Progress of heavy ion fusion science towards warm dense matter physics

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Lawrence Berkeley National Laboratory

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Princeton Plasma Physics Laboratory

Workshop on accelerator driven warm dense matter physics
Pleasanton, CA
February 22 - 24, 2006

- Dramatic progress compressing ion beams within neutralizing background plasma
- DOE grants Mission Need for a U.S. heavy-ion driven HEDP user facility (IB-HEDPX)
- Plans NDCX-I (now) → NDCX-II→ IB-HEDPX (2010-2012?)
- Simulation of candidate WDM targets driven by low energy ion beams in the VNL
- Proposal for joint VNL-GSI WDM experiment with Al Foams @ GSI

Our goal is to develop a user facility for ion beam driven HEDP, with several important characteristics.

- **Precise control and uniformity of energy deposition**
- **Large sample sizes compared to diagnostic resolution**
- **Pulse length limited by target depth: short beam pulses and low mass density preferred**
- **A benign environment for diagnostics (low gamma and activation**
- **Potential for high shot rates and multiple beamlines/target chambers**
- **Low accelerator cost**
- **Dedicated user facility devoted exclusively to WDM studies.**
- **Easy and frequent access for small university users.**

The question: "What is the best facility for WDM applications?" will be answered by the users, who will vote with their feet.

The NDCX facility may interest curiosity-driven university users more than application-driven users (Dick More's characterization)

Example problems we might be able to pursue over the next five years:

1. **Transient darkening emission and absorption experiment**

2. **Experiment to measure target kT using a beam compressed both radially and longitudinally with accurate beam deposition measurement**

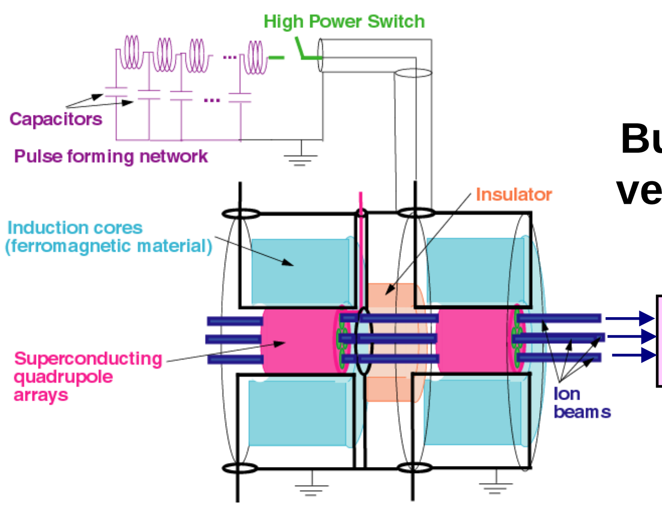
3. **Positive - negative halogen ion plasma experiment (kT >~ 0.4 eV)**

5. **Two-phase liquid-vapor metal experiments (kT > 0.5 - 1 eV for Sn) (maybe needs NDCX-II)**

6. **Critical point measurements (kT > 1 eV for Sn) (possibly only on NDCX-II)**

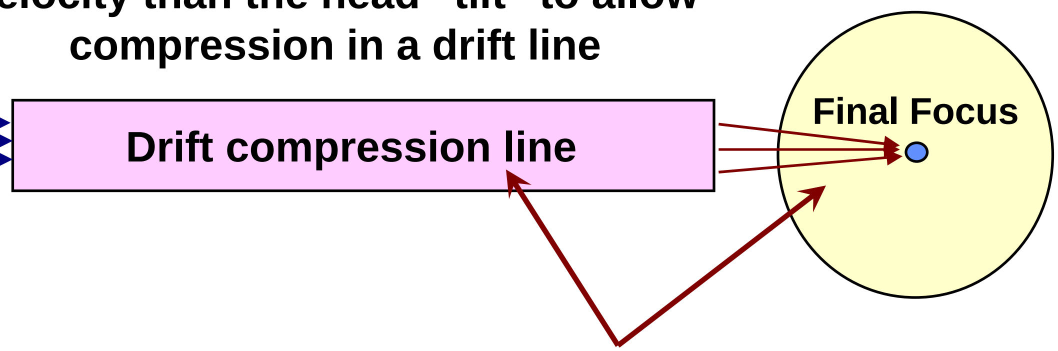
Drift compression of low cost, low energy ion beams (0.1 to 1 MeV/u) to the short pulses required to drive warm dense matter targets near the peak in dE/dx requires plasma neutralization of space charge.

Induction acceleration/ velocity “tilt” @ τ_{pulse} ~100 to 200 ns



Near term Warm Dense Matter targets require ~ 1-2 ns pulses

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



High beam perveances > 10^{-3} <u>requires</u> plasma neutralization of space charge during drift compression <u>and</u> final focus to target.

→Partial neutralization by electron cloud ingress was found to be unavoidable anyway!

Plasma neutralization of beam space charge *upstream* of final focus will likely be needed for HEDP targets driven by beams at the peak of dE/dx with lighter ions for affordable accelerator energies.

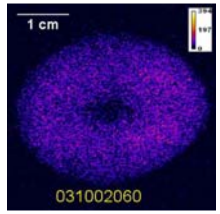
Beam ion	1.5xEnergy (MeV) @ peak dE/dx (cold aluminum)	Range (microns) (10% solid Al)	Target Δz (microns) **for <5% T variation**	Beam energy (J)/mm^2 for 10 eV 10%ρo Al	$\tau_{hydro}=\Delta z/(2Cs)$ (@10eV) (ns)	Beam power GW per mm^2	Beam current (A) for 1 mm dia. spot	Beam perve-ance@ final focus
Li	2.4	30	22	3.3	0.6	6.1	1990	0.93
Na	24	60	54	8.0	1.3	6.1	200	5.4×10^{-3}
K	68	140	91	13.6	2.2	6.1	70	5.1×10^{-4}
Rb	237	250	150	22.4	3.7	6.1	20	3.3×10^{-5}
Cs	456	400	190	28.5	4.7	6.1	11	8.5×10^{-6}

Likely too expensive for US budgets

These perveances are likely too high for ballistic focusing, even with plasma neutralization in the target chamber
→must extend plasma neutralization upstream of final focus
→use plasma-filled solenoids, plasma lens, or assisted-pinches for final focus

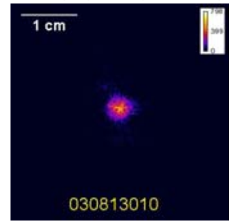
Neutralized Transport Experiment (NTX-2004) encouraged use of plasma neutralization for radial compression

Non-neutralized

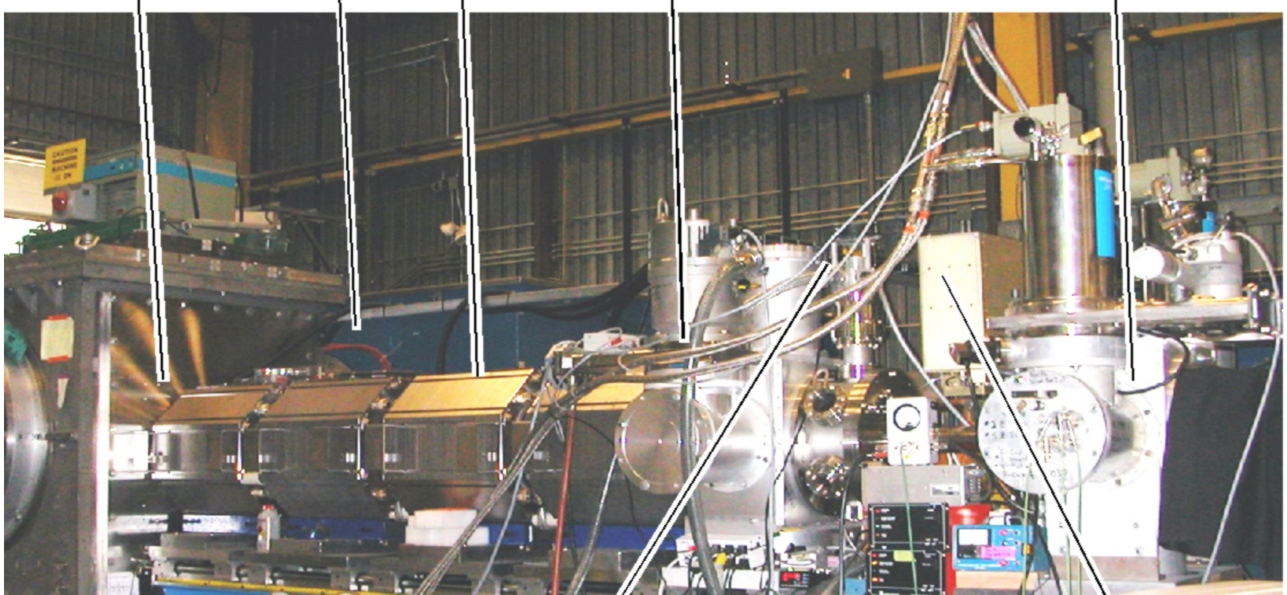


FWHM: 2.71 cm

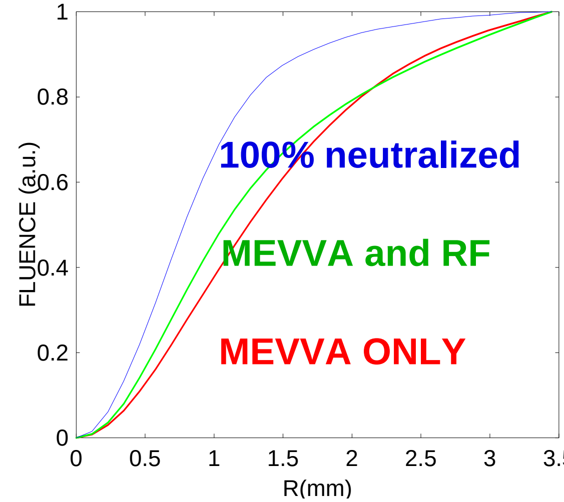
Neutralized



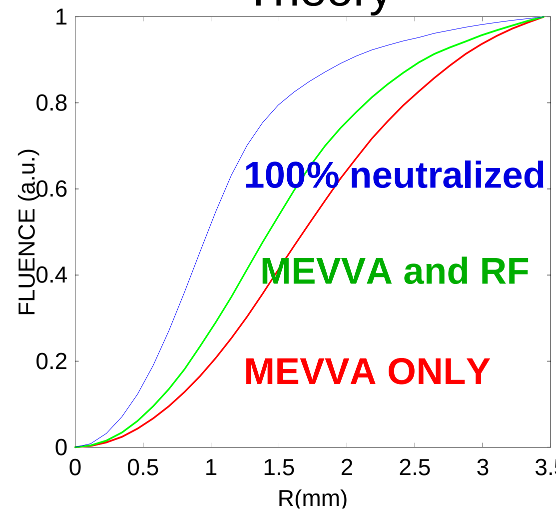
FWHM: 2.14 mm



Measurement

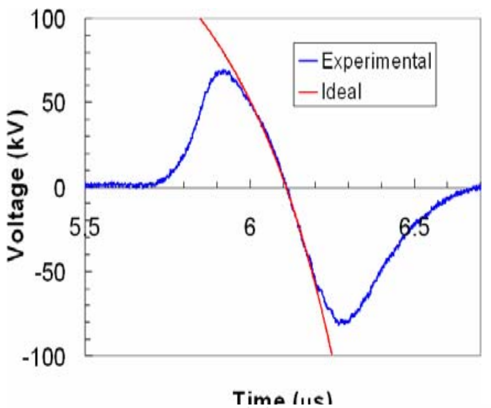


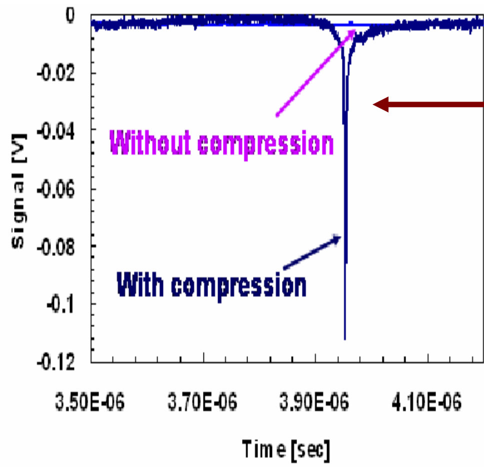
Theory



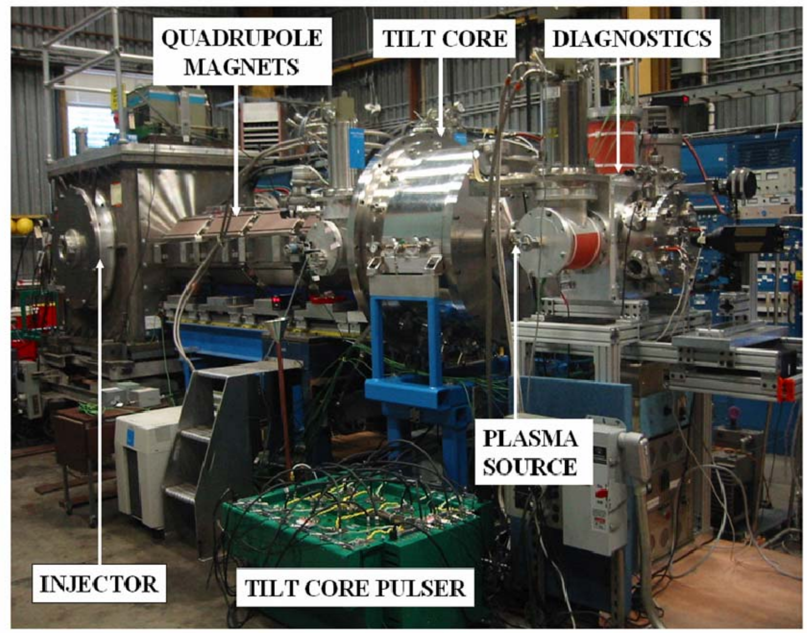
The neutralized drift compression experiment (NDCX) began operation Dec. 2004 to explore neutralized *longitudinal drift compression*

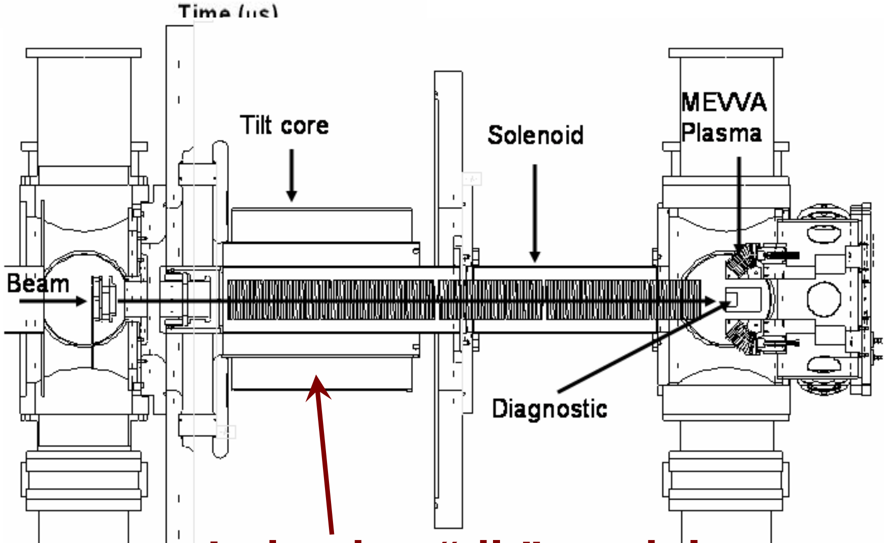
Tilt core waveform





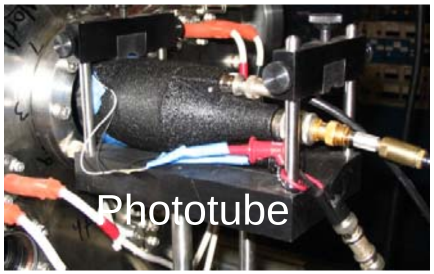
First beam current Diagnostic measurements showed large beam compressions!

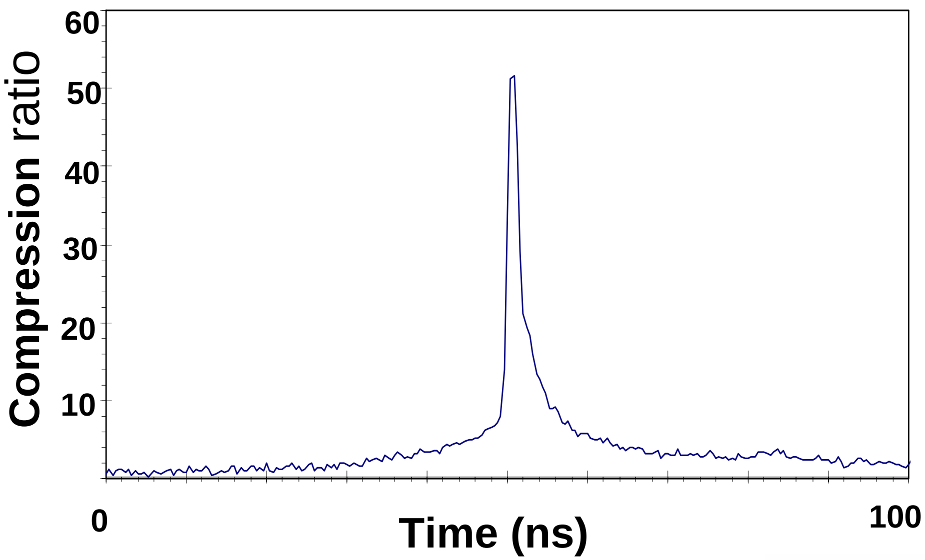


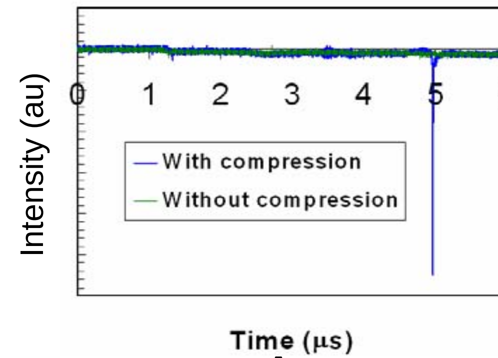


Induction "tilt" module

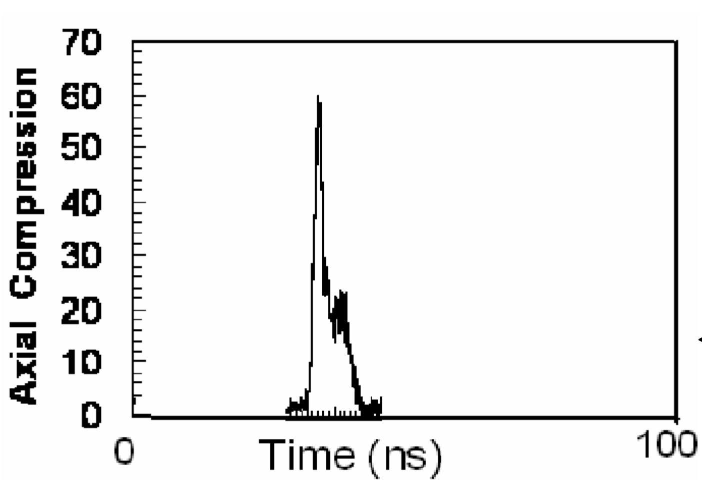
Surprising result: 50-fold beam compression achieved in the NDCX experiment is consistent with a very low longitudinal beam temperature T_{par} < 1 eV !





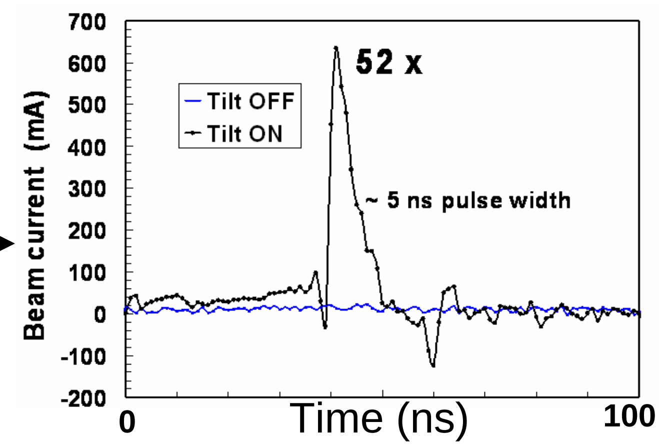


Optical data

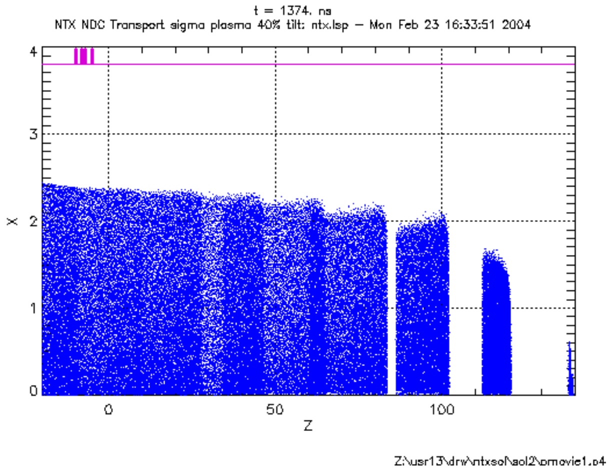


LSP simulation

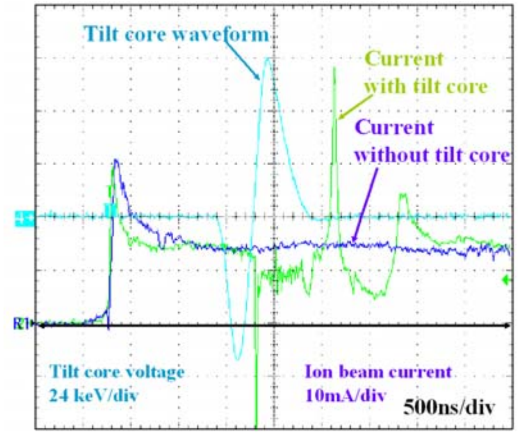
Corroborating data from Faraday cup



We don't know the limits yet on heavy ion beam compression in plasmas!

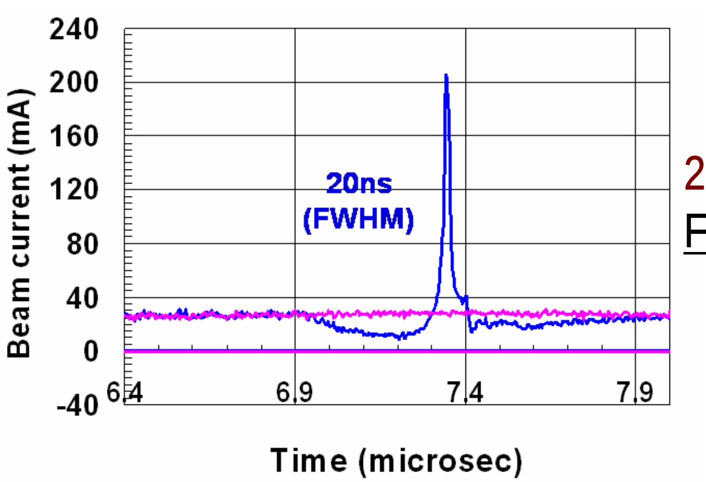


Simulation
of concept
Mar 11, 2004

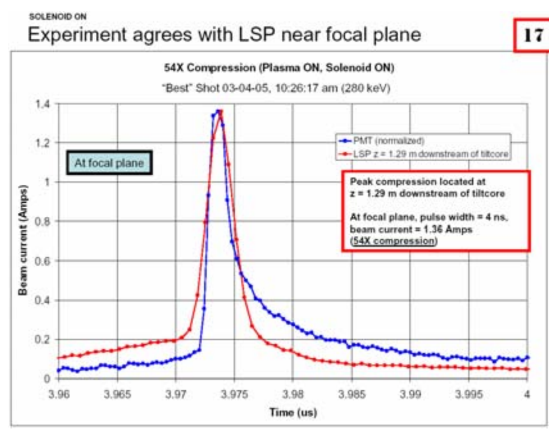


NDCX-1A
Constructed,
first data

40 ns FWHM
Dec. 9, 2004



20 ns FWHM
Feb 27, 2005



4 ns FWHM
May 2005

We have now achieved 2 ns pulses→ longitudinal beam temperature < 1 eV ! We know much of the present T_z is caused by known tilt core errors than can be further reduced.

Justification of Mission Need CD-0 for the Integrated Beam High Energy Density Physics Experiment (IB-HEDPX)

The overall IB-HEDPX program addresses a critical issue for high energy density physics in the near term, and inertial fusion energy in the long term, namely, the integration of the generation, injection, acceleration, transport, compression, and focusing of an ion beam of sufficient intensity for creating high energy density matter and fusion ignition conditions. The heavy ion beams required are very intense yet virtually collisionless, so that the beam distribution retains a long memory of effects from each region the beam passes through. Thus, the beam distribution that heats the target depends on the evolution of the beam distribution in all of the upstream regions. An integrated beam experiment IB-HEDPX is therefore essential for testing integrated beam models, and for accurate prediction of the beam energy deposition in target physics experiments. A secondary, but equally important, objective of the program is to create a critically needed user facility for experimental research in warm dense matter. Such a facility is lacking at present.

NDCX-II, requiring approximately $5 M hardware as an upgrade of the present NDCX-1 facility in Year 1 and 2, is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX .

APPROVAL

This Justification of Mission Need for the IB-HEDPX Project is satisfactory and Critical Decision 0 (CD-0) is approved and the Project is authorized to proceed with Conceptual Design activities.

Submitted by:

Francis Thio — 12/1/2005

Y. C. Francis Thio
Program Manager
Research Division
Office of Fusion Energy Sciences

Date

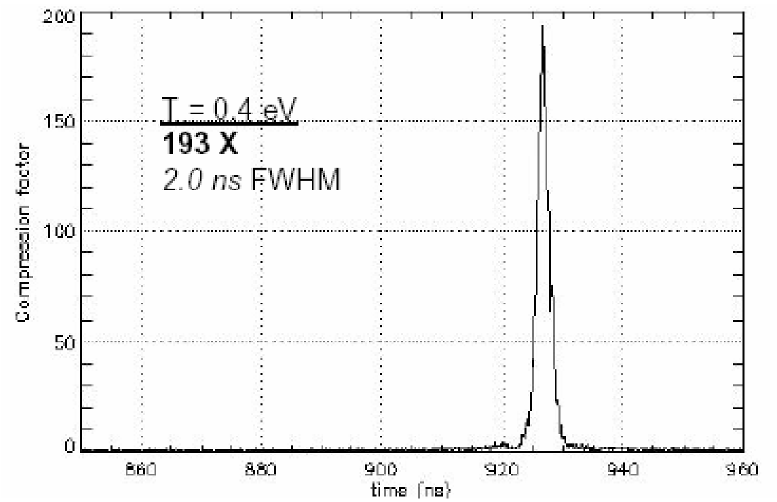
Approved by:

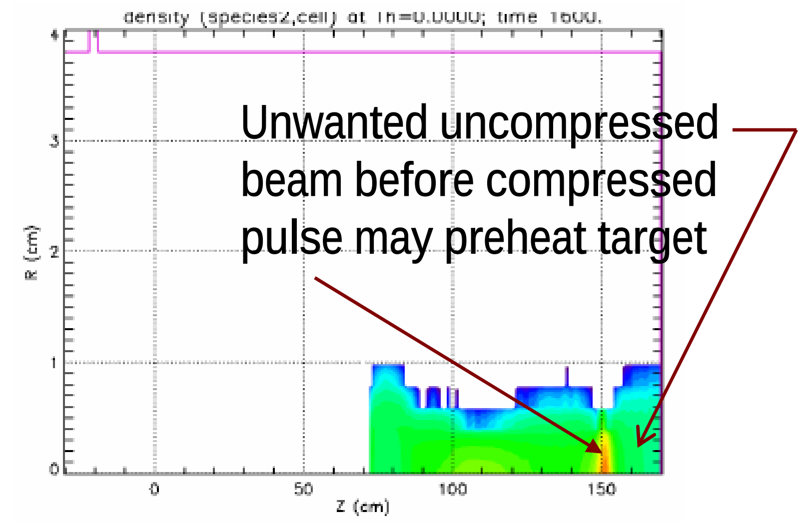
12/1/05

N. Anne Davies
Associate Director for Fusion Energy Sciences
Office of Science

Date

Near term plans: continue optimizing the existing NDCX 1A facility





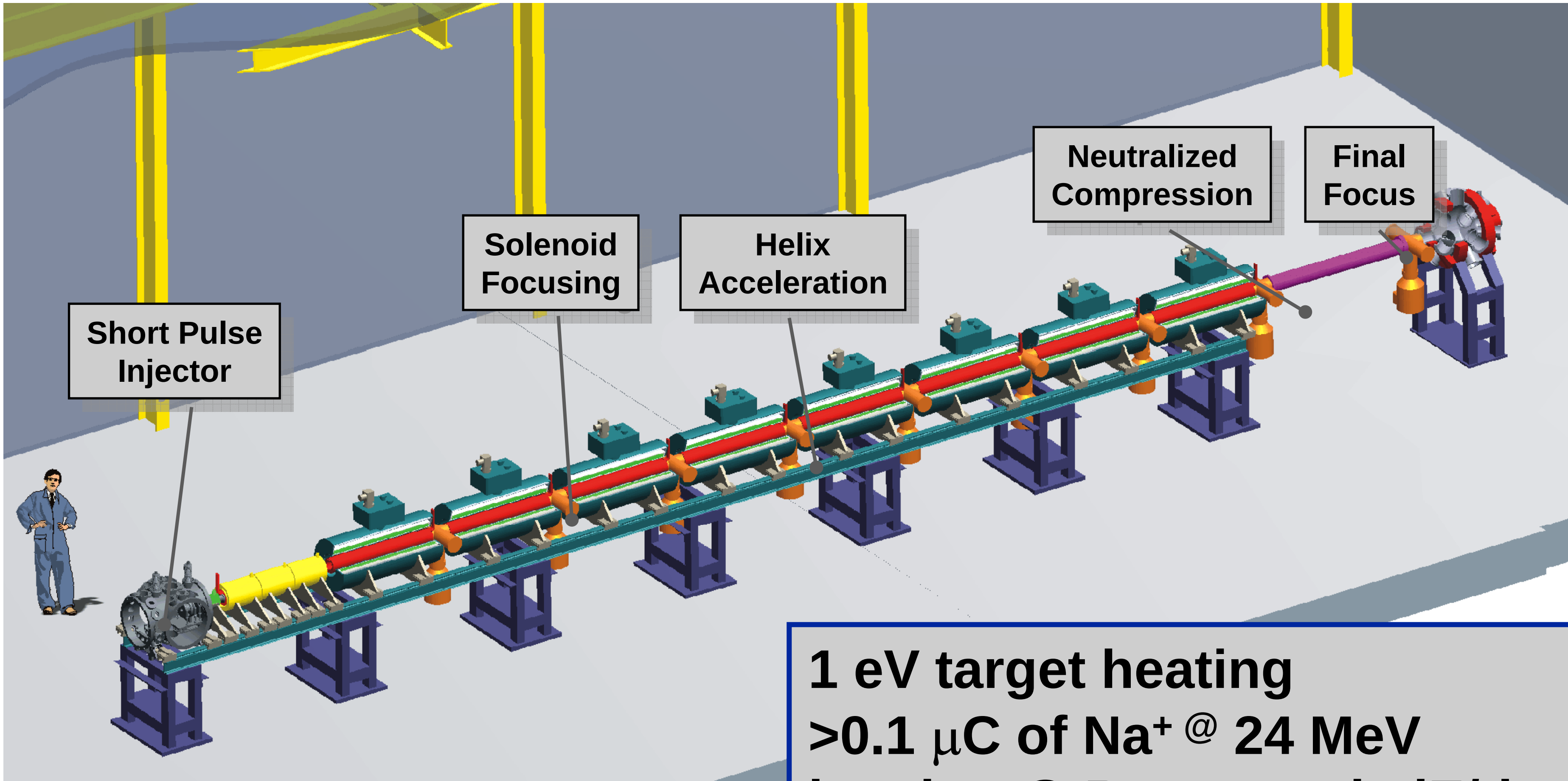
Adam Sefkow's simulations show higher potential compressions with improved tilt

Dale Welch's simulations show focus with less preheat is possible

John Barnard's heavy-ion beam-WDM target optimization code shows lower emittance apertured beams might focus to smaller spots

	Pulse duration (before drift compression) (ns)	Compression ratio C	Velocity tilt (Head to tail dv/v_tilt	Maximum rms velocity spread dp/p_rms (before drift comp)	Maximum emittance unnormalized 4 rms (mm-mrad)	Maximum normalized emittance 4 rms (mm-mrad)	Beam radius at solenoid entrance Ro (m)	Neutralized Drift length (m)	Maximum Longitudinal Temp (before comp) (eV)	Maximu Target Te (eV)
HCX	50	25	0.0625	7.2E-04	56.9	0.53	0.017	2.16	1.67	1.25
NDCX	100	50	0.2	1.2E-03	35.6	0.17	0.005	0.69	1.07	0.34
NDCX - apertured	100	50.00	0.2	1.15E-03	11.6	0.054	0.003	0.69	1.070	0.527

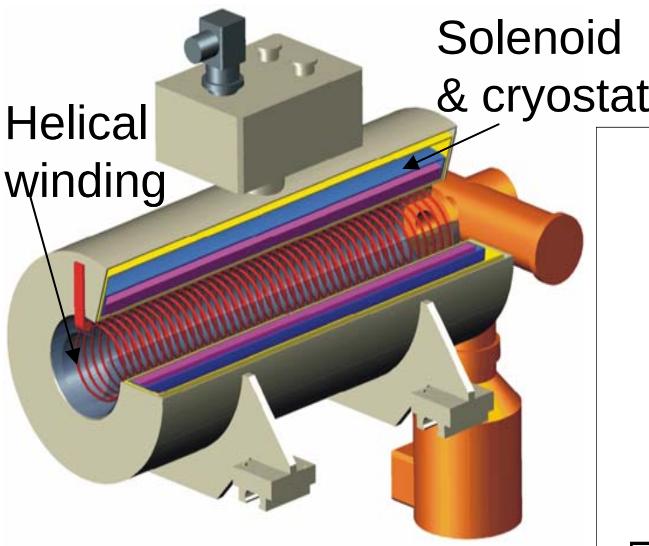
NDCX-II vision: a short pulse high gradient accelerator for ion-driven HEDP and IFE is being evaluated



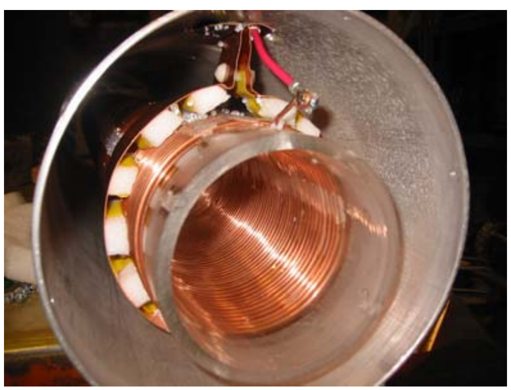
1 eV target heating
>0.1 μC of Na^+ @ 24 MeV
heating @ Bragg peak dE/dx
NDCX-1C + $5M hardware

A Pulse Line Ion Accelerator* (PLIA) has accelerated K^+ ion bunches with energy gain 150 keV >> than wave amplitude 15 kV

NDCX-II Accelerator Cell

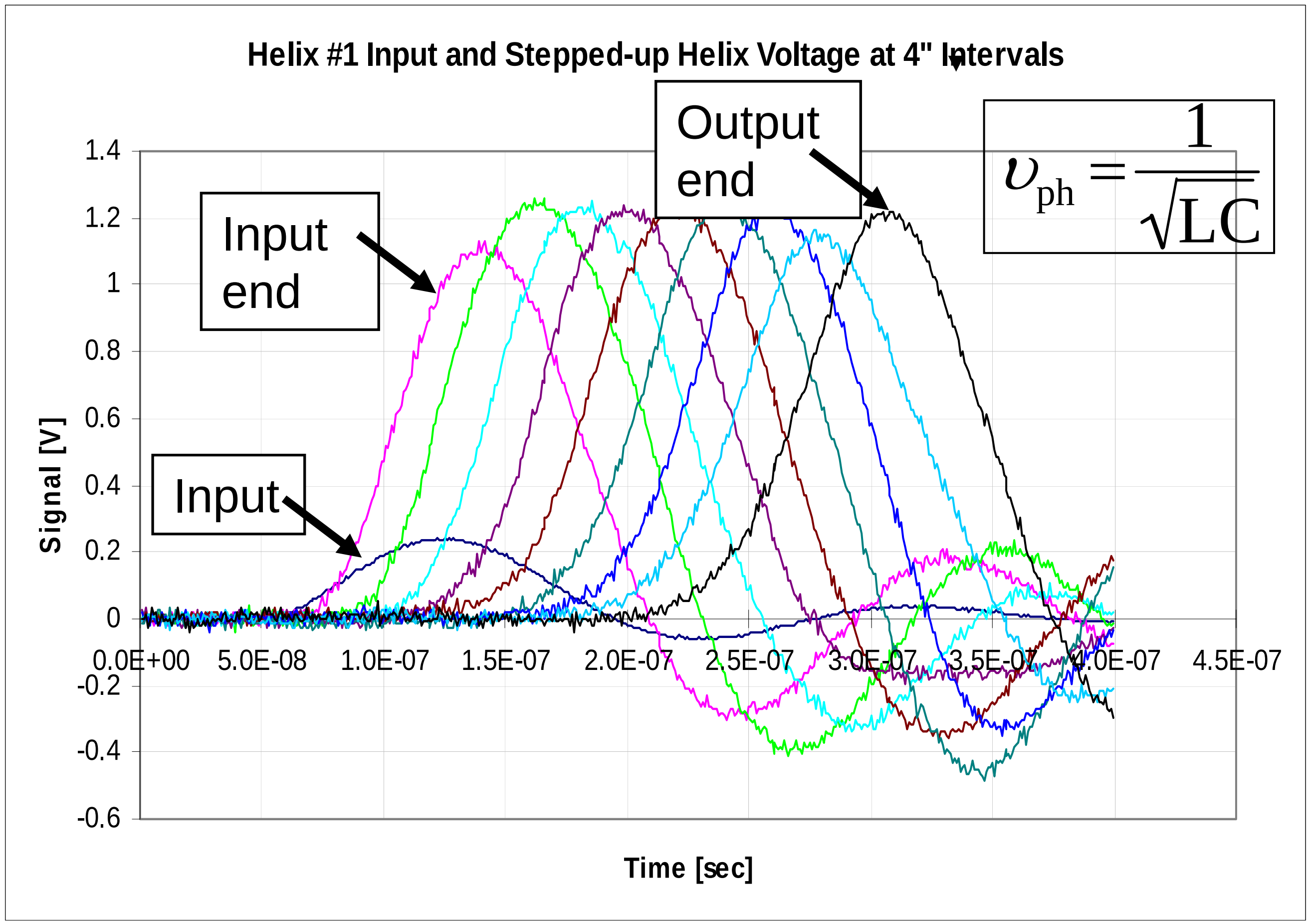


Compact transformer coupling (5:1 step-up)

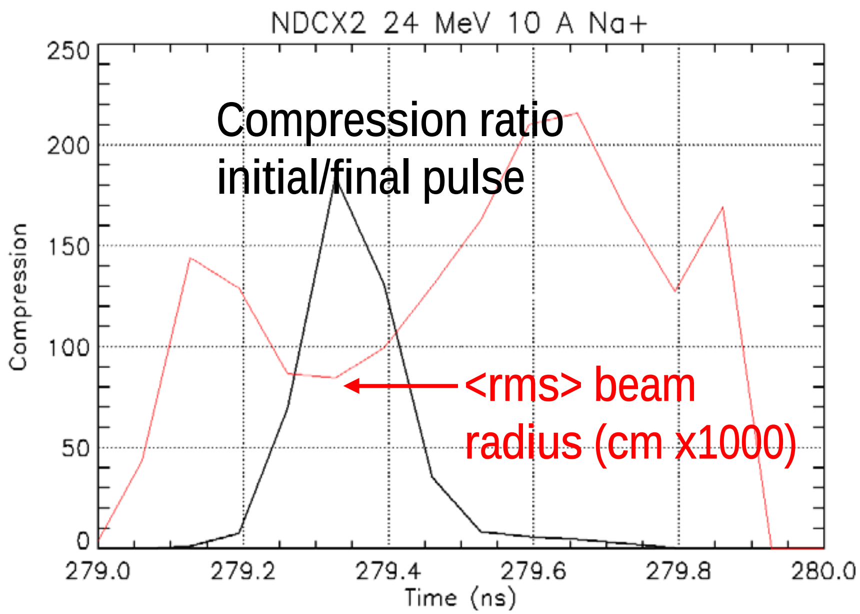


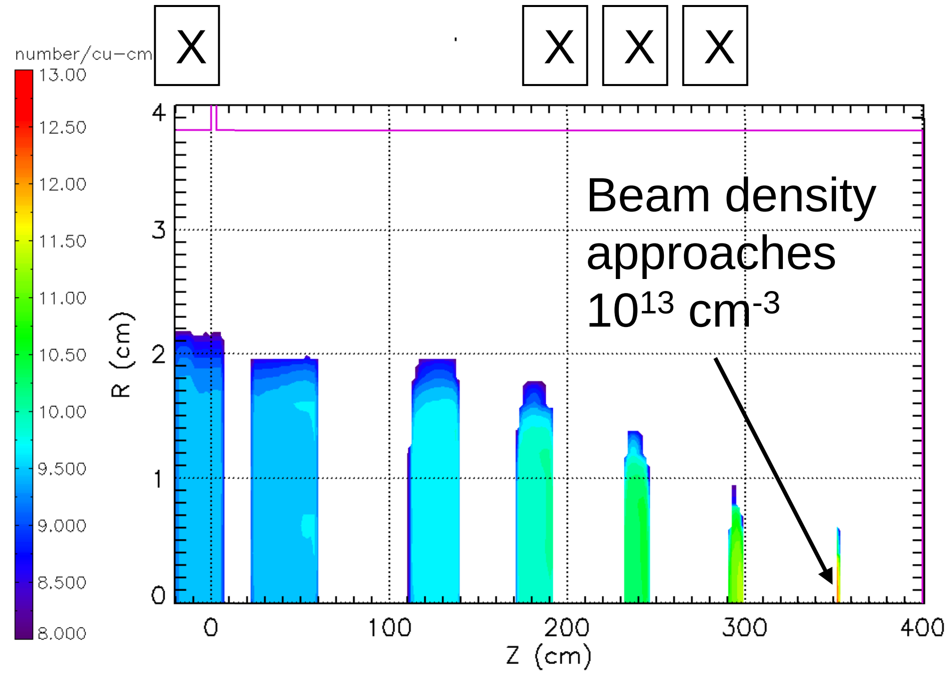
*R.J. Briggs, *et al.* - LBNL Patent, Aug 2004

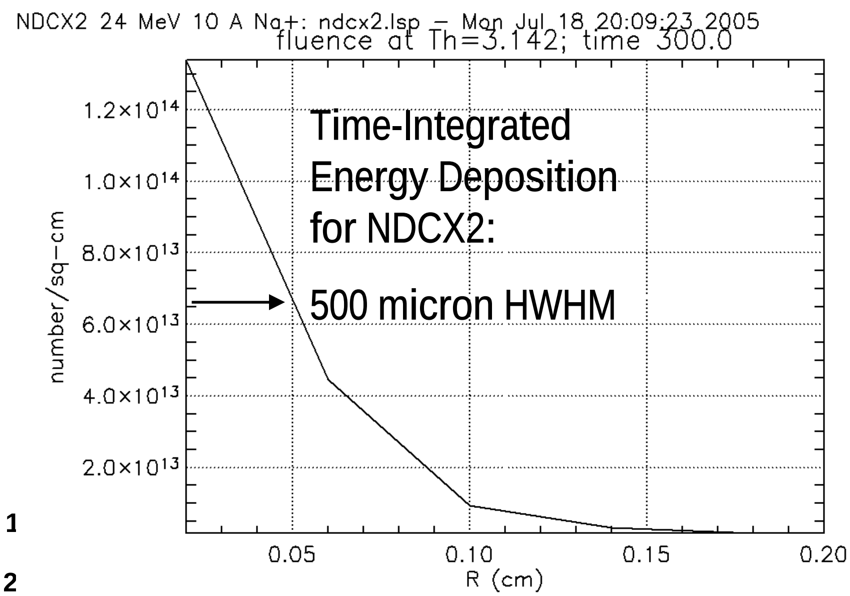
Pyrex tube vacuum wall breakdown currently limits average gradients < 100 kV/m. Tests with new vacuum wall continuing.



LSP simulation by Dale Welch for future 24 MeV Na^+ NDCX-II exp. shows compression to 100 ps (*ion fast ignition relevant*) with 500 micron central peak focus







Spot limited in simple solenoidal focusing (4T) by energy tilt (ΔE/E)

$$\frac{a_f}{a_0} \approx \frac{\pi \Delta E}{8E}$$

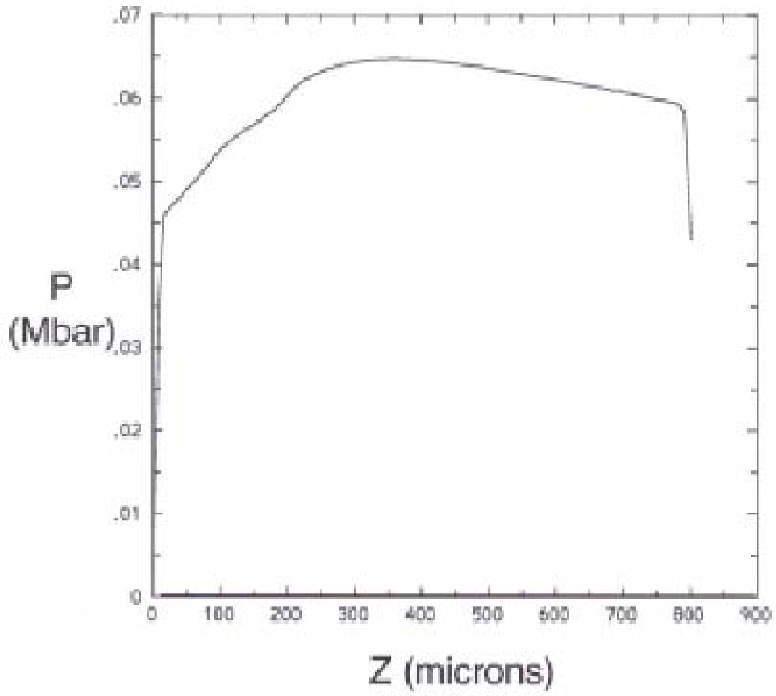
Smaller spot can be achieved by more aggressive focusing scheme

1

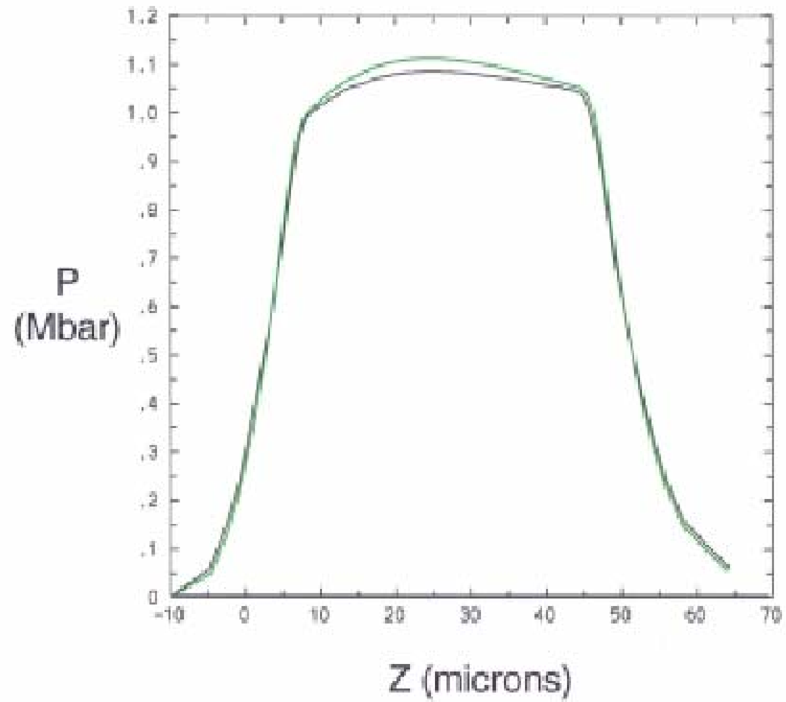
2

1-D Lasnex calculations of aluminum foam target examples driven by NDCX-II-like 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

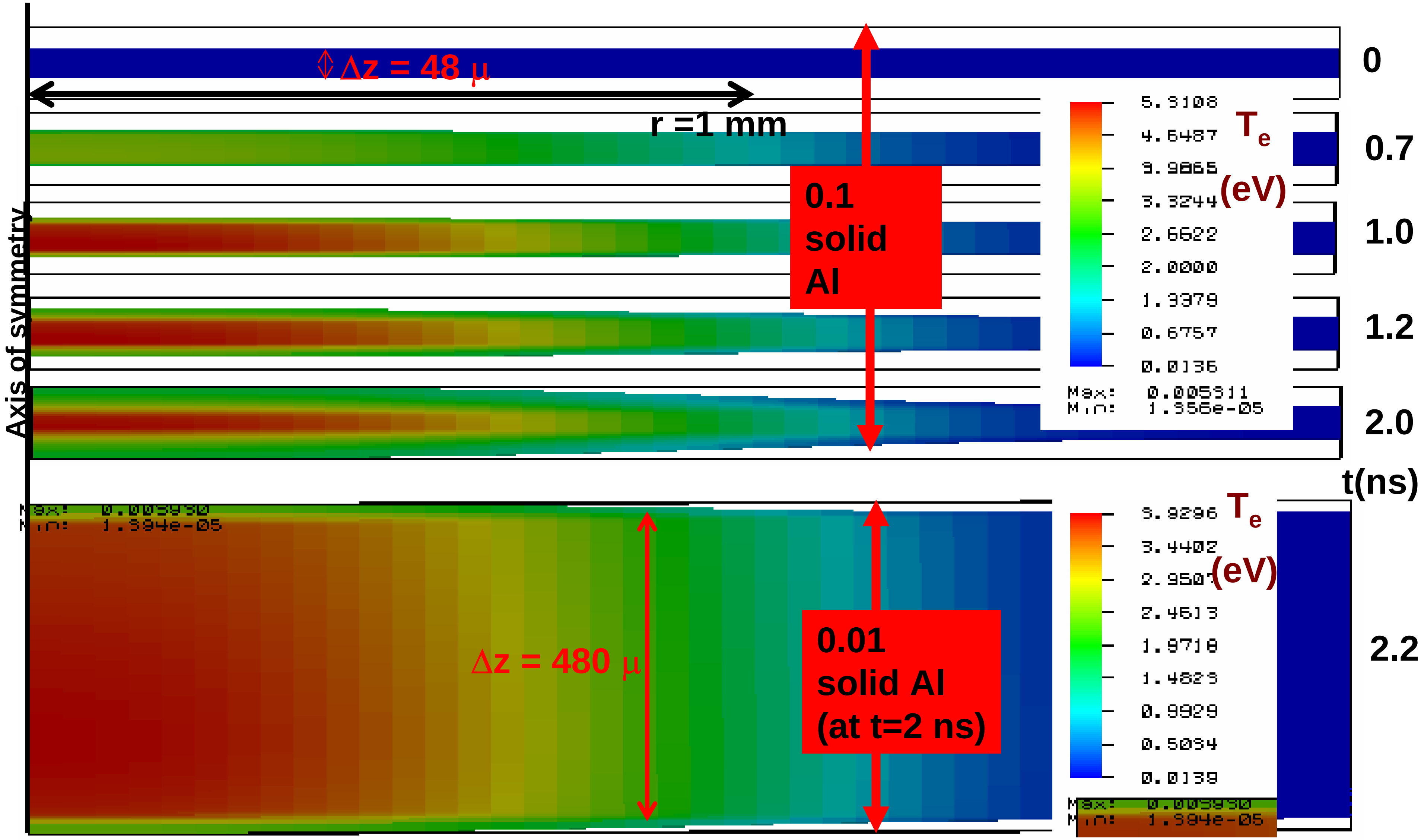


1% solid density
800 microns thick



15% solid density
53 microns thick

Hydra simulations (2-D) confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of aluminum (NDCX-II, 24 MeV Na$^+$)

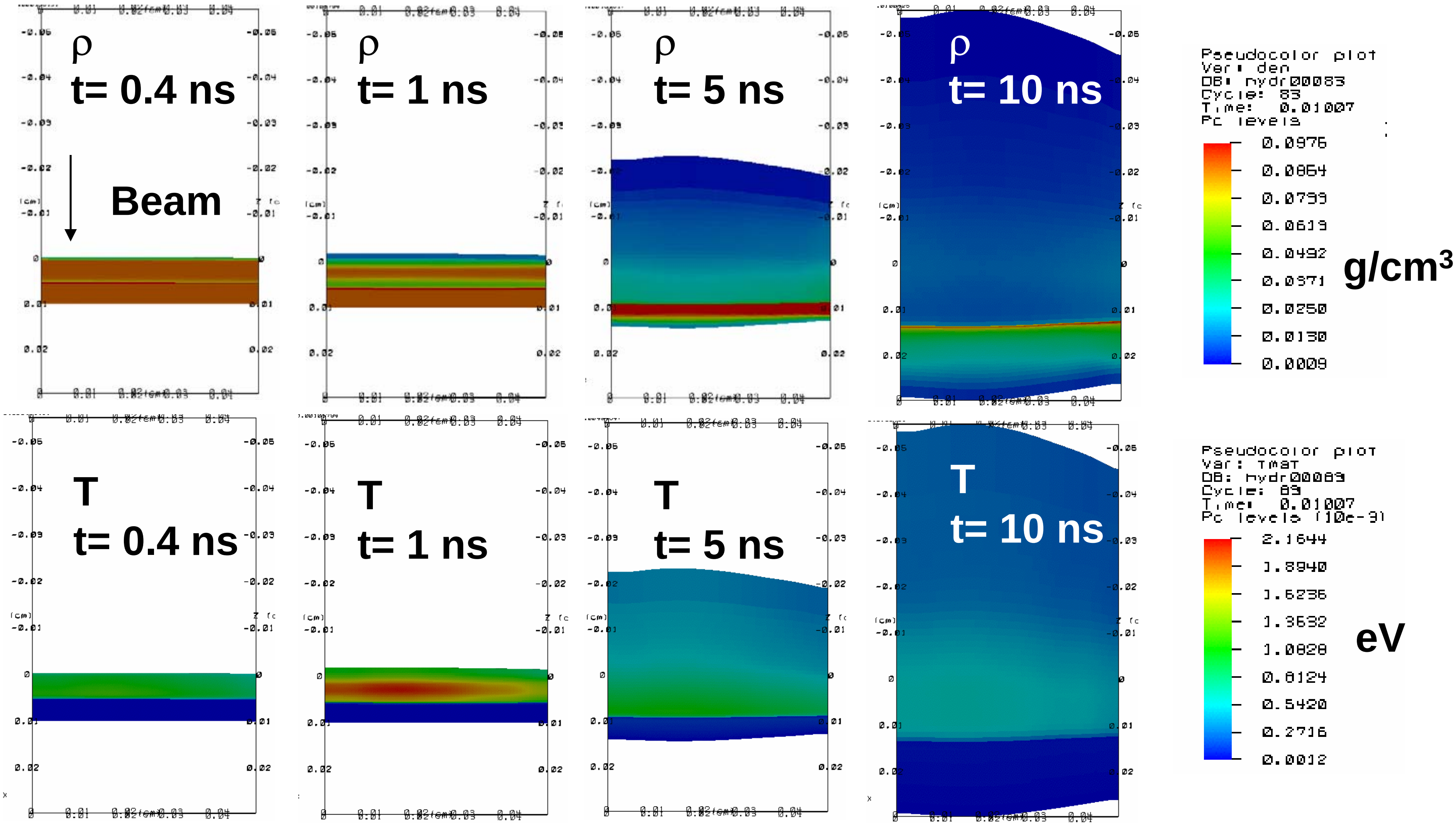


Proposed HIFS-VNL collaborative experiment at GSI

Opportunities for experimental collaboration

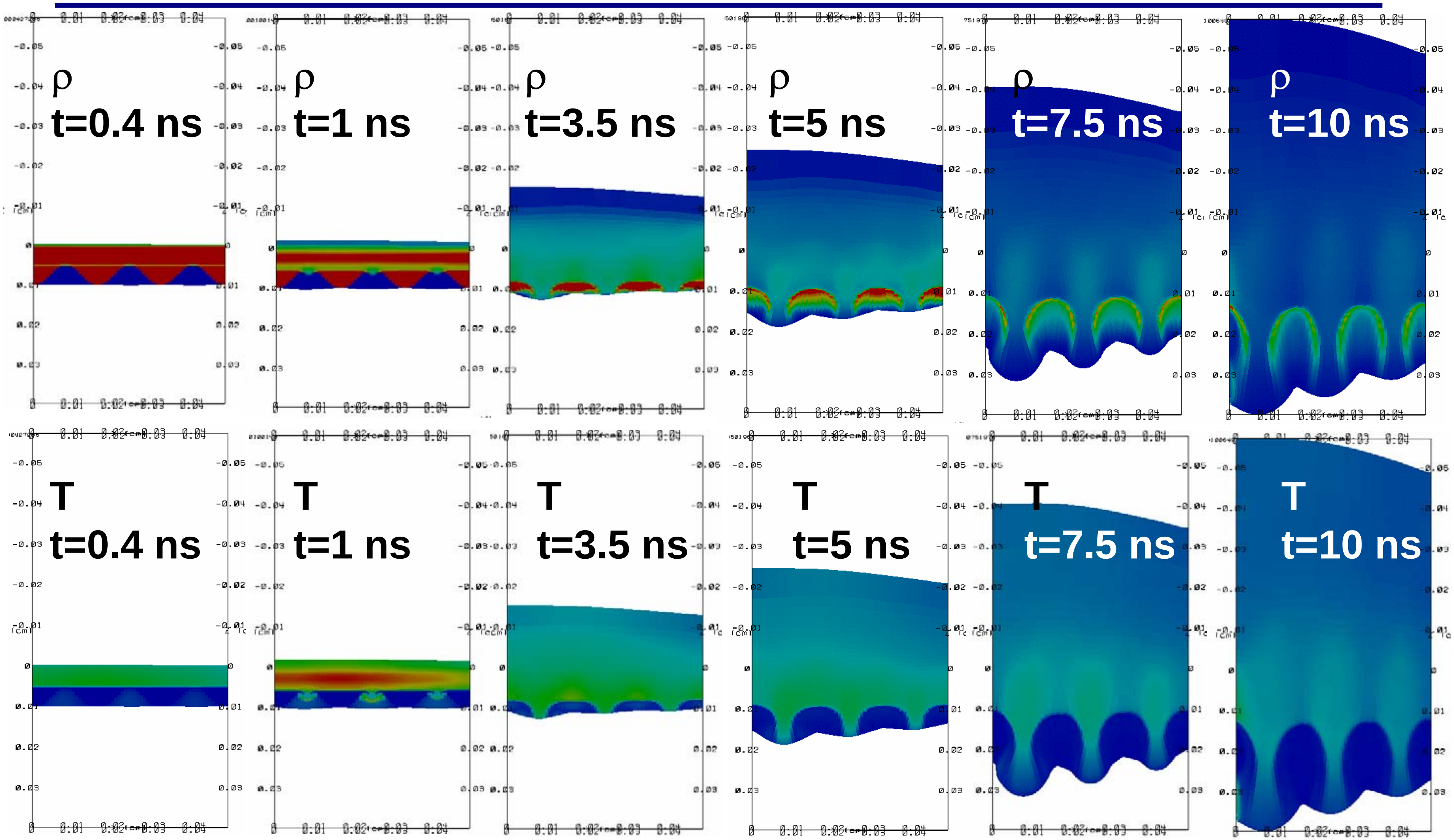
- **Foams are of interest to HIFS-VNL and others:**
  - **Extend range of low energy heavy ion beams to reduce hydro expansion time**
  - **Study issues of relaxation and homogenization as filaments expand into voids**
  - **Foams are also of interest in heavy-ion IFE targets**
- **Proposed experiment uses metal foams (~10-30% solid density metal) to study effect of pore size using dE/dx and other diagnostics:**
  - **initial experiments can be done non-destructively at low intensity; later experiments in WDM regime.**
- **GSI is equipped to make these measurements at existing facility**

We have begun using Hydra to explore accelerator requirements to study ion-beam driven Rayleigh Taylor instability (Barnard & Santhanam, LLNL)



23 MeV Ne, 0.1 μC, 1 ns pulse (NDCX II) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm3; No density ripple on surface→ blow-off stably accelerates slab

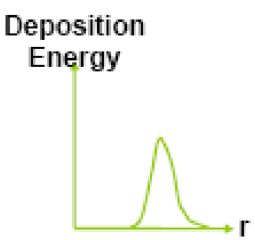
When initial surface ripple is applied, beam-driven Rayleigh-Taylor growth is clearly visible, looking 10 ns after the beam pulse. Longer beam pulses better?

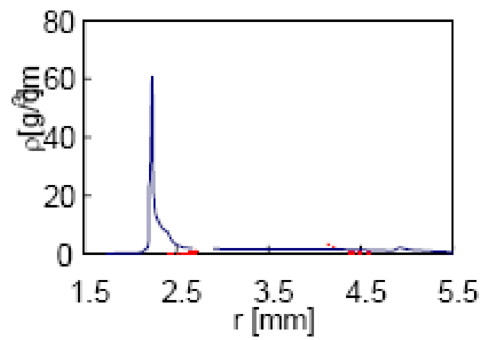


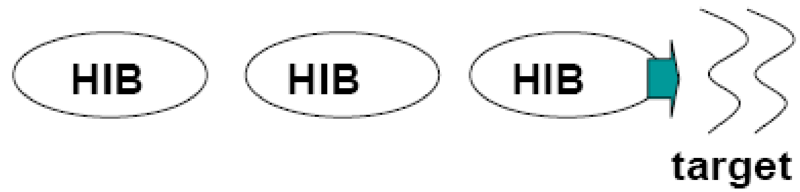
Would hyper-velocity ion direct drive be feasible with dynamic stabilization?

RT Instability Control by HIB *[S. Kawata, L&PB 11,(1993) 757]*

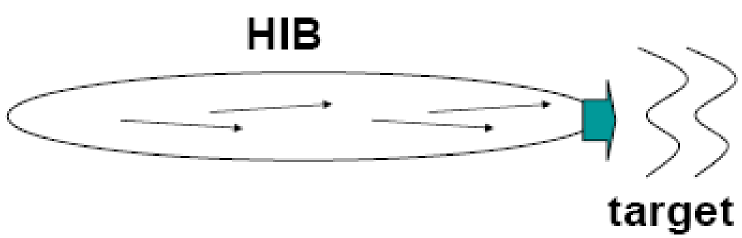
Large-scale HIB-energy deposition profile
-> Large-scale density gradient
-> Reduce the R-T growth!







Successive HIBs induce a dynamically Oscillating *g*!
-> reduce the R-T growth!

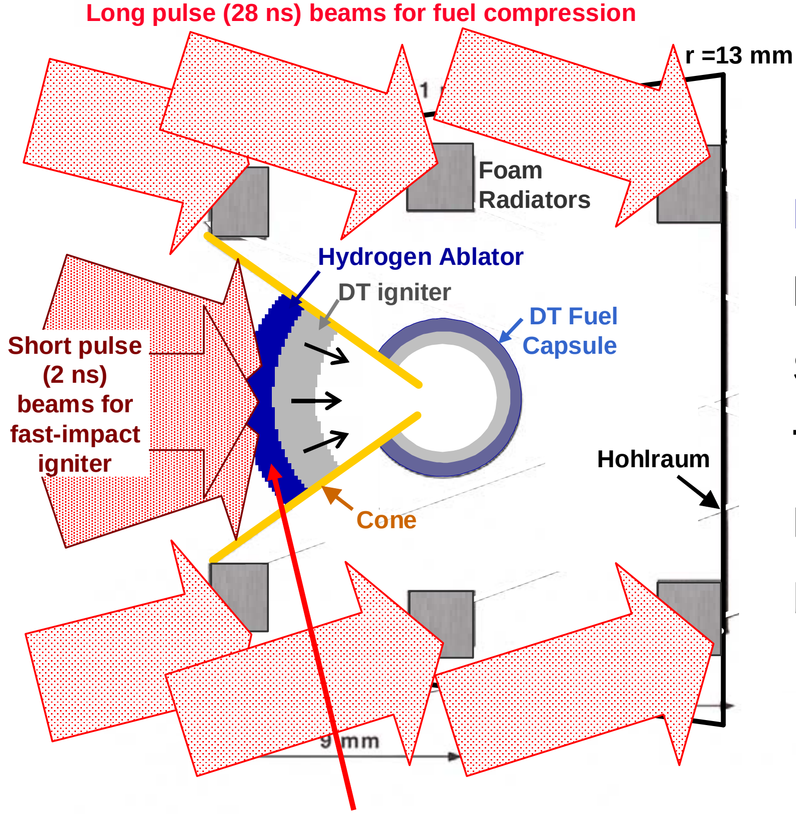


HIB axis rotation or swing
-> reduce the R-T growth!

←Sharkov, Piriz, Tahir, et. al. have designed an upstream GHz- RF cavity to “wobble” the heavy ion beam at GSI (for annular LAPLAS targets, but this also is enabling technology for RT control)

If neutralized compression and focusing of low range ions (0.001-0.004 g/cm²) to 1 ns, 1 mm spots can be achieved, then ion-direct-drive-impact fast ignition* may be feasible with RT-stabilization.

Schematic of fast impact ignition target:
-ion indirect drive for fuel compression
-ion direct drive for fast impact ignitor



NDCX may study DD RT-stability in 1-D

	Ion fast igniter**	Ion direct drive impact fast igniter
Ion range	0.6 g/cm²	0.001 to 0.004 g/cm²
Ion energy	100 GeV (Pt)	400 MeV (Xe)
Igniter drive energy	500 kJ	250 to 500 kJ?
Focal spot radius	50 microns	1000 microns
Final pulse width	200 ps	2000 ps

** ITEP scheme

Hydrogen -best ablator for ion-direct-drive (Tabak)

Implosion velocity $V_{imp} = \chi\ Cs \ln (M_H/M_{DT})$

Sound speed $C_s = [(Z+1)kT_H/(Am_p)]^{0.5}$

T_H=1 keV, (Z+1)/A =2 for hydrogen (=0.5 for plastic!)

M_H/M_{DT} = 5, χ ~1.5 → $V_{imp} = 10^6$ m/s, ~250 kJ ion beam drive energy @ ~2 ns: adequate for ignition?

**M. Murakami (ILE, Osaka) described impact ignition with laser direct-drive for a cone-igniter segment at HIF04. Here we consider ion-direct drive in the cone.*

US-Japan collaboration on ion-bunch compression and WDM-HEDS Experiments (Slide from K. Tanaka, ILE-Osaka, May 13, 2005, Re: proposed JA-US FI Project)

Micro-Beam Interaction Experiments With Laser-Accelerated Ions

Feed-back system

Impedance management

Source Improvement

Induction Beam Buncher R&D, and manufacturing

Power Modulator

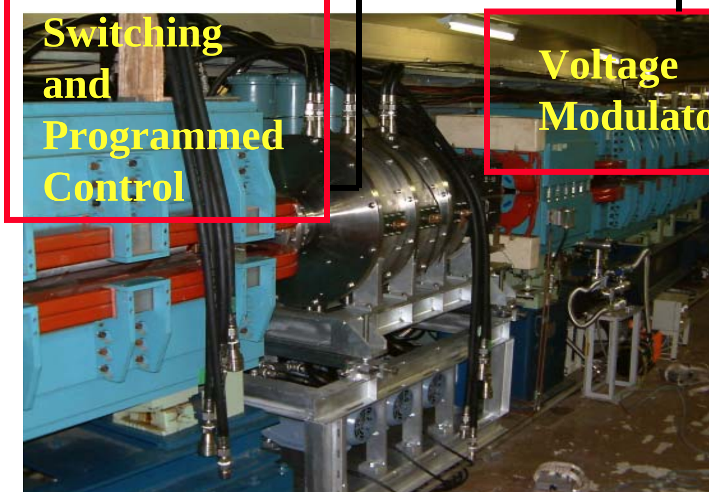
Cavity

Facilities

Bunch Compression in KEK 12GeV PS and Chirped compression at LBL

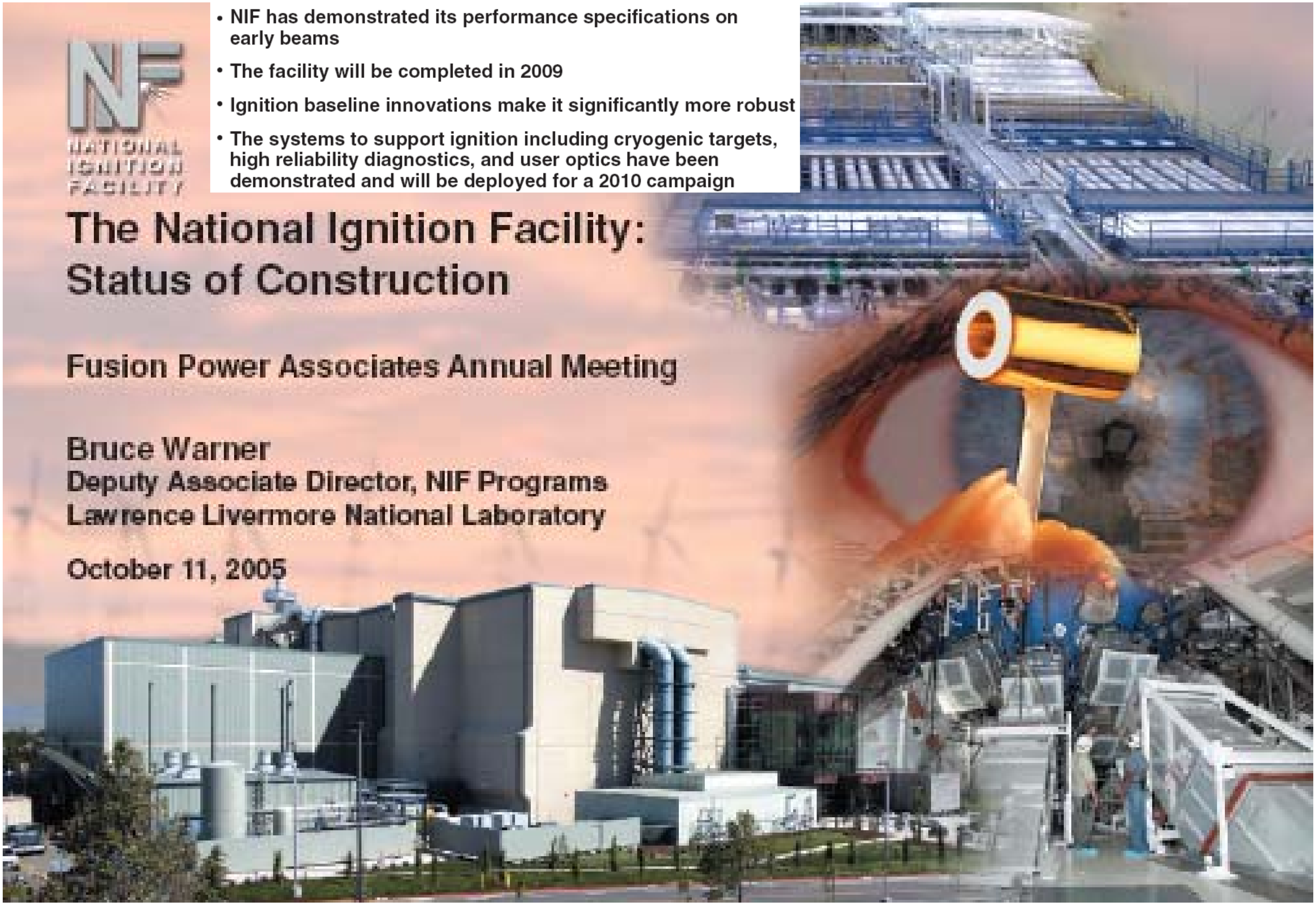
Experiments

Macro-Beam-Target Experiments
- Beam Energy Deposition
  - Stopping Power in WD Plasma
- Interaction Experiments
  - R-T Control
  - ion-driven FI target
- HED Physics

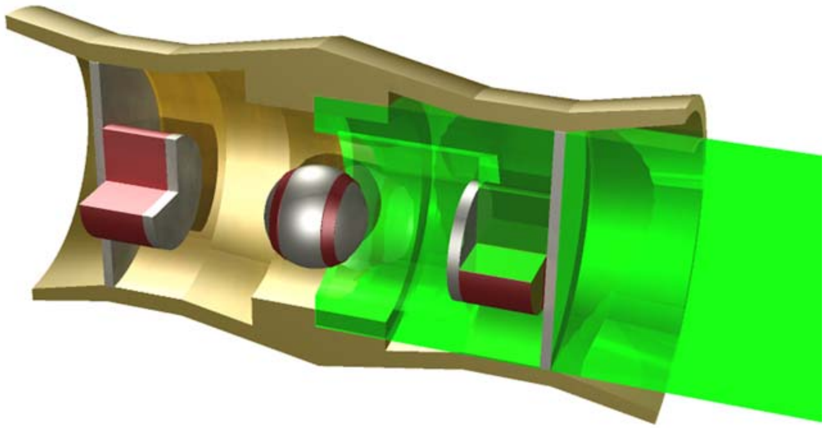


In collaboration with TIT, KEK, Osaka-U, Utsunomiya-U and LBNL, LLNL, and PPPL

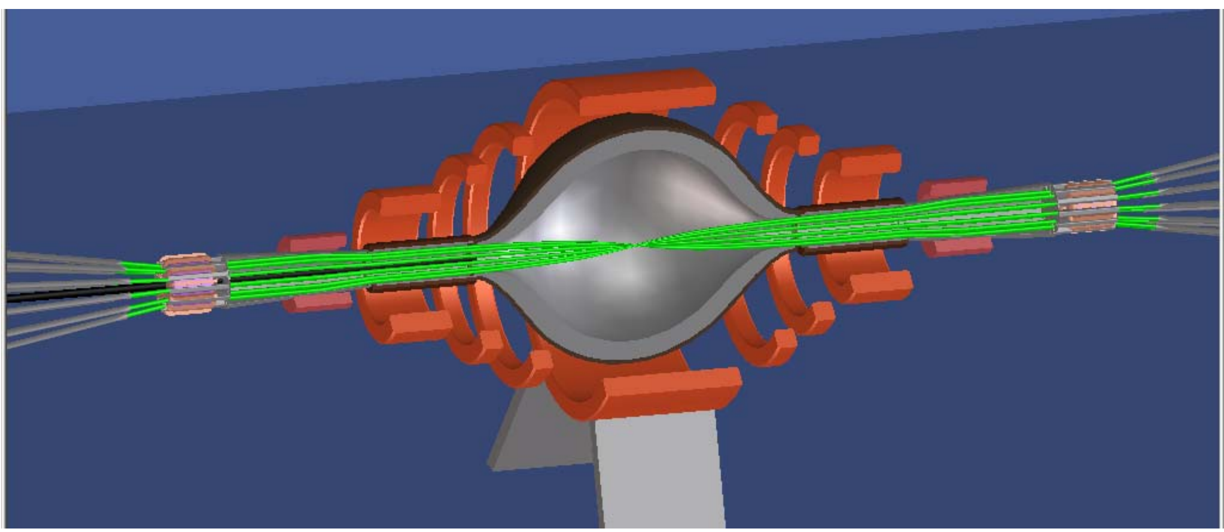
- NIF has demonstrated its performance specifications on early beams
- The facility will be completed in 2009
- Ignition baseline innovations make it significantly more robust
- The systems to support ignition including cryogenic targets, high reliability diagnostics, and user optics have been demonstrated and will be deployed for a 2010 campaign



Research on neutralized rift compression and focusing of velocity "chirped" beams for HEDP, together with larger-spot IFE target designs, may 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 Peterson, UC Berkeley)

Conclusions

There have been many exciting scientific advances and discoveries during the past two years that enable:

- **Demonstration of compression and focusing of ultra-short ion pulses in neutralizing plasma background.**
- **Unique approach to WDM with ion beams at the Bragg peak in dE/dx**
- **Contributions to cross-cutting areas of accelerator physics and technology, (e.g., electron cloud effects, Pulse Line Ion Accelerator, diagnostics, IFE, ion fast ignition).**

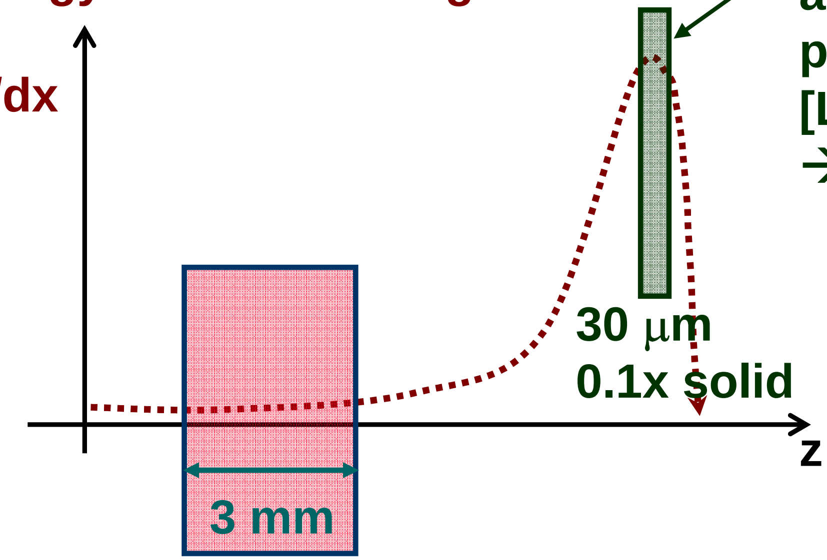
Experiments heavily leverage existing equipment and are modest in cost.

Theory and modeling play a key role in guiding and interpreting experiments.

Backup slides

In 2003 we began neutralized compression of short pulses to be applied to warm dense matter experiments at the peak of dE/dx.

Ion energy loss rate in targets



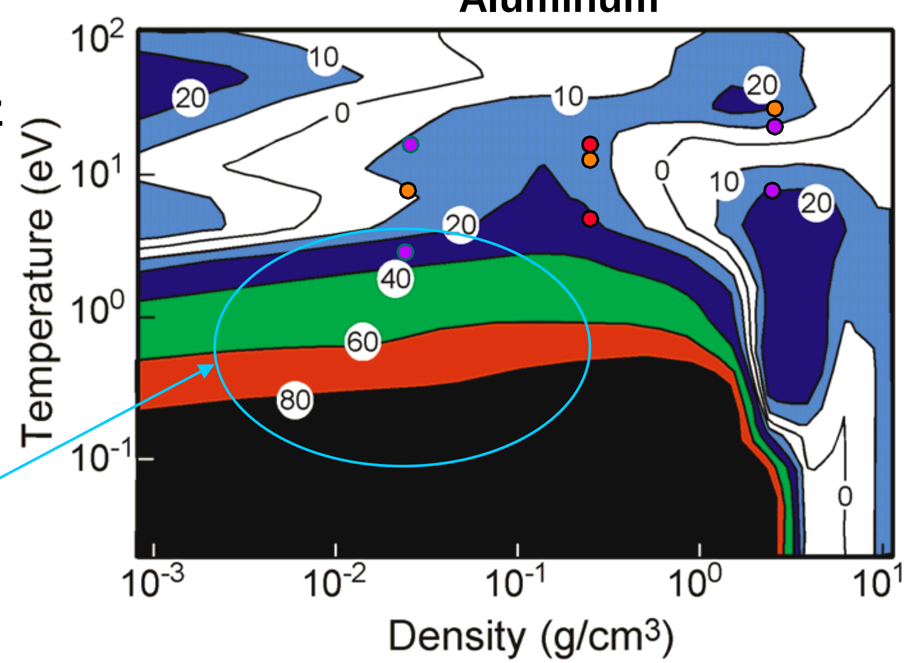
Maximum dE/dx *and* uniform heating at this peak require short (~ 1 ns) pulses to minimize hydro motion. [L. R. Grisham, Physics of Plas.,2004].

→Te > 10 eV @ 20J, 20 MeV

(Goal: future US accelerator-driven user WDM facility)

GSI (see Tahir's talk): 40-100 GeV heavy Ions→ thick targets→ Te ~ 1 eV per kJ

Aluminum



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

(Courtesy of Richard Lee, LLNL)

NDCX-II provides the basis for the IBX-NDC user facility

NDCX-II $4 to 6 M hardware	Ion	Tf MeV	Q (μC)	Shot rate	Linac Output (before NDC)	NDC	τ	E_{beam} P_{beam}	L_{focus} r_{spot}	Te max (eV)
Induction	Li+	2 (Bragg peak)	0.3	0.1 Hz	K~10^{-3} 1.5A 200 ns	100 X	2 ns	0.6 J 300 MW	0.12 m, 0.5 mm	1-1.5
PLIA	Na+	24 (Bragg peak)	0.1	0.1 Hz	K~$2x10^{-5}$ 1 A 100 ns	100 X	1 ns	2.4 J 2.4 GW	0.7 m 1 mm	2-3

IBX-NDC* ($TPC, inc. NDCXII MIE)	Ion	Tf MeV	Q (μC)	Shot rate	Linac Output (before NDC)	NDC	τ	E_{beam} P_{beam}	L_{focus} r_{spot}	Te max (eV)
Induction $ 50 M	Li+	3 (1.5x Bragg peak)	0.6	1 Hz	K~10^{-3} 3.6 A 170 ns	100 X	1.7 ns	1.8 J 1 GW	0.12 m, 0.5 mm	3-5
PLIA $ 40 M	Na+	24 (Bragg peak)	0.3	1 Hz	K~$8x10^{-5}$ 3 A 100 ns	100 X	1 ns	7.2 J 7.2 GW	0.7 m 1 mm	6-10

*Includes $ 5 m for target diagnostics and three experimental chambers for users.

Diagnostic development – fast optical pyrometer

- **GSI diagnostic of immediate interest to HIFS-VNL is the fast optical pyrometer**
  - **6 channel, 1 ns time resolution for measurements up to 6000 K, as developed at GSI**
  - **Detector may be a series of fast phototubes or streak camera**
- **Other diagnostics for joint development may also be discussed**

We have only just begun to optimize compression- many improvements remain to be explored:

▪ Use high precision parallel energy analyzer (July 2006), to measure effects of optimizing injector and tilt core waveforms

▪ Develop high-precision solid state agile waveform modulators, to fine-tune tilt waveform and to compensate injection voltage and final focus chromatic errors

▪ Redesign tilt core module to eliminate or compensate for radial variations in $E_z(r)$

▪ Start with shorter pulse (<100 ns) injectors with time dependent fine-tuning to correct for velocity tilt aberrations at final focus.

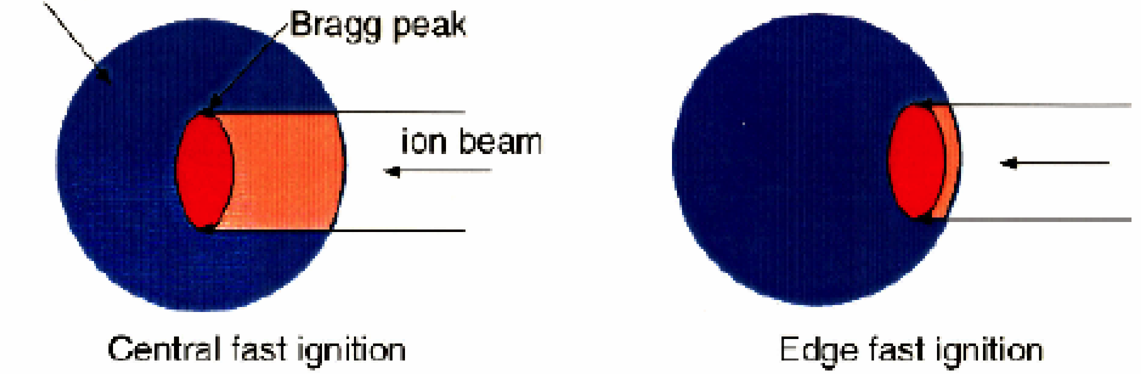
→No fundamental physics limit to pulses short enough for HEDP, IFE, or fast ignition (2ns for ion drive impact fast ignition, or 0.1-0.2 ns for ion-direct fast ignition)

Ion-FI idea: build from NDCX-II 24 MeV Na+ 100ps experiment (Dale Welch simulation) towards fast ignition (100 kJ in 100 ps in 100 μm)

- **Keep bunch length and number of ions per bunch, but Na → K**
- **Increase K-ion energy to 5 GeV for required range > > 2ρ_α ~1.5 g/cm2**
- **Strip at 5 MeV/u, accelerate at q = 9 up to final 100 MeV/u (to β=0.5)**
- **Linac length 250 m for 5 GeV K @ 2 MV/m ave. gradient**
-
- **Use # of linacs x # of bunches per linac~ 10 x 15 to get 100 kJ total**
- **30x NDC required (vs 300x NDCX2) for 100 ps due to 10x higher β**
- **Use 1 % velocity tilt (vs 10% for NDCX2)→100 μm spots (vs 1 mm)**

History (cont.)

Debbie Callahan (LLNL) assessed heavy ion fast ignition target requirements the following year in 1998



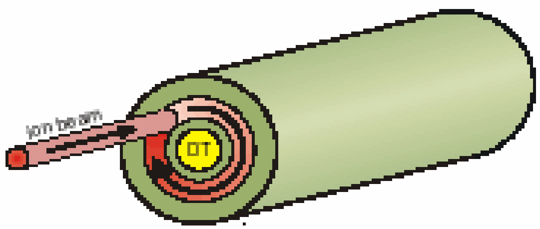
- By changing the ion range, the Bragg peak can be anywhere from the center of the compressed core to the edge of the compressed core.
- Igniting near the center may allow longer pulse durations due to tamping by the fuel.
- Edge ignition will require the smallest amount of energy since a smaller amount of fuel is being heated.

fuel ρr (g/cm^2)	density (g/cc)	τ (psec)	FWHM (microns)	T_{ion} (GeV Pb)	E_{beam} (MJ)	E_{prod} (MJ)
4.3	375	35	45	50	0.056	224
3	128	234	200	60	1.3	430
3	128	117	200	60	0.87	497
3	128	2.3	200	60	0.72	576

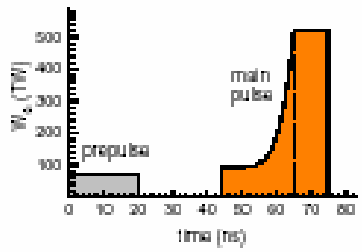
(IAEA-2004) M. Basko summary of Russian studies of fast ignition using 100 GeV heavy-ion synchrotrons:

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

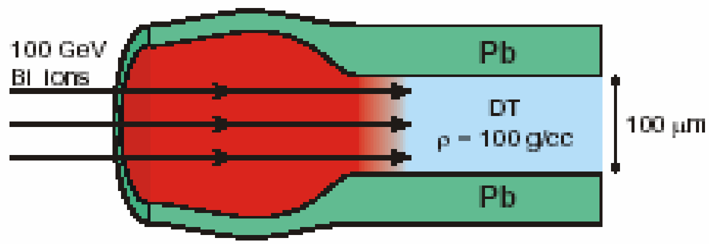


Compression pulse:



- Target compression is accomplished by a separate beam of ions with the same energy of E_i = 0.5 GeV/u.
- Azimuthal symmetry is ensured by fast beam rotation around the target axis (~10 revolutions per main pulse).
- Relative inefficiency of cylindrical implosion is partly compensated for by direct drive.

Ignition and burn propagation



Ignition pulse:

beam energy:	E_{igb} = 400 kJ
pulse duration:	t_{igp} = 200 ps
beam power:	W_{igb} = 2 PW
focal radius:	r_{foc} = 50 μm
irradiation intensity:	$I_{igb} = 2.5\times10^{19}$ W/cm²

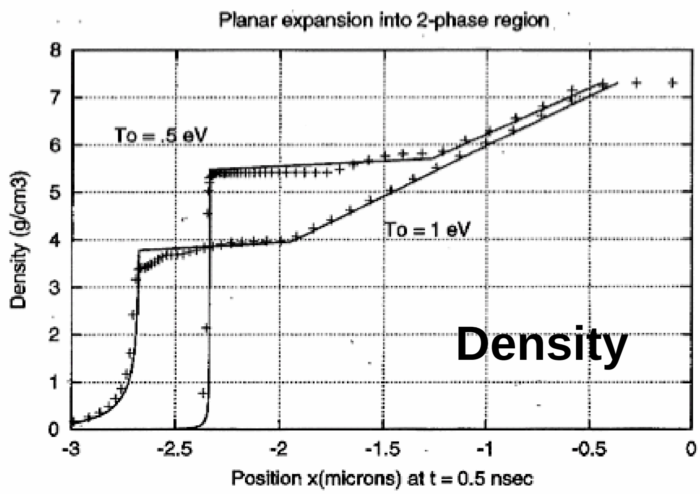
2-D hydro simulations (ITEP + VNIIEF) have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder.

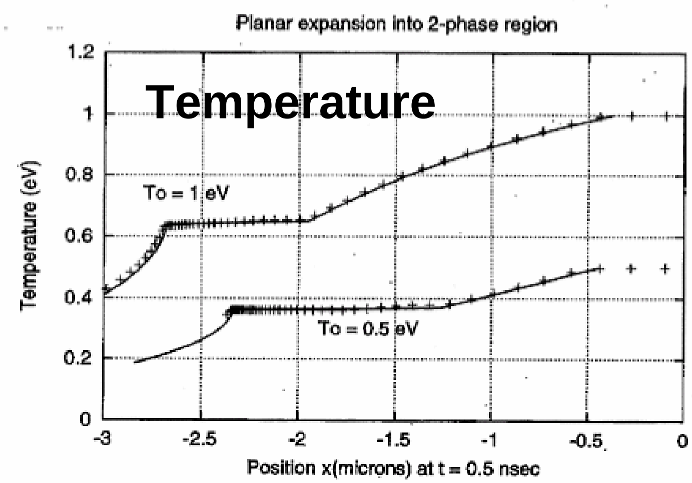
An energy gain of $G \approx 100$ can be expected.

New EOS predicts a sharp density cliff which may facilitate detection

R. More has used a new EOS in his own 1D hydro calculations.

Two-phase medium results in a temperature plateau and density cliff





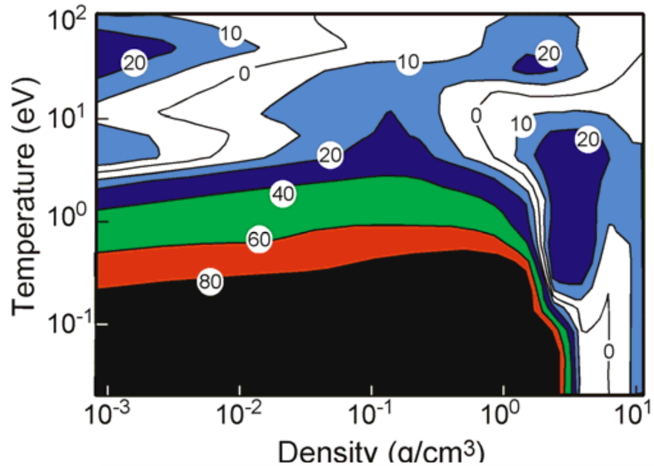
New theoretical EOS work meshes very well with the experimental capabilities we will be creating

R. More: Large uncertainties in WDM region arise in the two phase (liquid-vapor) region

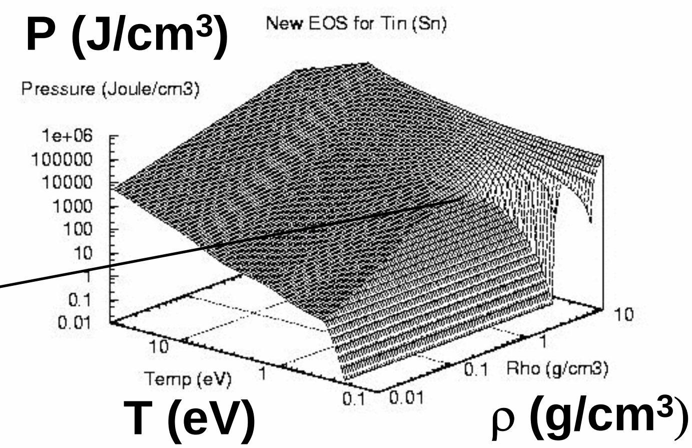
Accurate results in two-phase regime essential for WDM

R. More has recently developed new high-quality EOS for Sn.

Interesting behavior in the T~1.0 eV regime.



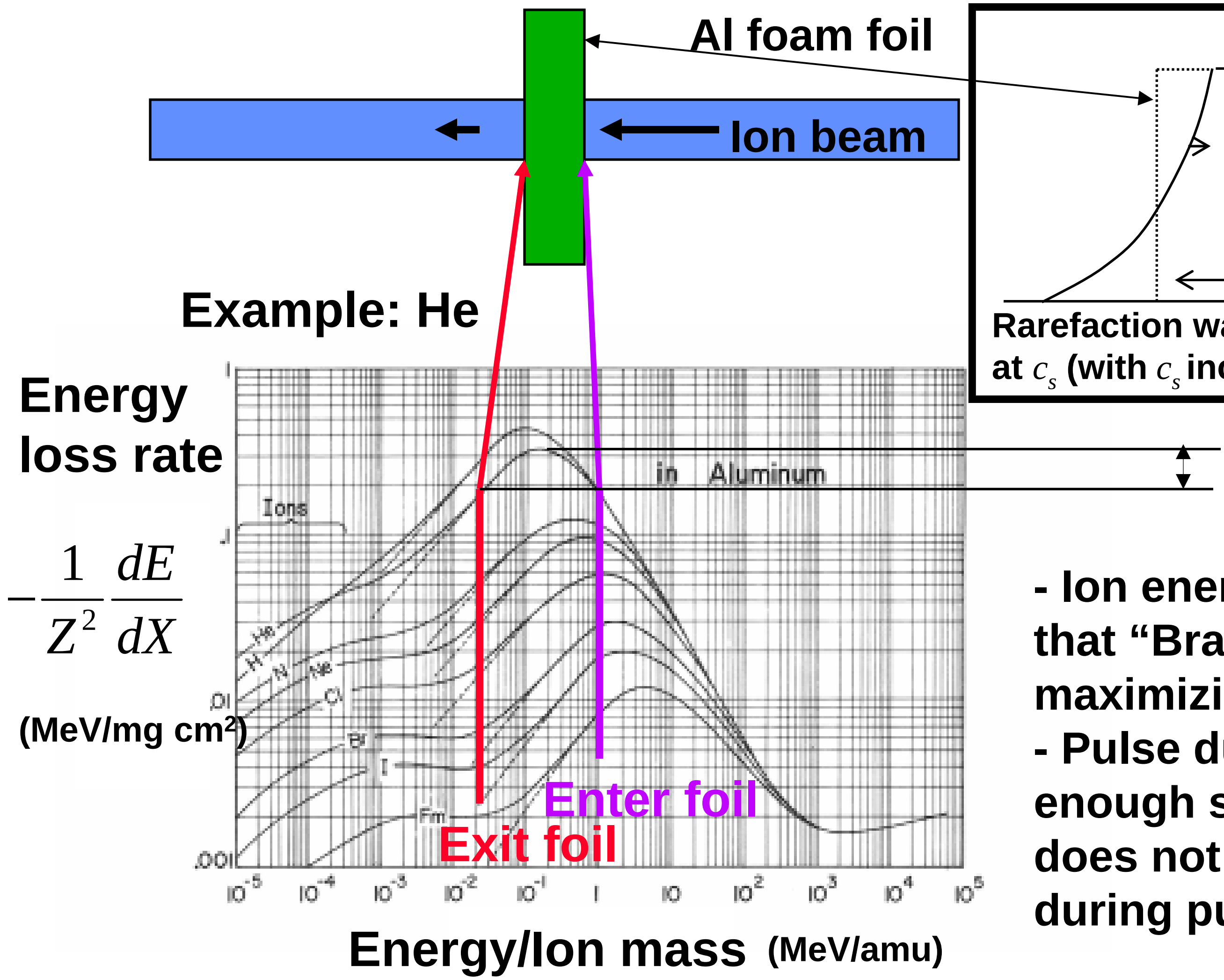
R. Lee plot of contours of fractional pressure difference for two common EOS

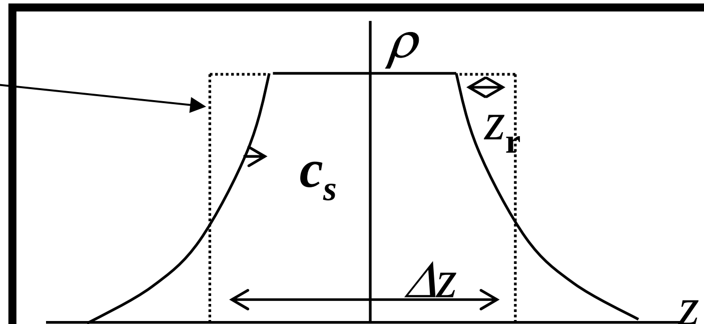


Critical point unknown for many metals, such as Sn

EOS tools for this temperature and density range are just now being developed.

Our strategy for WDM studies is to maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak





Rarefaction wave propagates inward at c_s (with c_s increasing with time)

- Ion energy and mass chosen so that "Bragg peak" falls within foil maximizing uniformity
- Pulse duration must be short enough so that rarefaction wave does not reach center of foil during pulse