

# The U.S heavy ion fusion science program pursues a new vision for heavy ion fusion exploiting high efficiency direct drive\*

Presented by B. Grant Logan

on behalf of the

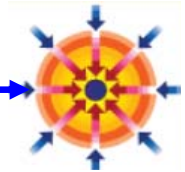
U.S. Heavy Ion Fusion Science Virtual National Laboratory  
(LBNL, LLNL, and PPPL)

**TITAN Workshop on MFE/IFE Common Research  
UCSD**

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*Advances in U.S. Heavy Ion Fusion Science enable exploiting the intrinsic high efficiency of velocity ramped-heavy ion beams for direct drive*



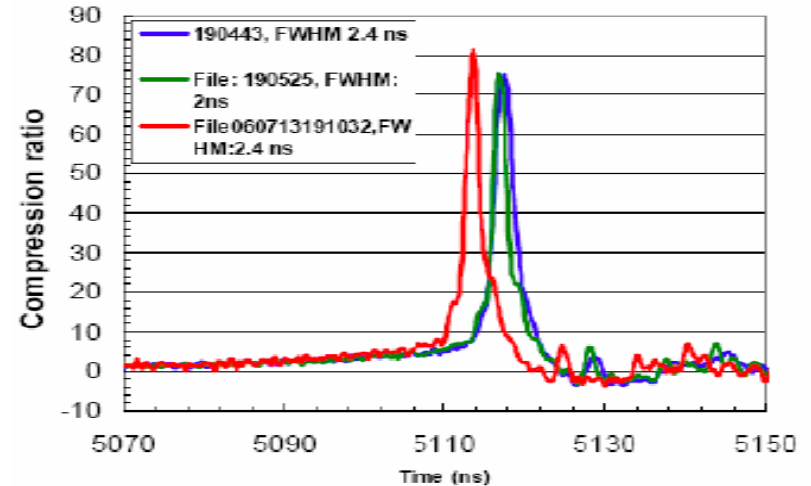
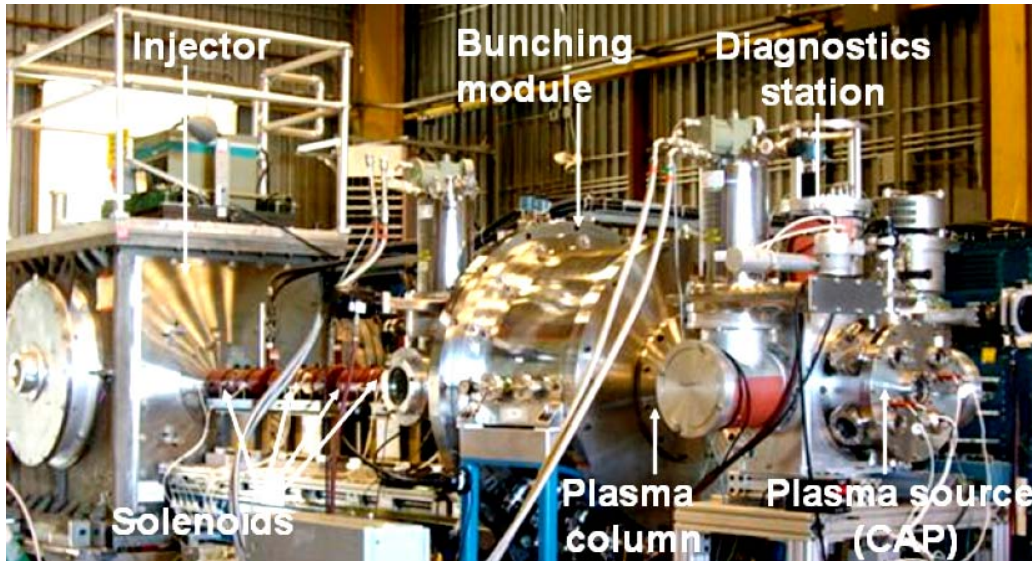
Anders, A.<sup>1</sup>, Barnard, J. J.<sup>2</sup>, Bieniosek, F.M.<sup>1</sup>, Briggs, R.J.<sup>1</sup>, Cohen, R.H.<sup>2</sup>, Davidson, R.C.,<sup>3</sup> Dorf, M.<sup>3</sup>, Efthimion, P.C.<sup>3</sup>, Faltens, A.<sup>1</sup>, Friedman, A.<sup>2</sup>, Greenway, W.G.<sup>1</sup>, Gilson, E.P.<sup>3</sup>, Grisham, L.<sup>3</sup>, Grote, D.P.<sup>2</sup>, Haber, I.<sup>5</sup>, Henestroza, E.<sup>1</sup>, Jung, J-Y.<sup>1</sup>, Kaganovich, I.<sup>3</sup>, Kisek, R.<sup>5</sup>, Kwan, J.W.<sup>1</sup>, Lee, E. P.<sup>1</sup>, Leitner M.<sup>1</sup>, Lidia, S.M.<sup>1</sup>, Logan, B.G.<sup>1</sup>, Lund S.M.<sup>2</sup>, Moir, R.W.<sup>2</sup>, Molvik, A.W.<sup>1</sup>, More, R.M.<sup>1</sup>, Ni, P.A.<sup>1</sup>, Perkins, L. J.<sup>2</sup>, Qin, H.<sup>3</sup>, Rose, D.V.<sup>4</sup>, Roy, P.K.<sup>1</sup>, Startsev, E.A.<sup>3</sup>, Seidl, P.A.<sup>1</sup>, Sharp, W.M.<sup>2</sup>, Vay, J-L.<sup>1</sup>, Waldron, W.L.<sup>1</sup>, Welch, D.R.<sup>4</sup>, Yu, S. S.<sup>1</sup>

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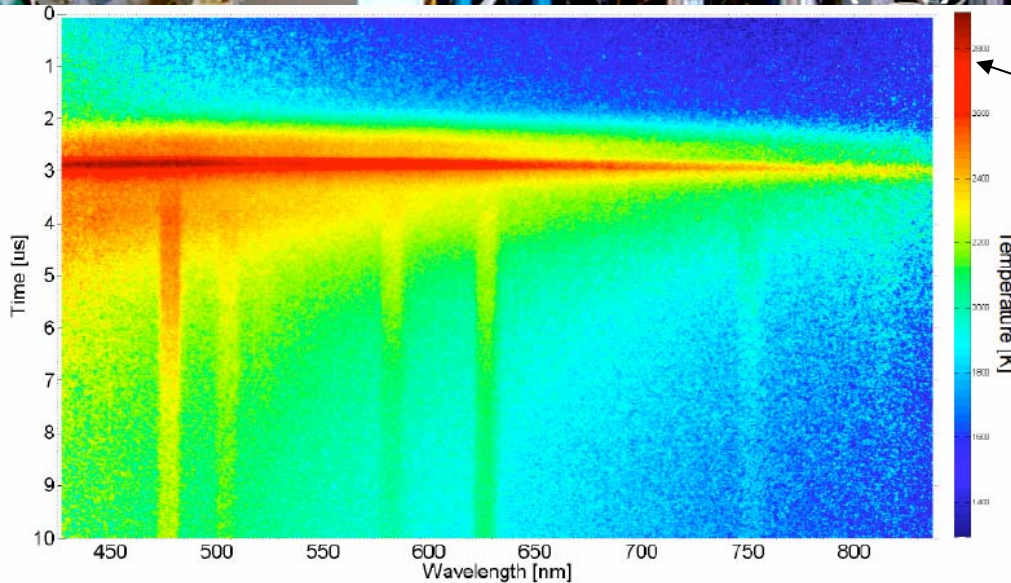
# Recent innovations, together with NIF ignition, support a new vision for heavy ion fusion:

- Heavy ion beam intensity increases  $> 1000X$  with **velocity increasing in time** with space charge neutralized by background plasma.  
*[Neutralized Drift Compression Experiment (NDCX): P. K. Roy, et. al. Phys. Rev. Lett. 95, 234801 (2005), and J.E. Coleman et al., in Proc. of the 2007 Particle Accelerator Conf., Albuquerque, NM, 2007(IEEE catalog# 07CH37866, USA, 2007). Time-dependent chromatic focusing correction experiment planned in NDCX next year].*
- High coupling efficiency of heavy ion beam direct drive in ablative rocket regime (**also uses beam velocity increasing in time**).  
*[B. G. Logan, L. J. Perkins, and J. J. Barnard, Phys. Plasmas 15, 072701 (2008)].*
- Beam spot rotation on target with helical RF-beam perturbations upstream  
*[B. Sharkov (Russia), S. Kawata (Japan), H. Qin (USA)]* → **enables direct drive with only 4 polar angles @  $< 1\%$  non-uniformity for direct drive** *[J. Runge, Germany].*
- New agile on/off valve technology for liquid jets **adapted to provide thick liquid protection for direct drive chambers**. *[R. Moir, LLNL, 1999 HYLIFE note and recent advances-see <http://videos.komando.com/2008/08/19/water-painting/>].*

# Breakthrough: Compression of intense velocity-chirped ion beams in plasma\*. Now, radial and temporal compression $\rightarrow > 2000 \times n_{beam}$



Velocity ramp accelerates tail, decelerates head, compressing beam  $\sim 2$  ns FWHM



2800 K (will be higher after emissivity correction)

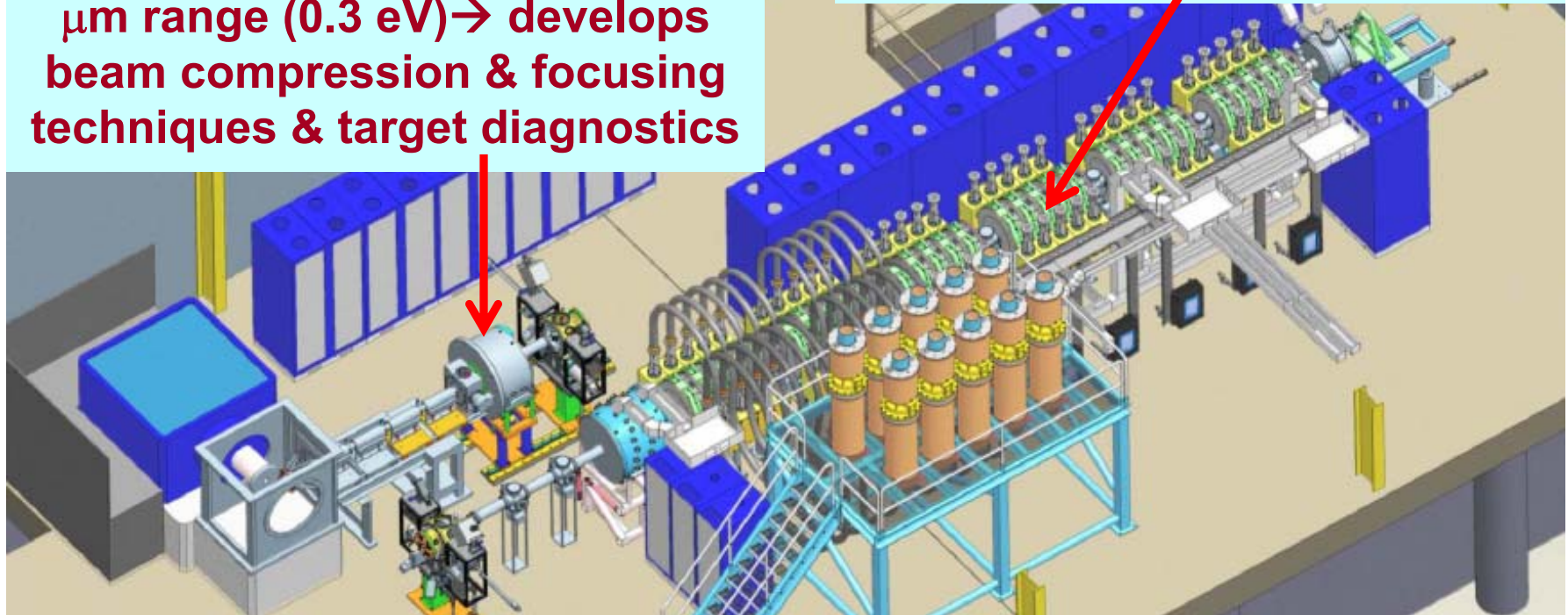
← time of arrival of 2 ns compressed pulse onto 100 nm gold foil target after 3  $\mu$ s of uncompressed beam preheating. Streak camera spectra showing emission lines from gold vapor indicating temperatures above 3100 K.

\*cf Roy, et. Al. PRL 95(2005) 23481

We plan to assemble NDCX-II with largely existing equipment, enabling higher energy WDM and planar direct drive hydro coupling experiments

Present NDCX-I beamline  
In Bldg 58 at LBNL: 1-3 mJ @ 0.2  $\mu\text{m}$  range (0.3 eV)  $\rightarrow$  develops beam compression & focusing techniques & target diagnostics

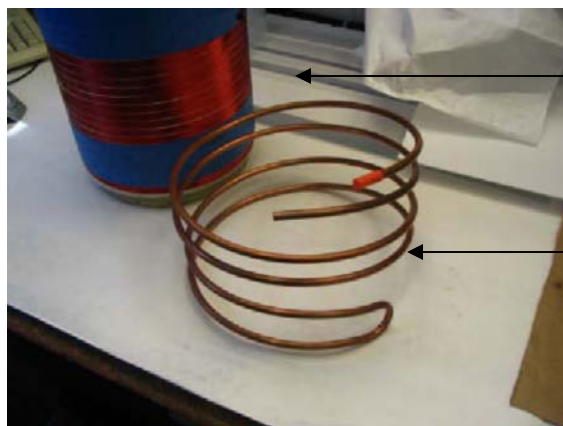
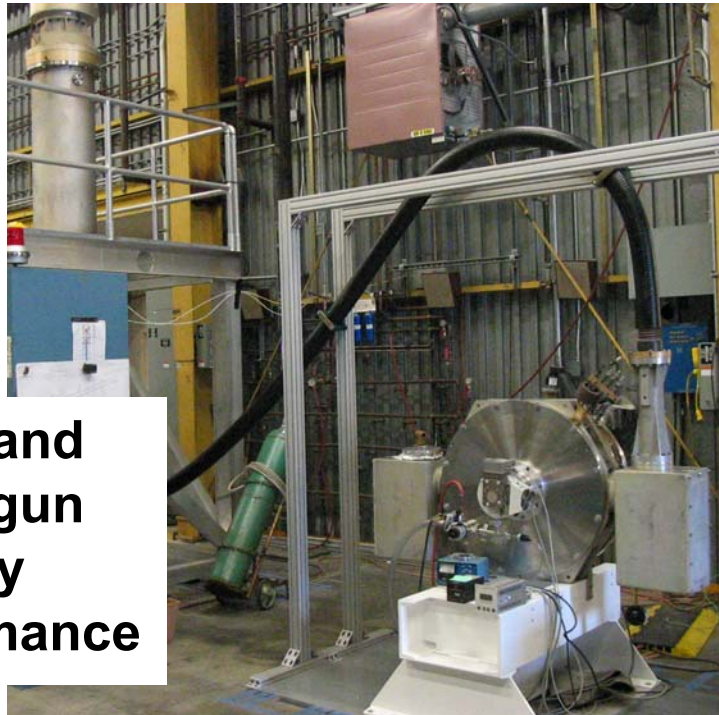
Planned NDCX-II beamline can use existing ATA equipment



**NDCX-II would increase beam energy on target 100 times  $\rightarrow$  enables HEDP-WDM and direct drive hydro-coupling experiments.**  
 **$\rightarrow$ Integrated Beam High Energy Density Physics Experiment: there are enough ATA accelerator modules to build a longer, 25 MV IB-HEDPX**

# Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility, sufficient for NDCX-II

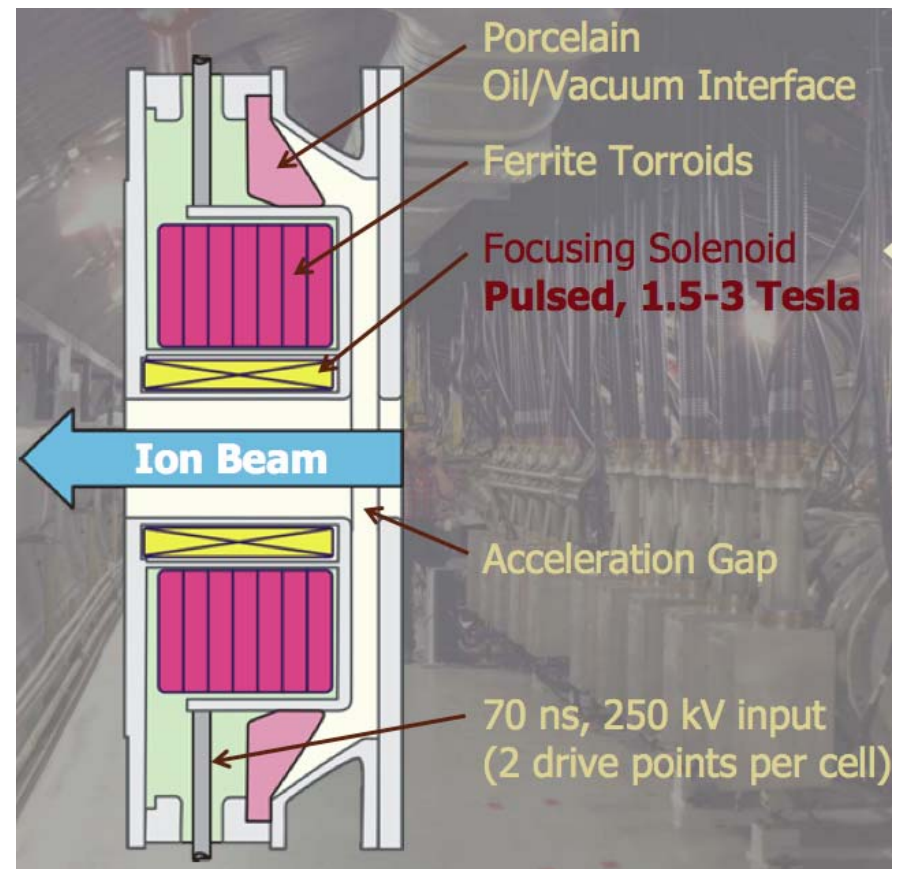
Test stand has begun to verify performance



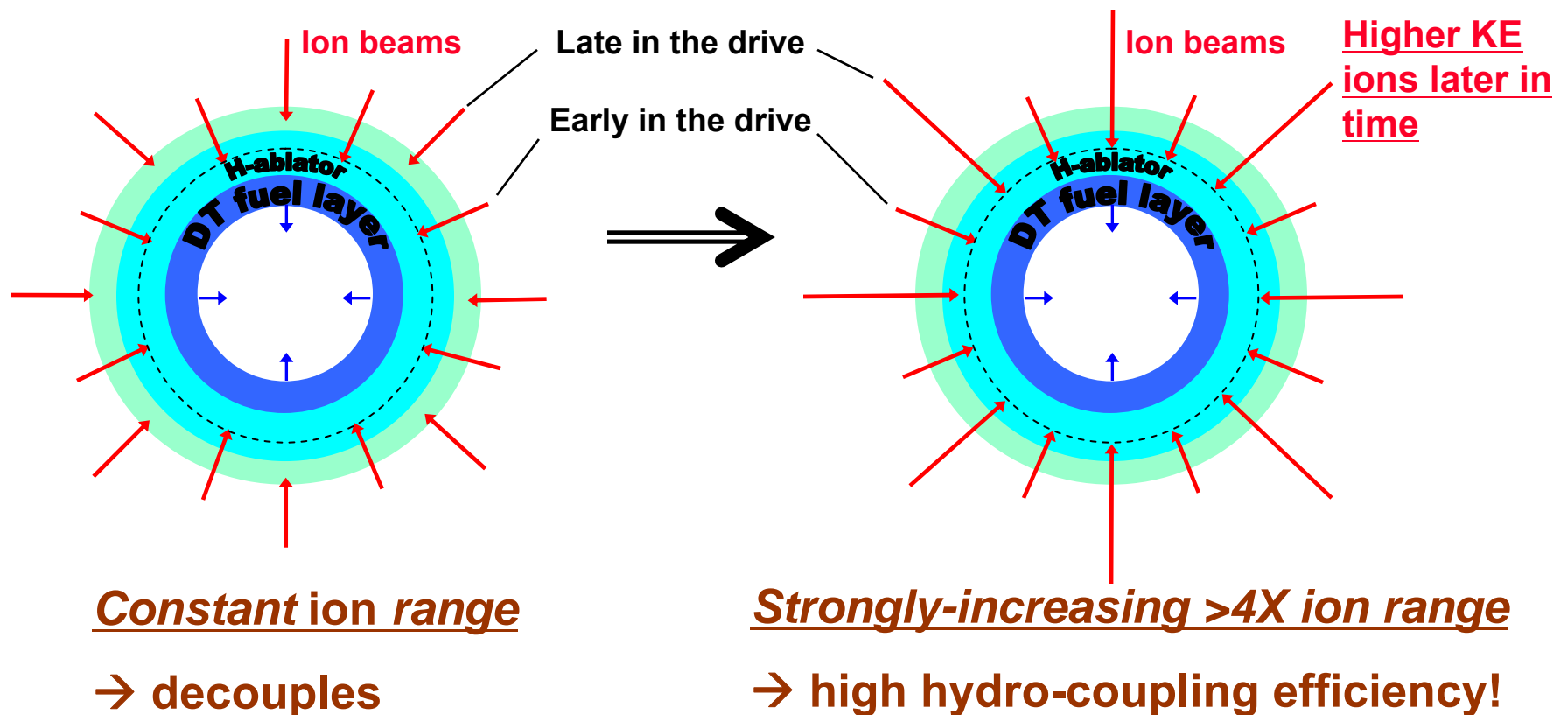
solenoid

water cooling

Cells will be refurbished with stronger, pulsed solenoids



Following our success in velocity-chirp compression of intense ion beams to few-nanosecond pulses in plasmas, we have another powerful fusion idea *which also uses ion velocities increasing in time:*



## Direct drive heavy-ion-beam inertial fusion at high coupling efficiency

B. G. Logan,<sup>1</sup> L. J. Perkins,<sup>2</sup> and J. J. Barnard<sup>2</sup>

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Issues with coupling efficiency, beam illumination symmetry, and Rayleigh-Taylor instability are discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. Efficient coupling of heavy-ion beams to compress direct-drive inertial fusion targets without hohlraums is found to require ion range increasing several-fold during the drive pulse. One-dimensional implosion calculations using the LASNEX inertial confinement fusion target physics code shows the ion range increasing fourfold during the drive pulse to keep ion energy deposition following closely behind the imploding ablation front, resulting in high coupling efficiencies (shell kinetic energy/incident beam energy of 16% to 18%). Ways to increase beam ion range while mitigating Rayleigh-Taylor instabilities are discussed for future work. © 2008 American Institute of Physics. [DOI: [10.1063/1.2950303](https://doi.org/10.1063/1.2950303)]

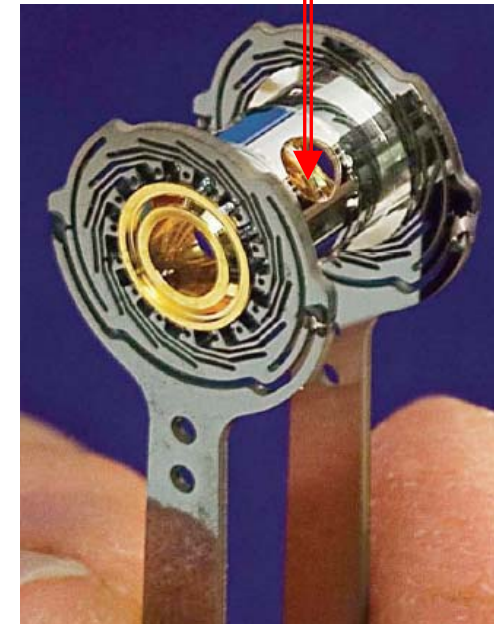
**John Nuckolls (April 2008) : “This is a real advance! Now, how are you going to exploit it? Can you apply this high coupling efficiency to reduce drive energy to much less than 1 MJ?”**

**NIF ignition, if successful, will validate 15% hydro-coupling efficiency in ablative capsule drive (capsule gain 100 with 200 kJ x-ray absorbed).**

→ Idea for an HIFTF test facility:

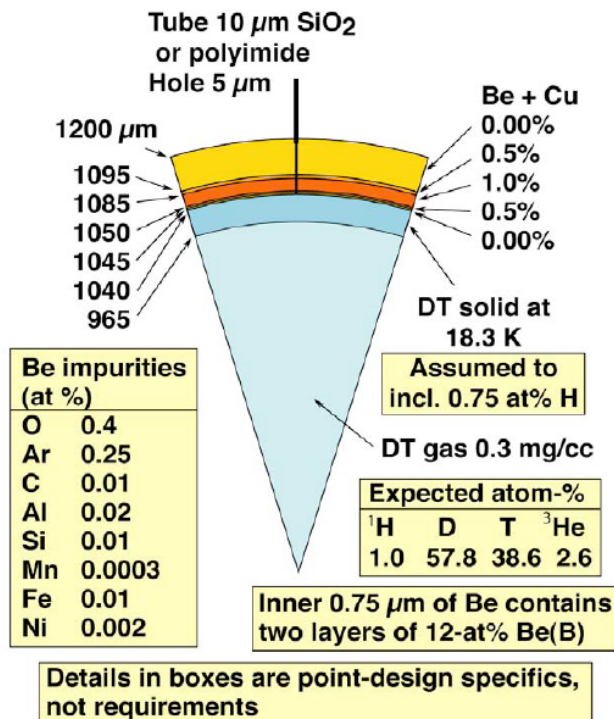
**LASNEX giving the same coupling efficiency, could 200 kJ of ions absorbed (300 kJ incident with spill) with *same power vs time* and the right range into H/DT ablators get gain >50?**

1 mm radius Be capsule



The National Ignition Campaign

(Cu doped Be shell for 285eV, 1.3 MJ)

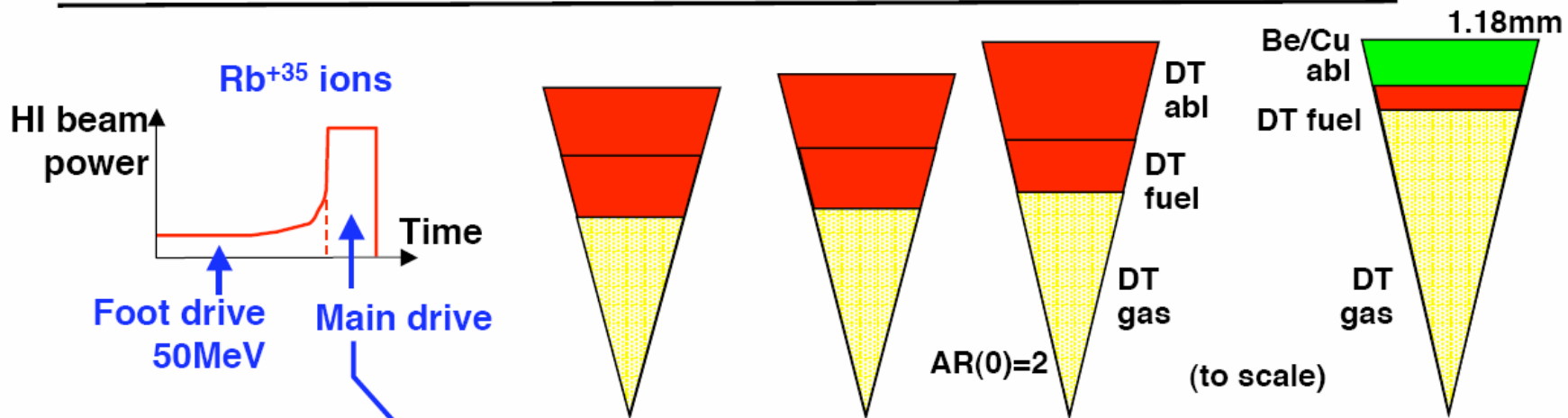


| Parameter                                    | Be(285)<br>"current best calc" |
|--|--------------------------------|
| Absorbed energy (kJ)                         | 203                            |
| Laser energy (kJ) (includes ~8% backscatter) | 1300                           |
| Coupling efficiency                          | 0.156                          |
| Yield (MJ)                                   | 19.9                           |
| Fuel velocity (10 <sup>7</sup> cm/sec)       | 3.68                           |
| Peak rhoR (g/cm <sup>2</sup> )               | 1.85                           |
| Adiabat (P/P <sub>FD</sub> at 1000g/cc)      | 1.46                           |
| Fuel mass (mg)                               | 0.238                          |
| Ablator mass (mg)                            | 4.54                           |
| Ablator mass remaining (mg)                  | 0.212                          |
| Fuel kinetic energy (kJ)                     | 16.1                           |

# Latest target designs by John Perkins (2-2-09) confirm:

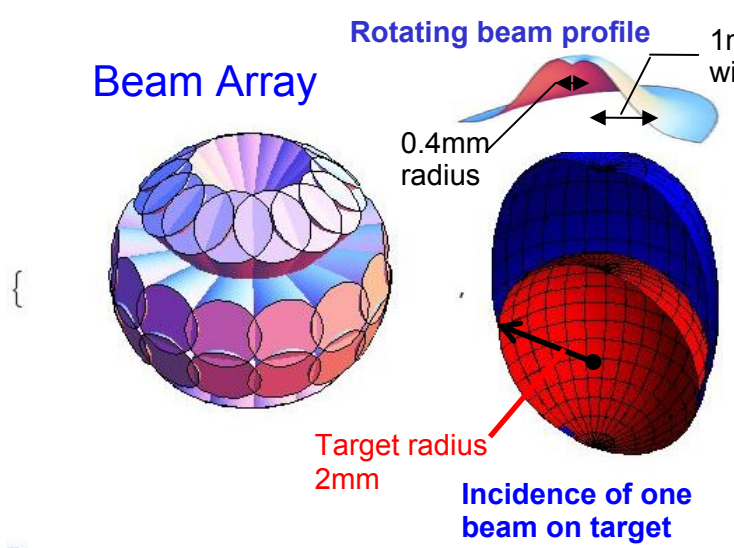
Objective: Design a high-gain HI direct target with:

- (a) NIF yield  $\sim 20\text{MJ}$ , (b)  $E_{\text{HI driver}} \ll 1\text{MJ}$ , (c) all-DT, (d) robust capsule



|                                      | 50MeV            | 200MeV           | 500MeV           | NIF              |
|--------------------------------------|------------------|------------------|------------------|------------------|
| $m_{\text{ablator}}/m_{\text{fuel}}$ | 1.8              | 2.1              | 3.0              | 18               |
| Driver energy (MJ)                   | 0.32             | 0.36             | 0.44             | 1.3              |
| Peak drive power (TW)                | 175              | 195              | 205              | 320              |
| Yield (MJ) / <b>Gain</b>             | 24.7 / <b>77</b> | 21.6 / <b>60</b> | 20.8 / <b>47</b> | 20.0 / <b>15</b> |
| $\eta_{\text{absorbed}} / \eta$      | 0.97 / 0.10      | 0.91 / 0.10      | 0.88 / .09       | 0.16 / 0.02      |
| In-flight aspect ratio               | 25               | 27               | 25               | 32               |
| Convergence ratio                    | 35               | 30               | 31               | 34               |
| In-flight adiabat $\alpha$           | 1.9              | 2.4              | 3.2              | 1.4              |

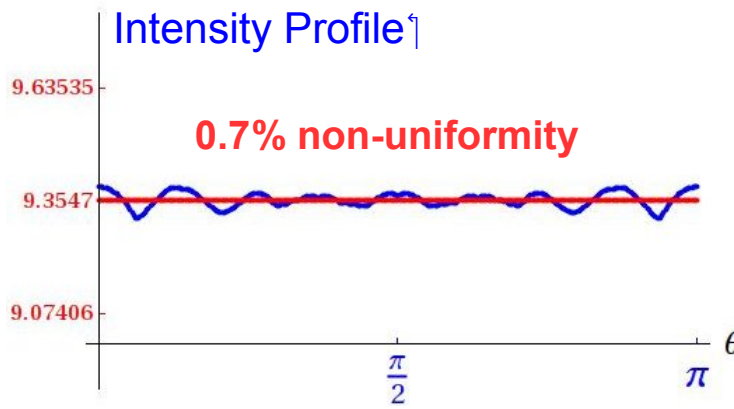
Jakob Runge, a German Fulbright summer student at LBNL, has developed a Mathematica model to explore the question: what minimum number of polar angles of annular ring arrays with beams *using hollow rotated beam spots* would be needed to achieve less than 1% non-uniformity of deposition?



16 each best for two-sided beamline layouts

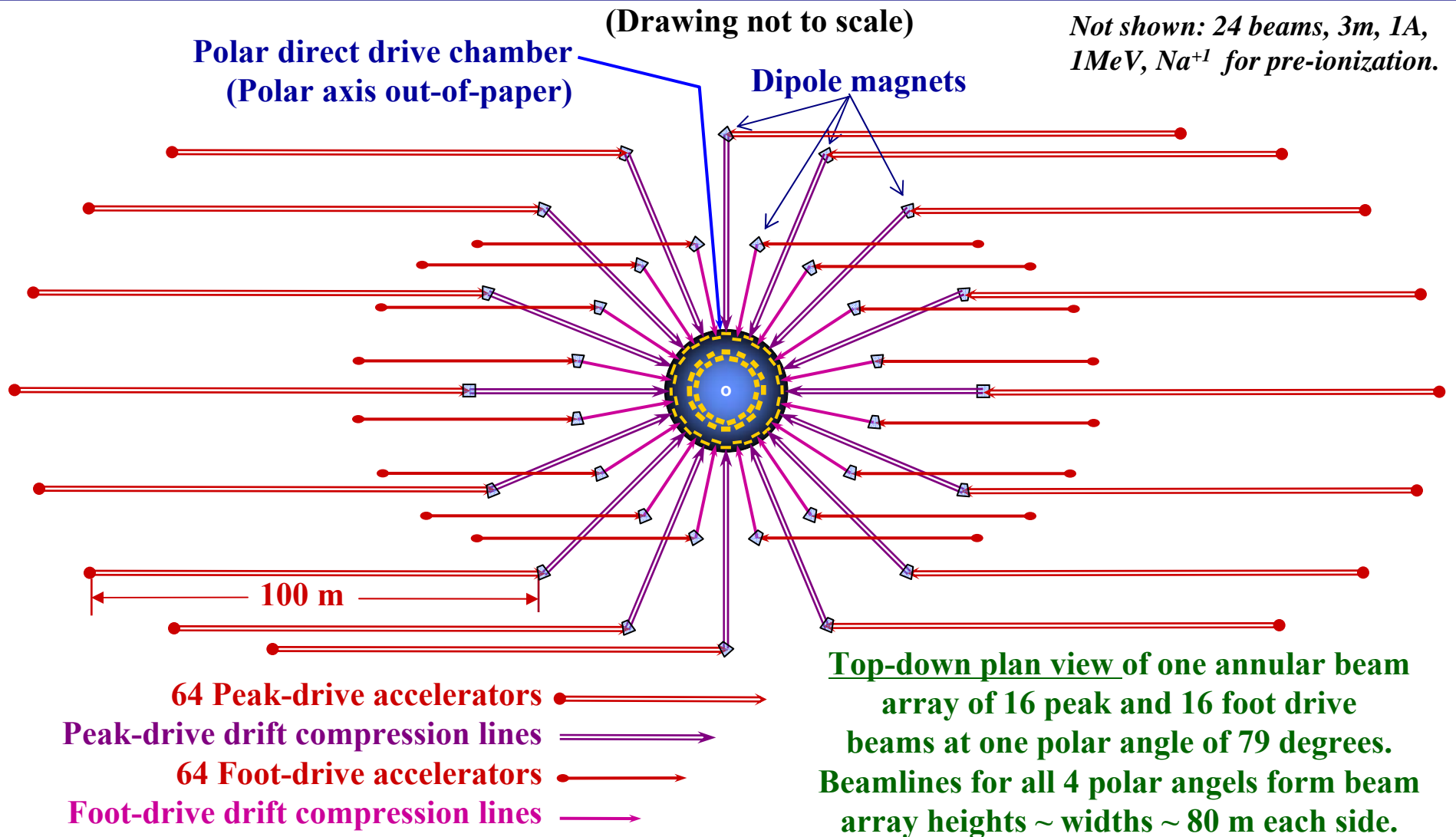
Just four annular rings of beams (15 each: 60 total) at  $\pm 37.3^\circ$  and  $\pm 79.3^\circ$ , with hollow, rotated beam spot projections give a maximum deviation from the mean of 0.7% (with 21% spilled intensity).

4 polar angles only, not  $4\pi$ !

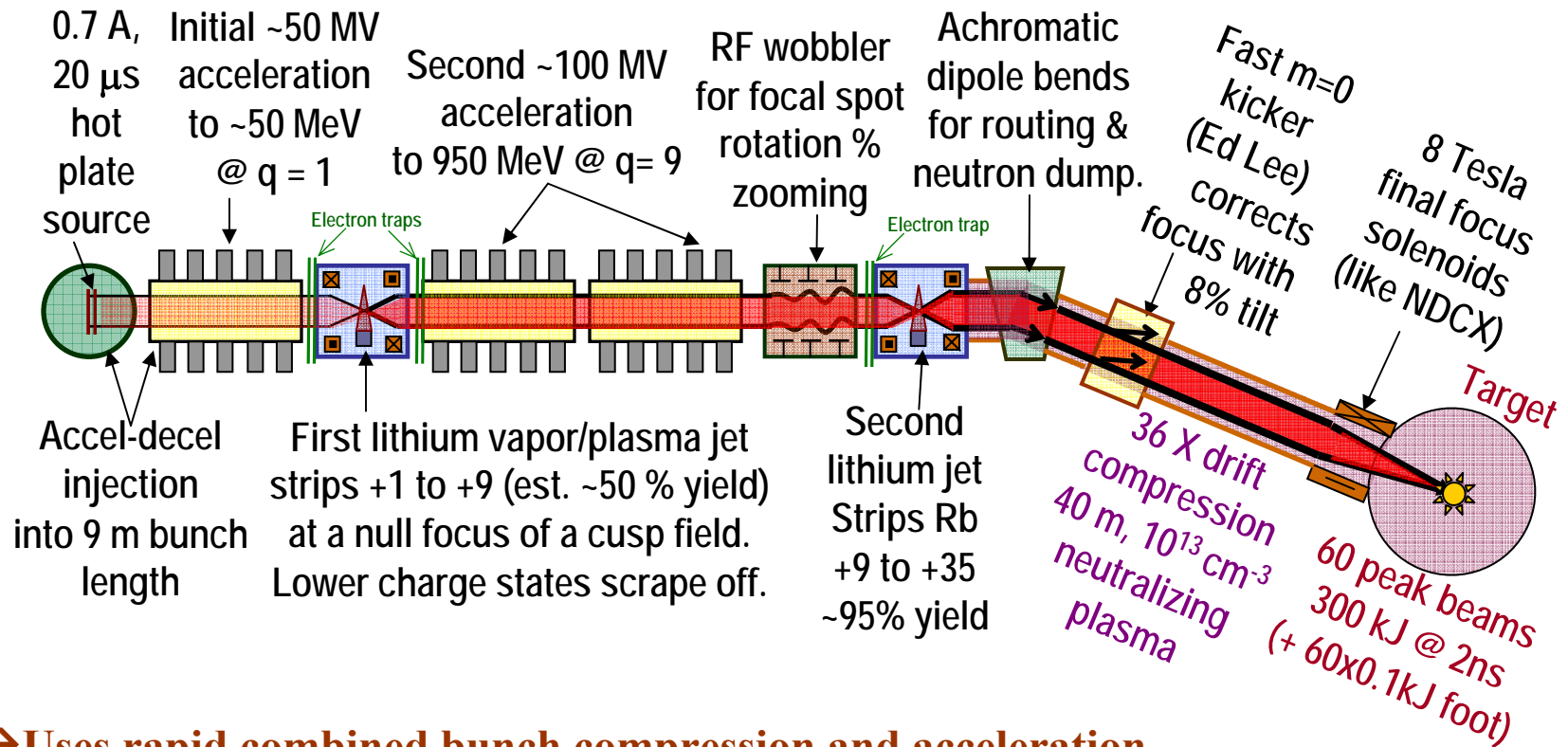


40 beams total give less than 1.4% and 32 beams total still give about 2%. With smaller ring radii the spill can be reduced, but unwanted radial incidence increases (RT instabilities). Smaller widths are desirable.

To compact beamline service and maintenance, dipole magnets bend 128 driver beams total from two beamline arrays into plasma-neutralized drift compression lines directed to final focus into the direct drive chamber:



**Option for a 5 kJ linac module for a 60-peak-beam HIFTF driver :**  
**Induction acceleration efficiency 13% (@ 640 A/beam),**  
**Modest linac length and cost (100-m linac @  $q = 9$ , 1.5 MV/m).**  
**Manageable beam perveance  $K \sim 10^{-3}$ , injector source  $I_s < 1$  A @  $q=1$ .**  
**1 GeV Rubidium<sup>+9</sup> beam linac module with two stages of beam stripping.**

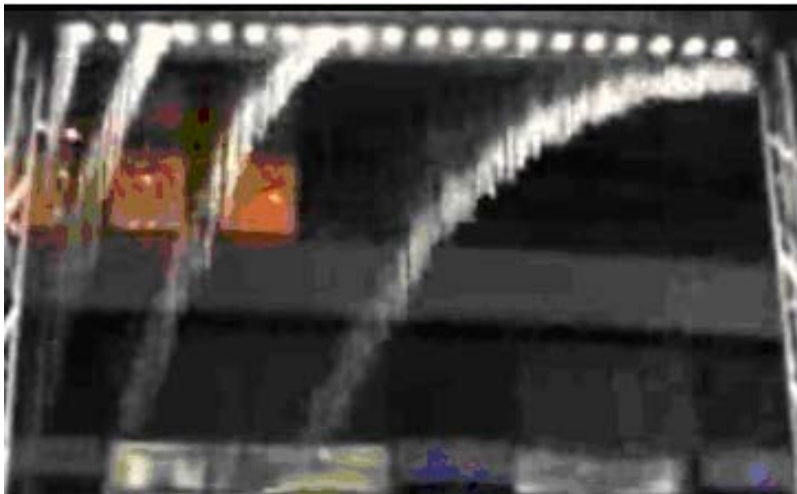
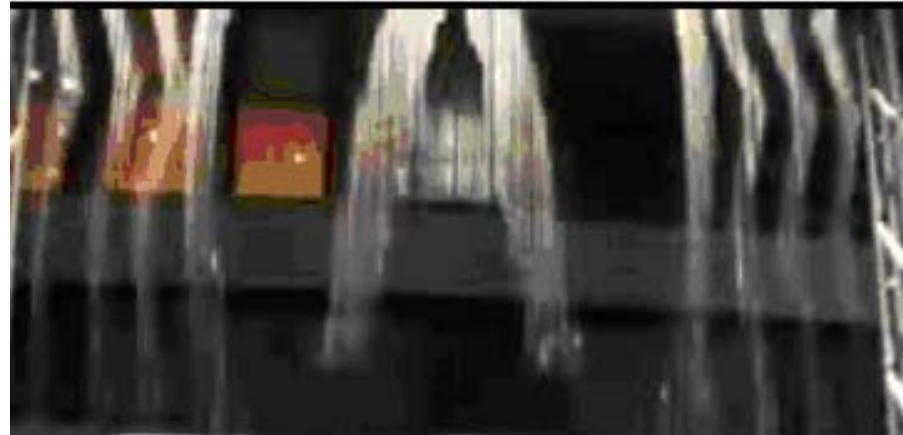
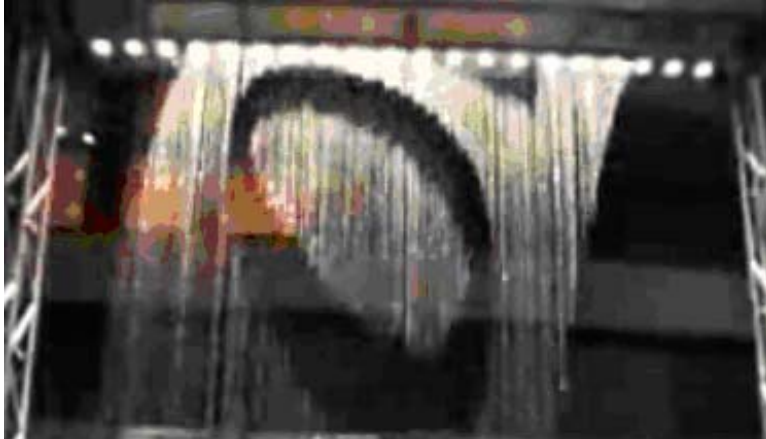


- Uses rapid combined bunch compression and acceleration with downstream beam manipulations to be tested on NDCX-I&II
- Two of these drive test implosions in HIDDIX; 64 for peak drive for HIFTF.

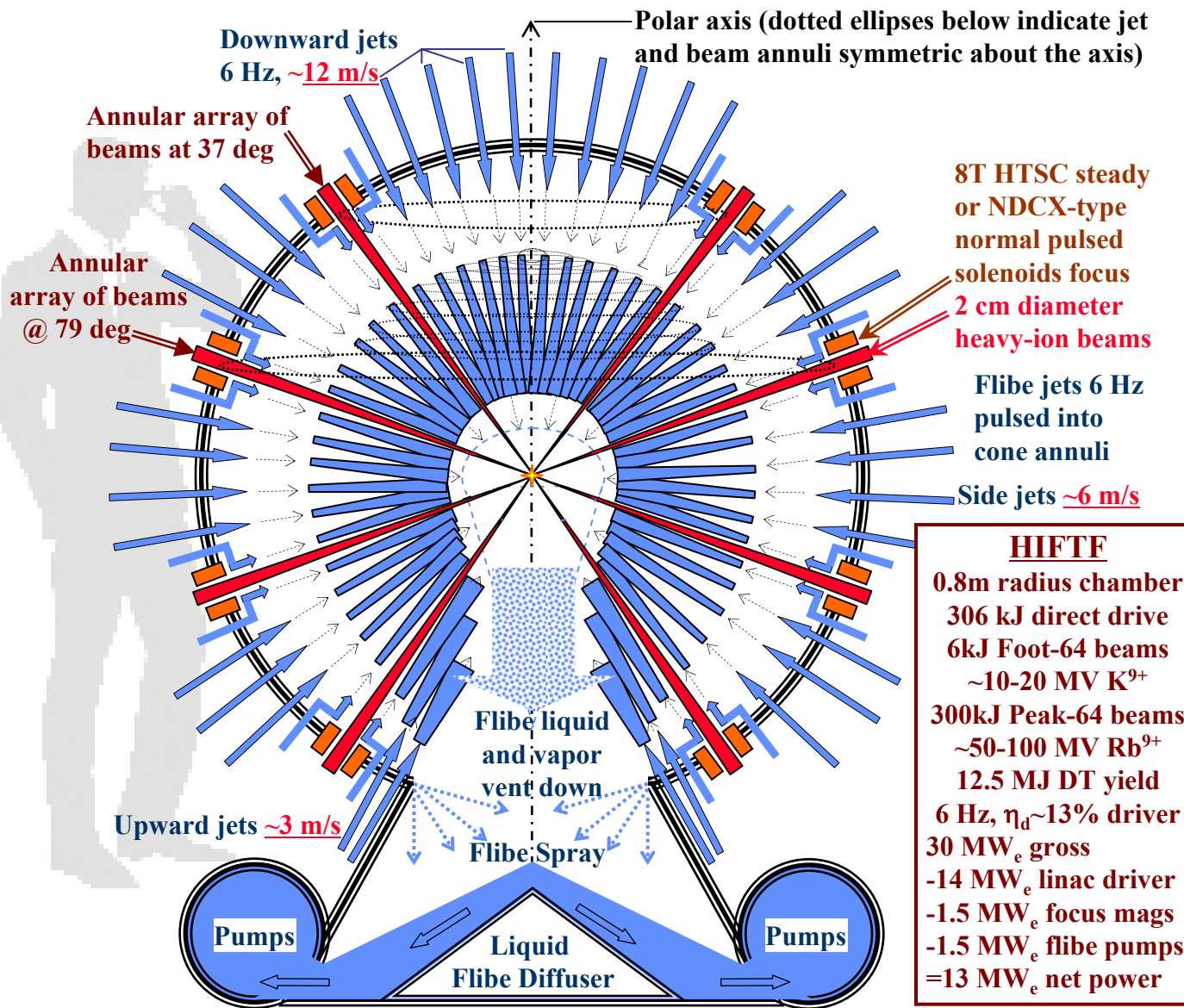
# New pulsed-jet valve capability would enable thick liquid Flibe protection like HYLIFE to be adapted to *direct drive chambers*

[R. Moir, LLNL, 1999 HYLIFE note.

Water fountain pictures from <http://videos.komando.com/2008/08/19/water-painting/>].



# Concept for a small heavy-ion fusion test facility (HIFTF): *polar direct drive*



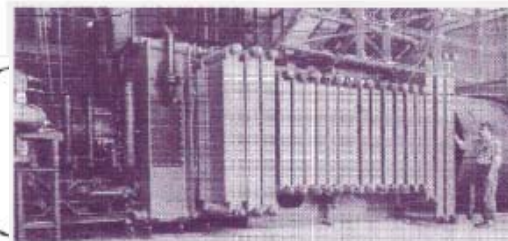
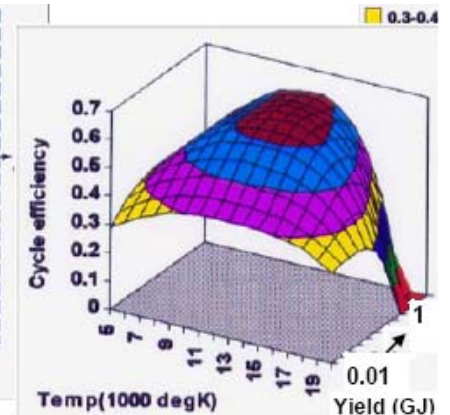
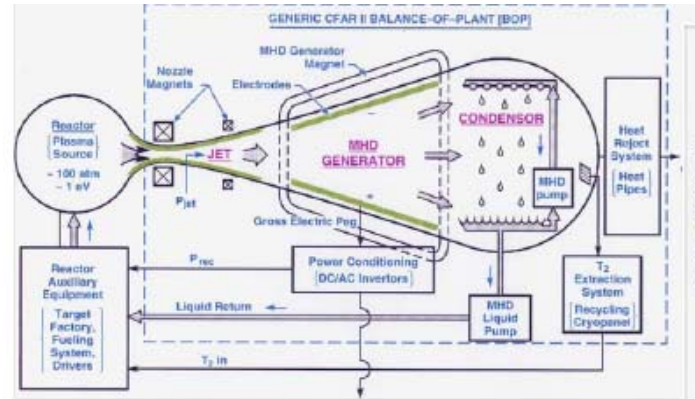
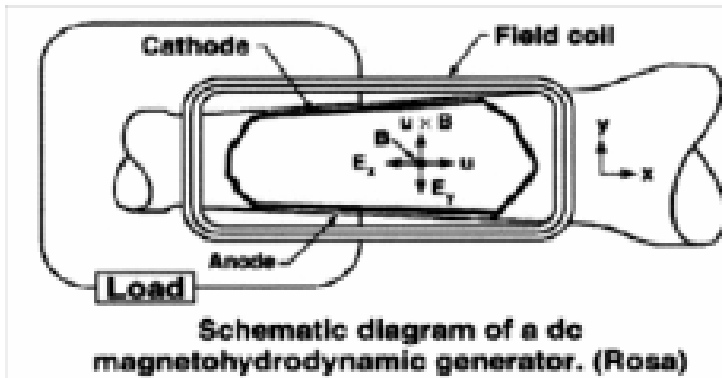
**HIFTF**

- 0.8m radius chamber
- 306 kJ direct drive
- 6kJ Foot-64 beams
- ~10-20 MV  $K^{9+}$
- 300kJ Peak-64 beams
- ~50-100 MV  $Rb^{9+}$
- 12.5 MJ DT yield
- 6 Hz,  $\eta_d \sim 13\%$  driver
- 30 MW<sub>e</sub> gross
- 14 MW<sub>e</sub> linac driver
- 1.5 MW<sub>e</sub> focus mags
- 1.5 MW<sub>e</sub> flibe pumps
- =13 MW<sub>e</sub> net power

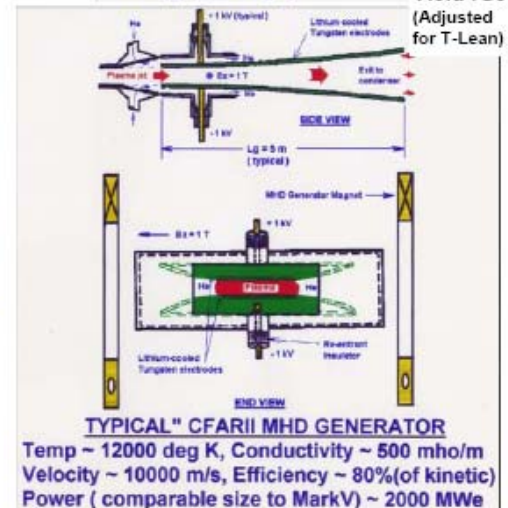
- **Pulsed jets** (Moir: 1999 HYLIFE notes) merge radially halfway into chamber, forming a 30-cm thick *liquid imploding shell* with annular beam access around the axis at shot time, @ 4 angles.
- **Liquid shell mass and momentum** sufficient that pocket pressurization due to non-neutron fusion yield slows but does not reverse the liquid radial velocities of all but the slowest upward jets.
- **Jet velocities decrease with polar angle** for net momentum of the liquid and post-shot vapor to vent downwards to clear the chamber.

# Ultimate Heavy Ion Fusion Energy Vision

High  $\rho r$  + 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 ( $\sim \sigma u^2$ ) than "old" MHD, →30X more kWe per ton power density than conventional steam-turbine generators → 10X lower balance of plant costs!



**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

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

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

**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 :**  
 Magnet Cost / m<sup>3</sup> ~ B<sup>2</sup> / (2μ<sub>0</sub>)

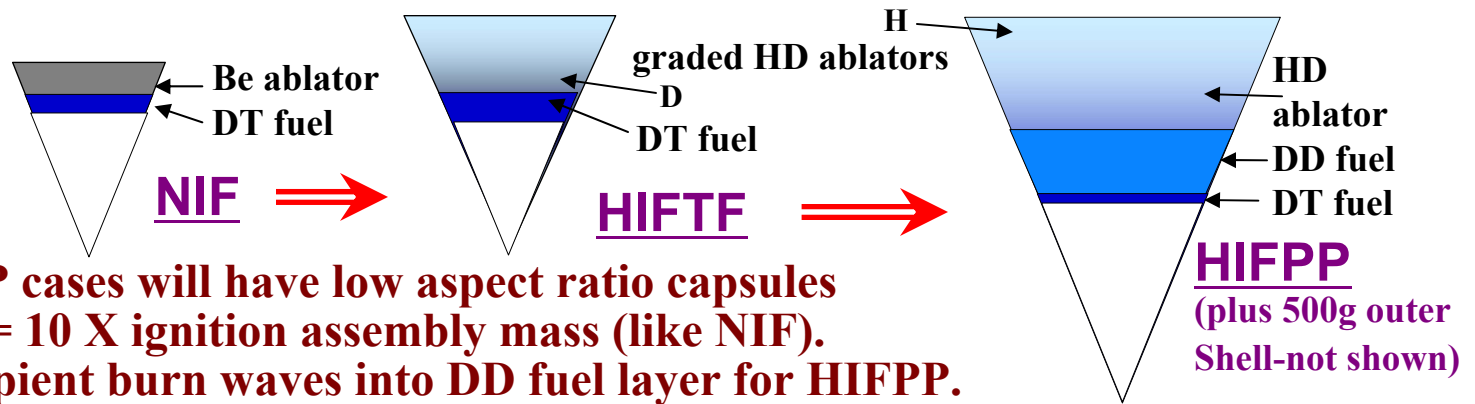
where  $\rho$  = mass density,  $u$  = velocity,  $x$  = distance along channel,  $p$  = pressure,  $j$  = current density,  $B$  = magnetic field,  $E$  = electric field,  $\sigma$  = electrical conductivity,  $\omega\tau$  = Hall parameter,  $h$  = specific enthalpy,  $f$  = friction due to mass inflow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

→ MHD Magnet Cost / kWe ~ B<sup>2</sup> / j · E → Figure-of-merit \$ / kWe ~ (σu<sup>2</sup>)<sup>-1</sup>

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

# NIF-scale capsules prototype central ignition for the smallest DT heavy-ion fusion test facility (HIFTF) and for follow-on T-lean power plant (HIFPP)

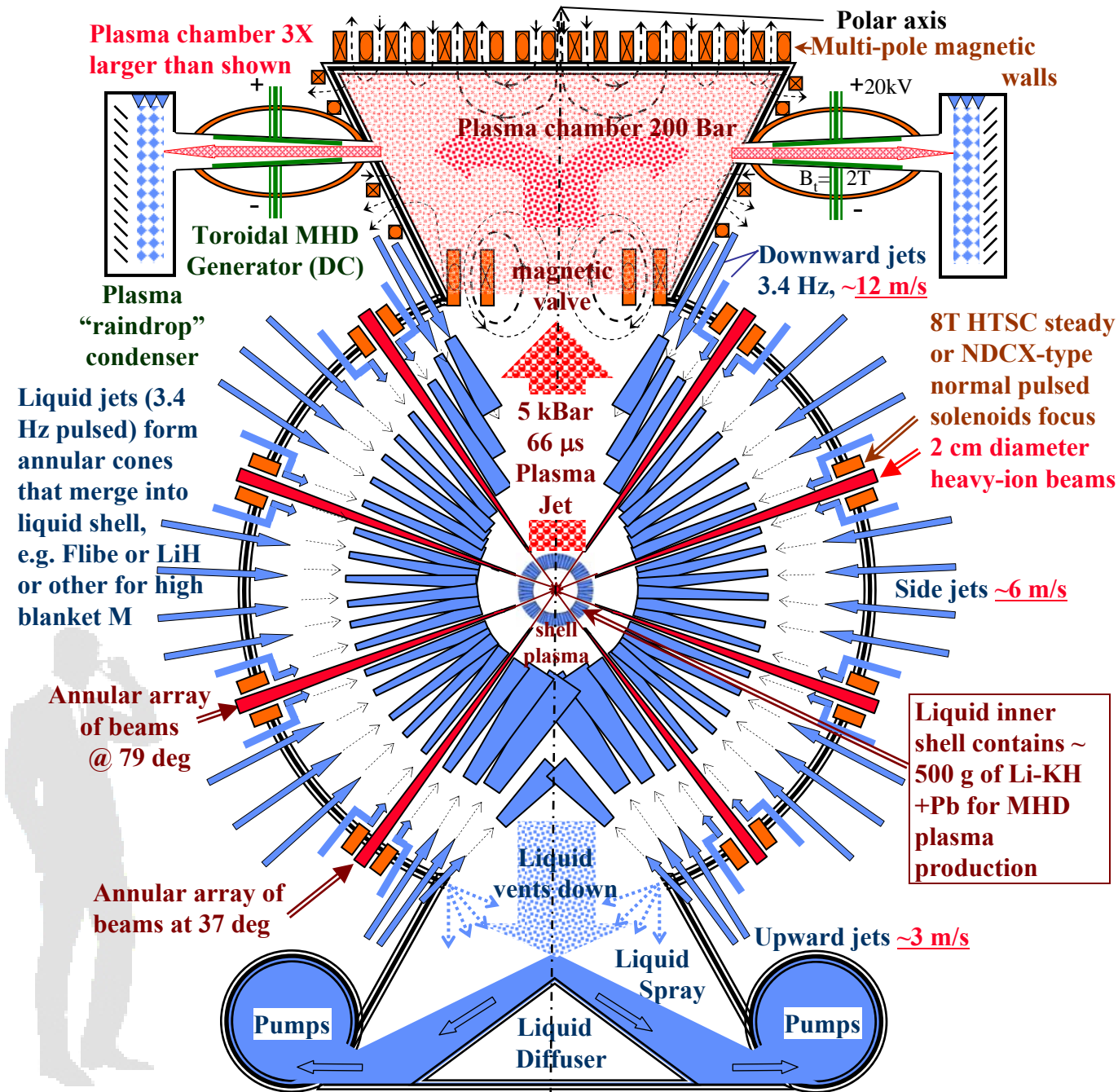
(Capsules not drawn to scale) →



→ HIFTF & HIFPP cases will have low aspect ratio capsules with ablator mass = 10 X ignition assembly mass (like NIF).

→ HIFTF tests incipient burn waves into DD fuel layer for HIFPP.

|                                       | NIF baseline                         | HIFTF (DT) (planned)                               | HIFPP (T-lean power plant)                               |
|---------------------------------------|--------------------------------------|--|--|
| Outer radius                          | 1.2 mm                               | 2 mm (TBD-Lasnex)                                  | 5 mm ( $M_o/M_f=10$ , Tabak dd core)                     |
| Energy into capsule                   | 200 kJ (300eV x-rays)                | 250 kJ (heavy ions 2→10 mg/cm <sup>2</sup> ranges) | 1.4 MJ (heavy ions 4→20 mg/cm <sup>2</sup> ranges)       |
| Ignition masses (at stagnation)       | 0.24 mg DT core<br>+0.21 mg Be outer | 0.24 mg DT core<br>+0.21 mg D outer                | 0.24 mg DT core ← equal<br>+6.5 mg D outer               |
| Imp. Velocity;<br>Coupling efficiency | 3.7 e7 cm/s<br>15%                   | ~3.9 e7 cm/s<br>17% (1-D Lasnex)                   | 3.3 e7 cm/s (Tabak dd model)<br>25% (analytic model)     |
| Fuel assem. energy                    | 30 kJ (16 in DT)                     | 30 kJ (16 in DT, 14 in D)                          | 350 kJ (in D+DT spark)                                   |
| Rho-r                                 | 1.85 g/cm <sup>2</sup>               | 1.2 - 1.8 g/cm <sup>2</sup> (TBD)                  | 8.1 g/cm <sup>2</sup> (not inc. outer shell)             |
| Fusion yield                          | 20 MJ (DT)                           | >12 MJ (DT-26% plasma)<br>(TBD-Lasnex)             | 100 MJ (DD-DT→92% plasma w/<br>K-LiH-Pb converter shell) |

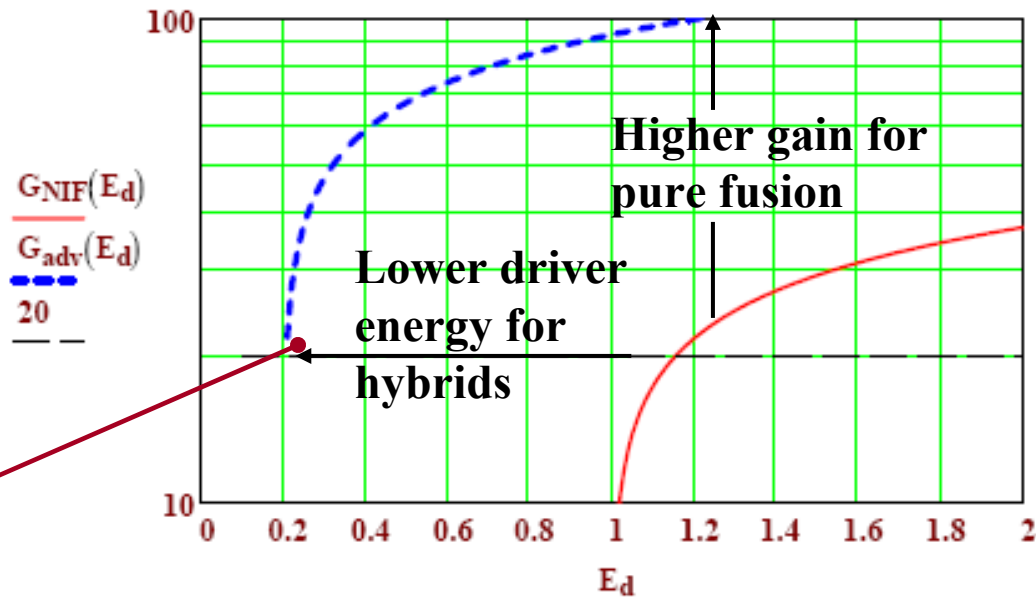


**Advanced fuel HIF Power Plant (HIFPP) using direct drive compression of DD fuel**

- with DT spark plug.**
- 1.4 m radius chamber**
- 1.6 MJ direct drive:**
  - Foot-64 beams ~20-40 MV  $K^{9+}$**
  - Peak-128 beams ~100-200 MV  $Rb^{9+}$**
- 100 MJ DD/DT yield**
- 1.5 Blanket energy M**
- 3.4 Hz,  $\eta_d \sim 13\%$  driver**
- $\eta_{conv} = 0.7$  [0.5 MHD + 0.4 thermal bottom]**
- 357 MW<sub>e</sub> gross**
- 42 MW<sub>e</sub> linac driver**
- 8 MW<sub>e</sub> all magnets**
- 7 MW<sub>e</sub> liquid pumps**
- = 300 MW<sub>e</sub> net power**

# In addition to high gain for pure fusion, heavy ion direct drive can enable *very small* fusion-fission hybrid power plants

Figure 10: Fusion gain  $G_{NIF}$  for laser-hohlraums (NIF) and for generic advanced IFE gain  $G_{adv}$  versus driver energy  $E_d$  (MJ). The horizontal line is for gain 20 needed for nominal  $\eta_d G > 2.5$  @  $\eta_d = 0.1$ , sufficient for a power hybrid.



→ *Advanced targets + added fission gains (8X) enable very small hybrids.*

→ *Lower cost stepping stone to pure fusion!*

Table 4: A small IFE hybrid example using the advanced gain curve in Fig. 10 at  $G = 20$ ,  $E_d = 0.25$  MJ

Fusion yield =  $20 \times 0.25$  MJ = 5 MJ.

$\eta_d G_{adv} = 2$ , @  $\eta_d = 0.1$

Low pulse repetition rate = 2 Hz

Average fusion power = 10 MW

Fission power = 80 MW

$P_{edriver} = 5$  MW<sub>e</sub>

$P_{enet} = 33$  MW<sub>e</sub>

Chamber radius = 1.2 m

Wall loading = 0.3 MW/m<sup>2</sup>

Blanket fission power density = 1 MW/m<sup>3</sup>

Uranium fuel mass = 1.3 tons

Low first wall loading -- afterheat removal by passive radiation cooling in LOCA → inherent safety

Conclusion: a sequence of cost effective heavy ion beam experiments and facilities can exploit high efficiency direct drive for an attractive new vision for heavy ion fusion energy. More work is needed on:

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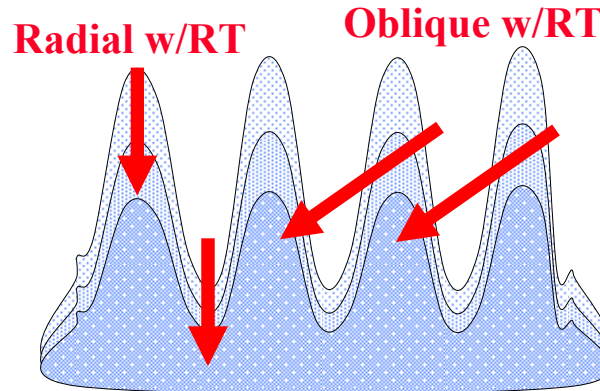
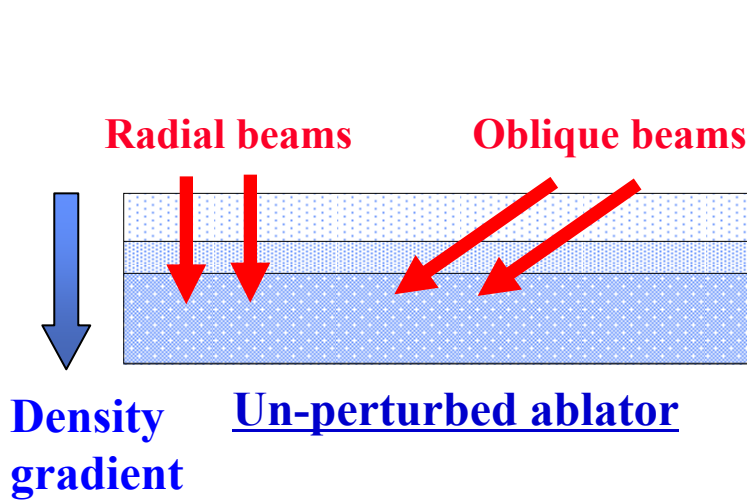
- **Beam brightness, neutralization, collective effects, stripping.**
- **More implosion calculations in the ramped ion energy,  $v_b > v_{eth}$  regime.**
- **Development of RF wobblers and time-dependent focus control for hollow-beam spots.**
- **2-D and 3-D symmetry and Rayleigh Taylor stability studies.**
- **Pulsed liquid jet control for direct-drive chamber protection.**
- **MHD conversion efficiency experiments using surrogate arc-jet plasma sources.**

*→We have workable designs for indirect drive HIF @ 7 MJ driver. The road to realize heavy ion direct drive fusion may be long, but the potential for very high coupling efficiency to reduce driver cost makes the effort worthwhile.*

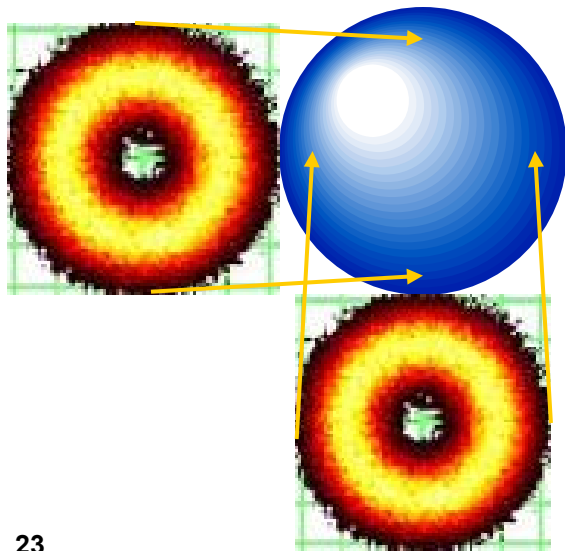
# Backup slides



# Oblique ion illumination with beam spot rotation (*RF wobblers*) can enhance ablative-stabilization and lengthen pressure gradient scale lengths behind the ablation front

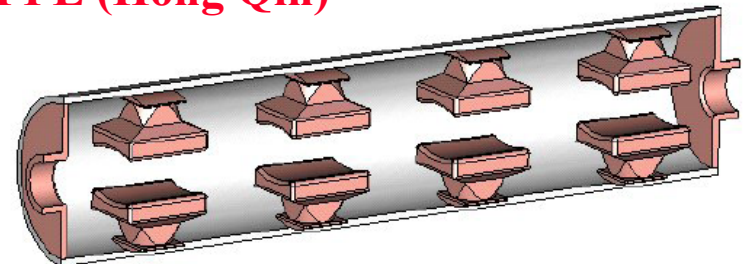


g-Acceleration, Gradient Te,

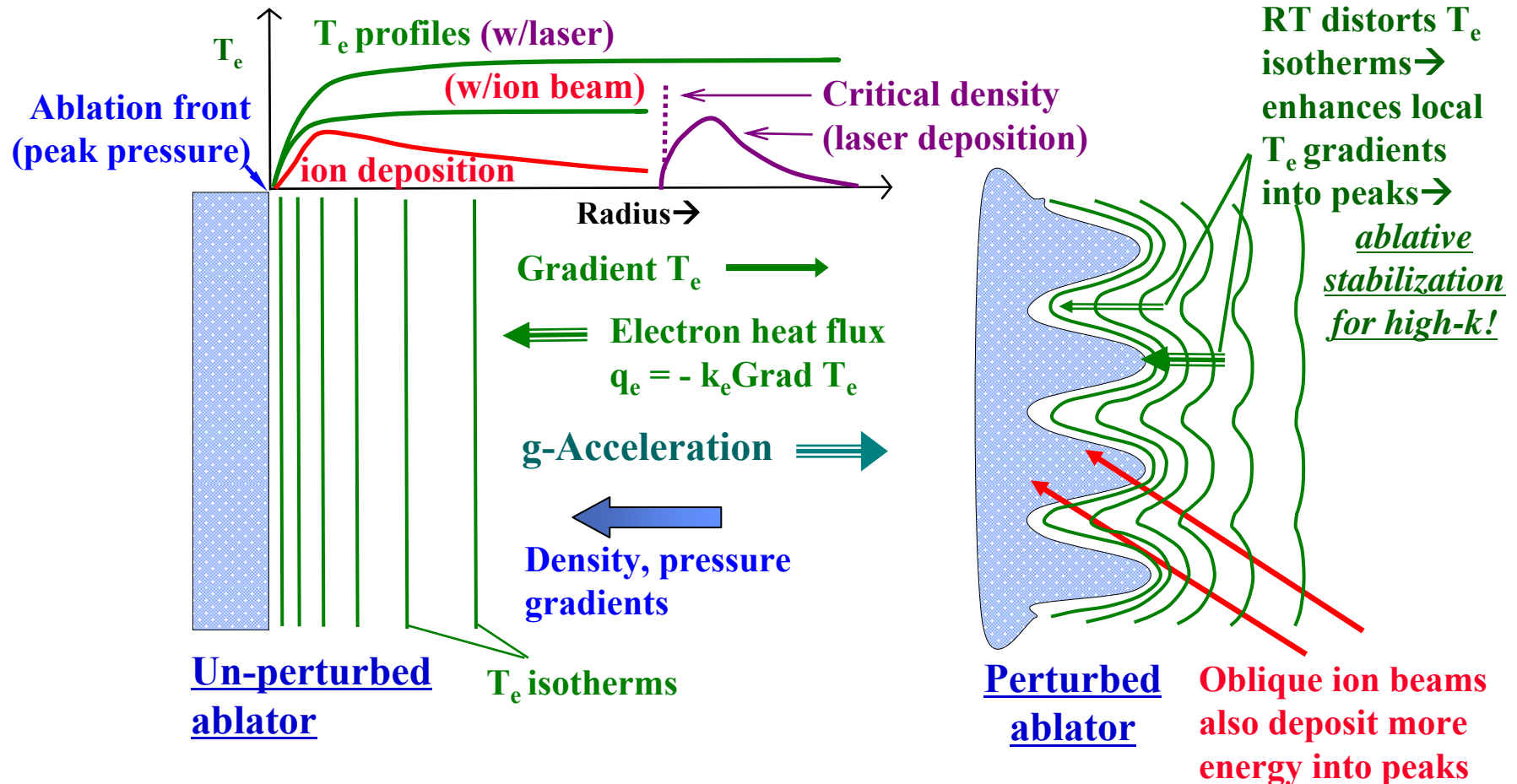


*Projection of many overlapping hollow beams onto a spherical ablator leads to mostly-oblique ray-illumination in the foot pulse, and smoother.*

RF wobblers useful for beam smoothing, focus zooming & RT control (GSI, ITEP, PPPL (Hong Qin))

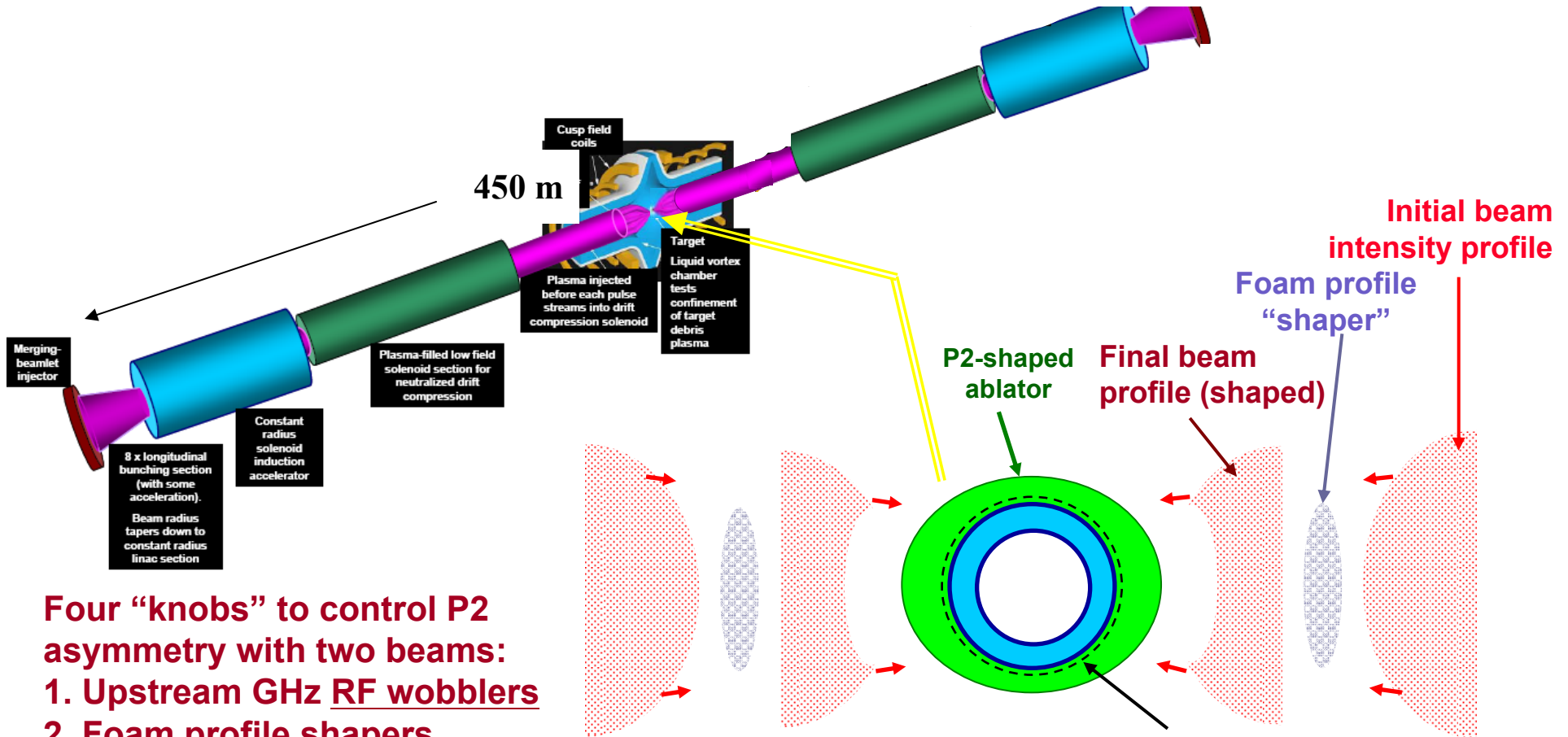


# Ablative stabilization of high-k RT modes depends on local electron temperature gradients from peak beam deposition to ablation front



*Ion versus laser beams-for the same PdV work at the ablation front:*  
 $\rightarrow$  ion beam energy deposited closer to ablation front (higher coupling efficiency)  
 $\rightarrow$  steeper pressure gradients behind ablation front (higher g driving RT for ions)

**Heavy-Ion Direct-Drive Implosion Experiment (HIDDIX):** use two 5 kJ-scale linacs with RF wobblers to drive cryo capsule implosions for benchmarking ion hydro-codes for heavy ion direct drive fusion.  
 → Provides a new accelerator tool to explore polar direct drive hydro physics with heavy ion beams, in parallel with NIF operation.



- Four “knobs” to control P2 asymmetry with two beams:
1. Upstream GHz RF wobblers
  2. Foam profile shapers
  3. Ablator shaping (shims)
  4. Zooming control

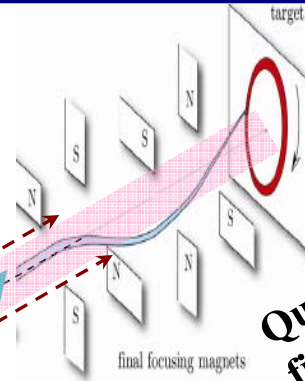
Goal is implosion drive pressure on the Cryo D<sub>2</sub> payload with < 1 % non-uniformity

# Beam filamentation (Weibel) instability should be investigated with *rotating helical beams* during NDC

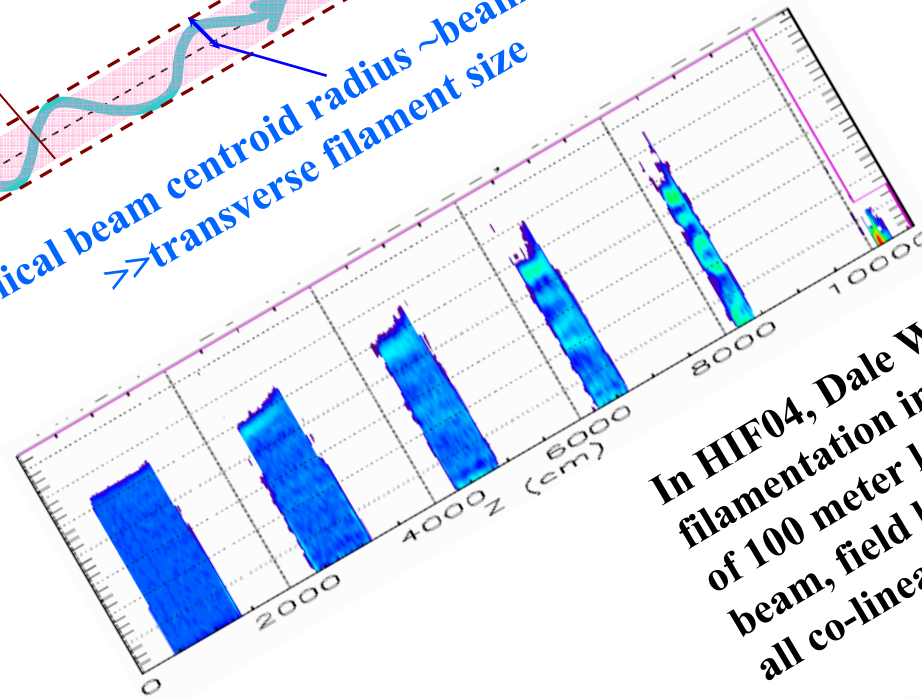
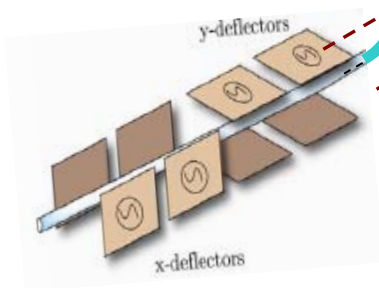
At sufficient magnetic fields, helical beam transport is not current neutralized

2.5 kg solenoid field constrains electron flow

Helical beam centroid radius ~ beam width  
 >> transverse filament size

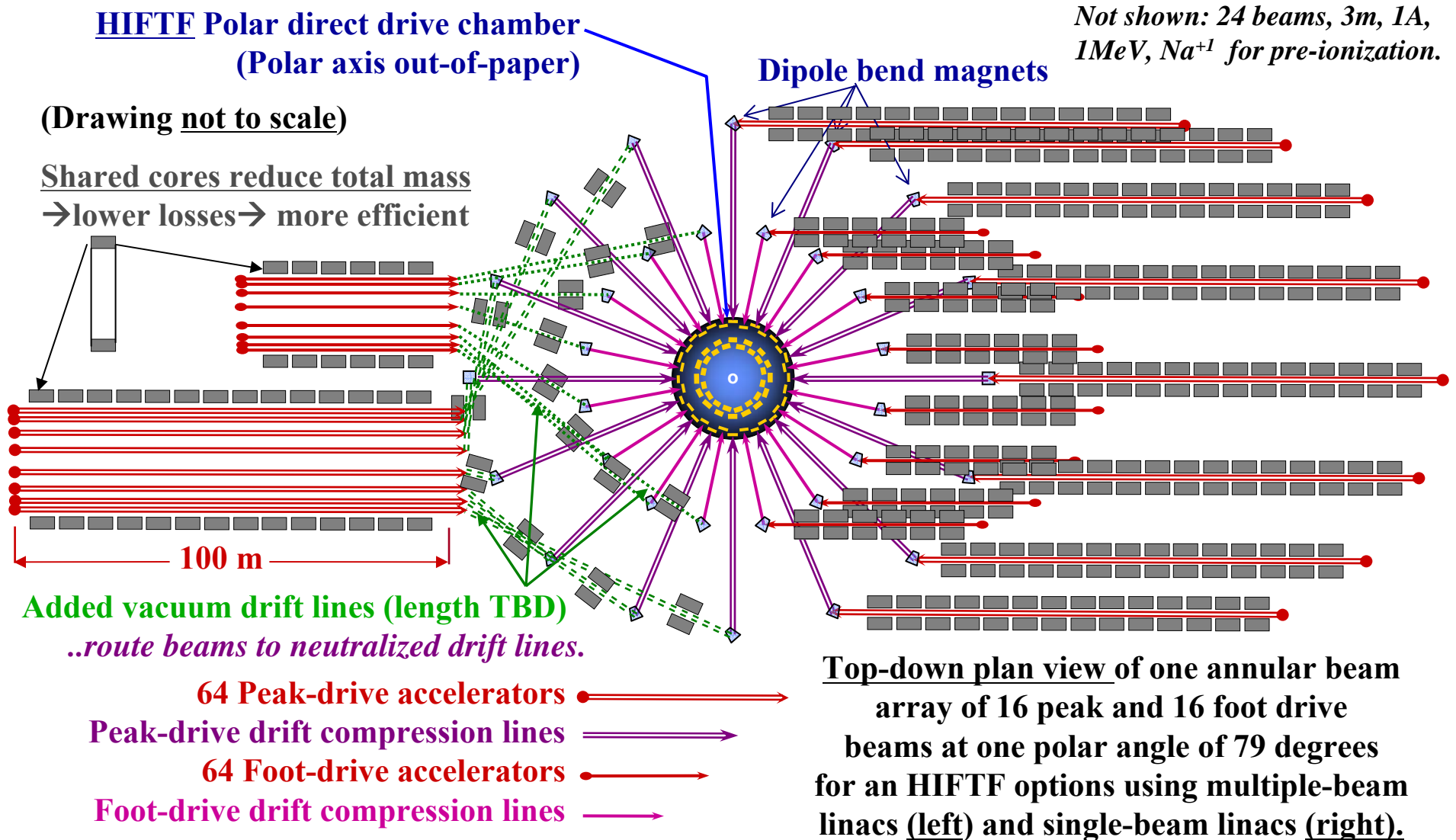


Quads or Solenoid final focus magnets



In HIF04, Dale Welch found filamentation in LSP simulation of 100 meter long NDC: beam, field lines, and electron flows all co-linear over 100 meters!

# Future studies should consider options to use multiple-beam induction linacs (more efficient with shared cores, but with added vacuum drift lines)



<sup>1</sup>LLNL presentation, "Implementing Ion Beams in Kull and Hydra," T. Kaiser, G. Kerbel, M. Prasad

A MathCAD model and LASNEX use the same ion ray dE/dx formulary as in the HYDRA ion package documentation

$$-\frac{dE}{dx} = \left[ \frac{4\pi e^4}{m_e c^2} \right] \left[ \frac{N_0 \rho_T}{A_T} \right] \left[ \frac{Z_{eff}^2}{\beta^2} \right] \left\{ (Z_T - \bar{Z}) \text{Log } \Lambda_B + \bar{Z} G(\beta / \beta_e) \text{Log } \Lambda_F \right\}$$

$5.1e-23 \text{ keV cm}^2$        $\frac{4\pi e^4}{A \cdot \text{cm}^2}$

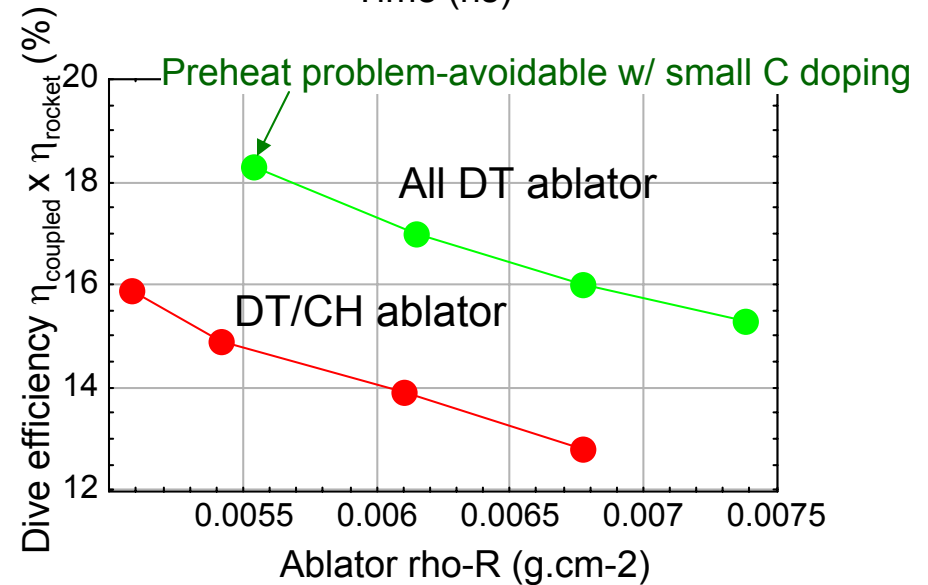
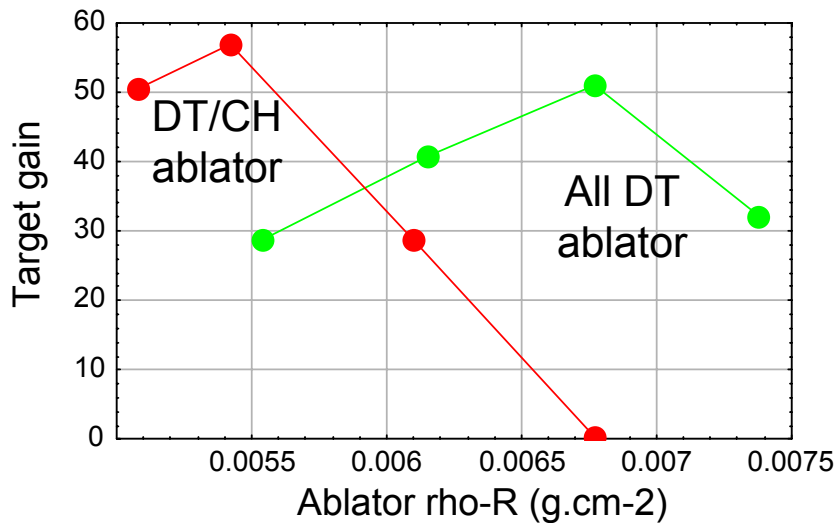
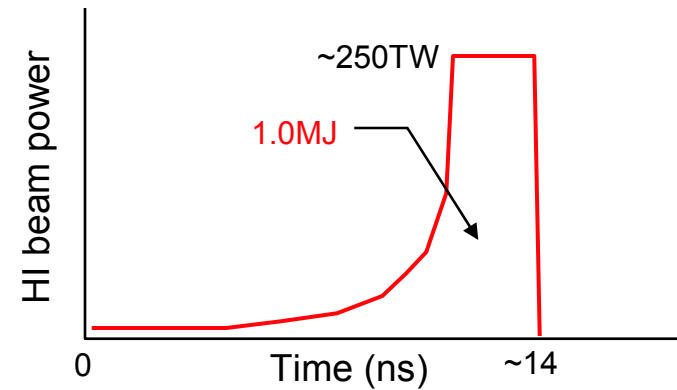
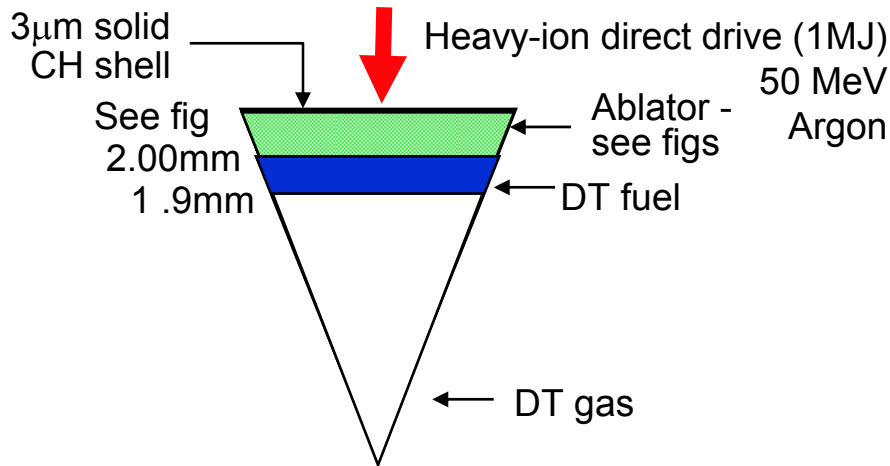
$\rho_T$  = target density in  $g / cm^3$ ,  $A_T$  = target atomic weight  
 $Z_T$  = target atomic number,  $\bar{Z}$  = target ionization state  
 $\Lambda_B = \frac{2m_e c^2 \beta^2}{\bar{I}}$ ,  $\Lambda_F = \frac{m_e c^2 \beta^2}{\hbar \omega_p}$ ,  $G(x) = \text{erf}(x) - x \text{erf}'(x) = 1$  for  $x \gg 1$   
 $\bar{I}$  = average ionization potential =  $.01 Z_T \text{ keV}$  (Bloch's rule)  
 $\omega_p$  = plasma frequency =  $\sqrt{4\pi e^2 n_e / m_e} = 56416 \sqrt{n_e} / \text{sec}$   
 $\hbar \omega_p = (3.7e-14) \sqrt{n_e} \text{ keV}$ ,  $n_e$  = electron density in  $1/cm^3 = \bar{Z} N_0 \rho_T / A_T$

Ion Beam :  $\beta = v/c$ ,  $\gamma = \frac{1}{\sqrt{1-\beta^2}} = 1 + \frac{E}{Mc^2}$   
 $E$  = Kinetic Energy of Ion Beam in  $keV$ ,  
 $Mc^2$  = Ion Beam Rest Energy =  $A_{ionbeam} (9.3e5) \text{ keV}$   
 $m_e c^2$  = Electron Rest Energy =  $511 \text{ keV}$

Betz Empirical  $Z_{eff} = Z_{ionbeam} [1 - \exp(-137 \beta_{eff} / Z_{ionbeam}^{.69})]$   
 $\beta_{eff}^2 = \beta^2 + \beta_e^2$ , with  $\gamma_e = \frac{1}{\sqrt{1-\beta_e^2}} = 1 + \frac{kT_e}{m_e c^2}$

This Chandrasekhar function G (x=ion/electron speed) explains why the range increased 4X during the drive to enable high coupling efficiency in Perkins' LASNEX run.

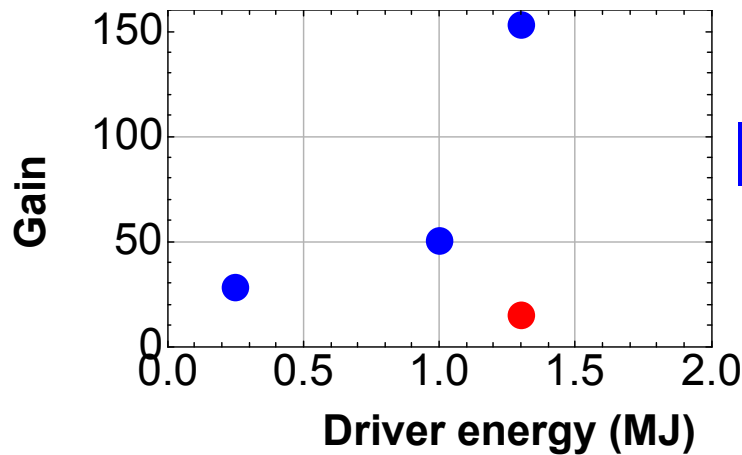
# Heavy-ion direct drive LASNEX runs (June 2007) by John Perkins (LLNL) found high target gains $\geq 50$ at 1MJ with low range ions @ high coupling efficiency (16%) (published Phys. of Plasmas 15, 072701 2008)



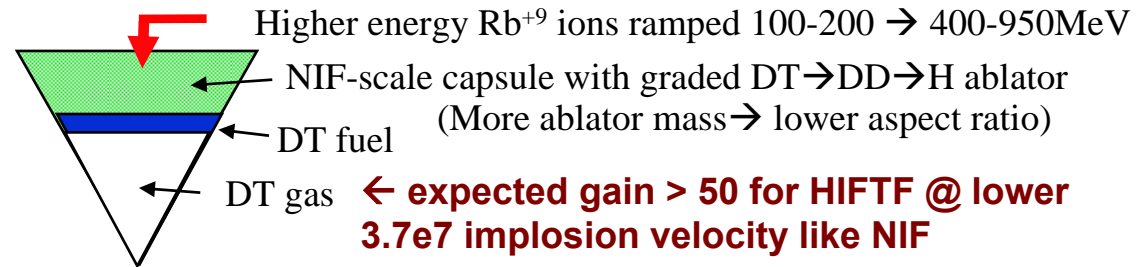
**Analytic calculations estimate higher efficiencies (20-25%) substituting H for DT ablators, ramping up ion K.E. in time.**

# LASNEX 1-D design for 250 kJ HIFTF heavy ion direct drive *in progress*

(John Perkins, 8-08)



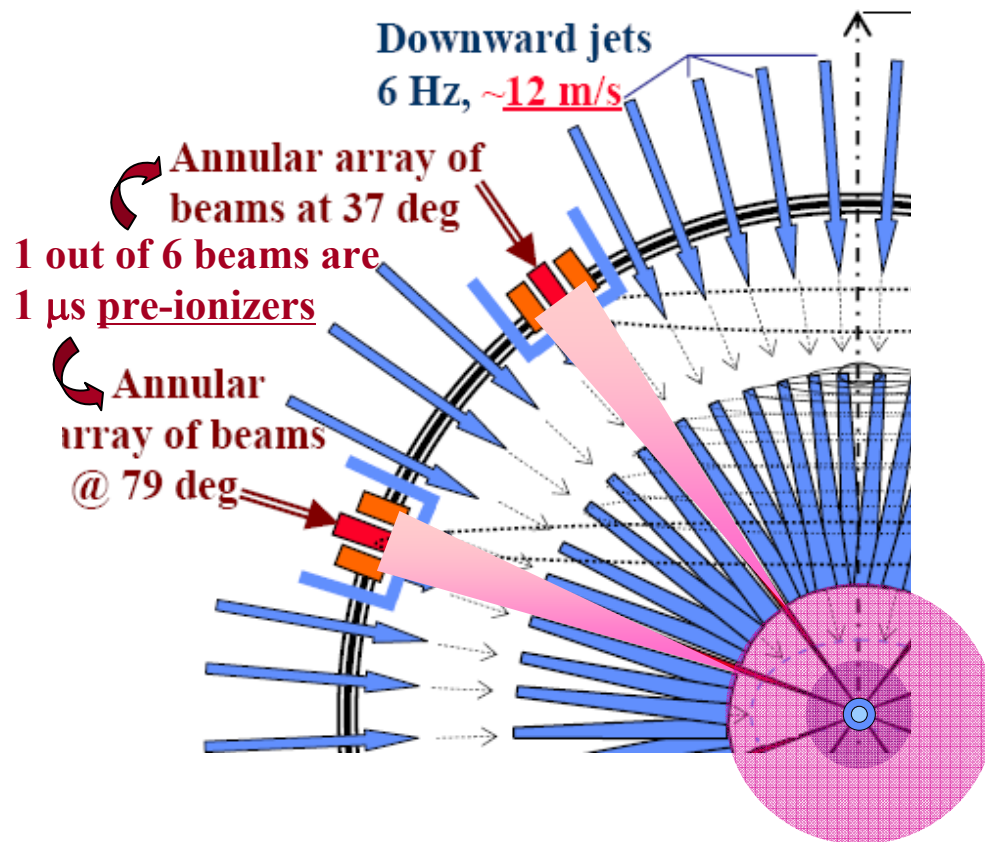
## Next iteration for HIFTF target



## 1<sup>st</sup> HIFTF example

|                      | NIF Ignition Baseline                  | 1 <sup>st</sup> HIFTF example HI Direct Drive NIF-like | HI Direct Drive MJ-Class | HI Direct Drive Shock Ignited       |
|----------------------|--|--|--------------------------|-------------------------------------|
| Drive type           | Laser indirect drive → x-rays at 285eV | HI direct drive 50MeV Ar ( foot) 100MeV (main)         | HI direct drive 50MeV Ar | HI direct drive + HI shock ignition |
| Drive energy (MJ)    | 1.3                                    | 0.25   | 1.0                      | 1.0 (assembly) +0.3 (shock)         |
| Yield (MJ)           | 20                                     | 7.0  | 50                       | 199                                 |
| Gain                 | 15                                     | 28   | 50                       | 153                                 |
| rhoR (g/cm2)         | 1.8                                    | 1.04   | 1.24                     | 2.25                                |
| Peak velocity (cm/s) | 3.7e7                                  | 5.2e7 (too high!)                                      | 4.44e7 (too high)        | 2.2e7                               |
| Drive efficiency     | 0.023                                  | 0.17   | 0.15                     | 0.086 (but low velocity!)           |

## Driver ion beam space charge is neutralized by a cold Hydrogen gas puff pre-ionized by 24-low energy beams (1A, 1 MeV Na<sup>+1</sup>)



*→This pre-ionization approach can be tested on HCX at LBNL*

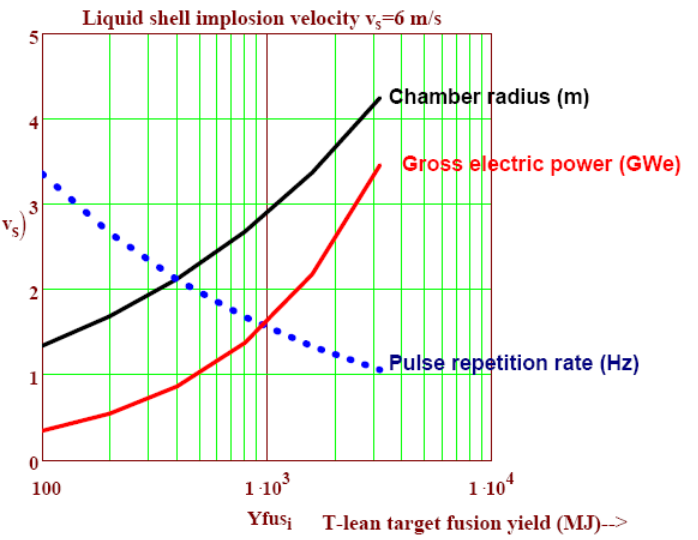
### Pre-ionization steps to neutralize foot and peak driver beam space charge

1. Cryo-capsule target injected @ 50-100 m/sec (may need some reflective coating or frost layer to avoid pre-heat in 600 deg C,  $10^{13}$  cm<sup>-3</sup> Flibe vapor)
2. A few ms before arrival of cryo-capsule target at chamber center, a pre-injected 1 mg H<sub>2</sub> pellet is vaporized by a low energy laser into 100 deg K gas cloud.
3. H<sub>2</sub> gas cloud expands to chamber wall, presenting H and e<sup>-</sup> densities = 10X the peak driver beam charge densities occurring at peak drive ( $6 \times 10^{16}$  cm<sup>-3</sup> at center to  $6 \times 10^{14}$  cm<sup>-3</sup> at final focus radii)
4. 24 pre-ionizer beams fire 1  $\mu$ s to ionize ( $\ll 1$  %) H<sub>2</sub> gas to electron densities  $> 2-3$  X the foot beam charge densities.
5. Foot beams further ionize the remaining H<sub>2</sub> neutrals to 10X the subsequent peak driver beam densities.

**SUMMARY**

|  | <u>POWER PLANT</u><br>1 MJ  | <u>DEMO</u><br>0.2 MJ   |                          |
|--|---|---|--------------------------|
| T-lean fuel energy at ignition   |   |   |                          |
| Energy delivered to ablation front   | $E_{da}(1.5, 1) = 2.55$   | $E_{da}(1.5, 0.2) = 0.49$   | MJ                       |
| Capsule implosion efficiency   | $\eta_c(1.5, 1) = 0.39$   | $\eta_c(1.5, 0.2) = 0.41$   |                          |
| Overall coupling efficiency<br>beam-to-fuel corrected for<br>parasitic loss on ablation plasma                                 | $\eta_{dfA} = 0.25$   | $\eta_{dfB} = 0.23$   |                          |
| H <sub>2</sub> ablation front temperature  | $T_{ex}(1.5, 1) = 26.3$   | $T_{ex}(1.5, 0.2) = 36$   | eV                       |
| Fusion yield   | $Y_f(1.5, 1) = 494$   | $Y_f(1.5, 0.2) = 43$  | MJ                       |
| Driver energy  | $1 \cdot \eta_{dfA}^{-1} = 4.06$  | $0.2 \cdot \eta_{dfB}^{-1} = 0.85$  |                          |
| Driver efficiency  | $\eta_{dA} := 0.4$  | $\eta_{dB} := 0.2$  |                          |
| Driver electric<br>input energy/pulse  | $1 \cdot \eta_{dA}^{-1} \cdot \eta_{dfA}^{-1} = 10.1$                       | $0.2 \cdot \eta_{dB}^{-1} \cdot \eta_{dfB}^{-1} = 4.3$                                      |                          |
| Target gain  | $Y_f(1.5, 1) \cdot \eta_{dfA} \cdot 1^{-1} = 122$                           | $Y_f(1.5, 0.2) \cdot \eta_{dfB} \cdot 0.2^{-1} = 51$  |                          |
| Fusion energy conversion eff.<br>(lowest CoE for Demo requires<br>35% steam bottoming cycle<br>to get 0.65 conversion overall) | $\eta_{MHD} := 0.65$<br>^  lowest CoE this case                             | $\eta_{MHD} := 0.4$<br>$\eta_{MHDsteam} := 0.65$  |                          |
| Gross electric output<br>(per pulse)   | $W_e(0.65, 1.5, 1) = 278$   | $W_e(0.65, 1.5, 0.2) = 20.5$  |                          |
| Net electric output<br>per pulse, inc 5 % aux  | $W_{netA} = 254$  | $W_{netB} = 15.2$   |                          |
| Pulse repetition rate  | $RR_A := 6$ ← higher jet<br>velocities                                      | $RR_B := 8$   |                          |
| Net electric power   | $P_{netA} = 1522$   | $P_{netB} = 122$  |                          |
| Driver direct cost   | $C_{driver}(\eta_{dfA}, 1) = 528$   | $C_{driver}(\eta_{dfB}, 0.2) = 111$   |                          |
| Vessel direct cost   | $C_{vessel}(1.5, 1) = 59$   | $C_{vessel}(1.5, 0.2) = 8.5$  | M\$                      |
| Balance-of-Plant direct cost   | $C_{mhdBoP}(1522) = 104$  | $C_{mhdBoP}(122) + C_{steamBoP}(122) = 64$  | M\$                      |
| Other direct costs   | $C_{other}(1522) = 103$   | $C_{other}(122) = 38$   | M\$                      |
| Cost of Electricity, inc.<br>targets and O&M   | $CoE_A = 29.4$<br>--> may meet affordable CoE<br>goal for 10 billion people | $CoE_B = 125$<br>--> total capital < 1 B\$ for DEMO for<br>net power and tritium production | mills/kW <sub>e</sub> hr |

# Summary of cost model for reference CFAR power plant and DEMO updated for T-lean targets.



If rep rate cannot be maintained at 6 Hz with faster jets in larger chambers, then this inset figure shows higher power levels are still achievable.



# Acknowledgements:

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Thanks to all who have worked on heavy ion fusion, still on-going, but in particular:

- To all those in the VNL who have made neutralized drift compression, a key enabling technique for HEDP and HIF, today a reality (in no particular order): Larry Grisham, Dale Welch, Adam Sefkow, Prabir Roy, Enrique Henestroza, Ron Davidson, Peter Seidl, Josh Coleman, Eric Gilson, Phil Efthimion, Matthaeus Leitner, Will Waldron, John Barnard, Alex Friedman, Bill Sharp, Hong Qin, Igor Kaganovich, Ed Startsev, and many others.
- To Dick Briggs and Ed Lee, who advocated and defined the modular solenoid approach to HIF more than 10 years ago, in 1997, and to Wayne Meier, for systems analysis of the approach.
- To Simon Yu, who organized modular solenoid driver studies in 2002-2003, and implemented elements of the approach in NDCX-I and in initial plans for NDCX-II.
- To Ralph Moir, who gave us an idea on how to apply liquid jets to protect direct drive chambers.
- To George Caporaso, who supported our efforts through the VNL PAC, and gave us the 40 ATA modules that will allow us to build NDCX-II for first direct drive experiments at a low cost.
- To Matthaeus and Daniela Leitner, who made us aware of possibilities for high-q ion sources using high-powered gyrotrons, and the related Russian work.
- To Roger Bangerter, who urged another, closer look at 6-D phase space constraints in our work.
- Last but not least: To our US target experts who have given us a great gift of research opportunity and guidance in re-considering heavy ion direct drive:

John Perkins, John Nuckolls, Max Tabak, Dave Bailey, Craig Sangster, and to our international colleagues who have encouraged us to pursue heavy ion direct drive: Masakatsu Murakami, Dieter Hoffmann, Naeem Tahir, Claude Deutsch, Juergen Meyer-Ter-Vehn, Boris Sharkov, Shigeo Kawata, and Roberto Piriz.

(Our apologies to any we may have forgotten to include here)

# Scientific objectives and key features of a sequence of heavy-ion-beam driven facilities for high energy density physics and fusion

*Ranges given in table reflect options under study*

| <i>HEDP/Inertial Fusion Energy<br/>Science Objective<br/>(Facility)</i>                            | Ion  | Linac<br>voltage<br>- MV | Ion<br>energy<br>- MeV | Beam<br>energy<br>- J  | Target<br>pulse<br>- ns  | Range<br>-microns<br>(in ..)     | Energy<br>density<br>$10^{11} \text{J/m}^3$ |
|--|--|--------------------------|------------------------|------------------------|--------------------------|----------------------------------|---|
| <i>Beam compression physics,<br/>diagnostics. Sub-eV WDM.<br/>(NDCX-I) (1 beam)</i>                | K <sup>+</sup>                               | 0.35                     | 0.35                   | 0.001-<br>0.003        | 2-3                      | 0.3/1.5<br>(in solid/<br>20% Al) | 0.04<br>to<br>0.06                          |
| <i>Beam acceleration and target<br/>physics basis for IB-HEDPX.<br/>(NDCX-II) (1 beam)</i>         | Li <sup>+1</sup> ,<br>or<br>Na <sup>+3</sup> | 3.5 -<br>5               | 3.5 -<br>15            | 0.1 -<br>0.28          | 1-2<br>(or 5 w<br>hydro) | 7 - 4<br>(in solid<br>Al)        | 0.25<br>to<br>1                             |
| <i>User facility for heavy-ion<br/>driven HEDP.<br/>(IB-HEDPX) (1 beam)</i>                        | Na <sup>+1</sup><br>or<br>K <sup>+3</sup>    | 25                       | 25 –<br>75             | 3 –<br>5.4             | 0.7<br>(or 3 w<br>hydro) | 11 – 8<br>(in solid<br>Al)       | 2.2<br>To<br>5.8                            |
| <i>Heavy-ion direct drive<br/>implosion physics.<br/>(HIDDIX) (2 beams)</i>                        | Rb <sup>+9</sup>                             | 156                      | 1000                   | 2x7.5<br>(kJ)          | 2 - 4                    | 1000<br>(in solid<br>Z=1)        | 18  |
| <i>Heavy ion fusion test facility -<br/>-high gain target physics.<br/>(HIFTF) ( 40-200 beams)</i> | Rb <sup>+9</sup>                             | 156                      | 1000                   | 300 to<br>1500<br>(kJ) | 12 -24                   | 1000<br>(in solid<br>Z=1)        | 90  |

**Table 4.1, page 43 of an HIF White Paper available upon request**