3.10.002 ADVANCES IN HIGH EFFICIENCY COUPLING TO HEAVY ION DIRECT DRIVE AND APPLICATION TOWARDS SMALL TEST REACTORS

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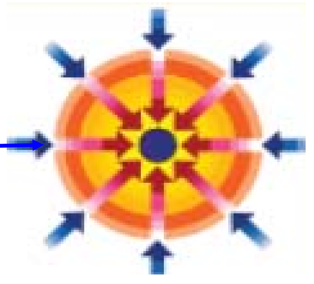
L. John Perkins (LLNL)
Michael Hay (UC Berkeley)
John Barnard (LLNL)

...exploiting the intrinsic high overall drive efficiency of heavy ion beams for direct drive

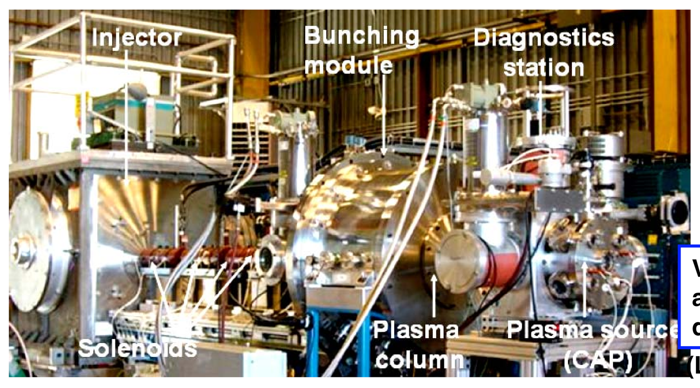


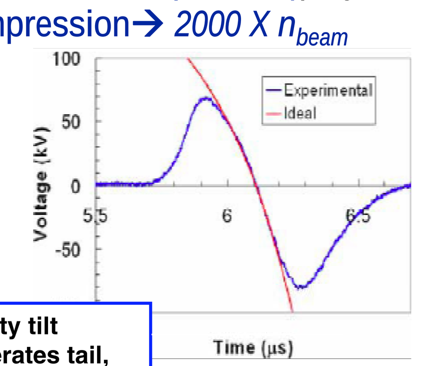
6th International Conference Inertial Fusion Science and Applications, San Francisco, California, Sept. 6 -11, 2009

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

1. 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].*
2. High hydro-drive efficiency of heavy ion beam direct drive in ablative rocket regime *(also uses beam velocity increasing in time-focus of this poster).* *[B. G. Logan, L. J. Perkins, and J. J. Barnard, Phys. Plasmas 15, 072701 (2008)].*
3. 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].*
4. 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/].*

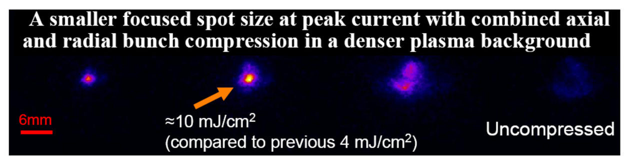
(1) Breakthrough: Compression of velocity-chirped ion beams in plasma ((Roy et al PRL 95(2005) 23481) Now, radial and temporal compression → 2000 X n_{beam}

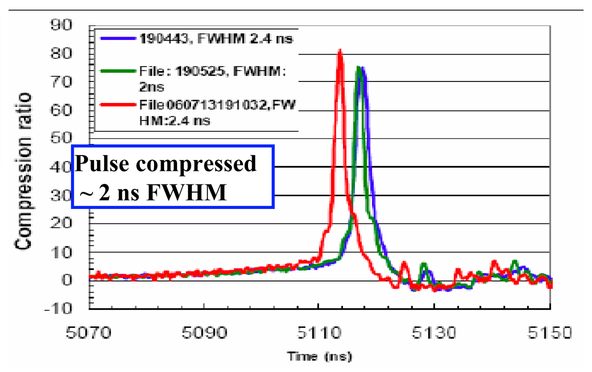




Velocity tilt accelerates tail, decelerates head

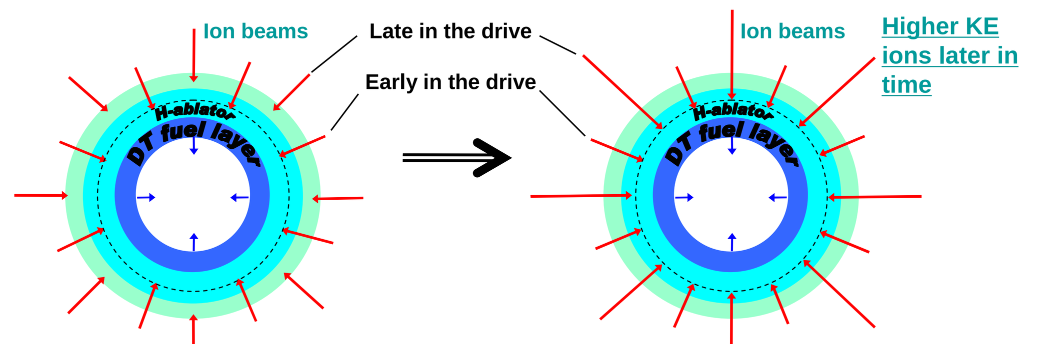
(Like chirped pulse compression)





(2) Following our success in velocity-chirp compression of intense ion beams to few-nanosecond pulses in plasmas...

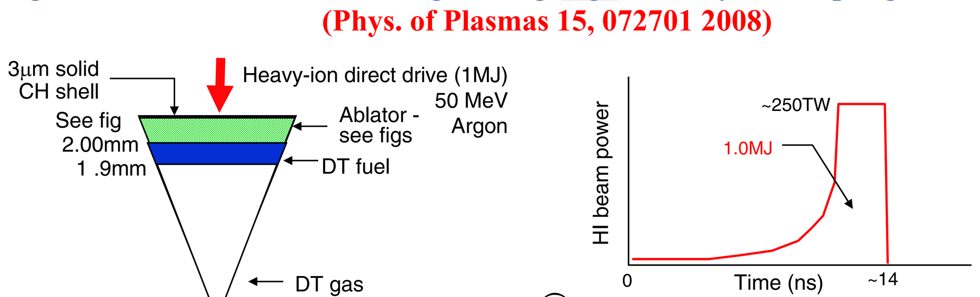
- we have another powerful fusion idea *which also uses ion velocities increasing in time:*

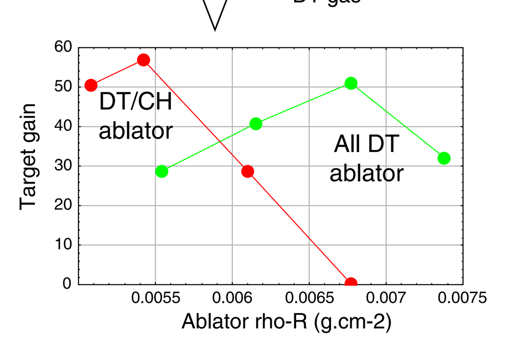


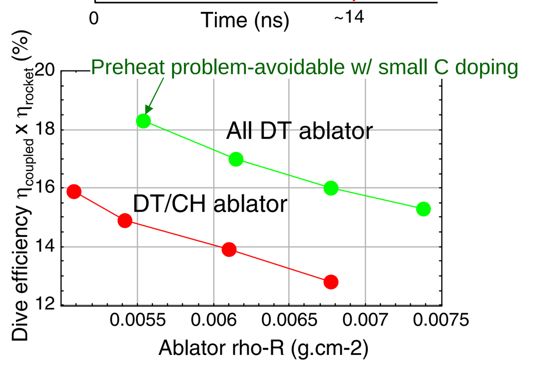
Constant ion range → decouples

Strongly-increasing >4X ion range → high hydro-coupling efficiency!

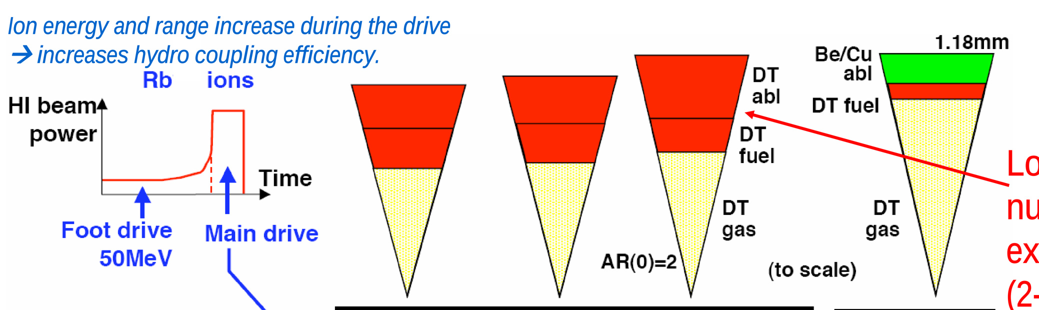
Heavy-ion direct drive LASNEX runs (June 2007) by John Perkins (LLNL) found high target gains ≥ 50 at 1MJ with low range ions @ high drive hydro coupling efficiency (16%) (Phys. of Plasmas 15, 072701 2008)







NIF ignition would validate key requirements for adequate gain HIF achievable in NIF-similar-scale fuel capsules *using direct drive @ 300-500 kJ driver energy. John Perkins, February 2009)*



Low aspect ratio and Atwood number at fuel-ablator interface--- expect robust RT stability (2-D RT calculations in progress)

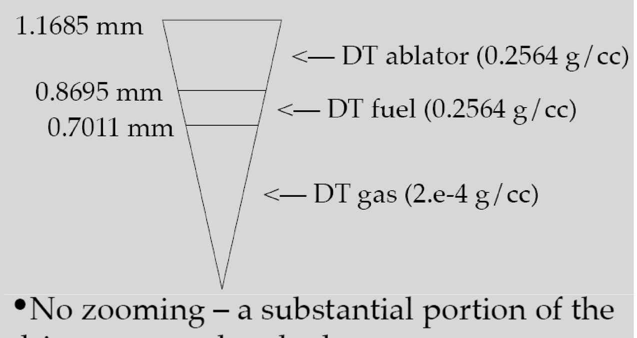
	50MeV	200MeV	500MeV	NIF
$m_{ablator}/m_{fuel}$	1.8	2.1	3.0	18
Driver energy (MJ)	0.32	0.36	0.44	1.3
Peak drive power (TW)	175	195	205	320
Yield (MJ) / Gain	24.7 / 77	21.6 / 60	20.8 / 47	20.0 / 15
$\eta_{absorbed}$ / η	0.97 / 0.10	0.91 / 0.10	0.88 / .09	0.16 / 0.02
In-flight aspect ratio	25	27	25	32
Convergence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

Optimizations of direct drive using HYDRA --in progress (Michael Hay)

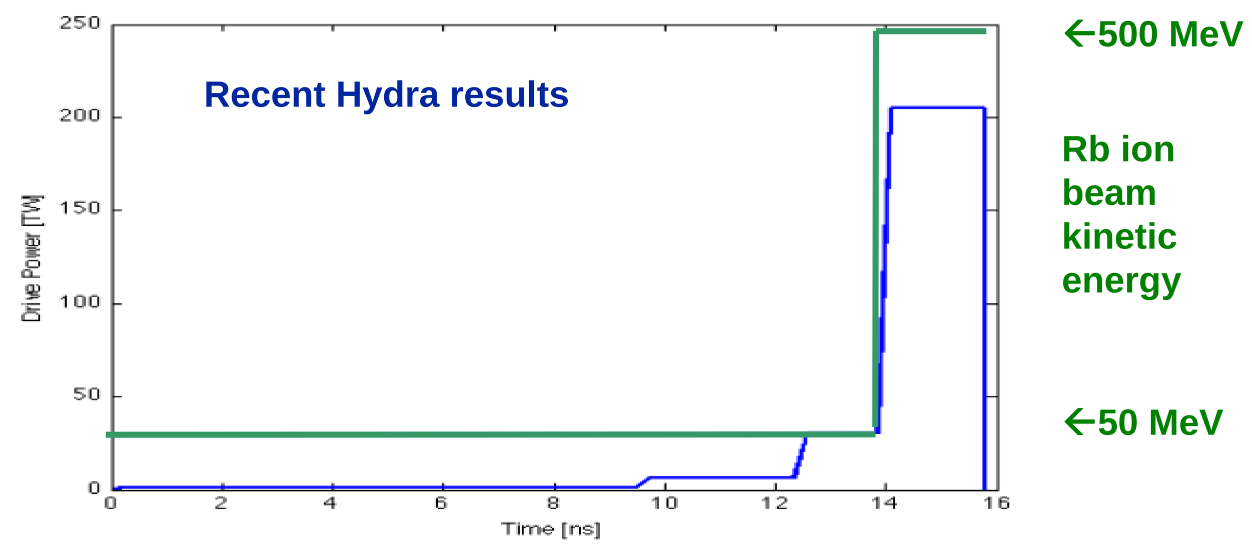
- Simulations conducted with HYDRA [2], a fully 3-D radiation hydrodynamics code developed at LLNL
- HYDRA employs arbitrary Lagrangian Eulerian hydrodynamics and a monotonic artificial viscosity model to resolve shock fronts
- Our implosion calculations utilize many of HYDRA's multiphysics capabilities e.g. 3-D raytrace, heavy ion deposition, flux-limited multigroup radiation diffusion, quotidian equations of state, and multigroup charged particle transport

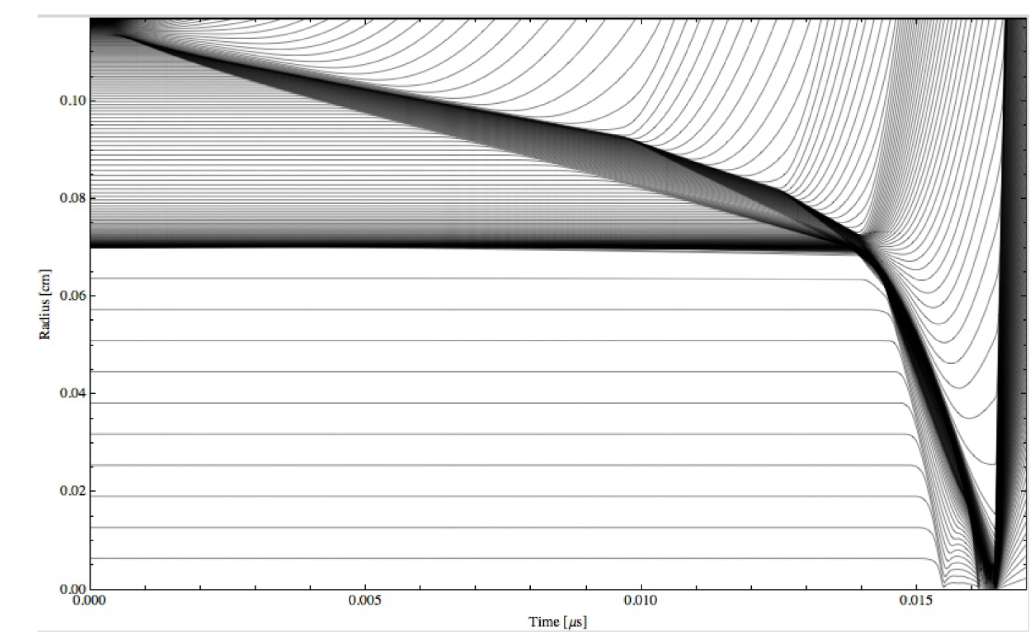
[2] M. M. Marinak, *et al*. Phys. Plasmas **8**, 2275 (2001).

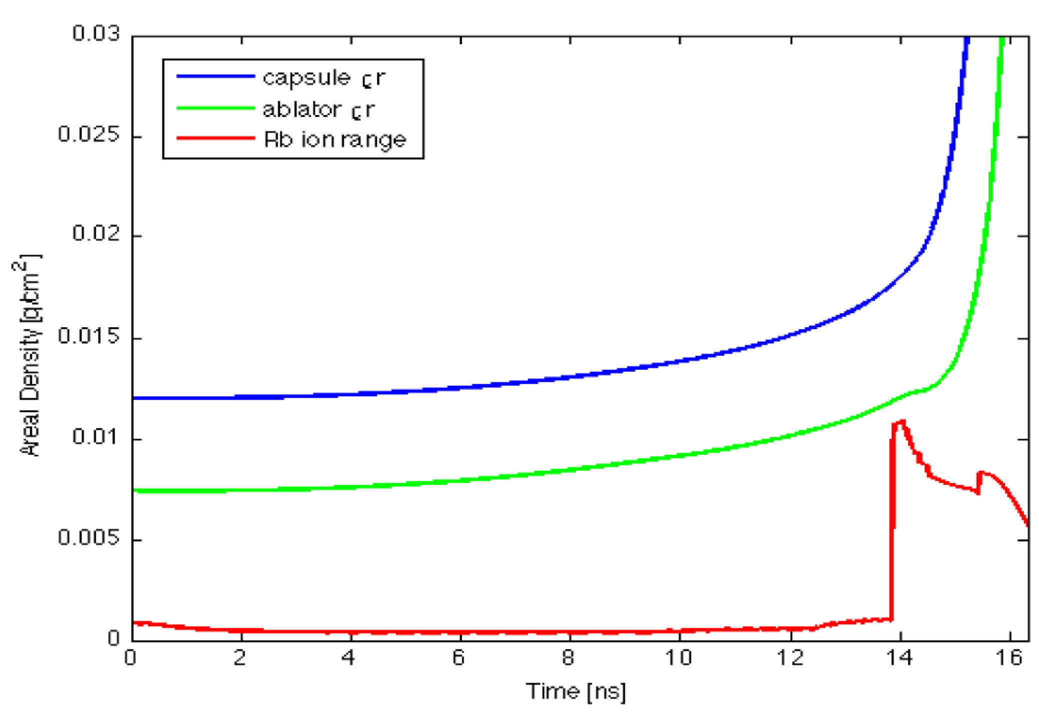
- Pure-DT targets are easily fabricated
- RT-robust: Atwood number = 0, no in-flight mixing of fuel and ablator material
- Total fuel mass = 1.344 mg; payload mass fraction = 1/3, corresponding to a rocket efficiency of 60%



- No zooming – a substantial portion of the drive goes unabsorbed
- Ion energy ramped from 50 to 500 MeV in a single jump as in Ref. 1 base case
- Lagrangian r-t plot follows location of each zone/mass element through implosion
- Minimal (passive) range lengthening at constant 50 MeV Rb ion energy through 14 ns

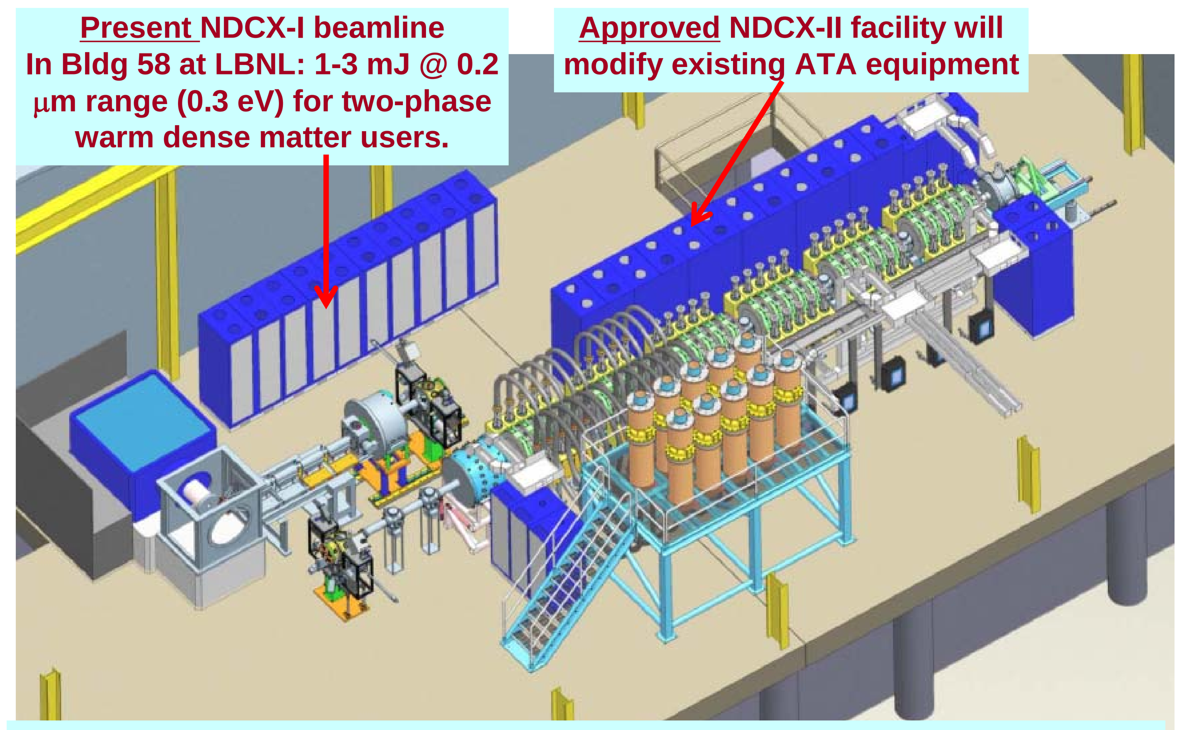






- Yield = 39.8 MJ / Gain = 90.4
- Absorbed energy fraction = 0.92
- Coupling efficiency = 0.099
- Hydrodynamic efficiency = 0.087
- IFAR = 27.5, convergence ratio = 29.5, adiabat = 2.72
- Max. shell velocity = 3.51*10⁷ cm/s

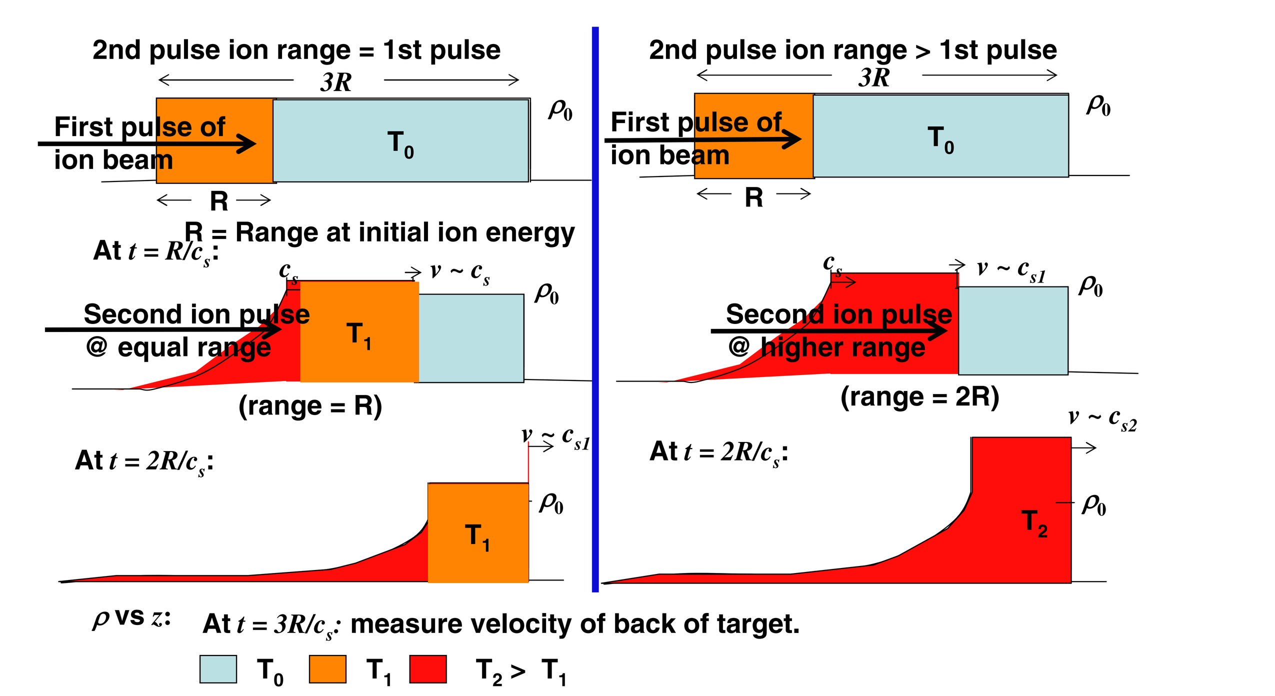
Construction of NDCX-II began July 2009 → enables higher energy warm dense matter and planar direct drive hydro-coupling research beginning 2nd half of 2012 (Joe Kwan, project manager)



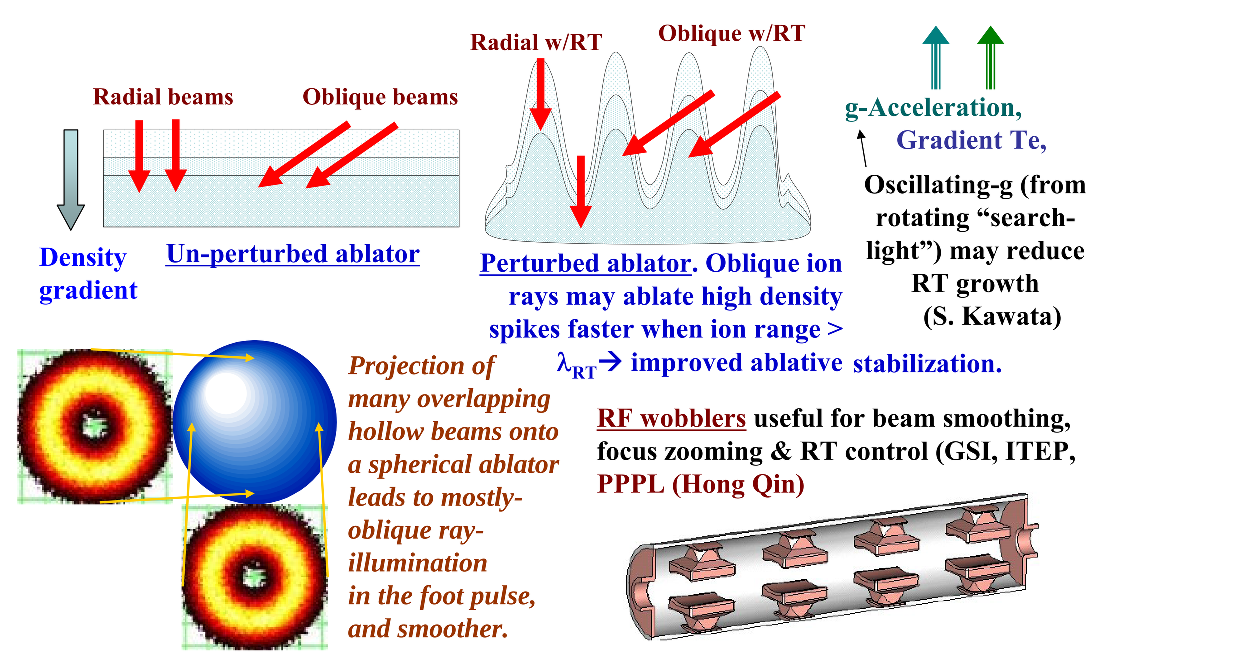
NDCX-II will increase beam power on target 100 times NDCX-I → enables WDM > 1 eV and direct drive hydro-coupling experiments.

NDCX II can explore improvement in hydro-coupling efficiency with increasing ion range, either ramped or double pulse.

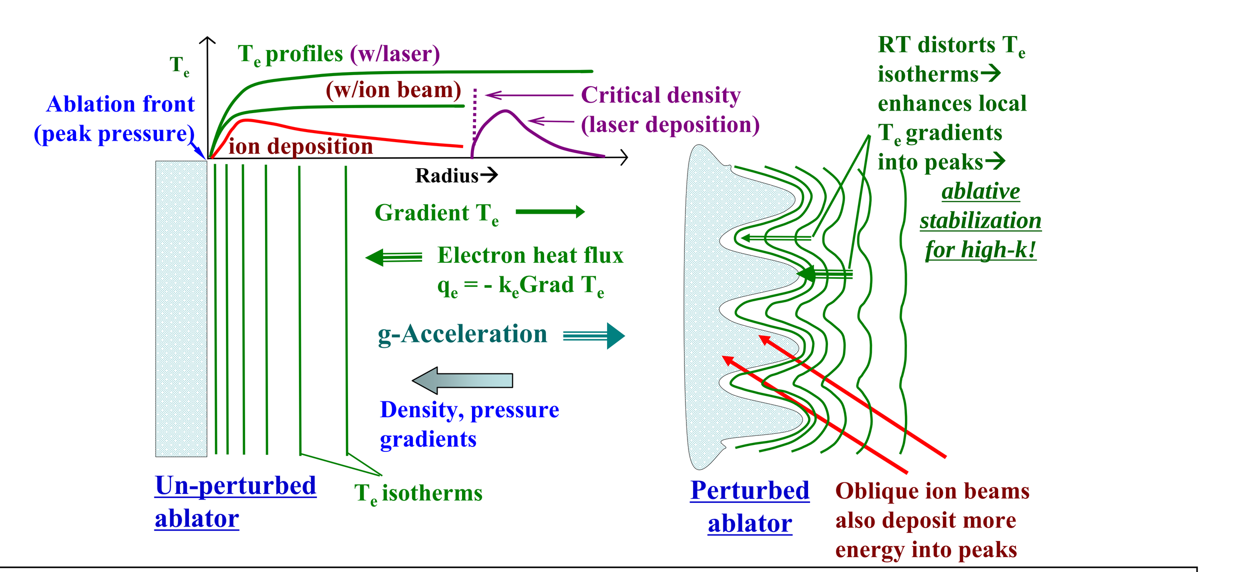
[Simulations by Siu Fai Ng & Simon Yu (CUHK), Seth Veitzer (Tech-X), John Barnard (LLNL)]



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



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:
→ ion beam energy deposited closer to ablation front (higher coupling efficiency)
→ pressure gradients and Atwood numbers may be smaller with DT ablators

The Heavy Ion Fusion Science Virtual National Laboratory

* This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH11123 and DE-AC52-07NA27344 , and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

(SUB-MJ DRIVE FUSION AND FUSION-FISSION HYBRIDS)*

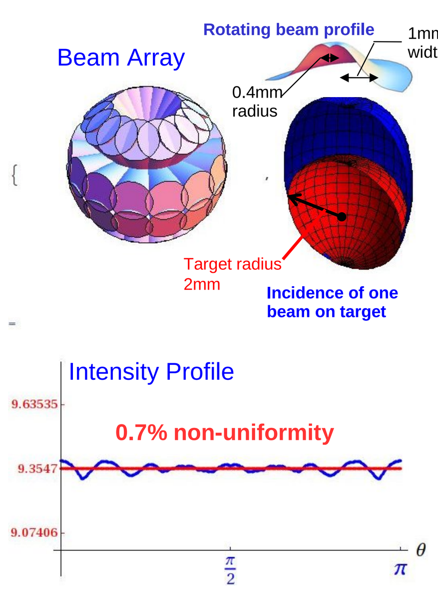
NIF ignition should renew interest not only in laser IFE, but also in Heavy Ion Fusion, for reasons that still apply today:

- MJ-beam accelerators have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.
- Thick-liquid protected target chambers are designed to have 30 year plant lifetimes.
- Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, n and g radiation.
- Heavy ion power plant studies have shown attractive economics and environmental characteristics (only class-C low level waste). *[Yu et al., Fusion Sci. Tech. 44, 2 (2003) 329]*

Copies of these IFE reviews available upon request
1979 Foster Committee
1983 Jason Report (JSR82-302)
1986 National Academies of Sciences Report
1990 Fusion Policy Advisory Committee report (Stever Panel)
1993 Fusion Energy Advisory Committee (Davidson Panel)
1996 FESAC report (Sheffield Panel)

Applications of heavy ion direct drive for fusion and fusion-fission hybrids requires R&D on targets, chambers, and accelerator drivers that can work together. .

(3) Illumination Geometry:
Jakob Runge, (Fulbright summer student 2008 in LBNL), 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* are be needed for 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 ±37.3° and ±79.3°, *with hollow, rotated beam spot projections* give a maximum deviation from the mean of 0.7% (with 21% spilled intensity).

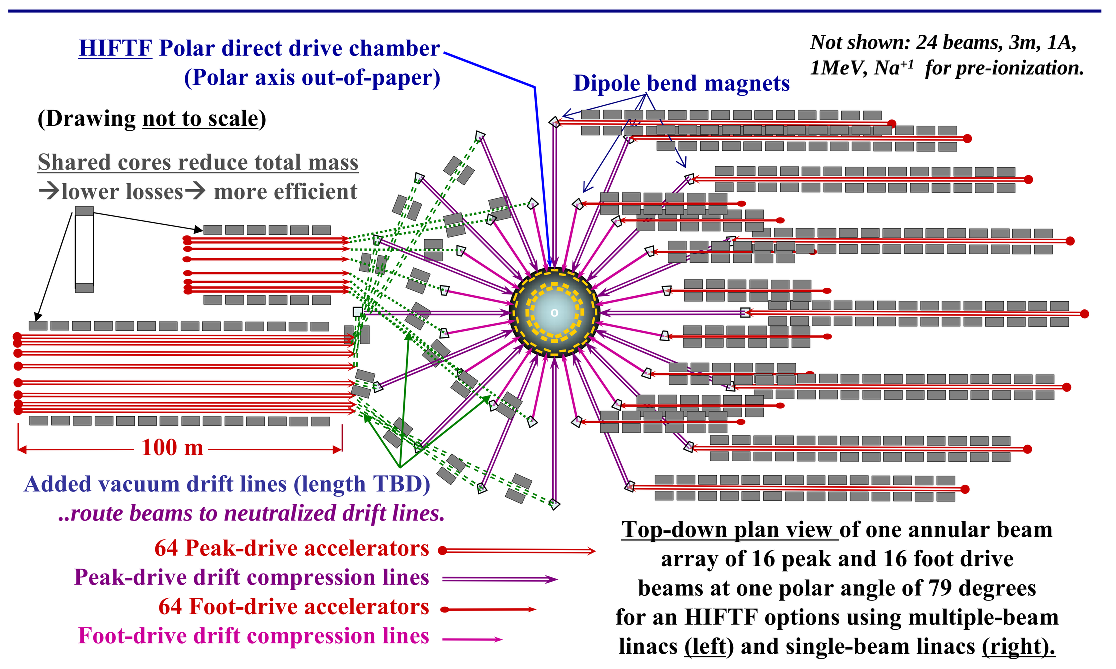
4 polar angles only, *not 4π!*

(J. Runge and B. G. Logan, "Nonuniformity for rotated beam illumination in directly driven heavy-ion fusion", accepted for publication, Physics of Plasmas, 2009)

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.

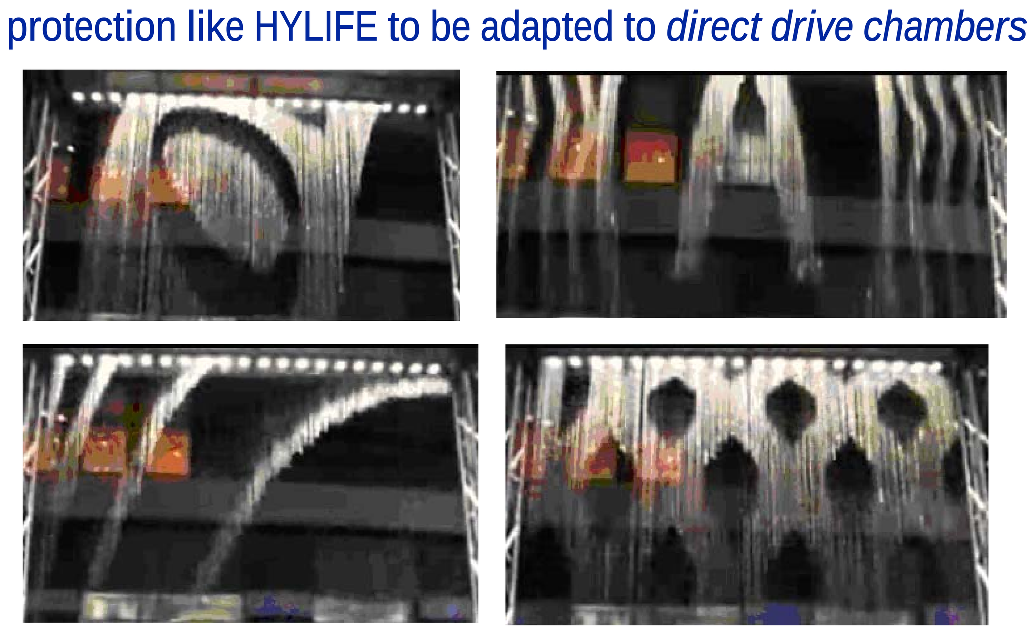
Induction linear accelerator design for heavy ion direct drive w/ four-ring polar angle target illumination: future studies can consider modular, single beam driver option if target gains > 100, otherwise, we can consider the option to use multiple-beam induction linacs (more efficient with shared cores)-both options are depicted below:

Top down plan view of two types of beam layout options:
→Multiple-beam linac option shown on the left half of beams
→Modular single beam driver system, shown on the right half



Top-down plan view of one annular beam array of 16 peak and 16 foot drive beams at one polar angle of 79 degrees for an HIFTF options using multiple-beam linacs (left) and single-beam linacs (right).

(4) 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/].

For R&D planning, its time to re-examine issues and needed facilities for *all* driver, target and chamber options. (Example tables below may be incomplete).

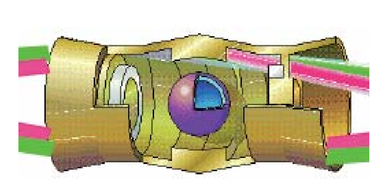
Example HIF driver options, some associated key issues & R&D facilities

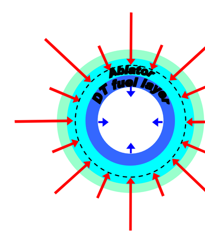
HIF Driver Options	Multi-beam LIA-magnetic quadrupole	Multi-beam LIA magnetic solenoids	Multi-beam LIA-electric quadrupoles	Modular set single-beam LIA-solenoids	Induction Synchrotron, RF linacs
Key Issues	SC magnet cost and multi-beam E-cloud issue	SC magnet cost & multi-solenoid field asymmetries	Limited λ_b & longitudinal compression under accel.	Efficiency>0.2 requires high λ_b>100 μC/m >2 kA/beam!	Viable only for 100 GeV targets? # of beams > 1?
R&D Facilities -up to non-ignition scale implosions	Modified HCX + 10 kJ IRE scale linac for direct drive exp. or MJ-scale for indirect drive	Modified HCX + 10 kJ IRE scale linac for direct drive exp. or MJ scale for indirect drive	Modified HCX + 10 kJ IRE scale linac for direct drive or MJ scale for indirect drive	NDCX-II experiments using higher q/A ions + 10 kJ IRE scale linac for direct drive	KEK-AIA? 10 kJ scale accelerator tests, then MJ scale for implosion test

Example HIF target options, some associated key issues & R&D facilities

HIF Target Options	Indirect-Drive Hohlraum, cylindrical, two sided illumination	Direct-drive, ablative, multi- polar angle ring illumination	Direct/Indirect "Cannonballs" (Spherical hohlraums)	Direct-drive Cylindrical (ITEP-TWAC)-Fast Ignition
Key Issues	Low ~<2% coupling efficiency→7 to 8 MJ (RPD)	High contrast pulse shape, beam balance, # beams need	Case losses, minimum Tr for radiation coupling test	Cost of 100 GeV, 10 MJ beams, beam spot rotation
R&D facilities (non-ignition scale)	1 GeV, > 1 MJ, >60 beams,~ 0.5 mm spots for hohlraum implosion test	HIDDIX (IRE~ 100 MeV, 10 kJ scale, 60+ ? beams for cryo implosion test	~> 1 GeV, > 1 MJ, spot size < 1 mm, > 60? beams for implosion test	TWAC, KEK-AIA? Beam requirements for implosion test?

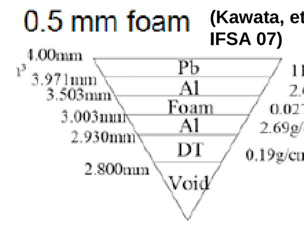
(Callahan, et.al. HIF-04)



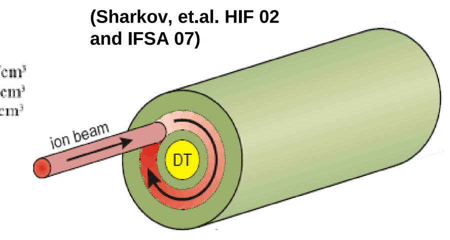


Perkins, et. al. HIF08

0.5 mm foam (Kawata, et.al. IFSA 07)

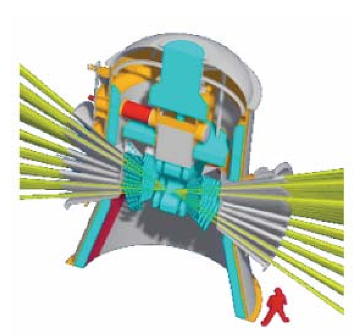


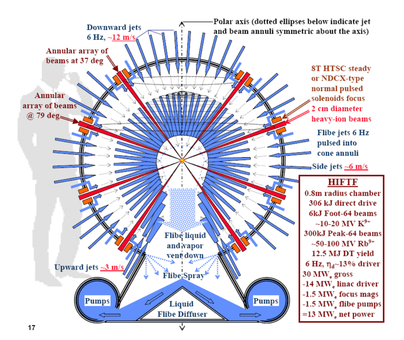
(Sharkov, et.al. HIF 02 and IFSA 07)

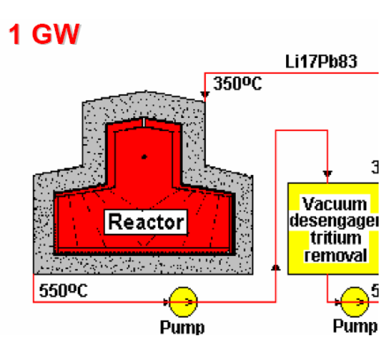


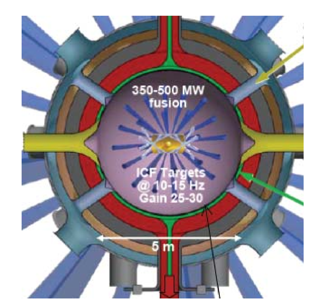
Example HIF chamber options, some associated key issues & R&D facilities

HIF Chamber Options	Thick liquid chambers-oscillating jets (HYLIFE)	Pulsed radial liquid jets, polar geometry (TOFE 08)	Thin liquid metal surface- protected chambers (ITEP)	Solid wall, gas protected Dry wall (LIFE)
Key Issues	Pumping power, oscillating nozzles, pulse rates < 6 Hz	Pumping power, precision jet control for polar beam ring access	Recovery rate for re-wetting walls. Neutron damage to structures.	Cryo targets in 6000K hot gas, solid wall metal dust blowout
R&D facilities (non-ignition scale)	1 M $ scale exp. followed by 10 M$ scale hydro-equiv water simulator tests	1 M $ scale exp. followed by 10 M$ scale hydro-equiv water simulator tests	1 M $ scale exp. followed by 10 M$ scale hydro-equiv Hg or NaK metal film recovery test	Collaborative experiments in planned LLNL Mini-Chamber facility for LIFE









→Peter Seidl will be organizing HIF "Renew" workshops (soon-dates TBD)

▪**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.**

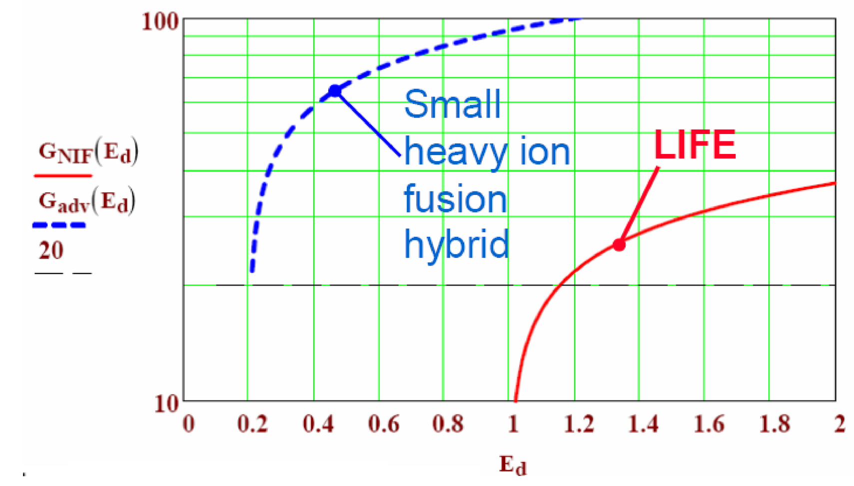
HIFTF
0.8m radius chamber
306 kJ direct drive
6kJ Foot-64 beams
~10-20 MV K^{9+}
300kJ Peak-64 beams
~50-100 MV Rb^{9+}
12.5 MJ DT yield
6 Hz, η_d~13% driver
30 MW_e gross
-14 MW_e linac driver
-1.5 MW_e focus mags
-1.5 MW_e flibe pumps
=13 MW_e net power

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, η_d~13% driver
η_{conv}= 0.7 [0.5 MHD + 0.4 thermal bottom]
357 MW_e gross
-42 MW_e linac driver
-8 MW_e all magnets
-7 MW_e liquid pumps
= 300 MW_e net power

Conclusions:
→Heavy ion direct drive results so far look very encouraging .
→Much more theory, experiments and conceptual design are needed for:

▪2-D and 3-D symmetry and Rayleigh Taylor stability studies.
▪Graded DT→D→ ablators for higher stopping power
▪Ion Beam brightness, neutralization, collective effects, stripping.
▪Multiple-beam induction linacs for higher efficiency, lower cost
▪Development of RF wobblers and time-dependent focus control for hollow-beam spots.
▪Pulsed liquid jet control experiments for direct-drive chamber protection.

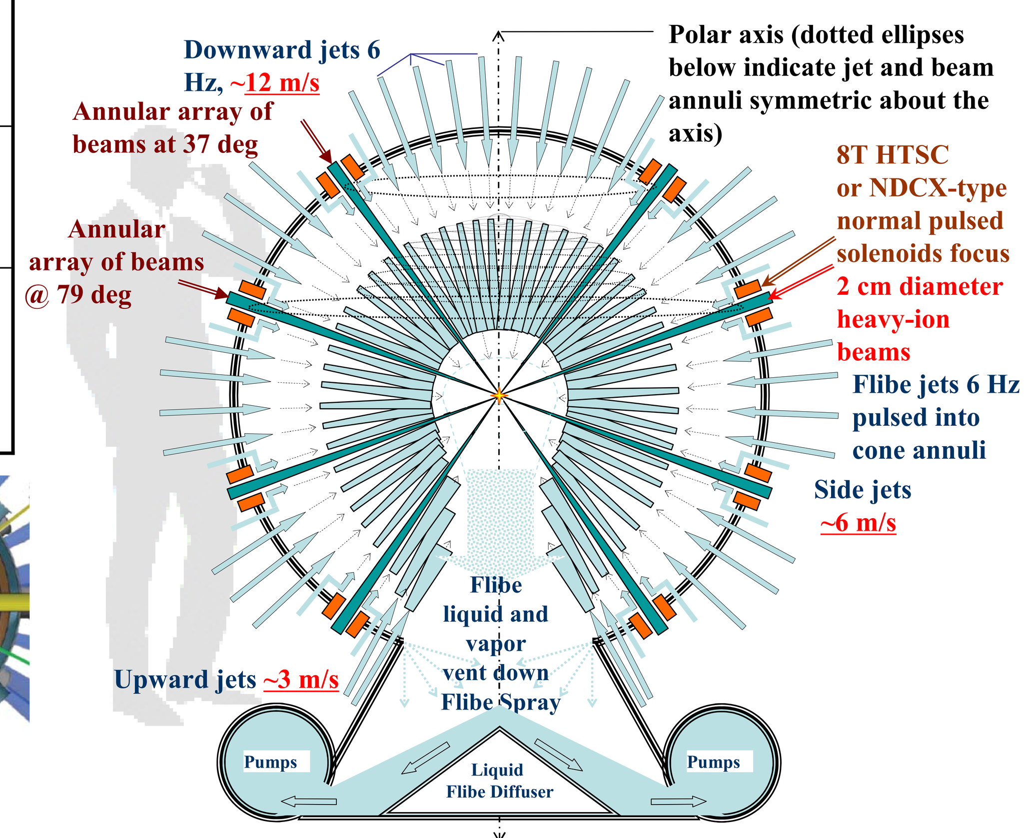
Heavy ion fusion direct drive might lead to a much smaller hybrid



Fusion gain G_{NIF} for laser hohlraums (like NIF) and for generic advanced IFE gain G_{adv} (such as heavy ion direct drive versus driver energy Ed (MJ).
→Small HIF hybrid example is given below

Fusion yield = 20 x 0.25 MJ= 5 MJ.
$\eta_d G_{adv}$=2, @ η_d=0.1
Low pulse repetition rate = 2 Hz
Average fusion power = 10 MW
Fission power = 80 MW
$P_{edriver}$= 5 MW_e
P_{enet} = 33 MW_e
Chamber radius = 1.2 m
Wall loading = 0.3 MW/m^2
Blanket fission power density = 1 MW/m^3
Uranium fuel mass = 1.3 tons

Concept for thick-liquid-protected HIFTF chamber for polar direct drive



Concept for Advanced T-Lean (Mostly DD) HIF power plant to produce plasma for MHD direct conversion