15th International Conference on Emerging Nuclear Energy Systems

Heavy-Ion-Driven Inertial Fusion Energy

(Invited Talk 4.3.2)

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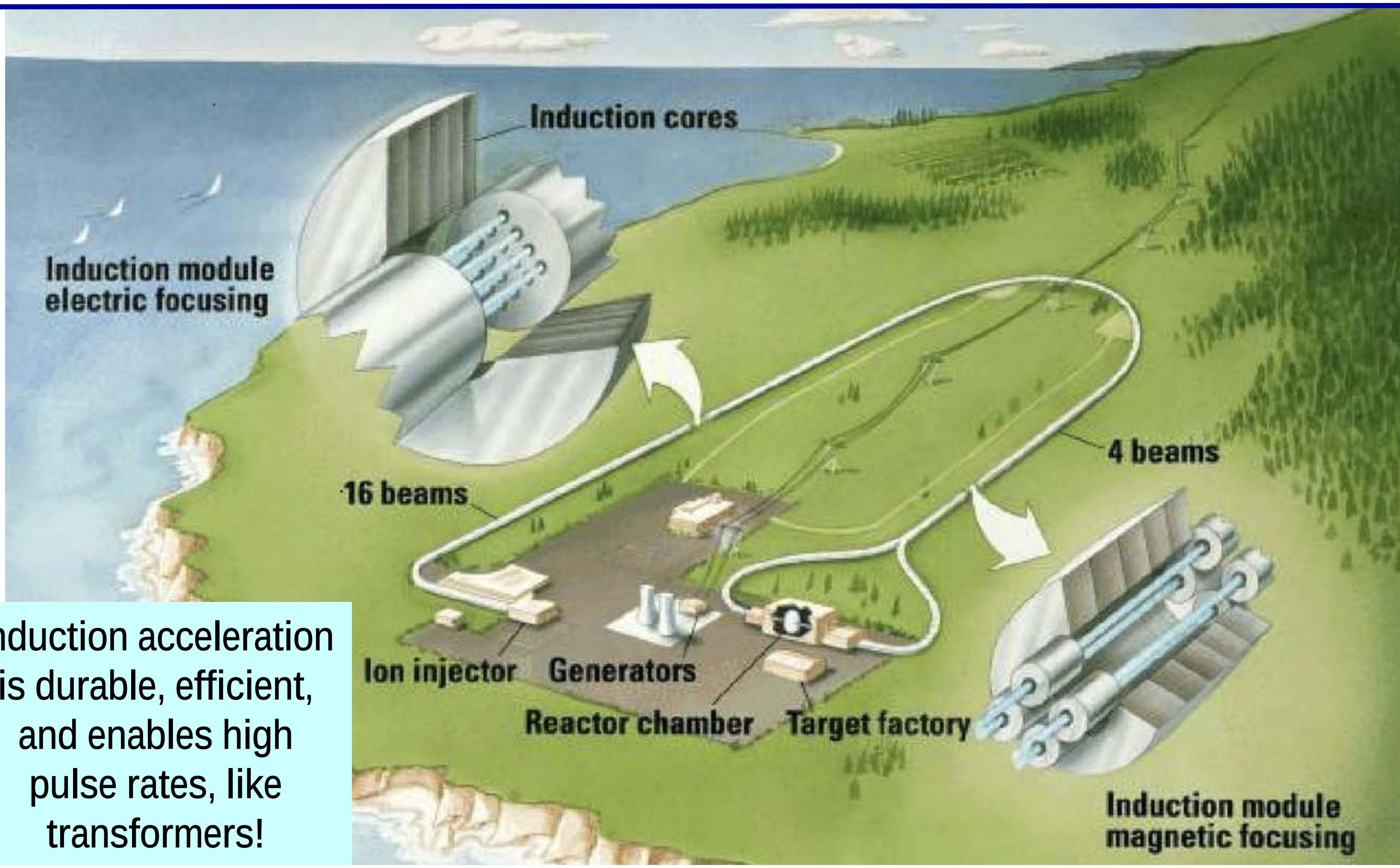
Outline

- Motivation for heavy ion fusion (HIF)
- Accelerator, focusing, chamber and target options
- New HIF target designs that may potentially improve hydro-stability robustness, expand options for ion range and illumination geometry, and enable lower current, higher voltage accelerator options.
- Requirements for ICF ignition and propagating burn emerging at this midpoint of the 3-yr National Ignition Campaign on NIF will help us assess HIF options.
- Opportunity to use NDCX-II (operation beginning next year) for HIF- relevant R&D
- Potential collaborations and applications to compact MHD direct conversion
- Conclusions.

Original heavy ion fusion concept: heavy ion dE/dx~Z^2 enables ~10 GeV to stop in targets. Induction acceleration with superconducting magnets enables high peak beam currents, 100's of TW peak power.



Induction acceleration is durable, efficient, and enables high pulse rates, like transformers!

Heavy ion accelerators of multi-MJ fusion scale would be comparable in scale to today's large NP accelerators like GSI-FAIR, RHIC →economical for 1-2 GW_e baseload power plants.

Heavy ion fusion is an IFE option because of long-recognized advantages:

- **Established accelerator base:** High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.
- **Liquid Chambers:** Heavy ion beams can propagate through the vapor pressure of thick-liquid-protected target chambers with 30 yr lifetimes.
- **Robust final optics:** Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.
- **Target injection:** Heavy ions can penetrate metal cases surrounding cryogenic-DT fuel, protects HIF targets injected into hot IFE chambers.
- **Competitive economics:** projected in several power plant studies and with no high level radioactive waste.

A number of driver, focusing, chamber, and target options have been considered for heavy ion fusion.

Accelerator
- Induction Linac
- RF Linac
- RF Linac + Storage Ring/ Synchrotron
- Induction Recirculator
- Dielectric Wall Accelerator

→

Focusing
- Ballistic, Neutralized
- Ballistic, Vacuum
- Self Pinch, 2-stage

→

Chamber
- Thick-Liquid-Protected Wall
- Thin-Liquid-Protected Wall
- Solid Dry Wall + Gas Fill
- Granular-Solid Flow Wall

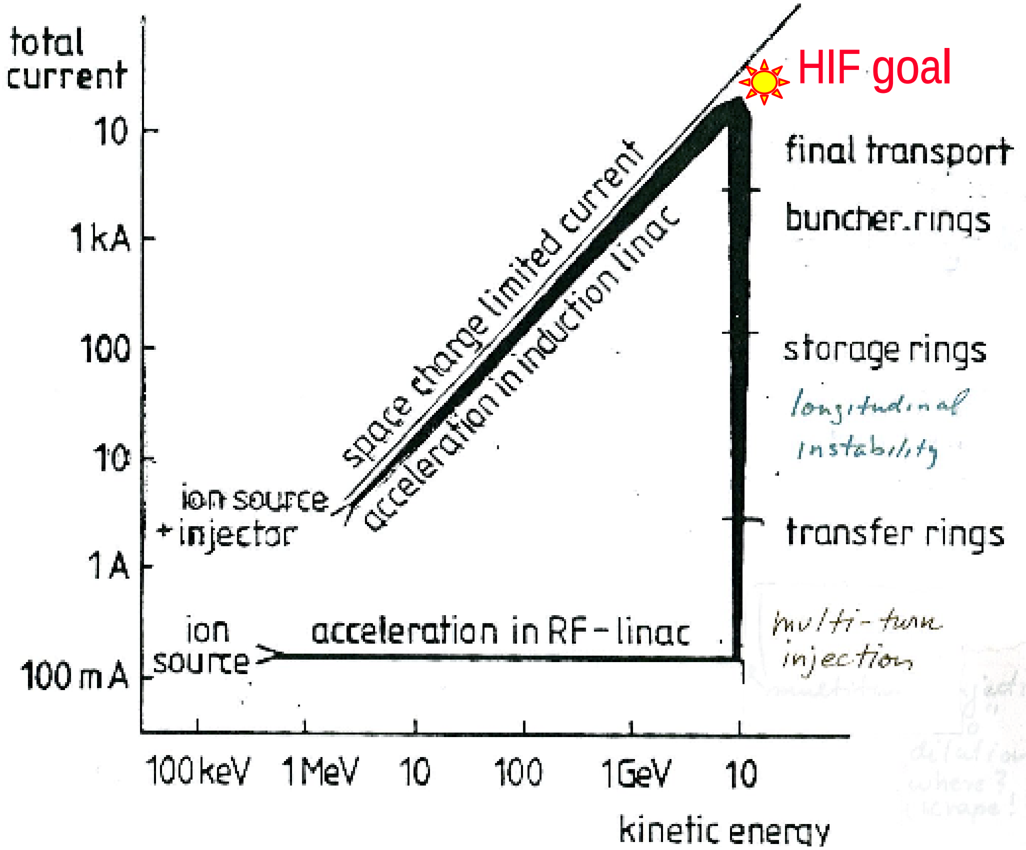
→

Target
- Indirect Drive, Central Hot Spot Ignition
- Indirect Drive, Fast ignition
- Direct Drive, Central Hot Spot Ignition
- Polar Direct Drive + Shock Ignition
- Hydro Drive +Fast or Shock Ignition

US effort has focused on induction linacs, ballistic neutralized focusing, thick liquid protected chambers, and indirect drive targets. We believe heavy ion linacs and thick liquid chambers can be applied to several target options.

John Nuckolls, et. al.’s seminal 1972 Nature article on laser fusion…. <u>also sparked interest for heavy ion fusion</u>→ *in the world’s high energy accelerator community and some weapons-lab scientists.*

Early workshops in the 70’s identified induction and RF linac candidate drivers. Later, storage rings were also considered at GSI and Russia (ITEP).

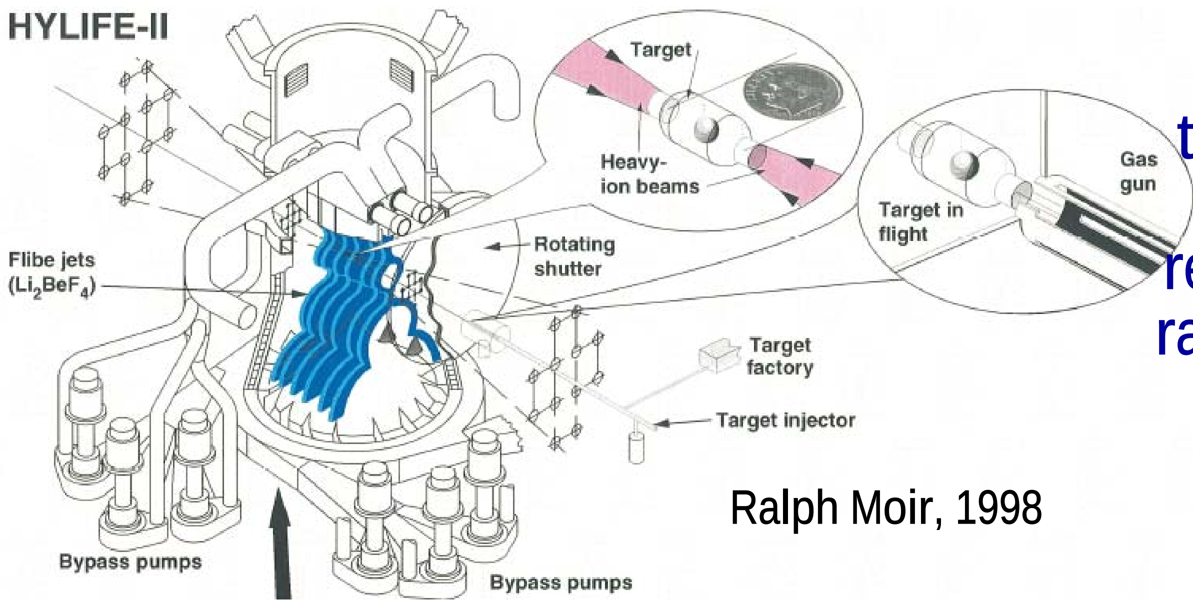


A new HIF workshop begins May 23 at LBNL to rekindle interest of the accelerator community

70’s and 80’s HIF workshops <u>had broad participation from</u>:

LBNL
LLNL
LANL
FNAL
ANL
BNL
SLAC
Rutherford
CERN

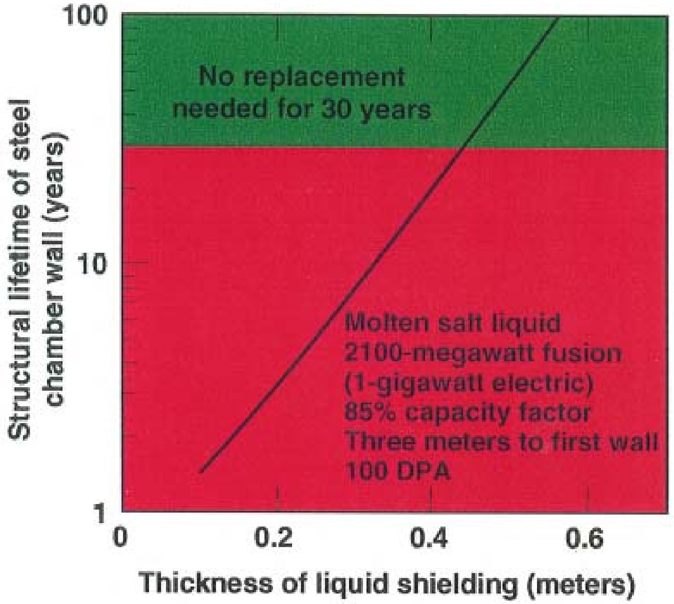
Even though target design details were classified at the time, accelerator scientists were confident they could design fusion-scale accelerators to deliver the required energy and peak power for HIF, with more efficiency, pulse rate, and durability than lasers.



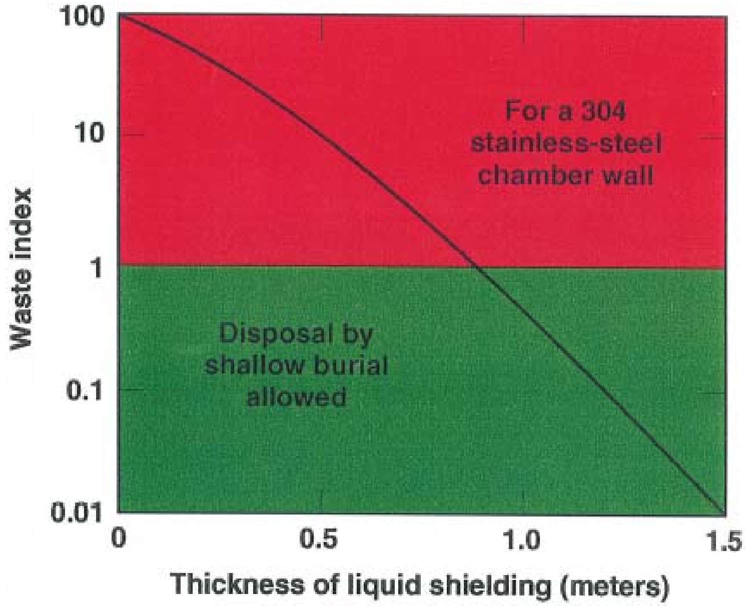
HIF chambers:

thick liquid-protected walls to avoid structural-wall replacements and high level radioactive waste, + inherent safety to LOCA / LOFA …is still our goal!

Ralph Moir, 1998



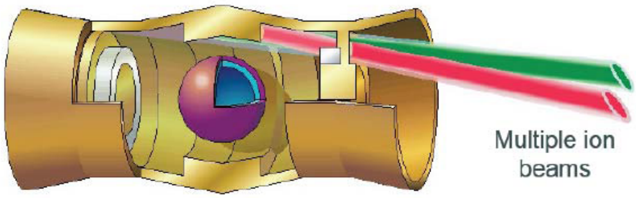
Sumer Sahin, R. W. Moir, A. Sahinaslan, and H. M. Sahin, "Radiation damage in liquid-protected first-wall materials for IFE-reactors," *Fusion Technology*, **30**, 1027–1035 (1996).



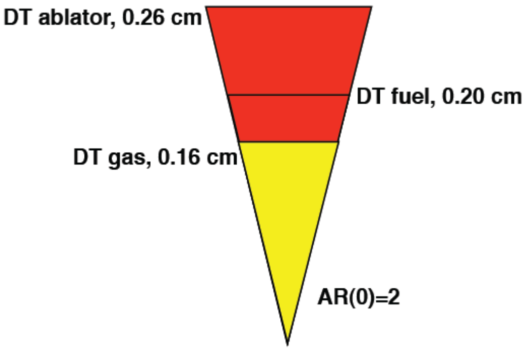
J. D. Lee, "Waste Disposal Assessment of HYLIFE-II Structure," *Fusion Technology*, **26**, 74 (1994).

Until NIF evaluates risk issues (high convergence, high implosion velocity, hydro-instability / mix), we are keeping 3 target options for HIF):

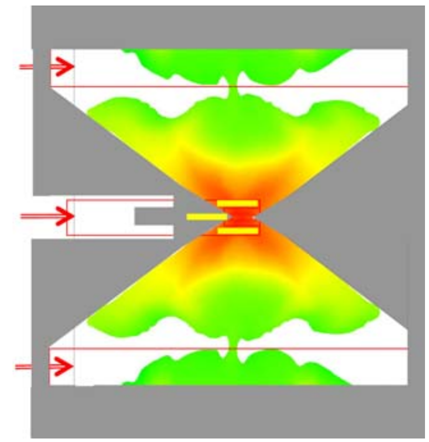
- **<u>Indirect drive</u>** <u>(2-sided hohlraum)</u> *2-D Lasnex design (2002):* 7 MJ, 3→ 4 GeV Bi^{+1} , gain 68. <u>Two-sided illumination, like NIF</u>.



- **<u>Polar direct drive</u>** *1-D Lasnex design (2010):* 3 MJ, 3 GeV, Hg^{+1} ion beams, gain ~150. Future 2-D design planned for polar drive illumination, <u>with tamper & shock ignition assist</u>.



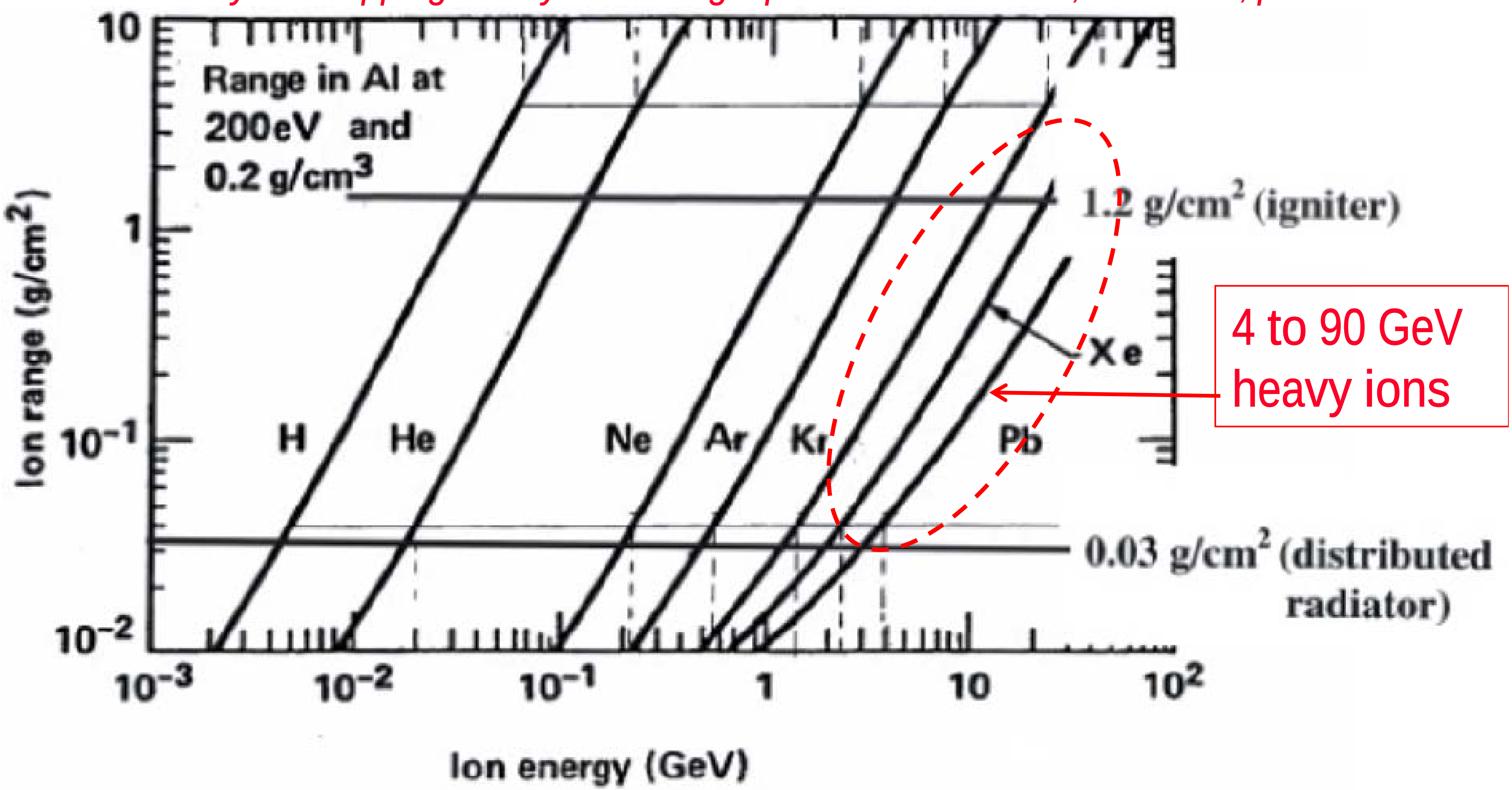
- **<u>X-target</u>** <u>single-sided direct-drive</u> *2-D Hydra design(2011)* [Henestroza, Logan & Perkins, Phys. of Plasmas 18 (2011)] Gain 50 @ 6 MJ, range ~1 g/cm^2 ions. <u>Now, with Al pusher→ **gain 600** with 3 MJ of 2 g/cm^2 range ions.</u>



→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

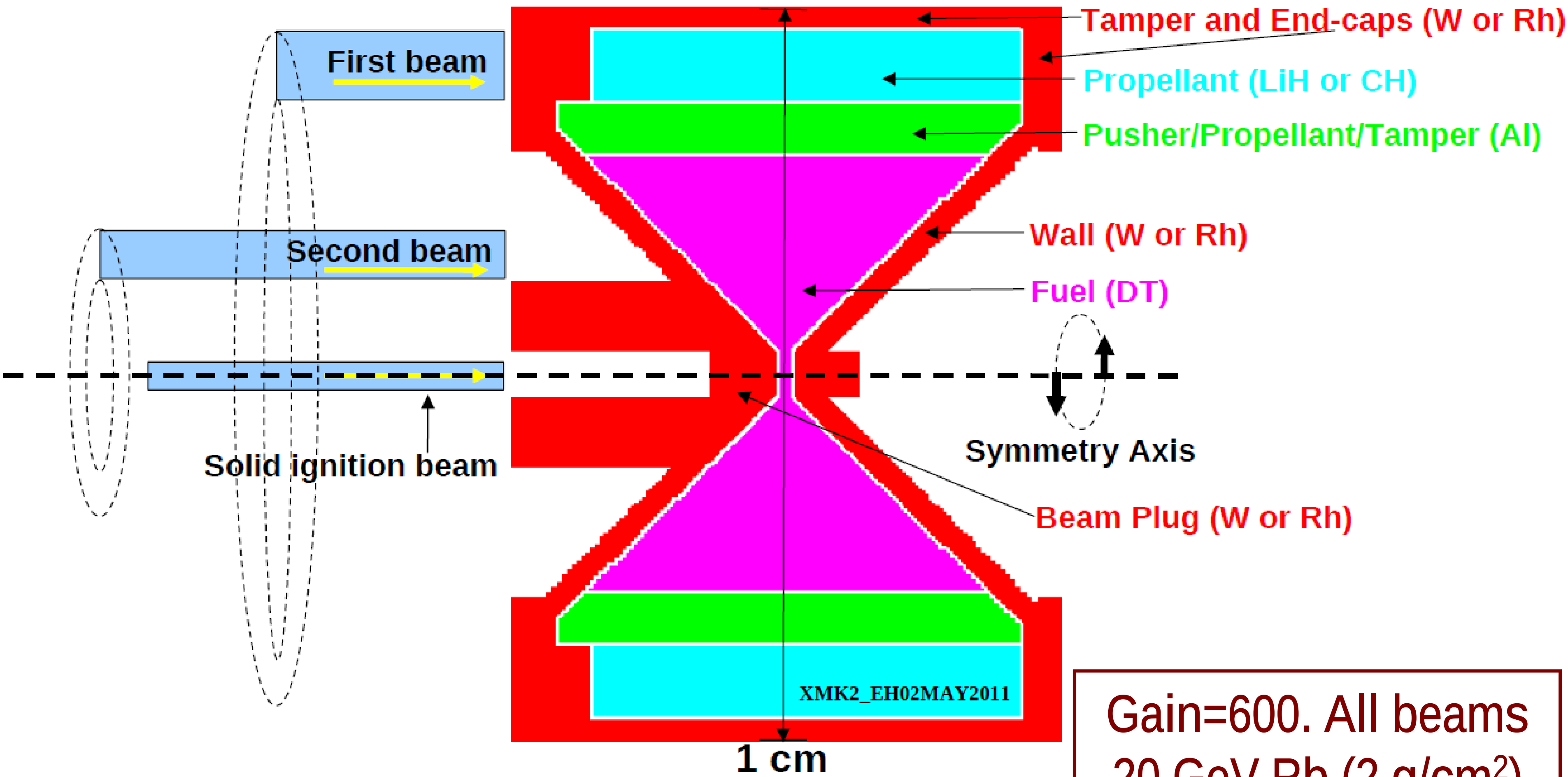
Either higher mass ions for targets with *given* ion range, or targets that allow higher range: enable delivery of energy at higher ion kinetic energies→ lower beam currents→ less space-charge effect on focus!

Heavy ion stopping in very dense target plasma is calculable, measured, predictable



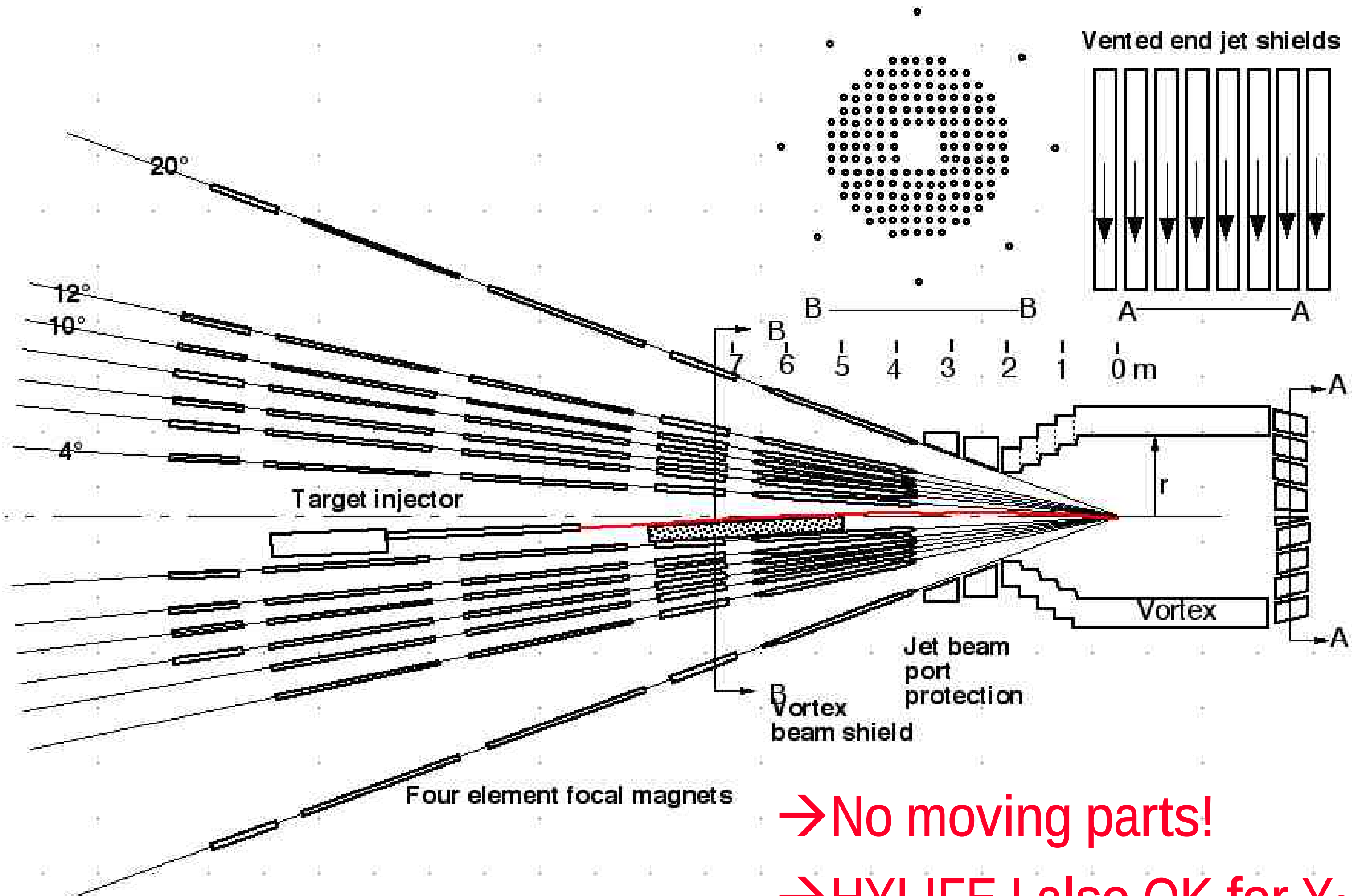
20 GeV Rubidium beams (0.5+0.5+2.0 = 3.0 MJ)
Yield = 1.8 GJ

1st, 2nd, and ignition beams are many beams with overlapping spots modeled as annuli



Gain=600. All beams 20 GeV Rb (2 g/cm^2)

Liquid jets and a vortex chamber protect solid structures for the life of the plant (R. Moir Dec. 6, 2010, for single sided targets)



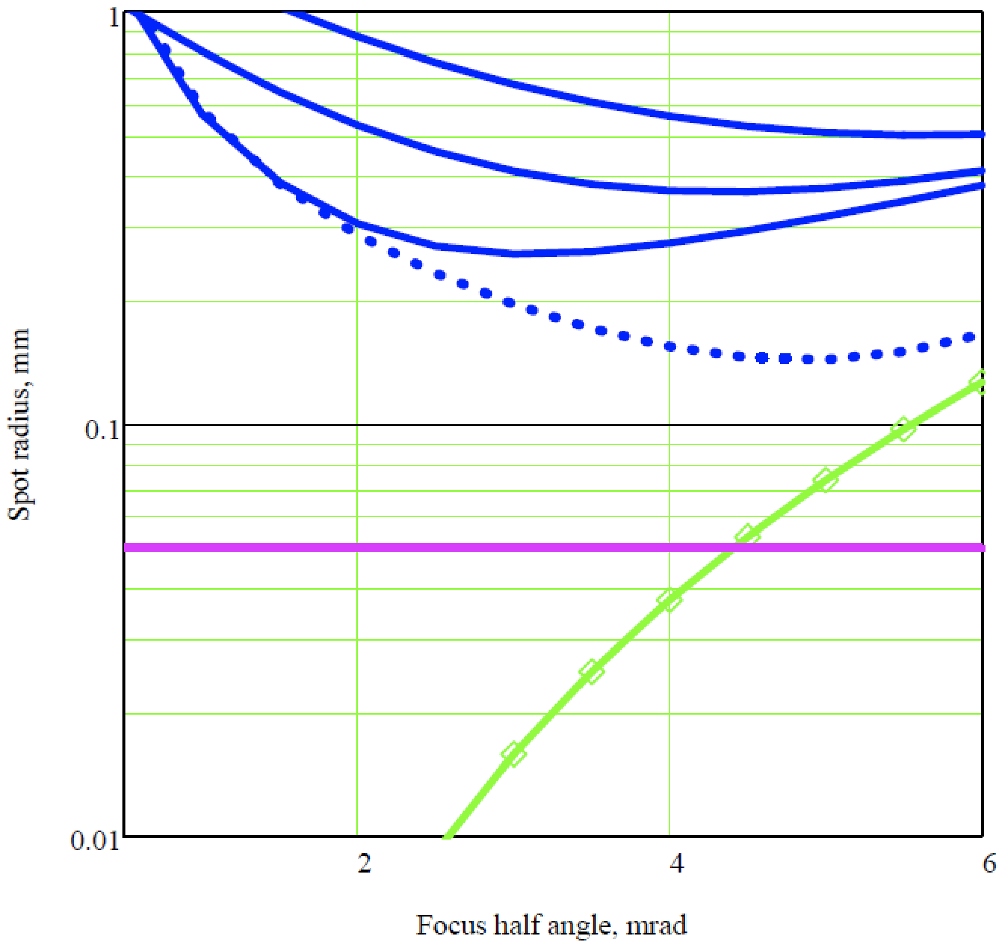
→No moving parts!

→HYLIFE I also OK for Y~2 GJ)!

Higher ion KE and higher chamber plasma $n_p/n_b > 10^3$ enables neutralized ballistic focusing to meet X-target ignition specs.

Total focal spot radii (mm) vs focus θ

(IBEAM systems code) Meier 2002



80 Ignition beams (20 GeV Rb)

←@ 98% neutralized

←@ 99% neutralized

←@ 99.9% neutralized ($n_p/n_b > 10^3$)

←40 Compression beams (20GeV Rb, dotted line)

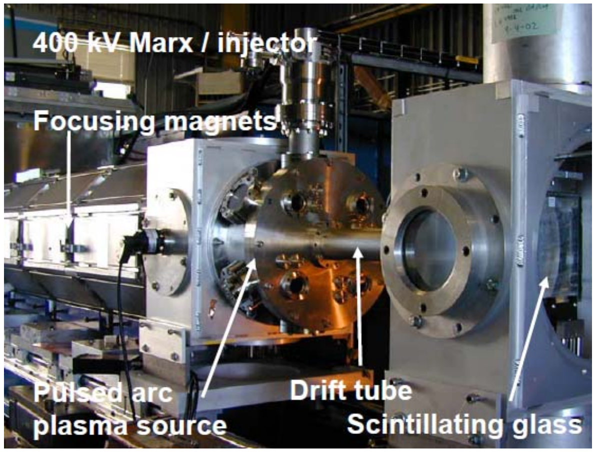
←Geometric aberrations

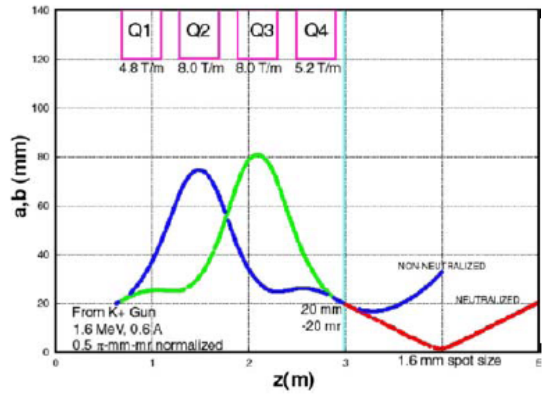
←Aiming errors

- Ignition beam spots overlap on axis
- Transverse and parallel emittance growth and equilibration over 7 km linac and effects of drift compression

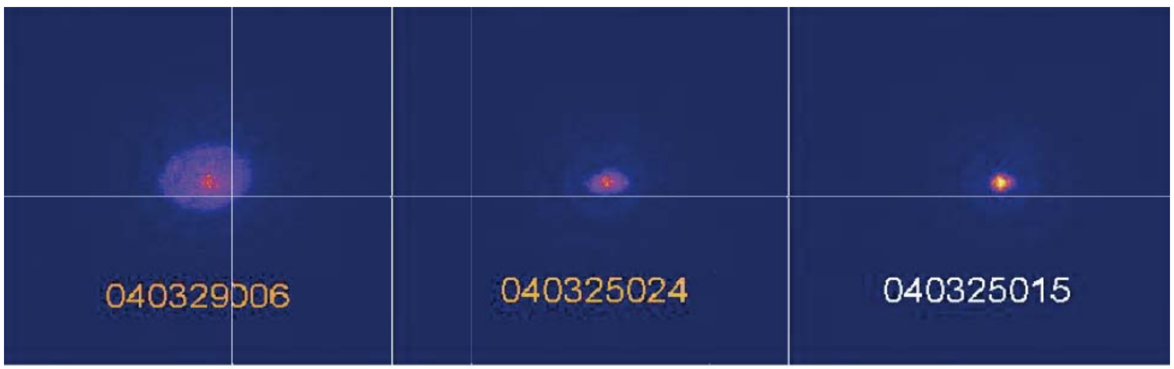
Focal length (last quad magnet to center= 4 m)

In 2004, the Neutralized Transport Experiment (NTX) achieved greatly reduced focal spot sizes by neutralizing the space charge of intense ion beams with background plasma in the target chamber.





Envelope simulation of NTX focusing with and without plasma



Neither plasma plug nor volumetric plasma.

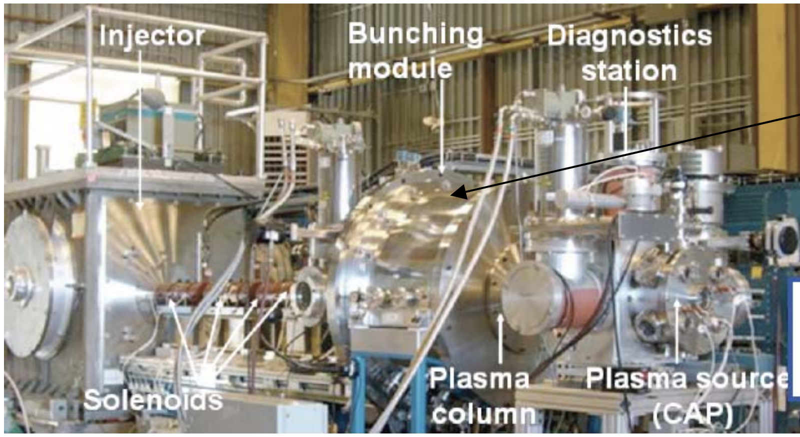
Plasma plug.

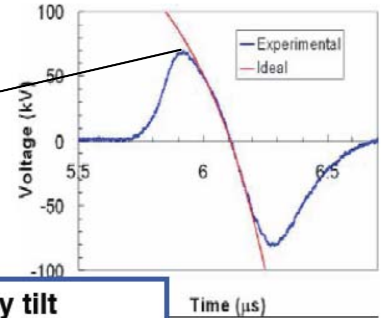
Plasma plug and volumetric plasma.

Ion species: K^+
Energy: $E_0 \leq 400$ keV
Current: $I_0 < 80$ mA
Beam radius: $r_b \sim 1\text{-}2$ cm
Temperature: $T_b \sim 0.2$ eV

P. Roy, et. al, Physics of Plasmas, 11, 2890, 2004.

After NTX showed improved transverse focusing with neutralizing plasma, we added a head to tail velocity ramp for improved longitudinal compression (Neutralized Drift Compression Experiment-I)

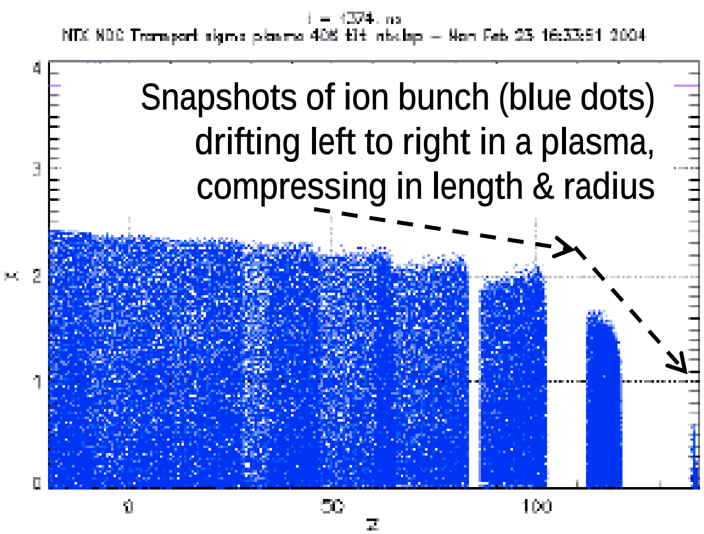


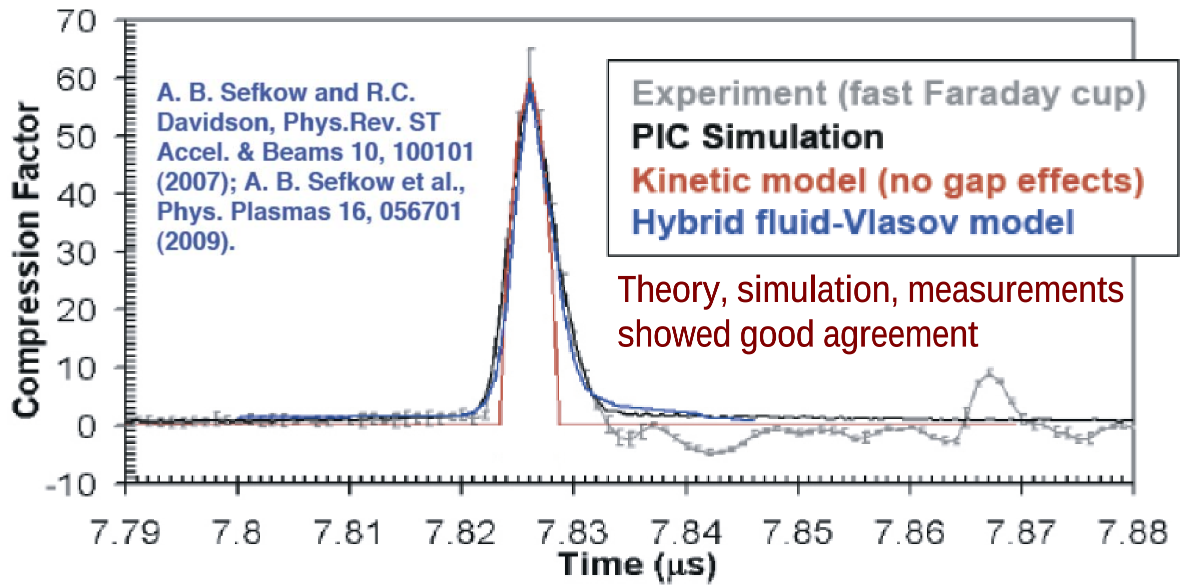


Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

* P. K. Roy, S. S. Yu et al. ,Phys. Rev. Lett. 95, 234801 (2005).



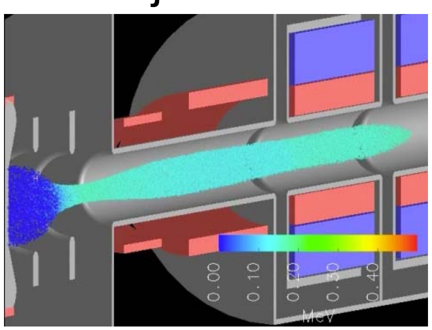


Pre-project simulation of the concept Mar 2004 led quickly to 60 X compression of peak current by May 2005

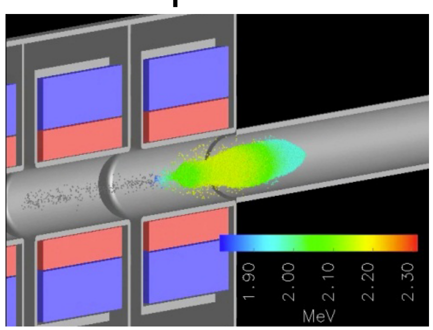
In addition to NDCX-I, NDCX-II will explore more intense compression and focusing physics needed for heavy ion fusion.

- 11 M$ construction began July 2009, to be completed in March of 2012 (ARRA project)
- Rapid initial bunch compression allows re-use of 70-ns pulsed power sources from the ATA accelerator, and compressed to sub-ns.
- Detailed 3-D simulations using the Warp code confirmed the physics design & set engineering requirements
- rapid initial bunch compression could reduce front end length and cost for HIF drivers

During injection



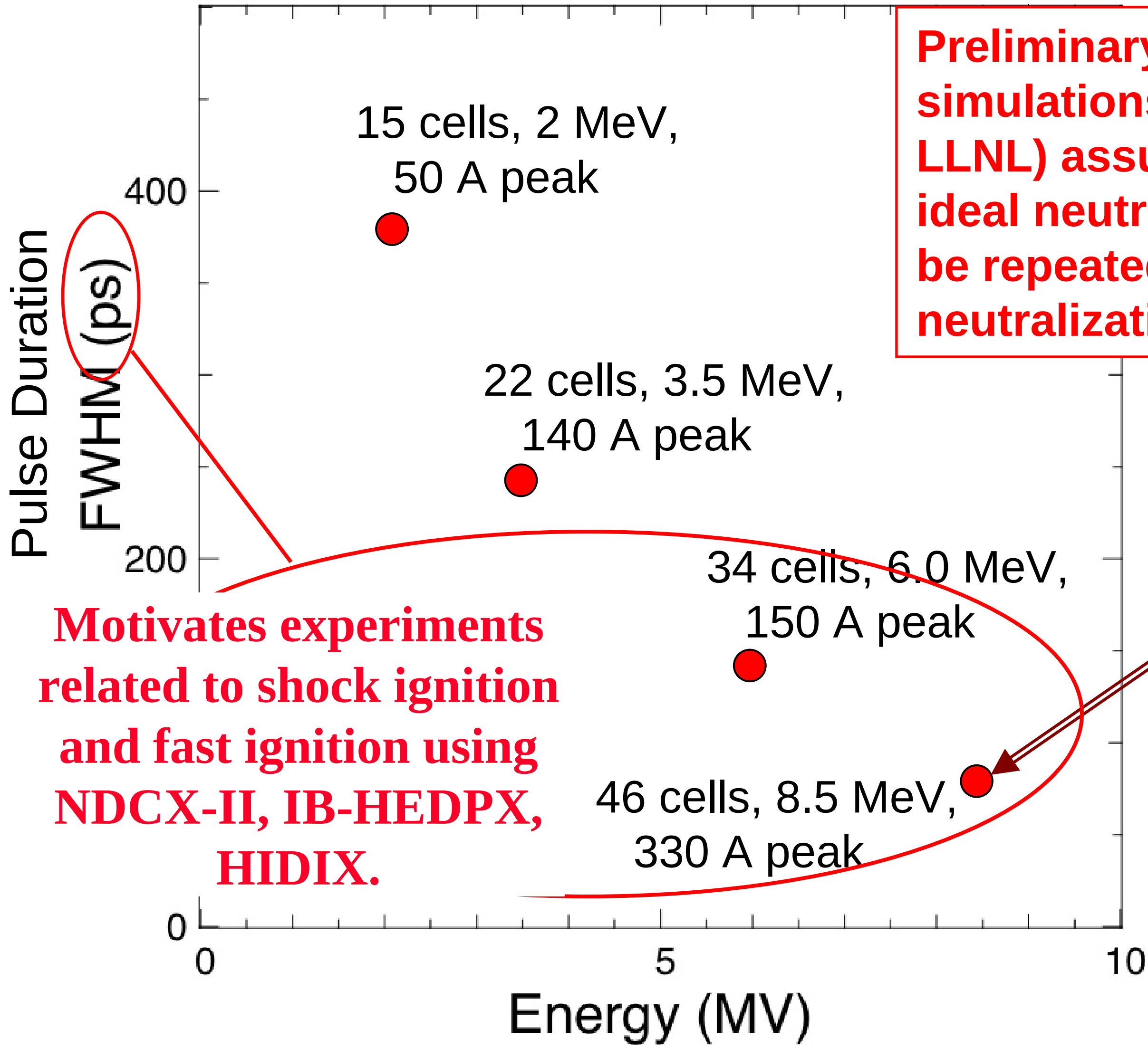
Entering final compression



Ref: A. Friedman, et al., *Phys Plasmas*, 2010)

	NDCX-I	NDCX-II (baseline)
Ion species	K^+ (A=39)	Li^+ (A=7)
Ion energy	300-400 keV	(1.2 MeV) → > 4 MeV
Focal radius	1.5 - 3 mm	(0.5 mm)
Pulse duration	2 - 4 ns	~(1 ns) → < 200ps
Peak current	~ 2 A	~ (10 A) → > 100 A

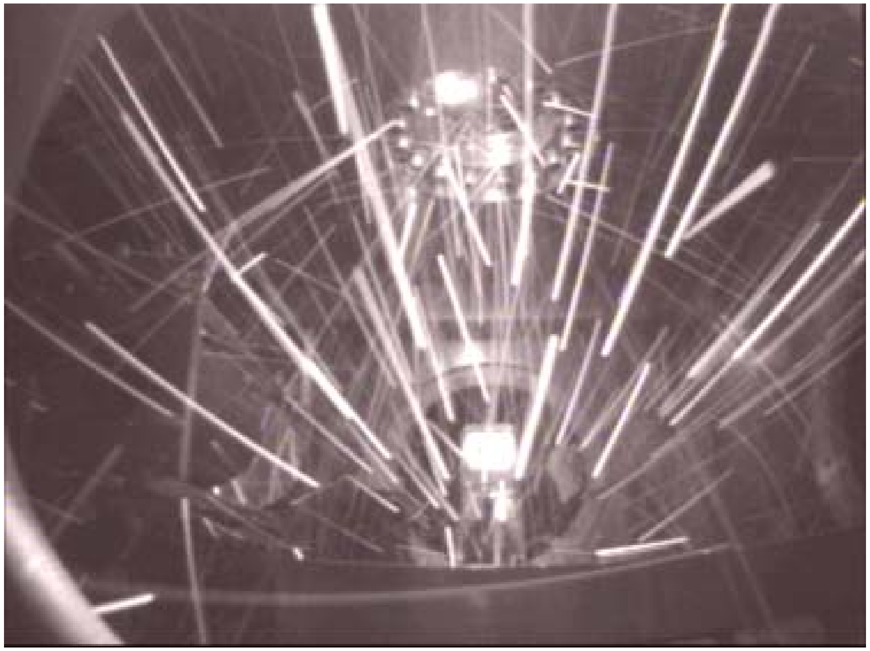
Simulations show compressed pulse duration in NDCX-II varies ~ inversely with kinetic energy—the same should be true for an IRE/HIDIX



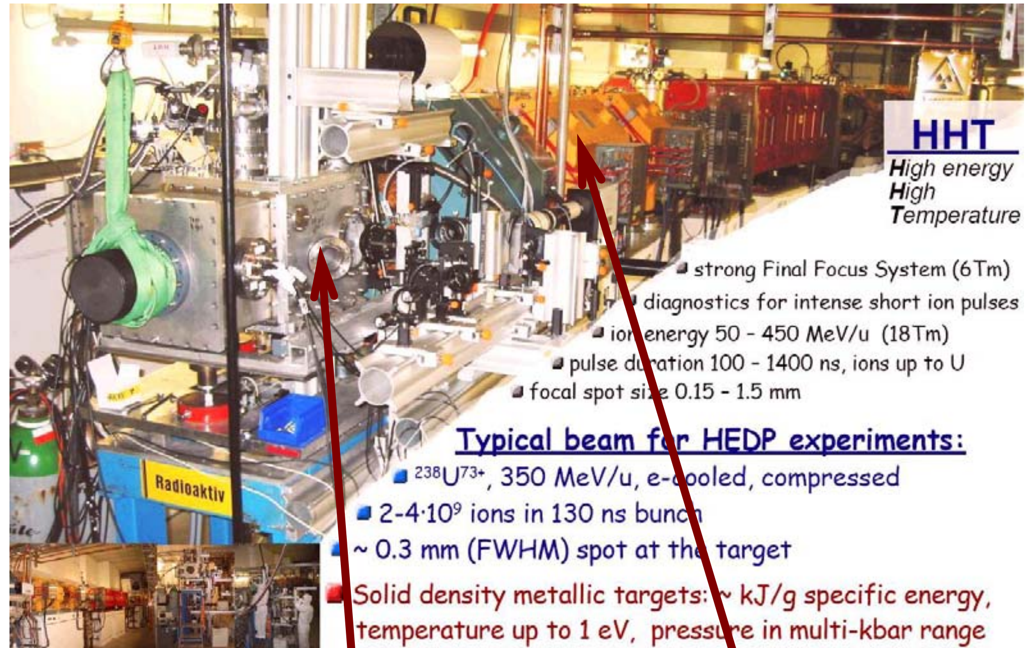
Preliminary results of Warp PIC simulations (Friedman, Grote LLNL) assuming jitter errors with ideal neutralization. These will be repeated with full plasma neutralization physics models.

We have 50 ATA cells to use, and could be added in < 2 years!

VNL targets have been heated with~ 0.3 A of 83 GeV U^{+73} ions focused to 150 micron radius spots on target at GSI

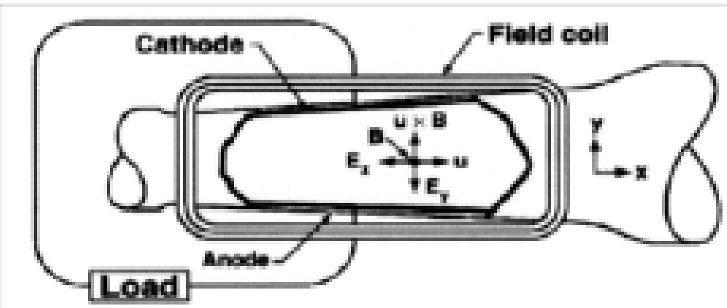


Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 130 ns, 50 J heavy ion beam to ~ 1 TW/cm^2 peak and 1 eV in joint experiments at GSI, Germany.

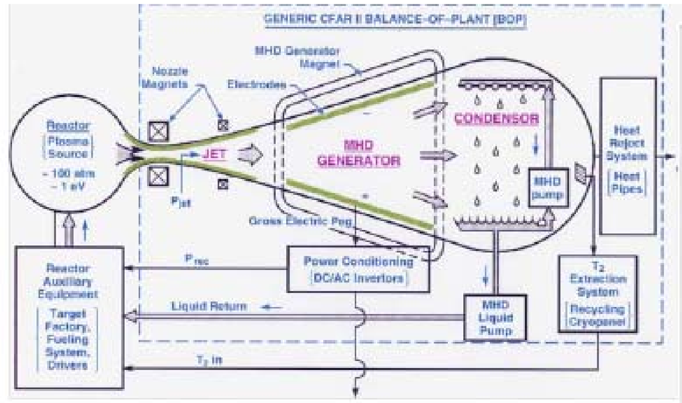


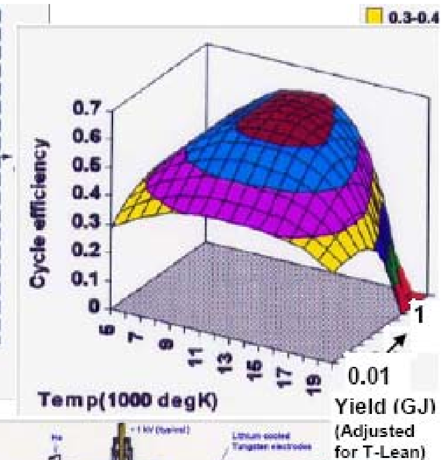
The new FAIR upgrade of GSI's accelerator will allow joint cryo hydrogen compression experiments relevant to heavy ion fusion with much more (80 kJ) of uranium beam energy.

High ρr + target shells capture >90% of fusion yield as 3 eV plasma →30X more energy per kg than chemical combustion with 15 x higher plasma temperatures →100X more power density (~ σu^2) than "old" MHD, →30X more kWe per ton power density than conventional steam-turbine generators → 10X lower balance of plant costs!



Schematic diagram of a dc magnetohydrodynamic generator. (Rosa)





Momentum :

$$\rho u \frac{du}{dx} + \nabla p = j \times B - \rho u^2 \frac{df}{dx}$$

Energy :

$$\rho u \frac{d}{dx}\left[\frac{u^2}{2} + h\right] = j \cdot E - q_r$$

Continuity :

$$\rho u A = \text{constant}$$

Load Factor :

$$K = \frac{E}{uB}$$

Electric Power Density :

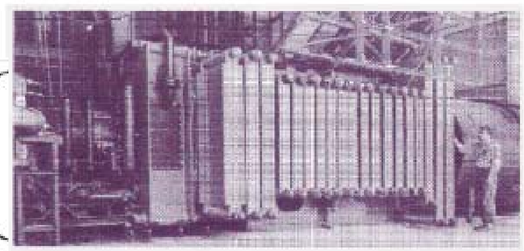
$$j \cdot E = -\frac{K(1-K)\,\sigma\, u^2 B^2}{1 + (\omega\tau^2)}$$

Magnet cost, Energy Density :

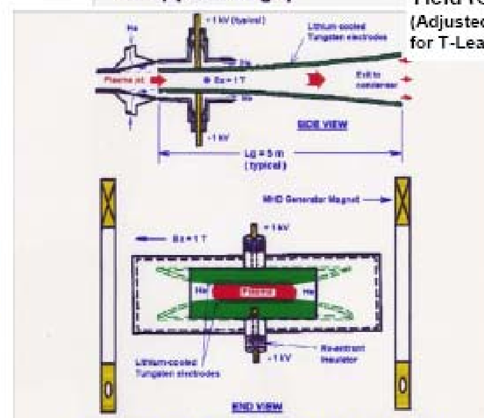
$$\text{Magnet Cost} / m^3 \sim B^2 / (2\mu_o)$$

where ρ = mass density , u = velocity, x = distance along channel, p = pressure, j = current density, B = magnetic field, E = electric field, σ = electrical conductivity, $\omega\tau$ = Hall parameter, h = specific enthalpy, f = friction due to mass inflow from wall transpiration cooling, qr = heat loss / m^3 due to radiation losses, A = channel area.

→ MHD Magnet Cost / kWe ~ $B^2 / j \cdot E$ → Figure-of-merit \$ / kWe ~ $(\sigma u^2)^{-1}$



THE AVCO MARK V "ROCKET GENERATOR"
(from Rosa, MHD Energy Conversion, 1968)
Temp ~ 3000 deg K
Conductivity ~ 100 mhos/m
Velocity ~ 1000 m/s
Efficiency ~ 10% (of chemical)
Power (above unit) ~ 20 MWe



TYPICAL" CFARII MHD GENERATOR
Temp ~ 12000 deg K, Conductivity ~ 500 mho/m
Velocity ~ 10000 m/s, Efficiency ~ 80%(of kinetic)
Power (comparable size to MarkV) ~ 2000 MWe

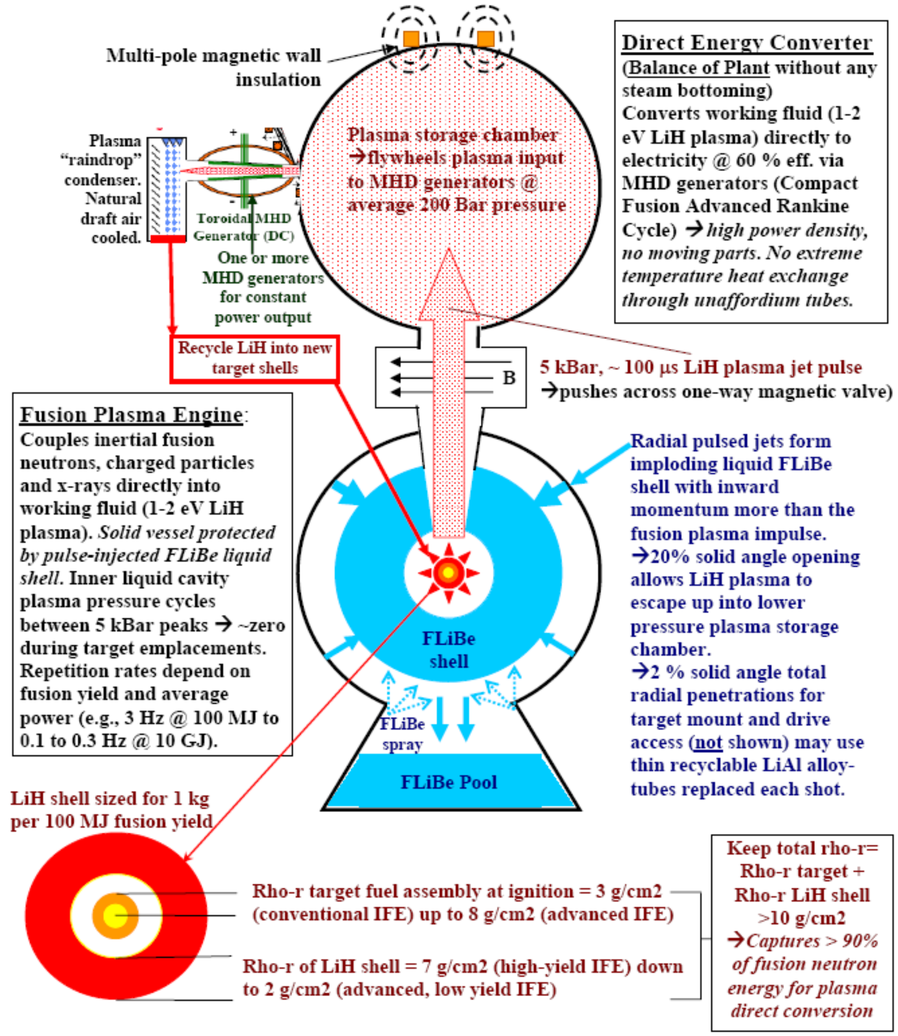
[B.G. Logan, Fusion Engineering and Design 22, 151,1993]

High energy density plasma *(energy conversion!)*

"Subsidies or taxes should not be counted on to sustain non-carbon alternatives in the long term, if those alternatives cannot become competitive with coal" ←Steven Chu

An IFE driver, target factory, chamber and primary coolant loop must total less than 3 cts/kW$_e$hr (< ~1 B$) to replace a coal boiler and CO_2 scrubber, *if the IFE Balance-of-Plant also costs $1B.*

What if the working fluid for an IFE engine (laser, heavy ion, or pulsed power) could capture 100 MJ of target yield/kg, including most neutron energy, for direct MHD conversion to electricity @ 60% efficiency and for less than 0.5 cts/kW$_e$hr cost?



Interested? Email John Perkins or myself, re 2-pg white paper. Join us in this exploration.

Conclusion- heavy ion fusion offers an attractive option for inertial fusion energy.

- Heavy ion fusion can build on long-recognized HIF advantages of durability, efficiency, robust chamber/final focus, and merits expanded research.
- New unclassified-code capabilities for HIF target design should yield more robust targets for IFE, and should help attract world intellectual effort into HIF.
- Existing facilities and NDCX-II can study beam compression and focusing relevant to new high gain HIF target designs, cost-effectively.
- Downselection of choice of HIF target can await NIF data on hydro stability/mix
- We have opportunities to develop collaborations with the US and world accelerator community on technology development and on experiments for compression and focusing of beams to high peak power.