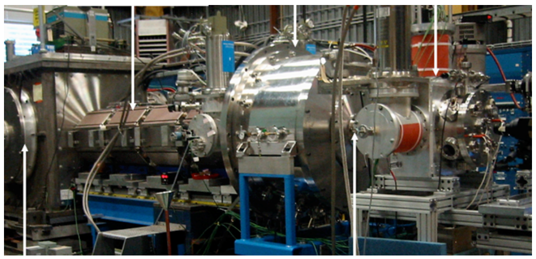
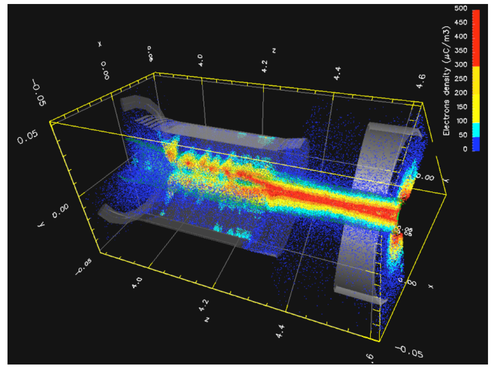
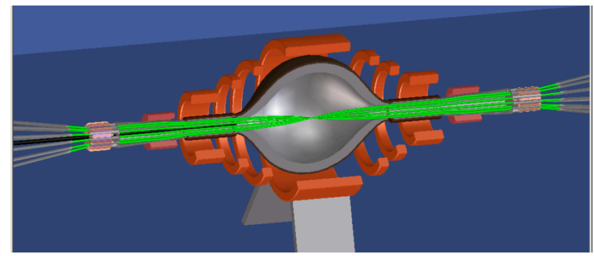
Heavy Ion Fusion Science*







Alex Friedman

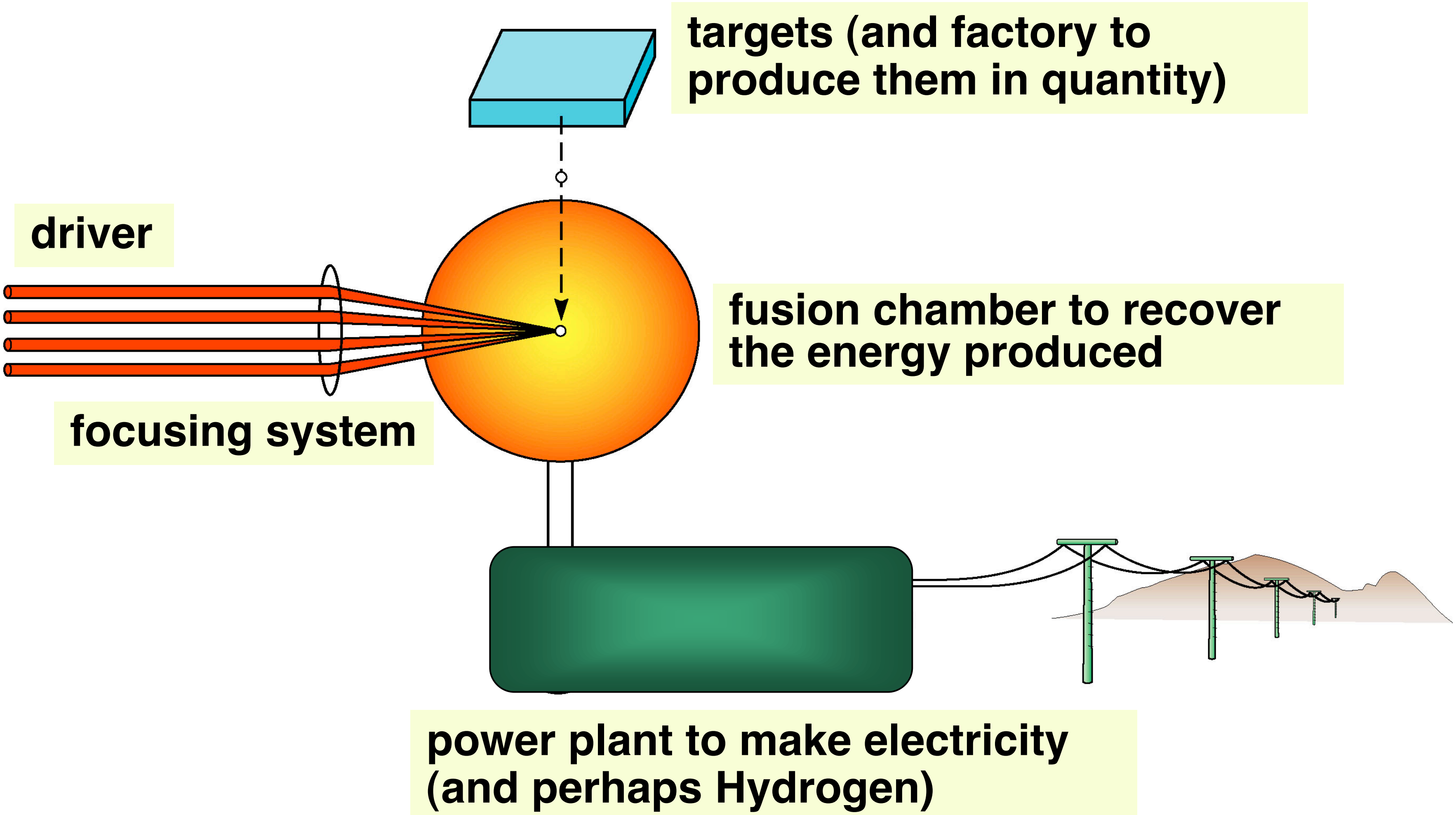
Heavy Ion Fusion Science Virtual National Laboratory

U. C. Berkeley Nuclear Engineering Colloquium

May 7, 2007

* This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract Number W-7405-Eng-48.

Inertial Fusion Energy (IFE) concepts are modular, and differ significantly from Magnetic Fusion Energy concepts



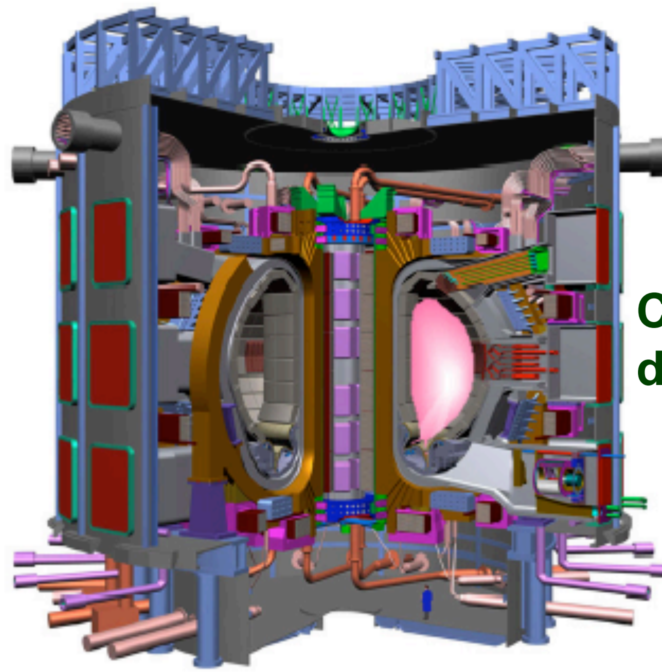
As NIF nears, we can anticipate increasing support for IFE research …

… *if* the IFE community has its act together!

Actual photo

$3B US National Ignition Facility (NIF) at LLNL will be the first demonstration of fusion ignition (alpha self-heating) in the world

ignition perhaps as early as 2011



CAD drawing

$10B International Thermonuclear Experimental Reactor (ITER) in France

ignition perhaps as early as 2021

In April 2007, LLNL hosted the first
IFE Science & Technology Strategic Planning Workshop

http://ifeworkshop.llnl.gov

- **Heavy ion beams - HIFS-VNL, U.Md, foreign**
- **Solid-state lasers - LLNL, Rochester, foreign**
- **KrF lasers - NRL**
- **Z-pinches - Sandia, Cornell**
- **"Magneto-inertial" - LANL, AFRL**

- **Fast ignition - of potential benefit to several approaches**

This meeting had significant OFES and NNSA participation, but not "sponsorship"

Today's HIFS program is directed at beam & Warm Dense Matter physics in the near term, and IFE in the longer term

Heavy Ion Fusion Science experiments:

The physics of compressing beams in space and time

-- Drift compression and final focus

-- High brightness beam preservation

-- Electron cloud, beam halo, non-linear processes

Warm Dense Matter (WDM) experiments

-- Equation of state

-- Two-phase regime and droplet formation

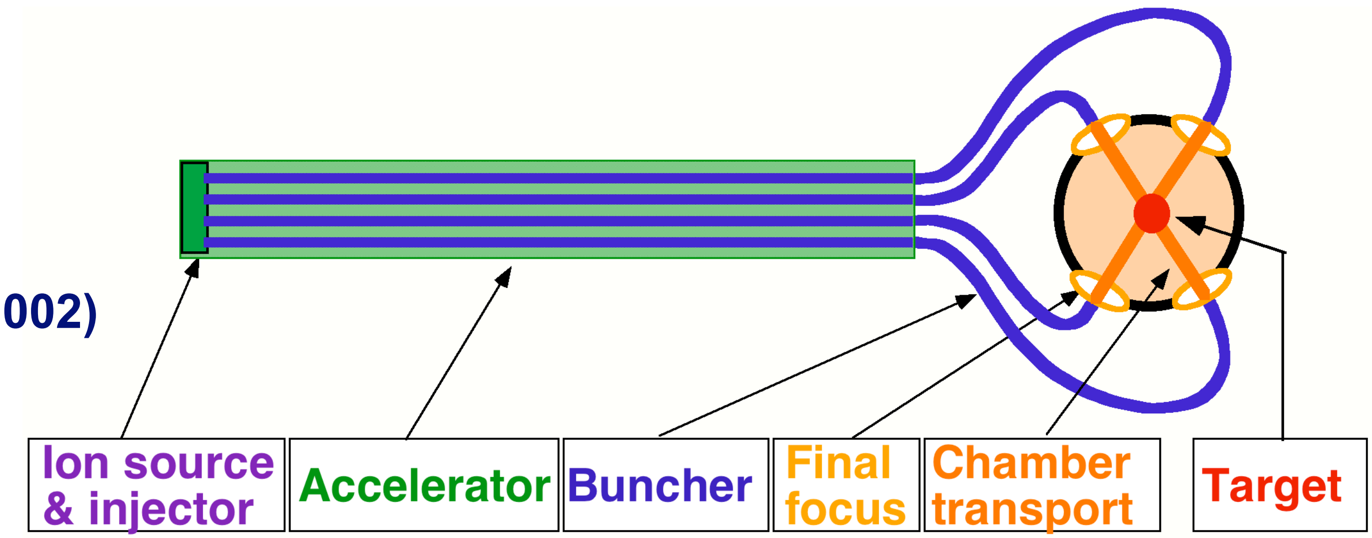
-- Insulator and metals at WDM conditions

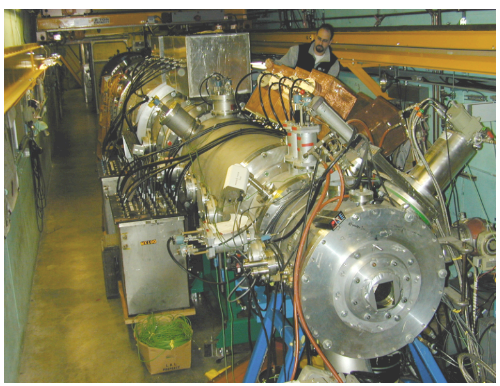
Hydrodynamics experiments relevant to HIF targets

-- Hydrodynamic stability, volumetric ion energy deposition, and Rayleigh-Taylor mitigation techniques

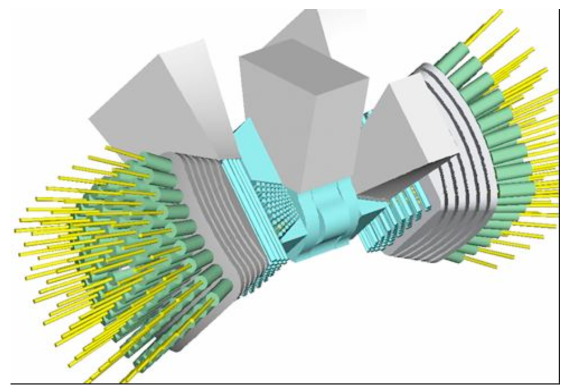
We look forward to resuming coordinated Heavy-Ion Fusion R&D, on drivers, chambers & targets that have to work together for IFE

(Slide from Snowmass 2002)

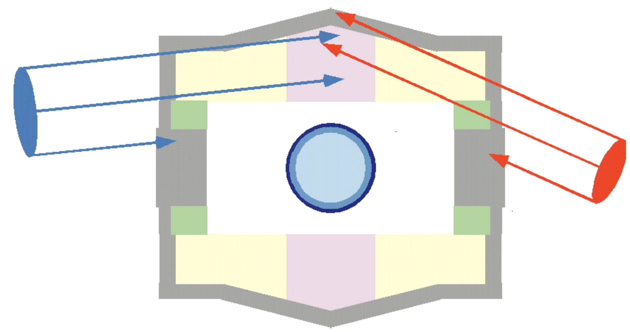




Beams at high current and sufficient brightness to focus



Long lasting, low activation chambers that can withstand 300 MJ fusion pulses @ 5 Hz



High gain targets that can be produced at low cost and injected

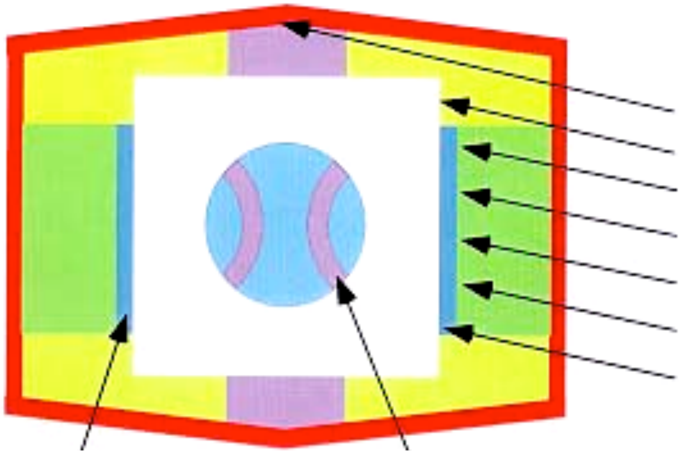
Outline

- Some basics & motivation
- Studies of the "driver"
  - Beam generation and acceleration
  - Pulse compression and focusing in plasmas
- Warm Dense Matter physics using beams
- Near-term plans
- New concepts, and a longer-range vision
- Concluding remarks

Some basics & motivation

"Conventional" HIF targets build on indirect-drive NIF target concepts

Hybrid target

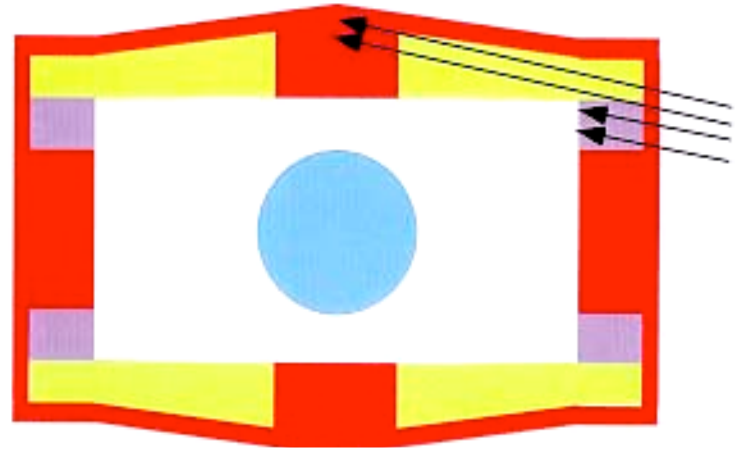


shine shield to control P_2

radiation shim to control early time P_4

Beam spot 3.8 mm x 5.4 mm
6.7 MJ beam energy
Gain = 58

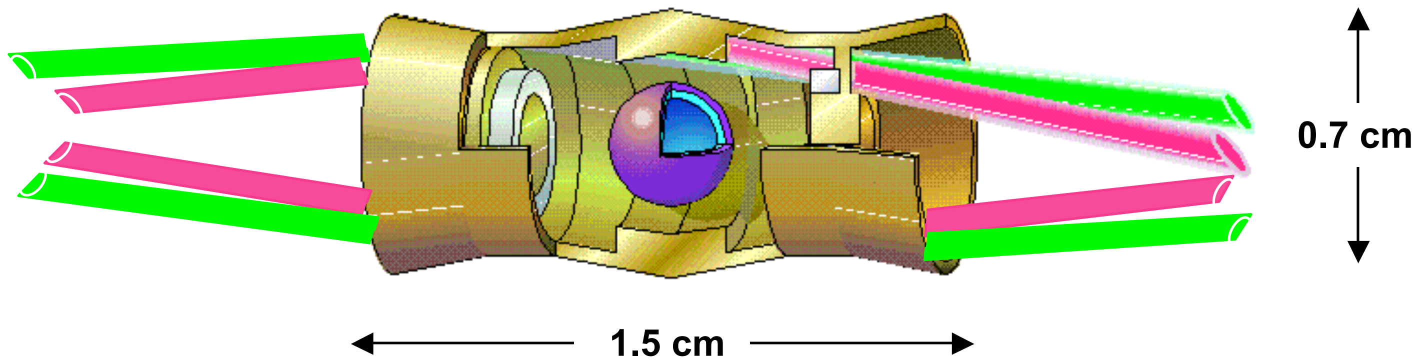
Distributed radiator targets



Original:
- Beam spot 1.8 mm x 4.1 mm
- 5.9 MJ beam energy
- Gain = 68

Close-coupled:
- Beam spot 1.0 x 2.78 mm
- 3.27 MJ beam energy
- Gain = 133

Target requirements imply multiple, intense beams



3 - 7 MJ x ~ 10 ns ⇒ *~ 500 Terawatts*

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1 - 10 GeV*

⇓

Example, for A ~ 200 → *~ 10^{16} ions*
1-2 kA / beam
~ 100 beams

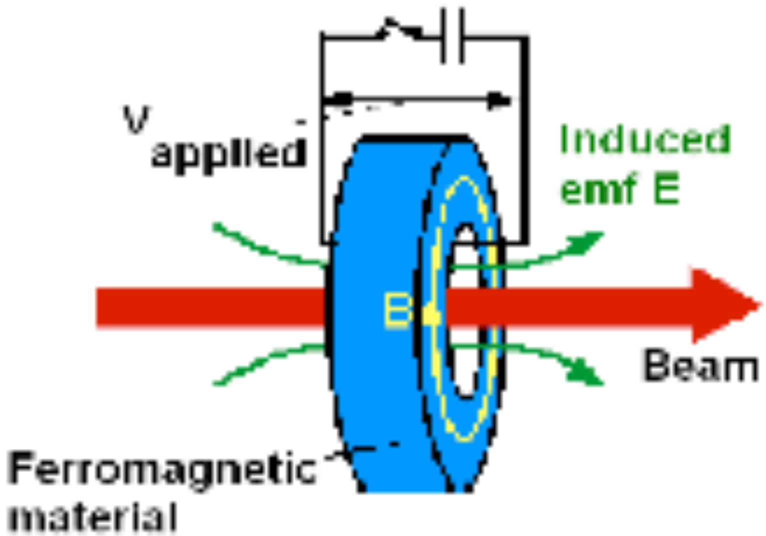
High currents → *space charge dominated* beam dynamics
→ nonneutral plasma physics
(a difference from high-energy physics accelerators)

Overseas HIF-related research is primarily rf-based, and exploits dual use of nuclear physics facilities

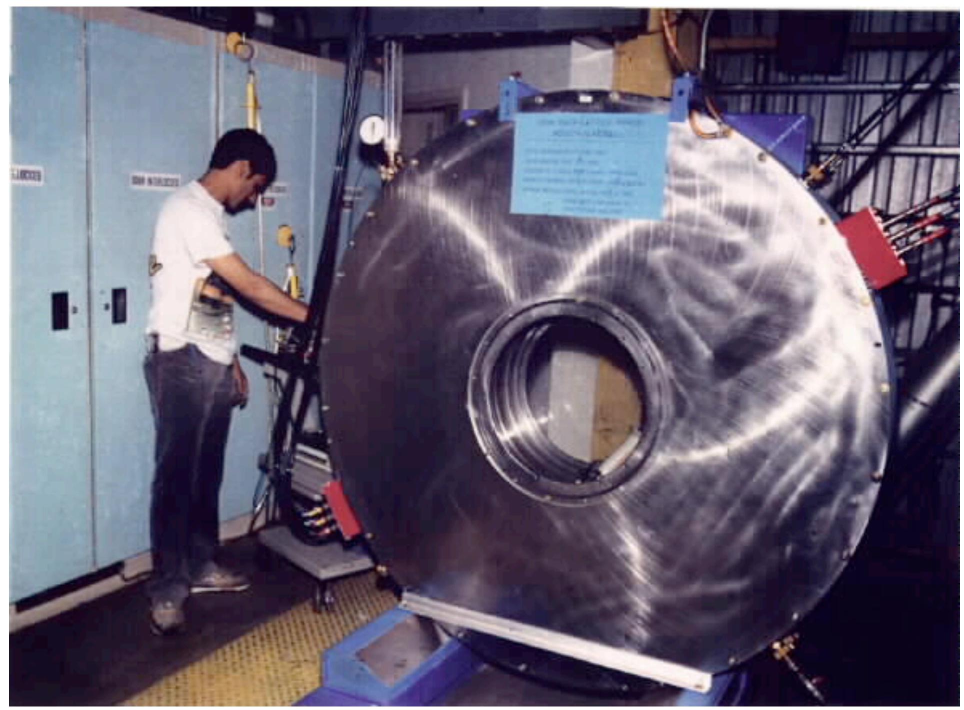
- **Accelerator facilities in progress**
  - GSI (Darmstadt): "FAIR" project ~10 y: > 10's of kJ, U^{28+} in 50 ns FWHM focused to ~ 1 mm spot, for 1.5 TW, 10 eV in solid target
  - ITEP (Moscow): TeraWatt Accumulator (planned): laser ion source (5×10^{10} ions of Al^{11+} or Co^{25+}) focused to ~ 1 mm spot, 100 ns, 1 TW
- **Target experiments**
  - ion energy deposition (GSI, Tokyo Inst. of Tech.)
  - ion transport through the target chamber (Utsunomiya U.)
  - Warm Dense Matter experiments (GSI, KEK)
- **Reactor studies in Russia**
  - interest in fission / fusion hybrids
  - work on "x-ray and ion debris impact on the first wetted wall of an IFE reactor"

US is pursuing induction linacs for HIF

- In contrast with RF systems, they naturally support the high line-charge densities required, without storage rings
- They are efficient - can couple a large fraction of stored energy into beam



- Beam is the “secondary” of a transformer



The reasons why past reviews supported HIF still apply

1. HIF builds upon a high-energy particle accelerator experience base for efficiency, pulse rate and durability.

2. Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron, and gamma radiation.

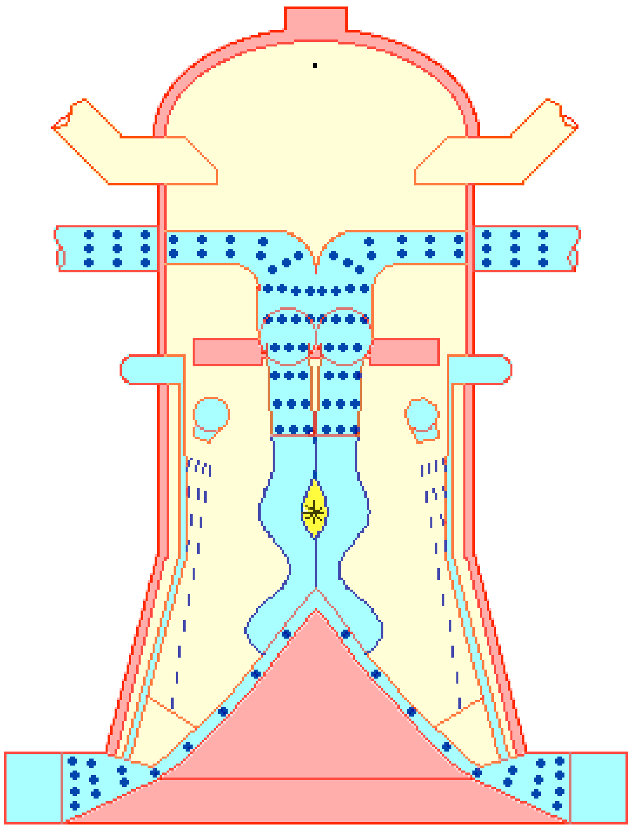
3. Thick-liquid protected target chambers with 30-year plant life may avoid the need for a long and costly fusion materials development program.

4. Several heavy ion power plant studies have shown attractive economics (competitive CoE with nuclear plants) and environmental characteristics.

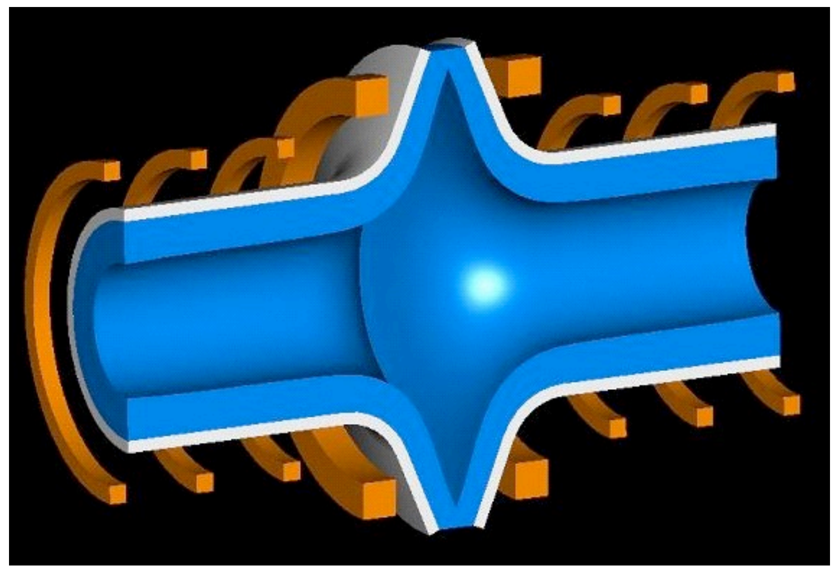
5. HIF target physics benefits from much of the target physics data being generated by NNSA.

Chambers protected with thick-liquid flows: liquid hydraulic dynamics experiments → better, faster, and cheaper than 200 dpa materials development!

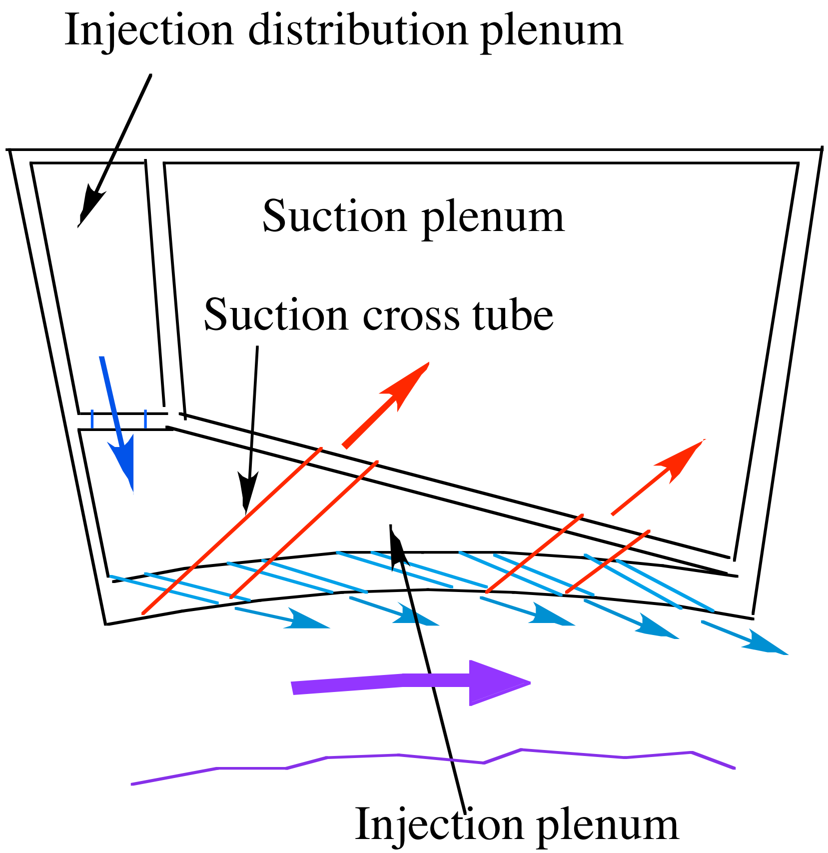
HYLIFE-II concept with oscillating jets of molten salt



Large liquid vortex chamber concept shields cusp-focusing magnets with low pumping power



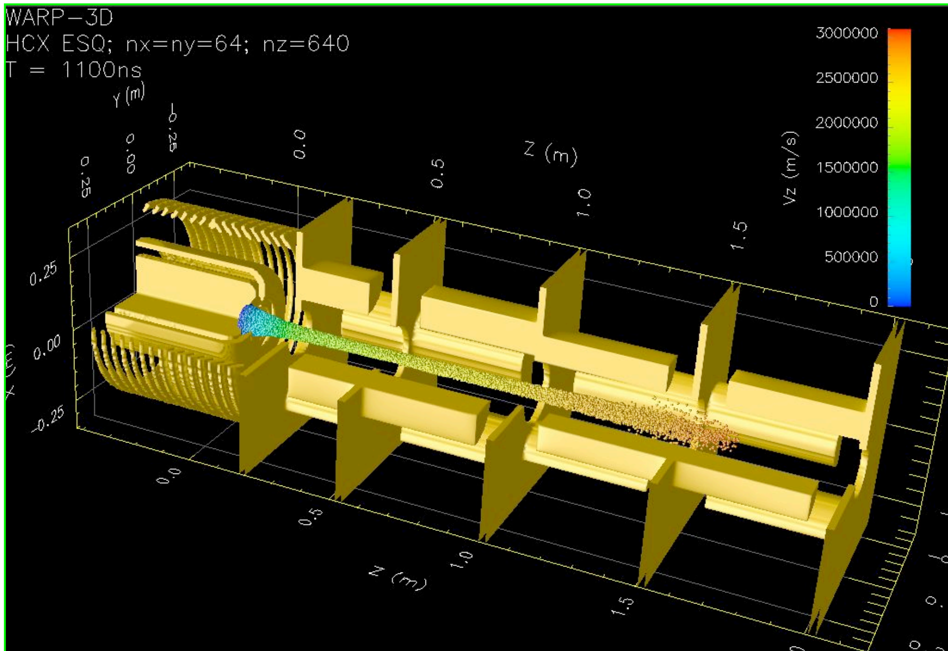
The current Large Vortex Experiment focuses on studies of a partial section



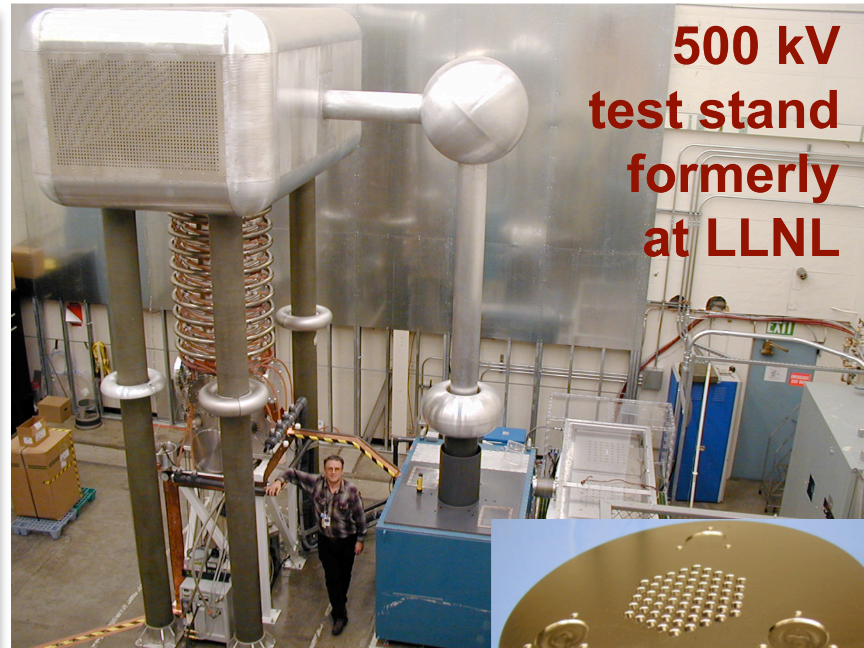
(composite of 2 slides from Per Peterson's talk at IFE ws, April 2007)

Beam generation & acceleration

Both ESQ and multibeamlet injector approaches can produce high-quality ion beams



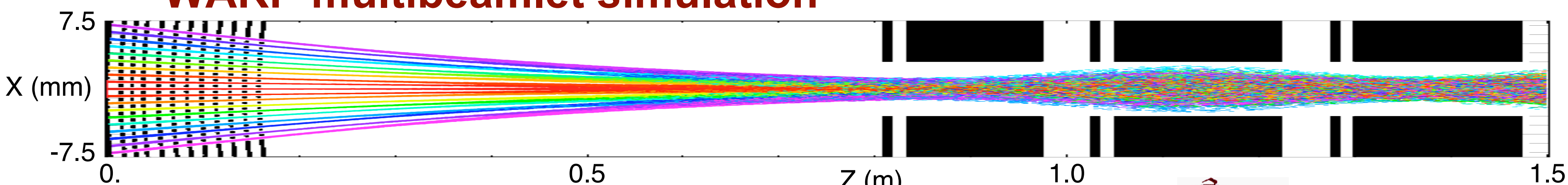
ESQ injector used in HCX at LBNL



500 kV test stand formerly at LLNL

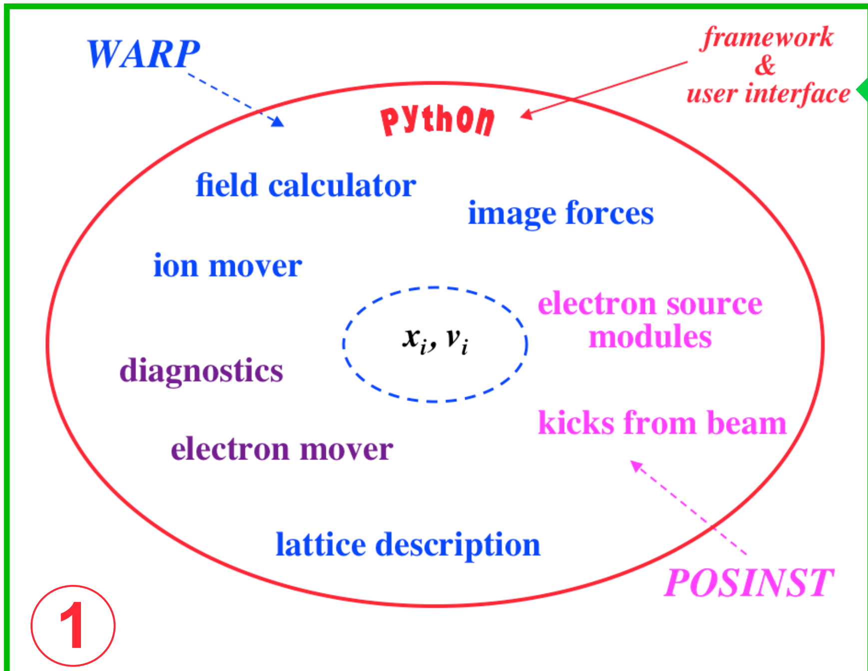
An aperture plate from the multibeamlet injector test

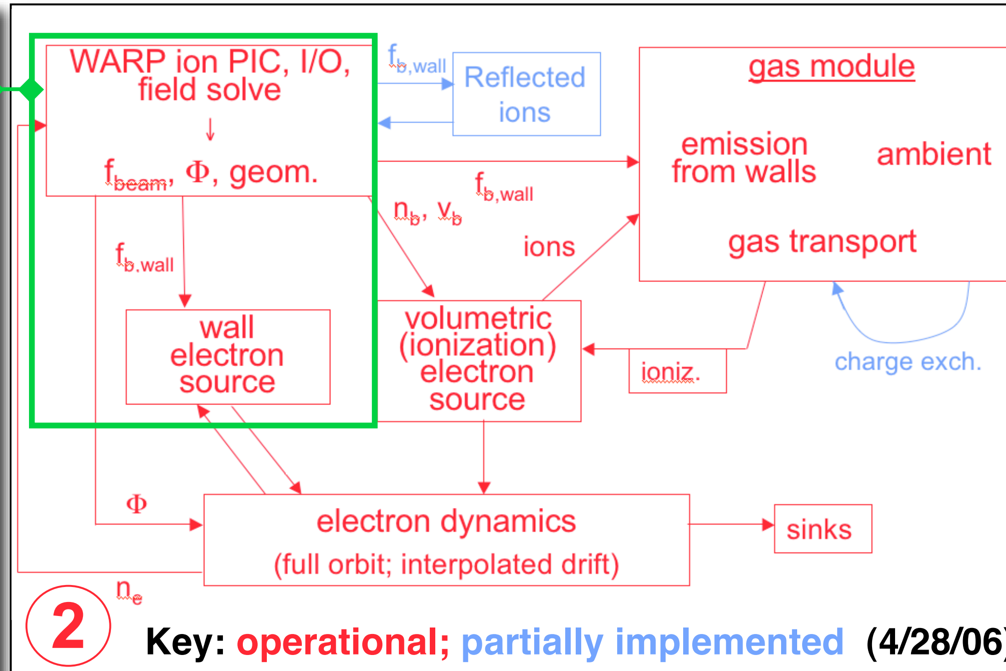
WARP multibeamlet simulation



WARP code suite is unique

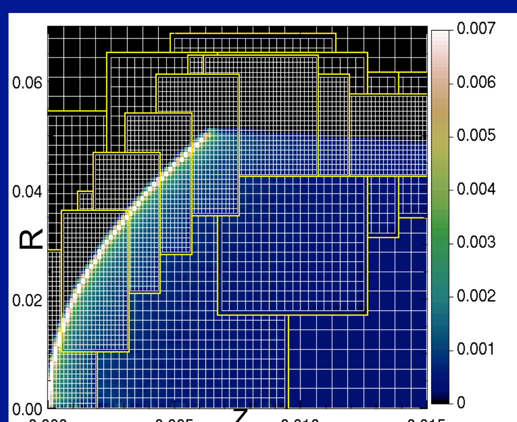
merge of WARP & POSINST + new e⁻/gas modules





+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

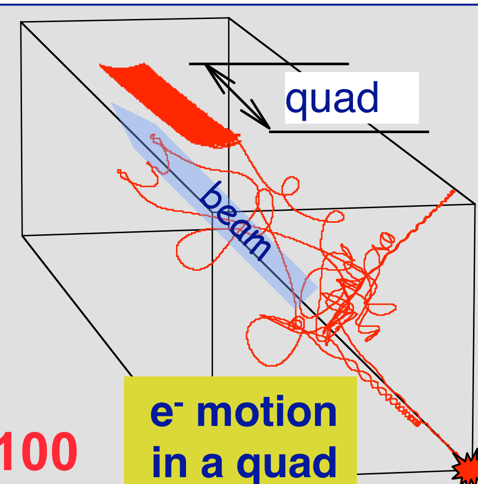


Speed-up

3 x10-10⁴

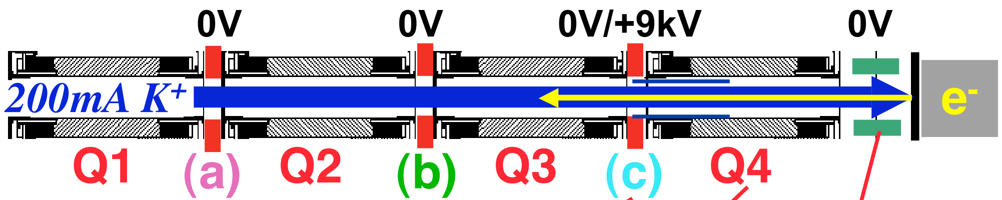
+ New e⁻ mover

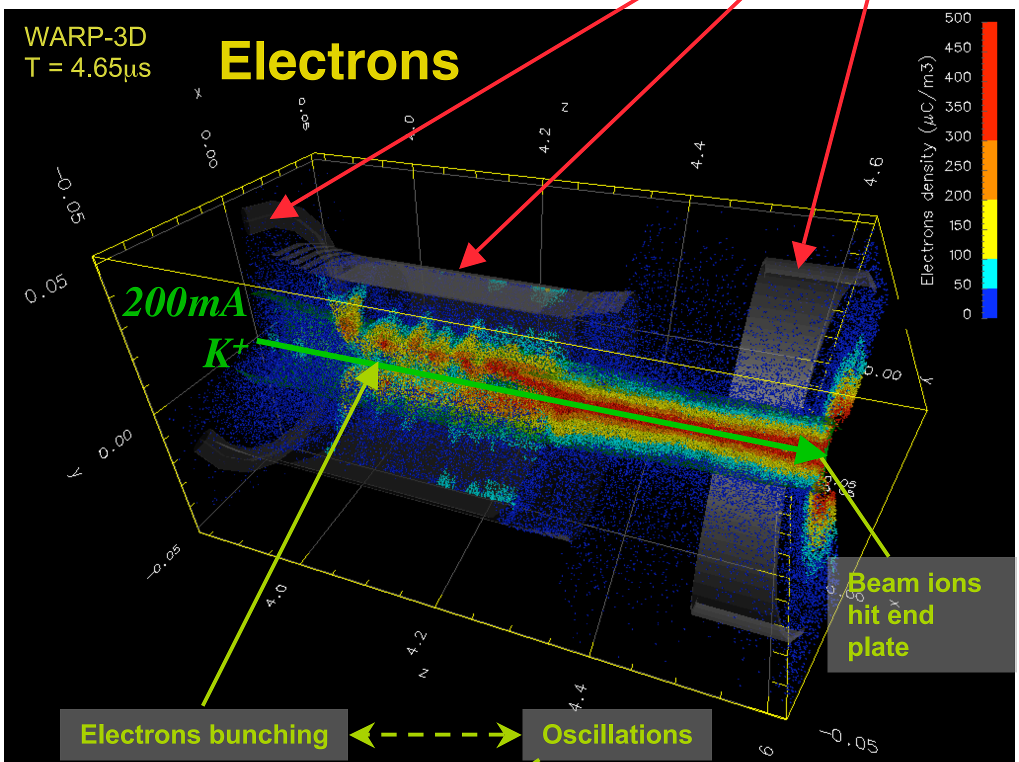
Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

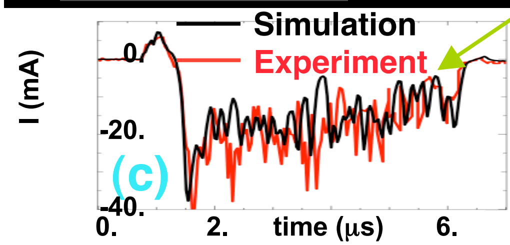


4 Speed-up x10-100

High Current Experiment (HCX) benchmarks our unique set of models for electron cloud and gas effects

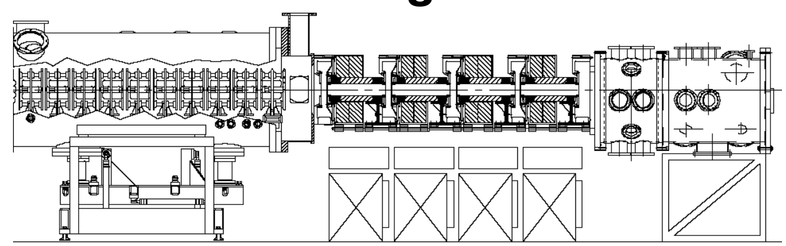






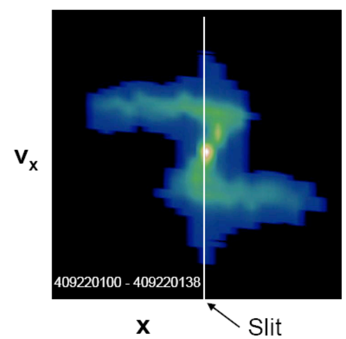
6 MHz oscillations in (C) in simulation AND experiment

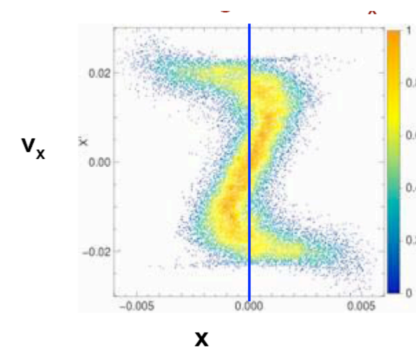
electrostatic **magnetic**



v_x vs. x phase space

measured **simulated**

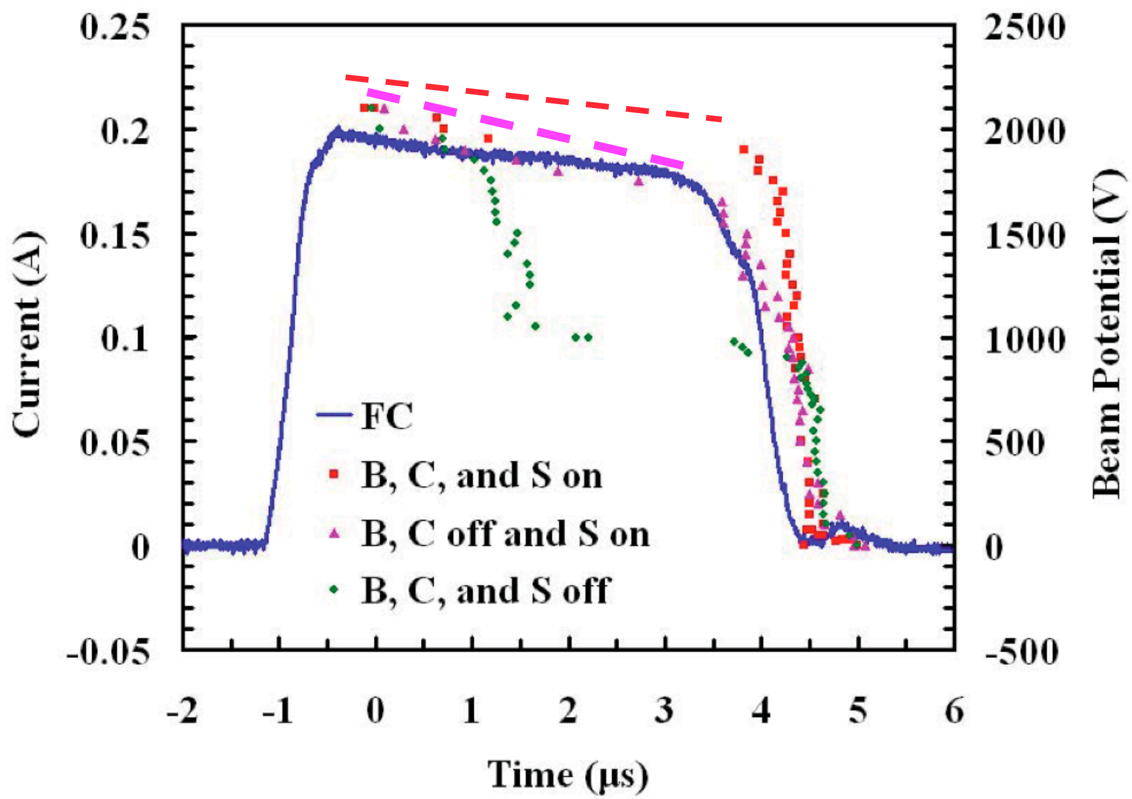




Electron and gas cloud modeling is critical to all high current accelerators, including LHC, ILC …and future fusion drivers

1st detailed measurements of electron density in an ion beam*

- **Retarding Field Analyzer RFA measures maximum expelled ion energy E_i (scan bias on successive pulses)**
- **$E_i=\phi_b$, peak beam potential, which is depressed by e-**
- **Clearing electrode current corroborates n_e**



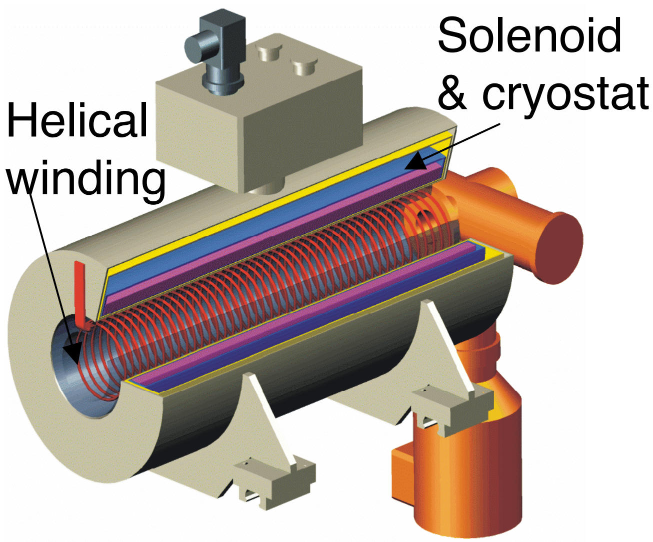
Absolute electron fraction can be inferred from RFA and clearing electrodes

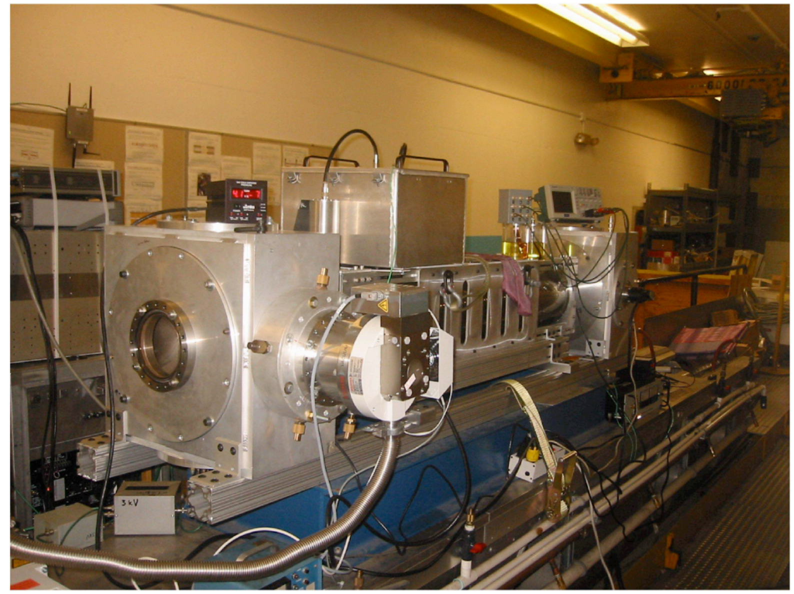
Beam neutralization	B, C, & S on	B, C, off S on	B, C, S off
Clear. Electr. A	~ 7%	~ 25%	~ 89%
RFA	(~ 7%)	~ 27%	~ 79%

*Michel Kireeff Covo, PRL 97, 054801 (2006)

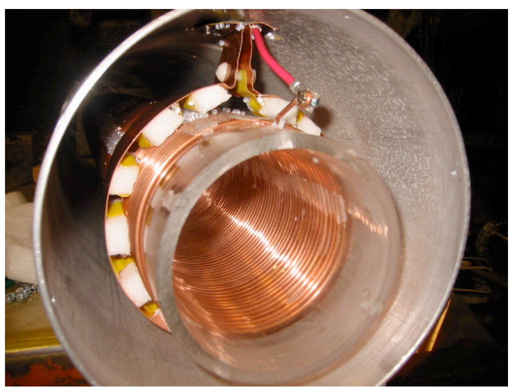
A Pulse Line Ion Accelerator* (PLIA) may serve as the front-end to an upgraded NDCX; it might also accelerate beam bunches inexpensively

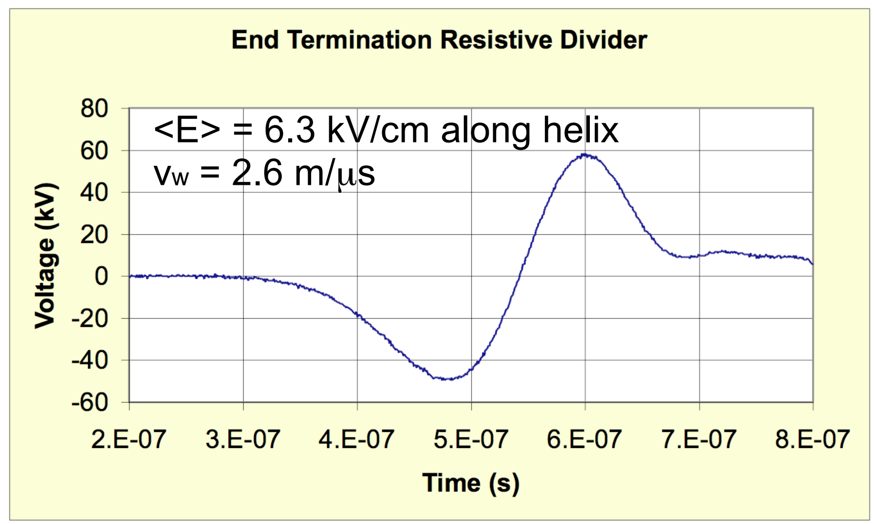
Accelerator cell concept





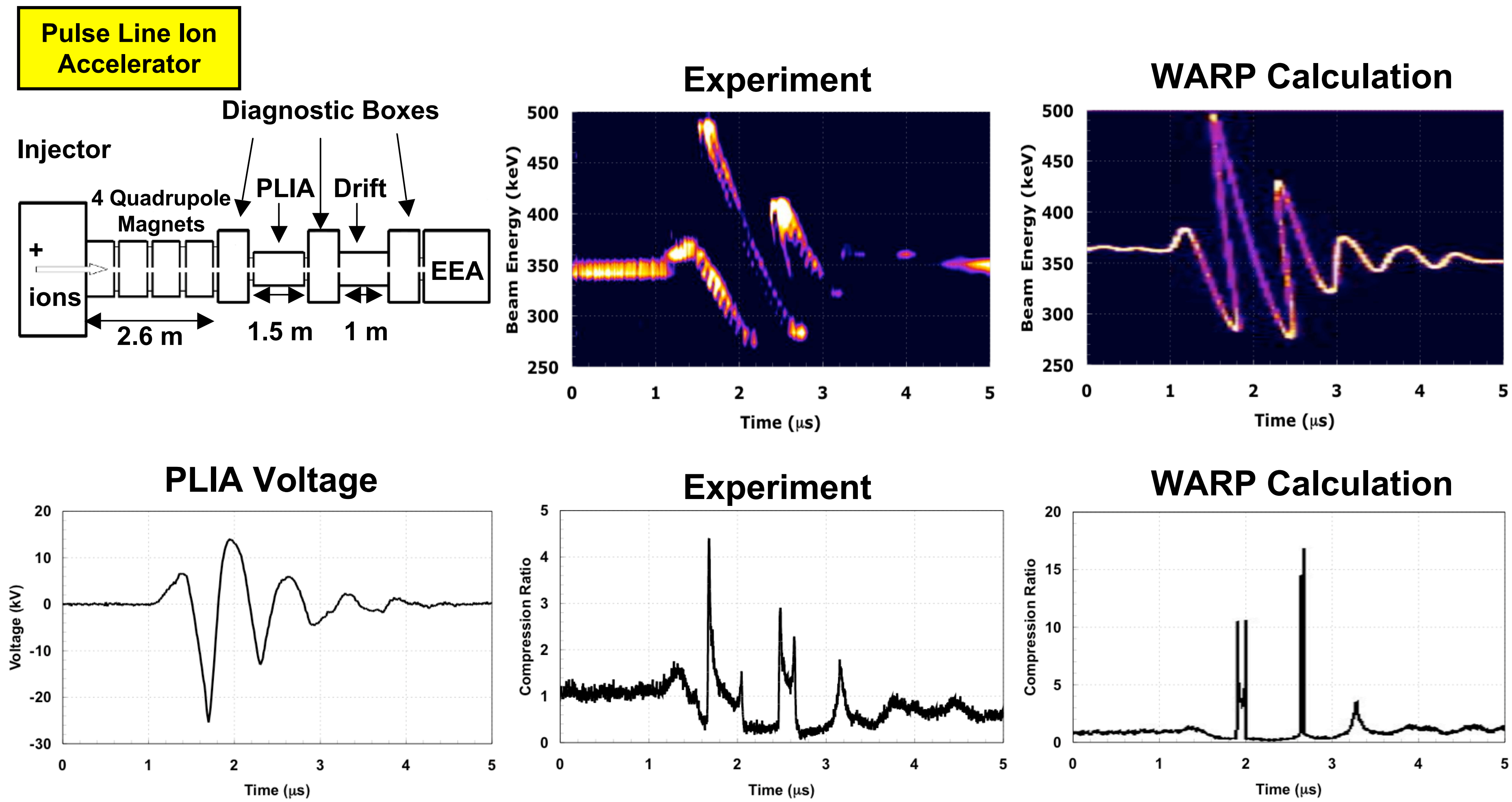
Compact
transformer
coupling
(5:1 step-up)





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

PLIA test displayed acceleration, deceleration, and longitudinal bunching



Slide courtesy Josh Coleman

Beam pulse compression & focusing in plasmas

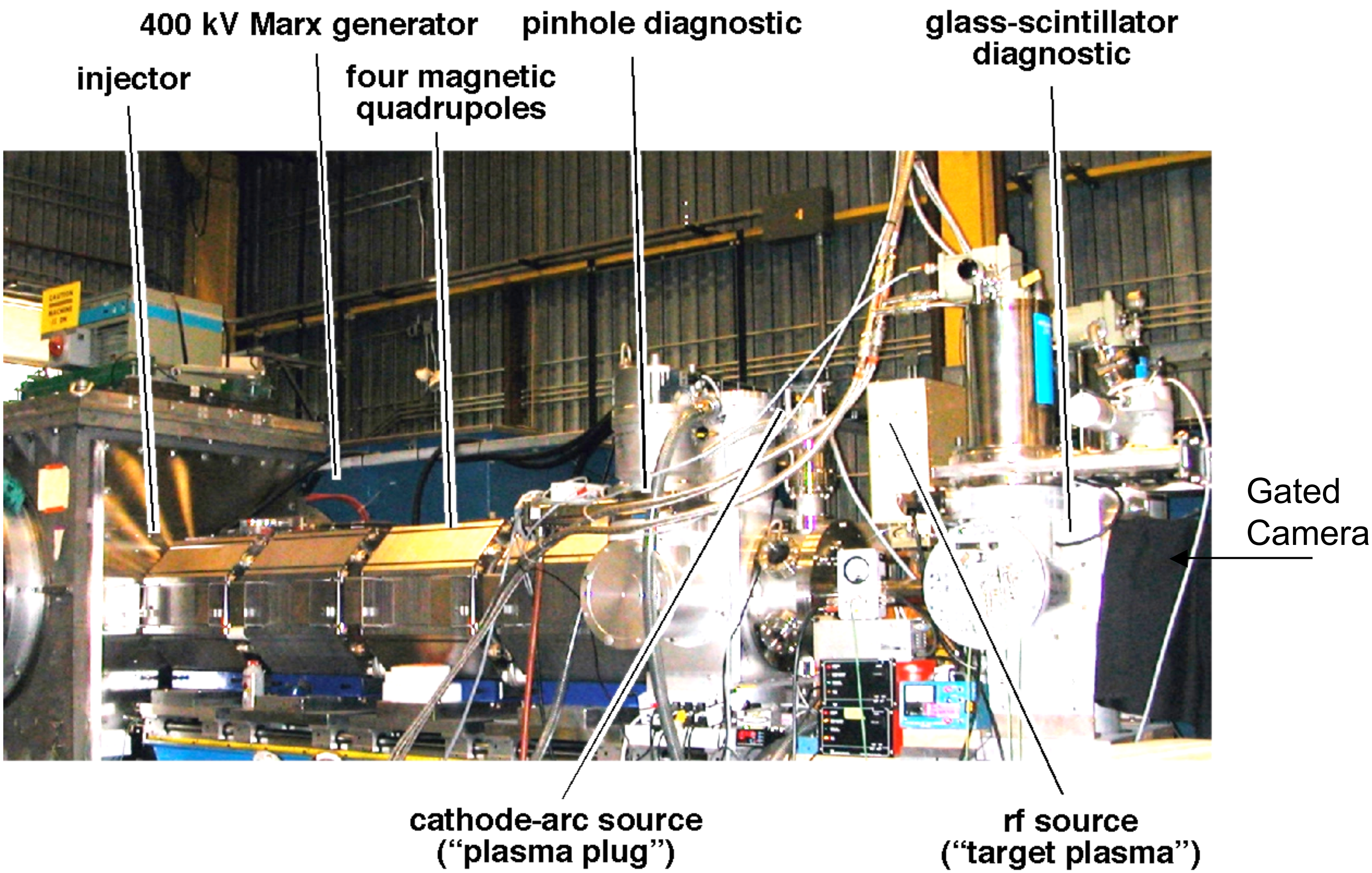
HIF/WDM beam science: neutralized focusing and drift compression are now being tested for use in WDM and HIF

- Both techniques virtually eliminate the repulsive effects of space charge on transverse and longitudinal compression

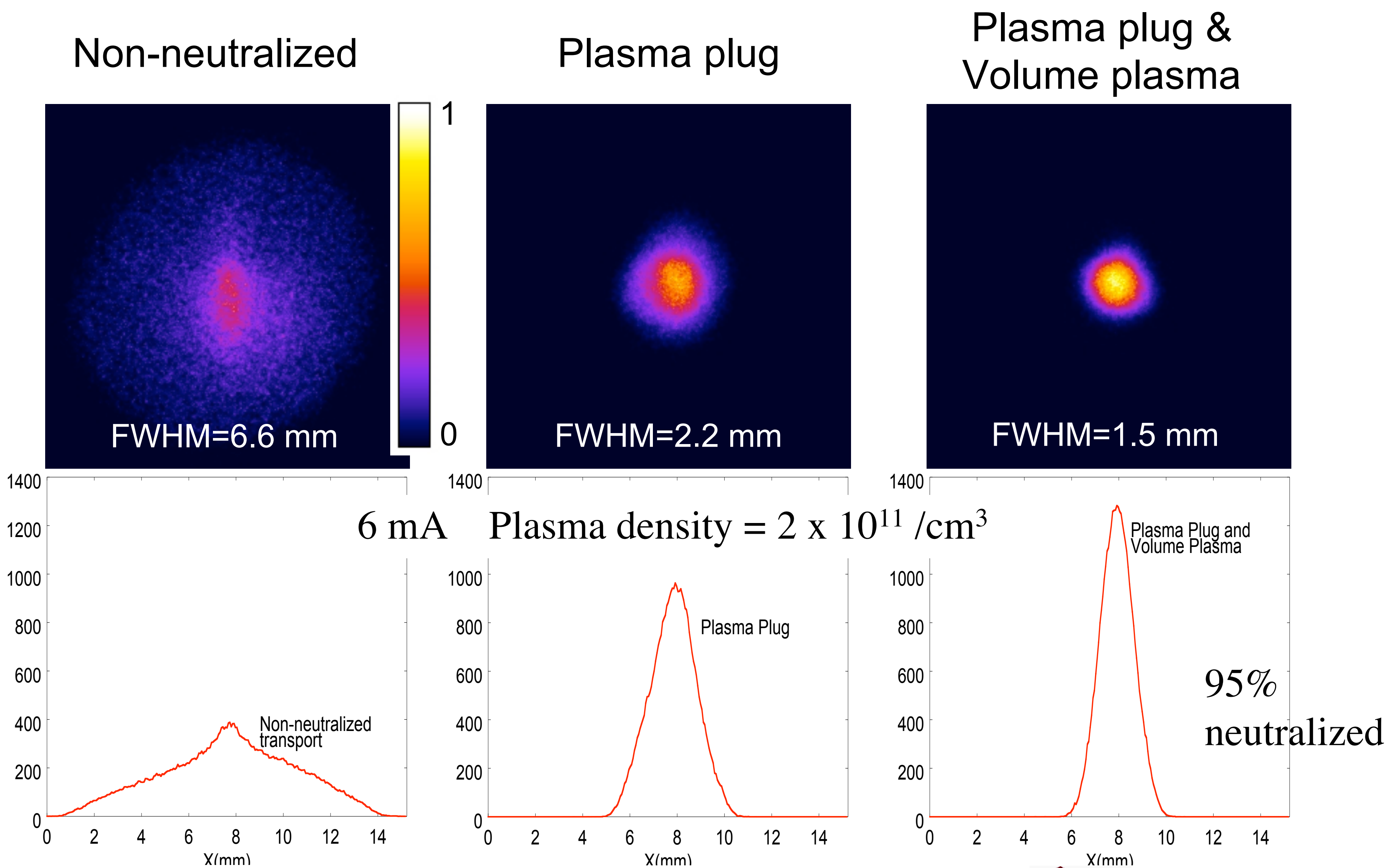
- Transverse compression (= focusing the beam to a small spot, raising the watts/cm^2): Recent VNL experiments, eg. scaled final focus experiment, (MacLaren et al 2002), NTX (Roy et al 2004), and current NDCX-1 have demonstrated benefits of neutralization by plasmas, also required for HIF.

- Longitudinal compression (= raising the watts): WDM experiments require very short, intense pulses (<~ 1 ns) (shorter than needed for HIF). Neutralization allows high current/high power beams. Modular HIF concept also pushes limit of high current.

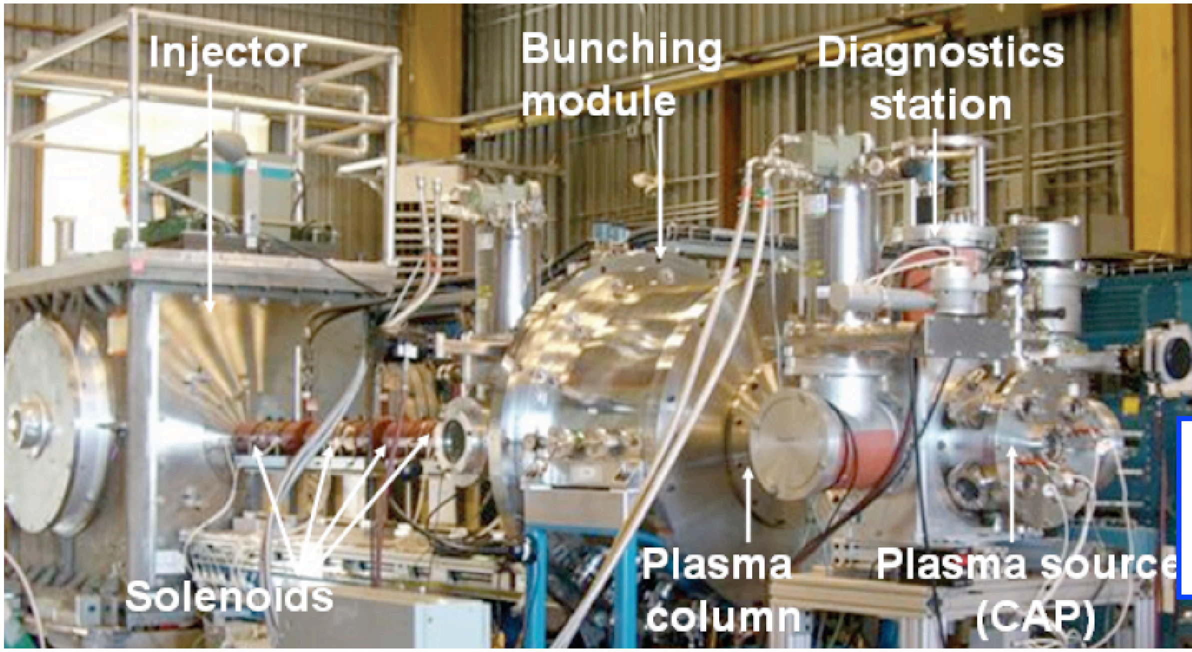
The Neutralized Transport Experiment (NTX) examined the benefits of plasma for focusing

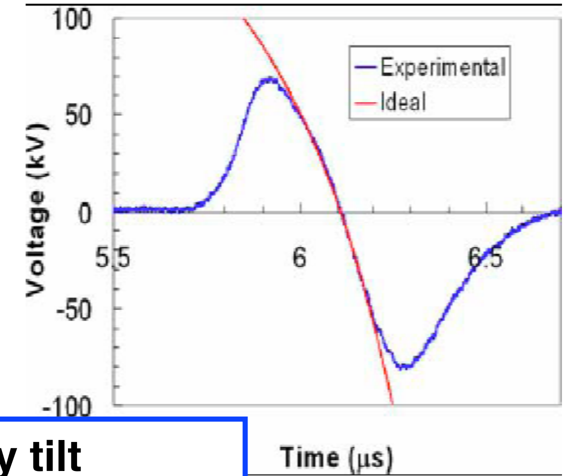


NTX experiments showed the reduction of spot size achievable using plasma plug and volume plasma



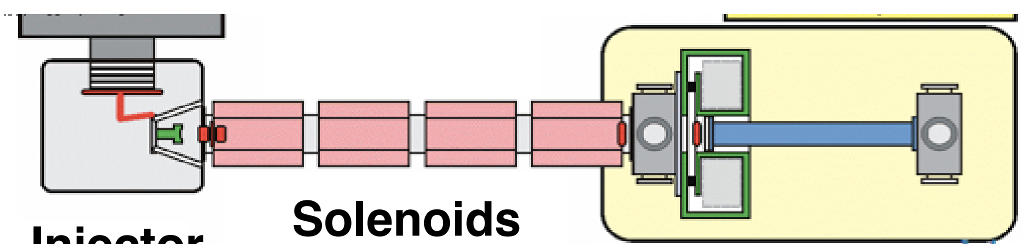
NDCX-1 has achieved > factor 70 pulse compression, and kinematically limited spot radius, consistent w/ simulations





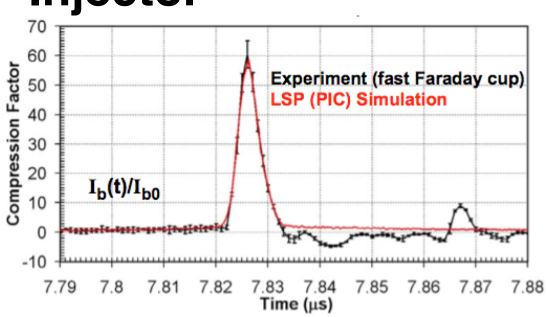
Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

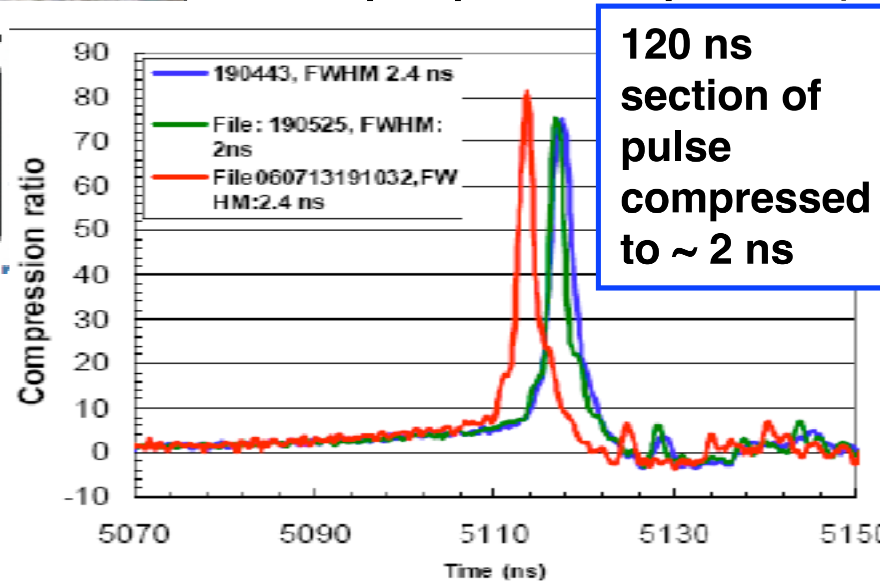


Injector

Solenoids



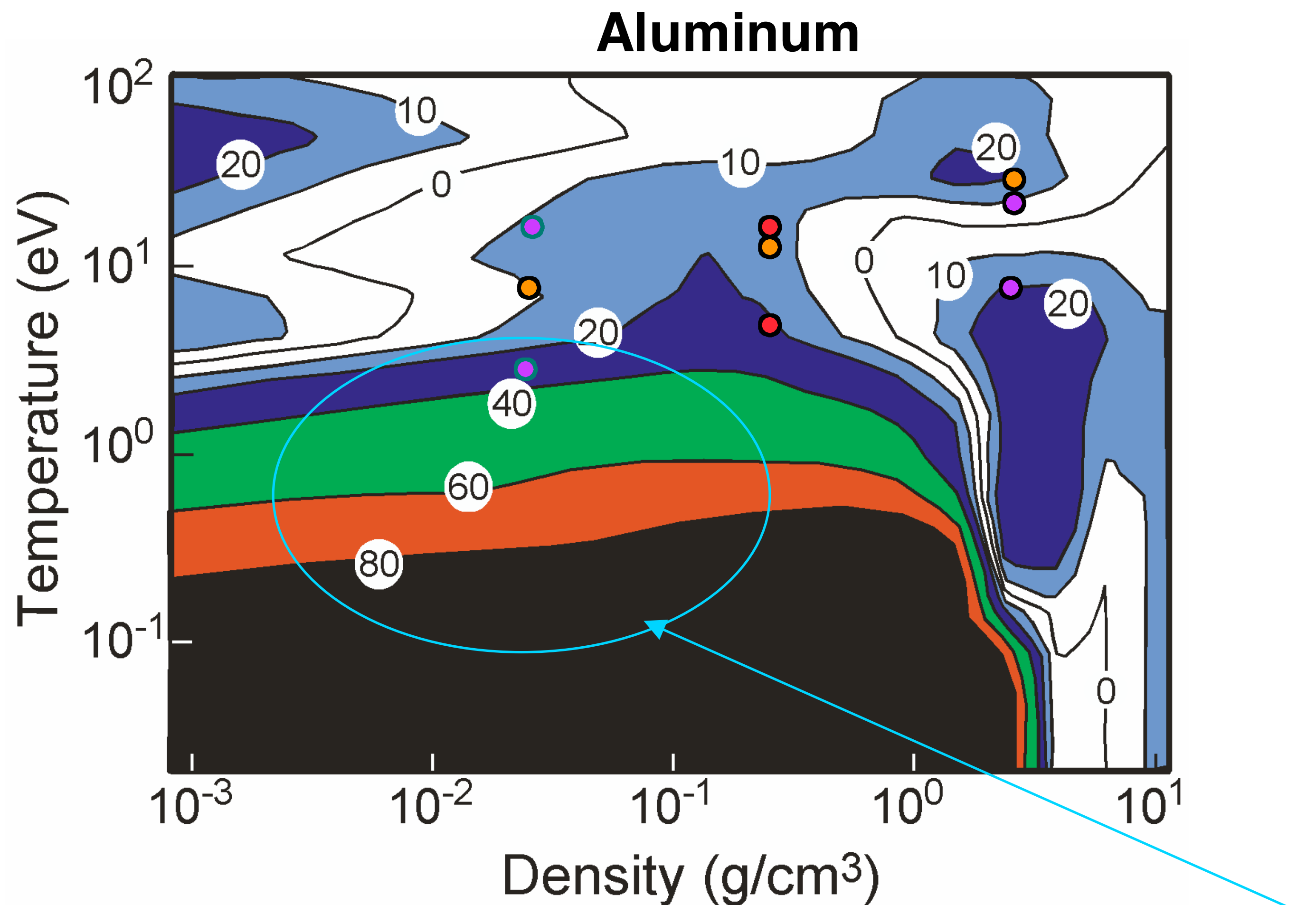
Plasma column/ Neutralized drift section (2 m)



120 ns section of pulse compressed to ~ 2 ns

Warm Dense Matter physics using beams

Strongly coupled plasmas at 0.01 - 0.1 of solid density are interesting areas to measure EOS



Numbers are % disagreement in EOS models; they are large where there is little or no data (Courtesy of Richard W. Lee, LLNL)

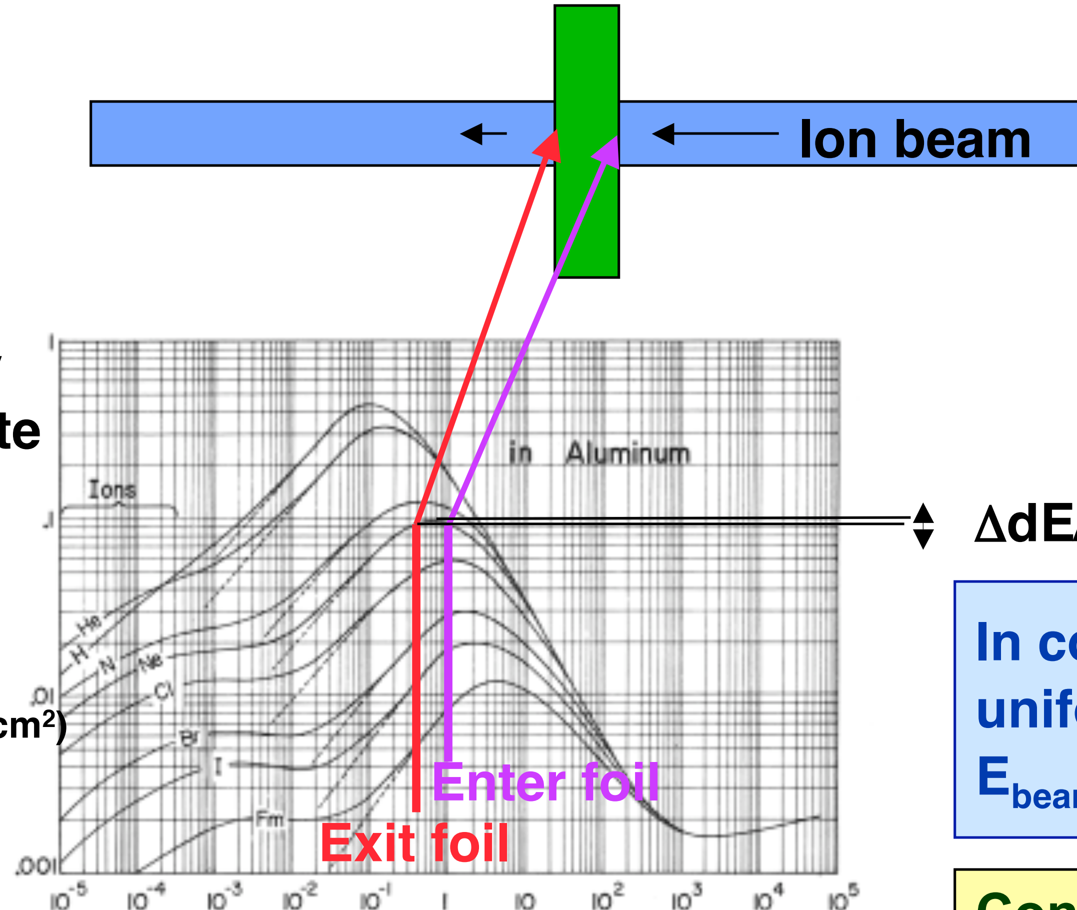
HIFS-VNL WDM strategy: maximize uniformity and use of beam energy by operating at Bragg peak

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

Energy loss rate

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

(MeV/mg cm^2)



Energy/Ion mass (MeV/amu)

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

Example:
Ne beam on Al
$E_{entrance}$=1.0 MeV/amu
E_{peak}= 0.6 MeV/amu
E_{exit} = 0.4 MeV/amu
$(\Delta dE/dX)/(dE/dX) \approx 0.05$

In contrast, GSI achieves uniformity by operating at E_{beam} >> Bragg peak

Concept: L. R. Grisham, Phys. Plas. 11, 5727 (2004)

Require ~ ns pulses to minimize hydro motion

 dEdX figure: L.C Northcliffe & R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

A user facility for ion beam driven HEDP/WDM will have unique characteristics

Precise control of energy deposition

Large sample sizes compared to diagnostic resolution volumes (~ 1's to 10's μ thick by ~ 1 mm diameter)

Uniformity of energy deposition (<~ 5%)

Ability to heat all target materials (conductors and insulators, foams, powders, ...)

Pulse long enough to achieve local thermodynamic equilibrium

A benign environment for diagnostics

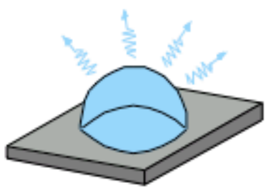
High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers

Intense heavy ion beam is an excellent tool to generate large-volume HED samples

HIGH ENERGY DENSITY MATTER

(WARM DENSE MATTER)



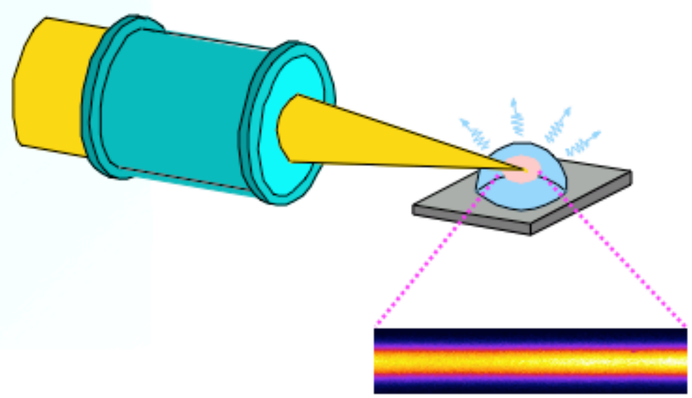
T ~ 2,000 – 200,000 K

ρ ~ solid density

P ~ kbar, Mbar

Intense heavy ion beams:

- ☑ large volume of sample (mm^3)
- ☑ fairly uniform physical conditions
- ☑ high entropy @ high densities
- ☑ high rep. rate and reproducibility
- ☑ any target material



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

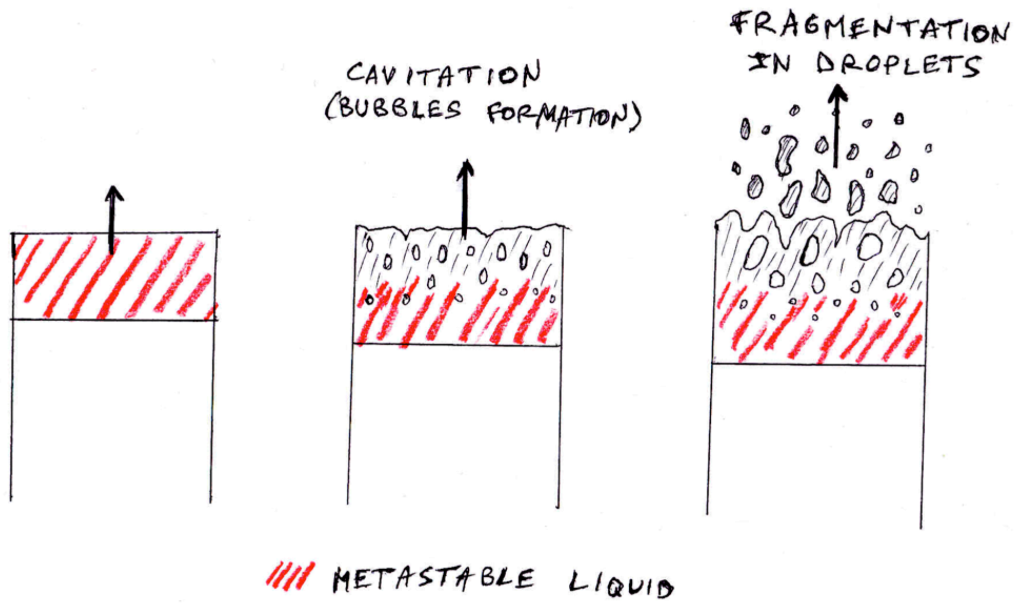
	Target temp.	NDCX-1 or HCX	NDCX-2
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	Low (0-0.4 eV)	√	
Measure target temperature using a beam compressed both radially and longitudinally	Low	√	
Thin target dE/dx, energy distribution, charge state, & 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

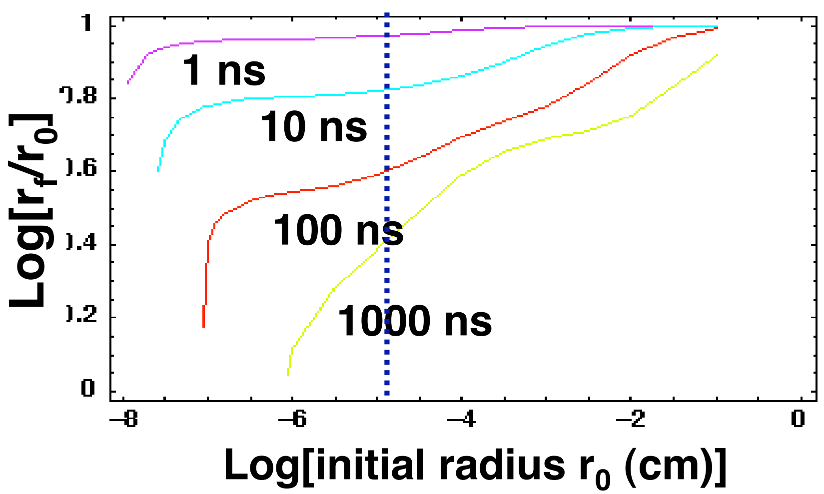
Formation of droplets during expansion of foil is being investigated

Foil is first entirely liquid then enters two phase regime

[J. Armijo, master's internship report, ENS, Paris, 2006.]

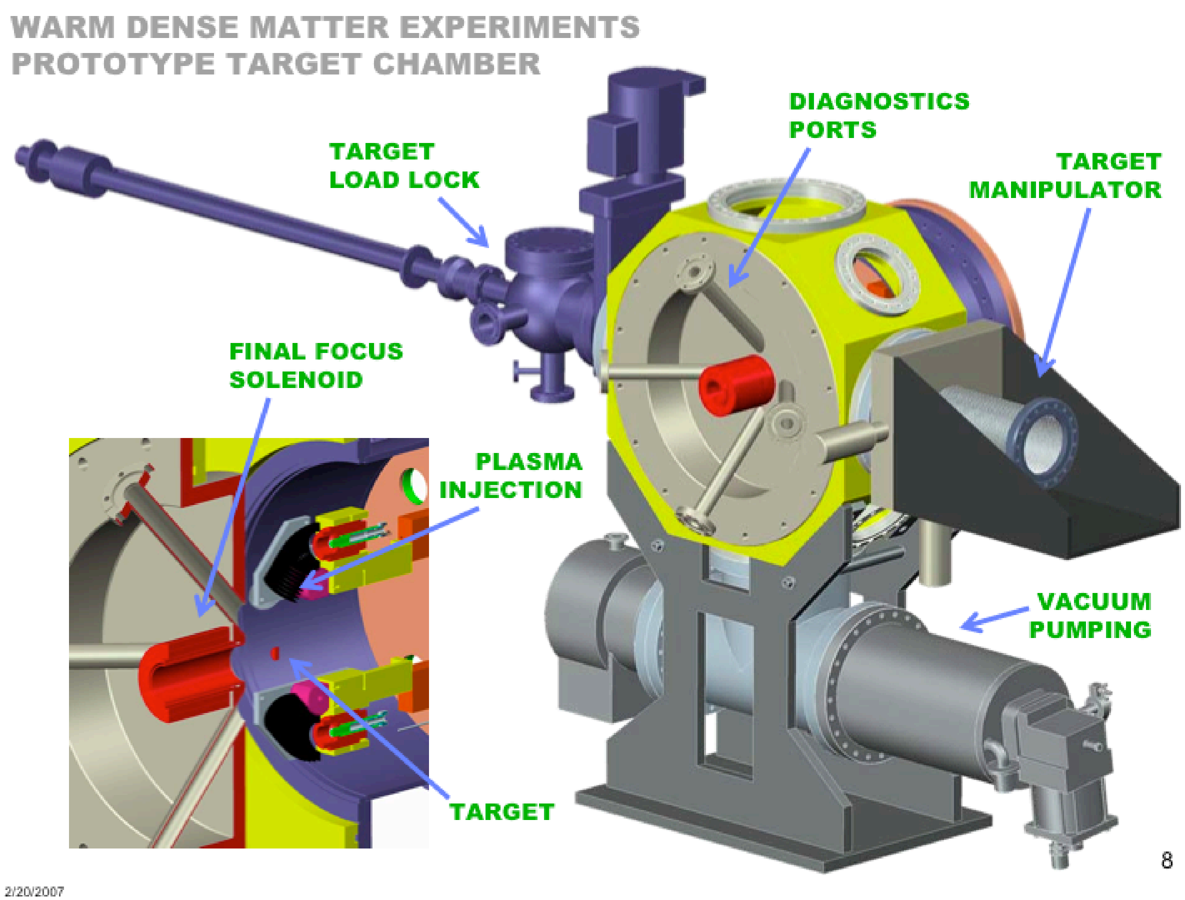


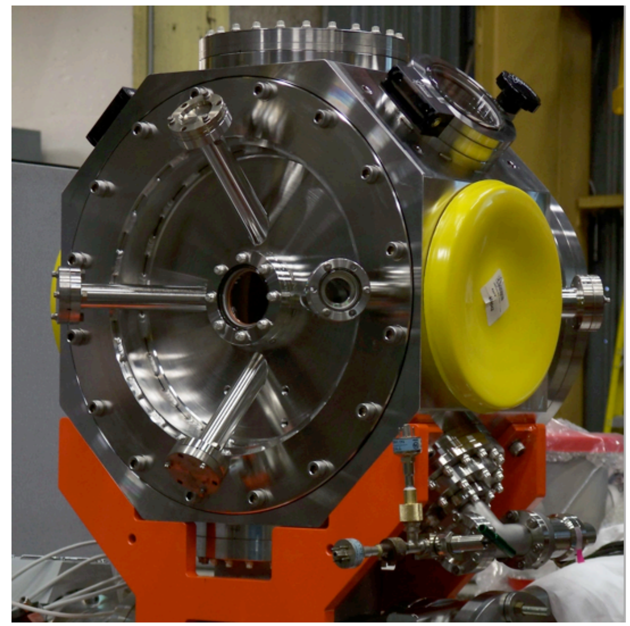
C. Debonnel and A. Zeballos are incorporating a model for surface effects into hydrodynamics code Tsunami



Evolution of droplet radius [Armijo et al., APS DPP 2006, and in prep.]

WDM target chamber is designed and being fabricated





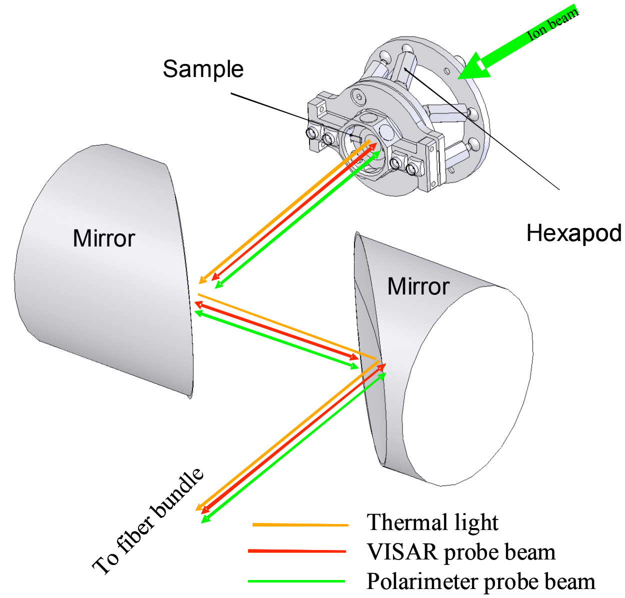
Target chamber as of

April 19, 2007

We are developing target diagnostics for first target experiments on NDCX-I

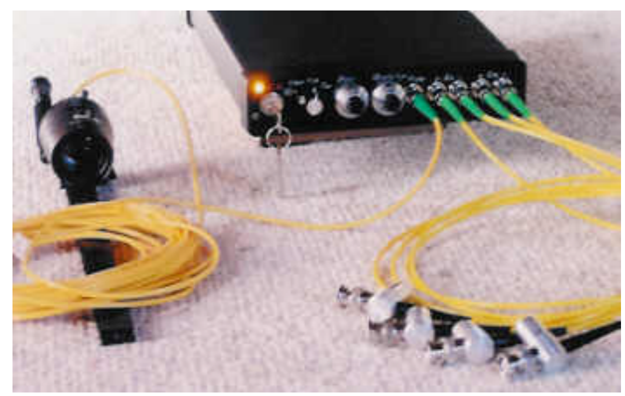
Fast optical pyrometer – ***now being assembled***

- **New design by P. Ni for fast response (~150 ps) and high sensitivity**
- **Temperature accuracy 5% for T>1000 K**
- **Spatial resolution about 10 micron at 1 eV**



Fiber-coupled VISAR system – ***now under test***

- **ps resolution**
- **1% accuracy**

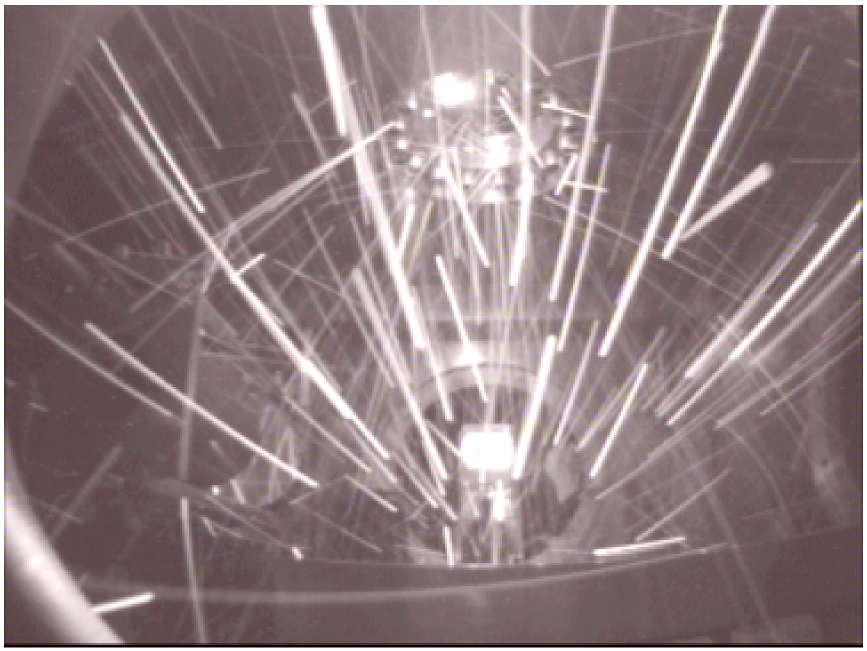


Hamamatsu visible streak camera with image intensifier

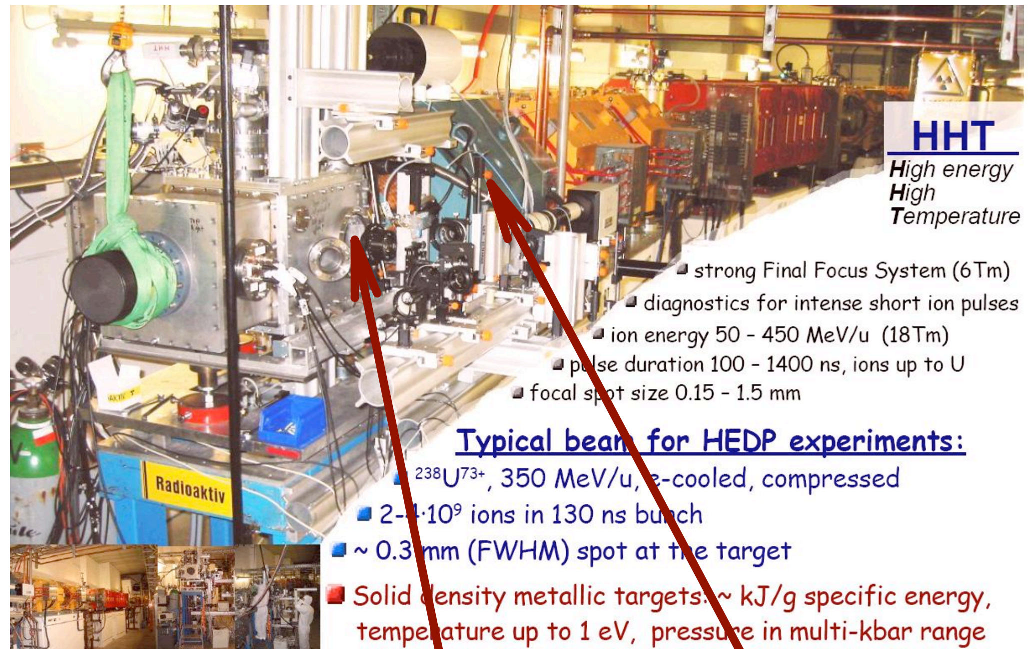
- ***arrived Feb. 2007***
- **ps resolution**

All ready by end of summer

Joint experiments with GSI are developing diagnostics and two-phase EOS models for isochoric heating & expansion, relevant to indirect drive HIF target radiators and droplet formation



Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 100 ns, 10 J heavy ion beam to 1 eV in joint experiments at GSI, Germany

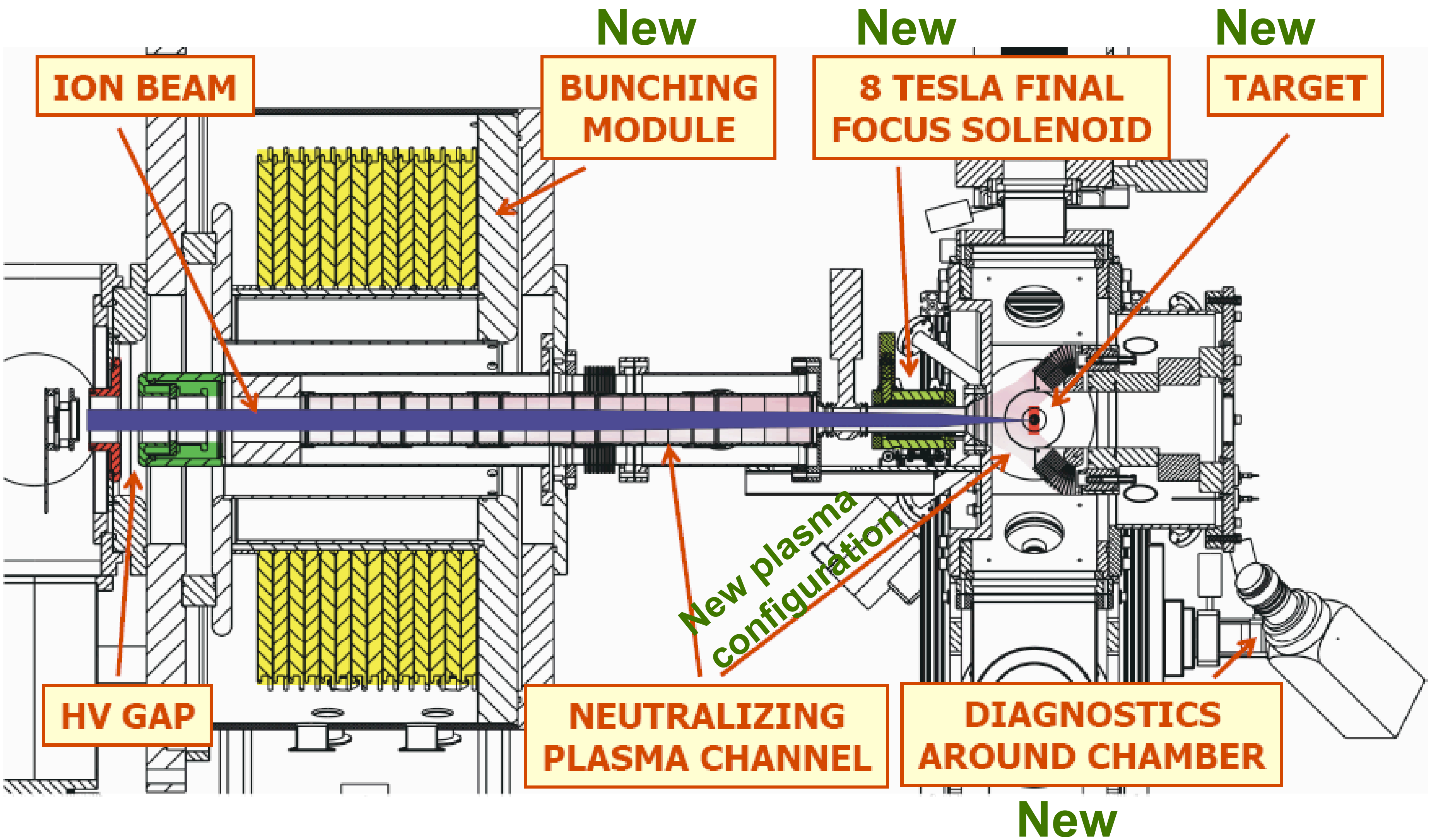


Final focus magnets

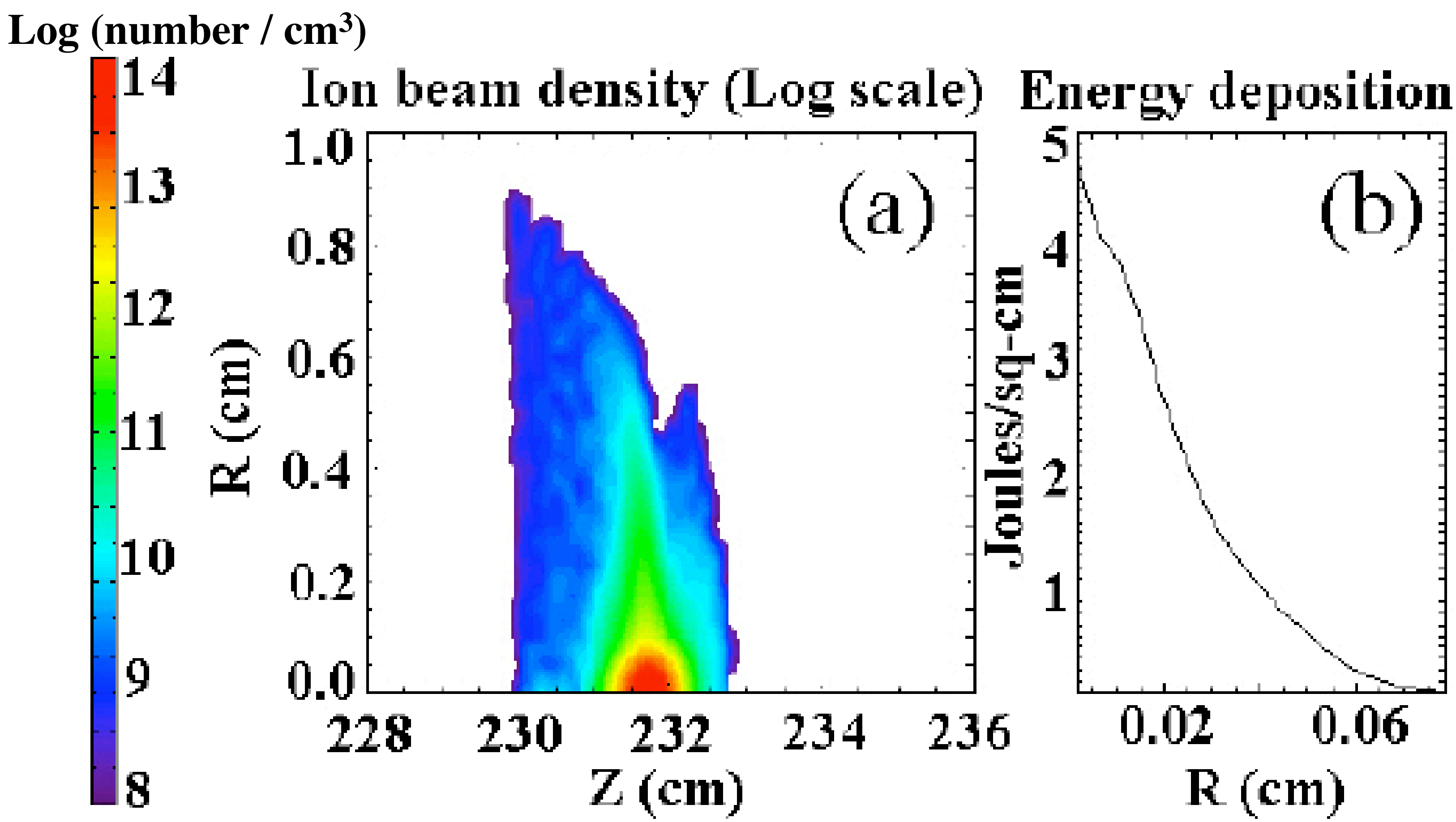
Optical diagnostic windows need to be periodically cleaned of target debris and sometimes replaced.

Near-term plans

Improving NDCX-I for FY08-09 warm dense matter experiments



With new bunching module to be installed later this year, plus a higher field 15T focusing magnet in FY09, NDCX-I is predicted to support > 0.5 eV target conditions with 2 ns pulses

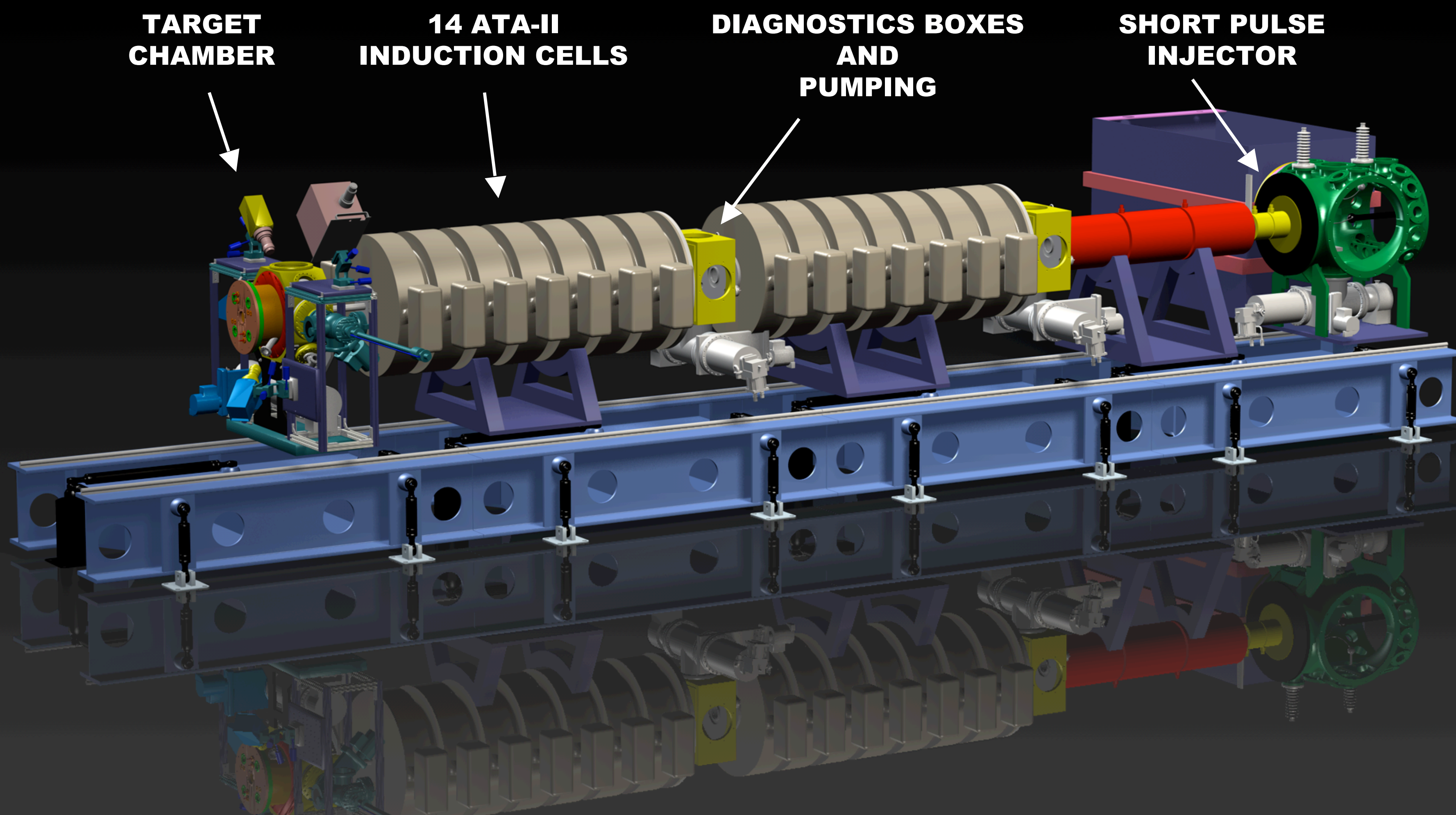


Actual achievable intensity on WDM targets in FY09 will range between 0.15 J/cm² (with an 8T magnet) and this simulation of best possible case ~ 4 J/cm².

Target temperature ~ 1 eV/ per J/cm² for NDCX-I ions, neglecting hydro motion (John Barnard's model predictions)

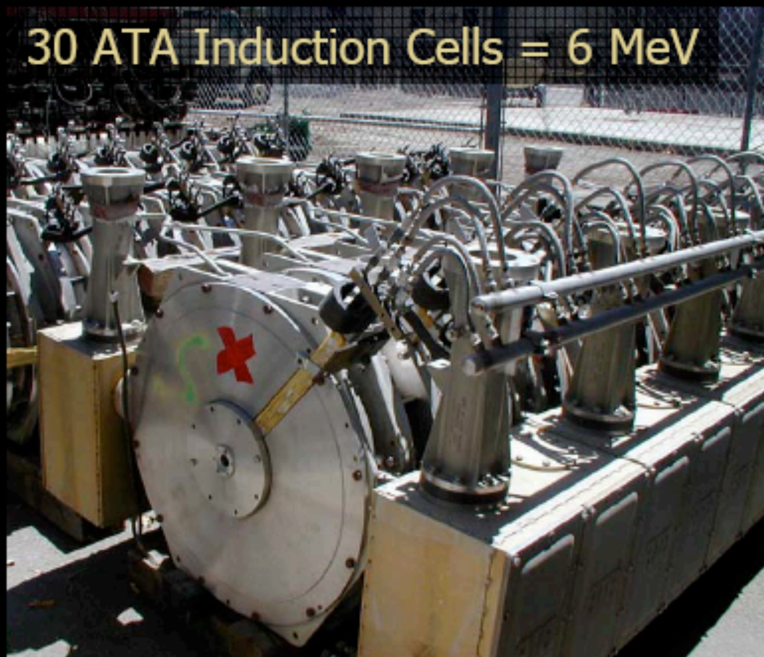
NDCX-II will use existing equipment for isochoric WDM physics and double-pulse direct-drive experiments

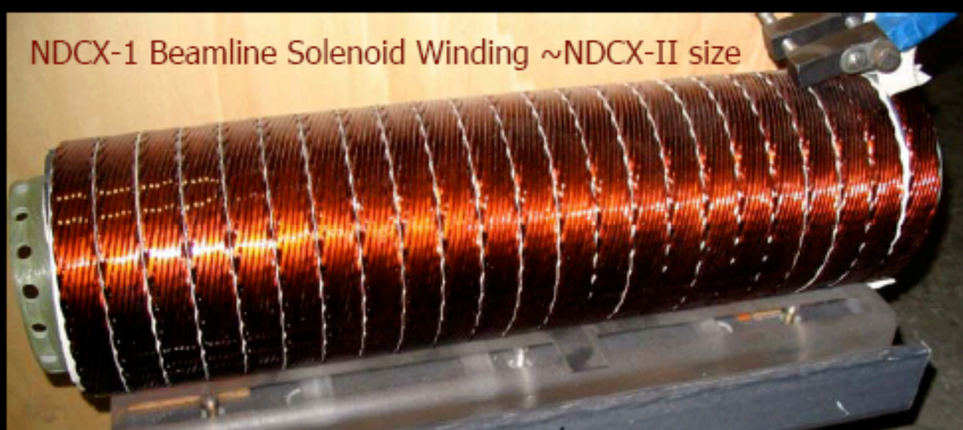
It will meet the pre-requisite set in DOE's "critical decision 0" for IB-HEDPX



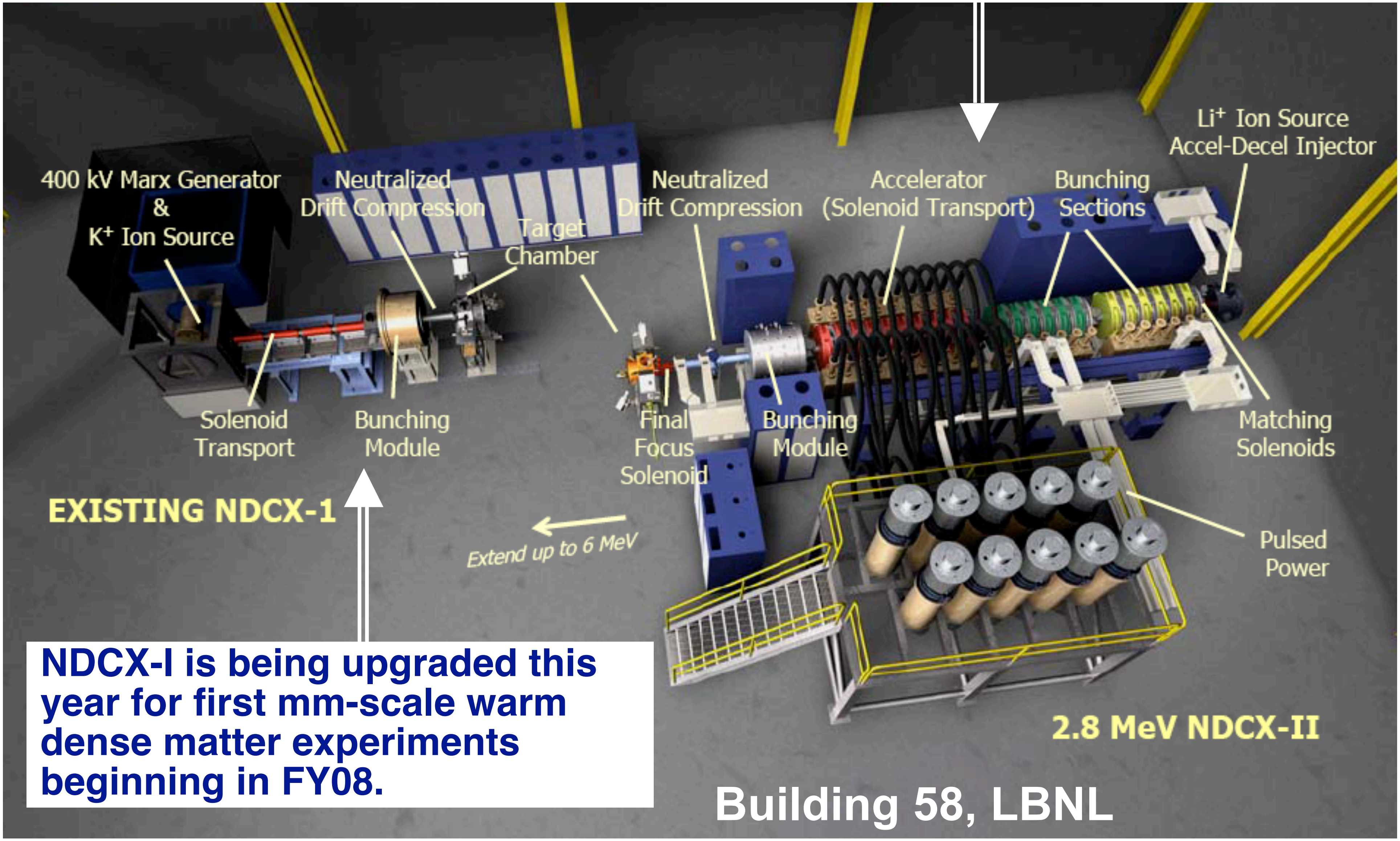
Largest cost is replacement solenoids (1.5 to 2 T); 6m x $100k/m ~ $600k

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



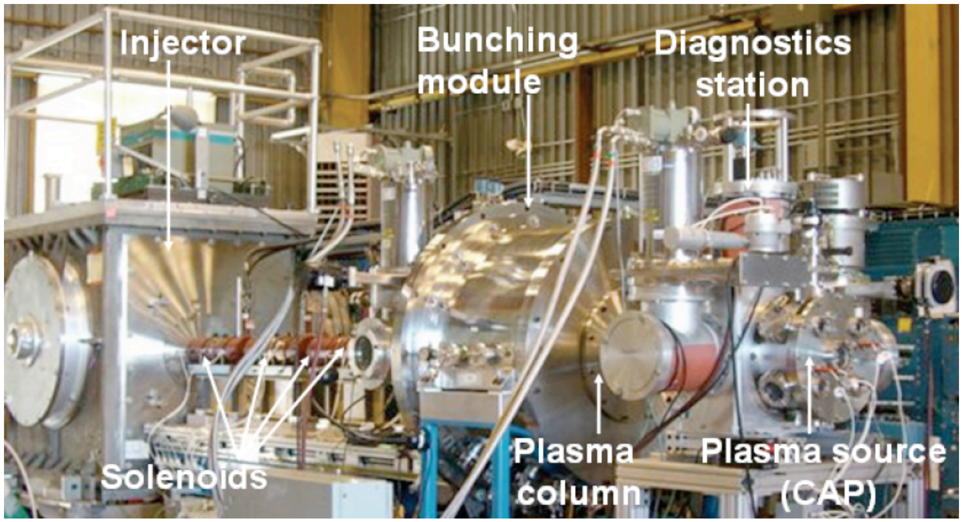


NDCX-II, using ATA components for more beam intensity and uniform deposition, could be completed by FY10 w/ incremental funding of $1.5 M

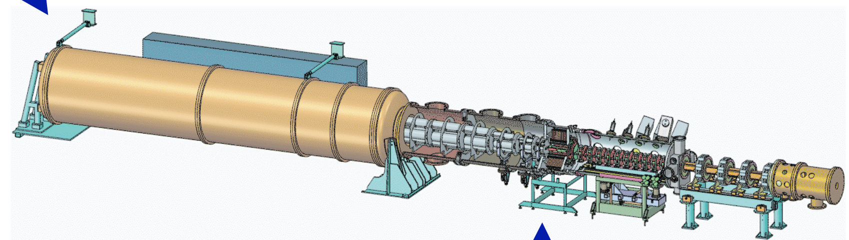


New concepts, and a longer-range vision for HIF

The HIFS VNL has developed a plan for using present and future accelerators for WDM and HIF experiments



Today:



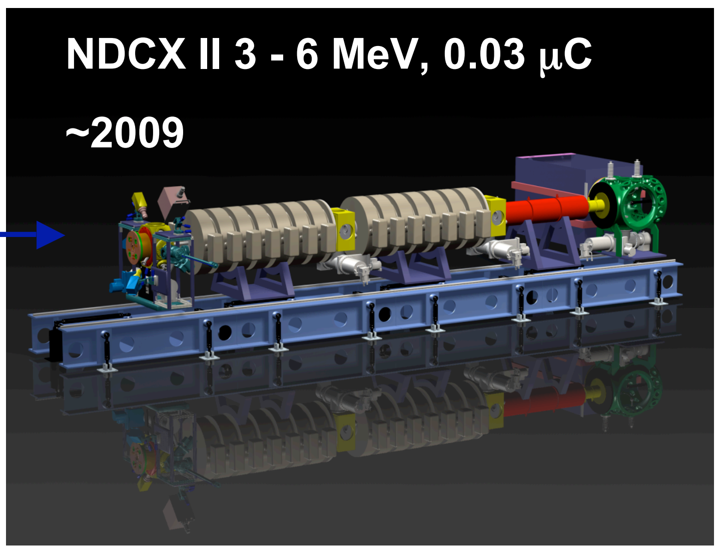
HCX

1.7 MeV, ~0.025 μC

NDCX I

0.4 MeV, 0.003 μC

Soon



Future

IB-HEDPX (with CD0)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

10 kJ Machine for HIF
10 - 20 year goal
Target implosion physics

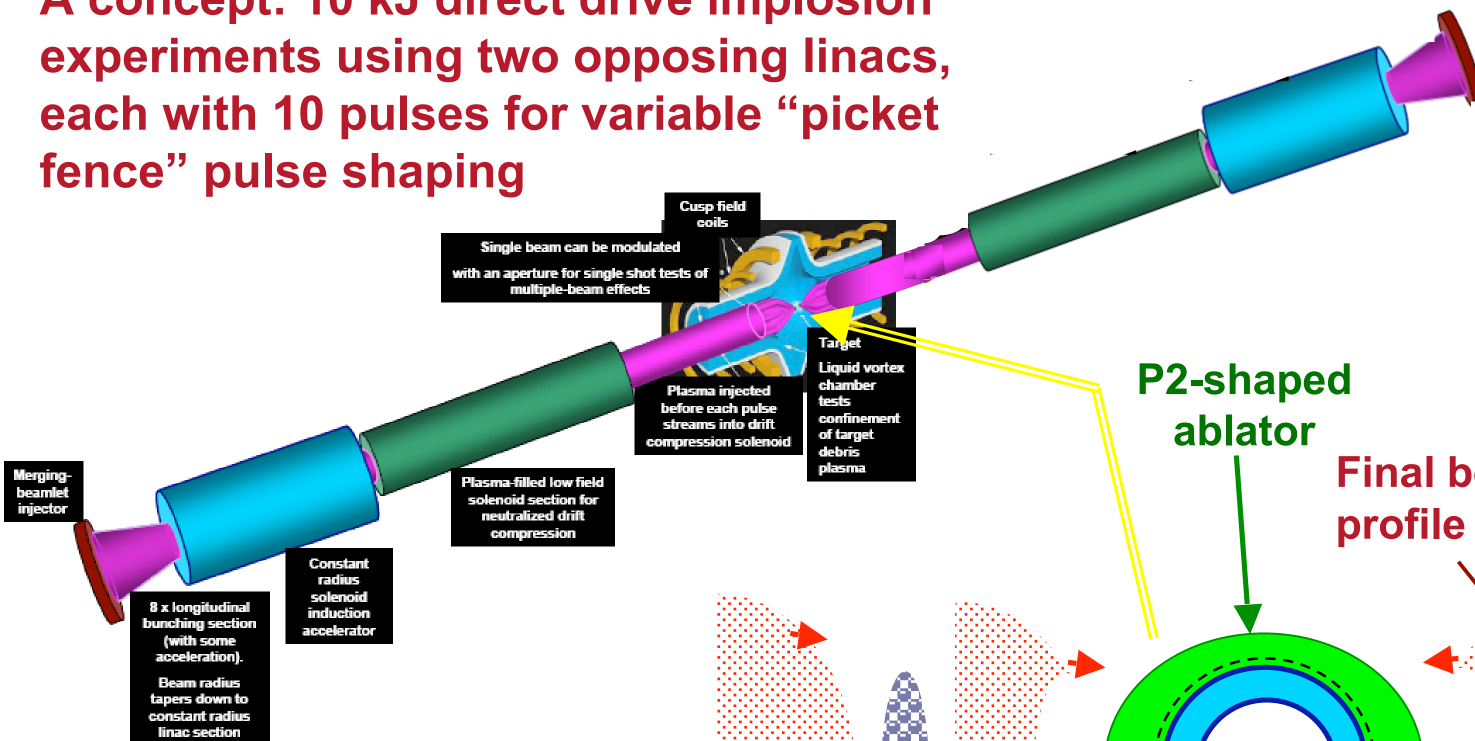
Indirect drive will remain an option for HIF, while we plan to explore heavy ion driven direct drive

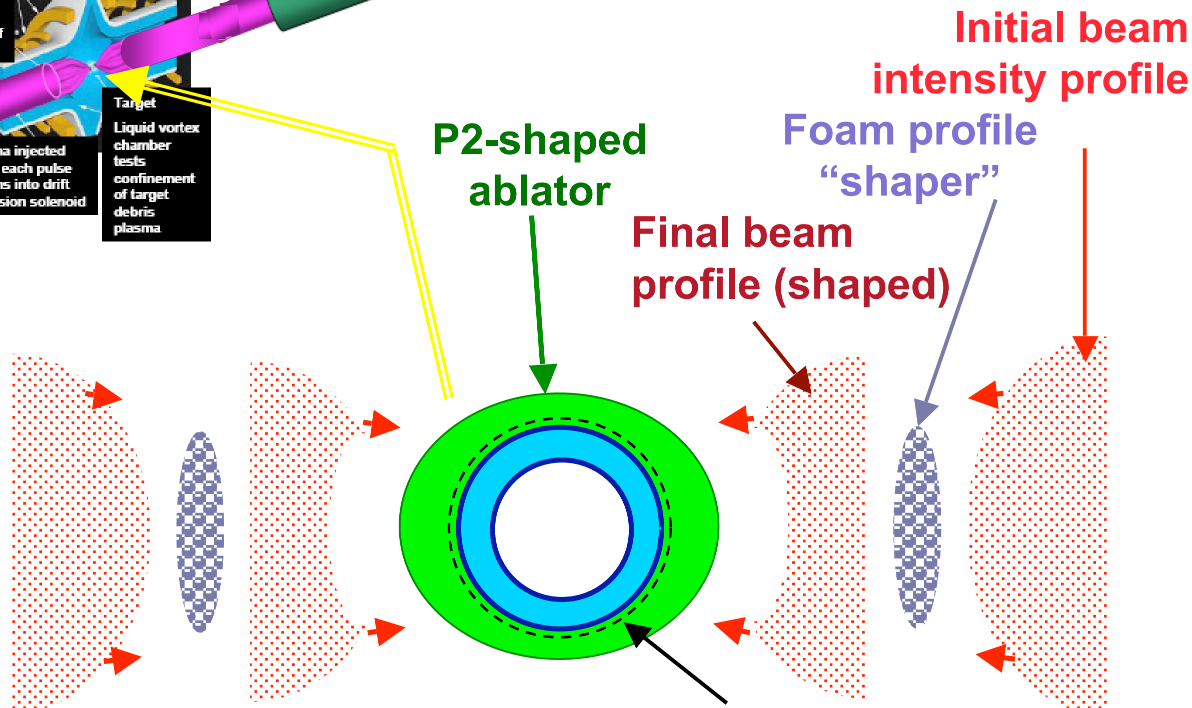
- **NIF first ignition will be based on laser indirect drive, but later polar direct-drive ignition experiments are planned**
- **The Robust Point Design study[1] was a self-consistent heavy ion accelerator and final focus/chamber design that met detailed 2-D heavy ion indirect drive target design requirements[2]**
- **Ion direct drive potentially offers higher target gains (John Perkins, work in progress)**
- **Ion deposition differs significantly from laser deposition; S. Kawata (Utsunomiya U.) has proposed several techniques to mimimize RT growth in ion-beam-driven direct drive**
- **NDCX-II provides an affordable opportunity to explore unique heavy-ion direct-drive coupling physics, using double-pulse and other techniques**

1) S. S. Yu, et. al., *Fus. Sci. & Tech.* **44,** 266 (2003).
2) D. A. Callahan-Miller and M. Tabak, Phys. Plasmas **7**, 2083 (2000).

After NDCX-II (in parallel with NIF operation & IB-HEDPX): a new tool to explore heavy-ion-driven fusion target physics and 100-eV foam HEDP

A concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable "picket fence" pulse shaping



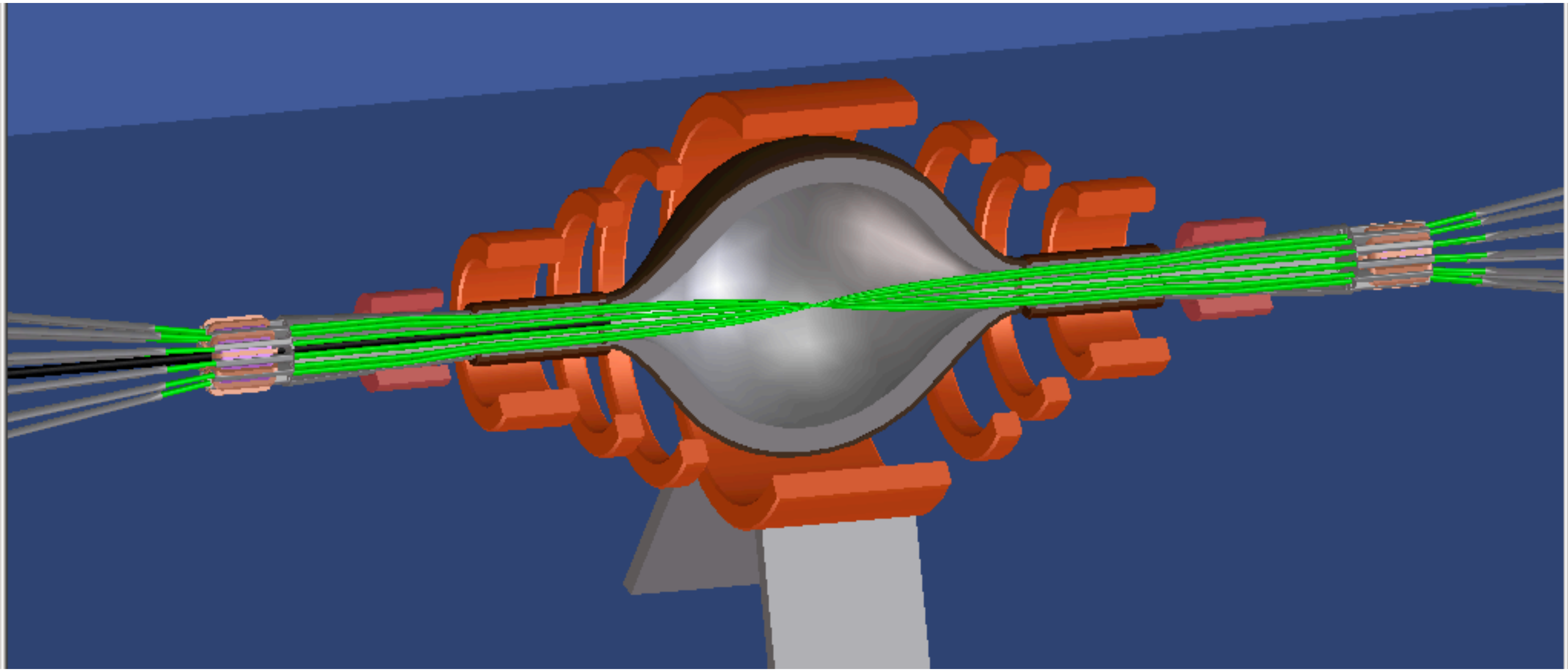


Three "knobs" to control P2 asymmetry with two beams:

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

Research on compression & focusing of "velocity chirped" beams suggests improved concepts for heavy ion fusion



Neutralized ballistic, solenoid-focused, plasma-filled liquid Flibe-wall vortex chamber concept (Per Peterson, UC Berkeley)

~ 20 beams/end x 3-5 pulses = 120 to 200 bunches for pulse shaping.
NDC enables 5X higher peak beam power than older concepts.

Other new ideas are just now gathering momentum

Recent analyses identified three major thrusts for improving HIF:

(1) High gain 1-2 MJ targets

(2) Modular HIF driver (and modular development path)

(3) Liquid vortex chambers supporting > 20 Hz pulse rates for > 5 GWe

Now - additional thrusts:

(4) Heavy ion direct drive, possibly 2-sided (w/o need for fast ignition)

- **potential 4x increase in beam-to-fuel coupling efficiency, and gain**
- **would reduce cost & size of 100 MWe DEMO & fusion driver**

(5) T-lean targets with reasonable size (< 3 MJ) drivers for:

- **30x more neutrons per fusion watt, for fissile fuel production**

  and / or

- **in-target breeding of T**

(6) Efficient plasma MHD direct conversion at 400 MJ yield, for low Balance of Plant cost; *requires:*

- **T-lean target's larger ρr, for >90% capture of fusion yield**
- **Direct drive's higher coupling efficiency**

Concluding comments

Concluding thoughts

- NDCX-I is a productive platform for science
  - beam compression and focusing methods
  - diagnostics
  - WDM experiments (beginning next year)
- Theory and simulations closely support our experimental program
- NDCX-II is a key step toward unique WDM studies and heavy-ion IFE
  - ATA parts enable us to build it with a modest $1.5 M investment
  - will be the basis for "IB-HEDPX" WDM user facility, as per CD-0
- NDCX-II + NIF provide basis for a ~ 10 kJ heavy-ion implosion facility
  - architecture close to that of a modular-driver module
  - enables study of direct drive HIF
- This program may lead to an improved vision for HIF
  - direct conversion
  - self-T-breeding targets.

The HIF program offers students a broad spectrum of opportunities for thesis research

- **Particle beam physics**
- **Accelerator engineering**
  - **pulsed power**
  - **mechanical**
- **Warm Dense Matter physics**
- **IFE target physics**
- **Inertial Fusion engineering**
  - **target chamber**
  - **target fabrication**
- **Systems studies for IFE**

- **Experiments**
- **Diagnostics**
- **Simulation**
- **Theory**

… and mixtures of these

For more information ----
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