Heavy-Ion-Driven High Energy Density Physics and Fusion: Issues/Challenges/Plans*

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

HIFS-VNL proposal for FY10 is consistent with the "Full Use" budget case presented in March 2007 to OFES, modified to reflect delays in NDCX-II funding in FY08.

→**Consistent with the five-year VNL program plan for 2009-2013, and the first quarter of a 20-year HIFS-VNL program plan for 2006 - 2025.**

→**Purpose of 5-yr plan: to achieve three major objectives:**

1. **Explore Warm Dense Matter (WDM) physics with unique intense heavy ion beam techniques, as part of the US HEDLP program, and to provide a user facility for collaborations with GSI, ITEP, Japan, and China, who will need access to an operating heavy ion WDM target facility during the next 3 to 4 years.**

   (Requires NDCX-I)

2. **Provide the basis for extending and expanding the heavy-ion driven HEDP program beyond WDM towards heavy ion inertial fusion target physics to be ready when ignition is expected in NIF.**
3. **Provide the basis for IB-HEDPX, a more capable heavy ion WDM user facility for the US HEDLP program in the 2015-2025 time frame.**

   (Requires NDCX-II)

NDCX-I: Develop experimental methods and diagnostics to enable heavy ion-beam-driven Warm Dense Matter and Heavy Ion Fusion Physics.

→Provide experimental data on intense beam compression to benchmark and improve theory and particle simulation codes:

--Transverse and longitudinal compression of intense beams in neutralizing background plasma: optimize transverse focusing in conjunction with induction waveforms for longitudinal compression.

--Advanced plasma sources to optimize beam neutralization in both drift and final focus regions.

→Provide platform for initial WDM target experiments

--Develop fast (ns-scale) beam and target diagnostics.

First NDCX-I target experiments planned; 4th QTR FY08 milestone: "Carry out initial target experiment in the new target chamber, using beams compressed and focused by an improved bunching waveform and a final focus solenoid".

→A preparatory step towards medium term WDM experiments with dense electronegative (positive and negative ion-ion plasmas), porous targets, and two-phase equations-of-state.

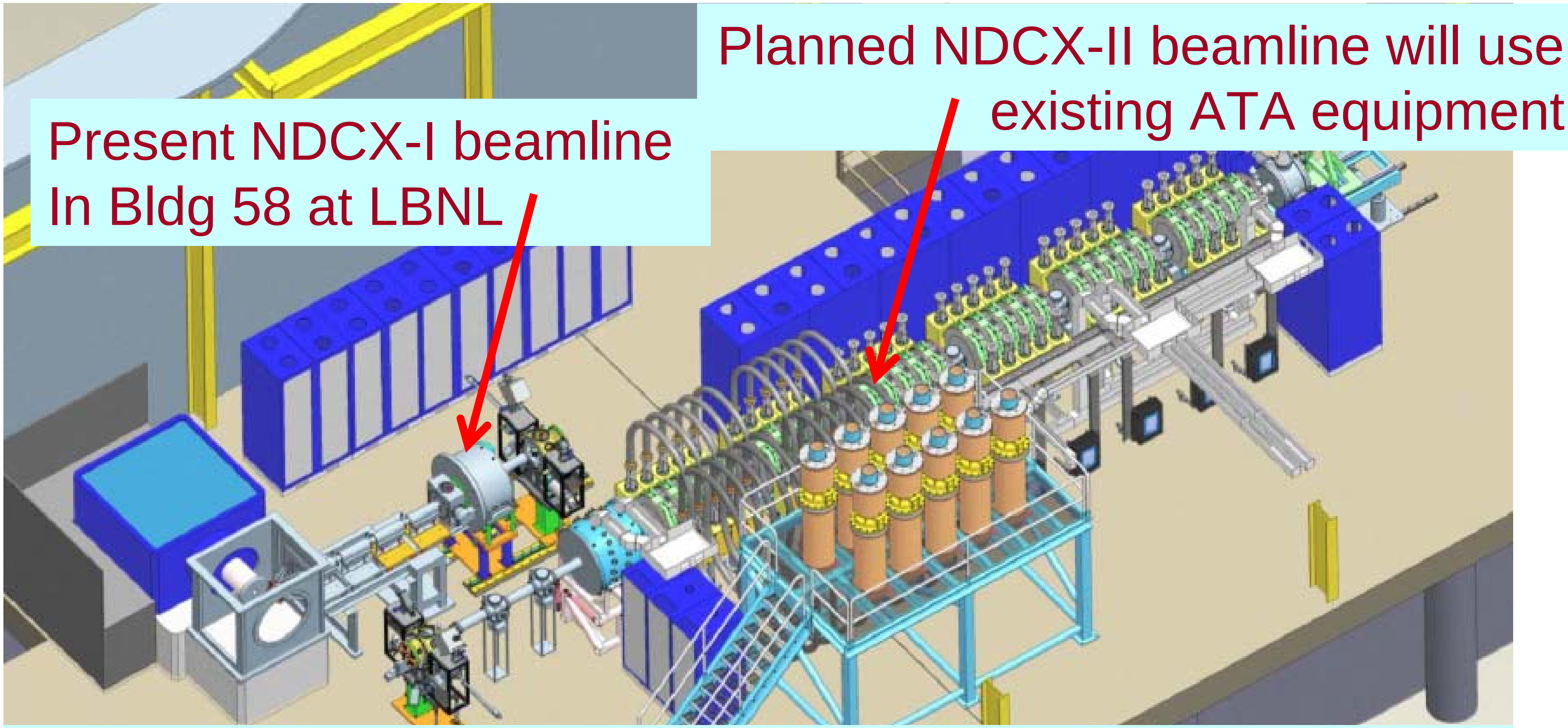
NDCX-II Physics Objectives

1. Provide the US HIFS-VNL program a capability for Warm Dense Matter target temperatures above beyond available in NDCX-I. This will allow continued collaboration with GSI under US-German agreements.

2. Explore heavy-ion direct-drive target physics relevant to fusion
   - ion ablative drive (w/ blow-off plasma) rocket efficiency with head-to-tail ramped ion energies
   - hydro stability (w/ volumetric stopping) with upstream beam modulations.

3. Provide the single-shot physics basis for short-pulse beam requirements for IB-HEDPX CD0.

The VNL full-use five-year plan will support continued operation of NDCX- I, with NDCX-II assembly completion (first operation) in FY2011, using existing ATA equipment now at LBNL.



The current NDCX-I beamline will continue to optimize beam compression techniques and WDM target diagnostics for NDXC-II while NDCX-II is being assembled in 09, 10 and 11

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:

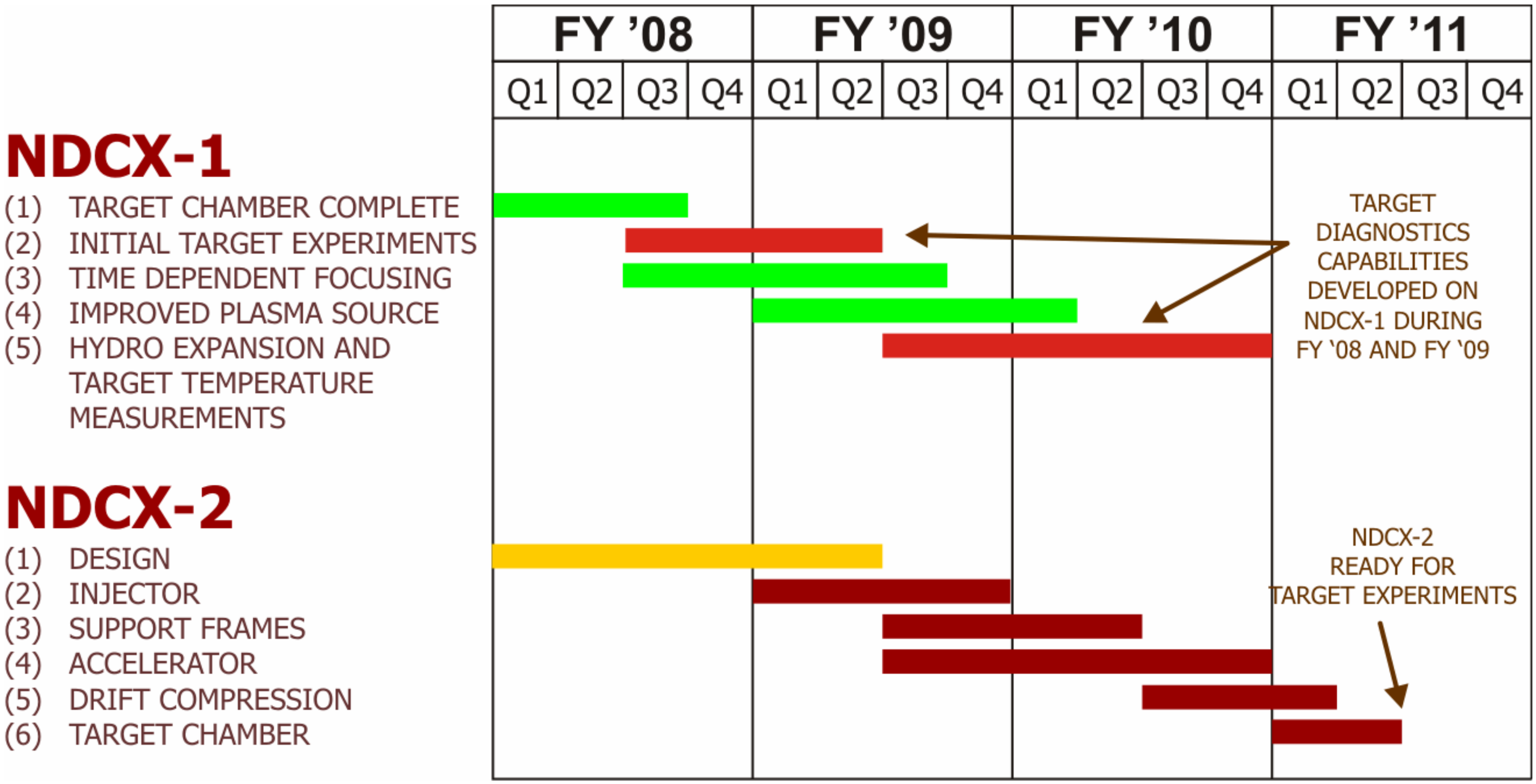
12/1/05

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

Date

Consistent with updated NDCX-II cost estimate Nov 2007

Proposed schedules for NDCX-I and NDCX-II in the updated HIFS-VNL Five-Year Plan for FY09-FY13



Proposed NDCX-II SPENDING PROFILE (Update by Matthaeus and Waldron, Nov 2007)

1st Year: 1.7 M$

2nd Year: 2.5 M$

3rd Year: 0.5 M$

Cost Estimate Total: 4.7 M$ (without contingency)

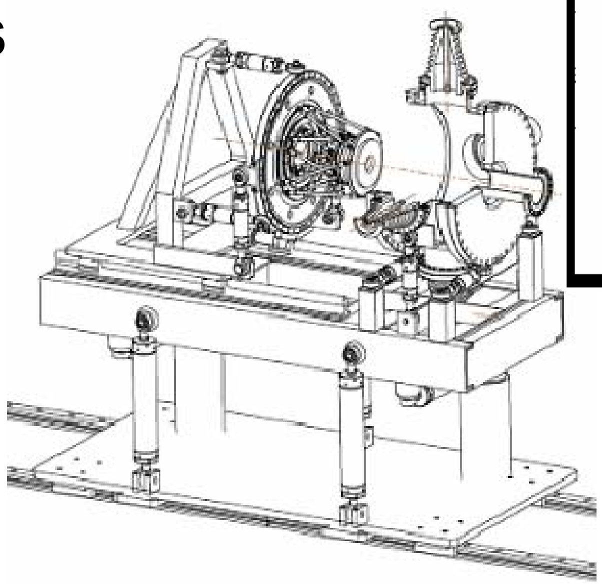
Compared to a year ago, this update utilizes more of the 40 ATA induction modules we have in storage, to satisfy recent NDCX-II physics design requirements (Friedman, Henestroza, Sharp) for simultaneous bunch compression and acceleration before final tilt core application and neutralized drift compression →More extensive pulse networks allow simultaneous bunch compression during acceleration. This updated cost is close to the original $ 4.5 M NDCX-II cost estimate presented at the BPM in 2004, and consistent with the target cost of $ 5M for NDCX-II prerequisite in the 2005 IB-HEDPX CD0. The 5-yr plan spreads these costs over FY09, FY10, and FY11.

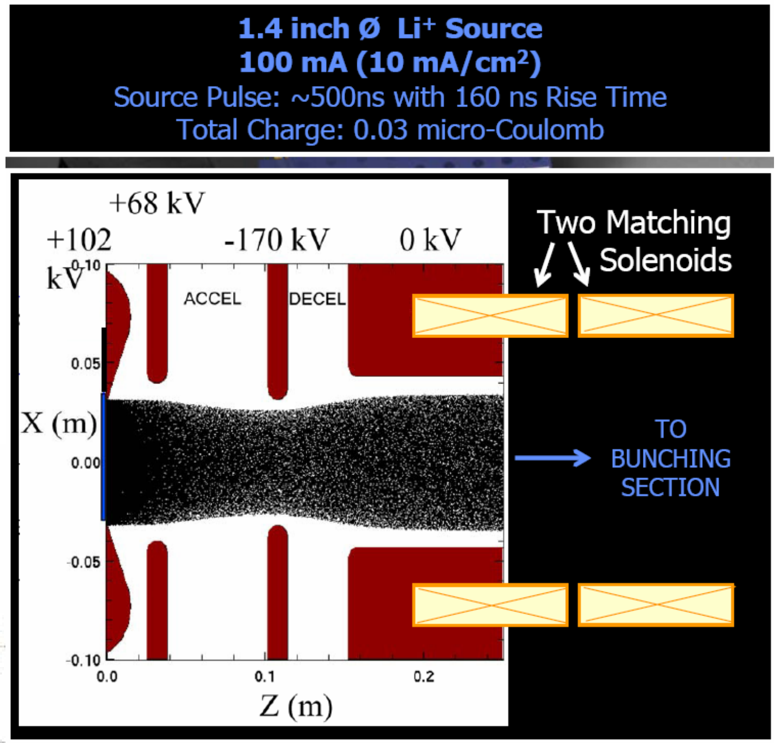
An early NDCX-II injector construction can expedite schedule to first HEDP and heavy ion direct drive coupling experiments.

- **Early beam brightness data on the NDCX-II injector will allow us to optimize the NDCX-II final focus and target chamber design.**

- **Need to build:**
  - **Vacuum vessel and vacuum pumping**
  - **Support structure**
  - **Ion Source**
  - **Aperture system with hexapods**
  - **Matching solenoids**

- **Approx. Cost ~ 400 K$**





The **full-use budget** supports a twenty-year science campaign* for heavy-ion-beam-driven HEDP *towards heavy ion fusion* following NIF ignition

Science Area	FY06 through FY08	Five-Yr-Plan FY09 through FY13	FY14 through FY 17	FY18 through FY25
Beam-Target Interaction	Target design, initial WDM experiments, fast beam diagnostics, beam dE/dx	Explore a variety of new WDM and Initial beam-cryo D2 or noble crystal target interaction	Construct upgrade IB-HEDPX 1 to 10 eV WDM user facility: EOS, critical points, properties	-Operate IB-HEDPX WDM user facility: -Physics of WDM phenomena and target physics relevant for high gain/ future IFE
Focusing onto Targets	Optimize high-B final focus together with near target plasma sources	Ramped energy and double pulse coupling experiments, time dependent focusing experiments	Ion planar direct drive hydro experiments with shaped ramp and double pulses	Optimize targets with pulse shaping in ion beam direct drive using multi-pulse bunch trains
Longitudinal Beam Compression	Optimize longitudinal and transverse focusing with new induction buncher	Compress and focus pulse-shaped ion bunches	Optimize compression with time-dependent focusing and ramped/ double-pulse beams	Optimize compression and focusing using multi-pulse bunch trains
High Brightness Transport	E-cloud in quads and solenoids, beam steering and brightness optimization	Perpendicular and parallel brightness in ramped/ double pulses	Optimize perpendicular and parallel beam brightness with ramped/double-pulse beams	Optimize perpendicular and parallel beam brightness with multi-pulse train bursts
Advanced Theory and Simulations	Advanced source-to-target models, and source-through-target modeling	Begin direct drive with ramped / multi pulse models	Further develop and apply ramped/multi-pulse beam acceleration/focusing models	Integrated accelerator beam dynamics with target hydro modeling and multi-pulse drive shaping
Facility & resource needs (Constant $ estimate)	1. Optimize NDCX-I with new tilt core, plasma sources, and higher-B final focus magnet. 2. Test ATA equipment for NDCX-II 3. Develop diagnostics $7.8 M/yr tot.	1. Operate NDCX-I for 0.5 eV WDM experiments, optimize with improved plasma sources and higher-B focus 2. Assemble NDCX-II using existing ATA accelerator modules 3. Operate NDCX-II for 1 eV WDM experiments and basis for IBHEDPX $12.7 M/yr rising to $16M/yr tot	1. Construct and operate IB-HEDPX and support users ($20M/yr) 2. Construct heavy ion implosion target physics facility ($20M/yr) ~ $40M/yr tot.	1. Operate IB-HEDPX and support users ($20M/yr) 2. Operate heavy ion implosion physics facility (20M/yr) 3. Target & chamber R&D needed for IFE ($20M/yr) ~ $60 M/yr tot.

First heavy ion WDM experiment @ 0.5 eV ↑

NIF Ignition Campaign →

←NDCX-II assembly→
1 eV target-basis, start IB-HEDPX→

→ Operate IB-HEDPX
→ Start heavy-ion target physics implosion facility; complete 2020→ ↑

20yr Objective: Develop the beam and HEDP target physics knowledge base for a heavy-ion fusion test facility (FTF) ↑

* Updated and extended from previous 10-yr campaign- Fig. 3.1 of National HEDP Task Force Report

HIFS-VNL budgets by year, for full-use (incremental) budget cases support NDCX-II procurement and staff levels needed for the 5-yr plan

($K)	FY05	FY06	FY07	FY08	FY09 (Full-use) Increments	FY10 (Full use) Increments
LBNL	6000	5,360	4,700	4,700	1,300 operating + 1,700 equip*	1,300 operating + 2,500 equip*
LLNL	2,650	2,475	2,035	2,120	1,180 operating	1,180 operating
PPPL	1,603	1,142	980	990	588	588
Totals VNL (total FTEs)	10,253 (43 FTEs)	8,977 (37 FTEs)	7,715 (33 FTEs)	7,810 (32 FTEs)	3068 operating +1,700 equip for NDCX-II (43 FTEs)	3068 operating +2,500 equip for NDCX-II (44 FTEs)
				Totals (K$)→	11,028 operating +1,700 equip	11,028 operating +2,500 equip

The proposed FY09 and FY10 milestones for the guidance budget case FY10=FY09=FY08+2% support key physics for warm dense matter and heavy ion fusion targets.

FY09 milestones for guidance budgets:

- **Q1: Simulate beam neutralization near target focus using reconfigured plasma sources.**
- **Q2: Compare theory/simulation and initial measurements of focal spot reductions using upstream time-dependent corrections of chromatic aberrations.**
- **Q3: Upgrade plasma source configuration and carry out initial experiments. Characterize improvements in focal spot beam intensity.**
- **Q4: Measure and simulate target temperature and hydrodynamic expansion response in optimized NDCX-I configurations with initial diagnostics suite.**

FY10 milestones for guidance budgets:

- **Q1: Carry out particle simulations of NDCX configurations to optimize halogen ion-ion WDM experiments.**
- **Q2: Measure properties of beam driven ion-ion WDM experiments in high electron-affinity targets.**
- **Q3: Assess key physics underpinning high hydro coupling efficiency in both NDCX experiments and high gain heavy ion direct drive target designs using proven hydro codes like HYDRA.**
- **Q4: Evaluate optical diagnostics to characterize beam coupling in candidate direct drive hydro targets.**

Proposed HIFS-VNL milestones for NDCX-II, in addition to NDXC-I milestones for the guidance budget case, assuming increments for the full-use budget case.

FY09 incremental milestones:

- **Q1 incremental: Complete Advanced Test Accelerator (ATA) module performance acceptance tests with new prototype solenoids.**
- **Q2 incremental: Complete the NDCX-II design and associated experimental and diagnostic plans.**
- **Q3 incremental: Measure full-scale NDCX-II source current density.**
- **Q4 incremental: Complete NDCX-II injector, and fabricate new solenoids.**

FY10 incremental milestones:

- **Q1 incremental: Measure NDCX-II injector beam quality.**
- **Q2 incremental: Complete accelerator pre-bunching section with first block of accelerator modules.**
- **Q3 incremental: Install remaining support frames and ATA induction accelerator modules.**
- **Q4 incremental: Complete accelerator and characterize accelerated beam quality.**

PPPL Heavy Ion Beam Research

PPPL Funding Request for FY2009 and FY2010 in VNL Task Areas

	FY2009/FY2010	FY 2009	FY 2010
Task Area	Guidance	Increment	Increment
1	$600K/$620K	$150K	$150K
2	$268K/$268K	$200K	$200K
3	$122K/$122K	$73K	$73K
4	----	$165K	$165K
Total	$990K/$1010K	$588K	$588K

1. Theory and modeling.
2. Plasma source development/neutralized transport experiments.
3. Warm dense matter/atomic physics.
4. Voss Scientific subcontract /compression and transport modeling.

Selected PPPL VNL Milestones for FY 2009 and FY 2010

Theory and Modeling Milestones at Guidance Funding Level*

- Complete large-scale particle simulations of electron-ion two-stream interactions in bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (September, 2009).

- Develop techniques for inferring the equation of state in the warm dense matter regime by diagnosing the expanding plasma front and comparing with numerical simulations and theoretical models (September, 2010).

Experimental Milestones at Guidance Funding Level*

- Evaluate candidate plasma sources for producing spatially localized, high density, plasma near the compressed-beam focal plane. Begin development and fabrication of the preferred options (March, 2009).

- Complete installation, testing, and characterization of high-density-producing plasma source on NDCX or its upgrades (September, 2010).

* *Blue denotes Fusion Execution Agreement (FEA) milestones.*

Impact on HIFS-VNL research in FY10 with FY09 budget =FY08 +2% and 10% below FY09/08 level

FY10=FY09=FY08+2%

- **Further loss of VNL staff (32 FTE→ 28 FTE)**
- **No NDCX-I improvements beyond present FY08 capability**
- **Eliminates e-cloud research (important to IFE, HEP, BES accelerators…)**

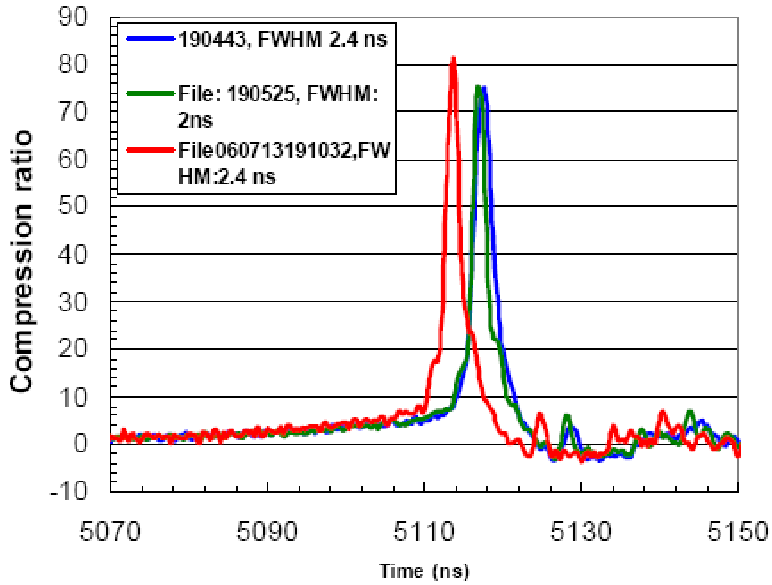
FY10=FY09=FY08 -10% (in addition to above impacts)

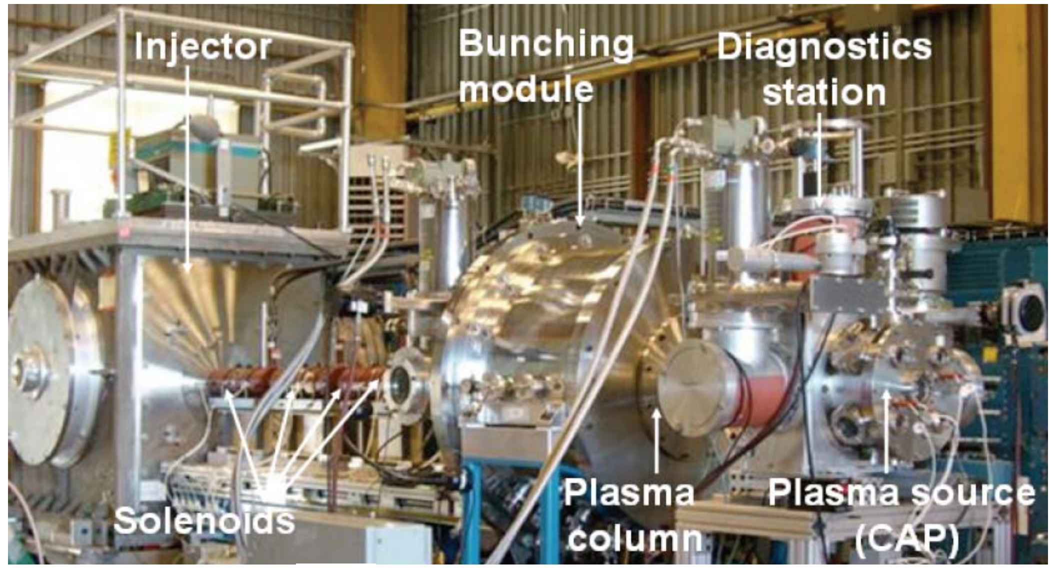
- **Additional loss of staff (32 FTE→25 FTE)**
- **Stop ATA component testing, modeling, and design support for NDCX-II.**
- **Eliminate possibility for first cryogenic target experiments for diagnostic development on NDCX-I preparatory to NDCX-II.**

→ Delays NDCX-II and IB-HEDPX, and jeopardizes HIFS-VNL readiness to capitalize on an extended IFES campaign for heavy-ion fusion target physics with NIF ignition.

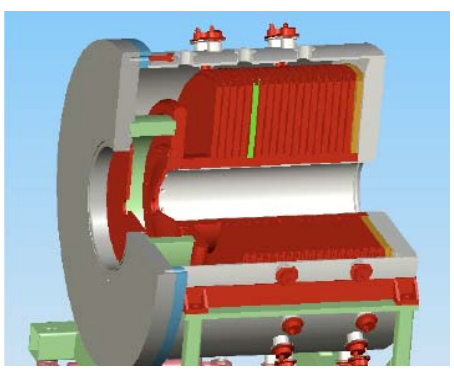
The neutralized drift compression experiment (NDCX-I) continues to improve longitudinal compression and combine with radial focusing

Shorter pulses (2.4 ns) obtained w/ new Ferro-electric plasma source

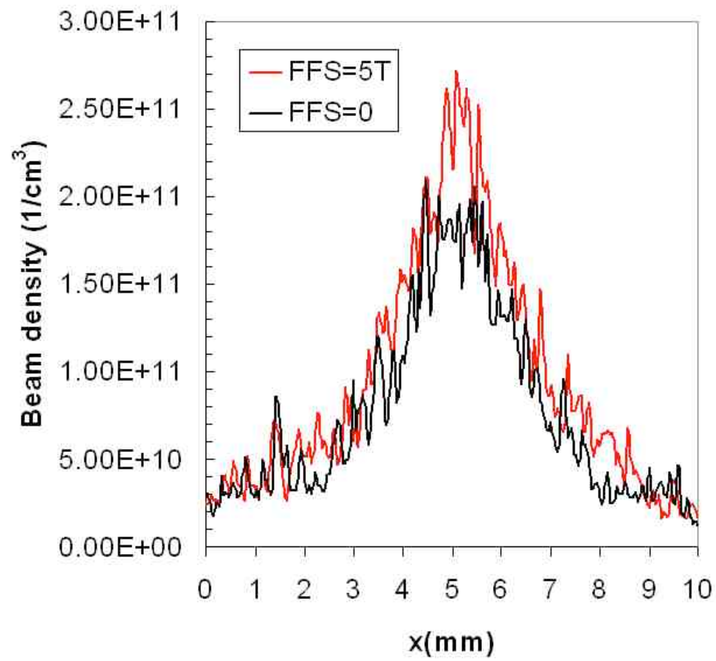




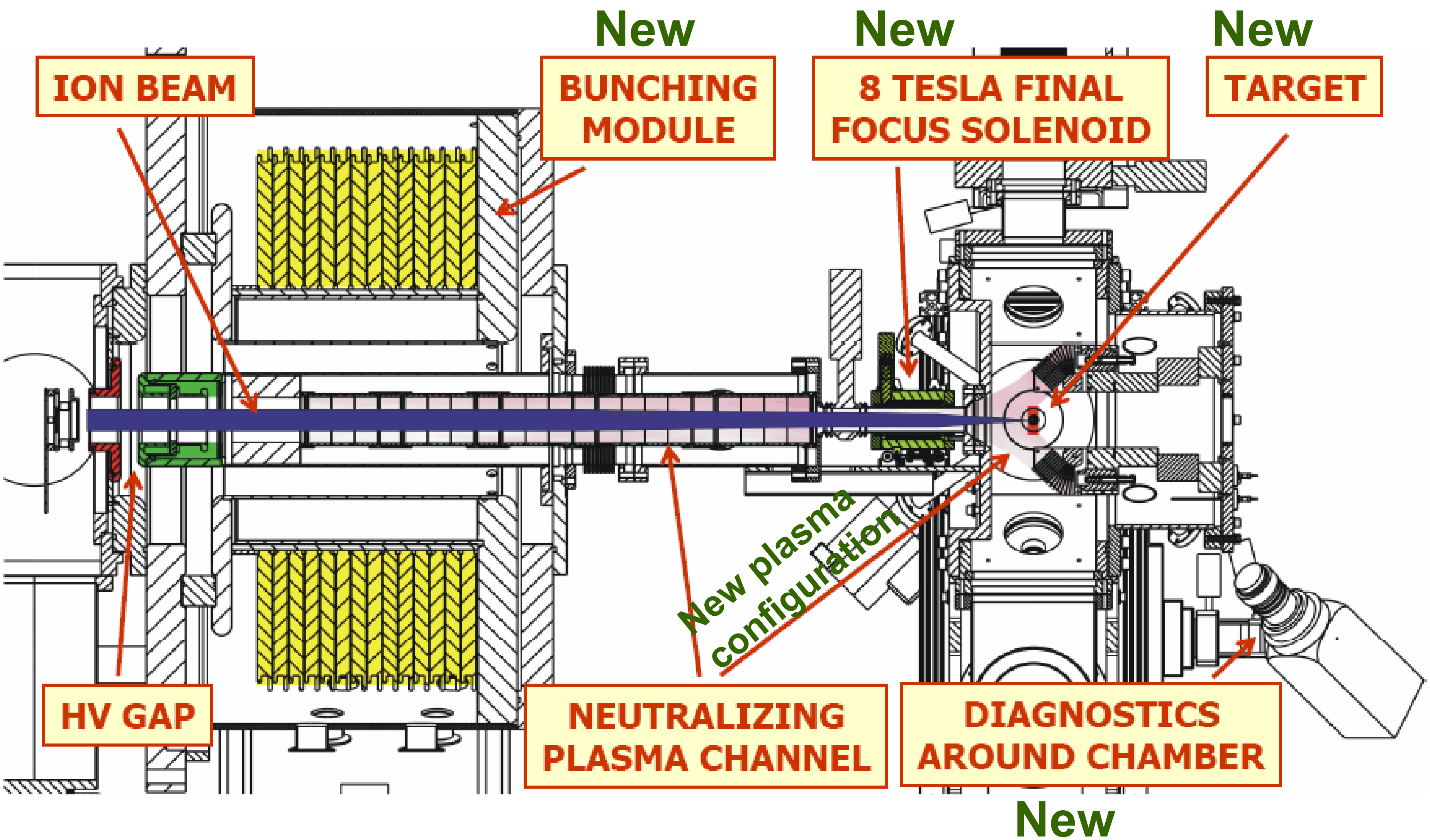
Simulations predict higher compression with new induction buncher



First combined radial and longitudinal compression: to be repeated with more plasma for better beam neutralization

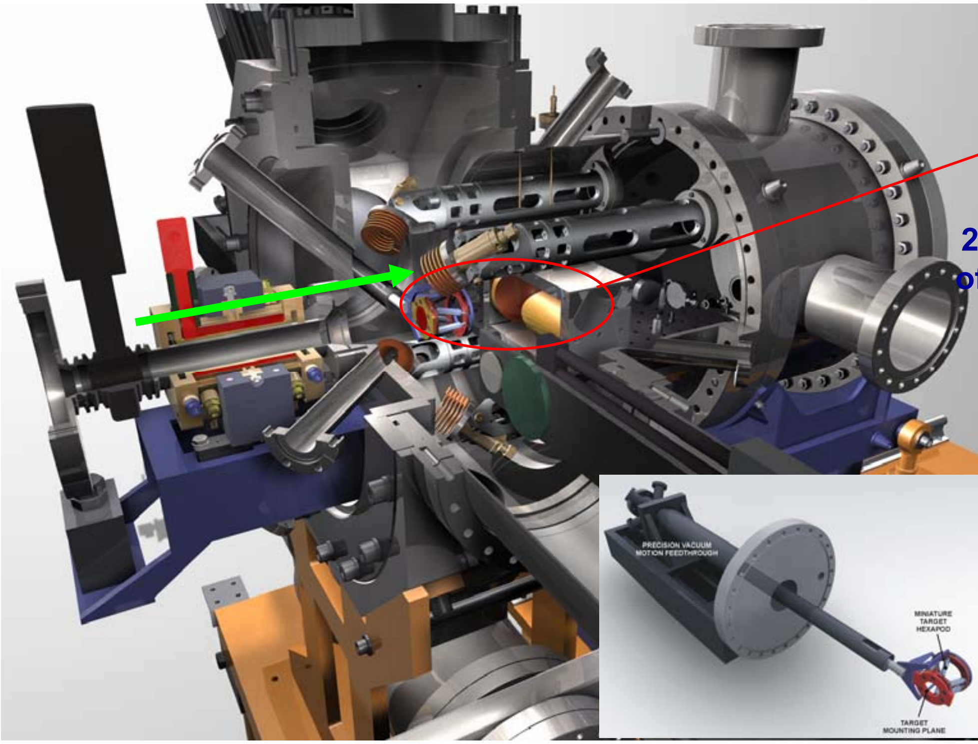


FY08-09 warm dense matter experiments on improved NDCX-I

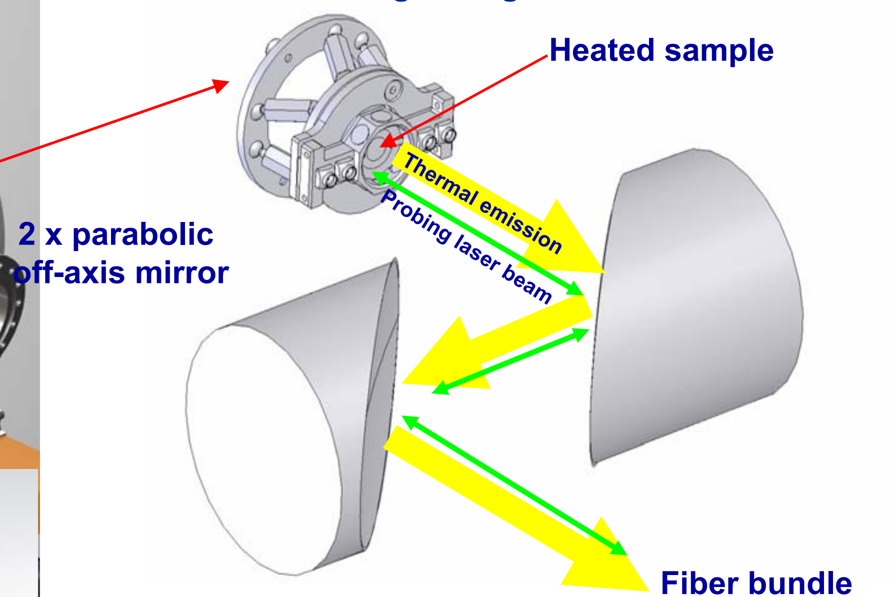


A new NDCX-I target chamber is being installed with new optical diagnostics for first target experiments

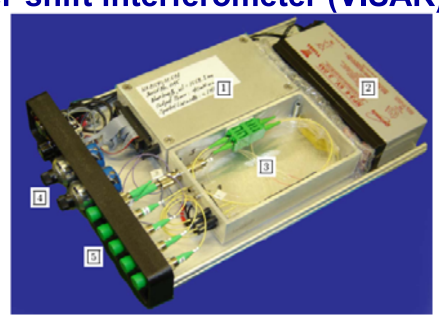
Target chamber:



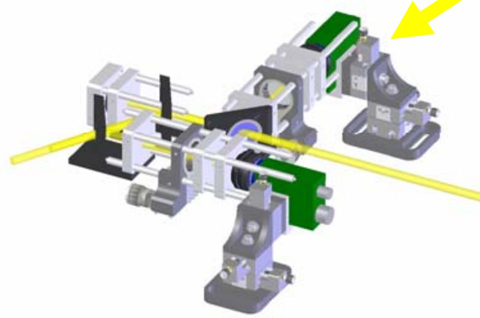
Probing of target:



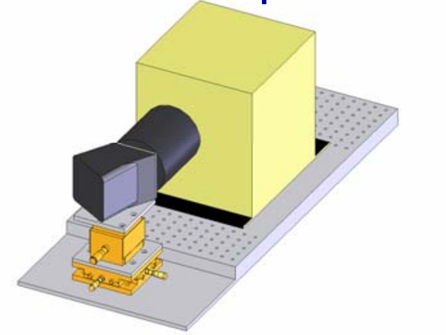
Doppler-shift interferometer (VISAR):



Pyrometer:



Streak camera spectrometer



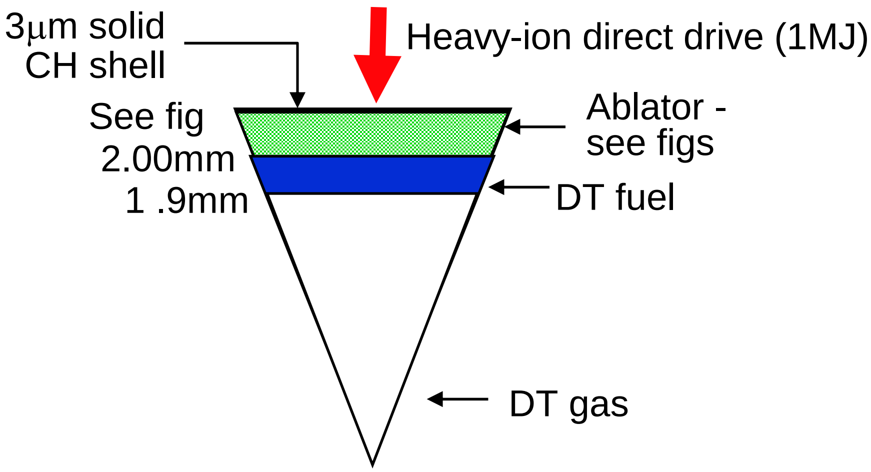
Selected Accomplishments* by PPPL in FY 2007

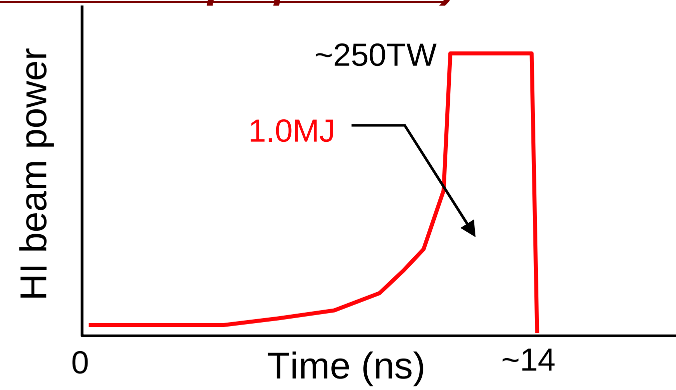
- Complete initial assessment of operating regimes that mitigate the deleterious effects of collective two-stream interactions on the integrity of the compressed beam pulse in solenoidal magnetic field configurations with neutralizing background plasma (Completed September, 2007).
- **Complete the development of optimized models for beam charge and current neutralization in solenoidal magnetic field configurations with neutralized drift compression (Completed March, 2007).**
- Identify characteristics of ion-ion electron-depleted plasmas as inferred from extracted ion and electron beams, and evaluate whether ion-ion plasmas offer advantages relative to ordinary ion-electron plasmas for ion-beam-driven high energy density physics applications (Completed September, 2007).
- **Optimize and upgrade plasma source to allow control of the plasma density profile in the neutralized drift compression of intense ion beam pulses on NDCX (Completed May, 2007).**

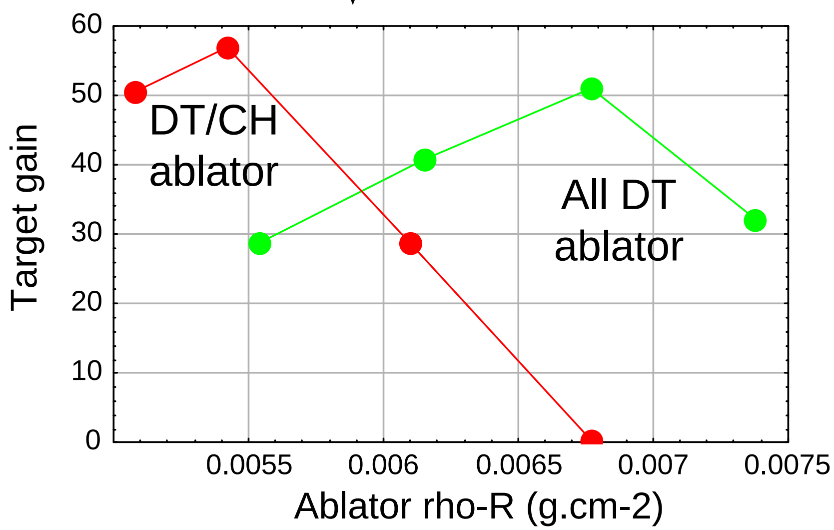
***Blue denotes Fusion Execution Agreement (FEA) milestone.**

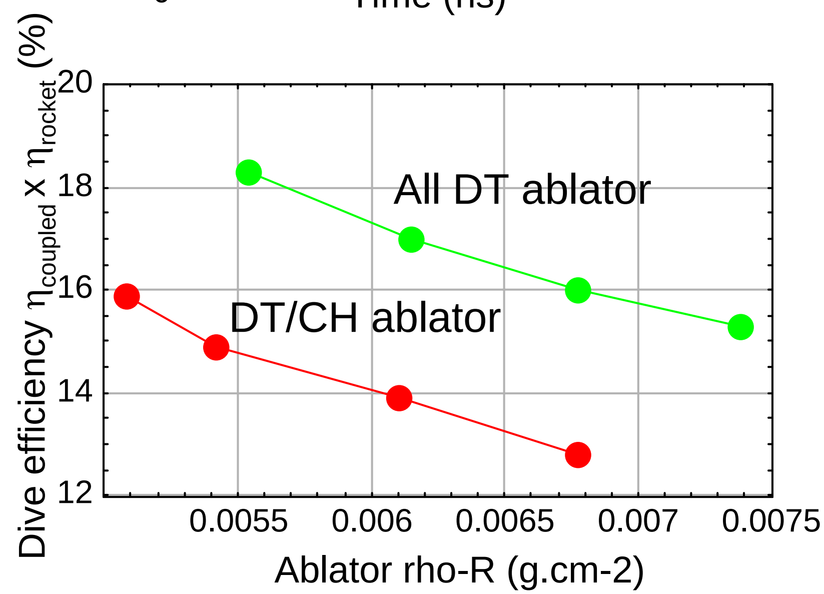
First heavy-ion direct drive LASNEX 1D runs by John Perkins (LLNL, June 2007) show gains ≥ 50 at 1MJ with drive efficiency twice that of laser direct drive.

(Publication in preparation)



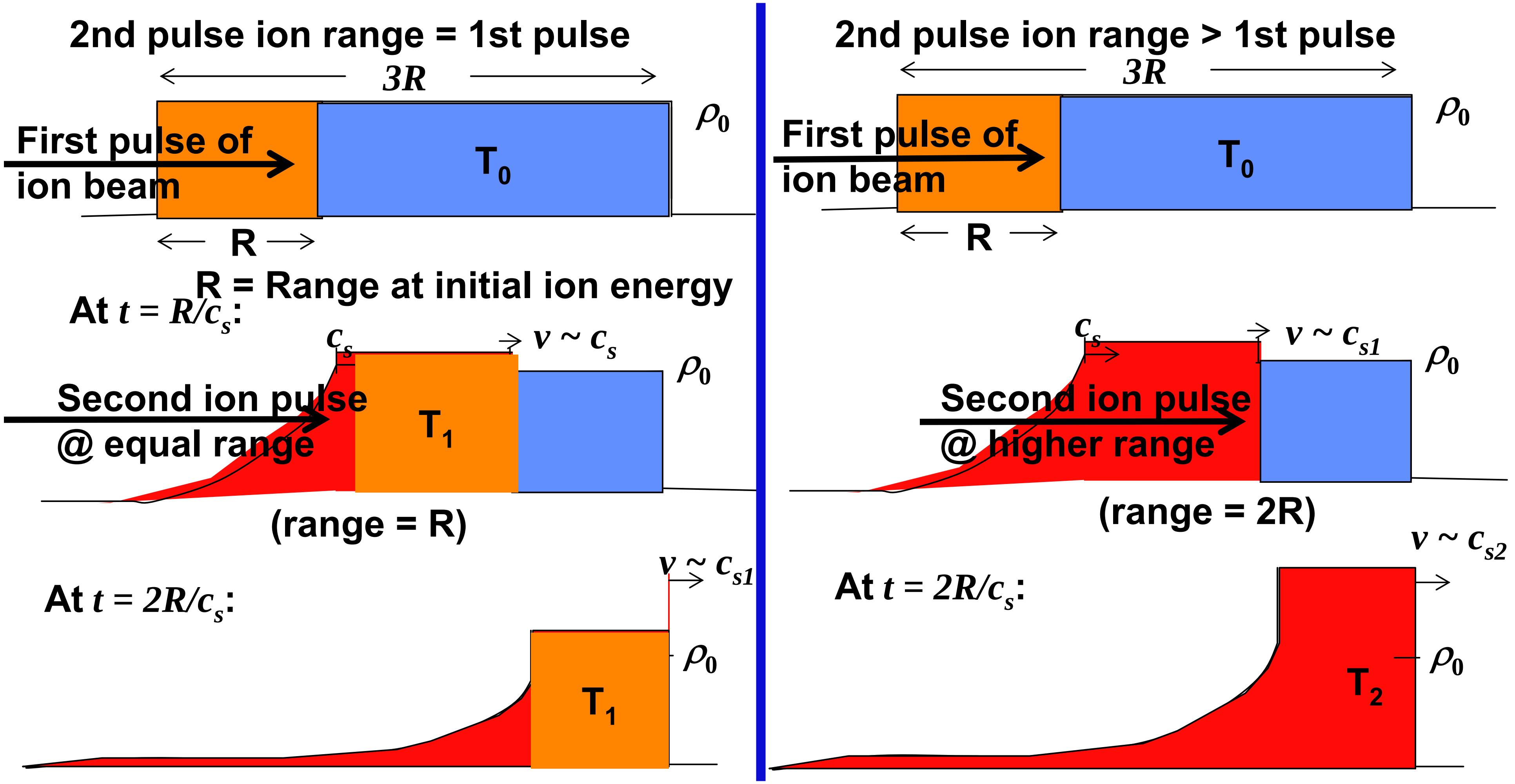






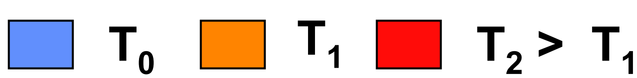
Higher drive efficiencies ≥20% may be possible by tuning the ion kinetic energy, 50 → >500MeV, as the capsule implodes

A "double-pulse" experiment on NDCX II will demonstrate the improvement in coupling efficiency with increasing ion range

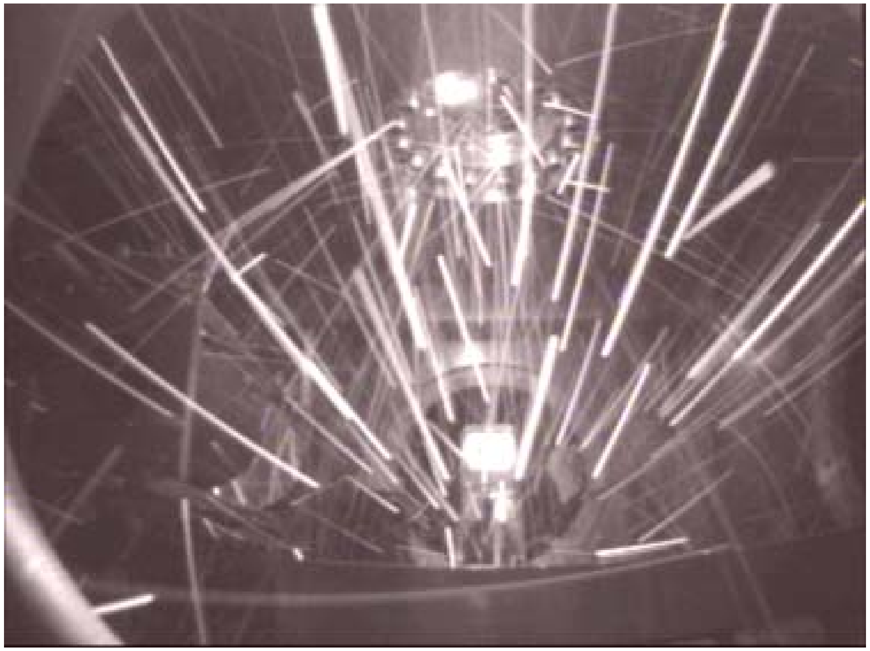


ρ vs z:

At $t = 3R/c_s$: measure velocity of back of target;



We are developing diagnostics and two-phase EOS models in joint experiments with GSI for isochoric heating & expansion relevant to indirect drive HIF target radiators and NIF target-holding materials.



Visible ms camera frame showing hot target debris. (The HIFS-VNL provided mg mass gold targets made at Berkeley- isochorically heated by a 100 ns, 100 J heavy ion beam @ 10^{12} W/cm^2 and 1 eV in joint experiments at GSI Germany)

Models for two-phase WDM isochoric heating and expansion/droplets first tested with heavy ion beams can later be benchmarked/improved with isochoric neutron heating data of NIF target-holder materials in high yield NIF shots.

The heavy-ion-driven HEDP program is part of Campaign 3 in the April 2005 FESAC Priorities Report: "Investigate the assembly, heating, and burning of high energy density plasmas"

Contributions to the three overarching themes of fusion research:

- **Chapter 10: Understand matter in the high-temperature plasma state**

  p.114: "…new generation of laboratory facilities that allow controlled and precise investigations of matter under extreme conditions." ***[Neutralized Drift Compression Experiment (NDCX-I and NDCX-II), and Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX)]***

- **Chapter 11: Create a star on earth**

  p.120 "..National Ignition Facility ..will establish the foundations for the development of inertial fusion energy". ***HEDP includes the science of how heavy ion fusion targets can reach conditions for high energy gain.***

- **Chapter 12: Develop the science and technology to realize fusion energy**

  p.136: "…physics limits to ion pulse compression within neutralizing background plasma, together with novel focusing methods, are essential to achieving cost-effective accelerator-driven high energy density physics in the laboratory, and may also lead to more compact, lower-cost modular accelerators for inertial fusion energy." ***We plan NDCX-1 experiments with foam targets, and NDCX-II planar hydrodynamics experiments, providing key physics for both indirect- and direct-drive HIF targets.***

Laser and pulsed-power drivers have advanced significantly, but the reasons HIF has advantages identified in many DOE reviews *still apply*:

(a) High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE. ***Advantage of being able to build upon a credible high energy particle accelerator experience base.***

(b) Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with indirect-drive or polar direct-drive target illumination geometries to be tested in the National Ignition Facility. ***Avoids the need for a long fusion materials development program.***

(c) Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation. ***Detailed studies show shielded final focus magnets can last for many full power plant years of operation.***

(d) Several heavy ion power plant studies have shown attractive economics (competitive CoE with nuclear plants) and environmental characteristics (no high level waste; only class-C low level waste). ***Molten salt (HYLIFE-II type) chambers cost < \$10 M / GW_{th} → multi-unit plants sharing one driver → < 3 cts /kW_ehr***

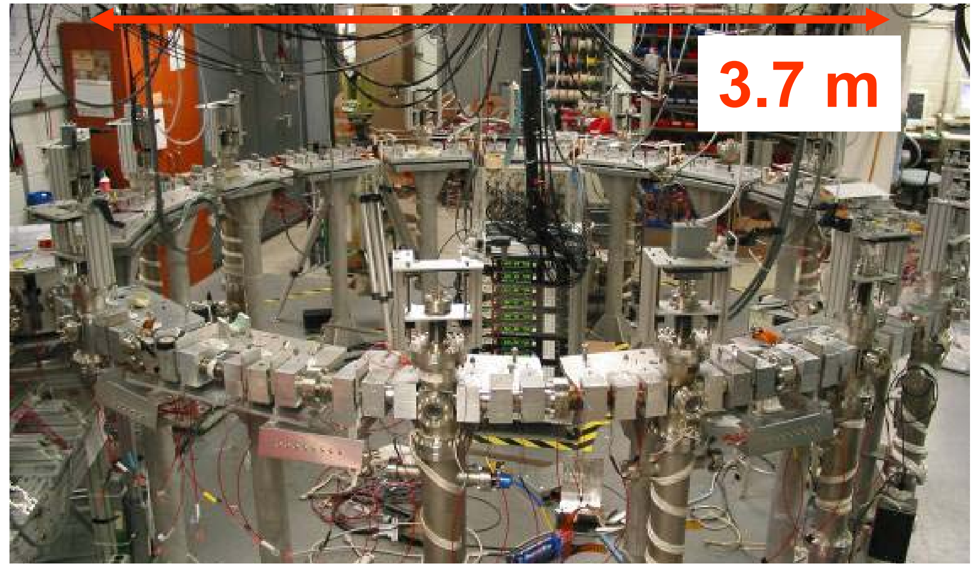
University of Maryland Electron Ring (UMER): Achieved multi-turn circulation of beams with extreme intensities

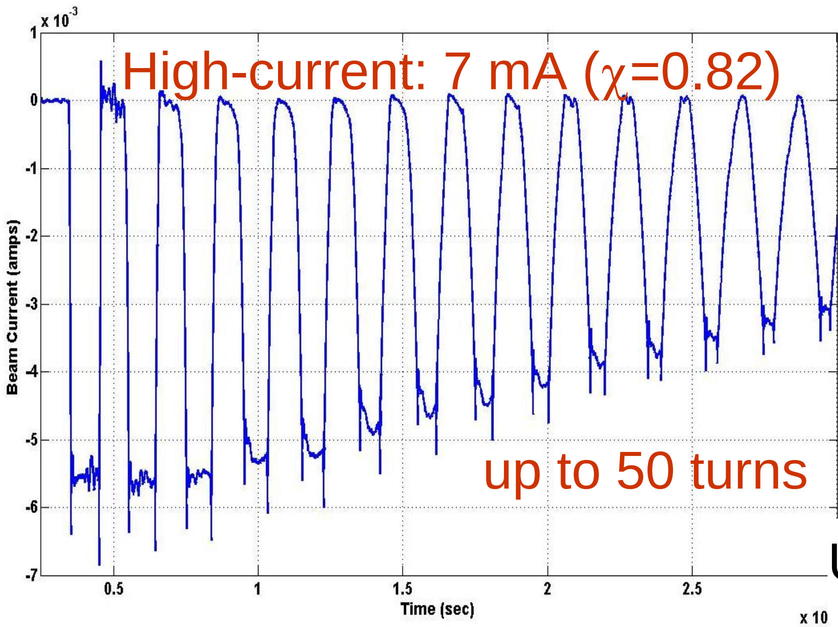
Goal: To demonstrate transport of intense beams for a long distance (exceeded 100 Turn design criterion)

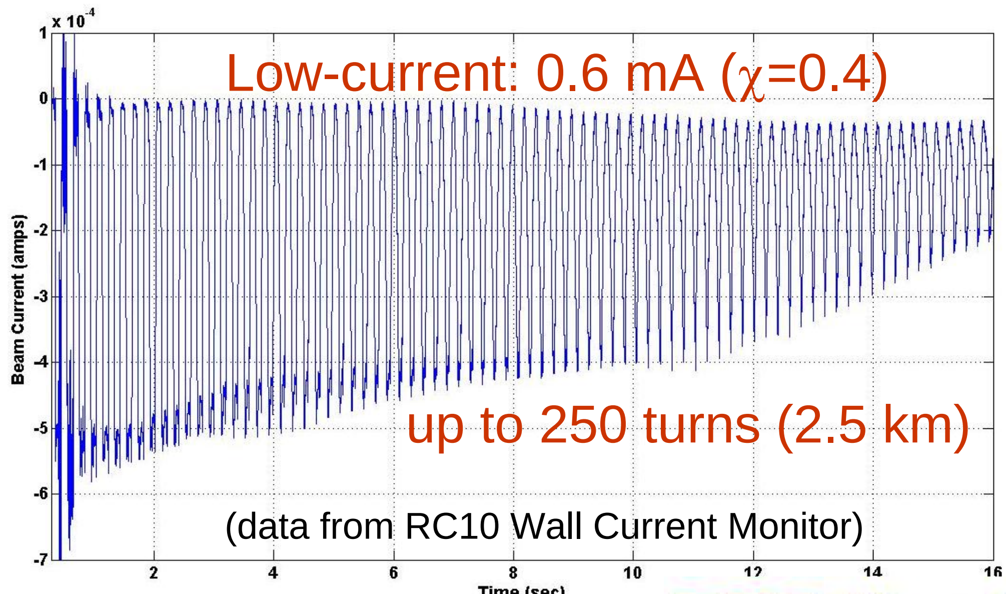
Investigate transverse and longitudinal beam dynamics relevant to HIF drivers

Ideal for student training

Opportunity to harvest the investment of the past several years.







UMER Construction funded by Office of Science U.S. DEPARTMENT OF ENERGY

Paul Trap Simulator Experiment (PTSX) Wholly Simulates Transverse Dynamics of Intense Beams by Working in the Beam Frame-of-Reference

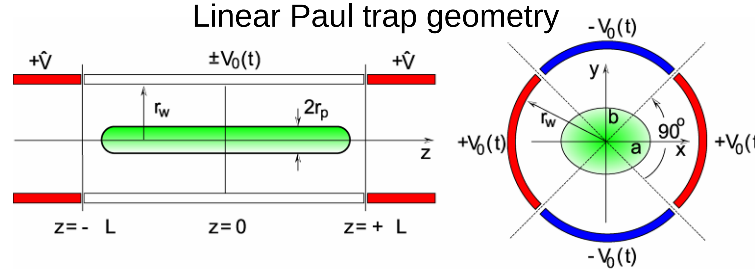
Ions in PTSX have the same transverse equations of motion, including space-change effects, as ions in an alternating-gradient system ***in the beam frame***. The PTSX waveform voltage and frequency correspond to the AG system's magnetic field strength and magnet spacing.

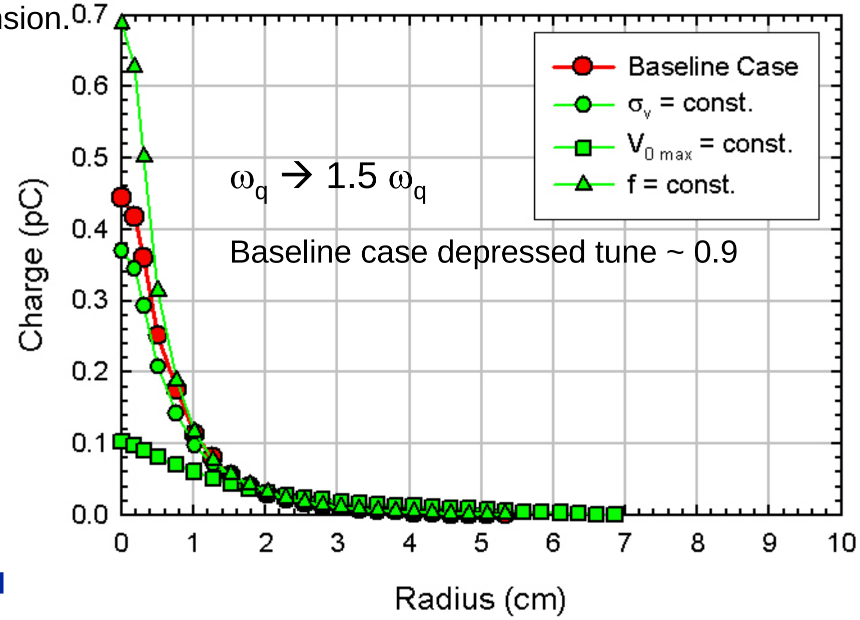
Recent experiments studied the effects of instantaneous and adiabatic lattice changes on on-axis density and emittance.

50% instantaneous increase in focusing force by increasing average transverse focusing frequency ω_q in three ways:

- ▲ at fixed lattice periodicity, the on-axis density increases while emittance grows 40%.
- ● at fixed vacuum phase advance, 60% emittance growth causes the beam to expand radially, decreasing the on-axis density.
- ■ at fixed lattice amplitude, 450% emittance growth associated with nearly exceeding the maximum allowed vacuum phase advance causes large radial expansion.

Linear Paul trap geometry





Instantaneous changes cause sudden beam mismatch, ultimately leading to emittance growth.

Adiabatic (over 4 lattice periods in this case) increases compress the beam without measureable emittance growth (< 10%).

Conclusions

- Exciting scientific advances and discoveries in the past year enable:
  - First compression & focusing of ultra-short ion pulses in plasmas, readiness to begin first target experiments on NDCX-I later this year.
  - Unique approaches to High Energy Density Physics (HEDP) and heavy ion fusion target physics.

- All proposed research is fundamental science important to both HEDP in the near term, and to heavy ion fusion target physics in the longer term.

- Proposed experiments leverage existing equipment and are modest in cost.

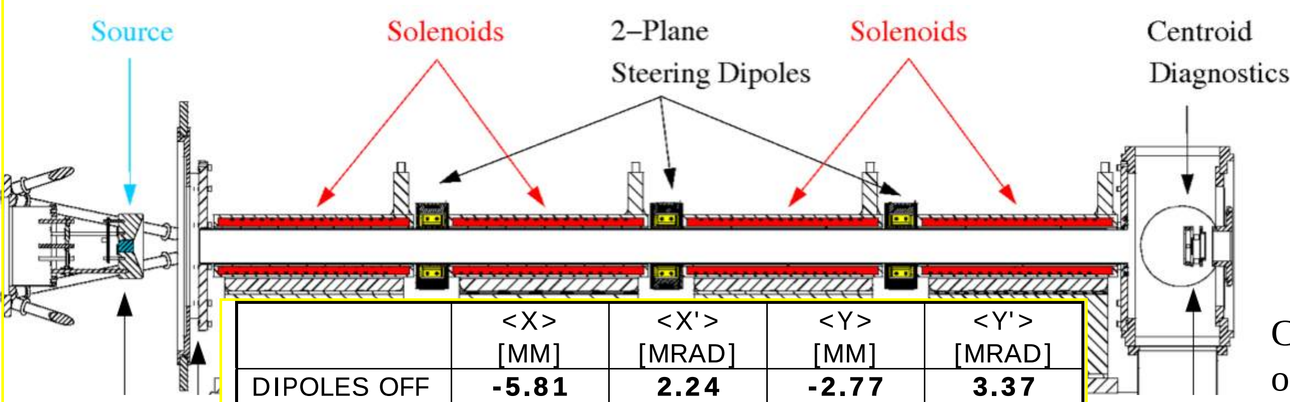
- The requested full-use budget case for FY09 and FY10 funding allows us to complete NDCX-II, needed to validate physics basis of IB-HEDPX, by FY11.

- FY09 and FY10 budgets flat at the present level would seriously reduce the rate of progress we can make:
  - Delay NDCX-II, and therefore IB-HEDPX CD1, beyond FY12, possibly beyond expected NIF ignition.
  - Result in 30 % VNL scientific productivity loss (staff loss) relative to FY05 level.

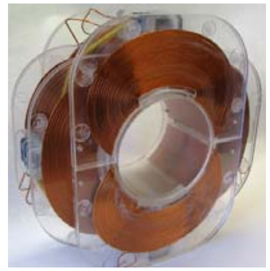
Backup slides-PART I:

Near-term VNL program on HEDLP and heavy ion fusion science

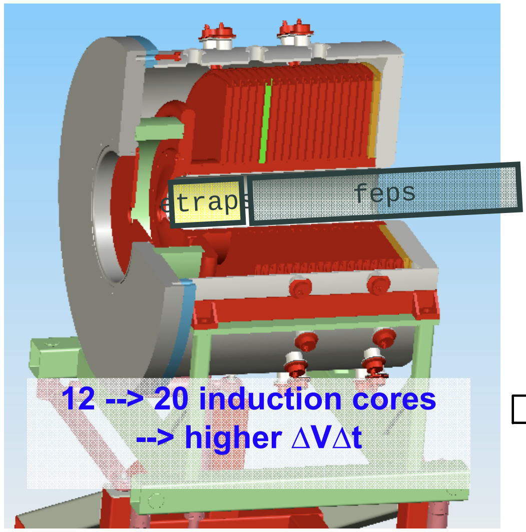
FY08 Q2: "Use beam steering dipoles to minimize aberrations. Design an improved NDCX-I drift compression section to make best use of the new bunching module to optimize planned initial NDCX-I target experiments."



	<X> [MM]	<X'> [MRAD]	<Y> [MM]	<Y'> [MRAD]
DIPOLES OFF	-5.81	2.24	-2.77	3.37
DIPOLES ON	-0.15	0.51	0.00	-0.31

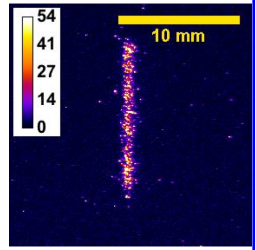


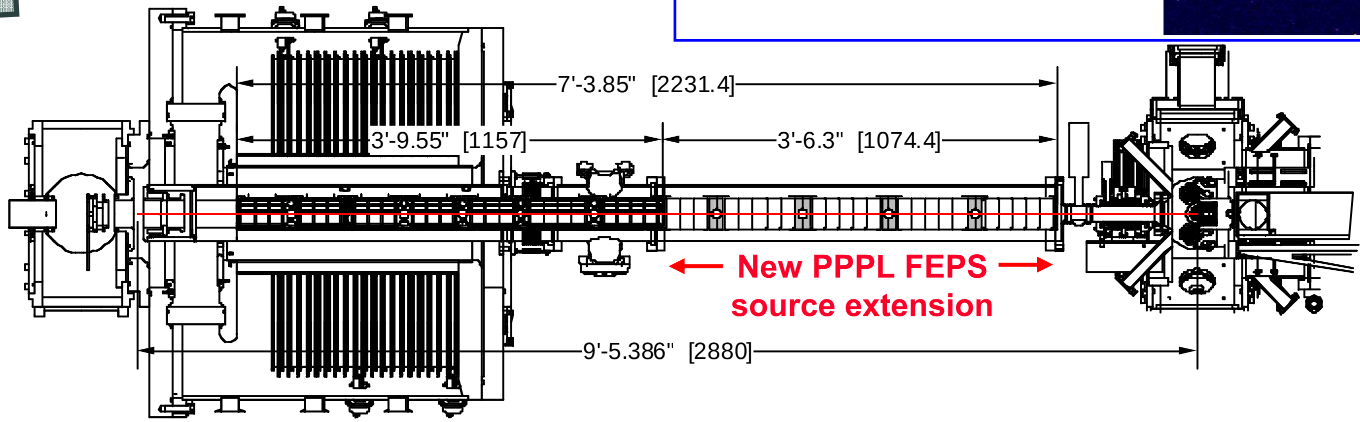
Compilation of data to infer solenoid offsets to correct β-tron motion within the lattice.



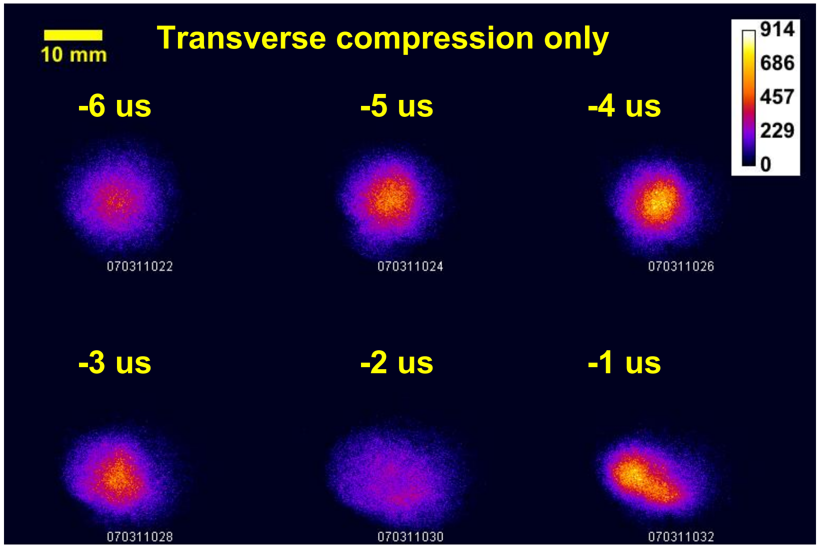
Simulations and analytic modeling:
Fix velocity excursion $\delta v/v_o$
Extend NDC length 1.44 m --> 2.88 m
Ferro-electric plasma source extension

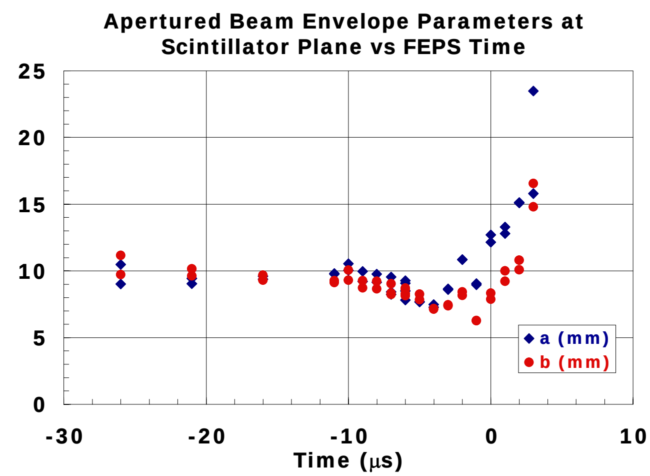
Hi -res energy analyzer
σ_E = 0.17 keV @ 300 keV.
($T_{\|} \leq$ 0.05 eV)

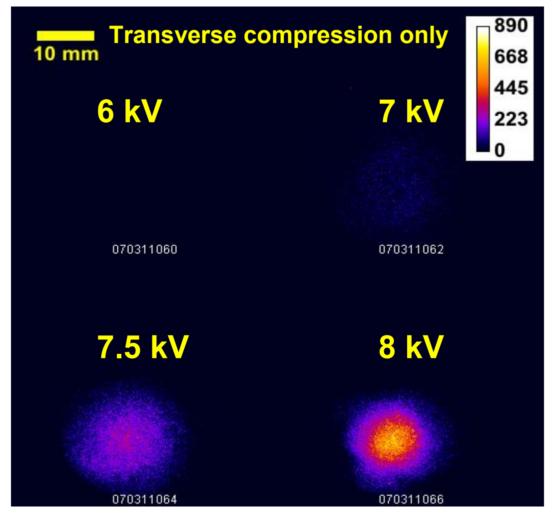




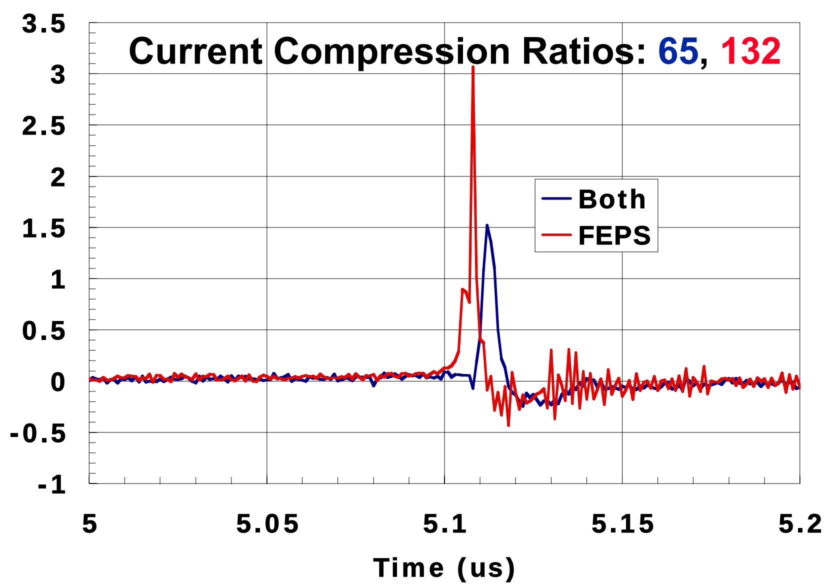
Ferroelectric Plasma Source Operating Parameters Optimized



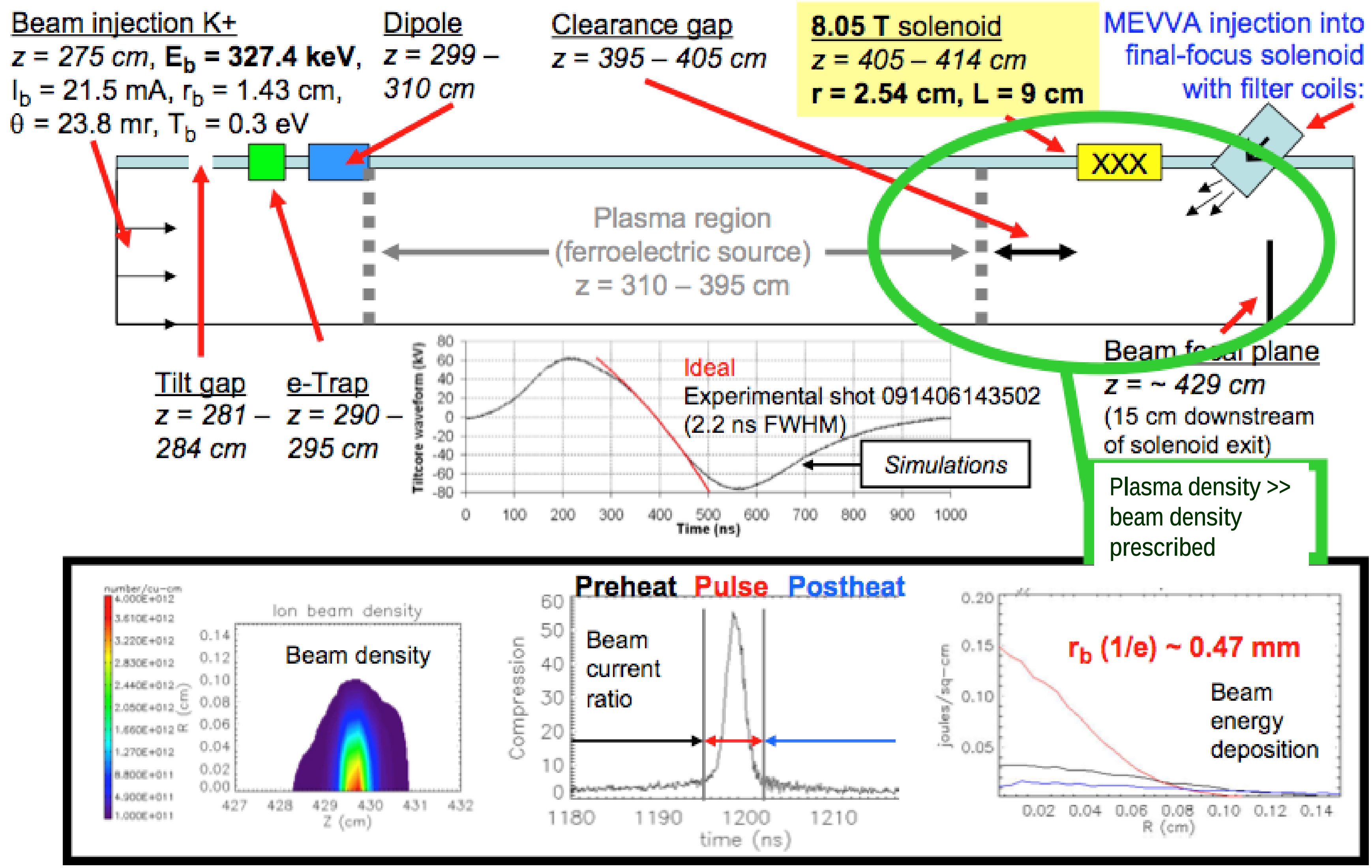




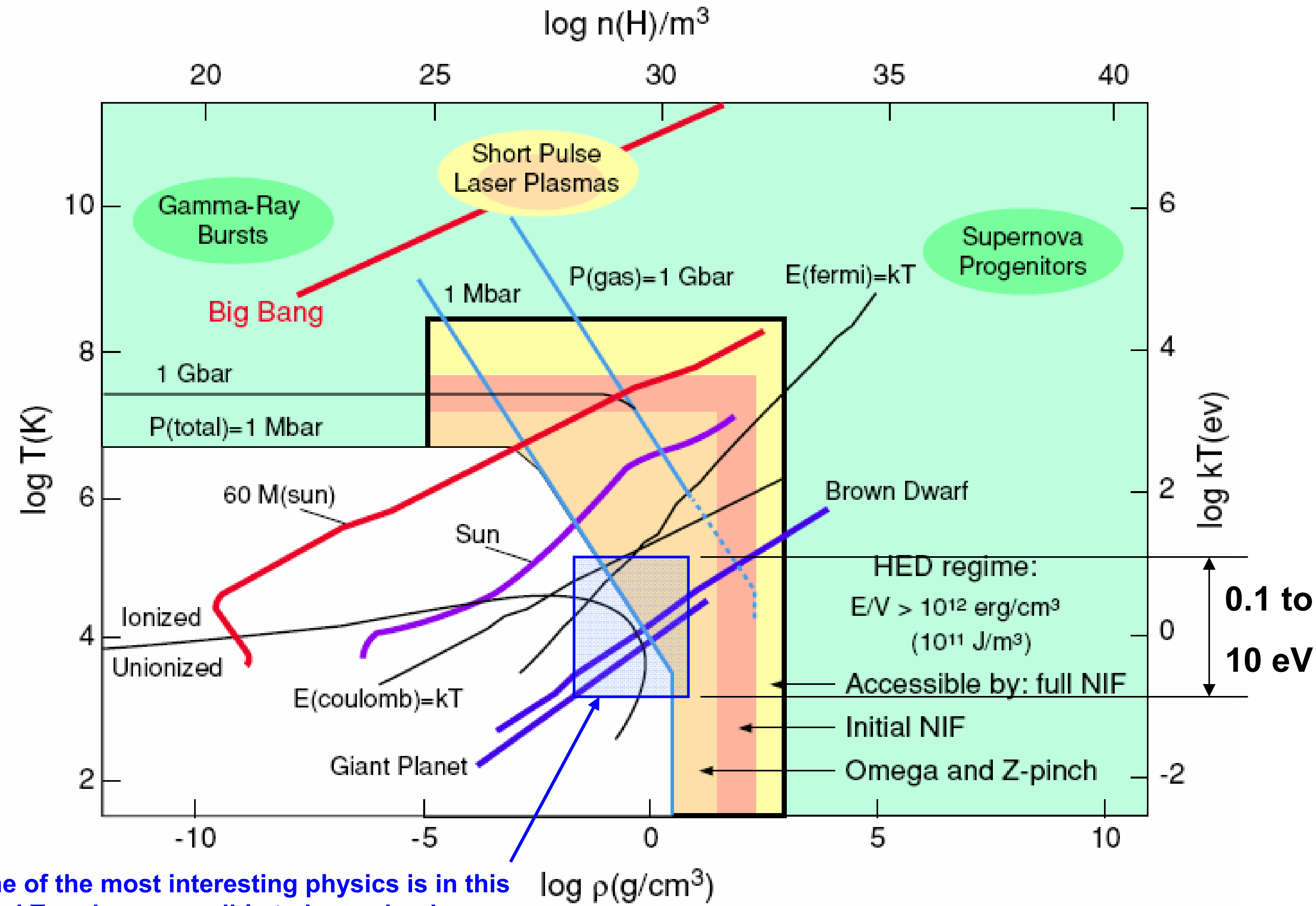
Better axial compression when plasma source is optimized.



Simulations (Adam Sefkow, PPPL) show smaller focal spots are possible with high field focusing solenoid to be installed in NDCX-I



Map of the High Energy Density Physics Universe



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

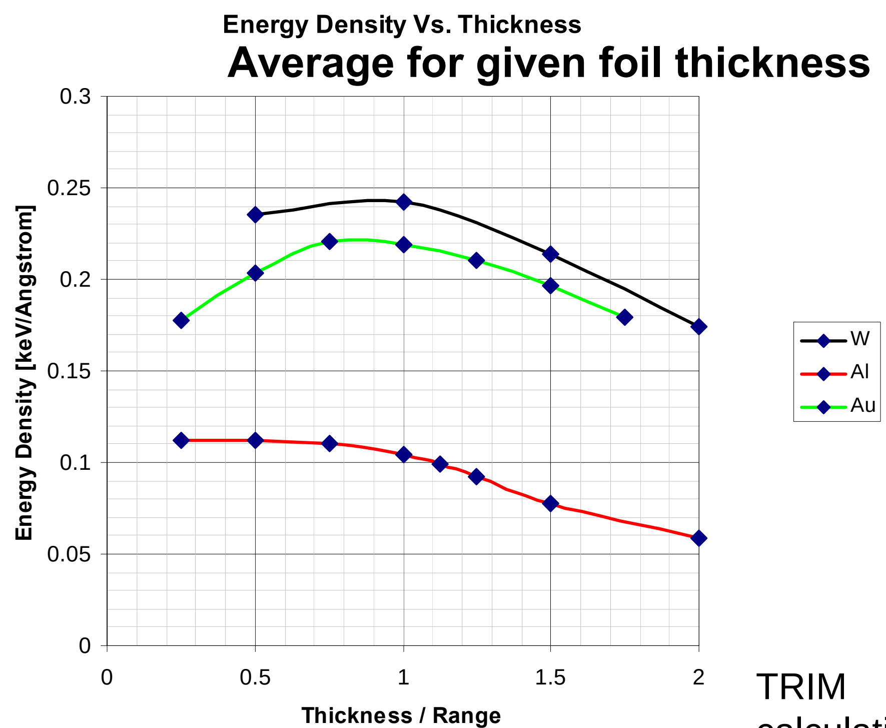
We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at T < 1 eV

	Target temp.	NDCX-I or HCX	NDCX-II
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	**Low (0-0.4 eV)**	√	
Measure target temperature using a beam compressed both radially and longitudinally	**Low**	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	
Positive - negative halogen ion plasma experiment	**>0.4 eV**	√	√
Two-phase liquid-vapor metal experiments	**0.5-1.0**	√	√
Critical point measurements	**>1.0**	**?**	√

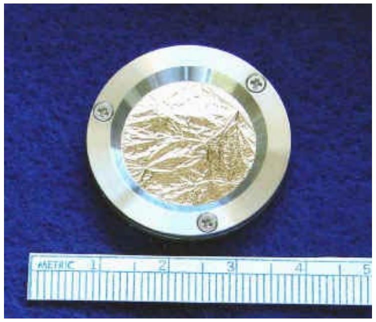
time

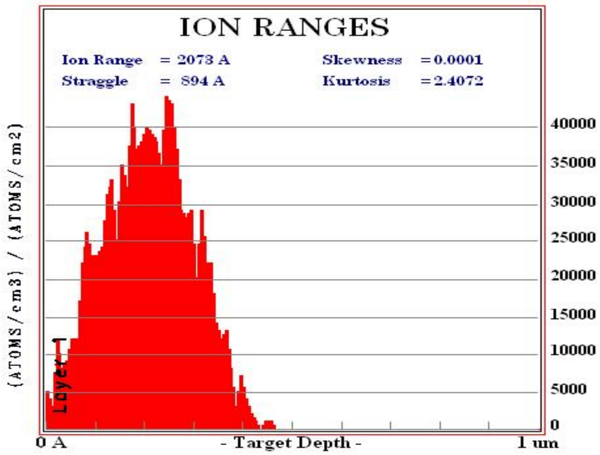
Initial target experiments on NDCX-1 will take place in next few months.

- **Initial set of targets is on hand**
- **Deposited layers on sapphire substrate**
  - **Al: 350 nm (1.2 x range)**
  - **Au: 150 nm (1.4 x range)**
  - **W: 150 nm (1.5 x range, for pyrometer calibration)**
- **Free-standing foils**
  - **350-nm Al**
  - **150 nm Au**

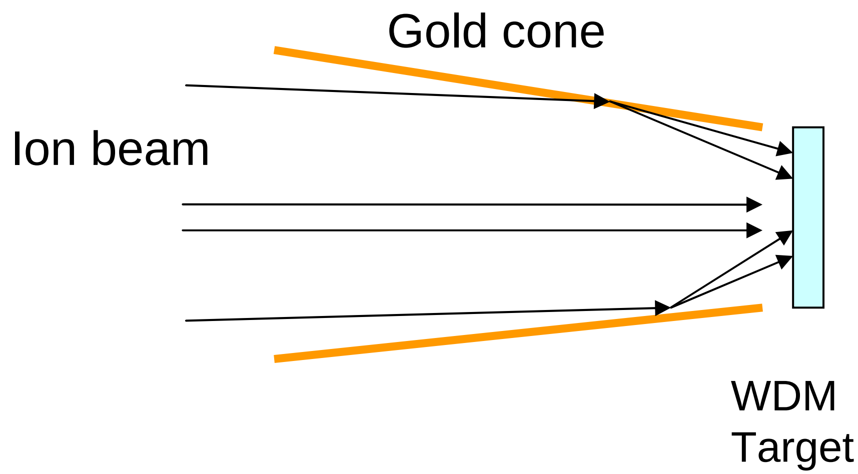


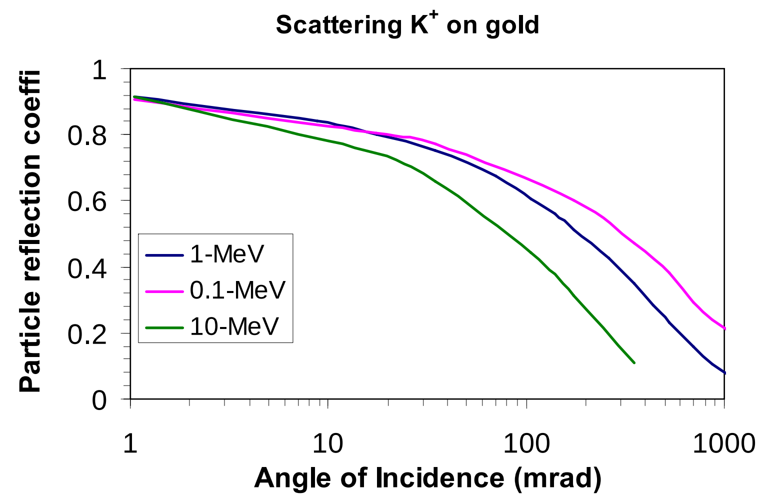
TRIM calculations





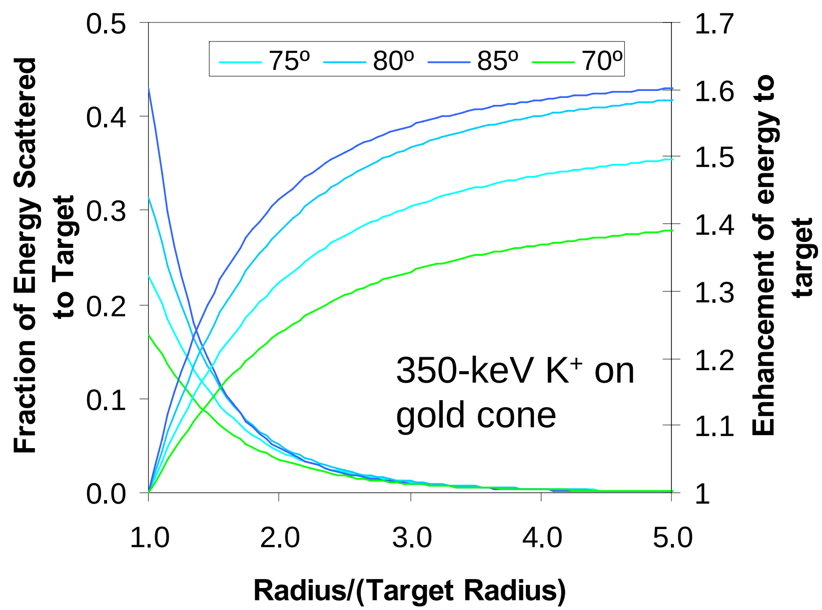
Concentration of ion beam using funnel (cone) to increase energy density on target.





TRIM calculations for a single reflection

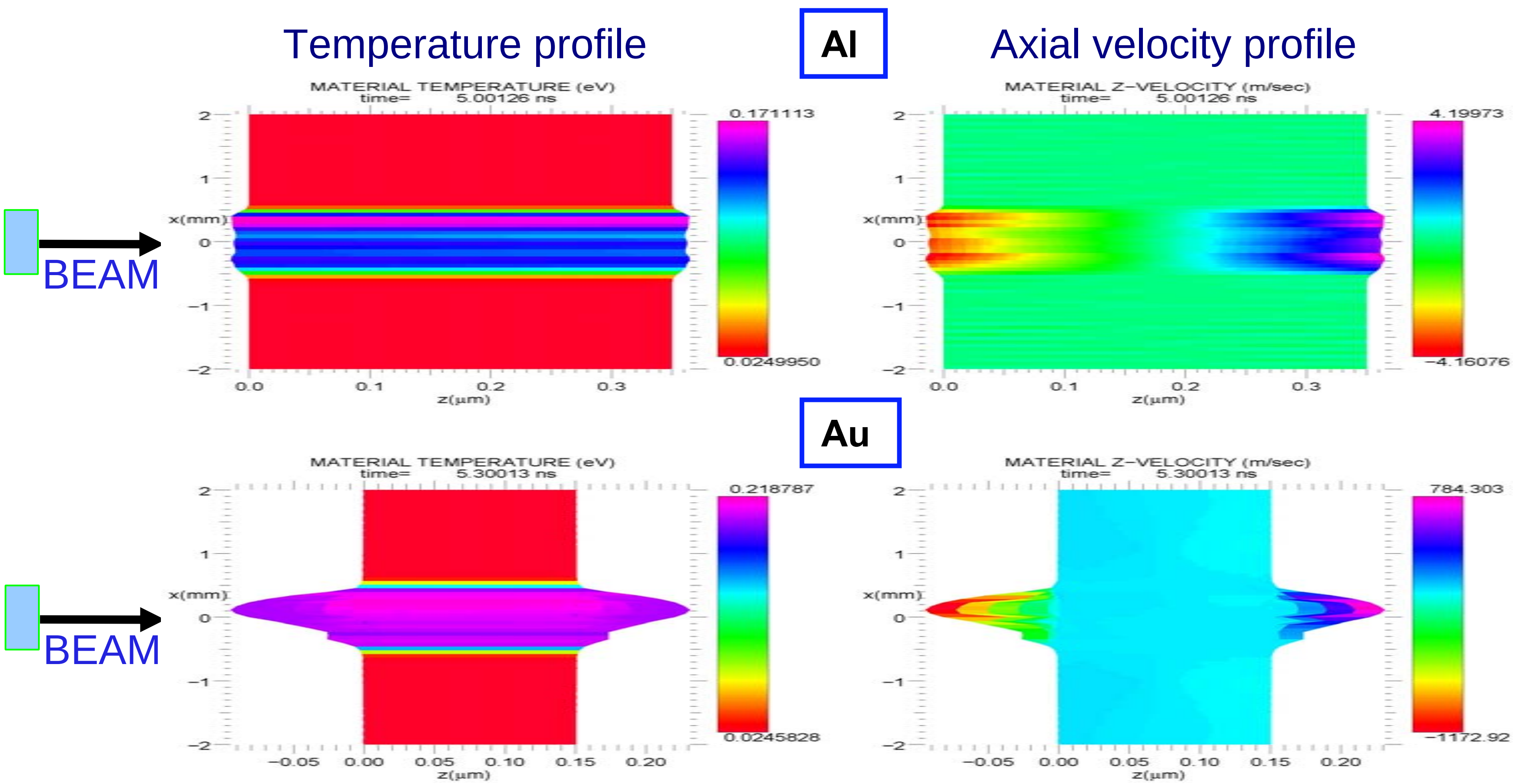
- **Cone acts as grazing incidence mirror. Beam particle reflection coefficient is >80% at 10 mrad incidence.**
- **Space charge neutralization of beam electric field, electron production.**
- **40% measured increase in intensity with 200 mrad (79°) gold cone.**
- **Improved geometry: e.g. parabolic concentrator takes advantage of specular reflection**



HYDRA simulations of the NDCX-1 experiment

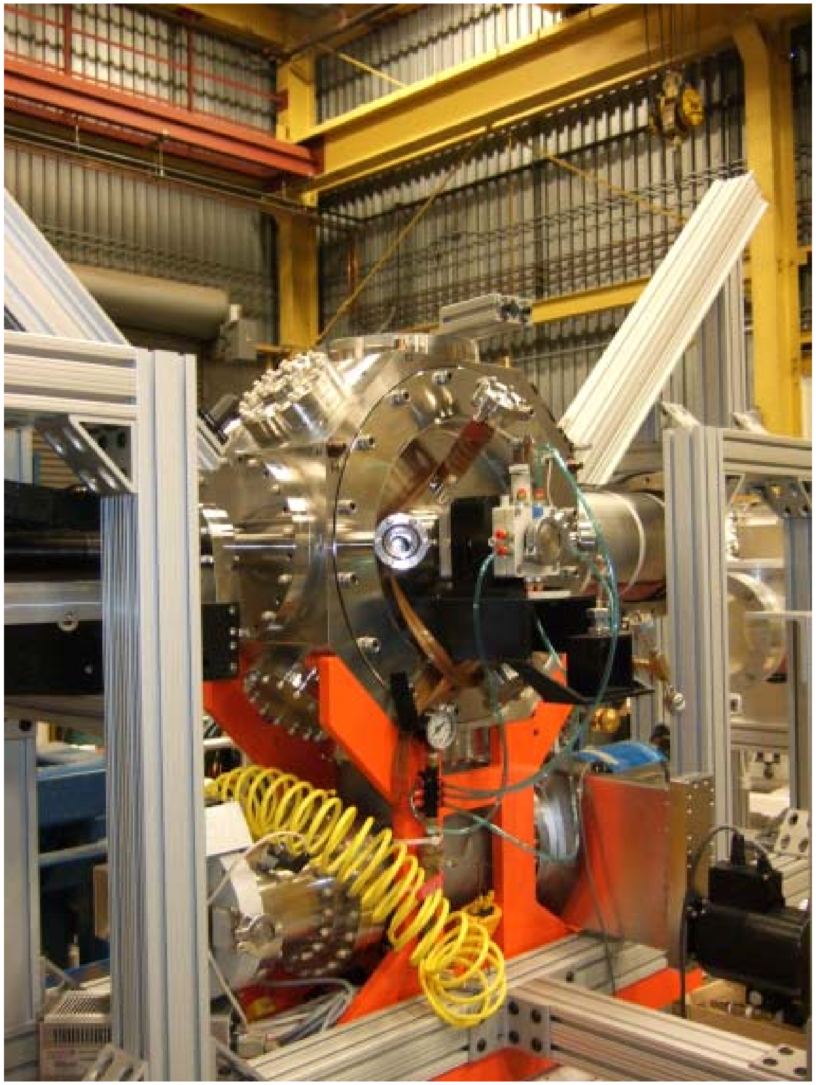
2A, 2 ns, 1 mm diameter, 350 keV K^+ beam will heat up a 350 nm solid aluminum target to ~ 0.16 eV, and a 150 nm solid gold target to ~ 0.2 eV. The simulation assumes a uniform transverse beam profile and EOS from QEOS for aluminum and SESAME tables for gold.

The (transverse) non-uniformity of the profiles is due to the small number of sampled beam rays.



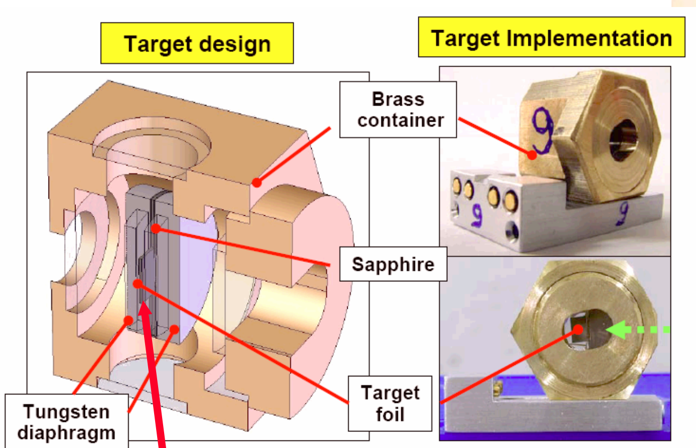
HIFS-VNL WDM Target Program Infrastructure

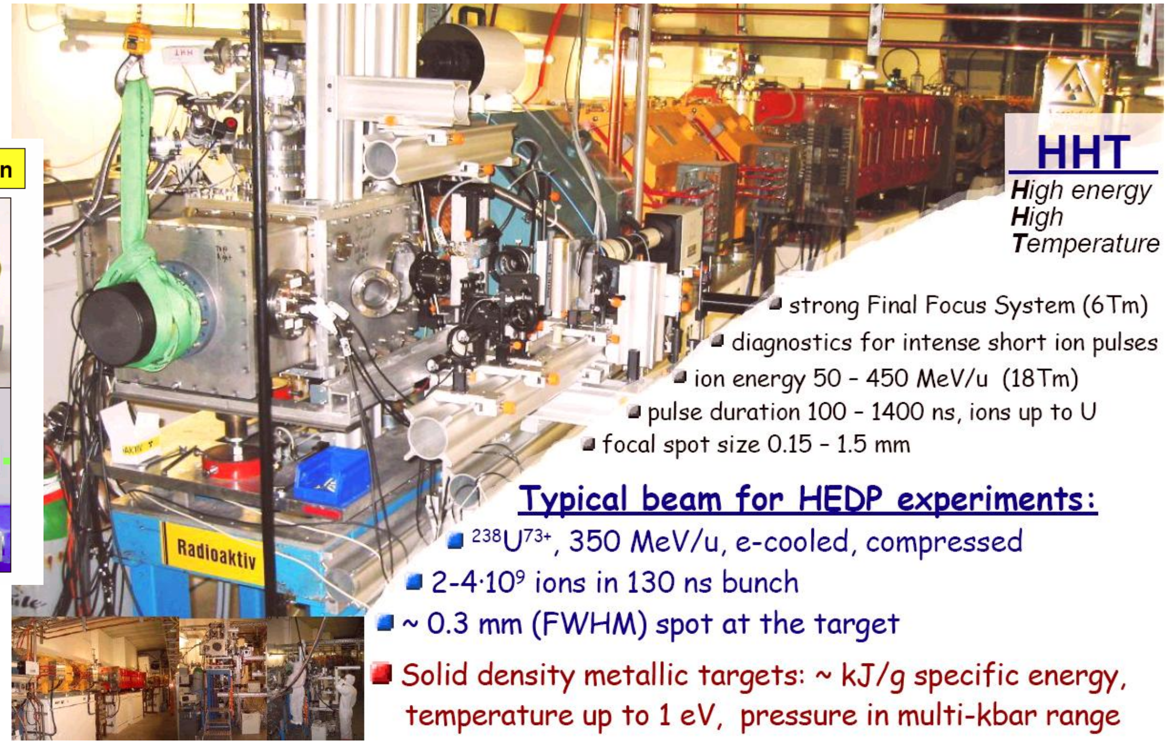
New target chamber

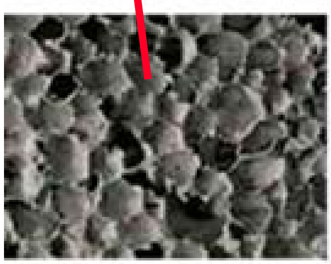


New optical diagnostics lab

Porous target experiment Dec. 2006 at GSI HHT target station (with GSI Plasma Physics group; IPCP Chernogolovka; ITEP Moscow).

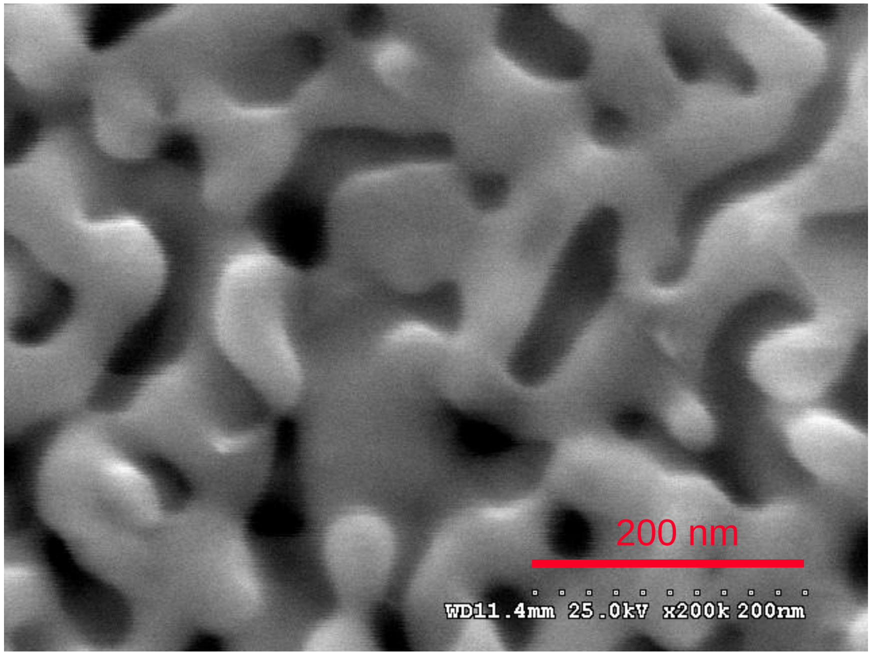


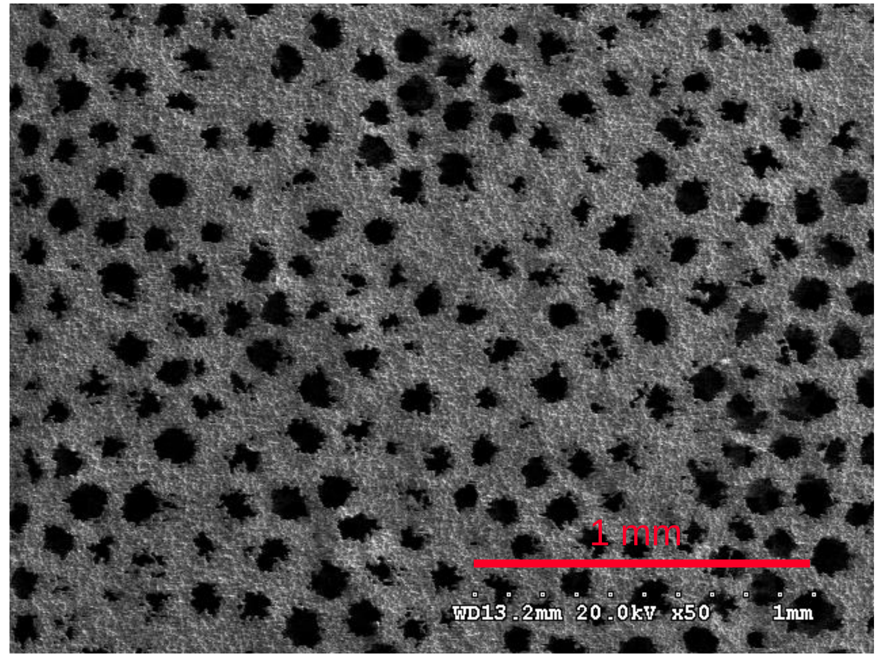




- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 50 nm), Mitsubishi (Cu, 50 micron). **(Frank Bieniosek, LBNL)**

Porous targets prepared for testing and comparison with solid targets in GSI beam.



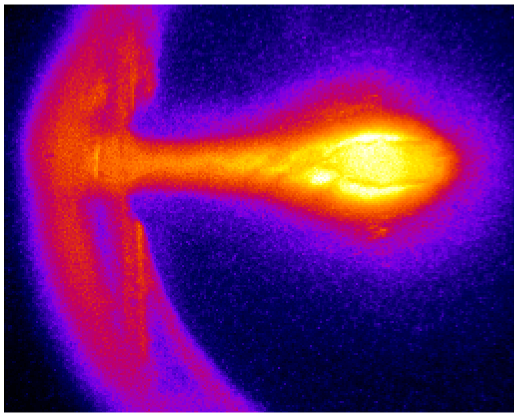


Porous gold target, 35% solid density, 50-nm pore size (Alex Hamza, LLNL)

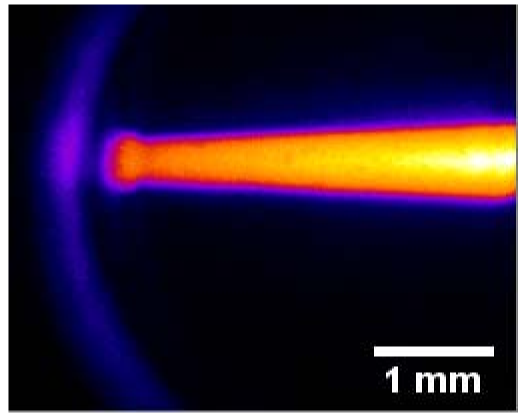
Porous copper target, ~25% solid density, 50-micron pore size (Mitsubishi)

Data analysis from GSI experiments is underway.

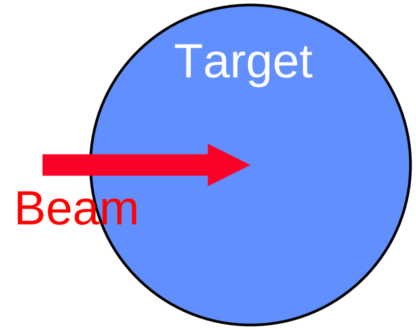
- **Gold targets heated to about 6000 K (T-boil = 2435 K). Solid and porous gold targets show similar behavior (temp, 1.4 km/s expansion).**



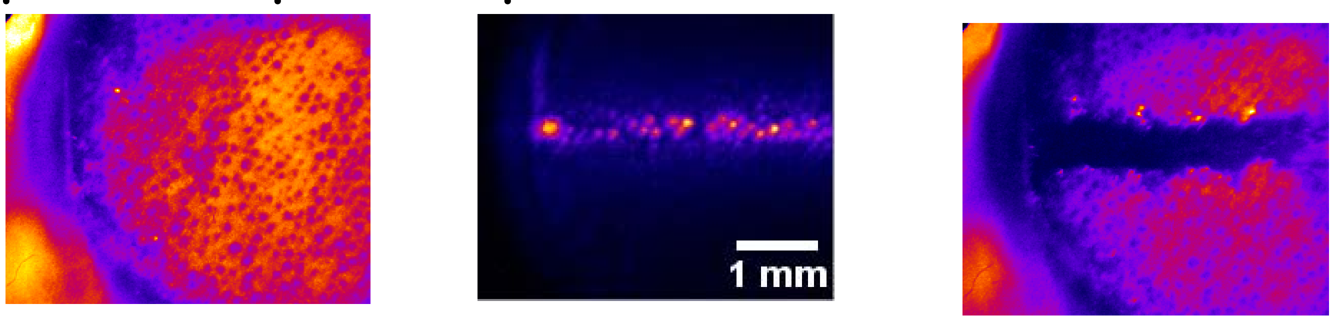
solid gold (note Bragg peak)



Porous gold



- **Copper targets heated to about 3000 K (T-boil = 3200 K). Porous copper broke up into droplets.**



Porous copper – before, during, after beam pulse

For a very modest investment of $5M, the NDCX-II accelerator can be assembled and offer high shot rates available for HEDLP science users:

- Precise control of beam energy deposition.
- 5 % uniformity over large sample sizes ~ mm^2.
- Pulses long enough to achieve local thermodynamic equilibrium.
- Maximum # of NDCX experiments ~100's of shots per day for user-available targets, ~ 500 more/day for beam/diagnostic tune-up.
- Benign environment (no intense x-rays or neutrons that require shielding for people or diagnostics).
- NDCX-I-II would be dedicated to HEDLP users-not encumbered by other programmatic priorities.
- Easily accessible site to visiting scientists and students.

The proposed five-year research plan for FY09-FY13 based on NDCX-I and NDCX-II is consistent with the February 2007 HIFS-VNL Program Advisory Committee recommendations.

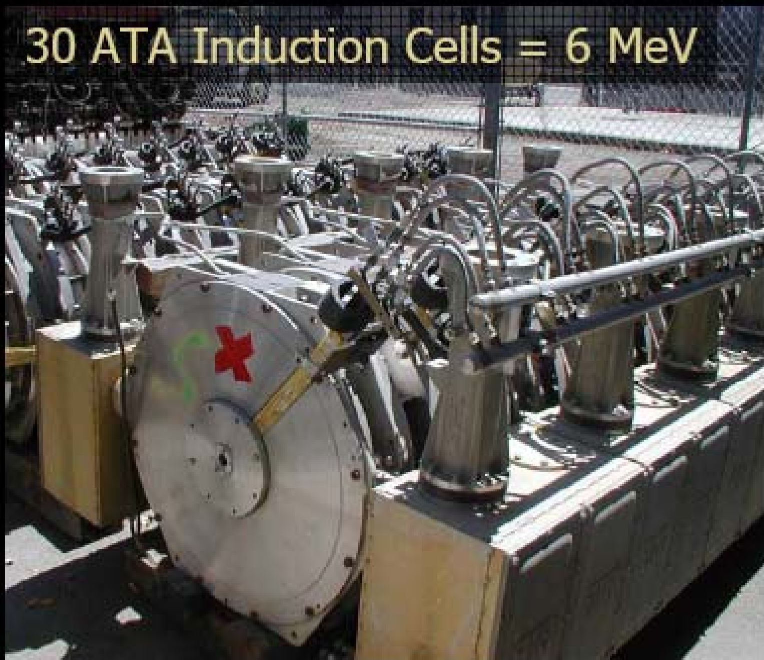
Quote from the 8th HIFS-VNL PAC 2-07:

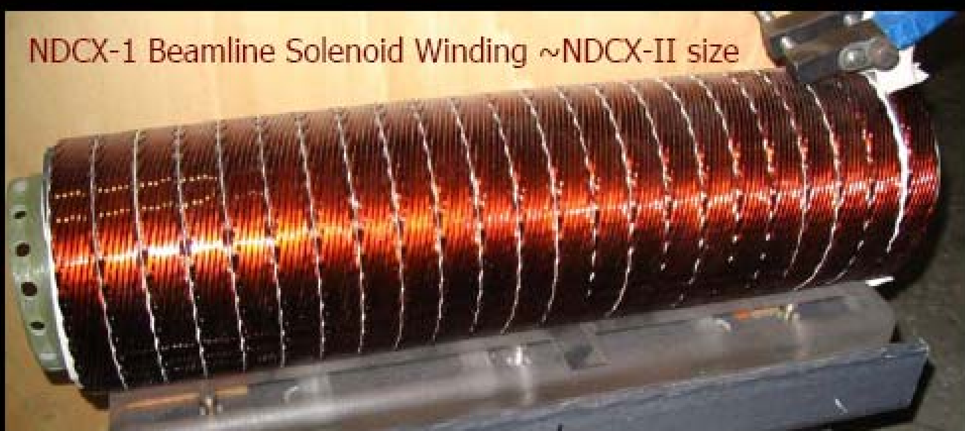
"The program should continue work on NDCX-I in order to enter the regime of WDM physics. This remains the highest priority activity. However to achieve regimes of greater interest, a plan should be developed and executed to construct NDCX-II per option 3 utilizing ATA components supplied at no cost from LLNL. The use of ATA provides a cost-effective approach to achieve >1eV temperatures in support of WDM physics experiments. This appears to be the least technically risky approach to extend the operating capabilities of the facilities. Moving towards NDCX-II may entail diverting resources and staff from other on-going highly productive research; however, a plan for the future is required to extend the capabilities of NDCX-I."

HIFS-VNL PAC Committee

- **Mike Campbell (Chair-GA)**
- **Richard Hawryluk, (PPPL)**
- **George Caporaso, (LLNL)**
- **Dieter Hoffmann, (GSI)**
- **Dave Hammer (Cornell)**
- **John Sheffield (ORNL)**
- **Bill Foster (FNAL)**
- **Mike Mauel (Columbia)**
- **Bruce Hammel (LLNL)**
- **Scott Parker (UCSD)**
- **Steve Obenschain (NRL)**
- **Keith Matzen (SNL)**
- **Bill Barletta (Cornell Univ.)**

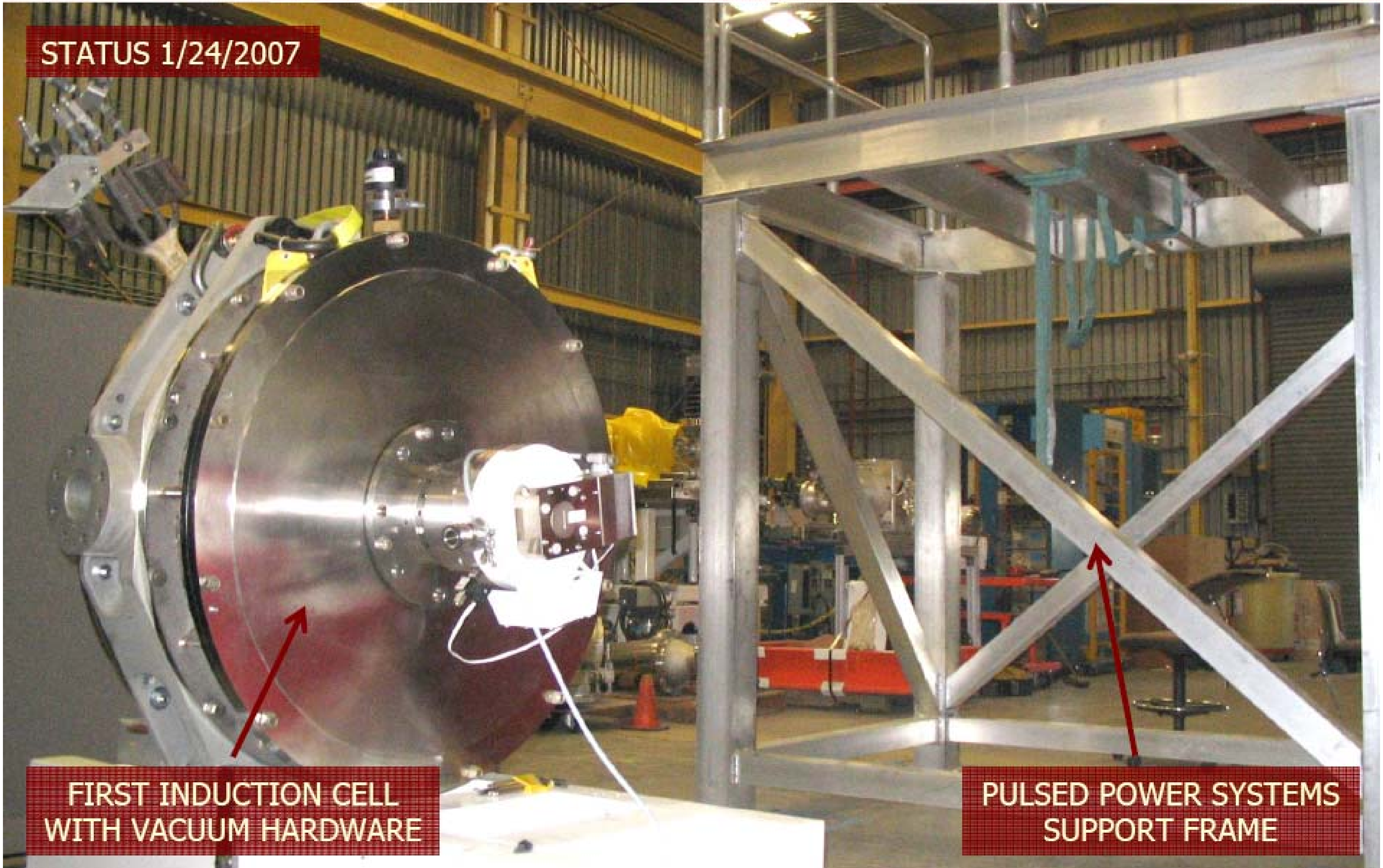
LLNL has donated 30 surplus ATA induction modules now located at LBNL- sufficient for NDCX-II





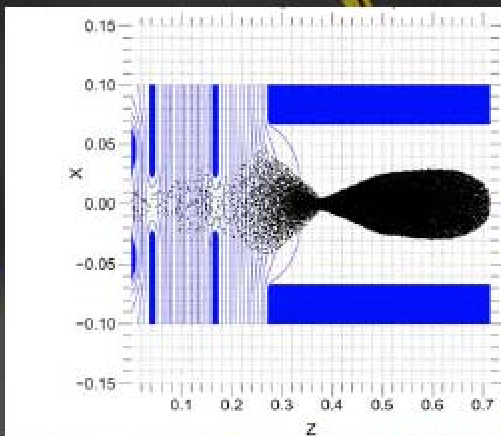
- We have shipped hardware for 30 induction cells to LBNL.
- We are building a high-field pulsed solenoid to fit into an ATA induction cell for tests.
- Hardware for two cell units has been refurbished for testing.

NDCX-2 TESTSTAND IS CURRENTLY UNDER CONSTRUCTION TO VERIFY CELL PERFORMANCE AND TO TEST HIGH FIELD SOLENOID

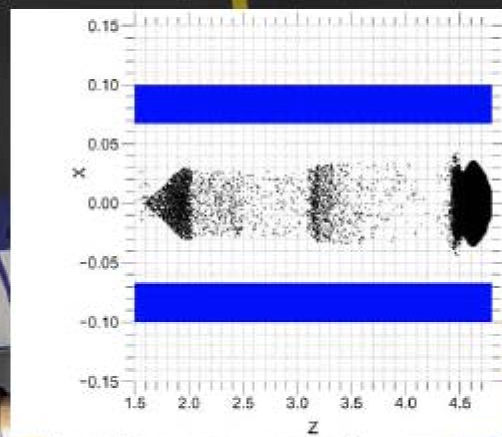


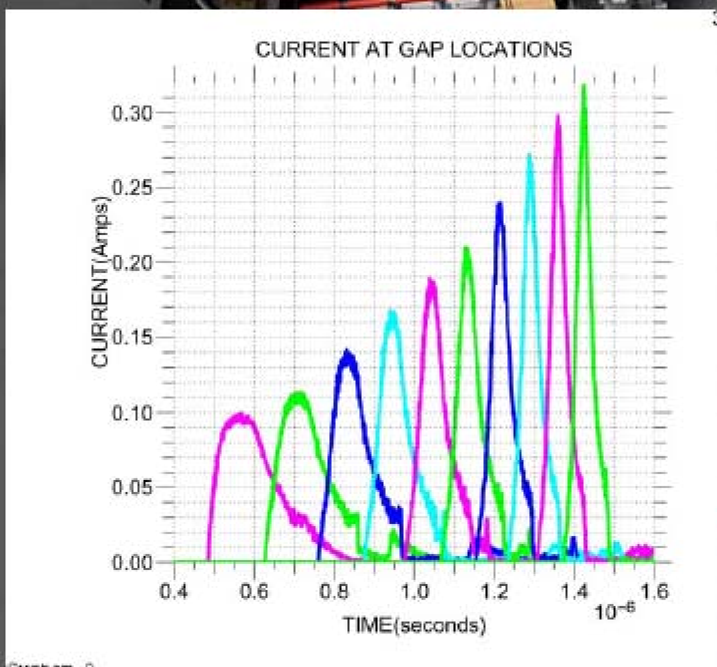
NDCX-2 INJECTOR AND BUNCHING SECTION

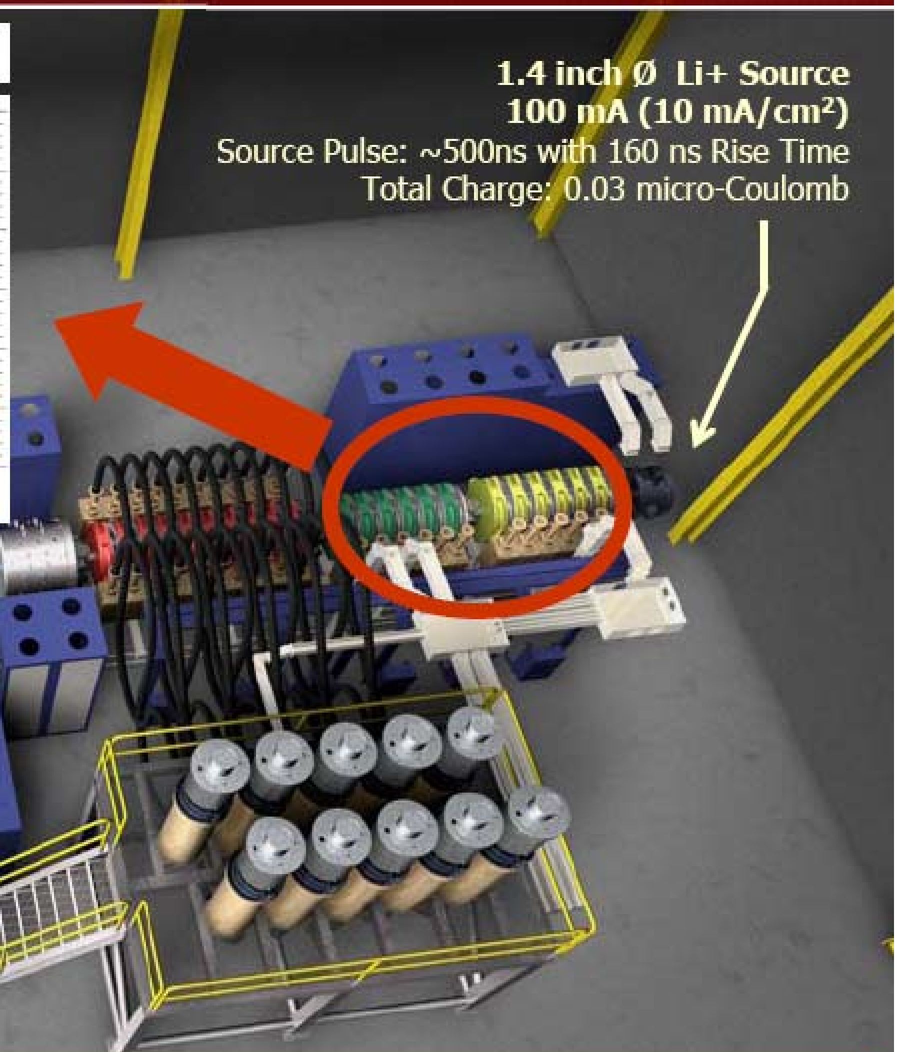
AT INJECTOR:



AFTER BUNCHING:







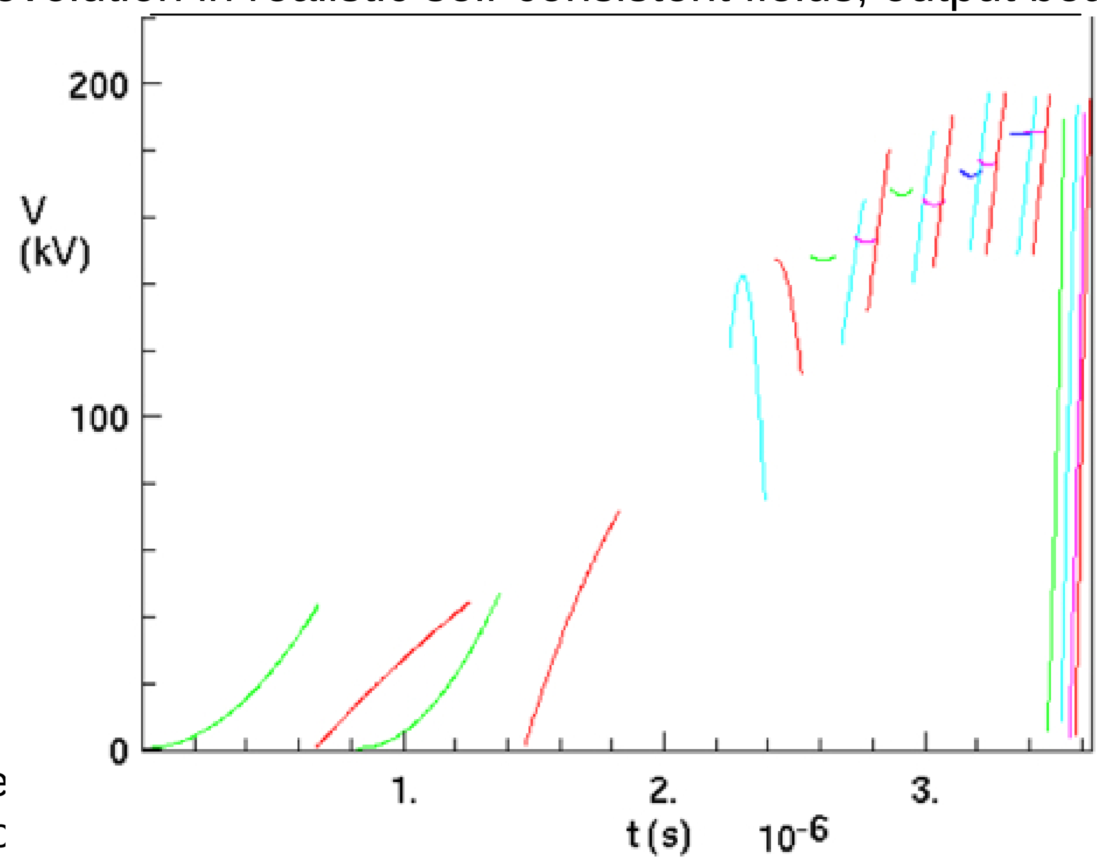
Bunching Section Compresses Beam for Further Transport in Short Pulse (70 ns) Induction Cells

NDCX-II will make effective use of assets (accelerating cells and Blumleins) from decommissioned ATA accelerator

- 1-D optimizing code develops waveforms; feeds into Warp
- The required waveforms are "simple" and can be generated via passive circuits
- We model the actual circuits, varying R, L, and C values within acceptable ranges
- Warp (r,z) runs capture beam evolution in realistic self-consistent fields; output beam to feed into target simulations

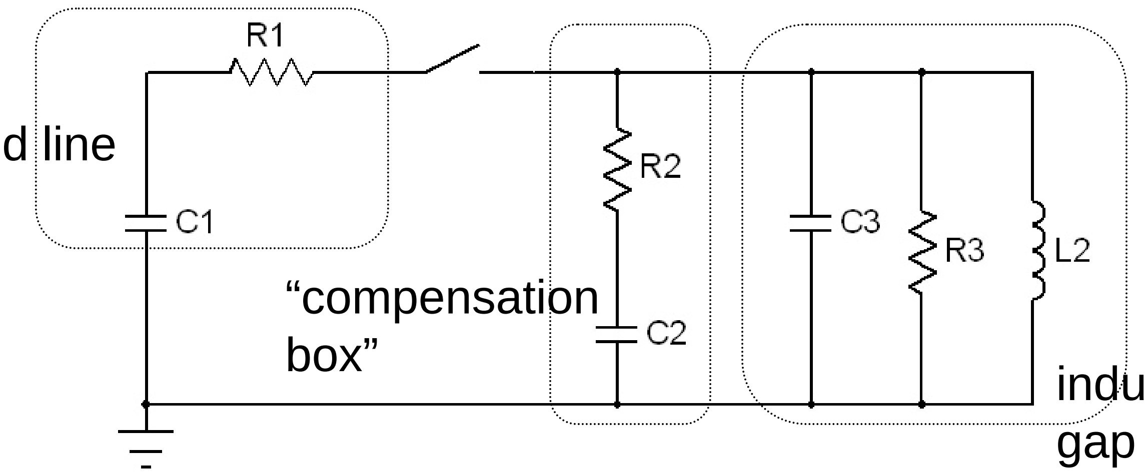
- Typical set of accelerating waveforms for Li beam ==> (yields 4.25 MeV, 30 nC)

- Need high longitudinal phase-space density; after neutralized drift compression, beam FWHM must be ~ 1 ns.



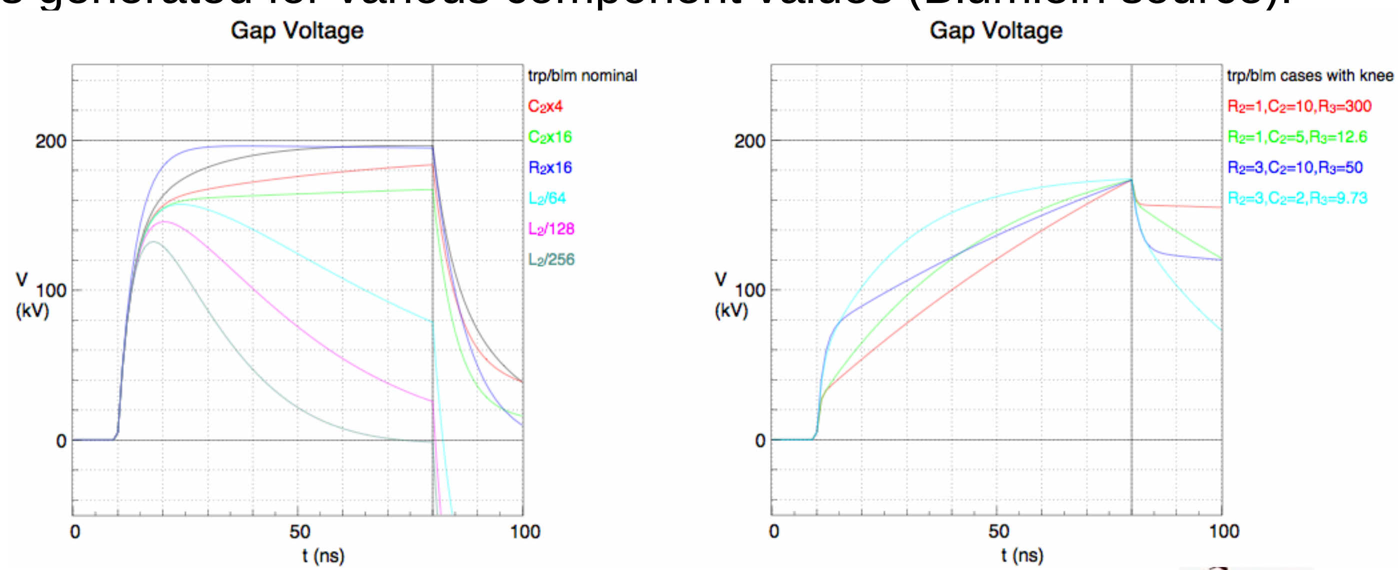
(For further information, contact Ale
Friedman, Bill Sharp, or Will Waldrc

This simple circuit can generate a wide variety of shapes; other equally simple circuits offer additional waveforms



(C3 can be increased, R3 or L2 decreased, by inserting additional components across the cell)

Waveforms generated for various component values (Blumlein source):

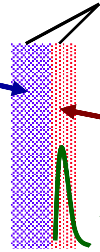


Double-pulse planar target interaction experiments should reveal *unique* heavy-ion direct-drive coupling physics

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

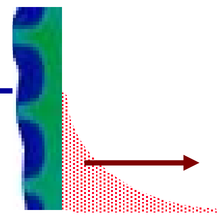
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

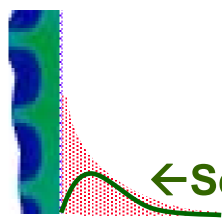
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops ***mostly within ablation blow-off*** (in 1-D approx.)!

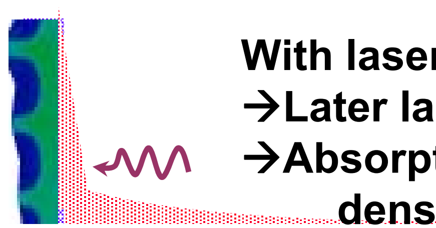


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

←Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through coronal plasma.
→Absorption in inverse bremsstrahlung layer lags behind dense shell trajectory

The HIFS-VNL addresses the High Energy Density Physics (HEDP) underpinning heavy ion fusion.

The program concentrates on ion beam experiments, theory and simulations to address a top-level scientific question central to HEDP and fusion (Topical Question T9, p.50 of Priorities Report):

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

FESAC 10 year goal for heavy ion research (p.54 of Priorities Report): Understand the beam and plasma target science for accelerator-driven high energy density physics that exploits the unique deposition properties of intense ion beams.

Relevant science thrust areas (p.53 of Priorities Report):

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

→Advances in these areas with current funding enable first heavy ion beam warm dense matter experiments to begin on NDCX-I in FY08. In the full-use budget case, heavy ion planar hydrodynamics experiments on NDCX-II could begin in FY11.

PPPL VNL Milestones for FY 2009 and FY 2010

Theory and Modeling Milestones at Guidance Funding Level

- **Determine the feasibility of inferring the equation of state in the warm dense matter regime by diagnosing the expanding plasma front and comparing with numerical simulations and theoretical models (December, 2008).**
- **Develop advanced algorithms and numerical capabilities for simulating collective instabilities in high intensity charged particle beams undergoing strong longitudinal and transverse compression (March, 2009).**
- **Develop reduced self-consistent analytical and numerical models to include ionization and finite electron temperature effects, and determine their influence on ion pulse charge neutralization and focusing in next-generation neutralized drift compression experiments; determine the optimum system parameters for effective transport and focusing of the ion beam pulse (March, 2009).**
- **Complete assessment of influence of transverse and longitudinal beam compression on the dynamics of collective two-stream interactions of an intense ion beam propagating through neutralizing background plasma (September, 2009).**

PPPL VNL Milestones for FY 2009 and FY 2010

Theory and Modeling Milestones at Guidance Funding Level

- **Develop and apply reduced self-consistent analytical and numerical models for describing plasma flows in strong solenoidal magnetic field configurations (December, 2009).**

- **Perform initial assessment of the influence of transverse gradients and profile shapes on intense ion beam-plasma collective instabilities (April, 2010).**

- **Develop self-consistent nonlinear delta-f perturbative particle simulation capabilities for describing intense beam compression dynamics and stability properties in neutralizing background plasmas (August, 2010).**

- **Investigate numerically and analytically the possible nonlinear effects of beam-plasma instabilities on beam current neutralization (September, 2010).**

PPPL VNL Milestones for FY 2009 and FY 2010

Theory and Modeling Milestones at Guidance Funding Level*

- Complete large-scale particle simulations of electron-ion two-stream interactions in bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (September, 2009).

- Develop techniques for inferring the equation of state in the warm dense matter regime by diagnosing the expanding plasma front and comparing with numerical simulations and theoretical models (September, 2010).

* Blue denotes Fusion Execution Agreement (FEA) milestones.

PPPL VNL Milestones for FY 2009 and FY 2010

Experimental Milestones at Guidance Funding Level

- **Proceed with detailed planning of warm dense matter ion-ion plasma experiments. If facilities and diagnostics are available in time, begin initial experiments (September 2009).**

- **Begin characterization of properties of ion - ion plasmas in warm dense matter regime (September 2010).**

PPPL VNL Milestones for FY 2009 and FY 2010

Experimental Milestones at Guidance Funding Level*

- Evaluate candidate plasma sources for producing spatially localized, high density, plasma near the compressed-beam focal plane. Begin development and fabrication of the preferred options (March, 2009).

- Complete installation, testing, and characterization of high-density-producing plasma source on NDCX or its upgrades (September, 2010).

* Blue denotes Fusion Execution Agreement (FEA) milestones.

PPPL VNL Milestones for FY 2009 and FY 2010

Additional Milestones at Incremental Funding Level

- **Develop atomic physics suite for high energy density physics experimental applications, including the calculation of charge-exchange, stripping and ionization cross-sections and equilibrium charge for intense beam propagation in gas, plasma and solid-state media (September, 2009).**

- **Complete assembly of advanced plasma source test stand and initial tests of plasma source configurations that can provide higher density plasmas in NDCX-II (March, 2010).**

PPPL VNL Milestones for FY 2009 and FY 2010

Additional Milestones at Incremental Funding Level

- **If funding has been provided to re-commission the 100 kV test stand at LBNL, begin experiments to better characterize the ion temperatures of positive and negative ions extracted from ion-ion halogen plasmas as compared to positive ions extracted from conventional electron-ion plasmas, and compare electron currents extracted from electron-ion plasmas to those from ion-ion plasmas (September, 2009).**

- **Assuming that the ion-ion plasma experiments have been initiated (see #3 of F.3 above), continue experiments on the 100 kV test stand at LBNL to develop an understanding of the ion-ion plasma state and its possible applications. Explore whether or not the magnetic filter field used in earlier experiments is necessary for the existence of a sustained-duration ion-ion plasma state, and how it affects beam extraction characteristics (September 2010).**

PPPL VNL Milestones for FY 2009 and FY 2010

Additional Milestones at Incremental Funding Level

- **Identify numerically the class of self-consistent periodic kinetic ‘equilibria’ for intense beam propagation in alternating-gradient focusing systems, and extend the nonlinear perturbative particle simulation method to intense beam propagation in periodic focusing systems with self-consistent, periodic kinetic equilibria; compare with the results of Hamiltonian averaging techniques for periodic focusing systems (September, 2010).**

The HIFS VNL continues to have a strong publication record

(To be updated)…

In 2006 and 2007 (to date):
26 Invited talks at major meetings
56 Refereed papers (including submitted, accepted, and published)
12 Un-refereed conference papers, publications, and reports
48 Abstracts (without associated papers)

This list includes:
21 presentations at APS DPP, Philadelphia, PA 2006
6 presentations at HEDP Workshop, Hirschegg, Austria 2007
21 submitted to Particle Accelerator Conference, Albuquerque, 2007, six are invited talks.

3 Physical Review Letters
9 Physical Review Special Topics Accelerators and Beams
30 Nuclear Instruments and Methods in Physics Research
2 Physics of Plasmas
1 PhD dissertation; 1 Masters Report

Heavy Ion Beam Research

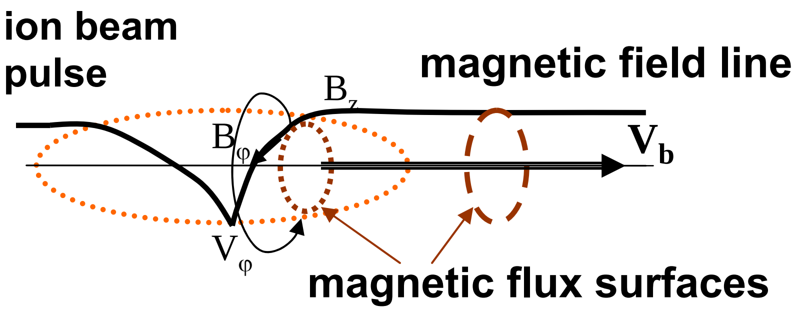
PPPL Research Productivity

2006-2007 has been a period of high research productivity in the nonlinear beam dynamics and nonneutral plasma area.

- **Forty-two journal publications, including thirty-one refereed papers (published or submitted) and eleven published conference proceedings.**
- **Eleven papers presented at the 2007 Particle Accelerator Conference held in Albuquerque, New Mexico (June, 2007).**
- **Eleven invited papers presented during 2005-2007.**
- **Two national awards received in 2005, including *Presidential Early Career Award for Scientists and Engineers* (Qin) and *2005 Particle Accelerator Science and Technology Award* (Davidson).**

Controlling charge and current neutralization of an intense ion beam in a plasma by application of a small magnetic field*

Schematic of self-magnetic field and magnetic dynamo effect.



Application of a solenoidal magnetic field leads to three unexpected effects:

1. *The dynamo effect.* The electron rotation generates an enhanced self-magnetic field.
2. *The generation of a large radial electric field.* Because the **v×B** force should be balanced by a radial electric field, the electron rotation produces a much larger self-electric field.
3. *The joint system consisting of the ion beam pulse and the plasma acts as a paramagnetic medium*, i.e., the solenoidal magnetic field is enhanced inside of the ion beam pulse.

Optimum value of B_z: The radial force is nearly zero when $(\omega_{ce} / \beta_b \omega_{pe})^2 = 1.5$ for the main part of the beam pulse. This value can be optimal for beam transport over long distances to avoid the pinching effect.

* I. Kaganovich et al., Phys. Rev Lett., 235002 (2007).

Selected scientific questions that can be pursued in NDCX–I at target temperatures below 1 eV (pressures below one megabar)

1. **Quartz transient darkening emission and absorption experiment.**

→*What is the physical mechanism for changes in the optical properties of glass, as matter approaches the WDM regime?*

2. **Measure target temperature, using a beam compressed both radially and longitudinally.**

→*How can we measure the thermodynamic properties of matter, heated by ion beams compressed in space and time?*

3. **Thin target dE/dx, energy distribution, charge state, and scattering in a heated target.**

→*Can an ion beam (after it heats and exits a target) be used as a unique diagnostic tool for WDM exploration?*

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

→*Can unique states of matter be created with nearly equal quantities of positive and negative ions (and few electrons)?*

5. **Two-phase liquid-vapor metal experiments (e.g. kT > 0.5 - 1 eV for Sn)**

→*In the two-phase regime, what is the best way to make predictive simulations of the dynamics including the effects of droplets?*

→**See 2006** ***and 2008 WDM workshops/schools (Barnard-add 08 website)***
(**http://hifweb.lbl.gov/public/AcceleratorWDM/TableOfContents.html**)

What science questions will these experiments address?

1. Transient darkening emission and absorption experiments:
What is the physical mechanism for changes in the optical properties of glass, as matter approaches the WDM regime? Can these optical changes be induced from excitation by ion beams? What information is obtained from the emission? How does the darkening differ in crystalline and amorphous materials (e.g. glass vs. quartz)? Can the darkening be used for fast switching of high power light beams?

2. Measure target temperature using a beam compressed both radially and longitudinally:
How can we measure the thermodynamic properties of matter, heated by ion beams compressed in space and time? How uniform must the target temperature be for useful equation of state measurements? What are the differences between foams and solids at low T? How can we go beyond specific heat, and expansion measurements to obtain liquid-vapor phase diagram, evaporation rates and EOS?

3. Thin target dE/dx, energy distribution, charge state, and scattering in a heated target:
Can an ion beam (*after* it heats and exits a target) be used as a unique diagnostic tool for WDM exploration? What are the differences in charge state and energy loss evolution between an ion beam propagating through a foam and a beam propagating through a solid of the same column density as a solid? What does this tell us about the lifetime of the excitation states of the projectile ions? Ion dE/dx is interesting partly because our ions have precisely determined E.

Questions -- continued

4. Positive - negative halogen experiment: Can unique states of matter be created with nearly equal quantities of positive and negative ions (and few electrons)? What are the physical properties of such a state? Is there a phase transition from low conductivity to a semiconductor? (Negative ions are like "donors" and positive ions like "acceptor" impurities.) Is there an emission (annihilation) line signature of this plasma? What are the photoconduction and junction non-linearities for these plasmas? Can these plasmas handle very large plasma densities?

5. Two-phase liquid-vapor metal experiments:
What is the temperature-density boundary between the liquid, liquid-vapor, and vapor regime for all of the elements? What is the equation of state (pressure as a function of temperature and density)? In the two-phase regime, what is the best way to make predictive simulations of the dynamics including the effects of droplets? (Are theory models for evaporation kinetics correct?) What determines the spectra of droplet sizes?

6. Critical point measurements:
What is the temperature (for each element) above which, there is no distinction between liquid and vapor, and what is the density at this point (i.e. what is the critical point)? What are the material properties (pressure, thermal and electrical conductivity, opacity, viscosity, etc) at this point? As material cools from above the critical point, do droplets form? What happens when ionization occurs at critical point for some materials?

HIF research connects with the broader fields of particle beam physics & plasma physics

- **Electron-cloud studies** are of wide interest; merger of HIF code WARP and HEP code POSINST (M. Furman) enhances both groups' capabilities: **LHC, ILC, Cornell CESR**
- **Combination of Particle-in-Cell and Adaptive Mesh Refinement** developed by HIF-VNL gives major efficiency gains; of interest across plasma physics and beam physics (developed in collaboration with Phil Colella's group)
- **New Vlasov simulation methods with moving and adaptive grids** developed in a collaboration of HIF-VNL + U. Strasbourg also promise broad utility
- **WARP code** is used for: **Non-neutral traps at PPPL and LBNL/UCB; VENUS ion source (for rare isotopes); U. Maryland (UM Electron Ring), and education;**
- **US-Japan HIF program** thriving; inc. collab's. on bunching, simulation
- **Collaborations with GSI** on accelerators and HEDP being strengthened

INVITED TALKS by HIF researchers at non-plasma conf's include:
- 6 at upcoming 2007 APS/IEEE Particle Accelerator Conference
- 1 at Spring APS meeting (Florida)
- 4 at recent "ECloud04" international electron-cloud conference

A new 5-year Memorandum of Agreement was signed 10/26/05 for the Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL)

a) Background: The Laboratories desire and are committed to collaborate as a Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL) in the conduct of heavy-ion-driven high energy density physics and fusion science, and to promote more rapid progress in these areas through technical management integration of the Laboratories' scientific staff, equipment, and experimental facilities.

The Regents of the University of California,
Lawrence Berkeley National Laboratory

Steven Chu, Director — Date: 22 Sept 2005
Lawrence Berkeley National Laboratory

William A. Barletta, Director — Date: 22 Sept 2005
Accelerator and Fusion Research Division

The Regents of the University of California,
Lawrence Livermore National Laboratory

Michael R. Anastasio, Director — Date: October 17, 2005
Lawrence Livermore National Laboratory

William H. Goldstein — Date: October 7, 2005
Physics and Advanced Technology Directorate

The Trustees of Princeton University,
Princeton Plasma Physics Laboratory

Robert J. Goldston, Director — Date: October 26, 2005
Princeton Plasma Physics Laboratory

Research at Voss Scientific in the areas of Warm Dense Matter and Heavy Ion Fusion

D. R. Welch, D. V. Rose, T. C. Genoni, and C. Thoma

Voss Scientific, Albuquerque, NM 87108, USA

March 5, 2008

Work supported by the Virtual National Laboratory for Heavy Ion HEDP through Princeton Plasma Physics Laboratory and Lawrence Berkeley National Laboratory

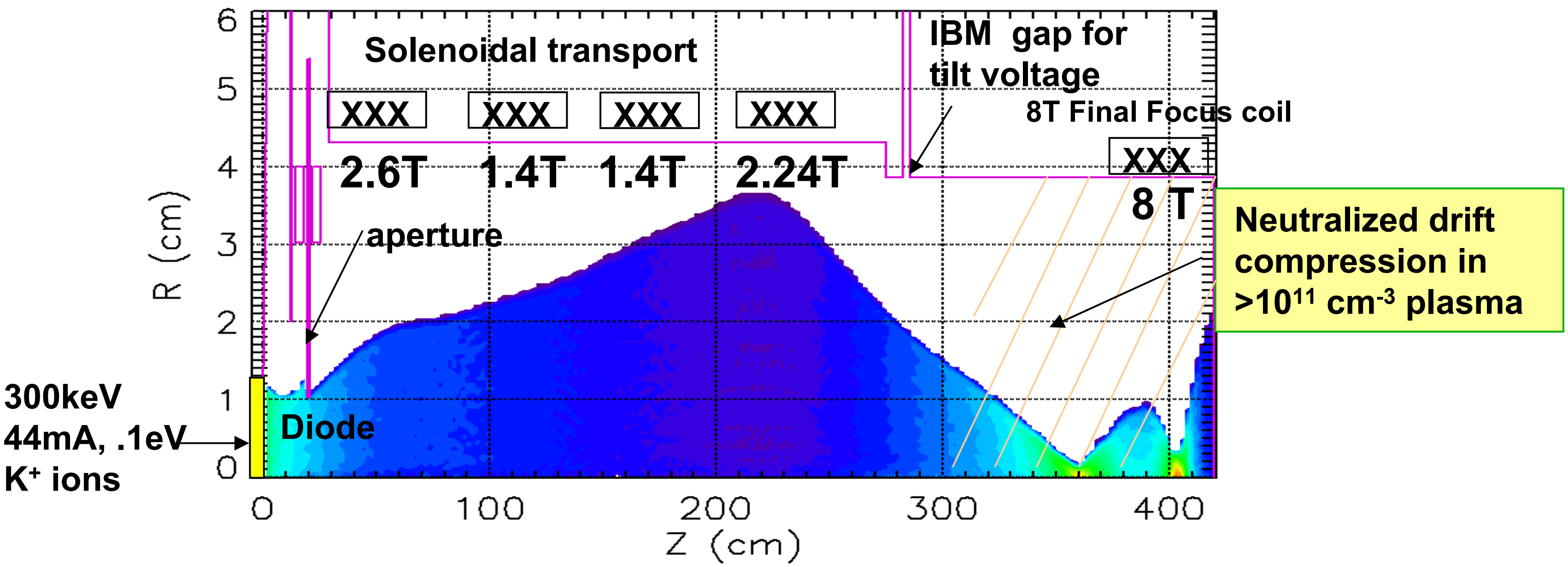
#*e-mail: dale.welch@vosssci.com*

Goal of supporting Voss Scientific, Inc. research is to help establish heavy ion beams as a reliable cost-effective source for Warm Dense Matter Studies

- Continue development of plasma physics code LSP
  - Code validation/verification carried out in concert with experimental measurements
- Investigate constraints of ion beam source temperature, diode voltage stability, longitudinal acceleration cooling
- Assess beam stabilities in magnetic section
- Instabilities in Neutralized Drift Compression section
  - Beam-plasma two stream
  - Plasma turbulence
- Establish required accuracy of applied tilt waveform and control of beam aberrations
- Plasma neutralization of compressing beam with and without strong solenoidal fields

Voss Scientific Research Highlights of past 12 months

- Established physics limitations on simultaneous compression of heavy ion beams (HIB) in a neutralizing plasma*
- Comparison of detailed integrated LSP simulations with NDCX experimental data has confirmed our predictions of cold incoming beam essential to focusing



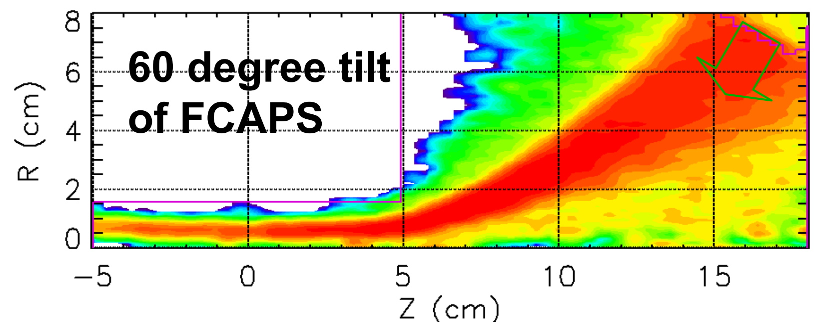
***Source-to-target simulation of simultaneous longitudinal and transverse focusing of heavy ion beams, D. R. Welch, et al., submitted to PRSTAB (2008).**

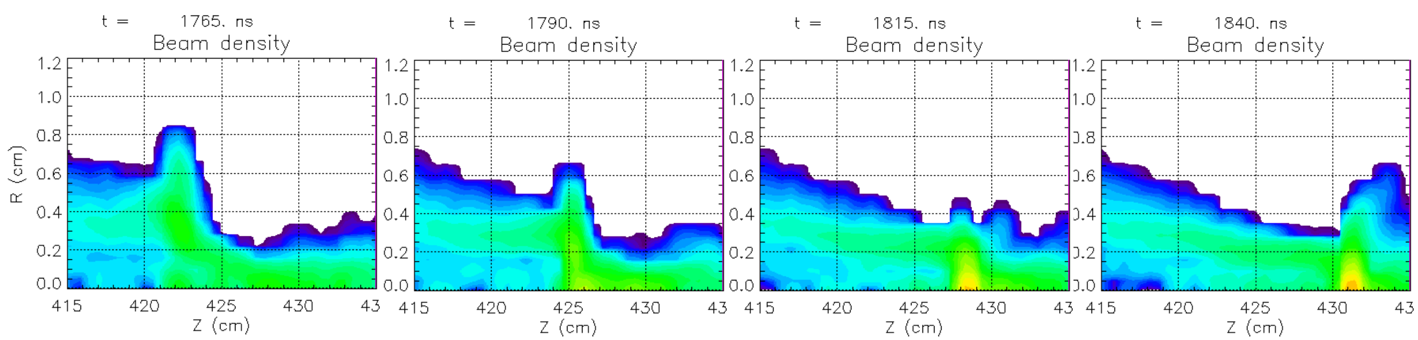
D. V. Rose, et al., Phys. Rev. ST Accel. Beams 10, 034203 (2007)

Research Highlights of past 12 months (cont.)

Examined plasma injection techniques for plasma filling of final focus solenoid and resulting HIB focusing. 3D simulations predict strong plasma confinement in solenoidal fields and stringent requirements for uniform filling. HIB focusing requires dense plasma at focus*

3D LSP simulation of plasma filling





LSP simulation of simultaneous focus with calculated plasma conditions

•D. R. Welch, D. V. Rose, et al., Presented at APS-DDP 2008, papers JP8.00056 and PP8.00033.

Budget, Plans for FY08-FY10

- Projected Budget for FY08 – $150k?
  - Assist in development of an WDM source on NDCX and NDCXII with strong final focusing
  - Benchmark 3D simulation of plasma filling of solenoid with NDCX data
  - Benchmark simulations of simultaneous beam focusing on NDCX
- Projected Budget for FY09 – $180k?
  - Develop advanced/fast implicit plasma simulation tool for modeling plasma injections, production
  - Assist in optimization of the design of WDM accelerator (NDCX-II)
  - Examine effects of beam-plasma stability and turbulence in multi dimension
- Plans for FY10 and beyond– $200k per year?
  - Optimized and begin application of advanced simulation tool to NDCX-II plasma and integrated transport simulations
  - Begin study of 3D beam-plasma instabilities/turbulence and impact on target heating
  - Examine intense beam-target interaction issues -- target blowoff interaction, atomic physics issues, self field effects

Impact of FY10 Budget Scenarios on research at Voss Scientific

- -10% budget impact
  - Theory work associated with beam plasma instability and turbulence and target interaction is delayed
- Flat budget
  - Theory work associated with target interaction is slowed but continued
- Full-use Budget
  - Advanced code optimization and benchmarking can move forward
  - Multi-dimensional instability/turbulence theory work
  - Fully integrated LSP simulation of NDCX-II including target interaction proceeds

Backup slides-PART II:
Longer-term prospects for heavy ion fusion

The long-range HEDP/HIF science campaign envisions three levels

- **Level I (before NIF ignition ~ 2011) Integrated beam-target physics: The beam intensity and profile heating the target depend on the accumulated beam phase-space changes through each region along the accelerator system. Source-through-target physics models need to be validated by experiments to predict target temperature profiles for WDM physics @ 1 eV. *Best opportunity*: Upgrade NDCX with existing ATA cells for 3 MeV lithium beam acceleration with NDC and solenoid focus (single and double pulses), ~ 0.1- 1 J, ~ $2M hardware over next 3yr VNL program.**

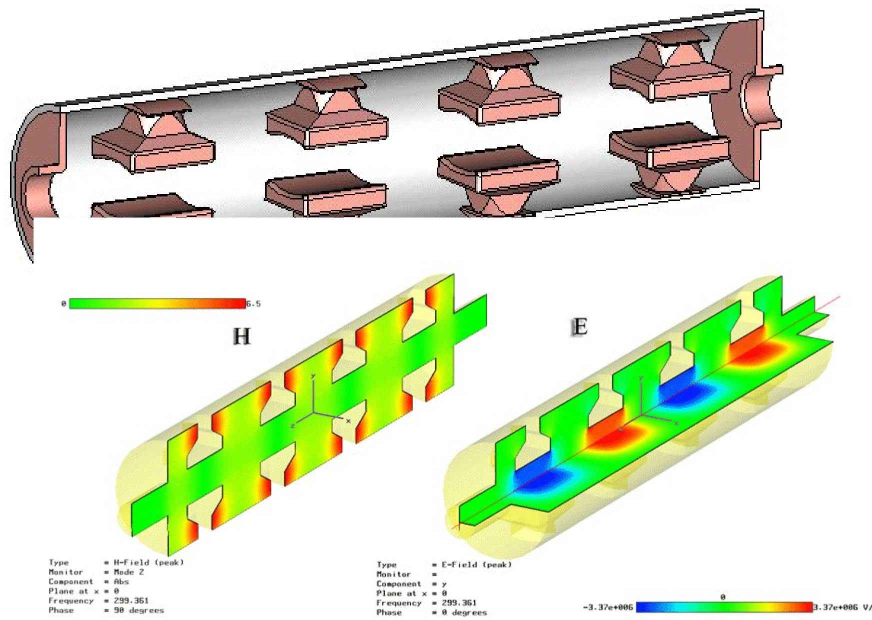
- **Level II (In parallel with NIF operation ~2012-2025) Ion direct drive implosion physics: E.g., 2-beam/20 pulse, 2-sided cryo-shell implosion experiments to explore heavy ion direct drive physics: two-sided ion-shell coupling, pulse-shaping, hydro, shock timing, and ion-RT stabilization. *Best opportunities*: Upgrade NDCX-II to IB-HEDPX. Build a new tool for fusion physics: 2 induction linacs @100 MeV, opposite a target chamber, ~500J/pulse, ~10 kJ total beam, ~ < $100M.**

- **Level III (Post NIF ~ 2025-2050) Heavy ion fusion physics: Burning plasma physics with high pulse rate targets, fusion chamber materials and gas dynamics). *Best opportunity*: Fusion test Facility (FTF) with HIF direct drive with gain 40 @ 1 MJ, 6 Hz, for < $ 0.5 B. Liquid vortex chamber hydro validation.**

Our GSI/ITEP collaborators are developing the tools we would need to test dynamic stabilization of ion direct drive RT instability

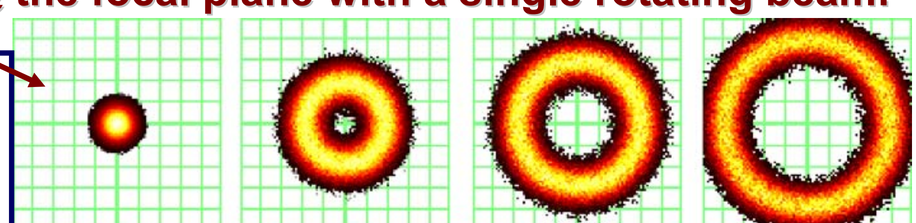
ITEP design of RF HIB GHz Wobbler for GSI

(Much lower RF fields are required to modulate 100 MeV Ar beams compared to 200 GeV Uranium beams!)



Beam spot rotation improves symmetry for direct drive: fewer beams needed for azimuthal symmetry

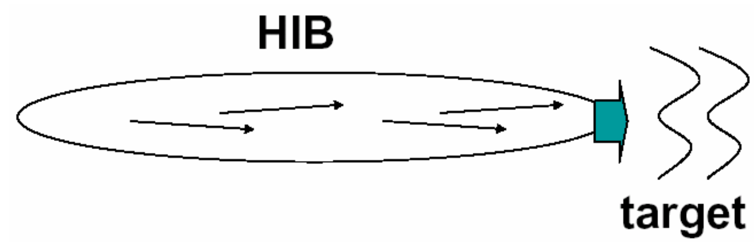
Transverse beam intensity distributions @ the focal plane with a single rotating beam!



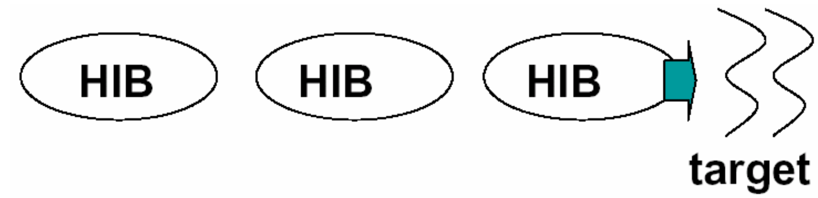
→Two sided (polar) direct drive implosion studies may be possible with two twirled ion beams from two linacs, each with 10-pulse picket fences

S. Kawata has proposed several techniques to reduce Rayleigh-Taylor (RT) instability growth in ion-beam-driven direct drive

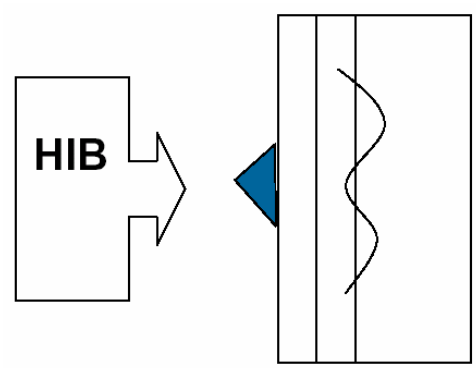
HIB axis rotation or swing
-> reduce the R-T growth!



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



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



$\delta g(x)$, induced by an shaped Ablator, controls R-T phase & growth

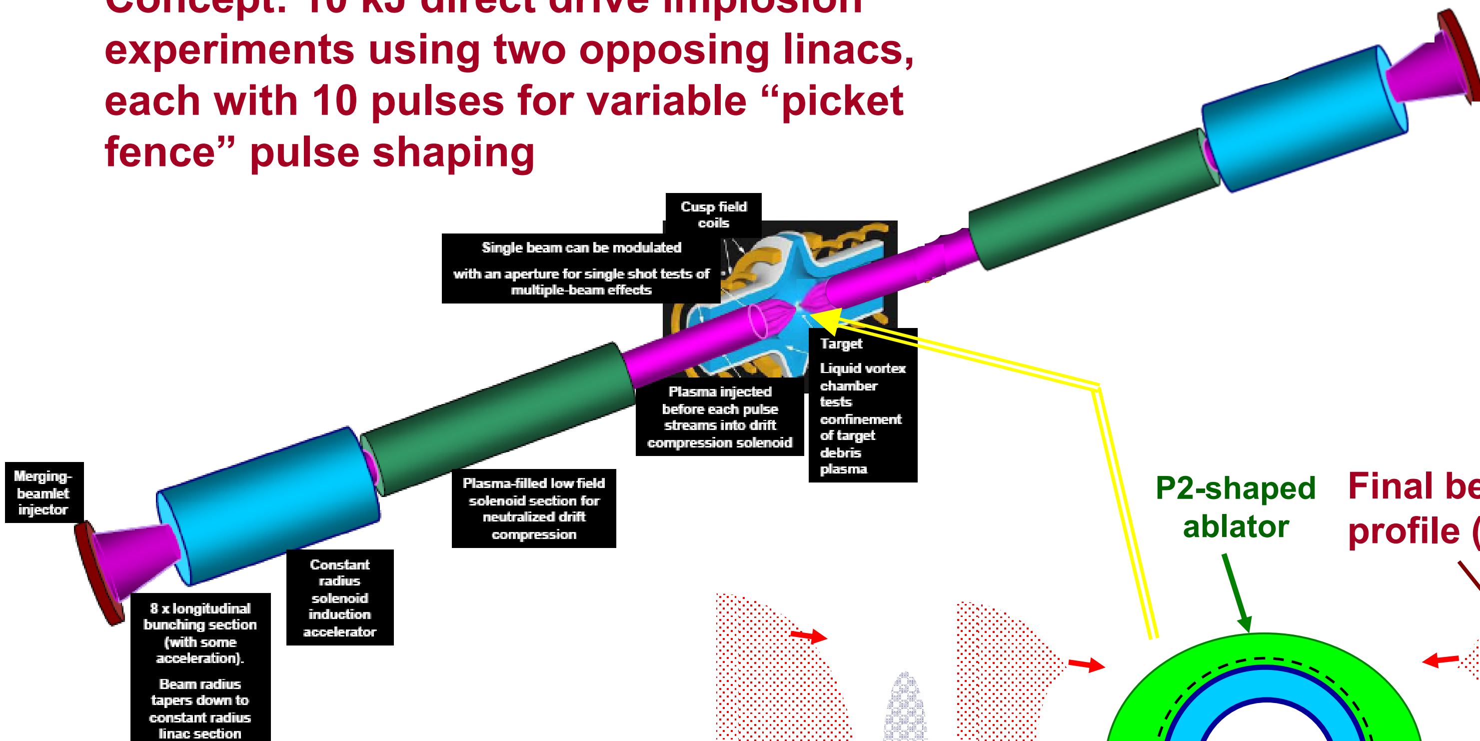
L&PB, 11(1993)757

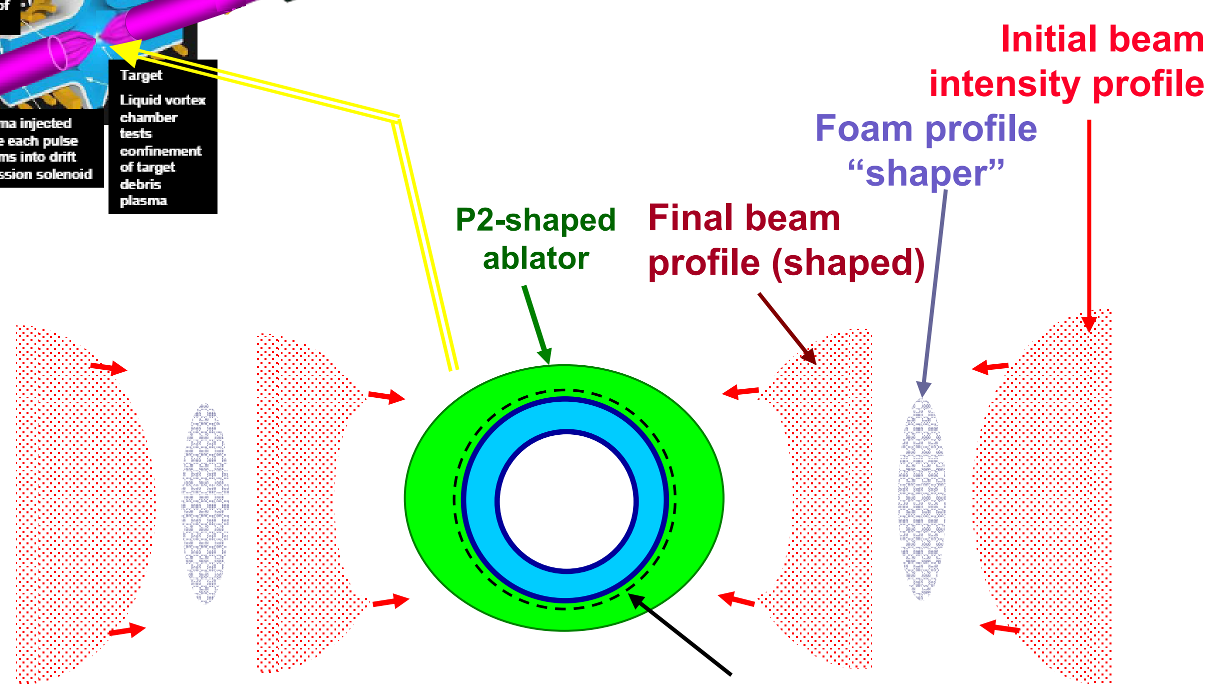
Shaped target with an Ablator for R-T phase control

→These techniques can be explored on NDCX-II

An IRE-scale new accelerator tool to explore polar direct drive hydro physics with heavy ions in parallel with NIF

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable “picket fence” pulse shaping



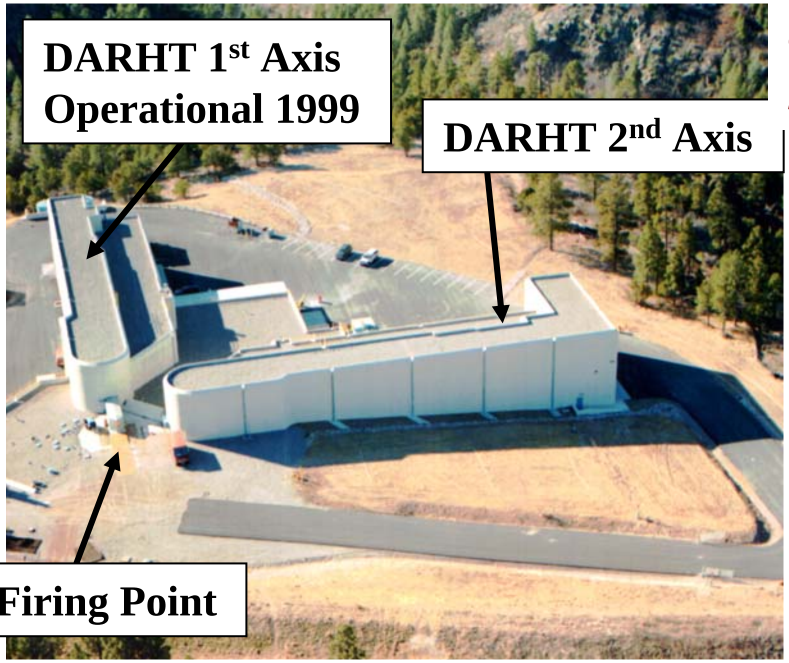


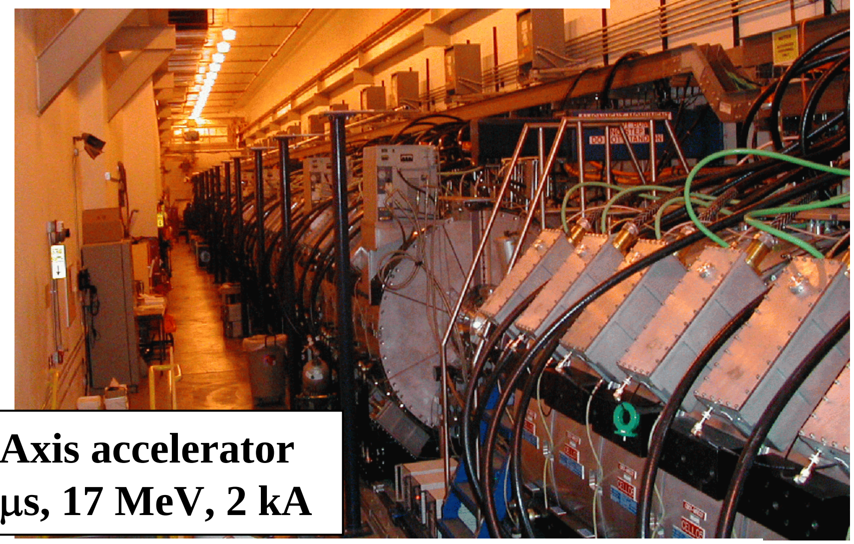
Three “knobs” to control P2 asymmetry with two beams:
1. **Upstream GHz wobblers**
2. **Foam profile shapers**
3. **Ablator shaping**

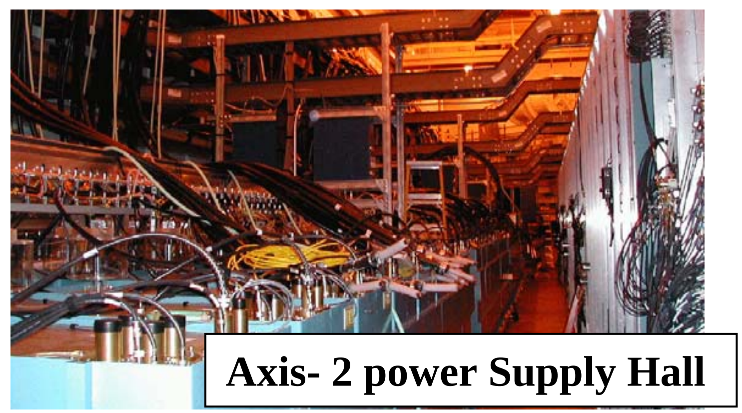
Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

The DARHT 2nd Axis: a state-of-the-art induction accelerator @ >50 kJ/ electron beam pulse. Technology *relevant to induction linac drivers for fusion!*

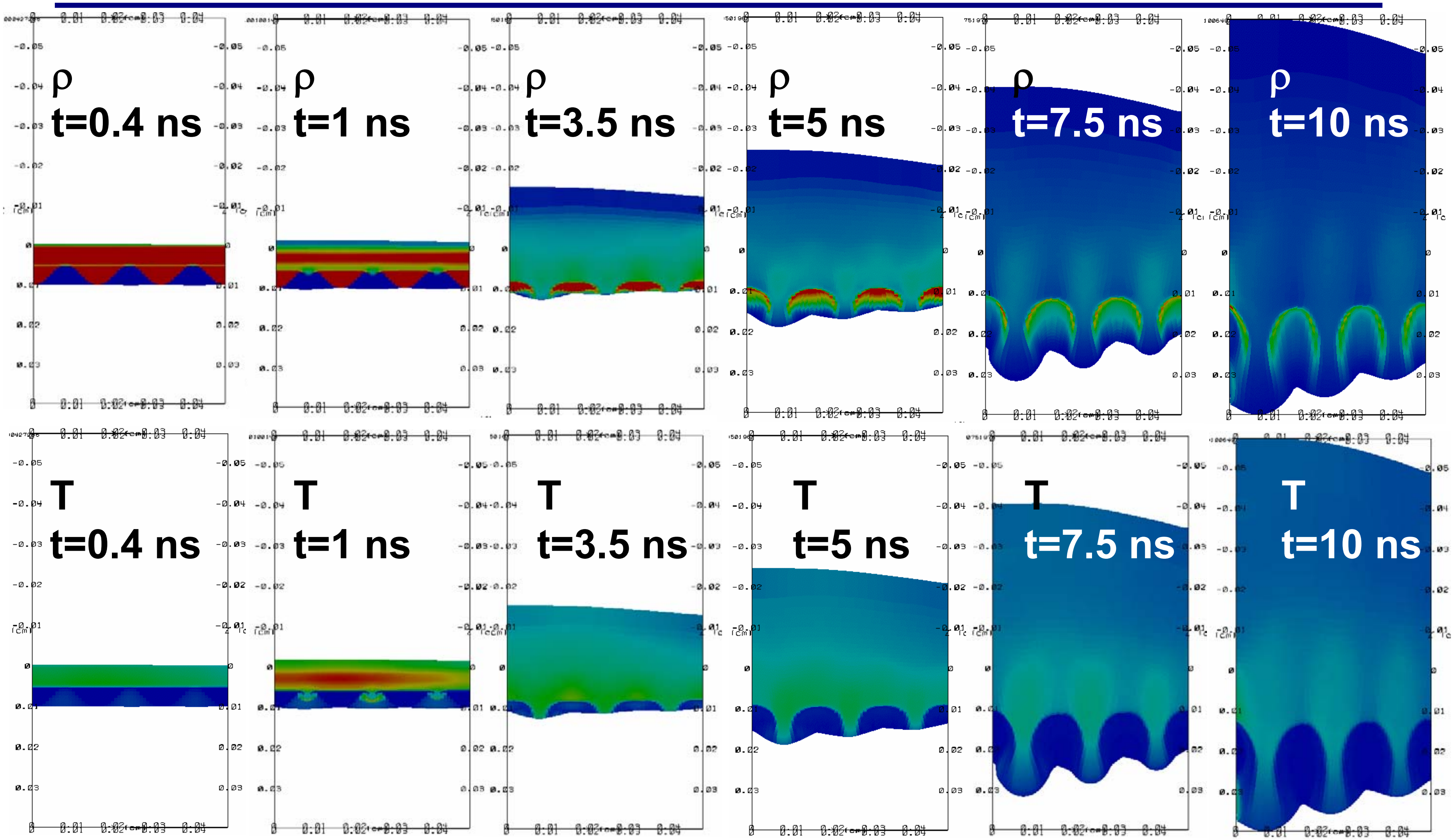
The DARHT 2nd Axis Project is a collaborative effort among LANL, LBNL, and LLNL





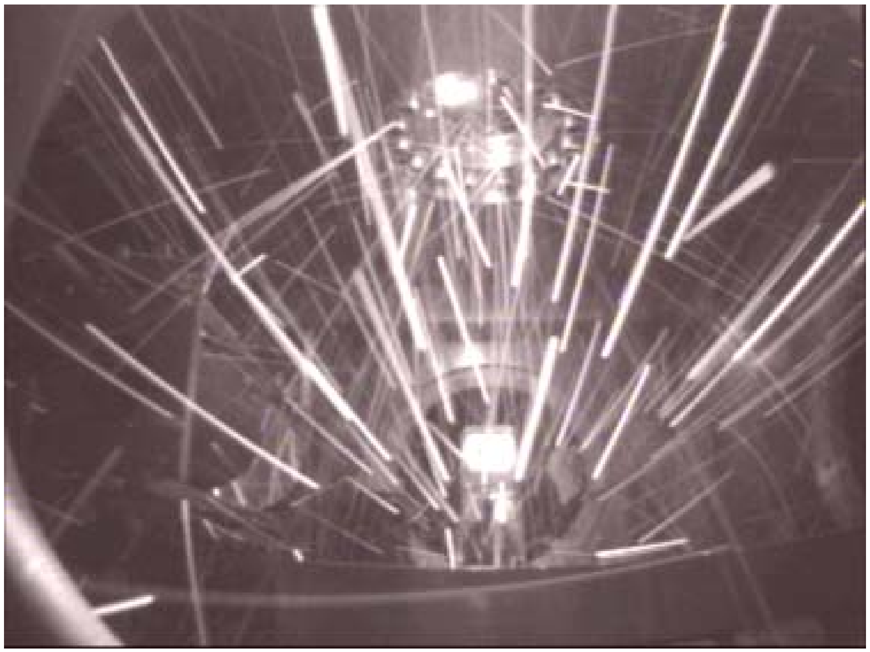


We have used the LLNL HYDRA code to show how unique heavy ion direct drive hydrodynamics as well as WDM can be studied on NDCX-II

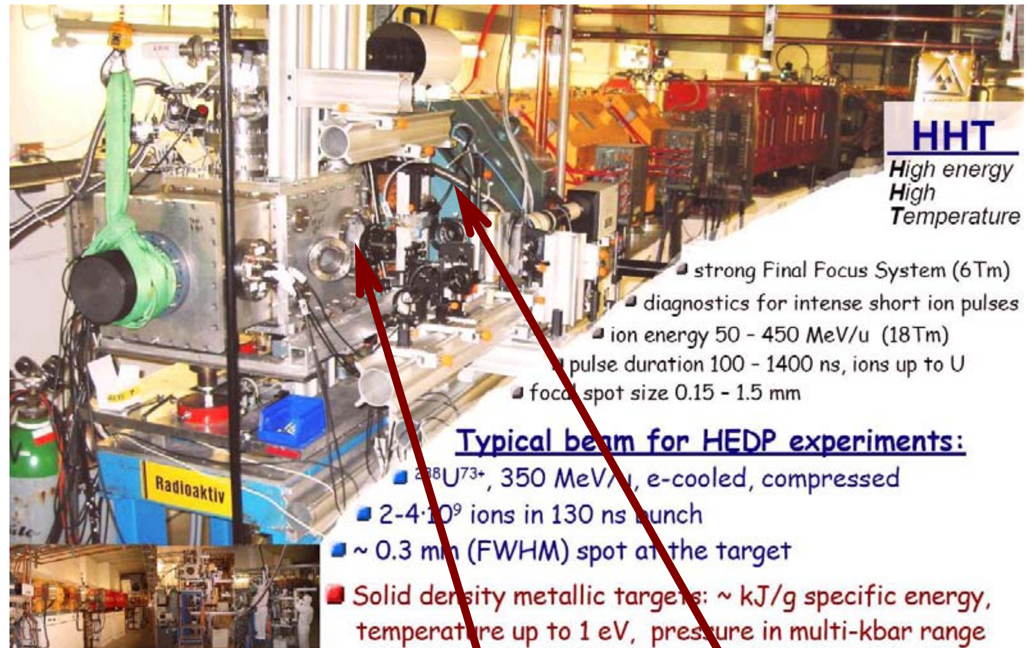


Can modulated beams stabilize ion Rayleigh-Taylor modes? (S. Kawata)

For IFE, practical considerations will be important as well as the beam and target science!



Visible camera frame showing hot target debris droplets flying from a US-made WDM target driven by a 100 ns, 10 J heavy ion beam in joint experiments at GSI, Germany



Optical diagnostic windows need to be frequently cleaned of target debris and/or replaced

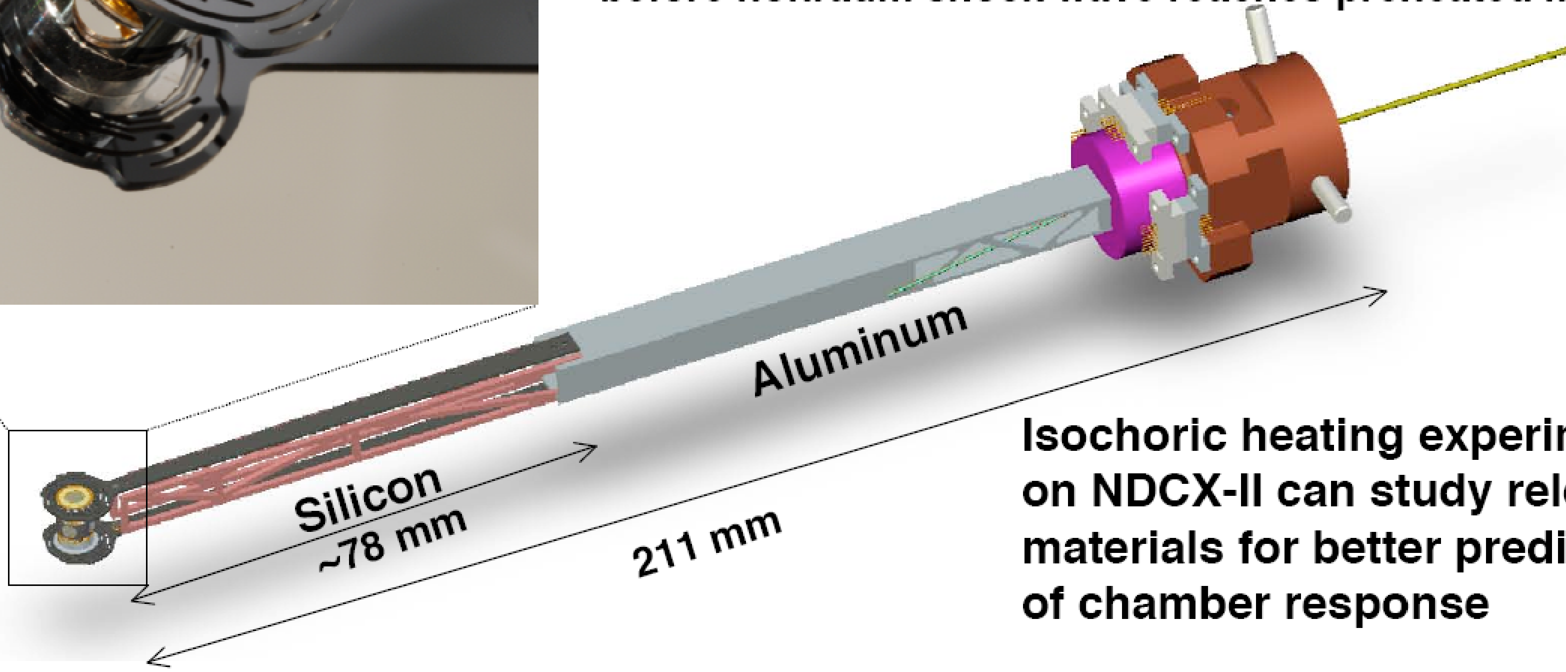
….but never the final focus magnets!

Isochoric heating by ion beams can simulate neutronic isochoric heating near NIF target (Dave Eder)

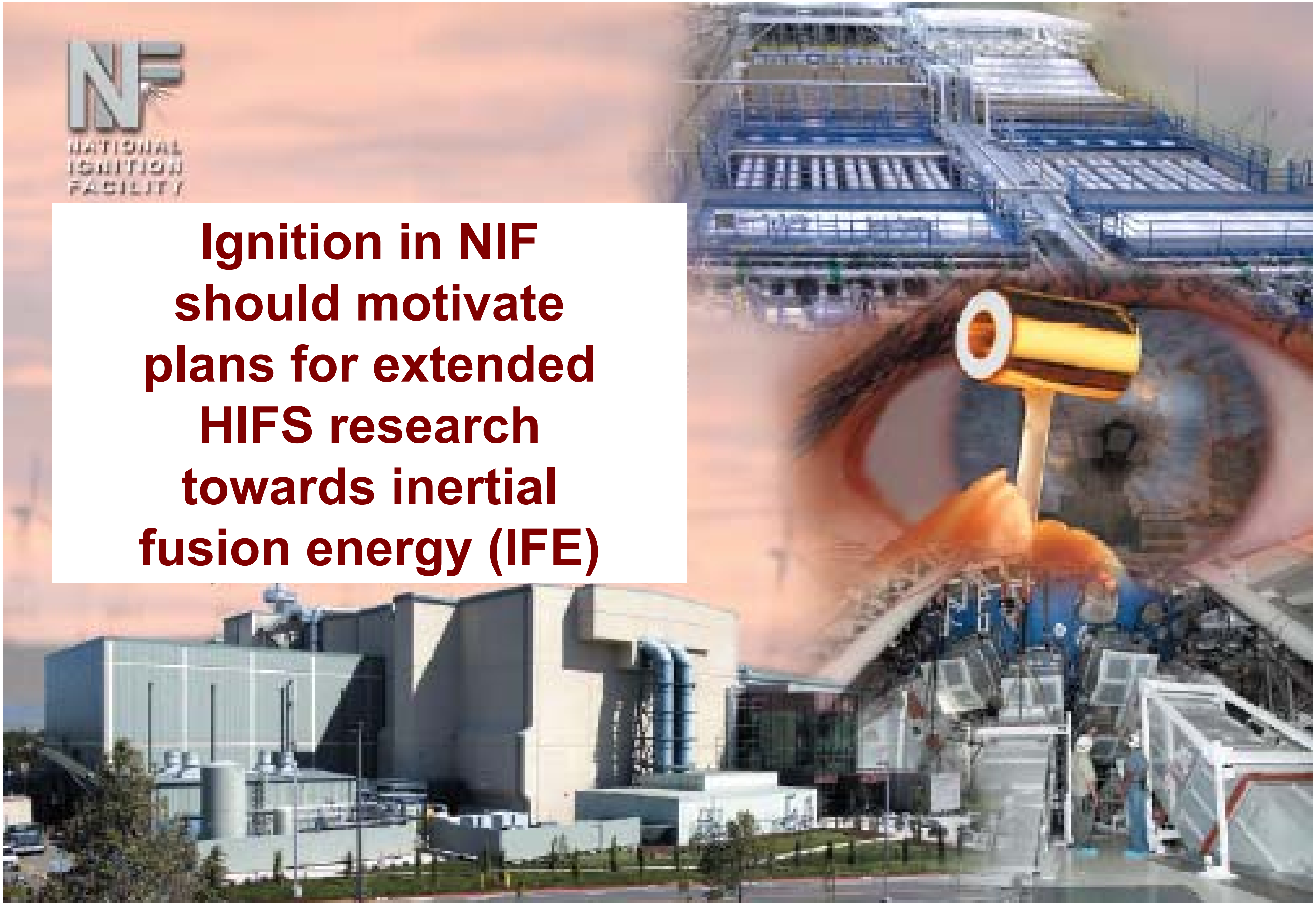
Exposure: 10^{17} - 10^{19} neutrons per shot

$kT \sim 4\ eV\ (1\ cm/r)^2\ (N_n/10^{19})(\sigma/10^{-24}\ cm^2)$

Near target, material is vaporized, but some material a few cm away is volumetrically preheated by neutrons to melting point or lower, changing material properties, before hohraum shock wave reaches preheated material



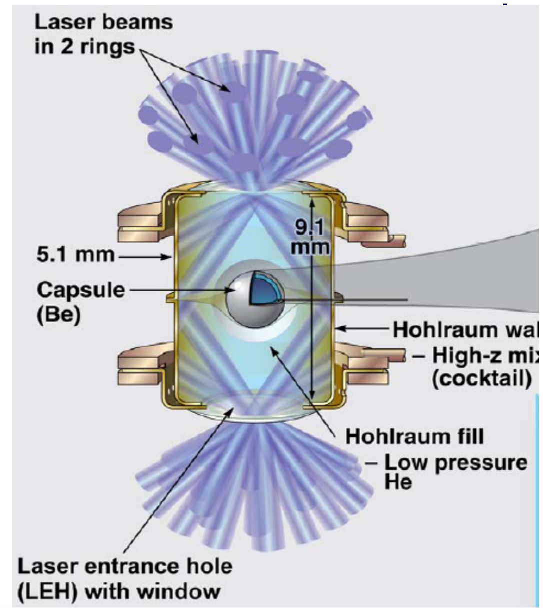
Isochoric heating experiments on NDCX-II can study relevant materials for better predictions of chamber response

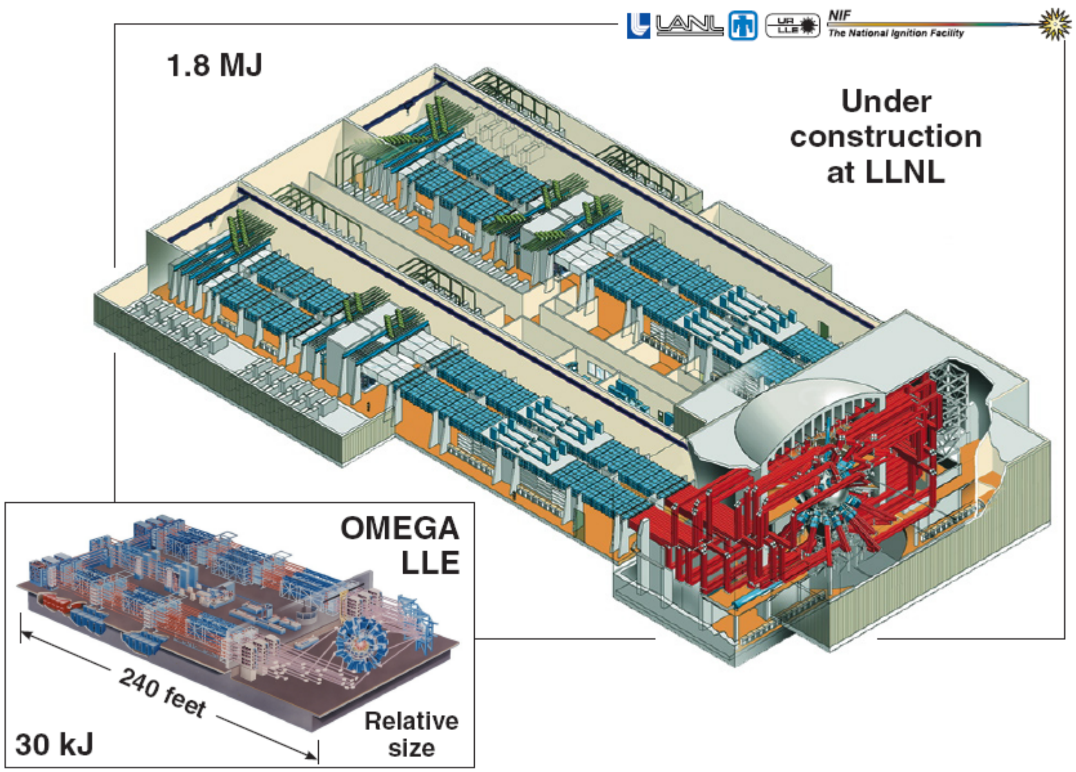


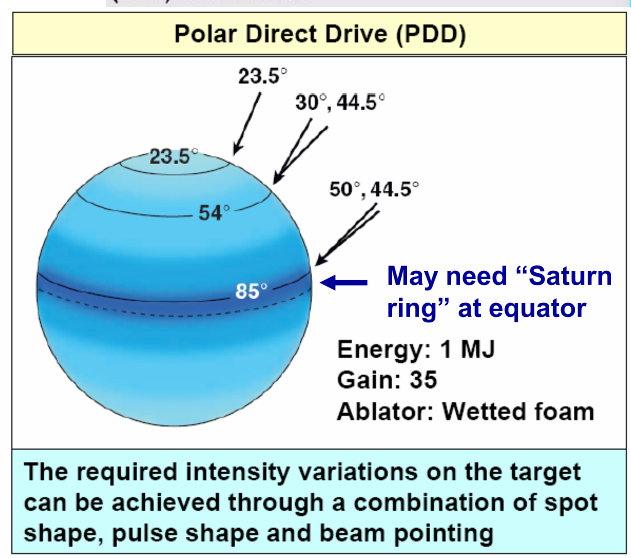
Ignition in NIF should motivate plans for extended HIFS research towards inertial fusion energy (IFE)

First ignition tests in NIF will be indirect drive, *but polar direct drive tests will soon follow.*

Meyerhofer (8-29-06) : "We expect ignition in polar direct drive on NIF soon after first ignition with indirect drive." Marshall, Craxton (11-06-APS) -showed new Rochester results on their 2-sided, polar direct drive experiments measuring 80-90% of the yield with full 4Pi drive.



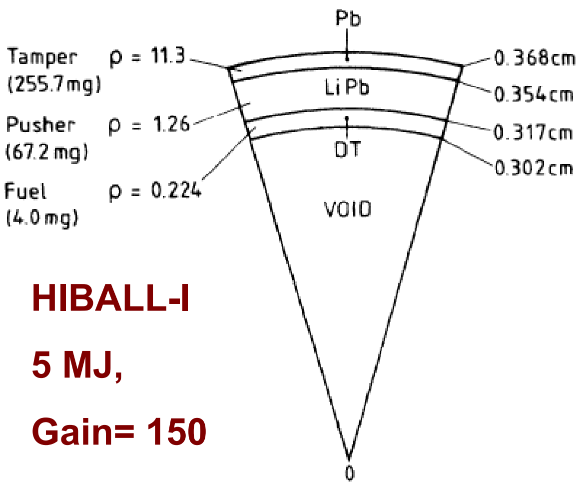




Review: Ion hohlraum targets (a) did not scale well to small 1 MJ drive due to large radiator&case mass; (b) had beam speeds > electron v_{eth}; (c) had modest ion energy ramps foot-to-peak (~25%) to compensate *range-shortening* (due to log λ_D increase) as targets heated up.

HIBALL (Long, Tahir)

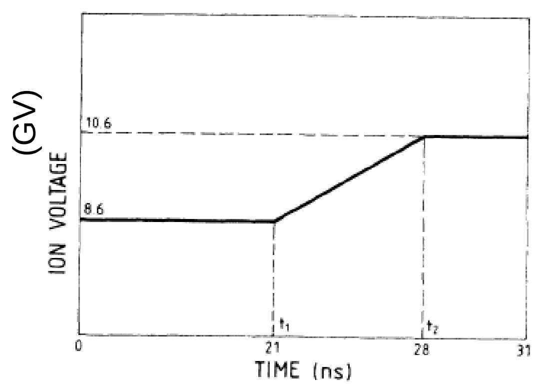
PR A Vol. 35, No. 6, March 1987



HIBALL-I

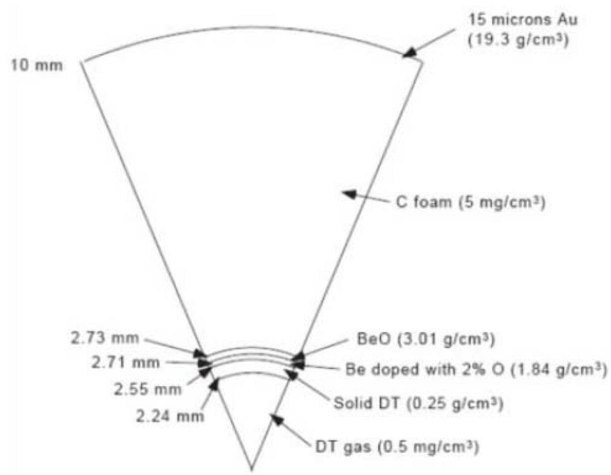
5 MJ,

Gain= 150



LIF Hohlraum (Allshouse, Callahan)

Nuc. Fus. Vol. 39, No 7 1999



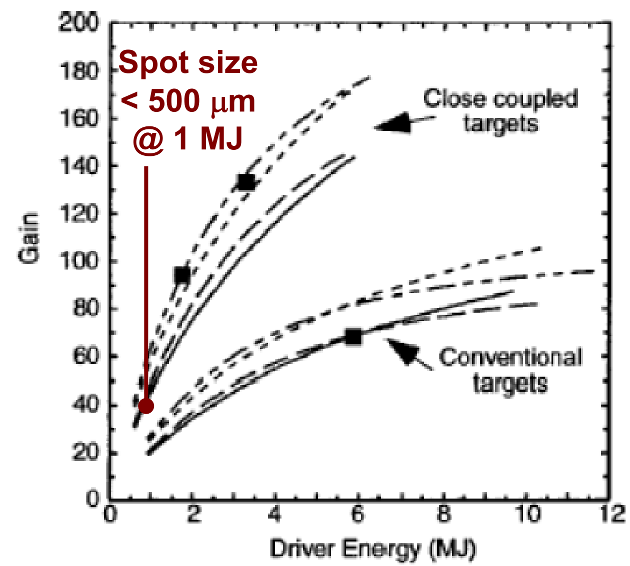
16 MJ Lithium ion drive

17→22 MeV,

Gain= 37

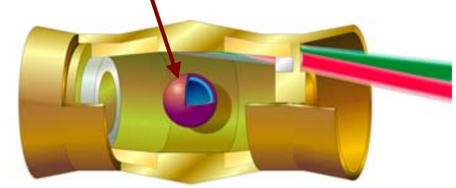
Distributed Radiator (Callahan, Tabak)

Phys. Plasmas, Vol. 7, No. 5, May 2000

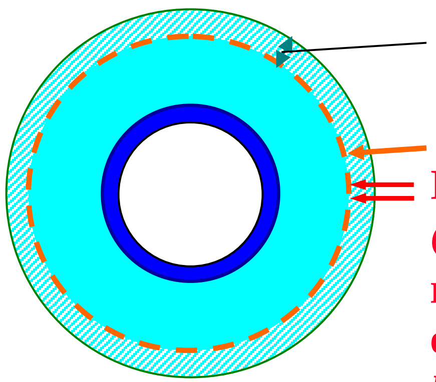


3.3 GeV Bi foot, 4 GeV for peak.

At gain=57, the 2 mm radius capsule absorbed 1 MJ out of 7 MJ total drive



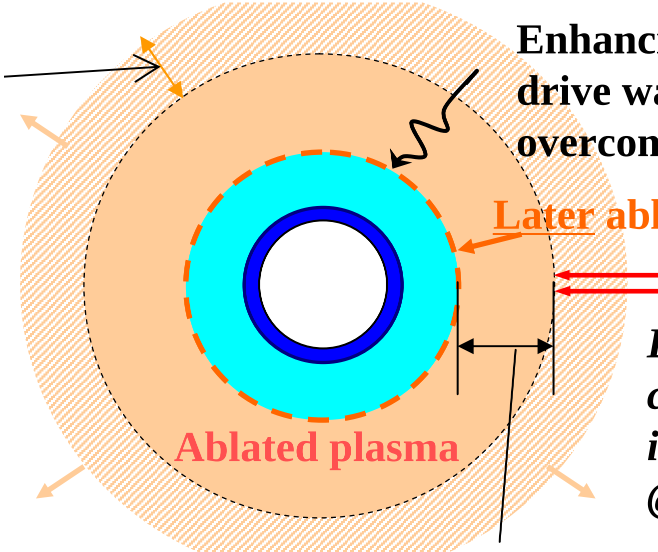
LLNL, 80's: tried low-range ion ablative drive around 500 MeV→ found to "<u>decouple</u>" in low-Z ablators→ solution was to use higher Z-ablators (e.g., aluminum), *forcing radiation drive*→ adding a radiation case→ direct-drive "cannonball" targets *became spherical hohlraums.*



<u>Basic cause of decoupling</u>:
Ablator mass layer that stops ions moves out radially during drive!

<u>Initial</u> ablation front

Incident ion beam
@ t = 0 "foot" pulse:
range < 0.25 of ρr
of ablator layer *for low adiabat* α



Enhancing radiation drive was one way to overcome decoupling

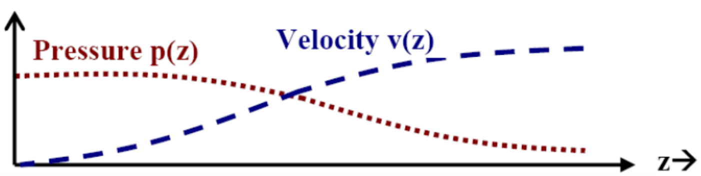
<u>Later</u> ablation front

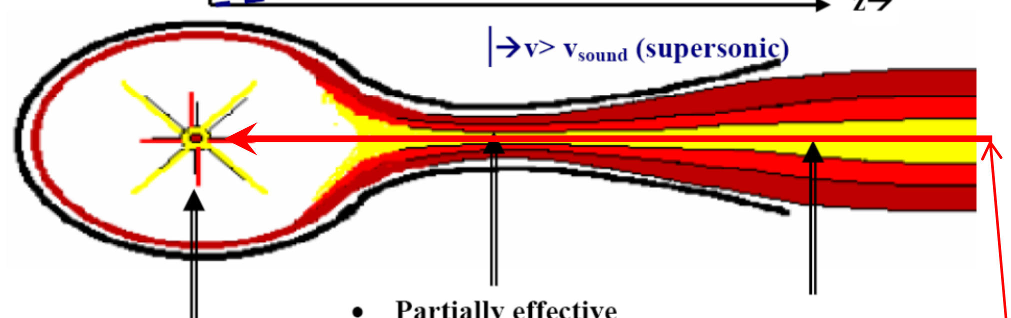
Ion beam

Electron heat conduction insufficient @ Te< 1 keV

Late in the pulse, as ablated plasma column density exceeds initial ion range, ions stop well before the ablation front: →"<u>decouple</u>"

<u>Location of energy input affects rocket efficiency</u>





- Ideal position of energy input (nearest max p)
- $v < v_{sound}$ (subsonic)
- Best rocket efficiency

- Partially effective
- $v \sim v_{sound}$ (sonic)
- Moderate rocket efficiency

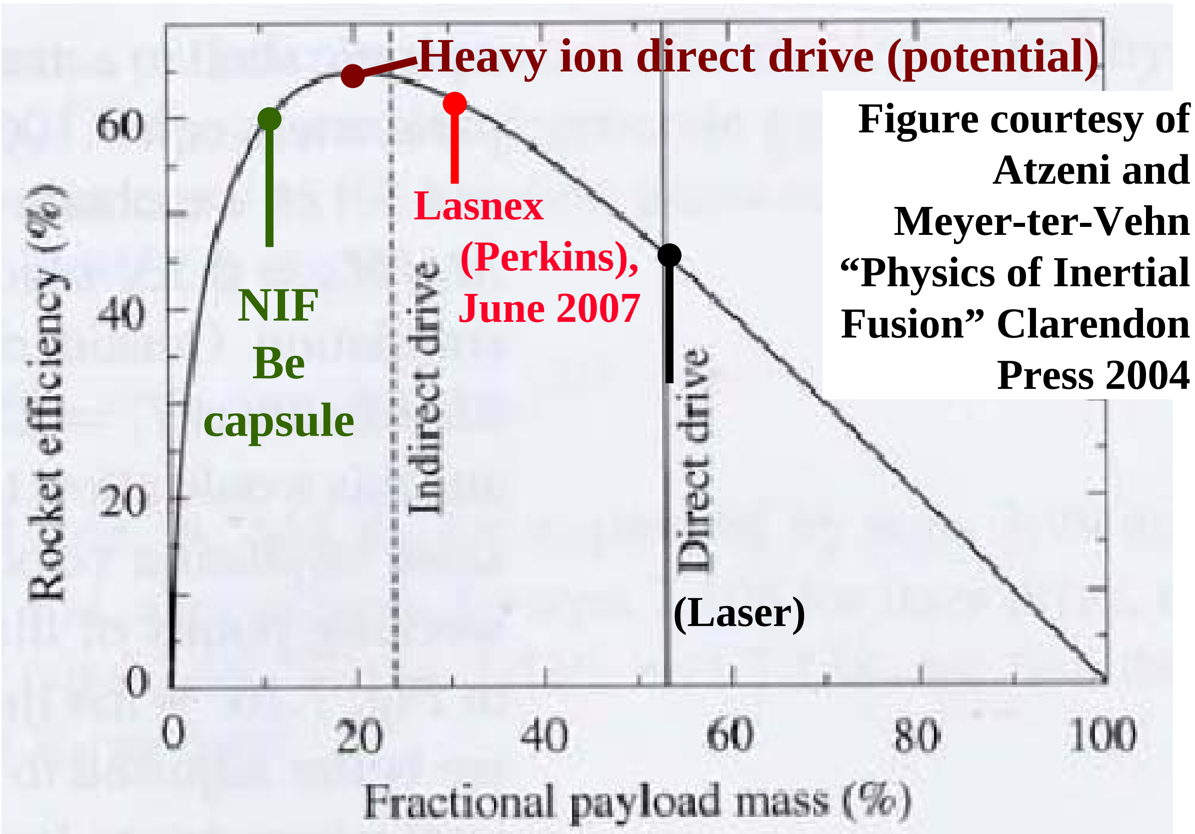
- Heating not effective
- $v >> v_{sound}$ (supersonic)
- Low rocket efficiency

Stopping regime: @ 500 MeV, Ar ion speed exceeds 500 eV electron speeds, but in Perkins' Lasnex runs @ 50 MeV, ion beam speed is *below* thermal electron speed.
→ *<u>increases ion range, reduces decoupling</u>!*

Ion deposition integrates <u>through</u> exhaust plasma

Laboratory

Nov. 2006: Realizing heavy ion direct drive with the right range might achieve peak rocket efficiency like x-rays, *without conversion loss*, and with less ionization loss, we asked LLNL for new LASNEX calculations.



- Low-Z ablators (DT or H) for ion direct drive have only 13.6 eV ionization loss
- Beryllium ablators have 180 to 400 eV ionization (three to four electrons ionized)
- Laser coupling is reduced with electron transport from critical density to ablation front

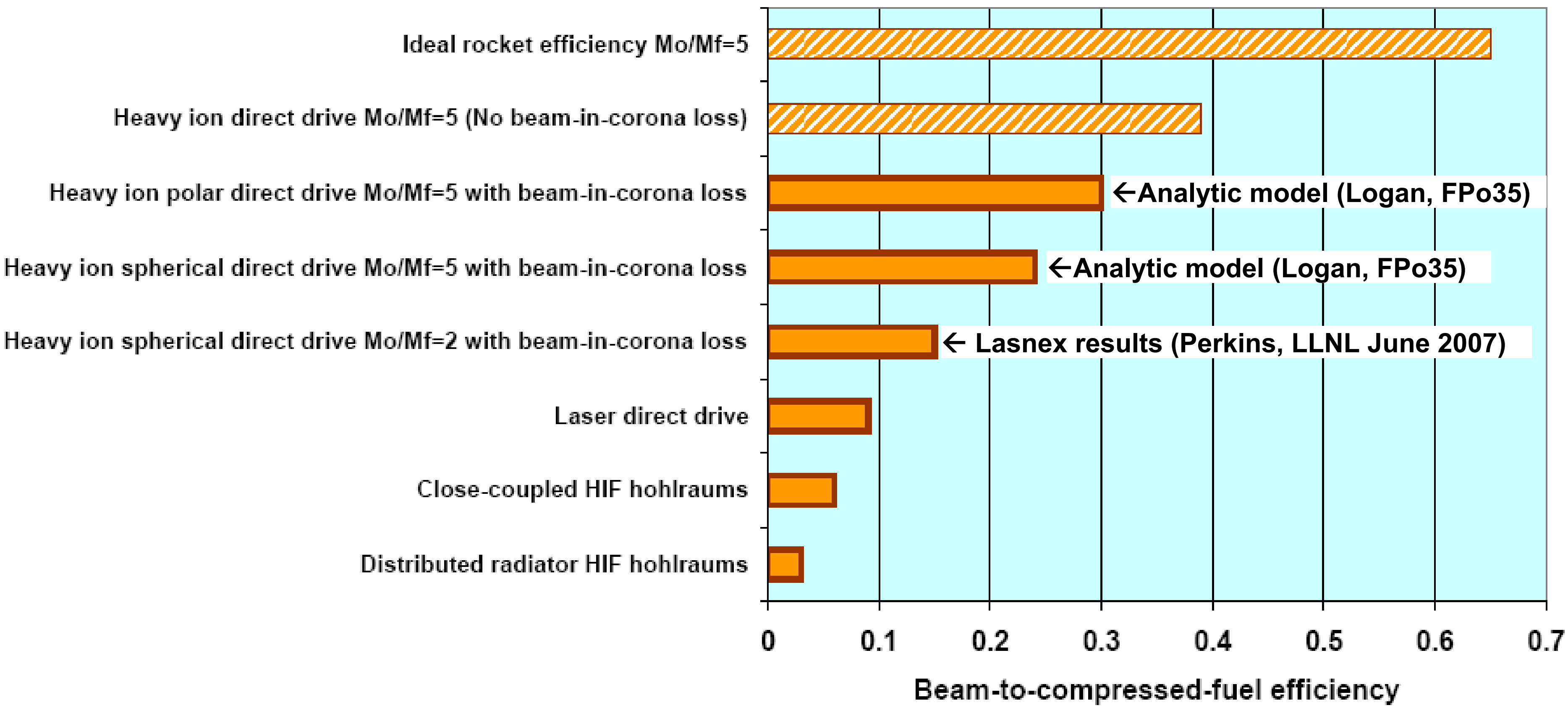
Heavy ion beams can suffer more parasitic energy loss on out-going ablation corona plasma than either x-ray or laser photons, *but with range-lengthening during the drive pulse, overall coupling efficiencies can still be higher*.

Comparing Perkins' case for heavy ion direct drive with KrF laser direct drive (ref. Atzeni-MTV book):

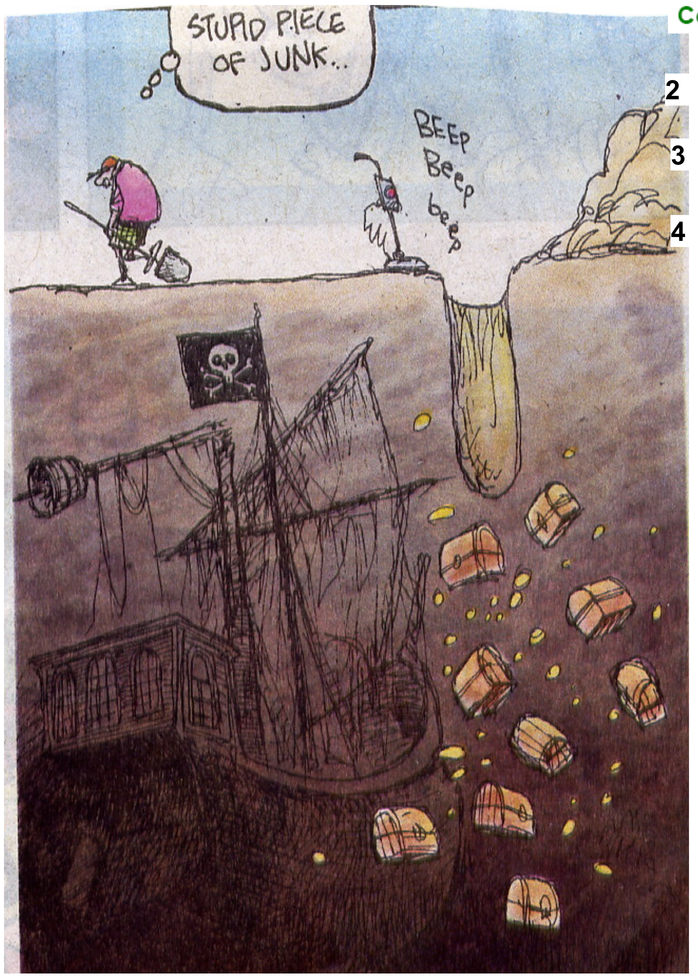
	Ion direct drive	Laser direct drive
DT Fuel mass (mg)	1.2	1.68
Ablator mass	2.8	1.67
Implosion velocity (10^7cm/s)	4.4	3.5
Incident beam energy (MJ	1	1.7
Absorbed beam energy*	1	1.35
Capsule hydro efficiency	0.15	0.09
Overall coupling eff.	0.15	0.07
Density at mid absorption (g/cm^3)	0.06	0.01
Electron temp at mid absorption (keV)	1	3
Target gain	50	65
Fusion yield (MJ)	50	100

Part of the explanation of the higher coupling efficiency in the ion drive case is the ~ 6 X higher average absorption density for ion stopping compared to laser absorption, leading to 3X lower average ablation temperatures, [3X less radial kinetic energy ~ (dM/dt) uex^2 that has to be supplied per unit of rocket momentum ~ (dM/dt) uex, to provide the same PdV rocket work].

Preliminary results for heavy-ion direct-drive efficiency are very encouraging. Validation with 2-D hydro codes are planned.



Many researchers (e.g. Max Tabak, Stefano Atzeni, John Perkins, Grant Logan…) have long been searching for a <u>self-T breeding target with direct conversion potential*</u> to make fusion <u>truly unique</u>…



1 B. Grant Logan "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD Conversion" Fusion Engineering and Design 22, 151 (1993)

2 Max Tabak, Nuc. Fusion 36, No2 (1996).

3 Atzeni and Ciampi Nuc. Fusion 37, 1665 (1997)

4 L. John Perkins "Advanced LASNEX model Advanced fuel IFE" LLNL (1998) unpublished?

* Mission-Impossible Quest? Yes, but very good company!

We all got discouraged when we estimated that large energy drivers > 10 MJ might be required, and associated large fusion yields (many GJ) ….

…so we mostly stopped working on this the last several years…..

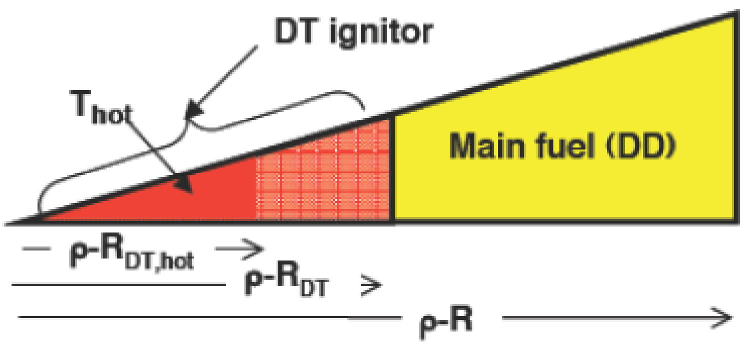
…until the possibility of coupling efficiencies 10 X larger than with HIF hohlraums motivated us to <u>dig deeper</u> on this quest in a new series of explorations!

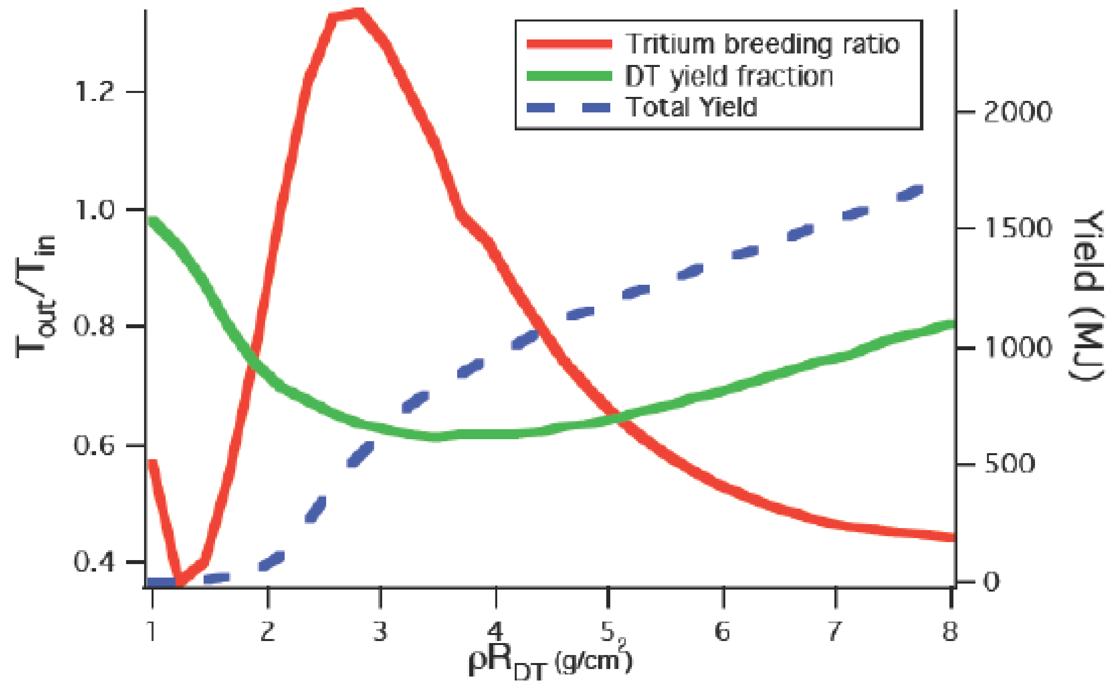
Recent LASNEX work confirms T-lean targets can self breed tritium @ ρR_{tot}~ 10 g/cm^2 and 500 MJ yields (Kai LaFortune, LLNL)

H. Takase, S. Kawata and K. Niu: , J. Phys. Soc. Jpn., 52 (1983)

Max Tabak, Nuc. Fusion 36, No2 (1996).

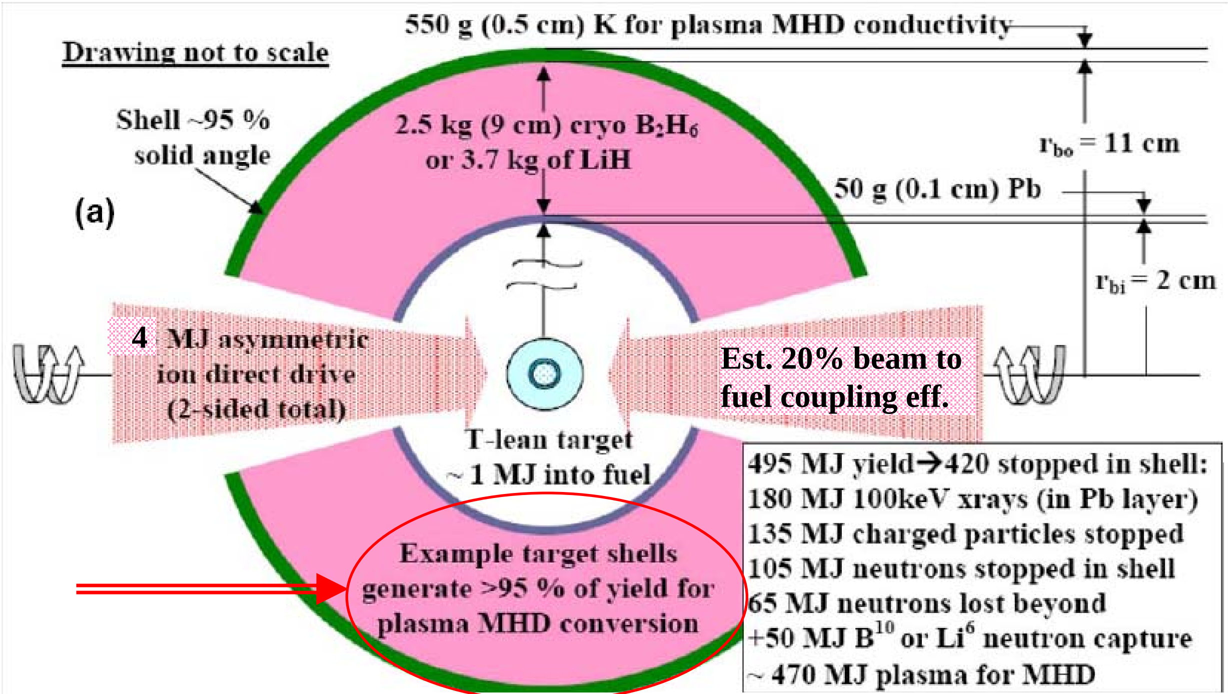
Atzeni and Ciampi Nuc. Fusion 37, 1665 (1997)





T- breeding ratio, DT yield fraction (mostly from T originating from D(d,p)T reactions of the majority DD fuel), and total fusion yield as a function of the DT core ρR_{DT}.

→ Required 1 MJ compressed fuel assembly energy → 3.3 MJ (5 MJ) drive energy with heavy-ion direct drive coupling efficiency of 30% (20%).



[2] B. Grant Logan "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD Conversion" Fusion Engineering and Design 22, 151 (1993)

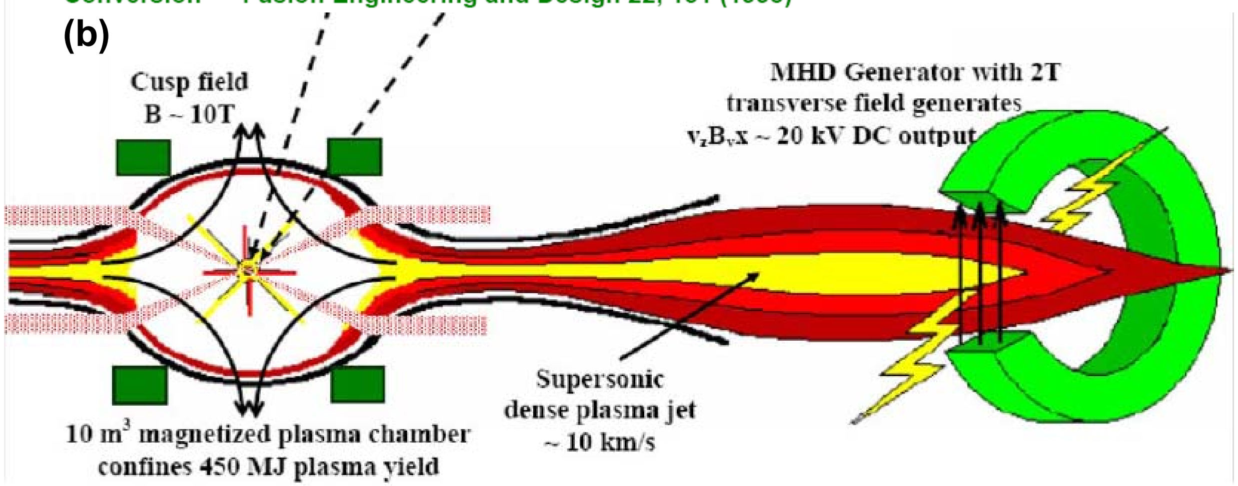


Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle).
(b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

High efficiency ion direct drive enables CFAR plasma direct conversion at moderate yields

Note key facts about the marriage of T-lean targets (Max Tabak 1996) to CFAR MHD conversion:
(1) Most T-lean target yield can be captured for direct plasma MHD conversion, even down to 1MJ–scale DEMO drivers.
(2) Plasma conductivity is 10^4 times greater at 25,000 K than at 2500 K→ the extractable MHD conversion power density ~σu^2, where u~10km/s is the plasma jet velocity, is >30 times the power density of steam turbine generators[2].
→As a consequence, the CFAR Balance of Plant *cost* can be much lower, < $ 80 M/ GWe!

Revisiting Heavy Ion Fusion direct versus indirect drive

The US HIF program has adopted indirect drive for the past 25 years, *despite higher drive energy requirements*, for several reasons:

(1) Indirect drive was necessary for early *non-uniform* laser beams, while the HIF program relied on defense laser facilities for much of its target physics validation.

(2) Thick-liquid protected chambers required *two-sided illumination*.

(3) Hohlraums might allow HI-beam spot sizes of order the hohlraum size, i.e., *bigger than the fuel capsule.*

(4) Indirect drive demands *lower drive pulse contrast ratios* (easier for heavy-ion accelerators) compared to direct drive.

(5) Laser ablative RT growth reduction *might not apply to ion drive.*

(6) Hohlraums could *protect cryo-capsules* from hot fusion chamber environments.

→In light of recent scientific advances, lets re-examine these issues!

Reasons to re-consider direct drive for heavy ion fusion

With modern (mostly DT) direct drive capsules *and* super-efficient heavy ion beam coupling, <1 MJ drive may suffice for ηG >10!

1. **Laser beam smoothness now makes direct drive viable for NIF→ enables early direct drive ignition tests *in polar geometry, suitable for liquid protected chambers.***
2. **Direct drive fuel capsule radii (~ 2mm) allow *ion beam spots comparable to indirect drive needs*. (The larger hybrid HI target exception unduly restricted beam illumination solid angle <10° → difficult for many beams).**
3. **Neutralized beam drift compression now allows multiple pulses of lower range ions *→ion picket fences→ more pulse shape contrast possible.***
4. **Upstream ion beam RF modulation→ *new dynamic RT stabilization!***
5. **Thin *metal enclosures might still be used* with ion direct drive, even if only as a thin sabot to protect the cryo-capsules.**

→ ***Pursuit of direct drive allows HIF to take advantage of ongoing progress in modern laser facilities as much as it has for indirect drive.***