Status of Heavy Ion Fusion Science Program*

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Presented on behalf of the
Heavy Ion Fusion - Virtual National Laboratory
LBNL, LLNL and PPPL

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Status: the US HIFS-VNL has made large advances over the last year to the beam science common to both High Energy Density Physics (HEDP) and fusion

→The program concentrates on ion beam experiments, theory and simulations to address a top-level scientific question central to both HEDP and fusion:

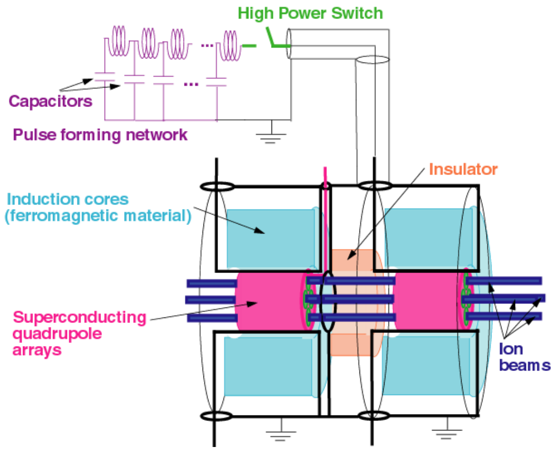
How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?

Topics to be addressed:

- New approach to accelerator driven HEDP and IFE
- Experimental and theoretical advances
- A new Pulse-Line Ion Accelerator
- Warm dense matter studies
- Future plans

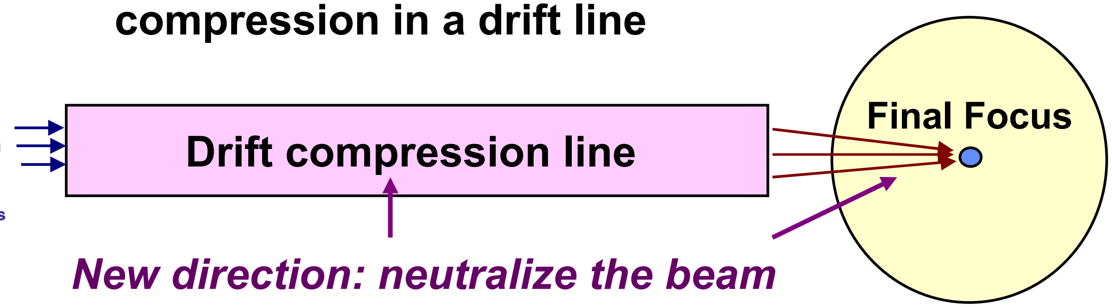
Creating warm dense matter and fusion ignition conditions requires *longitudinal* as well as *transverse* beam compression

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



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

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



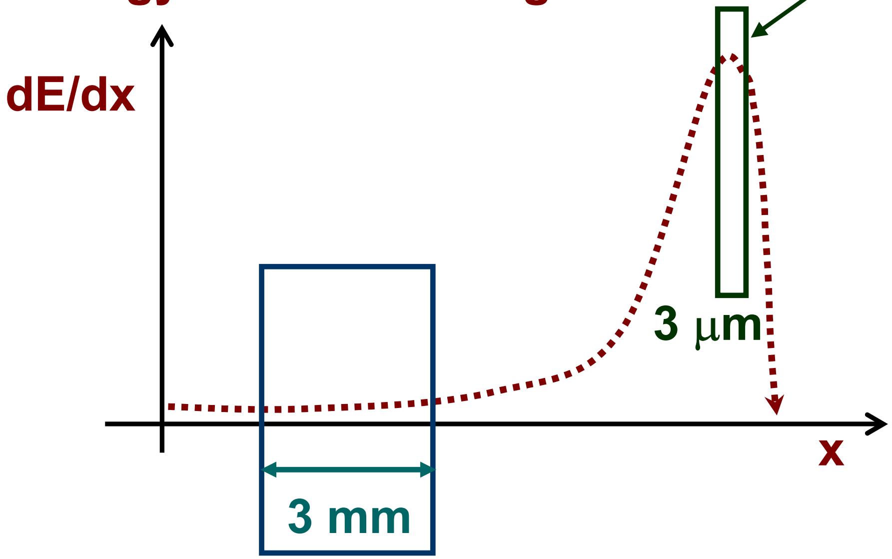
New direction: neutralize the beam space charge both in longitudinal drift compression as well as in final focus

Scientific issues under study:

1. **Electron cloud effects (wherever the beam transports in vacuum)**
2. **Beam-plasma instabilities during compression.**
3. **Beam heating due to compression (conservation of longitudinal invariant)**
4. **Focal spot (chromatic effects) vs minimum pulse-width trade off with tilt**

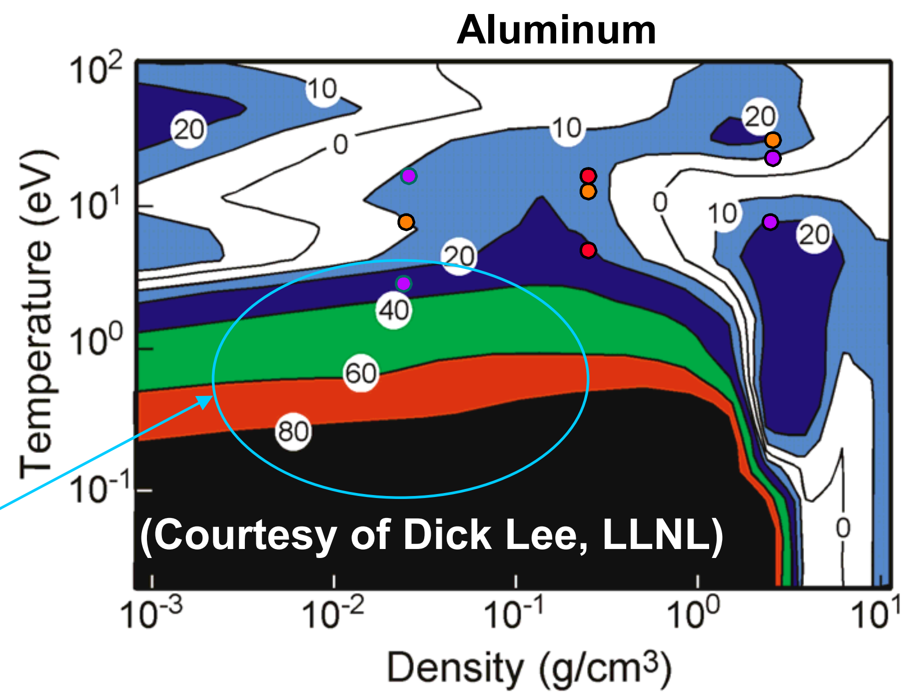
Neutralized beam compression and focusing: unique approach to ion-driven HEDP needed for shorter ion pulses (< few ns versus a few μs)

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)

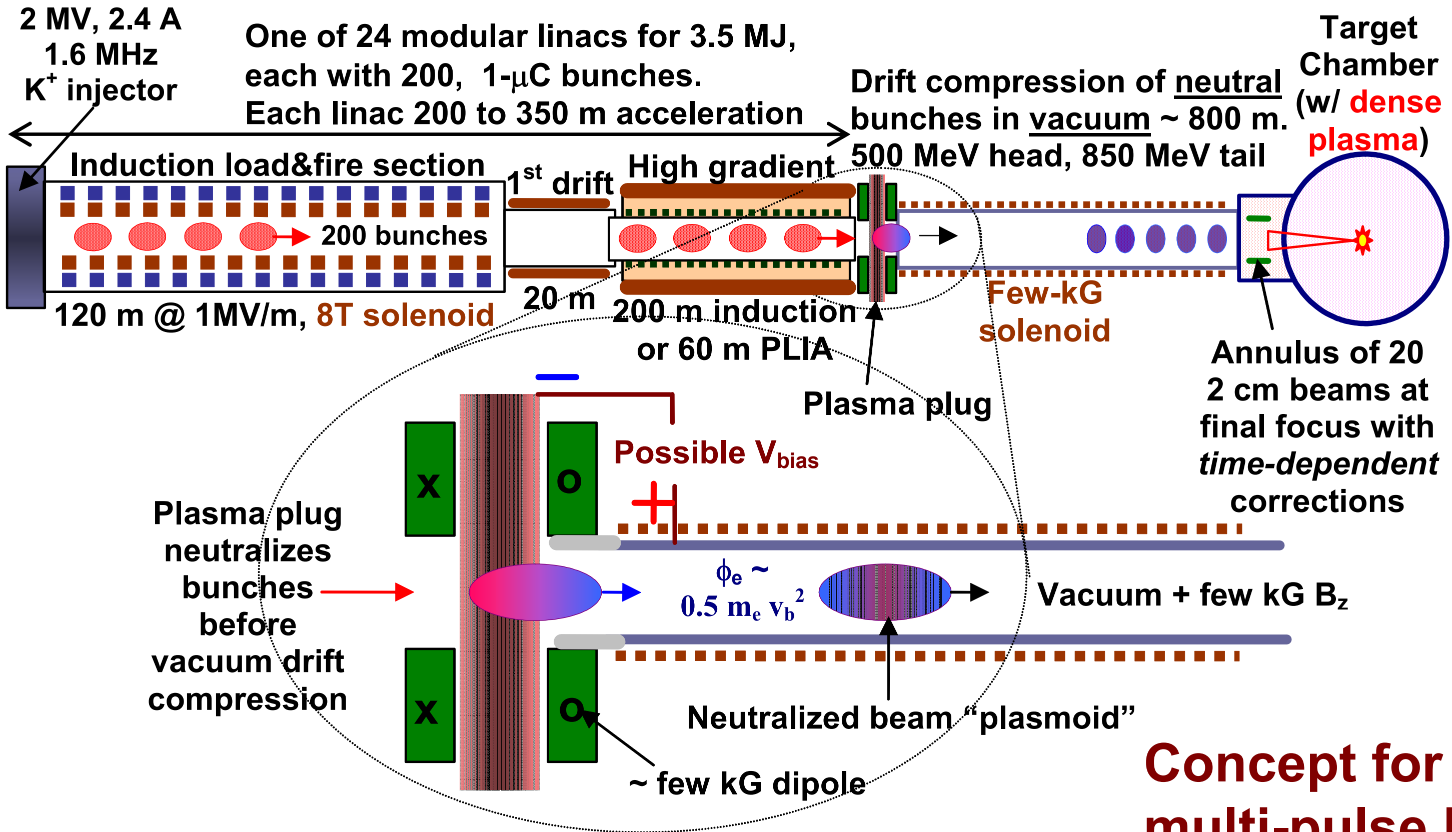
Plasma neutralization of beam space charge *upstream* of final focus is needed for HEDP targets driven by medium mass ions at peak of dE/dx.

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	τ_{hydro}= Δz/(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 vacuum compression, 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 drift compression and focusing is also key to enable a new modular driver development path to IFE



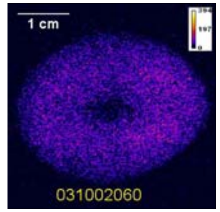
Concept for a modular multi-pulse heavy ion IFE driver (induction or PLIA)

→Key Enabling Advances:

- Neutralized drift compression and focusing
- Time dependent correction for achromatic focusing
- Multi-pulse longitudinal merging and pulse shaping
- Fast agile optically-driven solid state switching

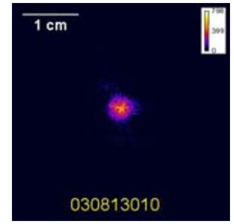
Neutralized Transport Experiment (NTX-2004) encouraged use of plasma neutralization for radial compression

Non-neutralized

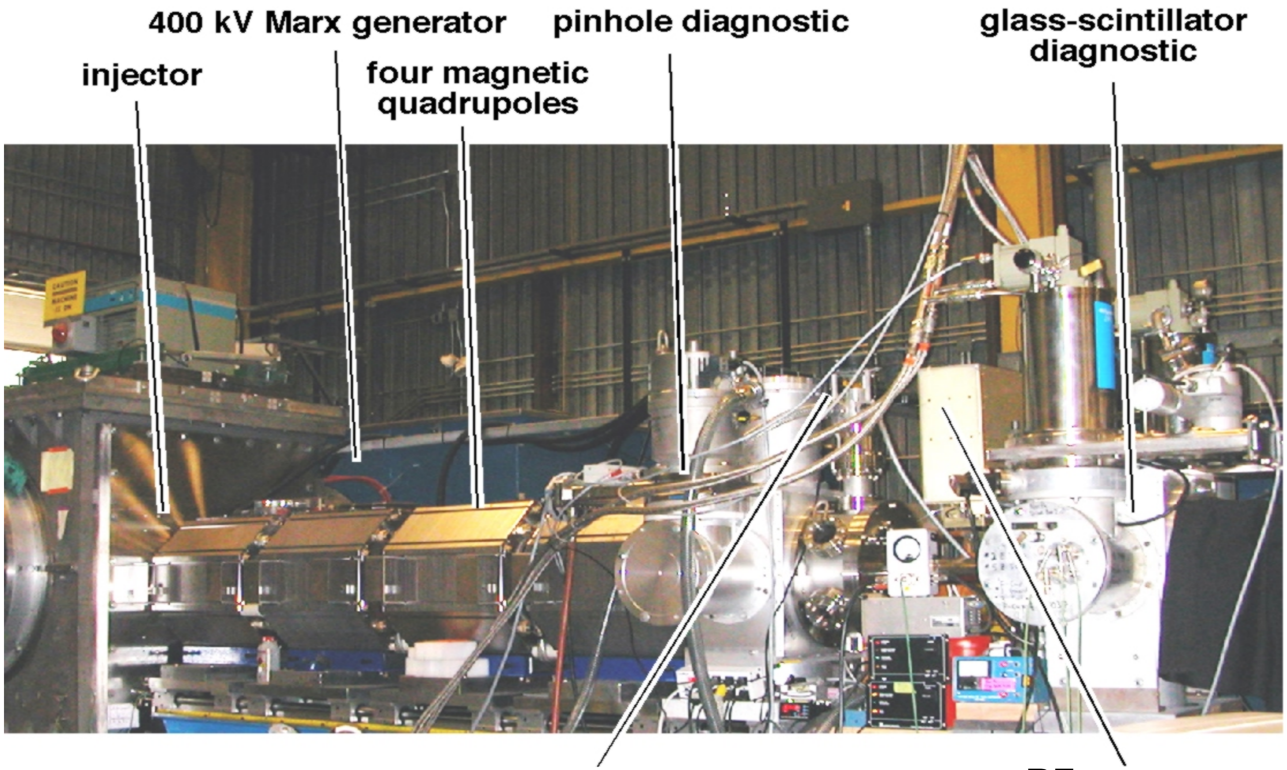


FWHM: 2.71 cm

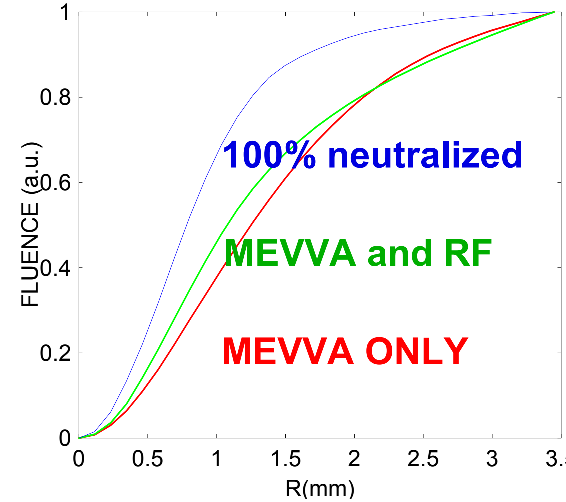
Neutralized



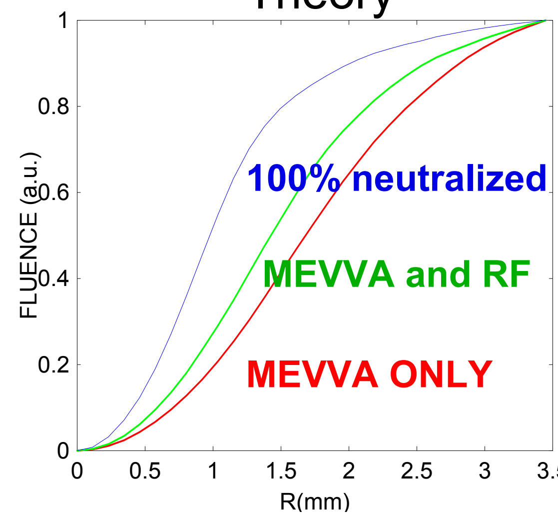
FWHM: 2.14 mm



Measurement

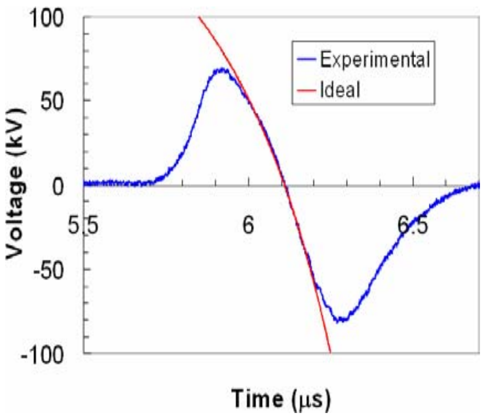


Theory

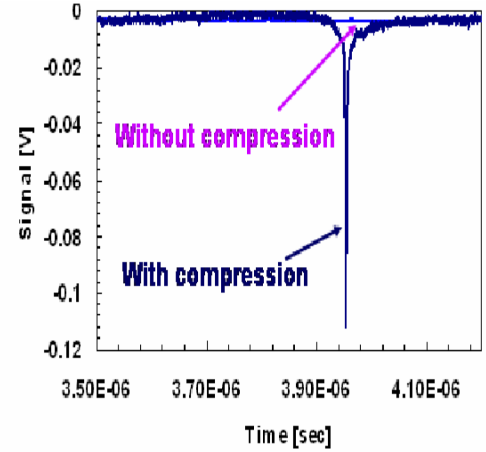


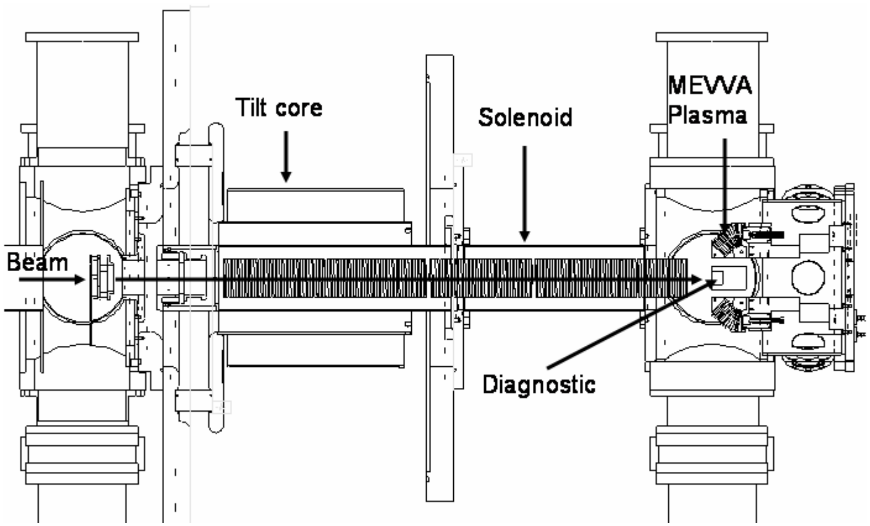
The neutralized drift compression experiment (NDCX) began operation Dec. 2004 to explore neutralized longitudinal compression

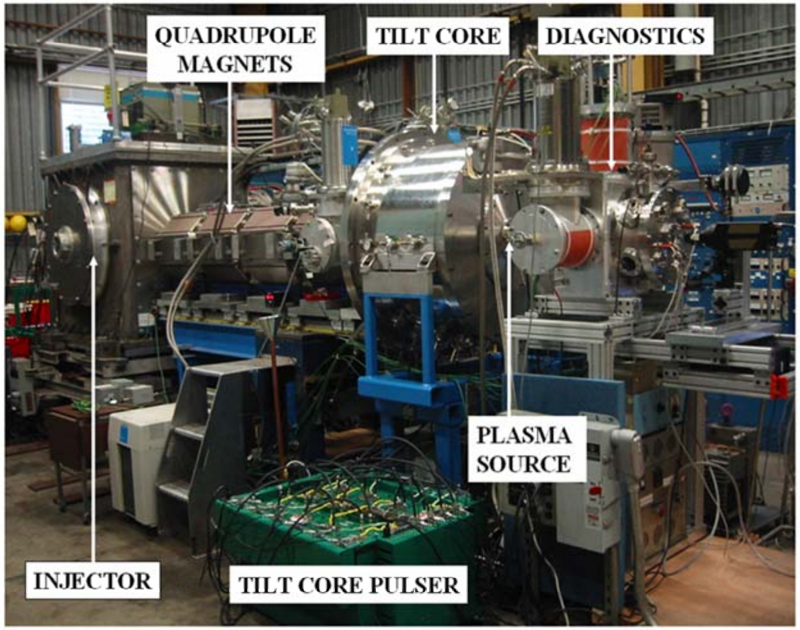
Tilt core waveform



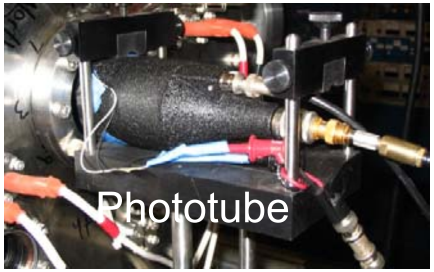
Beam current diagnostic

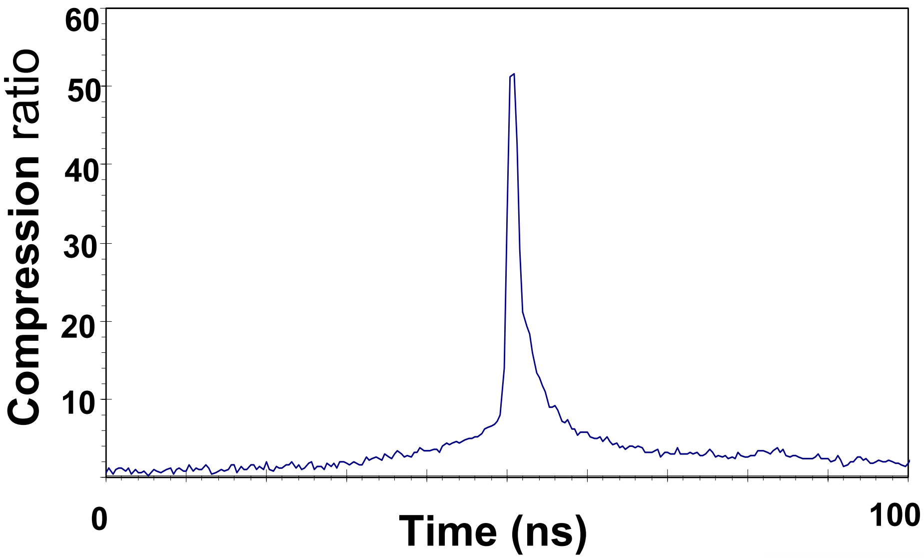


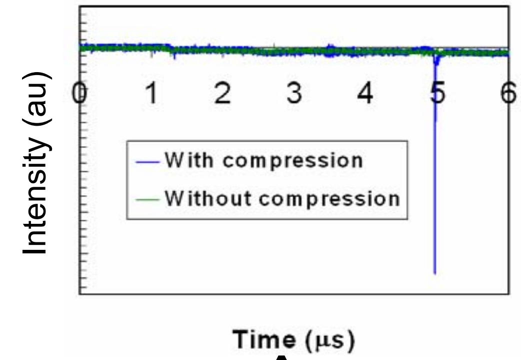




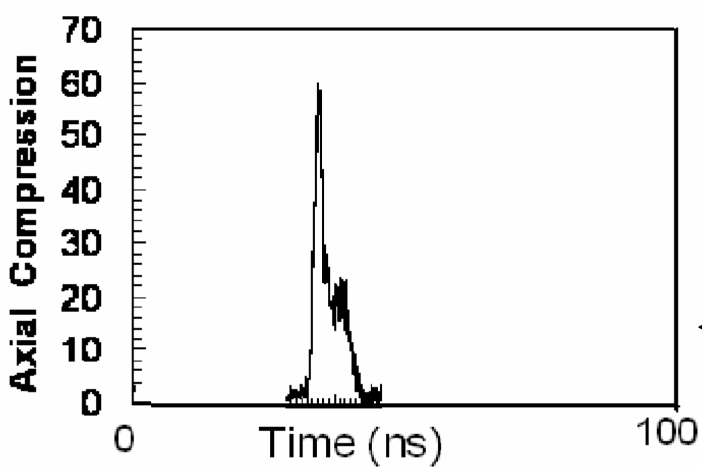
50 Fold Beam Compression has been achieved in the neutralized drift compression experiment





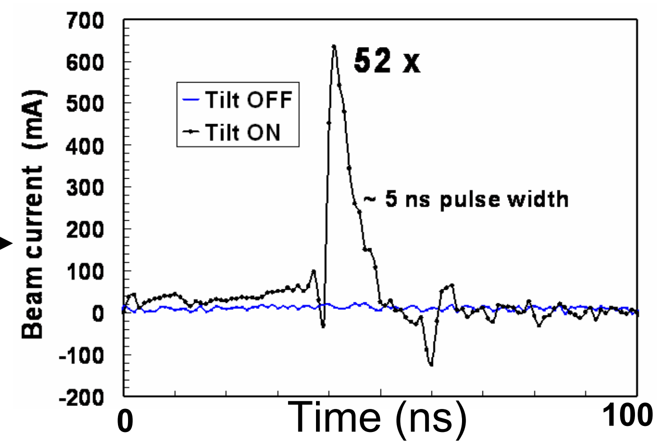


Optical data

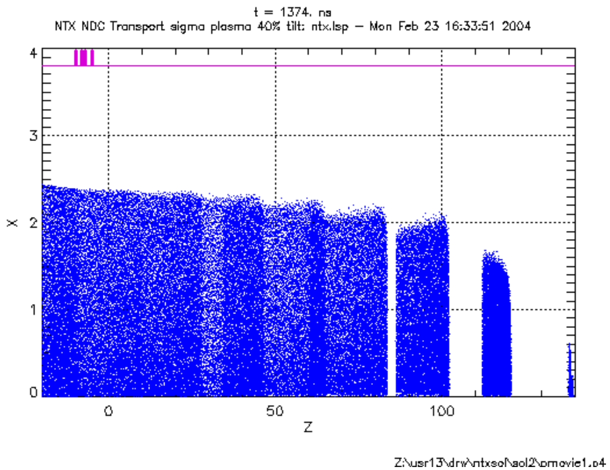


Corroborating data from Faraday cup

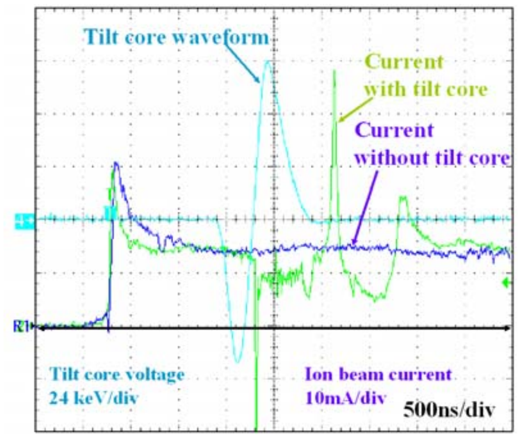
LSP simulation



Rate of progress in heavy ion beam compression in plasma points towards a revolution in high peak power ion beams

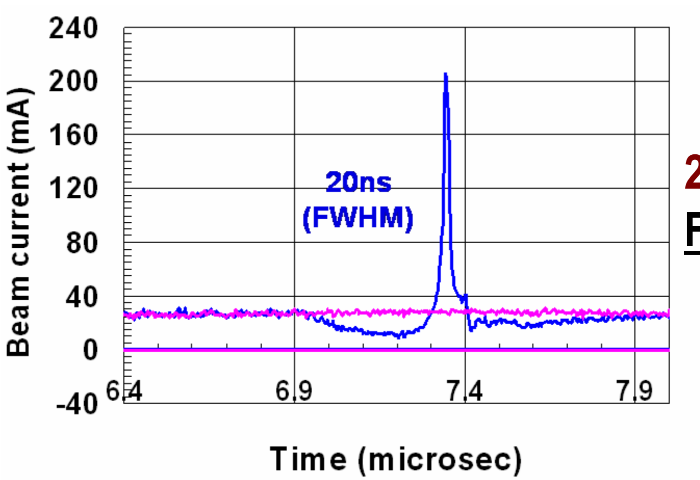


Simulation
of concept
Mar 11, 2004

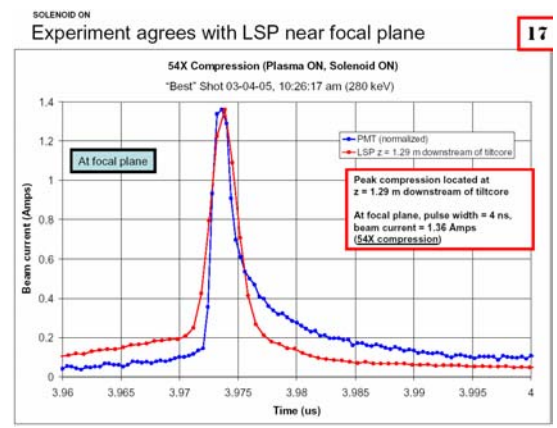


NDCX-1A
Constructed, first data

40 ns FWHM
Dec. 9, 2005

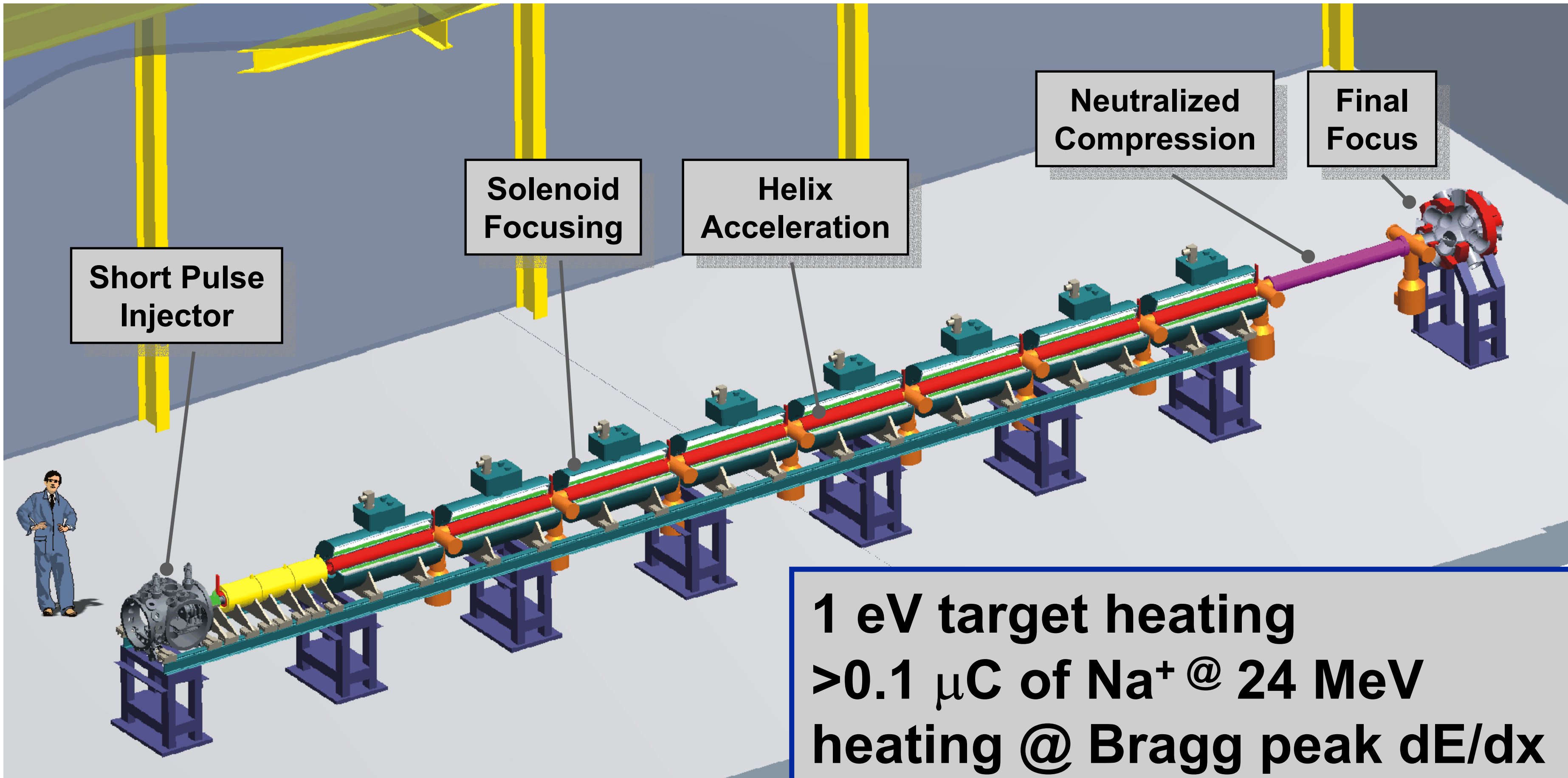


20 ns FWHM
Feb 27, 2005



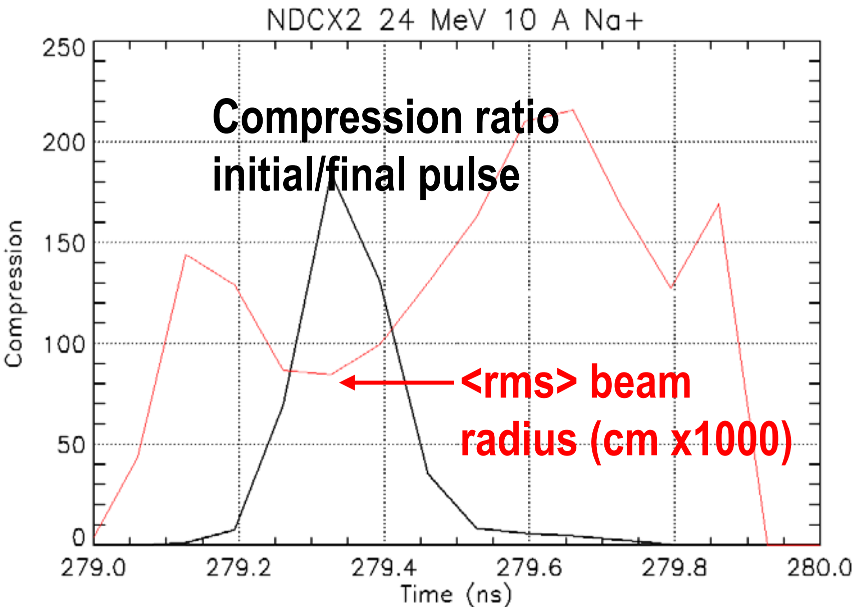
4 ns FWHM
May 2005

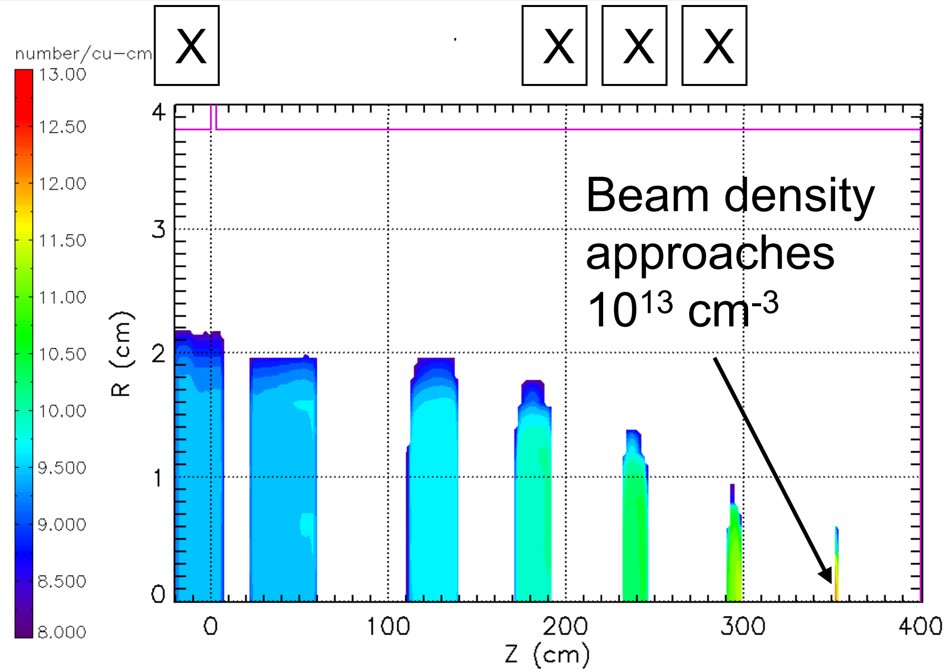
NDCX-II vision: a short pulse high gradient accelerator for ion-driven HEDP and IFE is being evaluated

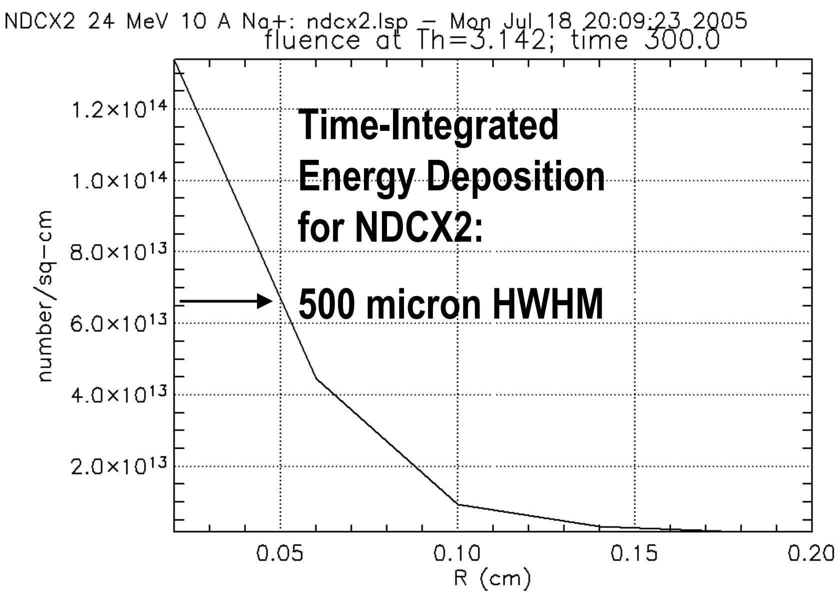


1 eV target heating
>0.1 μC of Na^+ @ 24 MeV
heating @ Bragg peak dE/dx
NDCX-1C + $5M hardware

LSP simulation by Dale Welch for future 24 MeV Na^{+} NDCX-II exp. shows compression to 100 ps with 500 micron central peak focus





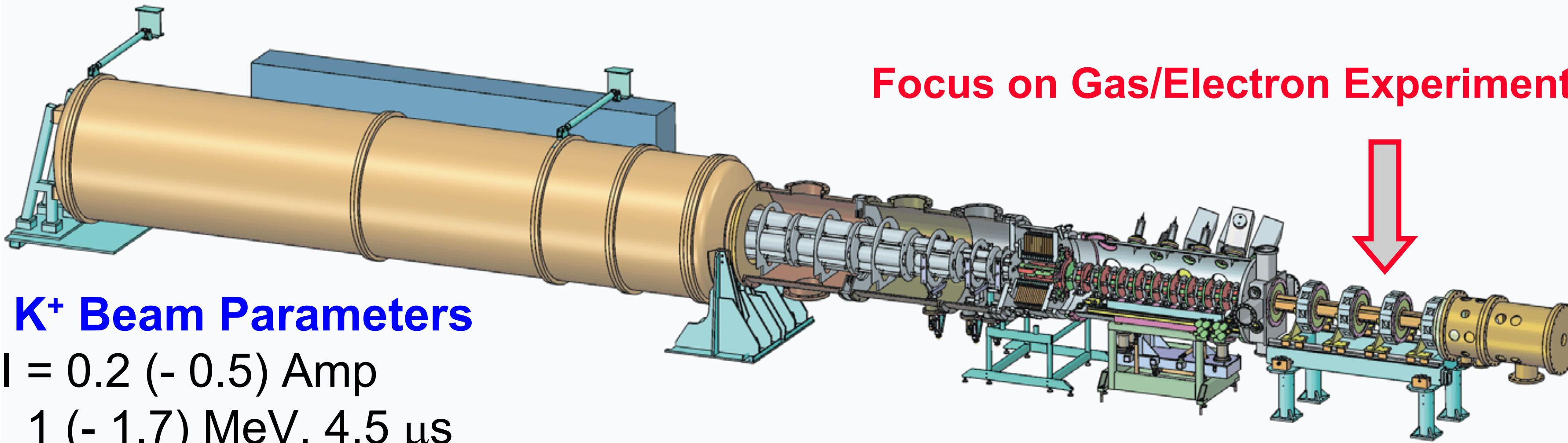


Spot limited in simple solenoidal focusing (4T) by energy tilt (ΔE/E)

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

Smaller spot can be achieved by more aggressive focusing scheme

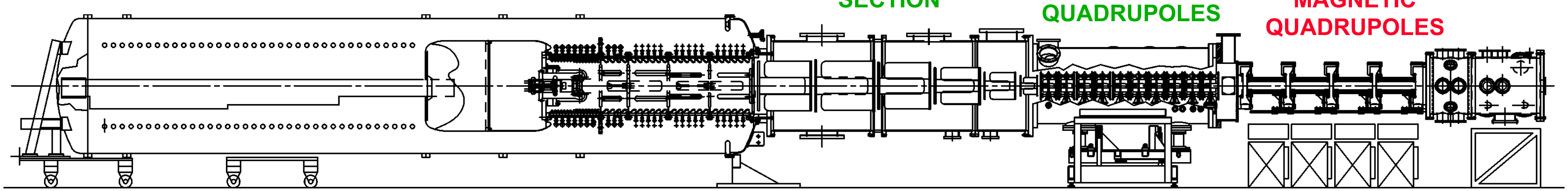
The High Current Experiment (HCX) is exploring beam transport limits



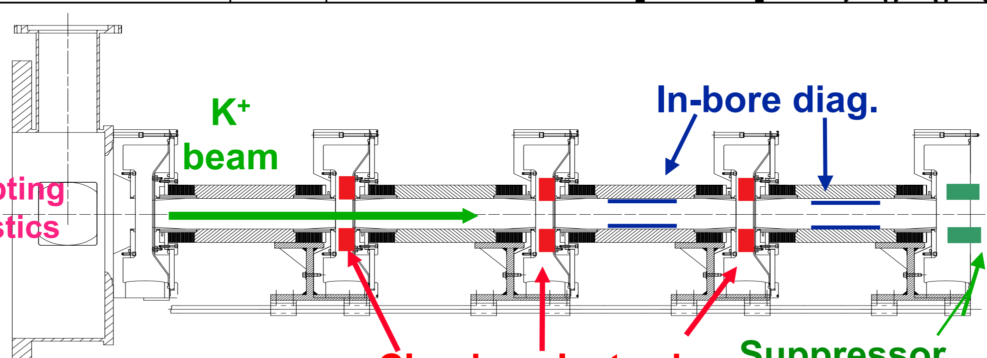
K^+ Beam Parameters

I = 0.2 (- 0.5) Amp

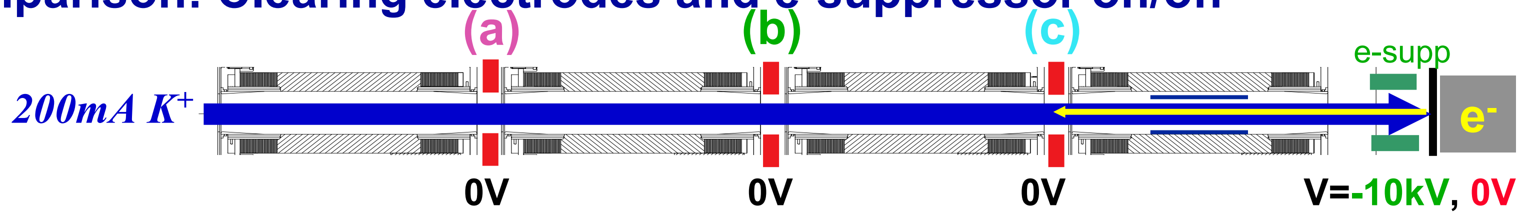
1 (- 1.7) MeV, 4.5 μs

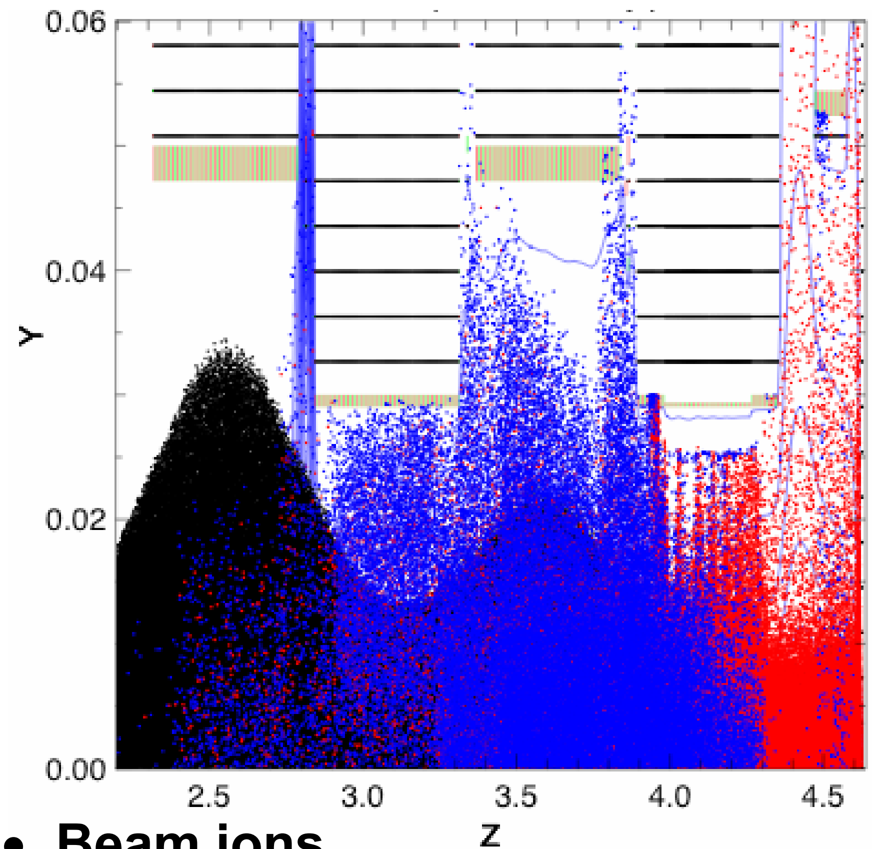


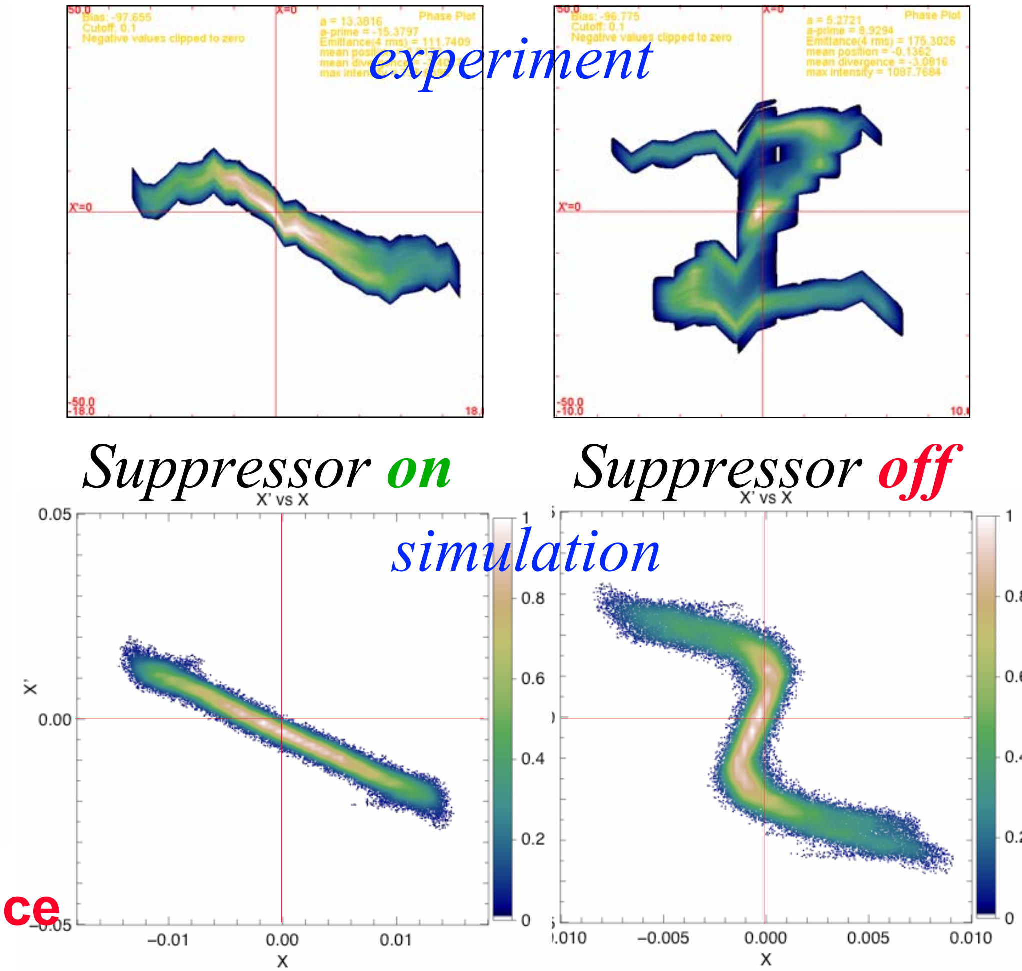
4 magnetic quadrupoles; many diagnostics



Comparison: Clearing electrodes and e-suppressor on/off







- **Beam ions**
- **Electrons from ions hitting surface**
- **Secondary electrons**

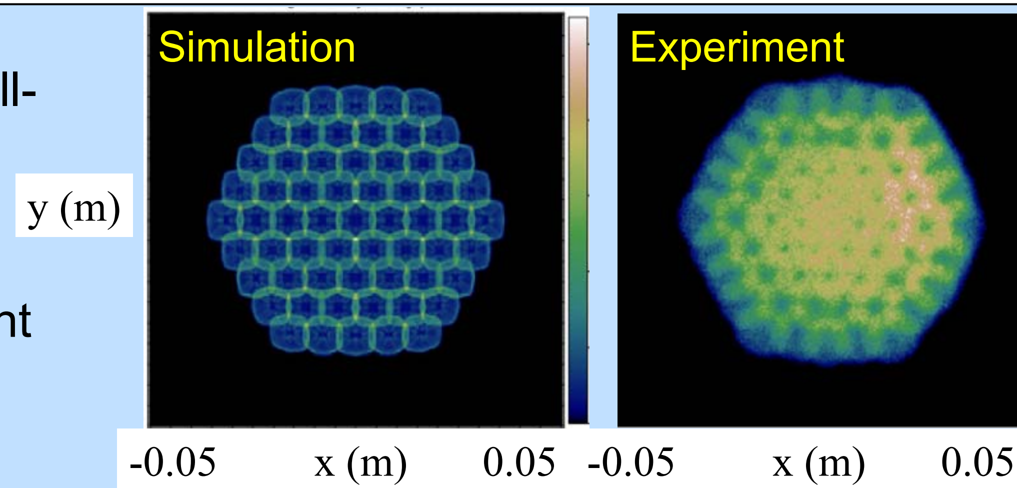
Comparison suggests semi-quantitative agreement.

Completed merging beamlet injector experiments on STS-500 validated the concept of this compact, high current source (Kwan, Westenskow)

Monolithic solid sources suffer from poor scaling vs. size at high currents

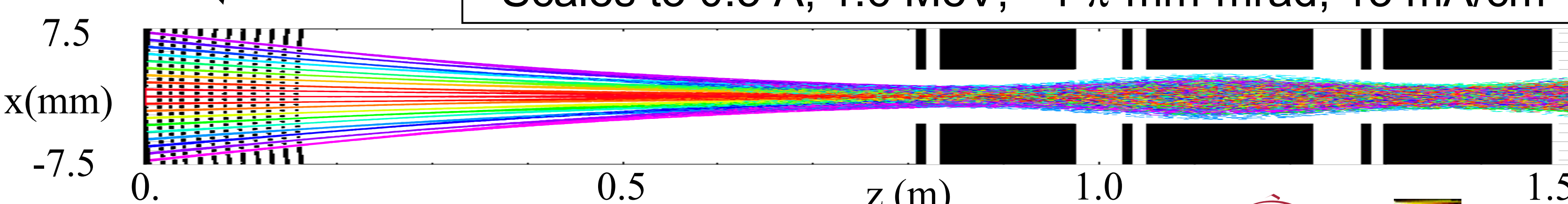
This new concept circumvents the problem via use of many small, low-current sources

From a full-gradient (parallel-beamlet) experiment



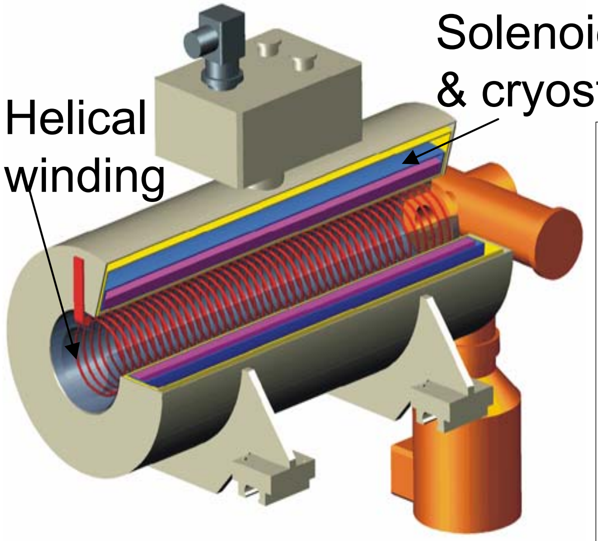
From scaled merging experiment:

- Obtained emittances comparable to simulation
- Effects of “dirty” physics (electrons, charge exchange) were minimal
- Scales to 0.5 A, 1.6 MeV, ~1 π-mm-mrad, 13 mA/cm^2



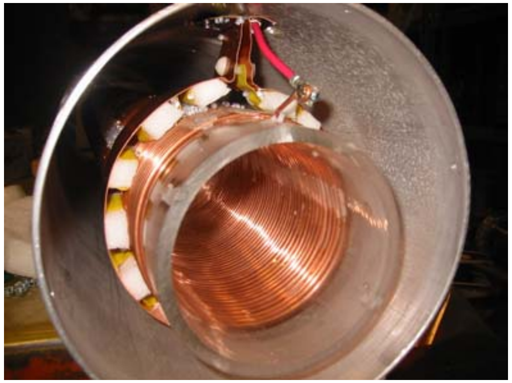
New Pulse Line Ion Accelerator (PLIA)*concept is being explored w/ accelerating fields traveling in a "distributed transmission line"

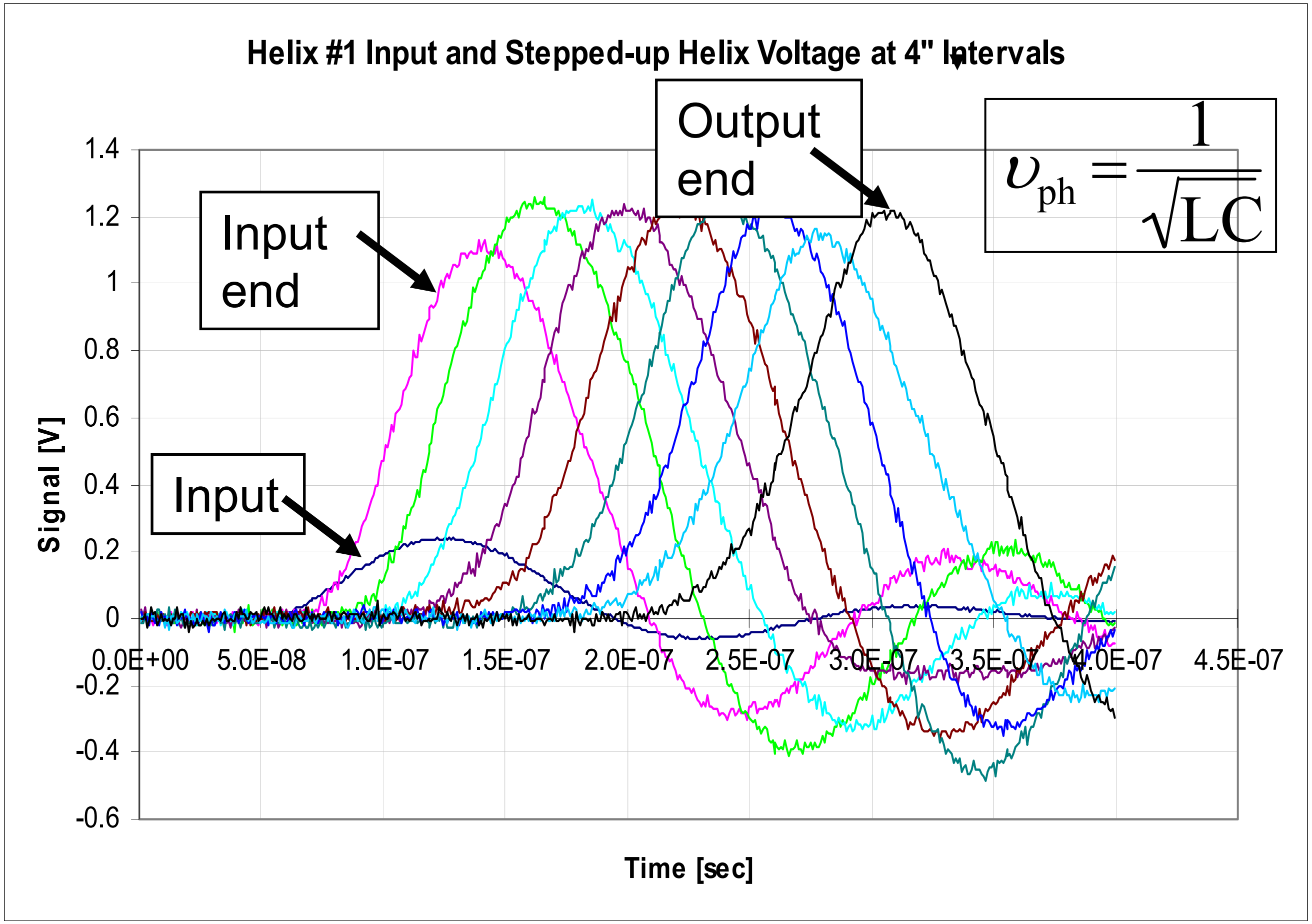
NDCX-II Accelerator Cell



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

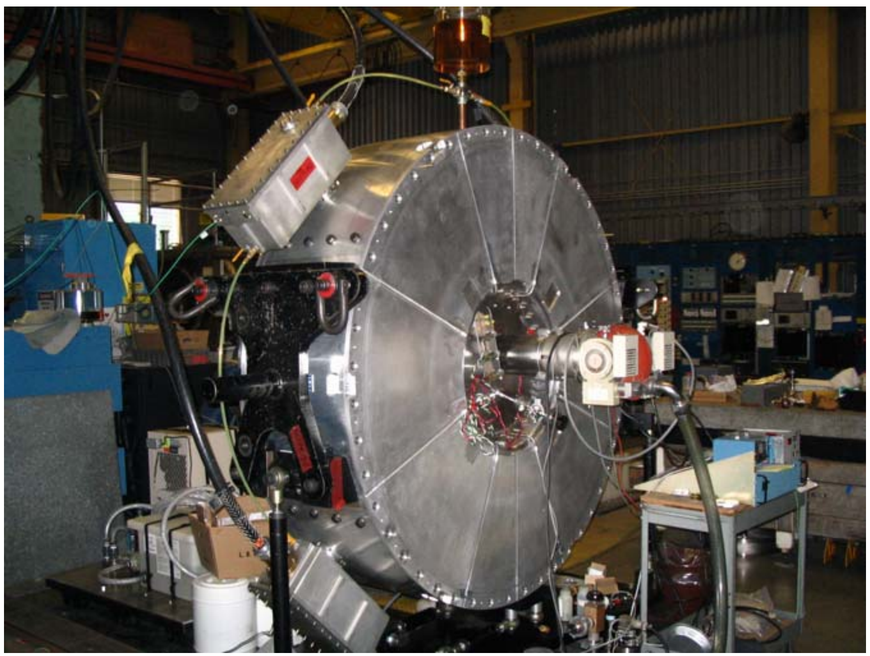
Compact transformer coupling (5:1 step-up)



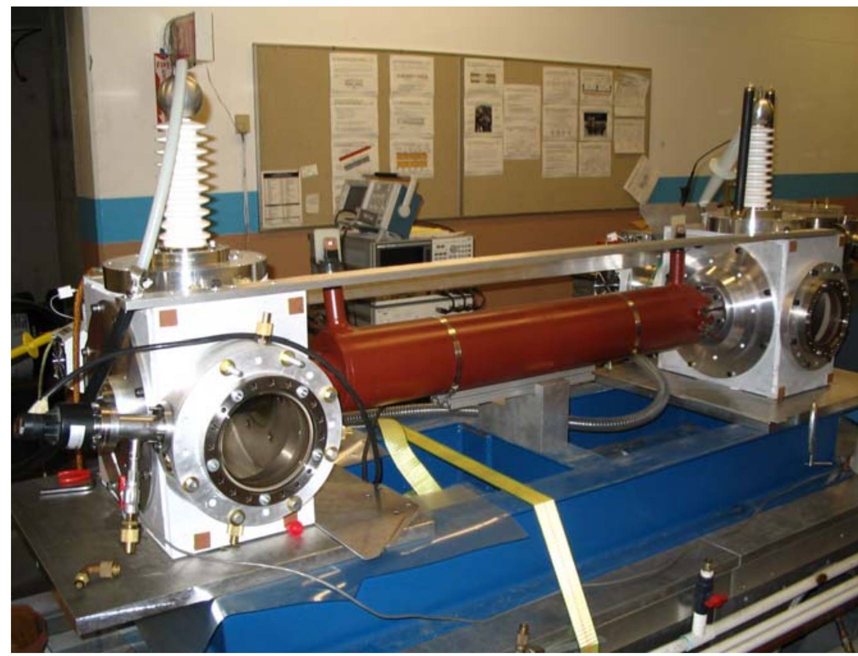


For low beta, high perveance, short ion bunches, the PLIA might reduce costs per volt by 100 X compared to induction linacs

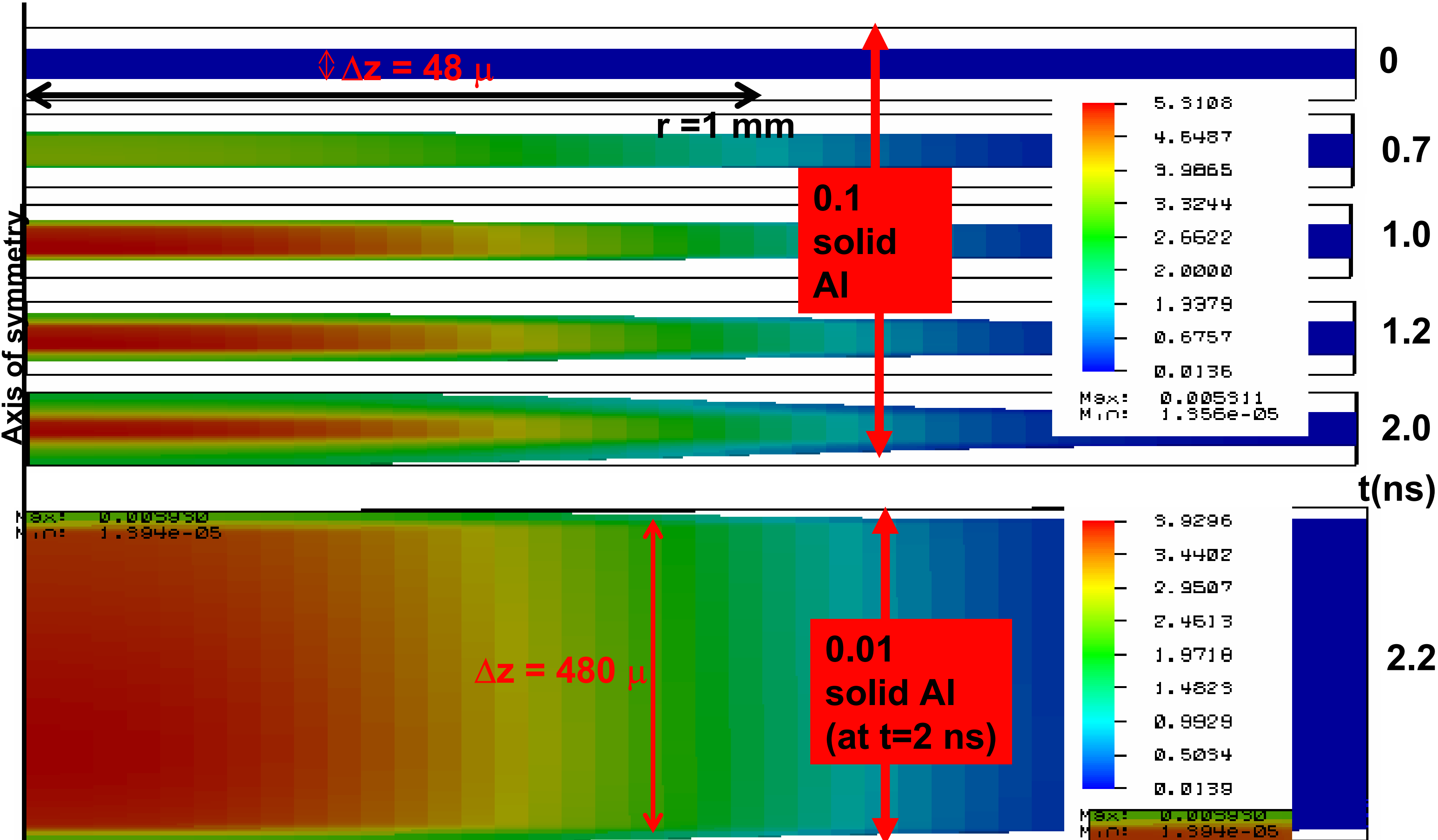
Induction Module for the Dual-Axis Radiographic Hydrotest Facility (DARHT:
0.4 V·s (200kVx2μs)
~10,000 kg, 1 M$
(without pulser or transport magnet)



PLIA
test module results (LBNL Dec 04)
0.4 V·s (2MVx0.2μs)
~40 kg, 10 K$
(without pulser or transport magnet)



Hydra simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of aluminum (NDCX-II parameters)



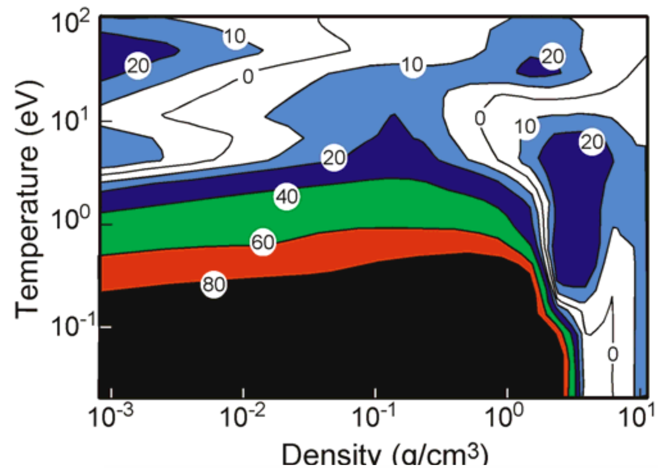
New theoretical EOS work meshes very well with the experimental capabilities we will be creating

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

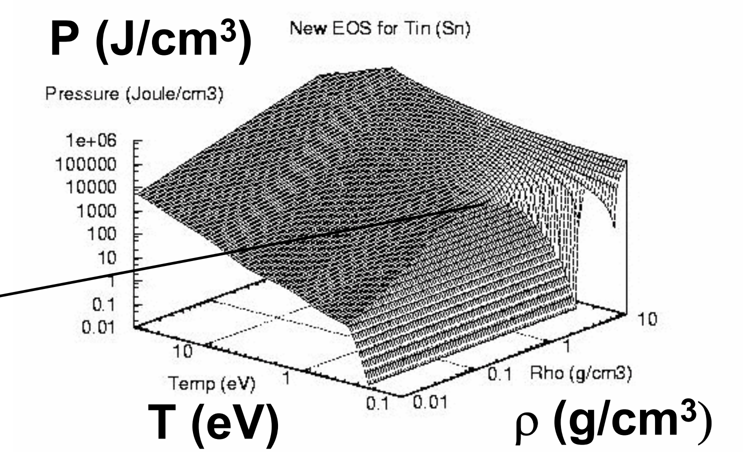
Accurate results in two-phase regime essential for WDM

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

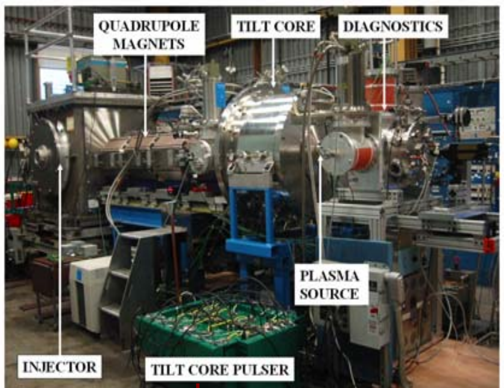


Critical point unknown for many metals, such as Sn

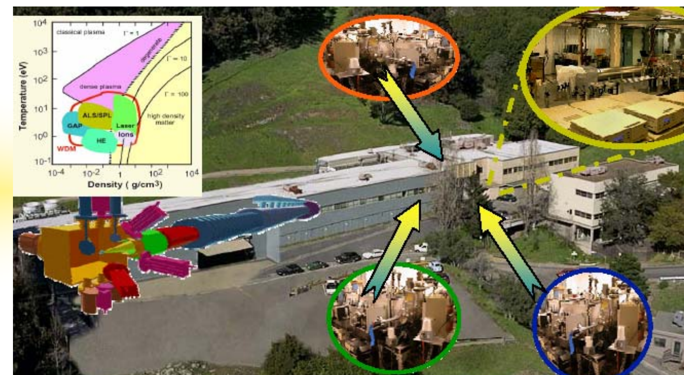
EOS tools for this temperature and density range are just now being developed.

Grand technical challenges in ten years

Challenge 1: Understand limits to compression of neutralized beams



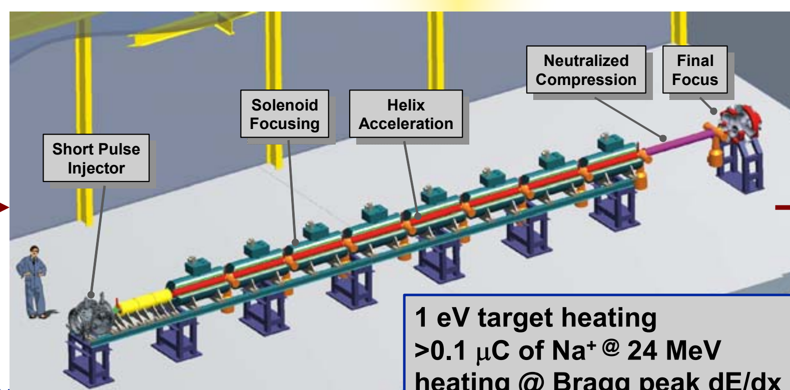
Challenge 3: Affordable *(<50M$)* high shot rate *(>10 Hz)* accelerator, laser, & targets for (a) HEDP user facility *(<5% EOS uncertainty)*, and for (b) prototype IFE driver module



Challenge 2: Integrated compression, acceleration and focusing sufficient to reach 1 eV in targets:

0.1μC NDCX1C +PLIA +5M$=NDCXII

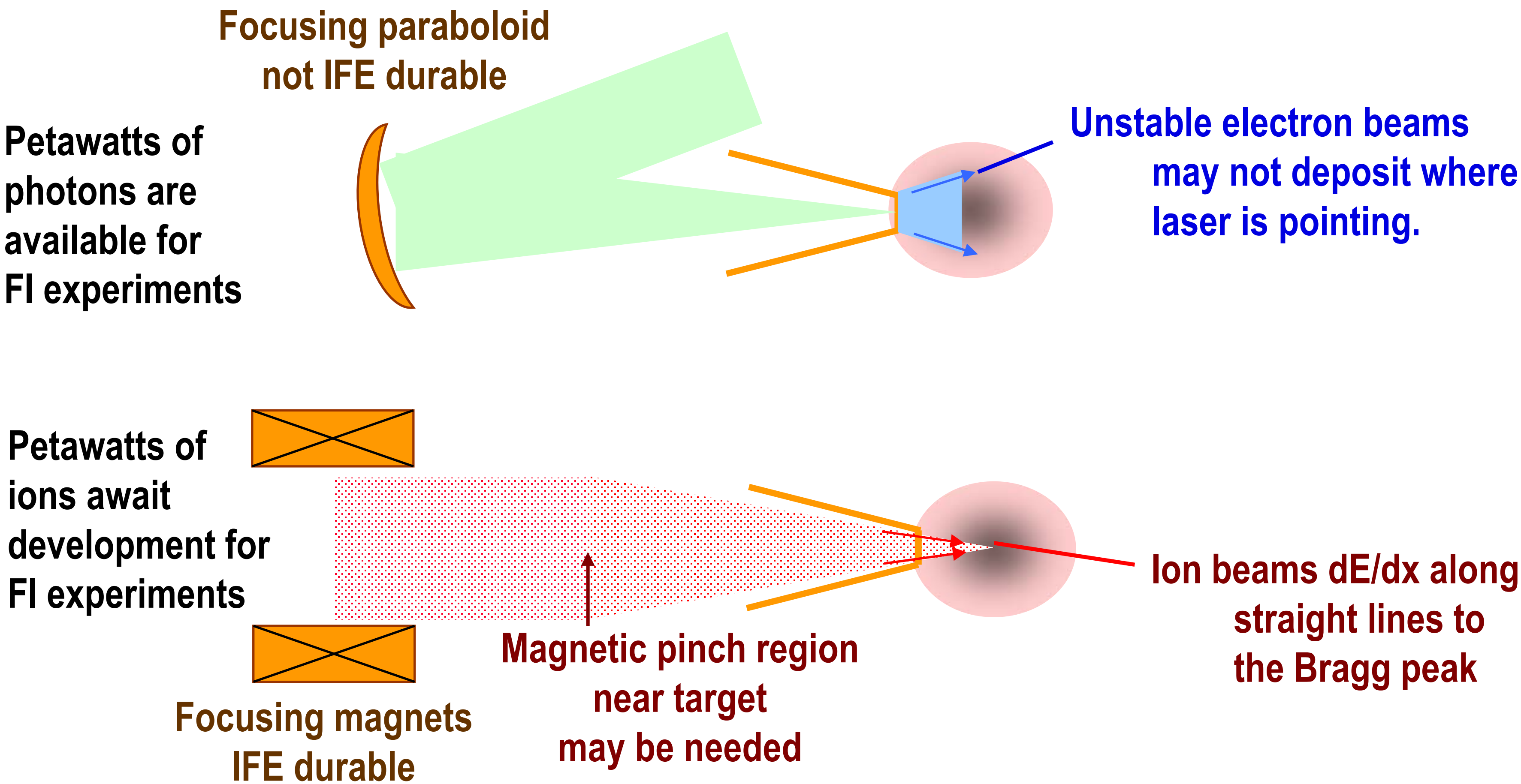
Add acceleration



Add chambers, targets, HEDP diagnostics

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

Adding accelerator ion beam R&D to exploratory fast ignition research portfolio →prudent risk management



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 contributions to High Energy Density Physics (HEDP) and to IFE, including fast ignition.
- Contributions to cross-cutting areas of accelerator physics and technology, e.g., electron cloud effects, Pulse Line Ion Accelerator, diagnostics.

▪Heavy ion research is of fundamental importance to both HEDP in the near term and to fusion in the longer term.

▪Experiments heavily leverage existing equipment and are modest in cost.

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