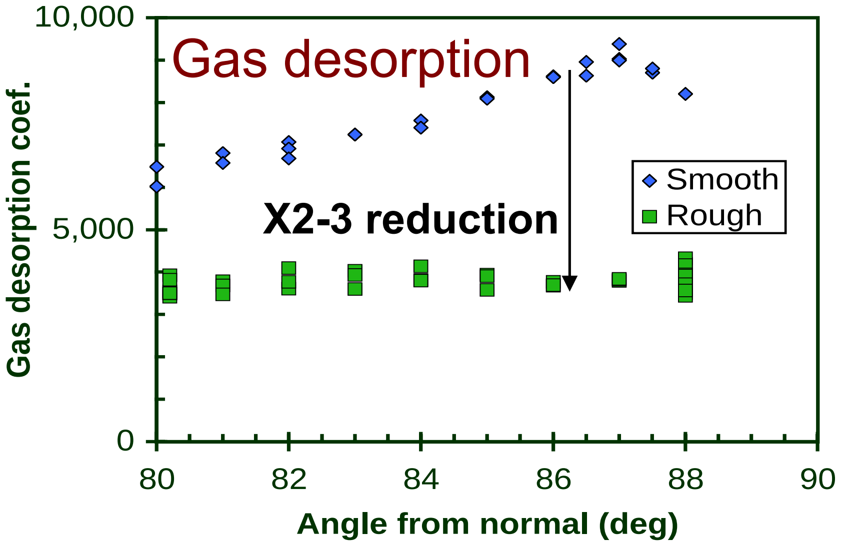


Beginning of Electrostatic Section

End of Electrostatic Section

Rough surfaces mitigate electron emission, gas desorption, and ion scattering

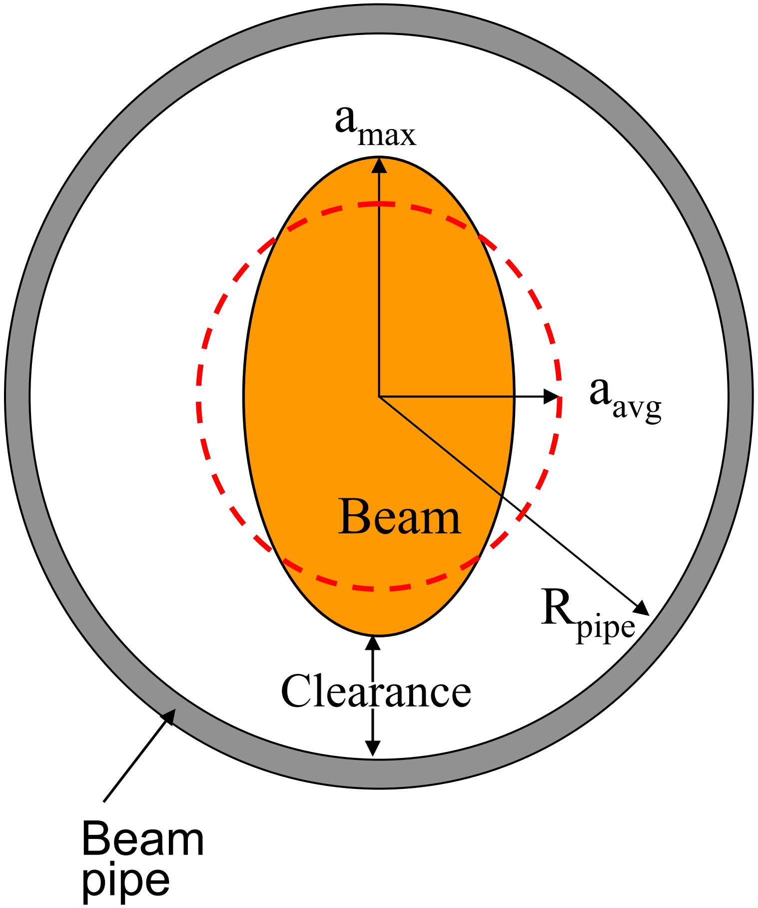




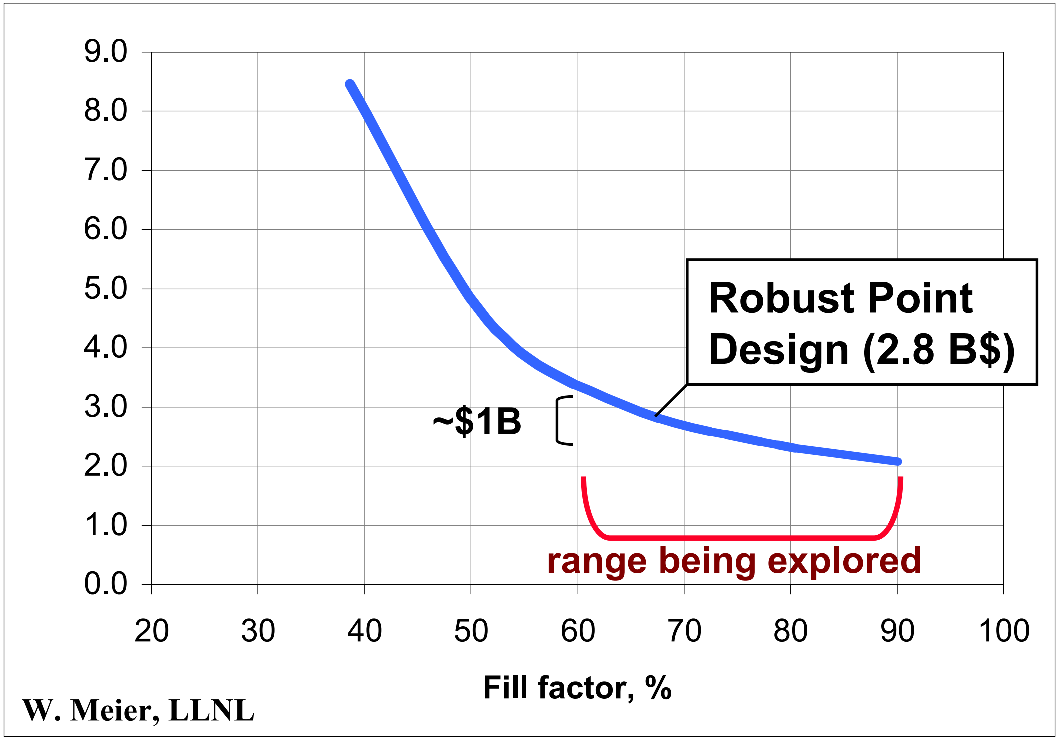
- **Surface roughened by glass-bead blasting (inexpensive)**
- **Angle of incidence: grazing ⇒ ~60° [from 1/cos emission]**
- **Sawtooth surface (CERN-SPS) more effective, but more expensive.**

Heavy ion fusion system studies show that driver cost is very sensitive to fill factor

Fill factor = a_{max}/R_{pipe}

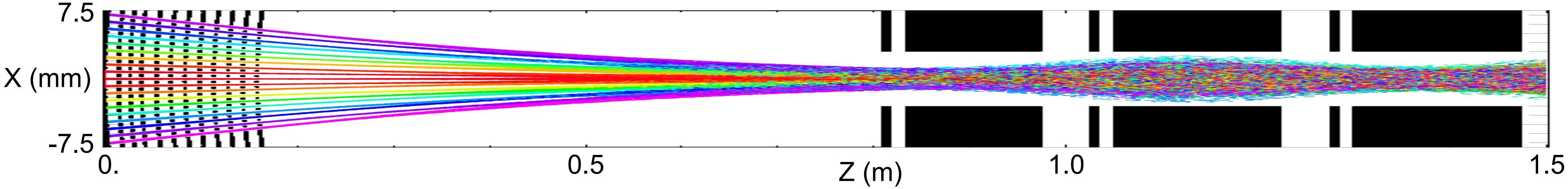


IBEAM results:

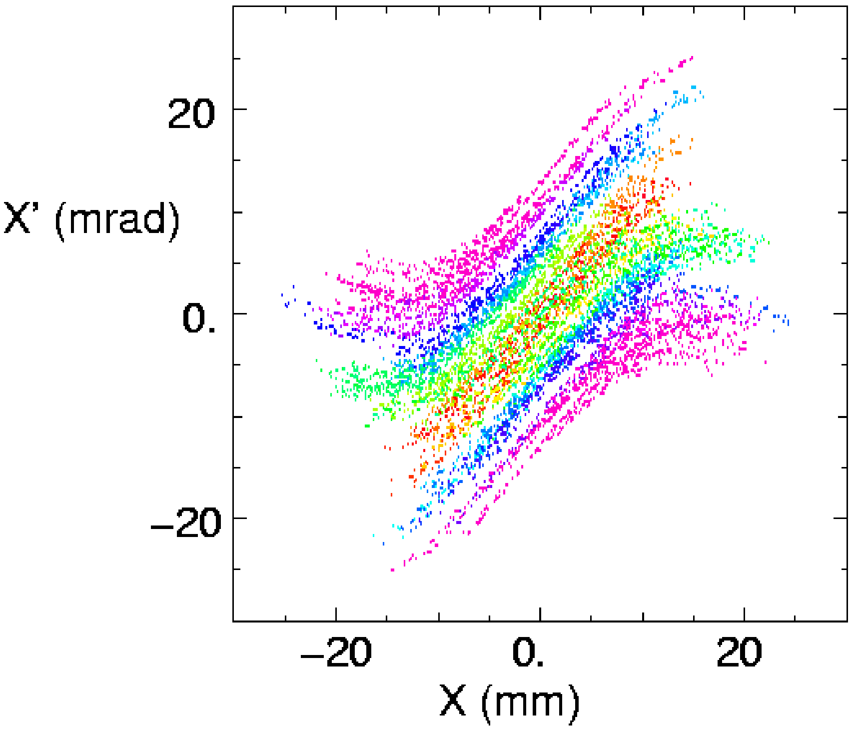


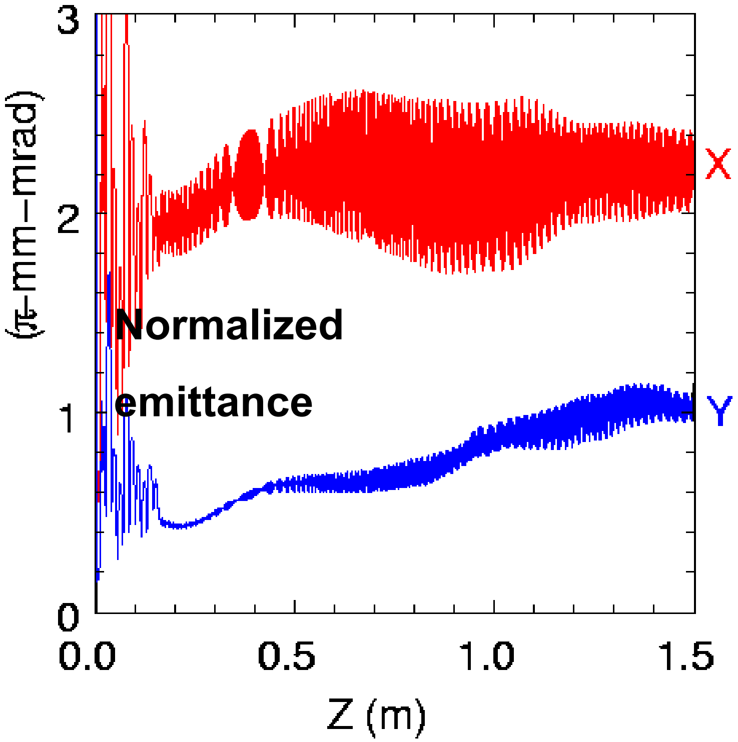
(fixed number of beams, initial pulse length, and quadrupole field strength)

Physics design of 119-beamlet merging experiment on STS500 is complete (see talk by Friedman W.I-08)



Current = 0.07 Amps, Final energy = 400 keV





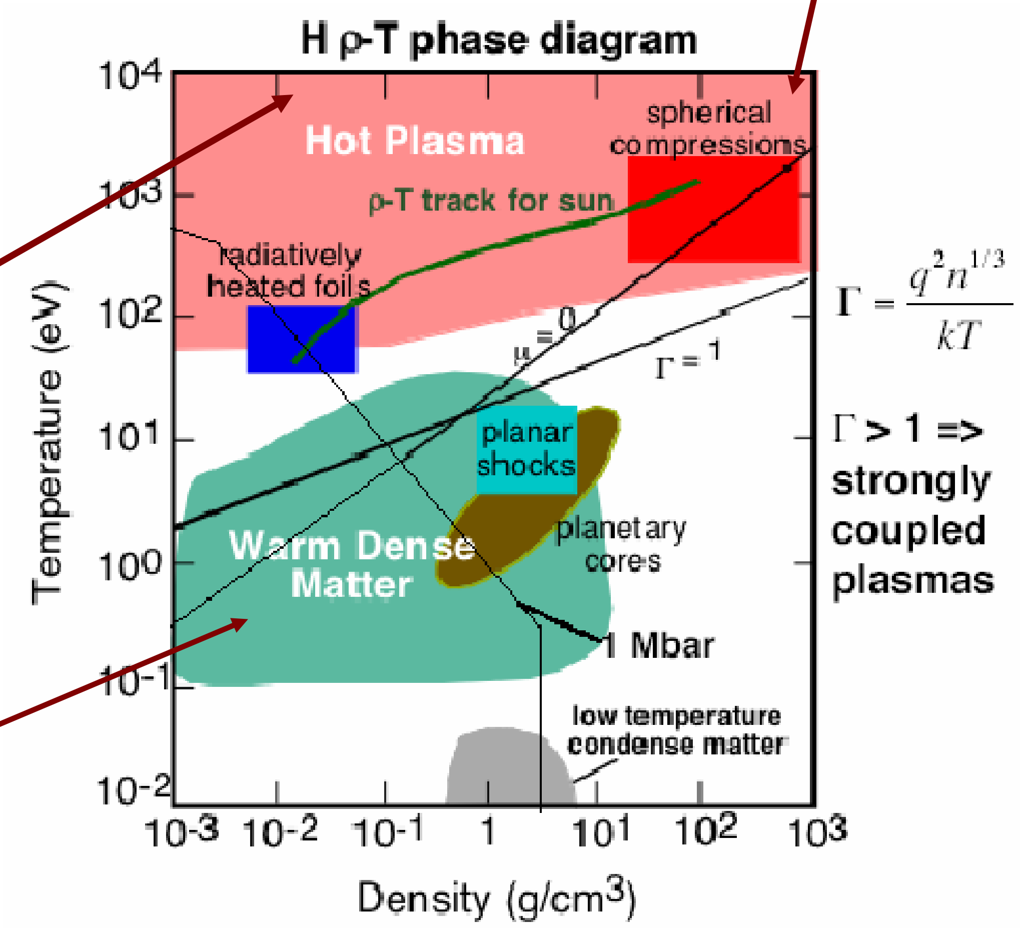
HEDP has rich discovery potential

__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



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

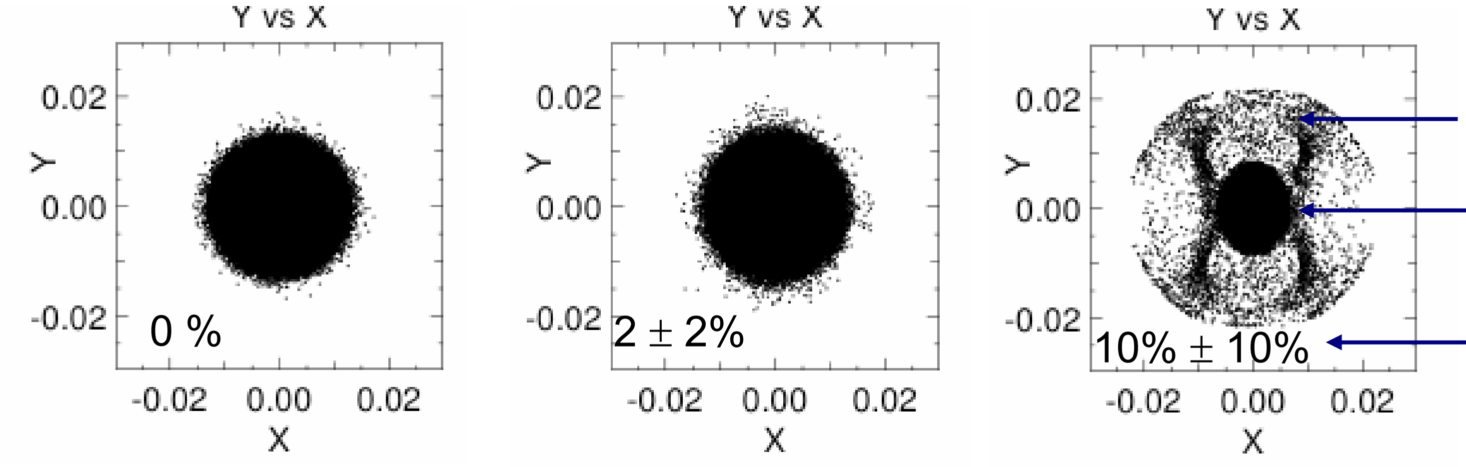
$\Gamma > 1$ => strongly coupled plasmas

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

Example of critical physics issue: beam loss in high intensity accelerators -a current world research topic (GSI-SIS-18, LANL- PSR, SNS)

- **Gas desorption** Gas desorbed by ions scraping the channel wall can limit average beam current.

- **Electron cloud effects** Ingress of wall-secondary electrons from beam loss and from channel gas ionization. WARP (below) and BEST simulations indicate incipient halo formation and electron-ion two-steam effects begin with electron fractions of a few percent.



Ion Halo

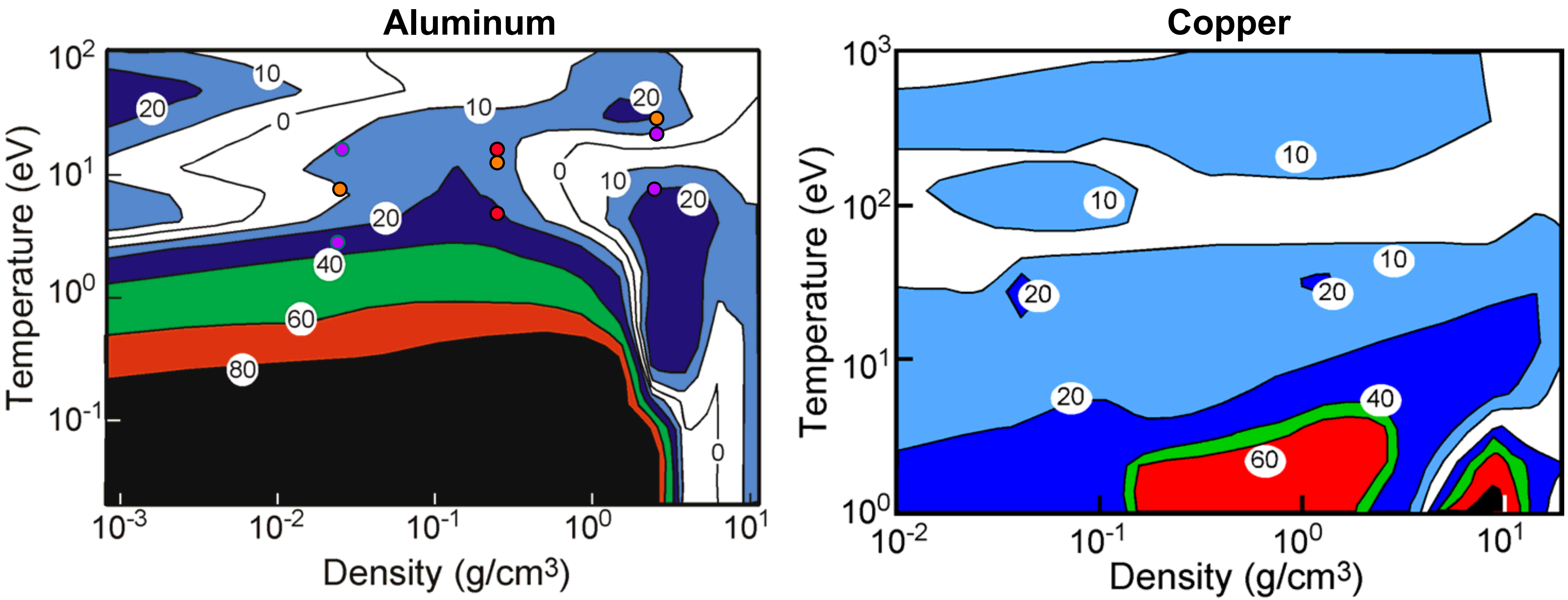
Ion Beam (core)

Electron Fraction (extreme case)

- **Random focusing magnet errors** Gradient and displacement errors can also create halos and beam loss.

In Warm Dense Matter regime large errors exist even for most studied materials (slide courtesy of R. Lee, LLNL)

Contours of % differences in pressure



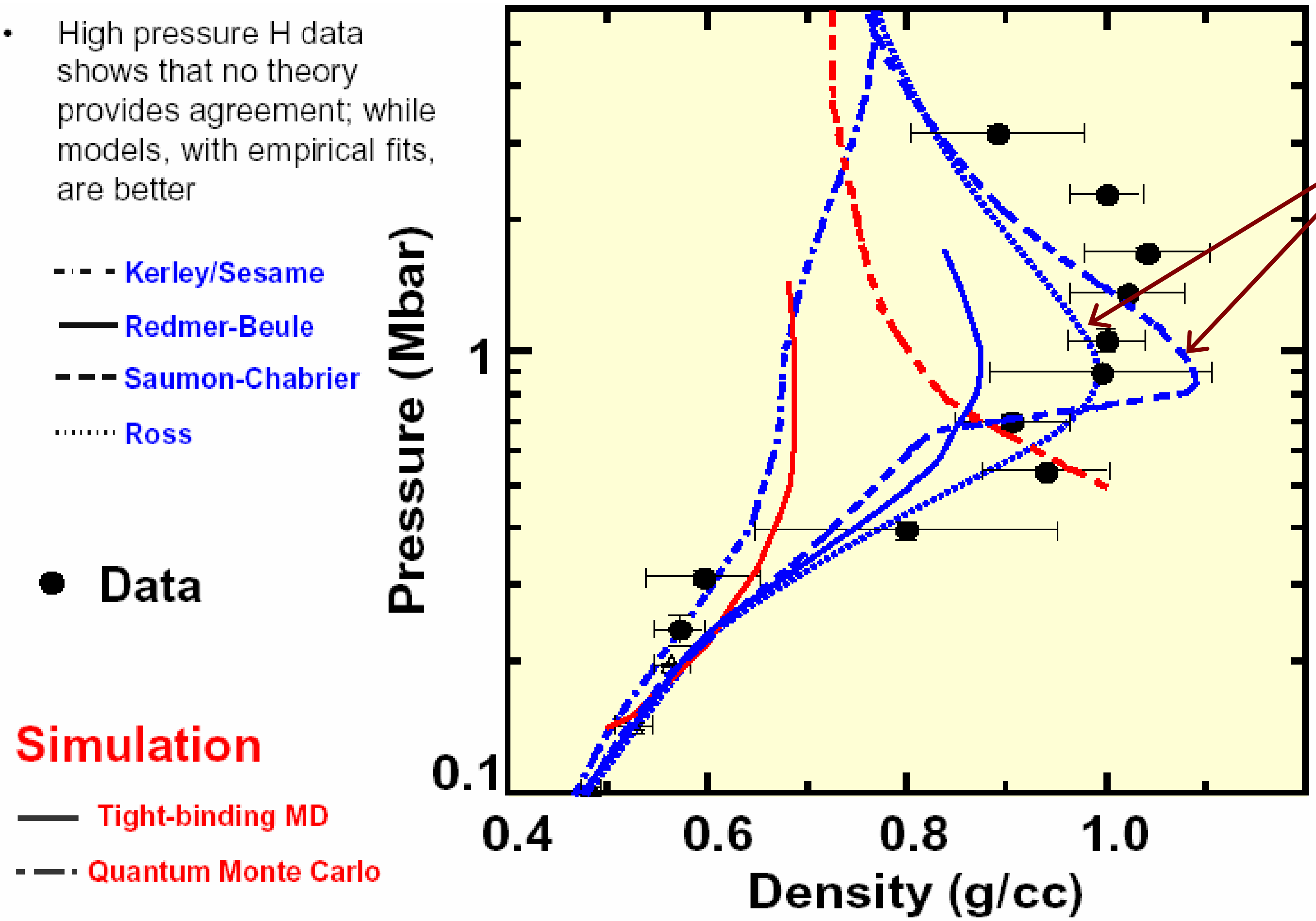
Aluminum

Copper

- EOS Differences > 80% are common
- Measurements are *essential* for guidance
- Where there is data the models agree!!
  - Data is along the Hugoniot - single shock ρ-T-P response curve

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



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

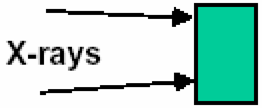
HEDP science would benefit from a variety of facilities offering different tools, shots on demand, and different convenient locations for students

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

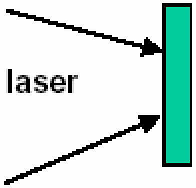
XFEL heating uniform but small volumes (10's of millijoules). High range electrons can heat < 1 mm spots –but too small for diagnostics

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



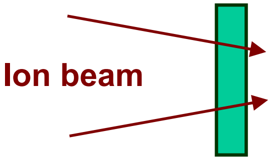
MJ of soft-x-rays available on Z but limited number of shots

- Shock compressed and heated thin foils



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

- Ion heated thin foils

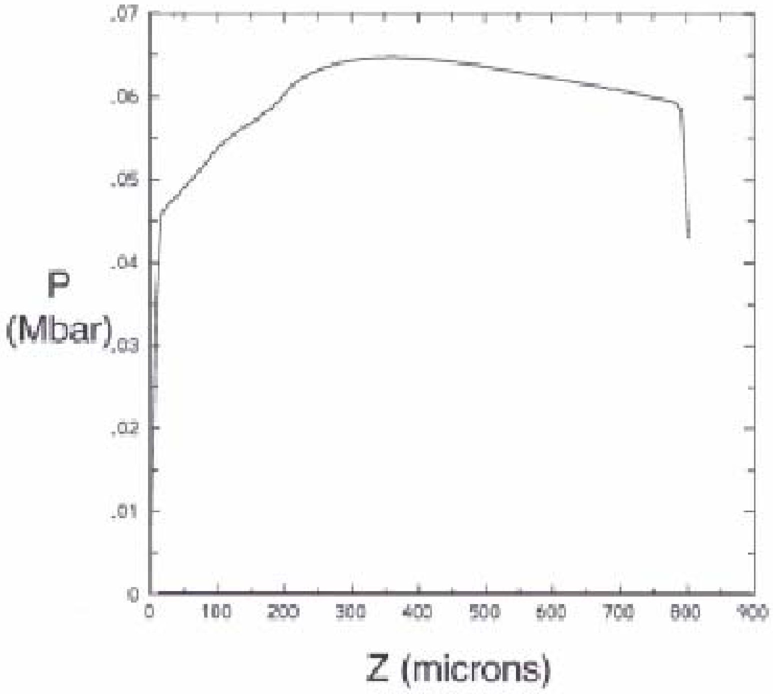


Fast heating of a solid with penetrating ions →lower gradients→ more accurate EOS

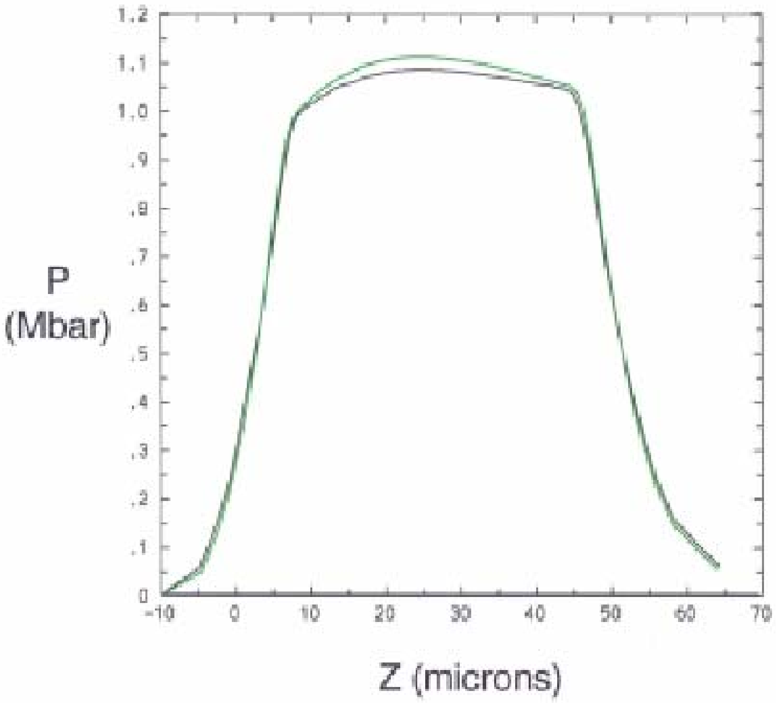
- 100TW lasers →10-50 mJ, ps ion bunches →large energy spreads, non-uniform deposition
- GSI-SIS-100 plans 10-40 kJ of ions @100GeV,100 ns→ large volumes but limited T < 1 eV

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 !)

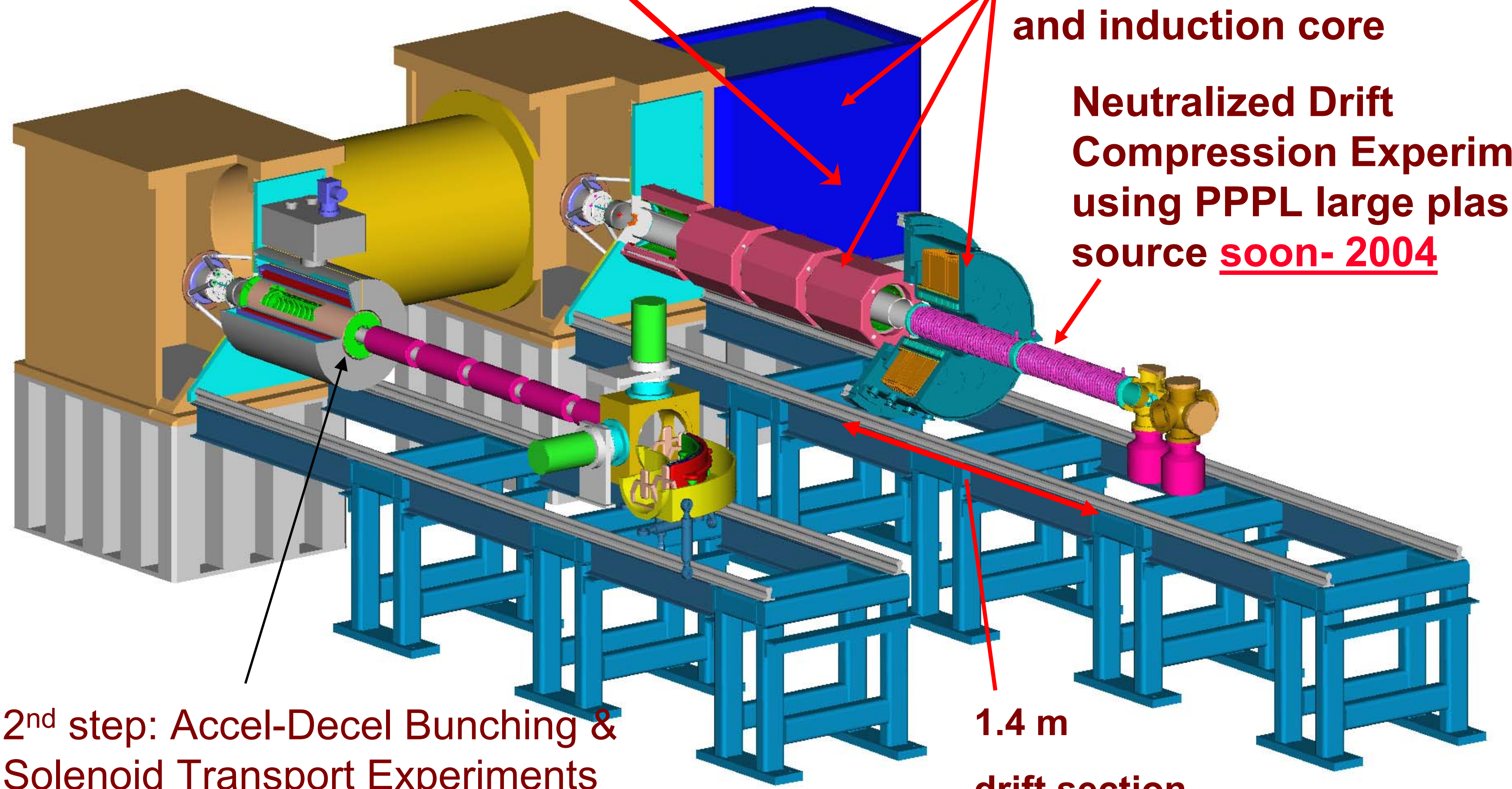
➔Requires perveance x longitudinal compression ratios > 0.1 upstream

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).)

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

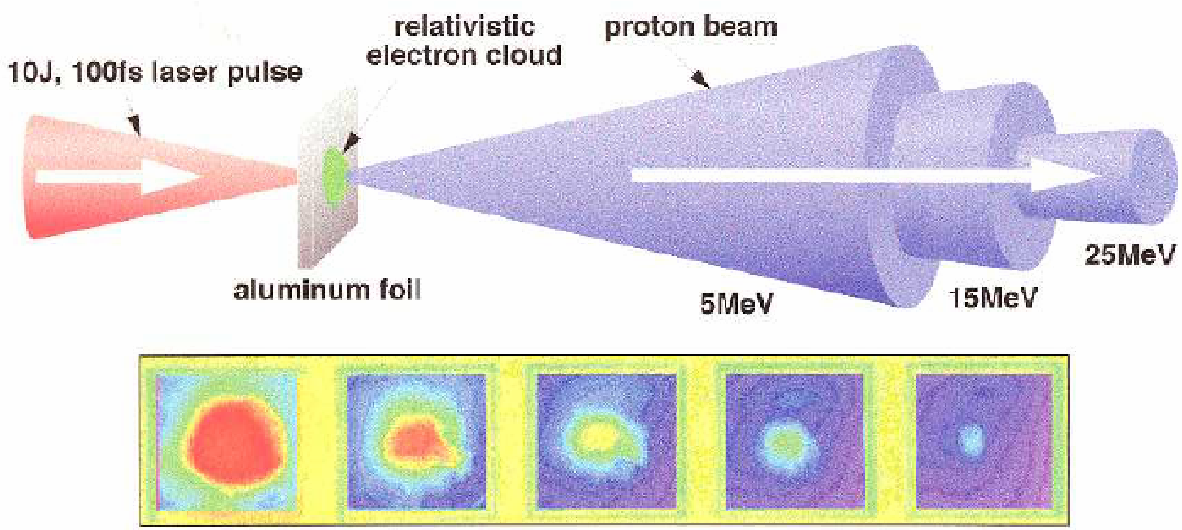
Neutralized Drift Compression Experiment using PPPL large plasma source soon- 2004

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

1.4 m

drift section

Isochoric heating with laser produced fast proton beams for HEDP can complement accelerator driven HEDP. Laser methods needs better understanding and control of ion beam distribution and improved resolution EOS diagnostics together with modeling



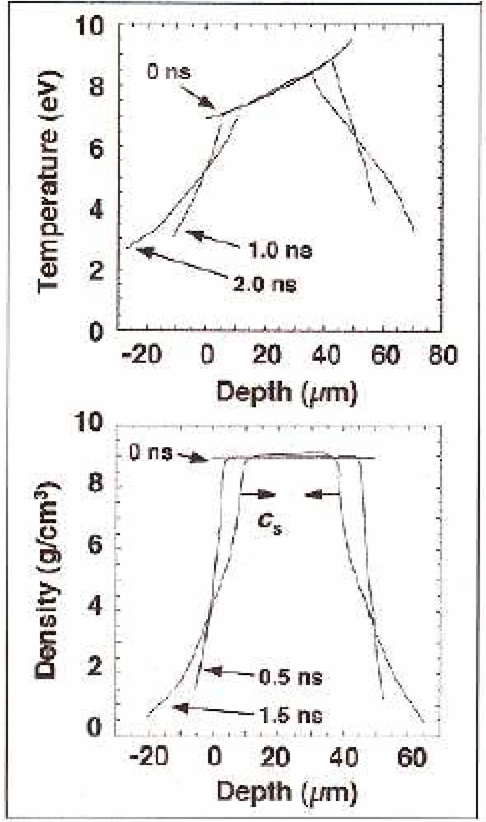
Proton beam from 10J JanUSP laser

- High flux (1-2% of laser energy)
- Exponential distribution (kT~2-3MeV)
- High peak energy (up to 25MeV)
- Strongly collimated (1-20°)
- Temporally short (few ps)

P K Patel *et al*

(from Prav Patel LLNL)

Simulations of isochoric heating of a 50 micron copper cube by a 2×10^{11} proton pulse

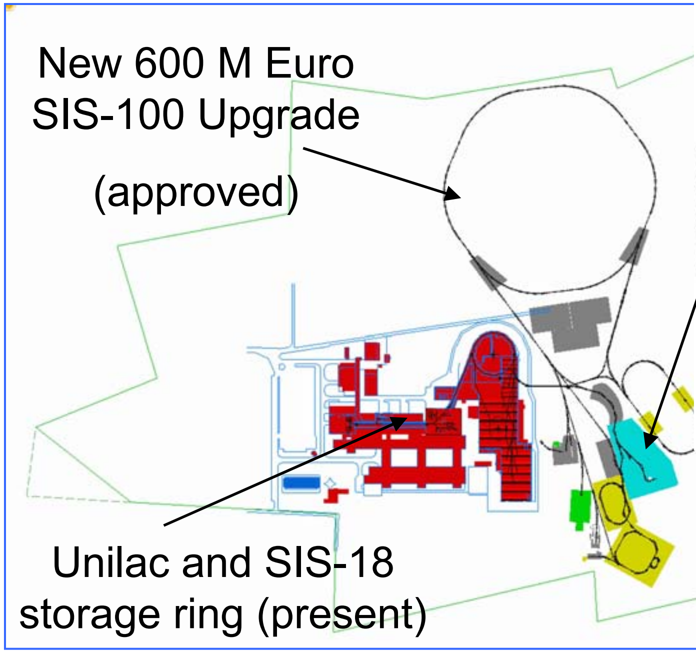


A US-DOE and German Government agreement* supports cooperation in dense plasma physics

- 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.

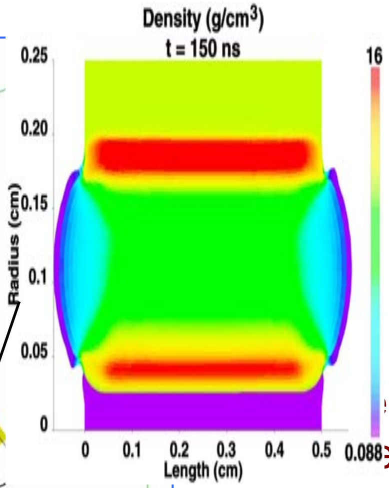
Technical Coordinators:
Arthur Molvik LLNL
Hartmut Reich-Sprenger GSI



New 600 M Euro SIS-100 Upgrade

(approved)

Unilac and SIS-18 storage ring (present)

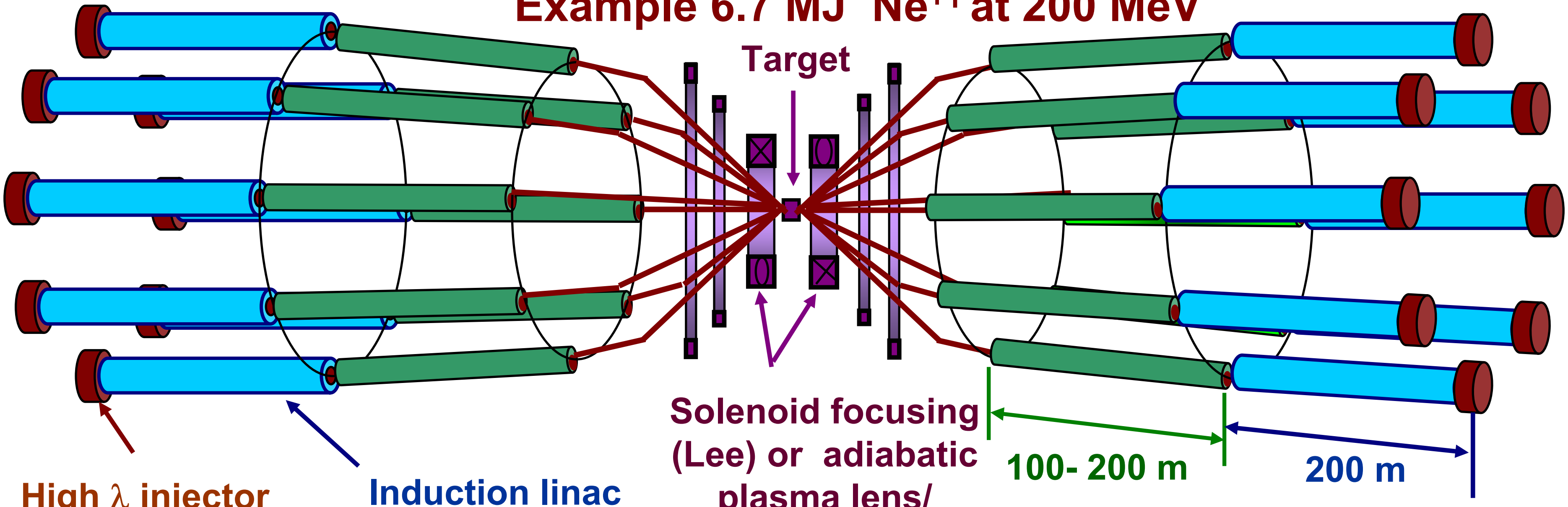


Simulation of a cylindrical target driven by GSI heavy ion beam

nting Agreement between the
ent 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

Example 6.7 MJ Ne^{+1} at 200 MeV



Target

Solenoid focusing (Lee) or adiabatic plasma lens/ assisted pinch (Yu, Welch)

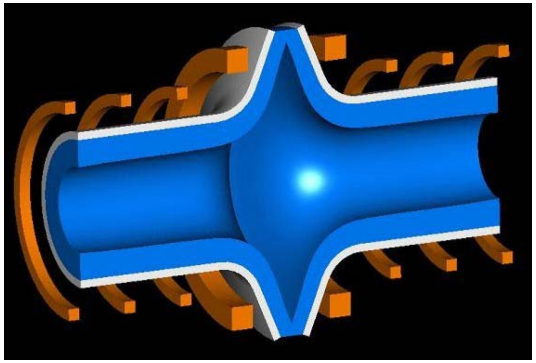
100- 200 m

200 m

Neutralized drift compression

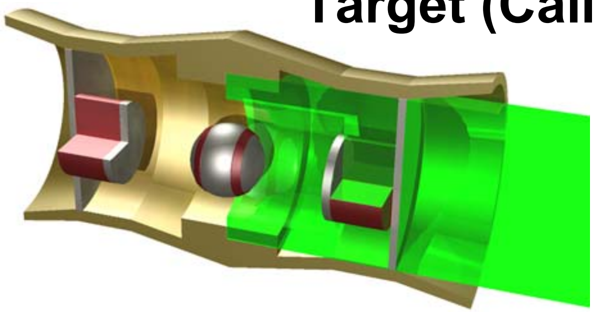
High λ injector

Induction linac



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)