High Gain Heavy-Ion Direct Drive Targets for Inertial Fusion Energy

12th US-Japan Workshop on
Heavy Ion Fusion and High Energy Density Physics

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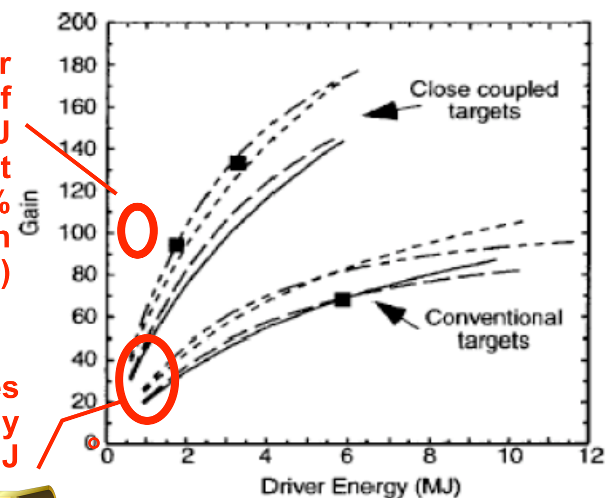
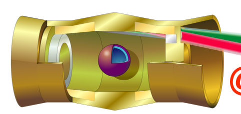
It is time to reconsider direct drive for HIF

With modern, mainly/all-DT, direct drive capsules and efficient heavy-ion beam coupling, ~1MJ drive may suffice for gains>100 (~200 with shock ignition)

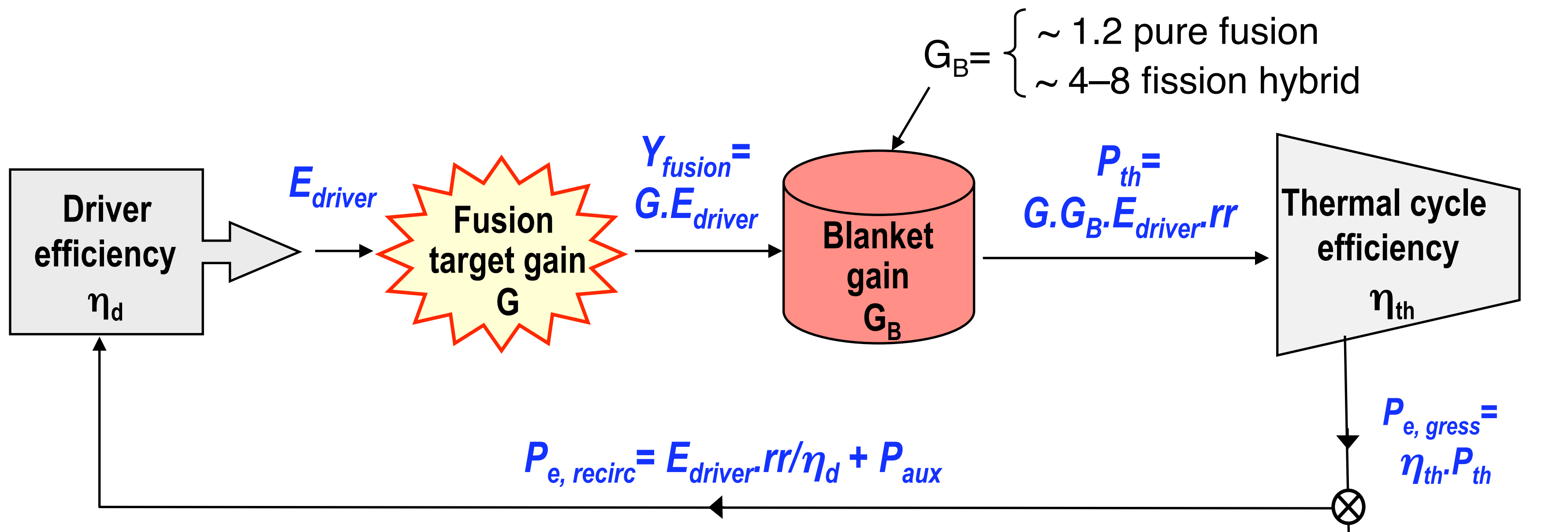
- Emerging work on HI direct drive with tuned ion ranges indicates potential for high beam-target coupling efficiencies and high gain
- Adiabat shaping + SSD beam smoothing makes *laser* direct drive viable for NIF and laser IFE (FTF, HAPL, HiPER….). NIF polar-direct-drive will test geometries suitable for liquid protected chambers
- HI direct drive capsule radii >2mm allows large beam spots
- Neutralized drift compression allows multiple pulses of lower ion ranges



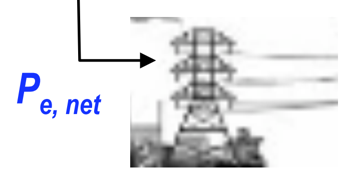


⇒ Pursuit of direct drive allows HIF to take advantage of ongoing progress in modern laser direct drive ICF as it did for <u>in</u>direct drive a decade ago

The required fusion gains for advanced targets are determined by power plant economics

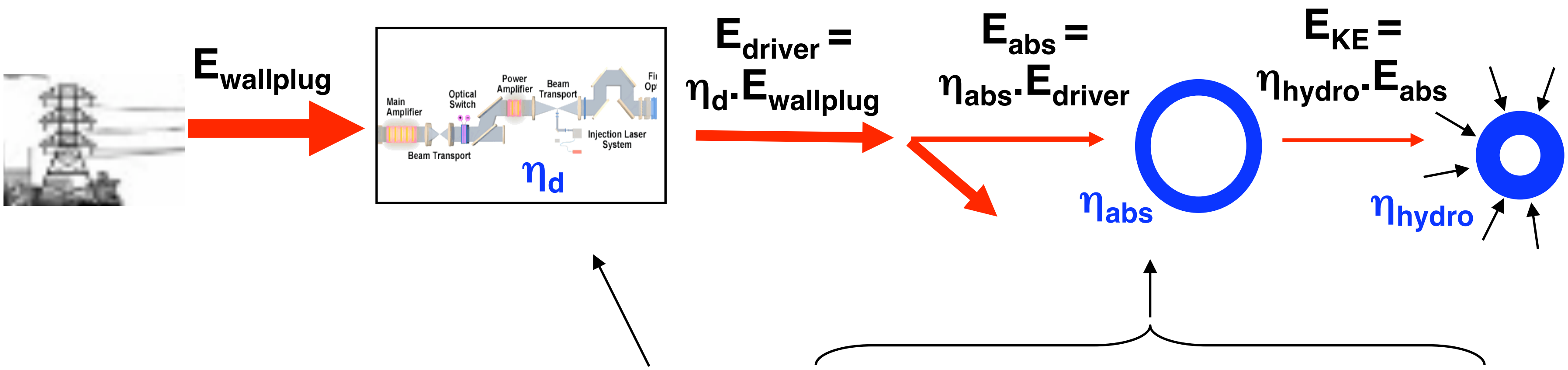


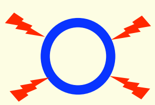
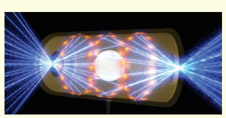
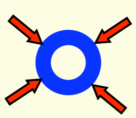
$$P_{e,net} = P_{e,gross} - P_{e,recirc} = \eta_{th}.G.G_B.E_{driver}.rr - E_{driver}.rr/\eta_d + P_{aux}$$



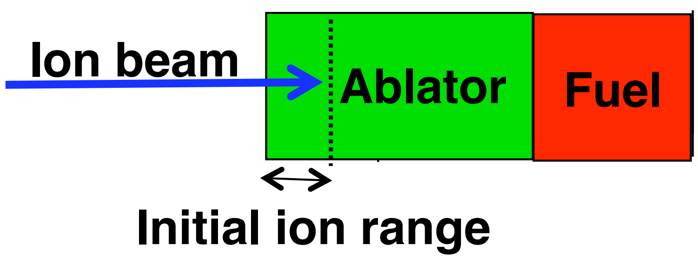
- Select req'd net electric output, $P_{e,net}$
- Specify driver efficiency η_δ, thermal cycle efficiency η_{th},
- $\Rightarrow$ Determine ***required*** target gain *G* for a given driver energy E_{driver}

Heavy ion direct drive promises high drive efficiencies (⇒high gain!) with very robust capsules

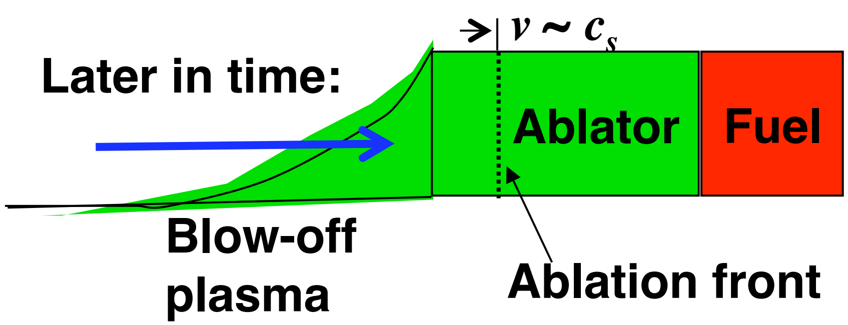


	Driver electrical efficiency η_d	Absorption efficiency η_{abs}	Hydro (rocket) efficiency η_{hydro}	Target drive efficiency $E_{driver} \rightarrow E_{KE}$ $= \eta_{abs} * \eta_{hydro}$	Ablative stabiliz. of R-T
Laser direct 	~0.05-0.15	~0.9	~0.06-0.1	~0.05-0.09 x3	OK w/ adiabat shaping
Laser indirect 	~0.05-0.15	~0.015-0.2	~0.10-0.15	~0.02-0.03 x1	Good
Heavy ion direct 	~0.35	~0.9	≤ 0.20	~0.10-0.20 x6	Very good (?)

A unique advantage of HI direct drive: We can tune the ion deposition range in the target to optimize the ablation drive



Ion beam initially heats ablator



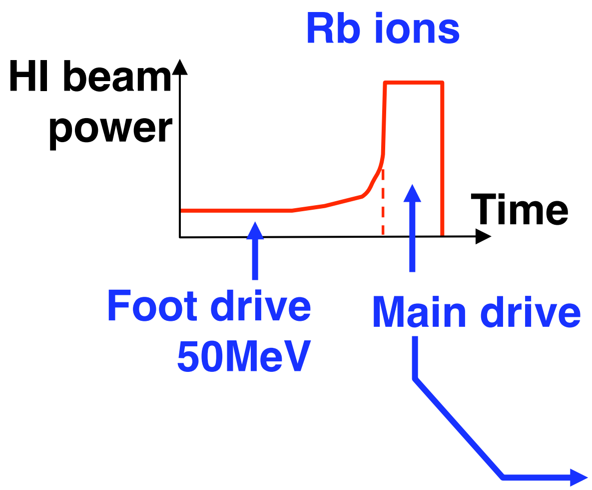
Ablation front decouples from location where energy is deposited => Potential low drive efficiency

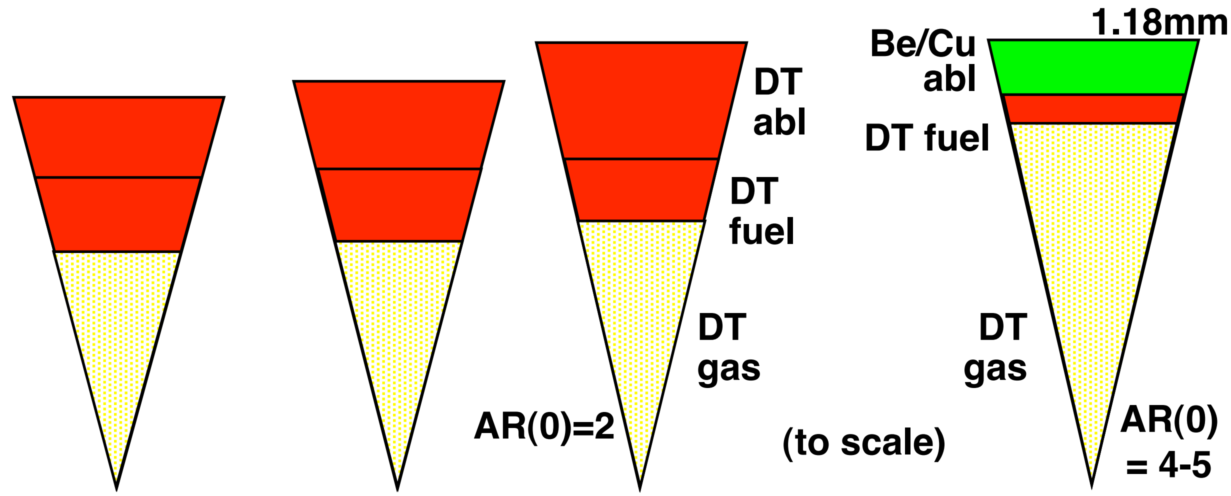
Unique features of heavy ion direct drive to maximize drive efficiency:

1. Passive approach: Ion beam heating causes electron thermal speed to go above ion velocity ==> range lengthens, and ion beam can stay close to ablation front, under special circumstances

2. Active approach: Ramping ion beam energy over the course of the pulse, will also increase range.

Objective: Design a high-gain HI direct target with: (a) NIF yield ~20MJ, (b) $E_{HI\ driver}$<<1MJ, (c) all-DT, (d) robust capsule





	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	350-425
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	36
In-flight adiabat α	1.9	2.4	3.2	1.4

John Nuckolls : *"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 <u>much less than 1 MJ?</u>"*

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

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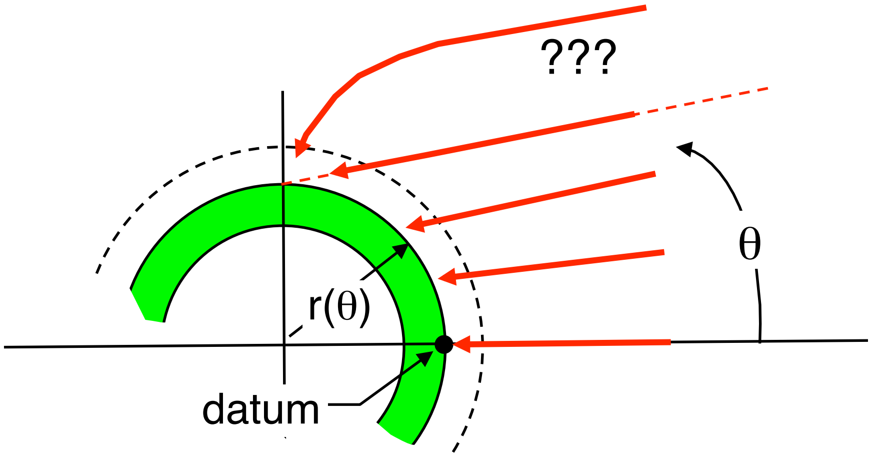
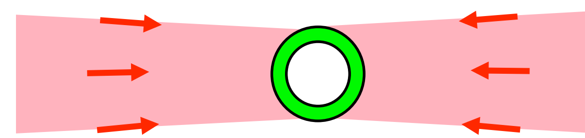
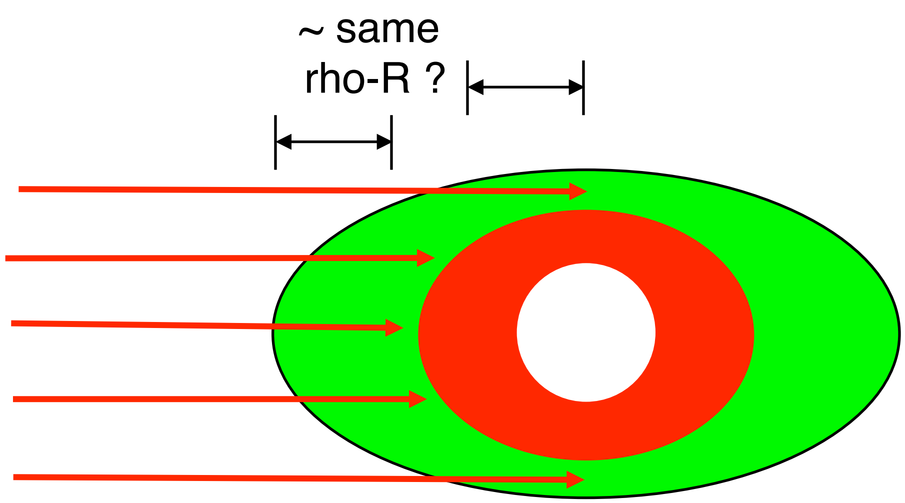
Issues with coupling efficiency, beam illumination symmetry, and Rayleigh-Taylor instability are discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. Efficient coupling of heavy-ion beams to compress direct-drive inertial fusion targets without hohlraums is found to require 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.
[DOI: 10.1063/1.2950303]

But, Without Refraction, How Do We Achieve Two-Sided Direct Drive with Heavy Ions?



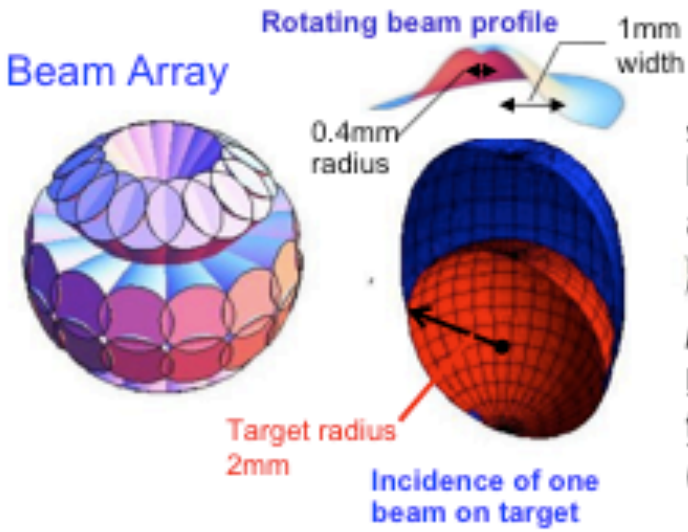


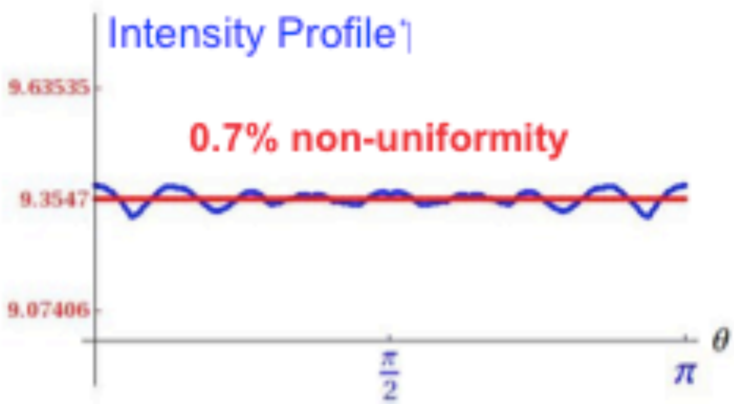


Heavy ions don't refract. But they can deposit volumetrically!

⇒ Target shimming and/or radial/temporal energy control. Is there is a solution – and can we find it?

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 2% non-uniformity of beam deposition?





<u>Just four</u> annular rings of beams (15 each, 60 total) at ±37.3° and ±79.3°, *with hollow, rotated beam spot projections* give a <u>maximum deviation from the mean of 0.7%</u> (with 21% spilled intensity).

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

S. Kawata and his HIF collaborators have agreed to collaborate with us in exploring symmetry and stability for HIF direct drive in the high efficiency ablative rocket regime. We very much appreciate their interest!

Two-sided "Polar Direct Drive" and "Saturn" targets Look promising for NIF direct drive (LLE/Rochester)

LLE/Rochester's NIF polar-direct-drive ("Saturn") target: Gain~17 predicted with all 2D sources applied

PHYSICS OF PLASMAS 13, 056311 (2006)

Polar-direct-drive simulations and experiments[a)]

J. A. Marozas,[b)] F. J. Marshall, R. S. Craxton, I. V. Igumenshchev, S. Skupsky, M. J. Bonino, T. J. B. Collins, R. Epstein, V. Yu. Glebov, D. Jacobs-Perkins, J. P. Knauer, R. L. McCrory, P. W. McKenty, D. D. Meyerhofer, S. G. Noyes, P. B. Radha, T. C. Sangster, W. Seka, and V. A. Smalyuk
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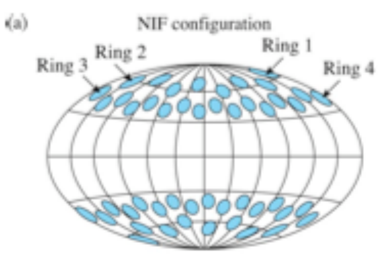
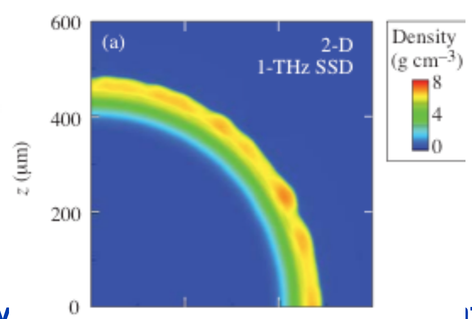
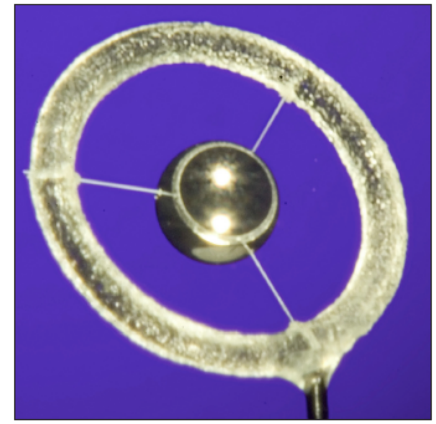
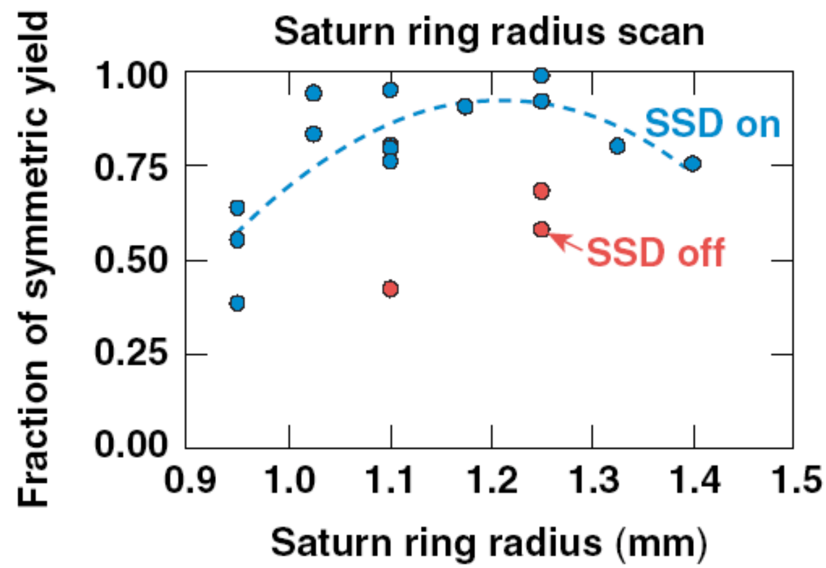
Polar direct drive (PDD) [S. Skupsky *et al.*, Phys. Plasmas **11**, 2763 (2004)] will allow direct-drive ignition experiments on the National Ignition Facility (NIF) [J. Paisner *et al.*, Laser Focus World **30**, 75 (1994)] as it is configured for x-ray drive. Optimal drive uniformity is obtained via a combination of beam repointing, pulse shapes, spot shapes, and/or target design. This article describes progress





"Saturn" polar direct drive targets have been shot on Omega and have achieved ~80-90% of the full 4-Pi symmetric yield

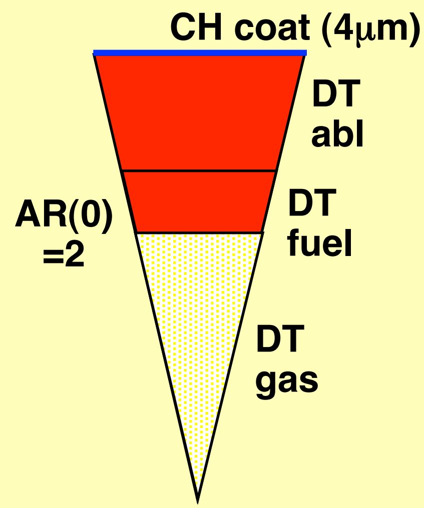




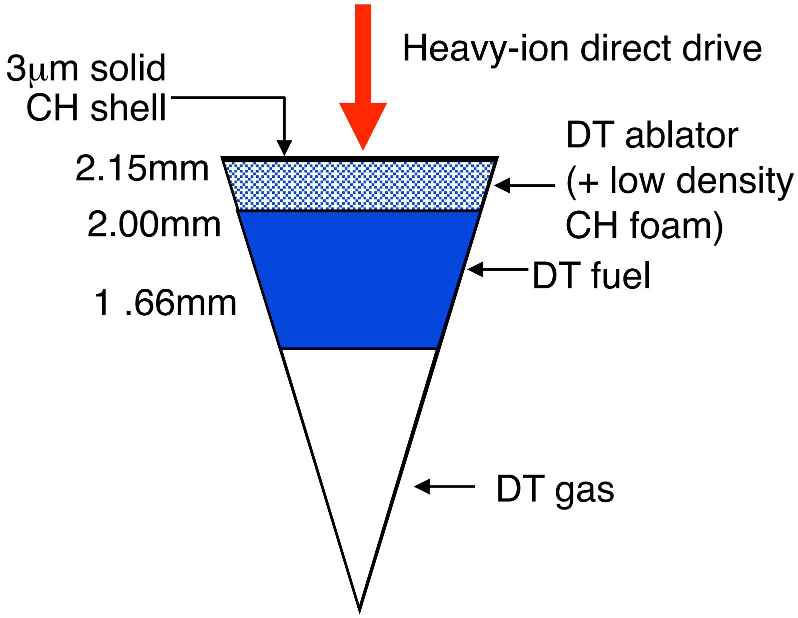
F.Marshall, *Bull APS* 51 106 (2006)

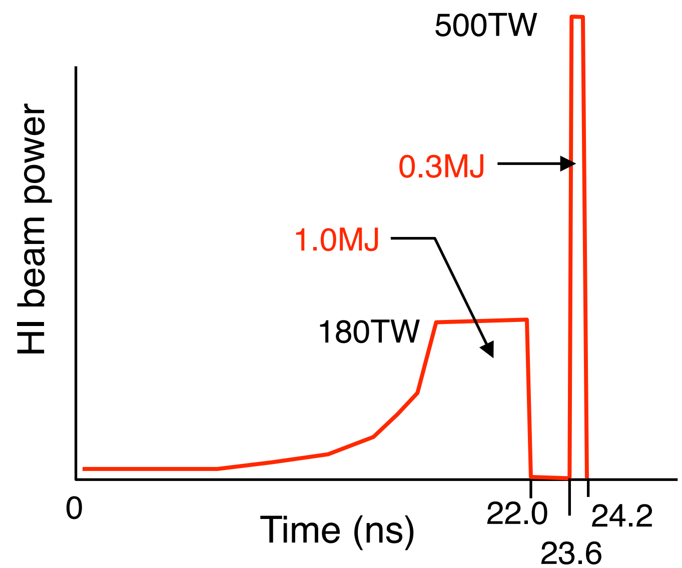
Conclusions and recommended further work

- **It should be possible to design high gain, HI direct drive targets at <<1MJ with robust performance**
- **All-DT targets are the simplest target designs around**
- **Implosion stability should be good because:**
  (a) high ablation stabilization of outer RT modes, (b) no ablator/fuel mix , (c) low Atwood numbers, (d) low inflight aspect ratios (big fat shells)
- **Further gain increases in gain are possible by:**
  (a) zooming (b) relaxing IFAR constraints (c) adding shock ignition, (d) H ablators
- **Next steps:**
  - ***Produce 1D gain curves from 0.1-2MJ (G~10-100's??)***
  - ***Determine minimum main drive ion energies for smaller targets***
  - ***Consider H ablators***
  - ***Single-mode 2D stability (is ablative stabilization really good?)***
  - ***2D/3D symmetry (and stability) with two-sided drive***



Initial LASNEX Results Suggest Promise for "Shock-Ignited" Heavy-Ion Targets at ≥1MJ Drive Energy

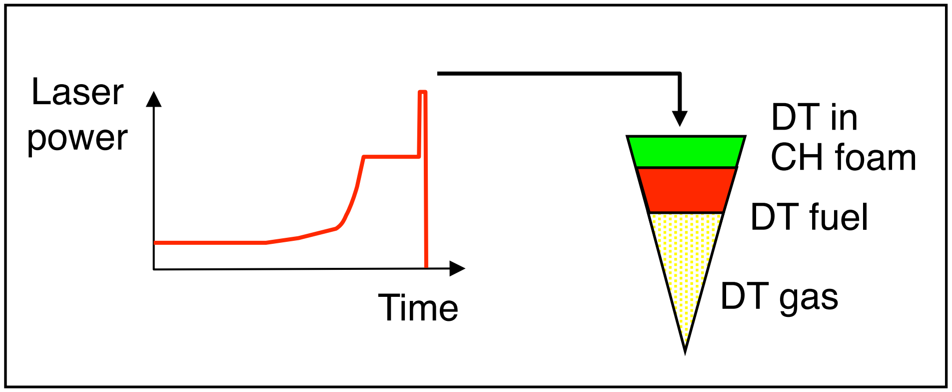


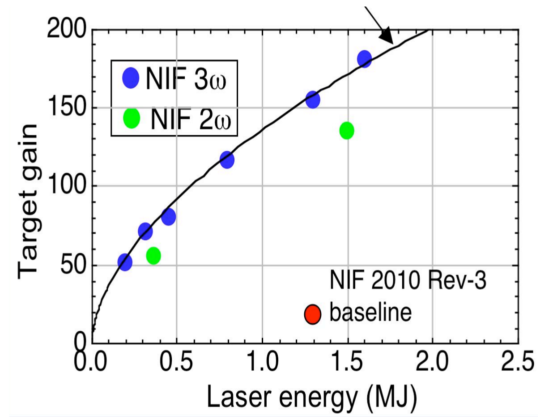


Heavy-ion drive	**50MeV Ar (z = +8 accel, +16 drift/focus)**
Drive energy	**1.0(main) +0.3(shock) = 1.3MJ**
Yield	**199MJ**
Gain	**153**
Peak velocity	**2.2e7cm/s**
Drive efficiency ($\eta_{coupled}$ x η_{rocket})	**8.6% (*)**
Peak rho-R	**2.25 g.cm-3**

*Inefficient as assembling large fuel mass to low velocity; "conventional" heavy-ion direct drive gives ~15-18%

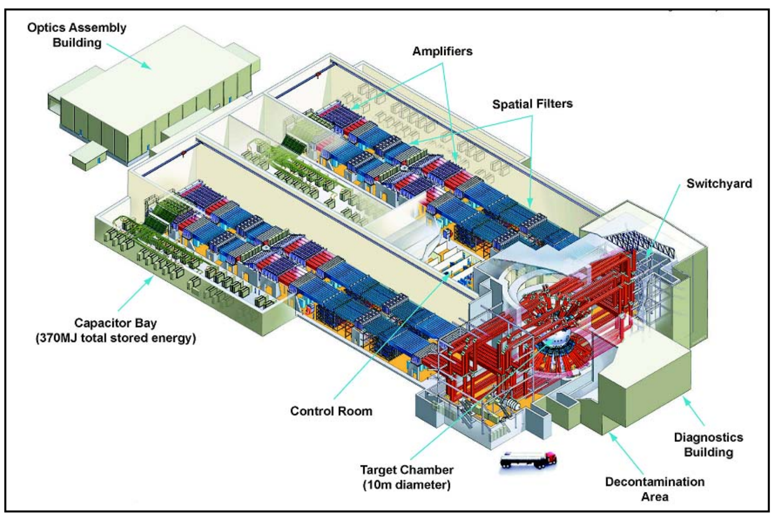
"Shock Ignition" for high gain NIF targets: Can we apply the principles to heavy ion direct drive?

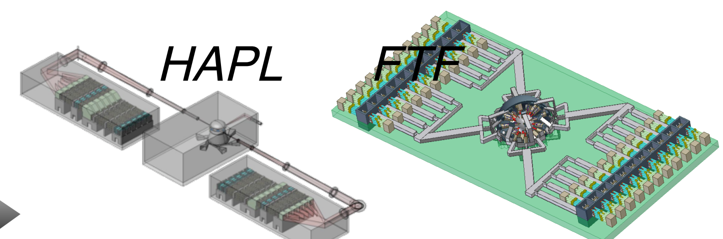




High gain/yield NIF targets

NIF (polar) direct drive campaign (≥2012)





High gain targets for laser IFE

High gain targets for heavy ion IFE?