LLNL-PRES-462831

An Overview of High-Gain Targets for Inertial Fusion Energy

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The National Academies – Committee on Inertial Confinement Fusion Energy
San Ramon CA
January 30, 2011

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Is the target concept consistent with the integrated power plant design?

How do we test it on an implosion facility – and at gain and yield?

Don't *implicitly* believe the codes outside of their experimental benchmarks

An ... High-Gain Targets ... Fusion Energy

L. J...

Lawrence Livermore National Laboratory

The National Academies – ... Confinement Fusion Energy

...CA

...y 30, 2011

...under the auspices of the U.S. Department of Energy by ...ore National Laboratory under Contract DE-AC52-07NA27344.

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With thanks to…….

- **R.Betti, D. Meyerhofer, O.Gotchev, J.Knauer, J.Marozas, S.Craxton, K.Anderson, P.McKenty, W.Theobald** *(LLE/U.Rochester)*
- **P.Amendt, P.Patel, J.Nuckolls, M.Dunne, J.Lindl, D.Callahan, W.Meier** *(LLNL)*
- **S.Obenschain, A.Schmitt** *(NRL)*
- **G.Logan, E.Henestroza, P.Seidl** *(LBNL)*
- **G.Schurtz, X.Ribeyre, E. LeBel** *(CELIA/U.Bordeaux)*
- **A.Casner** *(CEA, France)*
- **M.Roth** *(Technical University of Darmstadt/GSI, Germany)*
- **S.Atzeni** *(Universita' di Roma, Italy)*
- **R.Vesey, S.Slutz, M.Herrmann, M.Cuneo, A. Sefcow** *(SNL)*
- **M.Murakami, H. Azechi** *(ILE/Osaka, Japan)*

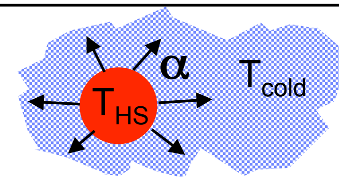
Target physics: High gain targets will *probably* require……

Cryogenic fuel compressed to high density, close to Fermi degenerate (FD) conditions

- ρR_{α}~0.4g/cm^2 req'd
- mass=$(4\pi/3)(\rho R)^3/\rho^2$
- If ρ_{DT}=0.25g/cm^3, ⇒Yield ~10's kilotons
- If ρ_{DT} =500g/cm^3, ⇒Yield ~500MJ

Ignition from a hotspot over a few-% of the fuel mass

Propagating α burn
⇒ T_{HS}~10keV,
⇒ ρR_{HS}~0.4g/cm^2

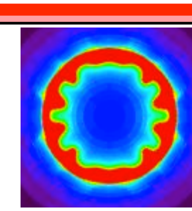


An alpha burn wave propagating into the cold FD fuel mass with adequate inertial confinement

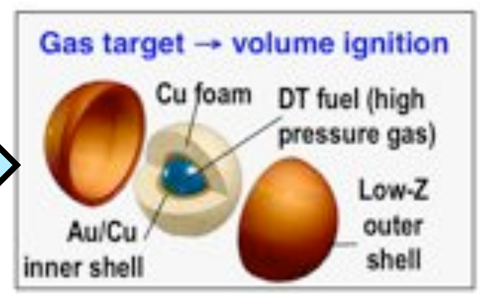
$T_{cold} \lesssim$ 1keV at α_{FD}~1, ⇒ pulse-shaping
$f_{burn\text{-}up}$ ~ρR/(ρR+7) , ⇒ ρR~3g/cm^2

Good symmetry and stability. Low laser-plasma instabilities (ICF is 3D!)

- ⇒ Convergence ratios $\lesssim$ 35
- ⇒ In-flight aspect ratios $\lesssim$ 35
- ⇒ $I_{laser} \cdot \lambda^2 \lesssim 10^{14}$ Wcm^{-2}μm^{-2}

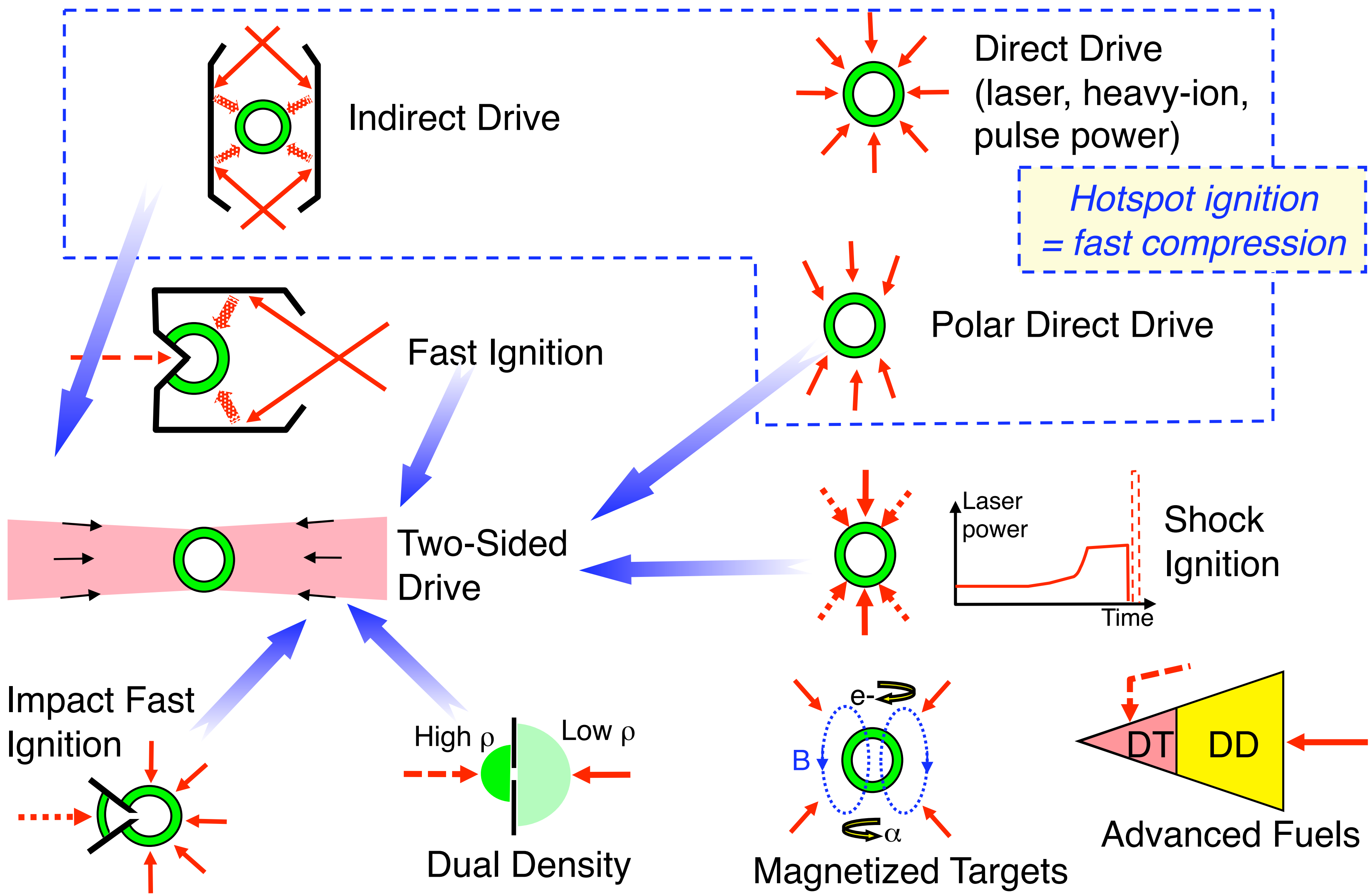


This probably precludes room-temperature, high pressure gas targets
(But gas targets may be a route to ignition and burn at gain ~unity)

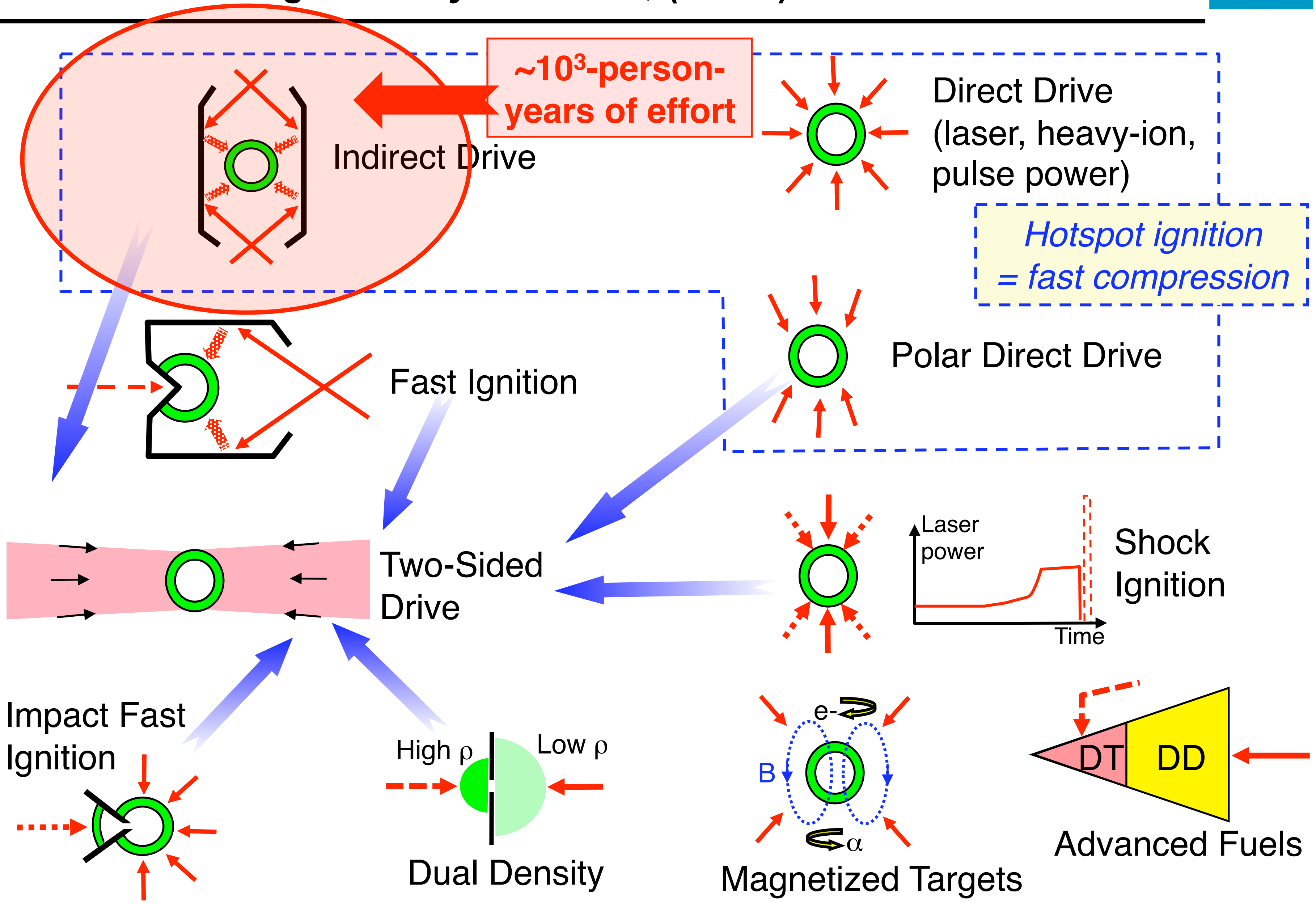


It's all about this!!

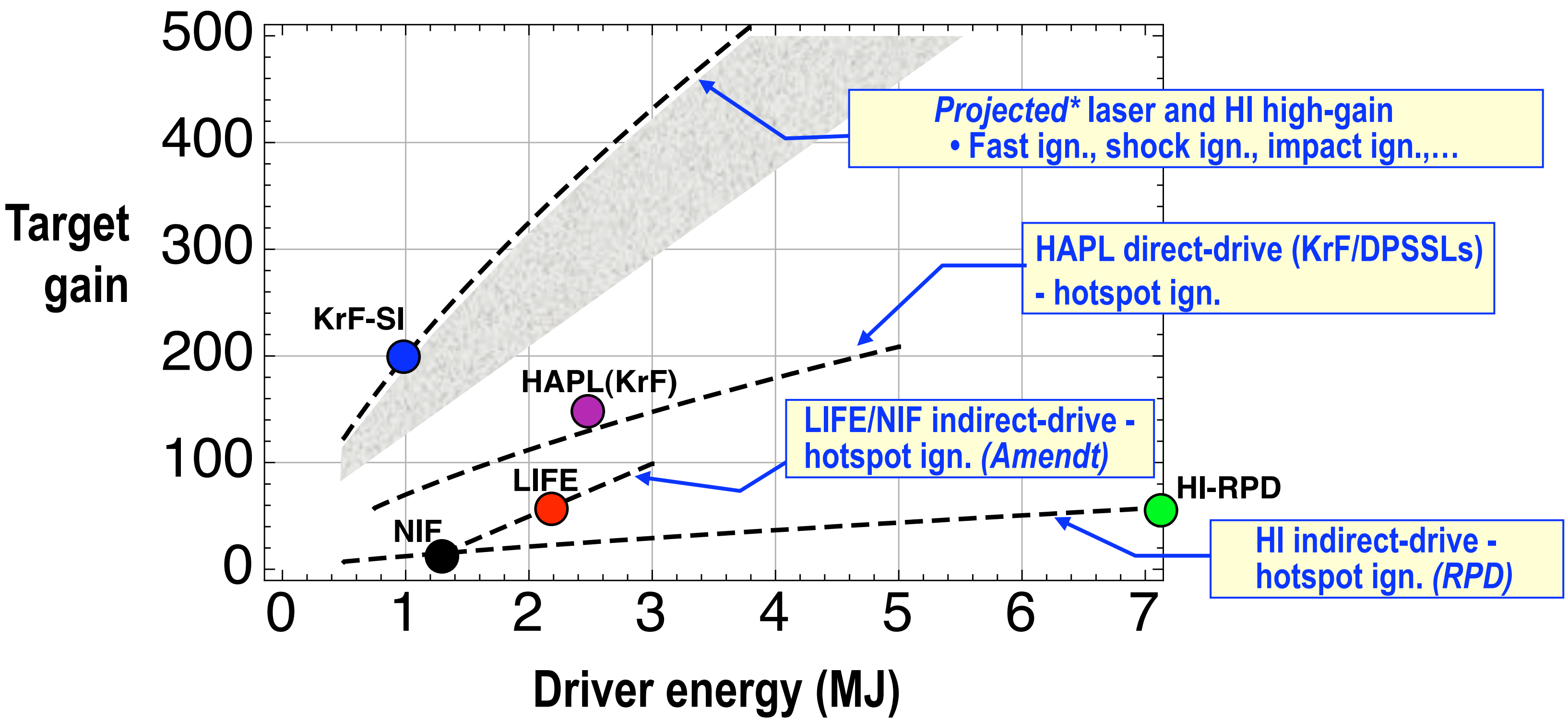
A survey of ICF targets – Where do we test these on implosion facilities – and at gain and yield… NIF, (LMJ?)... ?



A survey of ICF targets – Where do we test these on implosion facilities – and at gain and yield… NIF, (LMJ?)… ?



But what target gains might we achieve?
Candidate gain curves...



(See later in presentation for details of these gain curves)

** Projected = projected in 1-D and initial 2-D studies*
but not established in integrated designs

The key to higher gain *Part-1*: Low implosion velocity

High target gain requires:

- High ρR, ⇒ more fuel burnup
- Low V , ⇒ more fuel mass assembled for given driver energy

$$G = \frac{Y_{fusion}}{E_{driver}} = \frac{Y_{fusion}}{\frac{1}{2} m_{fuel} V^2 / \eta} \sim \frac{\rho R / (\rho R + 7)}{V^{1.3}}$$

Ref. 1

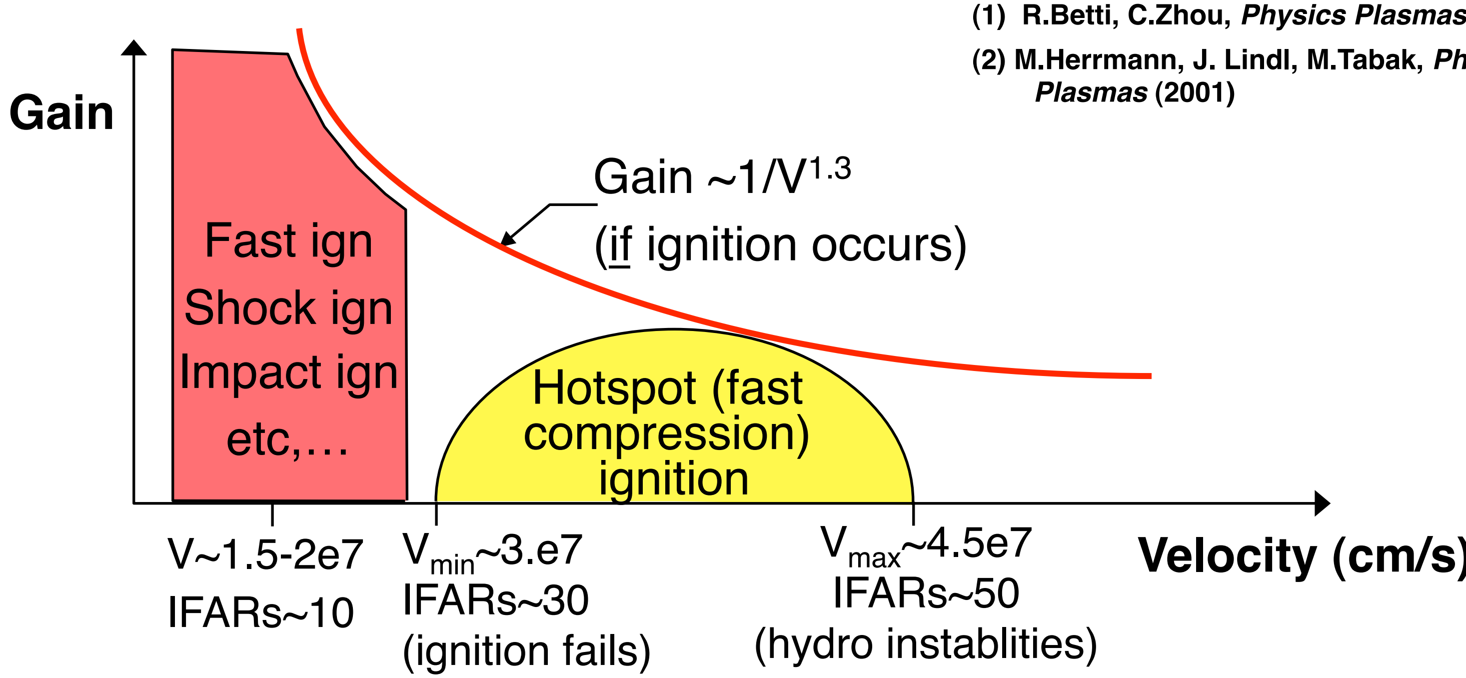
But "hotspot" (= fast-compression) ignition needs high velocity to minimize ignition energy

$$E_{ign-req'd} \sim \frac{\alpha_{FD}^{1.8}}{V^6}$$

Ref. 2

(1) R.Betti, C.Zhou, *Physics Plasmas (2005)*

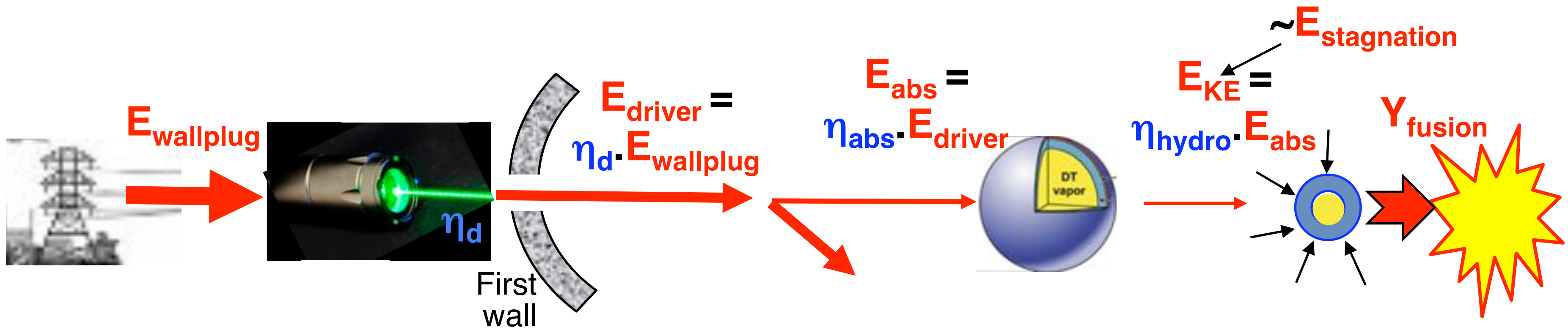
(2) M.Herrmann, J. Lindl, M.Tabak, *Physics Plasmas* (2001)

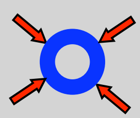
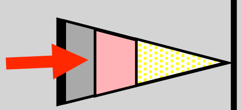
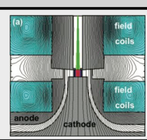


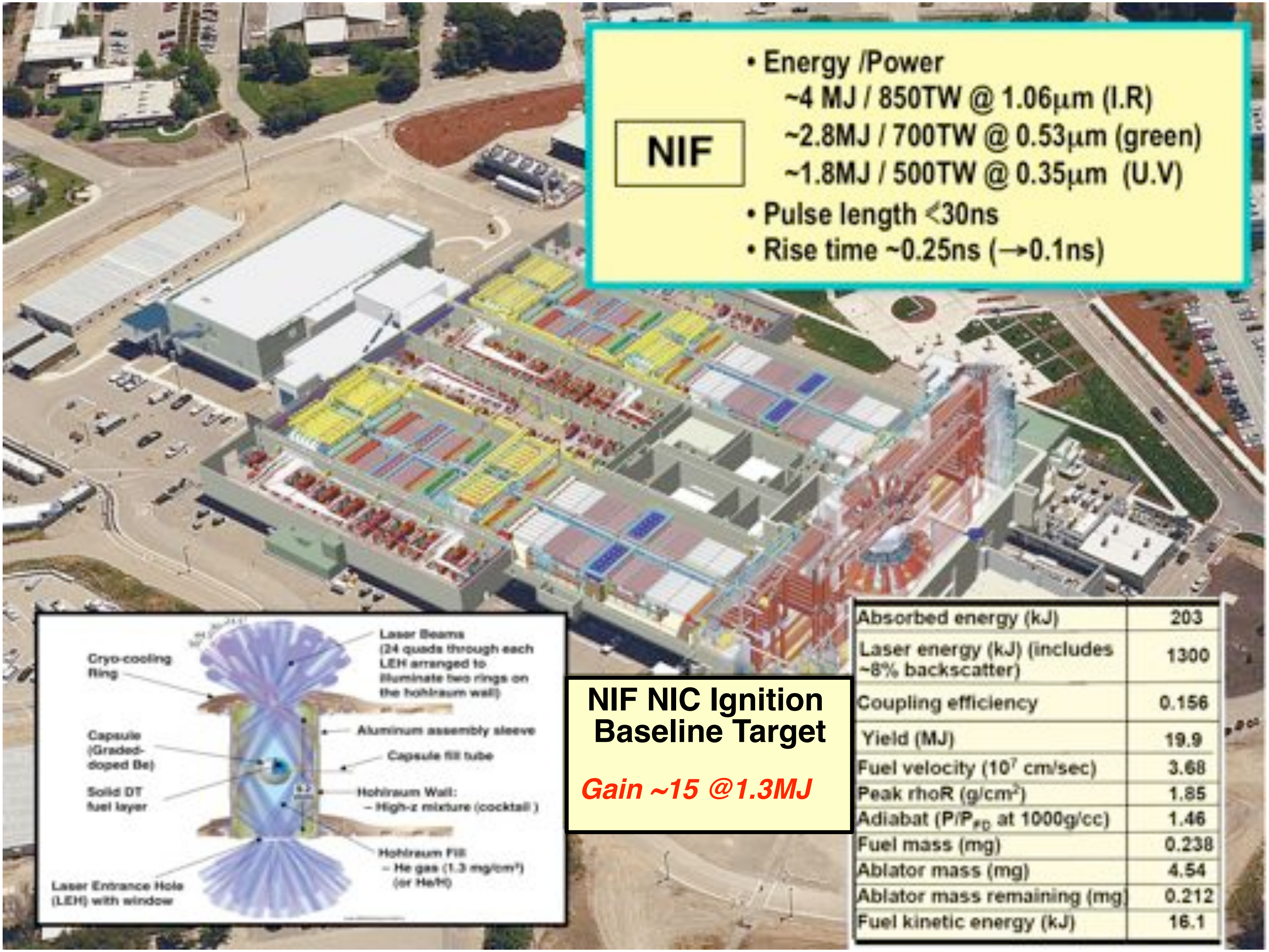
R.Betti

LLE/U.Rochester

The key to higher gain *Part-2*: High driver-target coupling efficiencies



	Driver electrical efficiency η_d	Absorption efficiency η_{abs}	Hydro (rocket) efficiency η_{hydro}	System drive efficiency $E_{wallplug} \rightarrow E_{KE}$ $= \eta_d \cdot \eta_{abs} \cdot \eta_{hydro}$
Laser direct 	~0.05-0.20	~0.85	~0.06-0.1 (ablative)	~0.01
Laser indirect 	~0.05-0.20	~0.15-0.3	~0.1-0.15 (ablative)	~0.005
Heavy ion direct 	~0.25-0.40	~0.9	~0.20 (tamped ablative)	~0.05
Pulsed power direct 	~0.3	~0.2 - 0.3 (direct magnetic)		~0.05



NIF

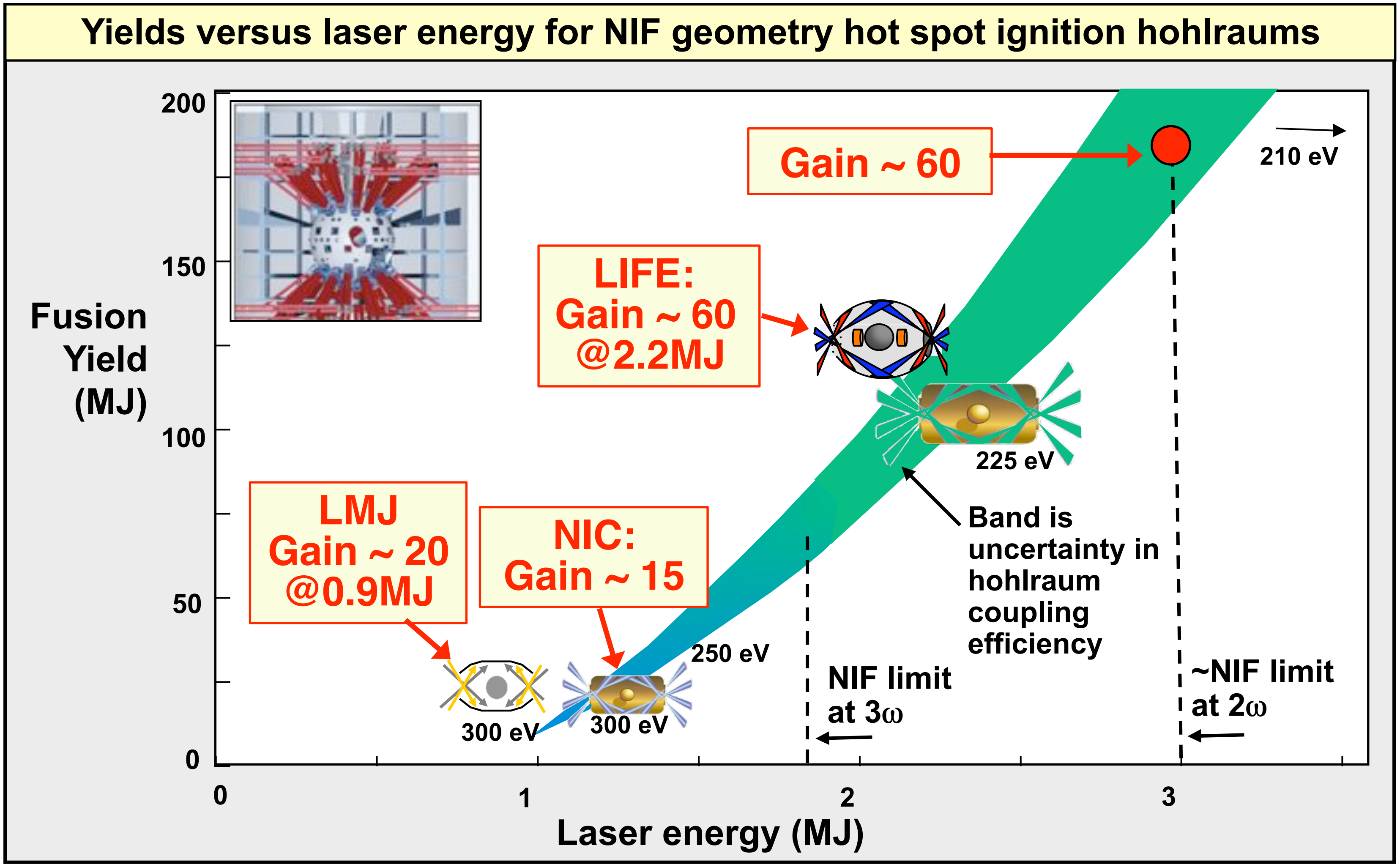
- Energy /Power
  - ~4 MJ / 850TW @ 1.06μm (I.R)
  - ~2.8MJ / 700TW @ 0.53μm (green)
  - ~1.8MJ / 500TW @ 0.35μm (U.V)
- Pulse length <30ns
- Rise time ~0.25ns (→0.1ns)

NIF NIC Ignition Baseline Target

Gain ~15 @1.3MJ

Absorbed energy (kJ)	203
Laser energy (kJ) (includes ~8% backscatter)	1300
Coupling efficiency	0.156
Yield (MJ)	19.9
Fuel velocity (10^7 cm/sec)	3.68
Peak rhoR (g/cm²)	1.85
Adiabat (P/P_{FD} 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

Indirect Drive Hohlraums in NIF geometry with hotspot ignition are enabling for IFE for *near term* application



J.Lindl "Ignition Campaign Strategy" (2007)

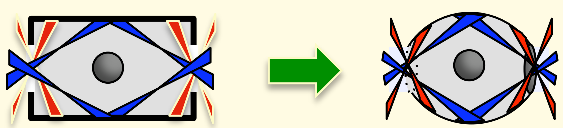
P.Amendt (2011); Lafitte (2010)

Indirect Drive: NIC-like tune with rugby hohlraum and LEH-shields is progressing towards higher gain for LIFE

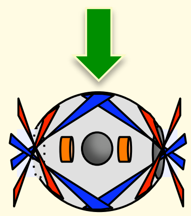
Strategy

- ~ 20% improvement with rugby-shaped hohlraums is expected:

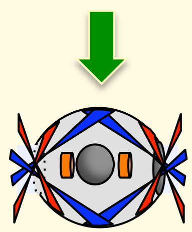
NIC-like



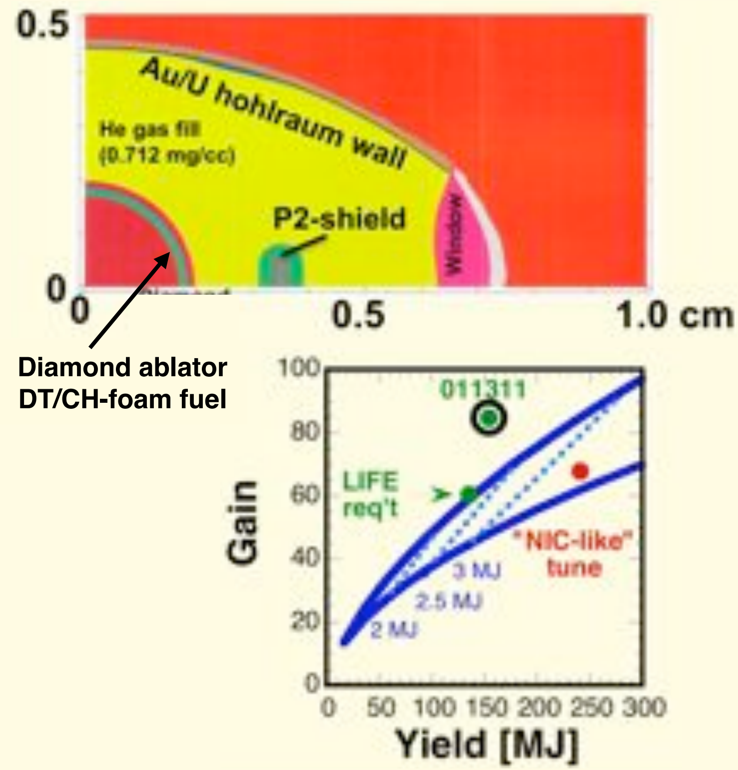
- ~ 15% improvement with use of LEH-shields is predicted:



- ~15% further improvement from 5% greater capsule size is expected:



Gain ~60 @ 2.2MJ



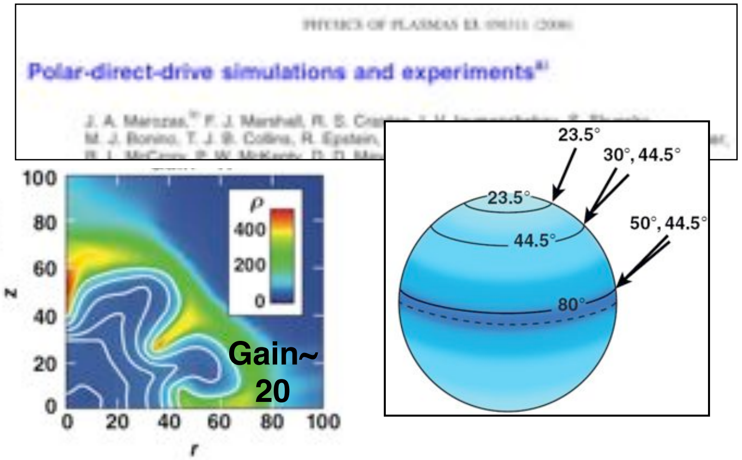
These planned improvements in efficiency (~50%) will be directly tested on the NIF

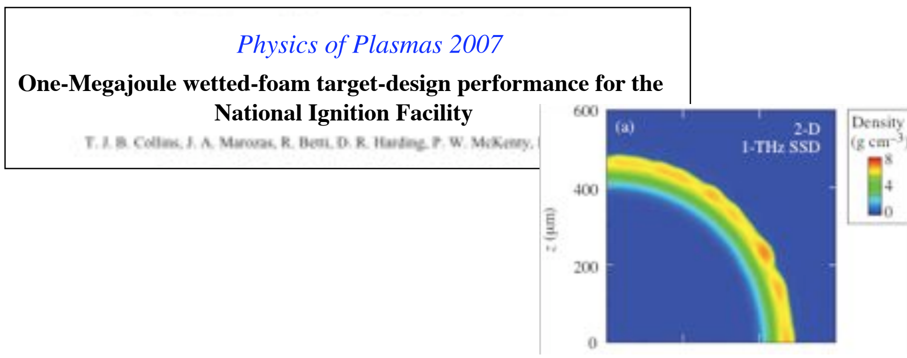
P.Amendt , Jan 2010

Laser Direct Drive (hotspot ignition): LLE's NIF designs predict gains ~20-40 at 1MJ. HAPL results suggest >100 at 2MJ for KrF

NIF Polar Direct Drive *(Skupsky, Marozas)*

Gain~20-35 @1MJ ; with all 2D sources (beam balance, imprint, outer/ice roughness, ...etc)



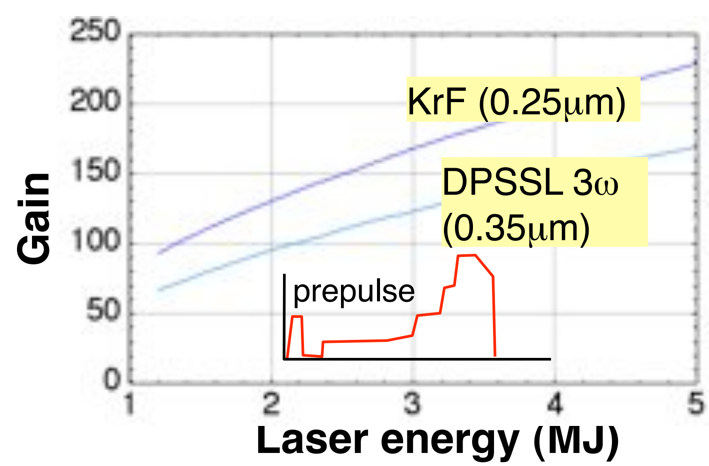


NIF Symmetric 4-Pi Direct Drive *(Collins)*

Gain~40 in 2D @1MJ

Direct Drive Simulations for HAPL

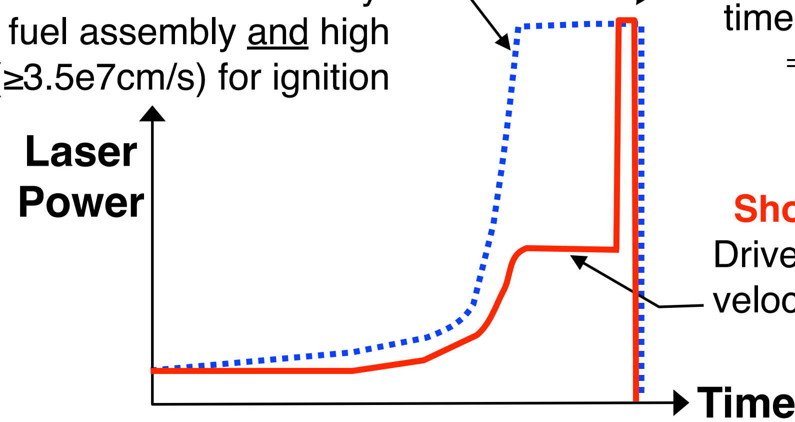
Gain >100@2MJ w/ KrF and zooming



Shock Ignition*: Implode at low velocity and ignite separately

Conventional hotspot (fast compression) drive

Does double duty: fuel assembly <u>and</u> high velocity(≥3.5e7cm/s) for ignition



Shock ignition - shock pulse

Spike launches late-time shock timed to reach fuel at stagnation
⇒ Ignition

Shock ignition – Compression

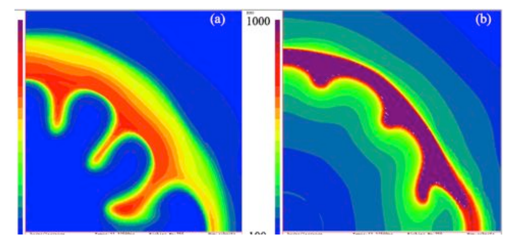
Drive pulse assembles fuel at low velocity (≤2e7cm/s)
⇒ No ignition

$E_{laser} \rightarrow E_{fuel,\ max\ KE}$

$\sim 1/2\ m_{fuel} V^2$

high (↑ m_{fuel}) low (↑ V)

- **Higher gain/yield for a given laser drive energy in a more robust capsule**
- **Relative to "fast-ignition" :**
  - Time/spatial requirements less stringent (~ x10)
  - Uses same laser (no separate short pulse laser req'd)
  - Process modeling is (more or less) standard hydro
  - ***But*** conventional symmetry/stability constraints apply



Compression only *Compression plus shock*

Hotspot at ign./stagnation

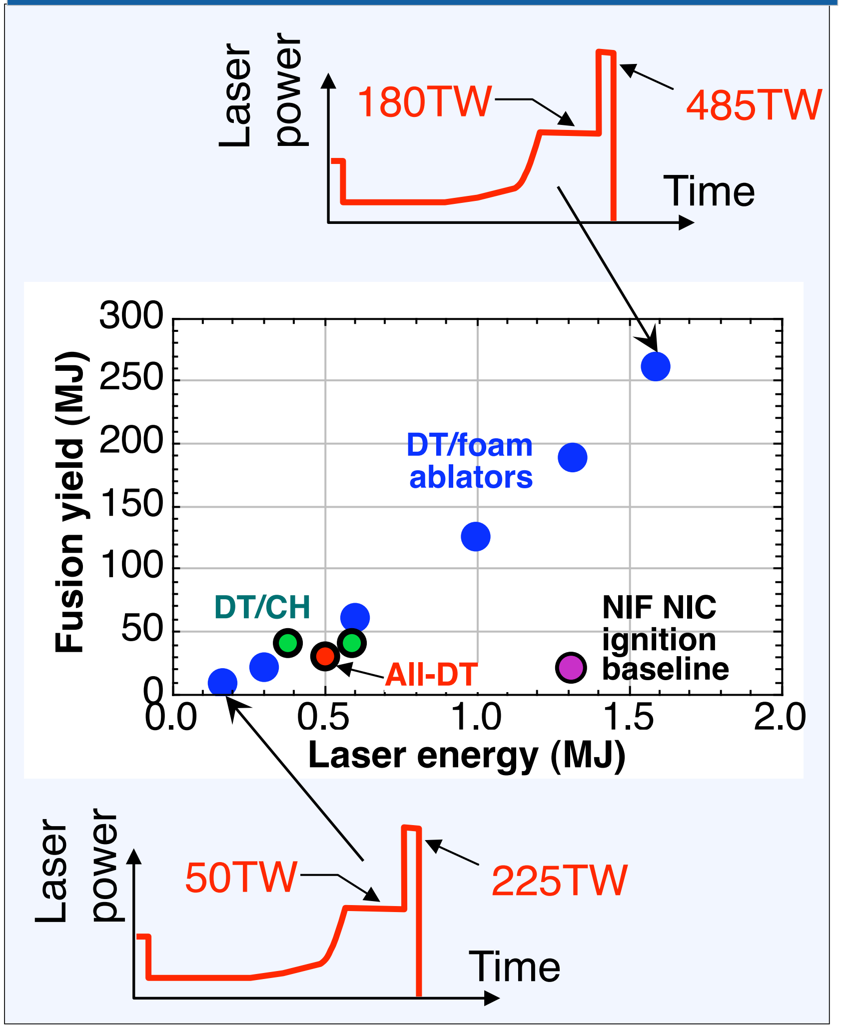
Are these more forgiving relative to a conventional hotspot ignition target?

Schurtz, Atzeni, et al

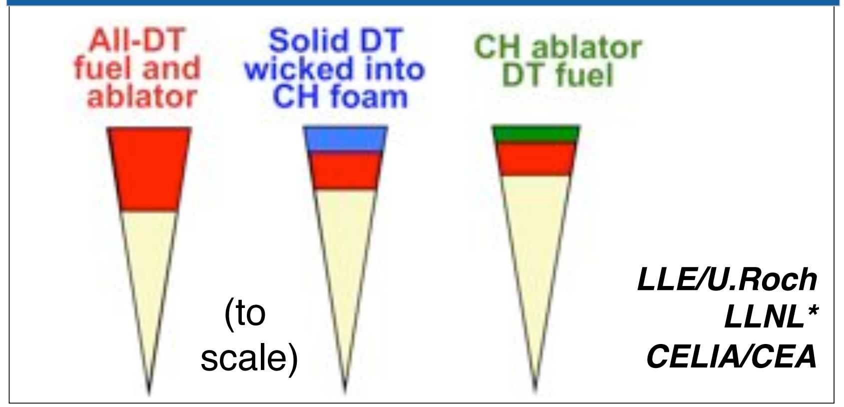
* R. Betti, et al., *Phys. Rev. Lett.*, 98, 155001 (2007)

Shock Ignition: Preliminary yield and gain curves for NIF*

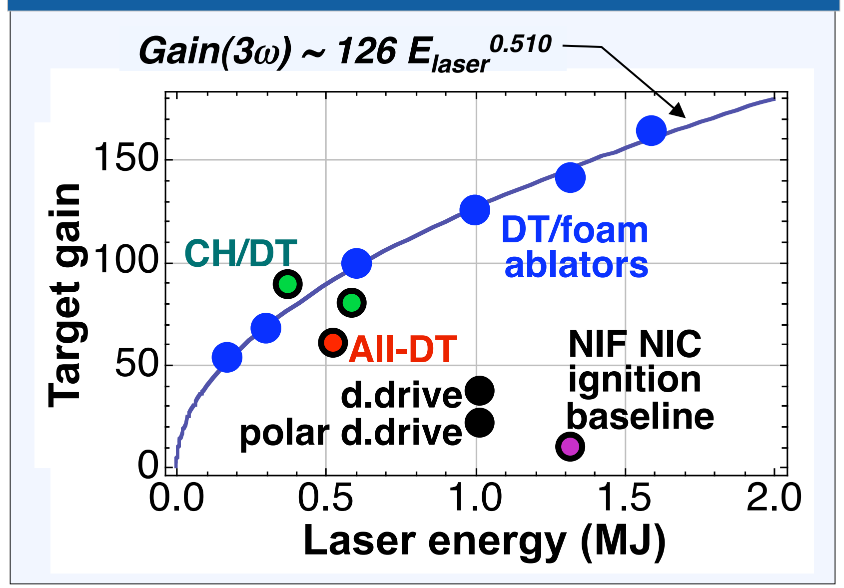
NIF Shock Ignition Yield Curve



NIF Shock Ignition Targets are Simple

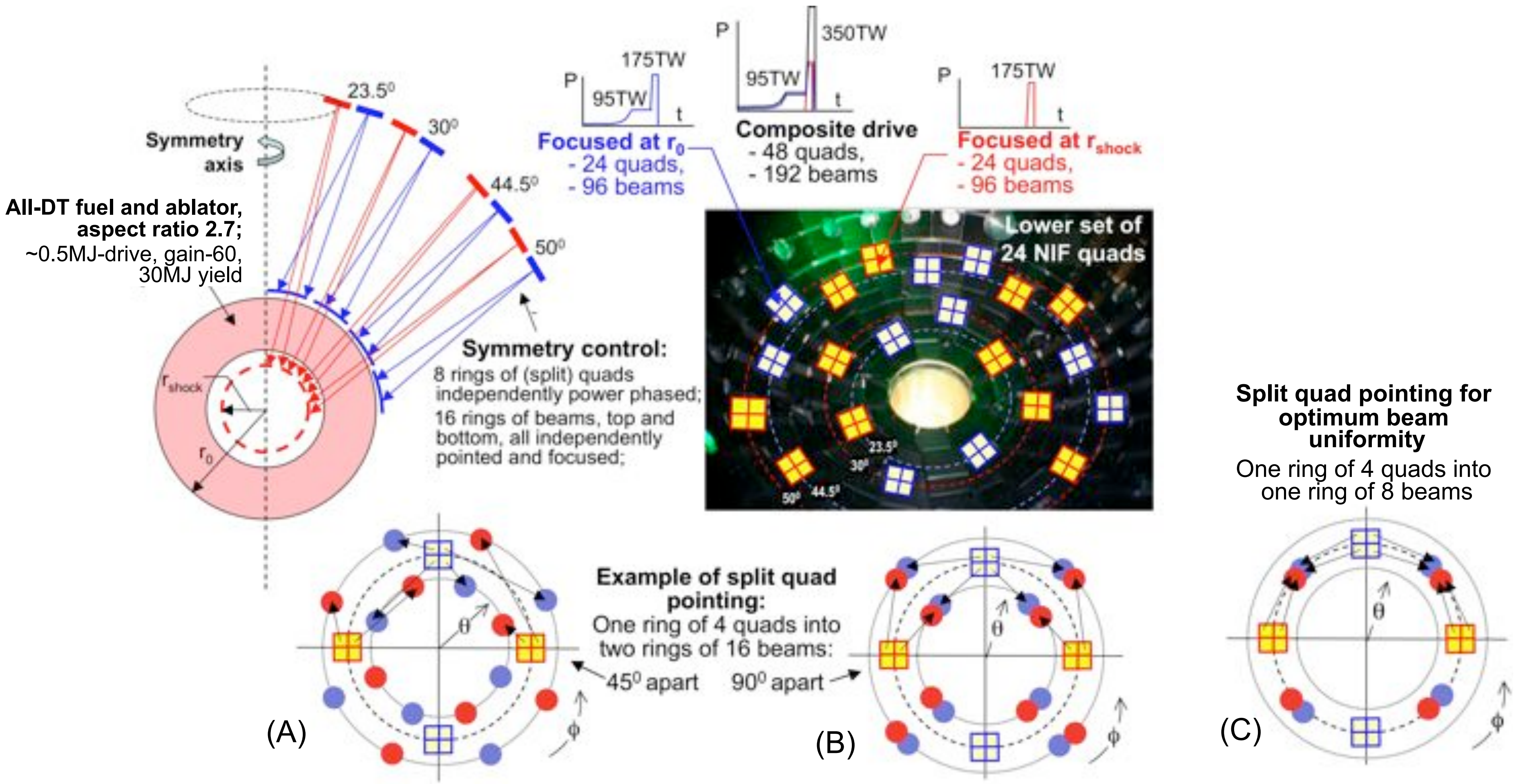


NIF Shock Ignition Gain Curve



* L.J.Perkins, et al., *Phys. Rev. Lett.*, 103, 045004 (2009)

Shock Ignition: In the near-intermediate term must be fielded on NIF in polar direct-drive. ⇒ Optimization of NIF polar drive symmetry

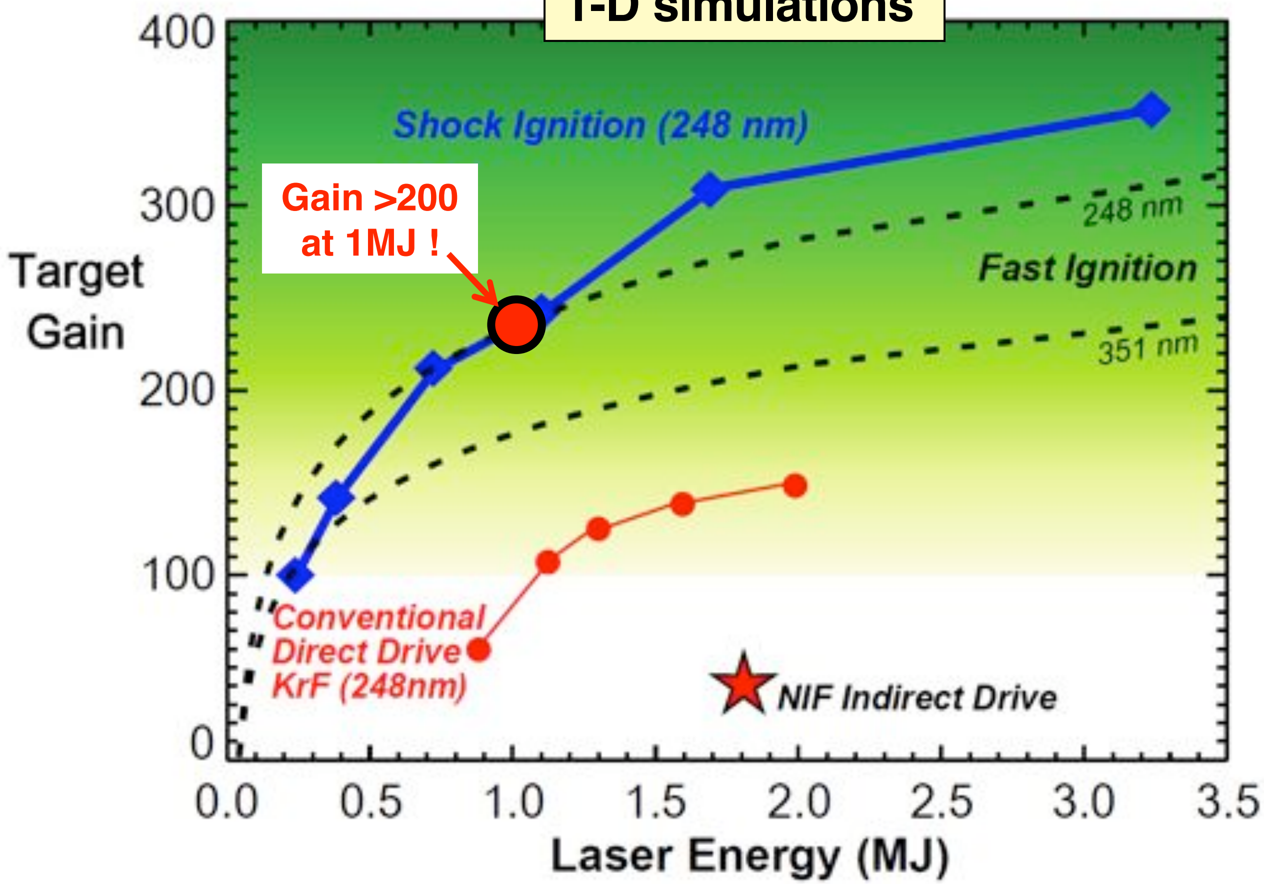


Present work at LLE and LLNL is focused on optimization of drive symmetry and shock coupling efficiency using static "zooming"

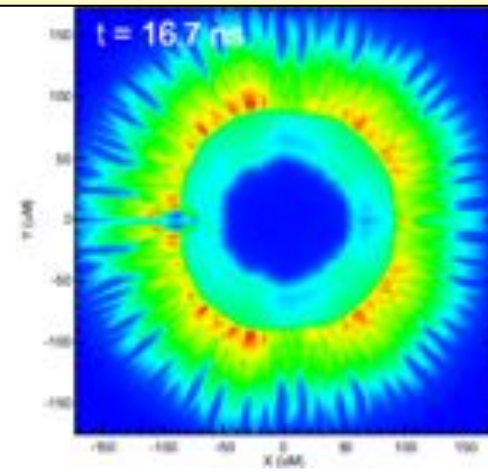
Shock Ignition – KrF lasers potentially offer higher-gain with smaller lasers and power-plant-class yields

Enabled by KrF attributes: *Shorter UV wavelength, higher bandwidth, "zoomed" focal profile, higher threshold for laser plasma instability*

1-D simulations



High resolution 2-D simulations
Gain = 102 @ 521 kJ

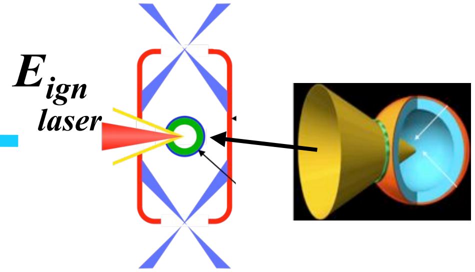


Realistic 2D simulations typically give ~70% of the 1D gain

S.Obenschain, A.Schmitt NRL

Fast Ignition: Decouple compression from ignition (and alleviate conventional symmetry/stability constraints)

Fast ignition offers potential target gains of ~100 at 1MJ

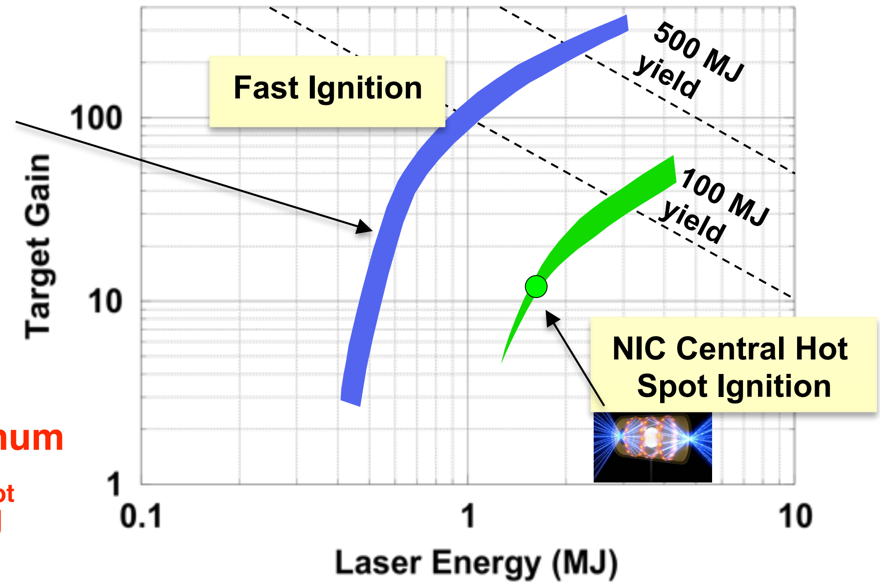


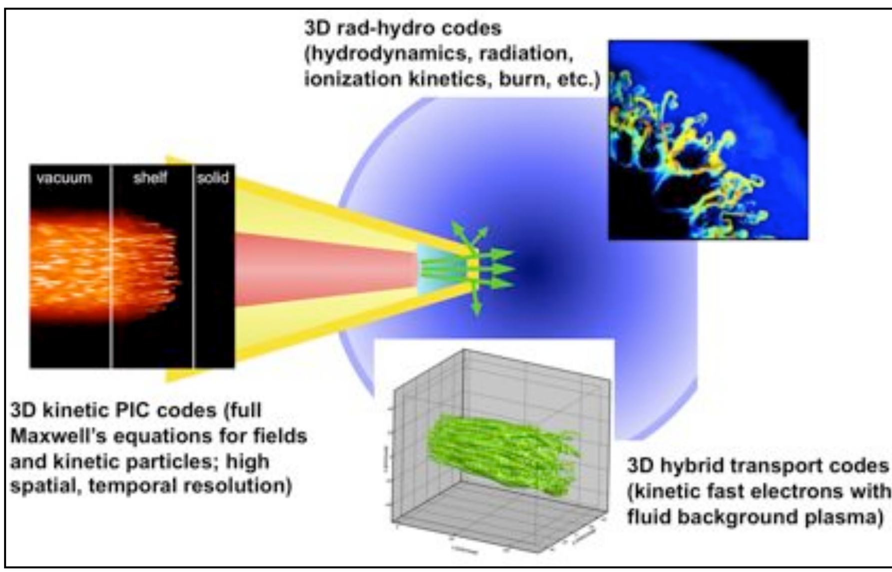
≳0.5g/cm²

~10keV

$$E_{ign\,laser} \sim \frac{1}{f_{coupled}}\left[\frac{(\rho r)^3_{hot}\,T_{hot}}{\rho^2}\right]$$

minimum $E_{hotspot}$ ~15kJ





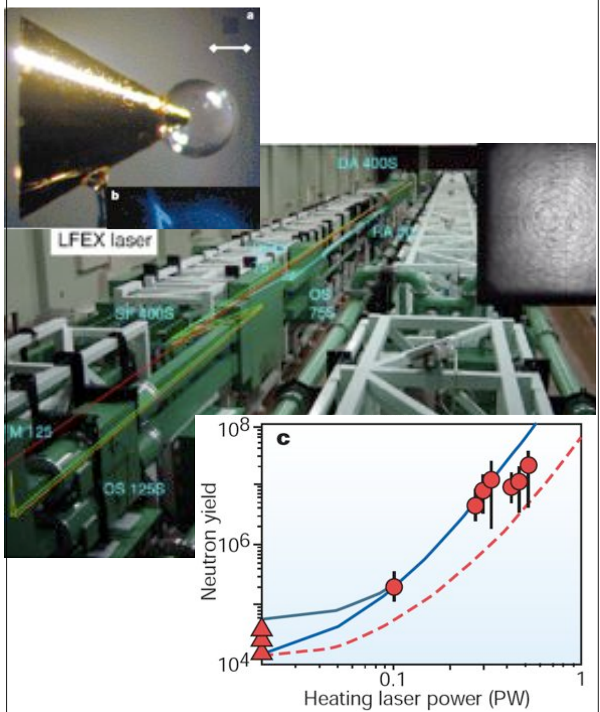
FI target design:
Conventional ICF (rad-hydro) plus relativistic laser-plasma interactions (kinetic-PIC)

⇒ Rich multi-scale physics

P.Patel LLNL
S. Atzeni Phys Plasmas (1999)

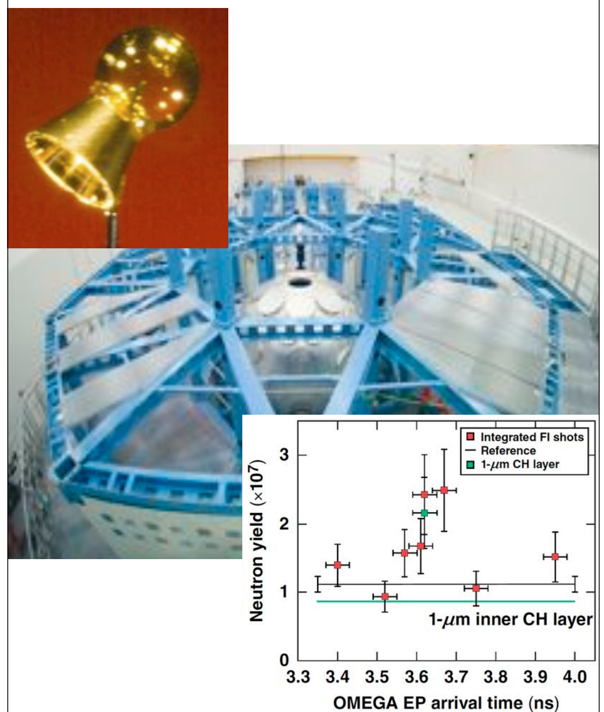
Fast Ignition: Integrated compression/core heating experiments will validate key coupling physics prior to a fast ignition demonstration

FIREX *(ILE Osaka)*



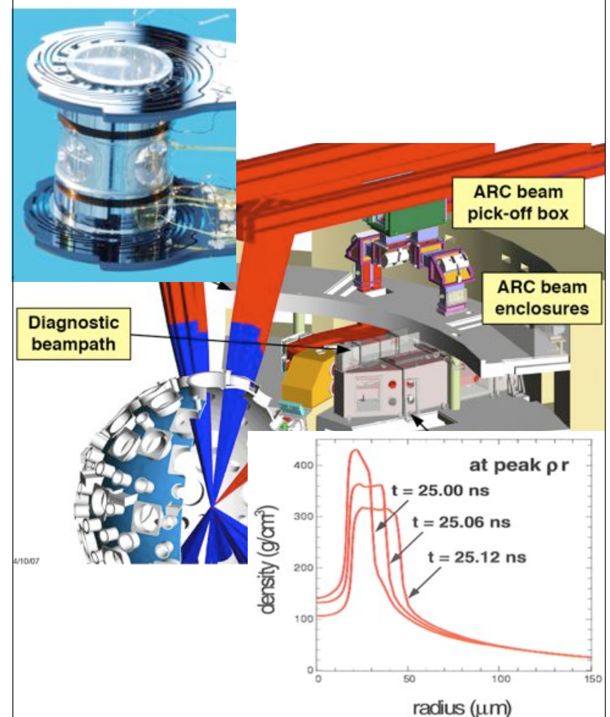
10 kJ, 2ω compression, 10 kJ, 10 ps ignitor

OMEGA EP *(LLE U.Roch.)*



30 kJ, 3ω compression, 2.6 kJ, 10 ps ignitor

NIF ARC *(LLNL)*



1.7 MJ, 3ω compression, 10 kJ, 10 ps ignitor

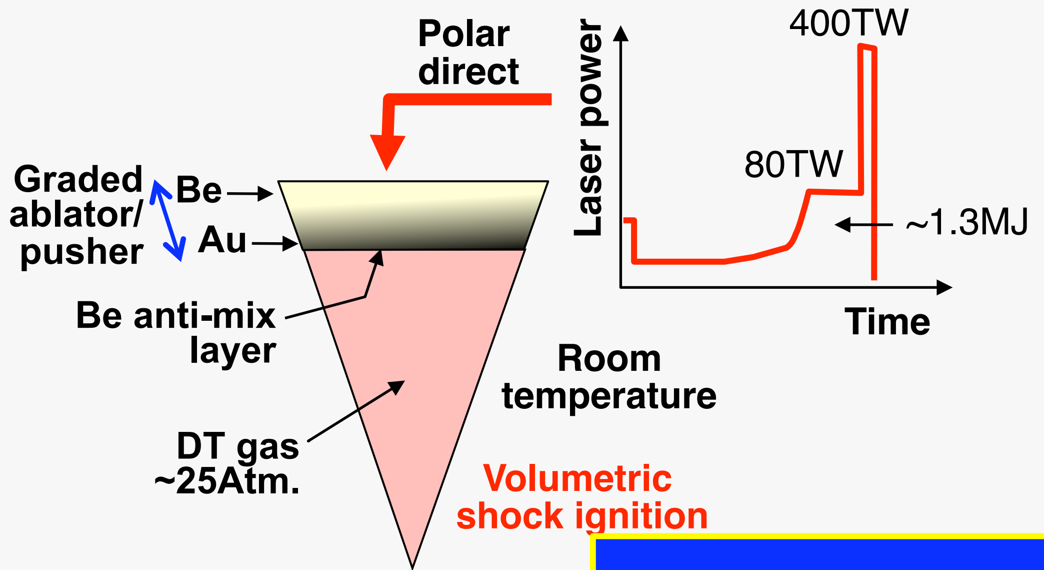
- **NIF+ARC can evaluate core heating of an ignition-scale fuel assembly, and thus determine the requirements for high gain fast ignition**

P.Patel LLNL

Gas Targets: Non-cryogenic, room-temperature single- and double-shell targets may offer an alternative route to ICF ignition (but at low gain)

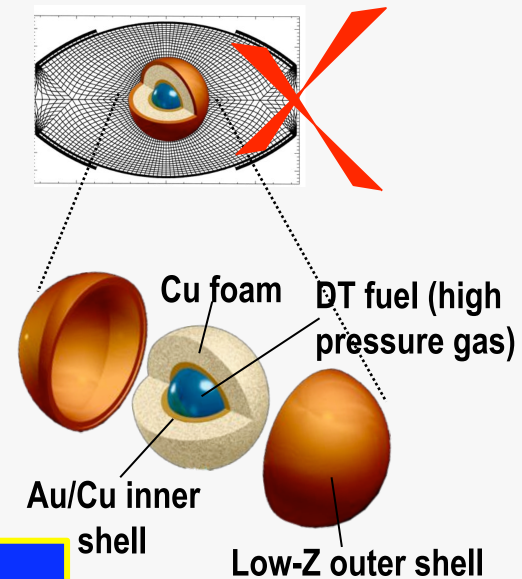
Single Shell – (Volume) shock Ignition

- polar direct drive -



Double Shell

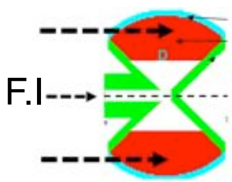
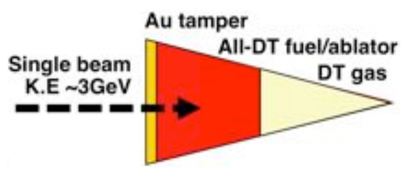
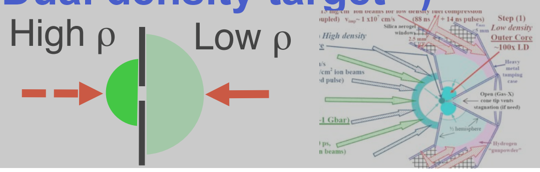
- indirect drive -



NIF 1D yields >1MJ, but....

- High fuel burn fractions (~50%)
- Simple to field (room-temperature, no cryo…)
- Pusher shells are graded low Z to high Z
- Volumetric burn, ~4keV ignition temperatures
- Recognized challenge is controlling fuel/pusher mix
- But……inherently low gain (~1-10) – no propagating burn into cold fuel

Heavy Ion Targets: There are several target classes under study....

	Features	Issues
Indirect drive 	• Integrated 2D designs exist • Ablation physics on NIF • Natural two-sided geometry	• Low drive efficiency • Lower gains, high driver energies
Direct drive X-target 	• Inherent one-sided drive, all-DT • High coupling efficiencies • Reduced stability issues • Potential for high yields (~GJ) and gains	• Higher ion kinetic energies • High gains require high densities under quasi-3D compression • Hollow beams desirable for fast ignition • Driver concepts immature
Direct drive - tamped, shock ign. 	• High coupling efficiencies (tamped ablation) • Simple targets • High gains consistent with single ion-kinetic-energies (~2-10GeV)	• Optimum ion species and energy • Stability to be confirmed • Two-sided (polar) geometry to be established*
(Dual density target)** 	• Highest potential gains • Potential one-sided drive • Application to advanced energy conversion	• Complex hydro design process to achieve two-sided assembly

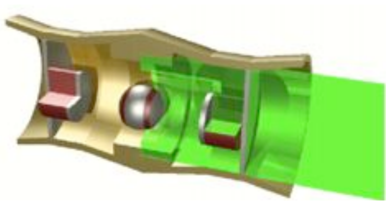
An integrated target-driver R&D program can be identified for each of these target design classes.

*Will leverage present NIF PDD studies ** J. Nuckolls IFSA San Francisco (2009)

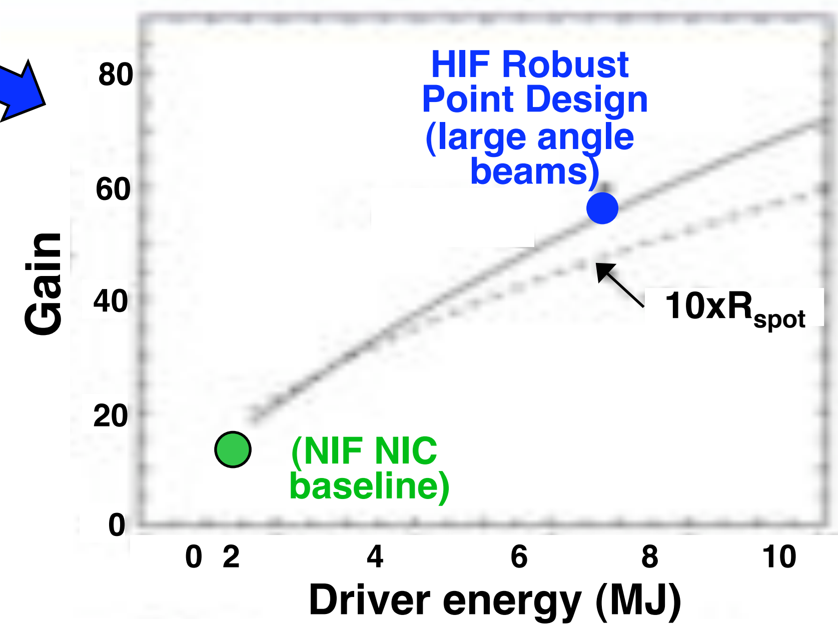
Heavy Ion Targets: Indirect drive hohlraums with ~NIF hot-spot-ign implosion physics are a well documented approach

Standard Hohlraum
Gain ~60 at 6MJ
(CCR=2.1 Beam spot ~2x4mm)

Close-Coupled
Gain ~130 at 3.3MJ
(CCR=1.6 Beam spot ~1.7mm)



Hybrid Target
Gain ~60 at 7MJ
(Beam spot ~4x5.5mm)

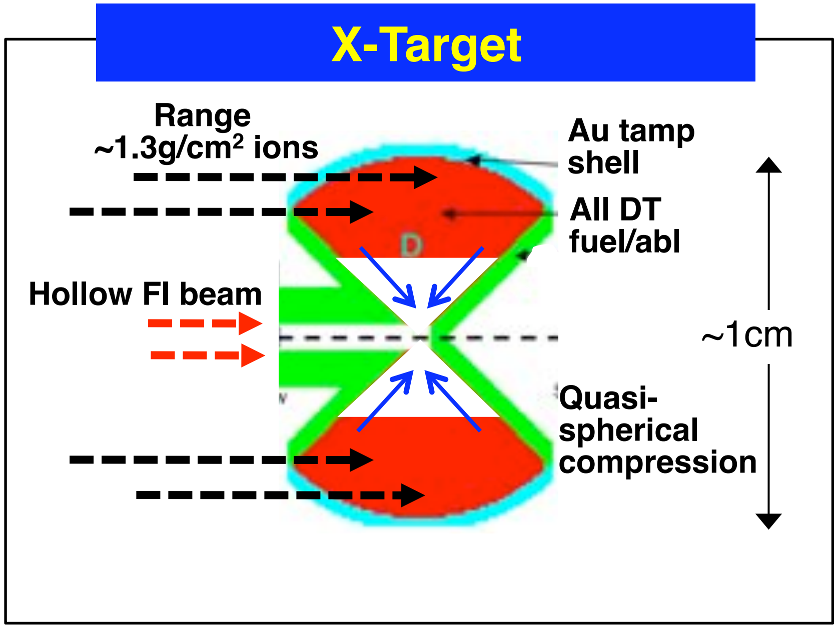


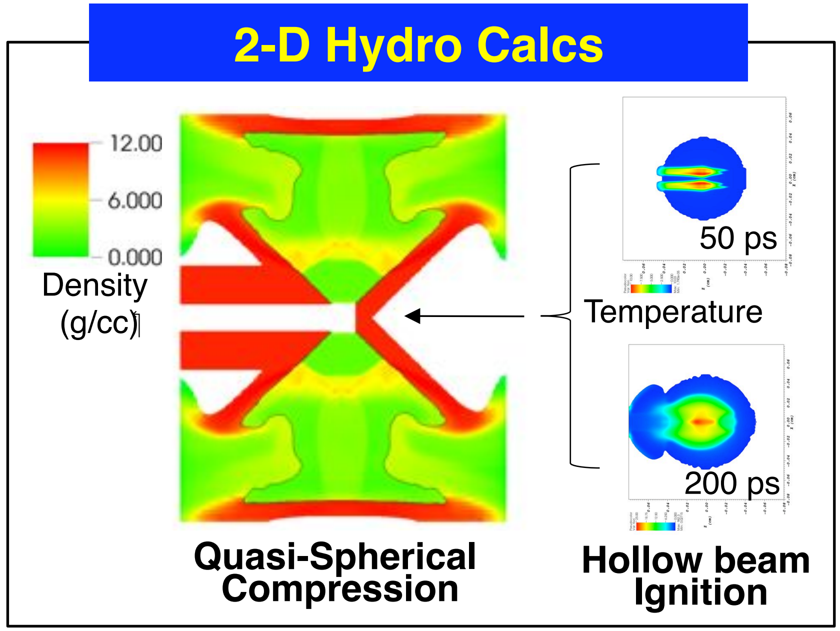
Heavy ion indirect drive will likely require larger driver energies

~3-4.5Gev Pb^{+}

Heavy Ion Targets: The X-target:
Potential for one-sided drive and high gain/yield

- **Potential one-sided drive (⇒thick liquid wall chambers)**
- **Large fuel masses, high gains/yields (>1GJ)**
- **Low-velocity low-aspect-ratio fuel assembly**
- **More robust to high mode stability (fast ignition)**



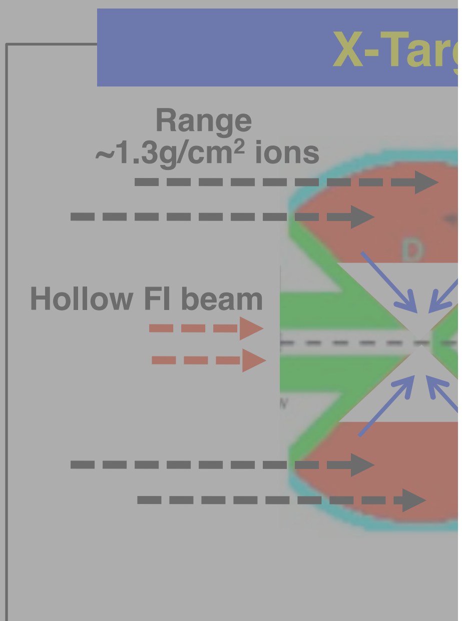


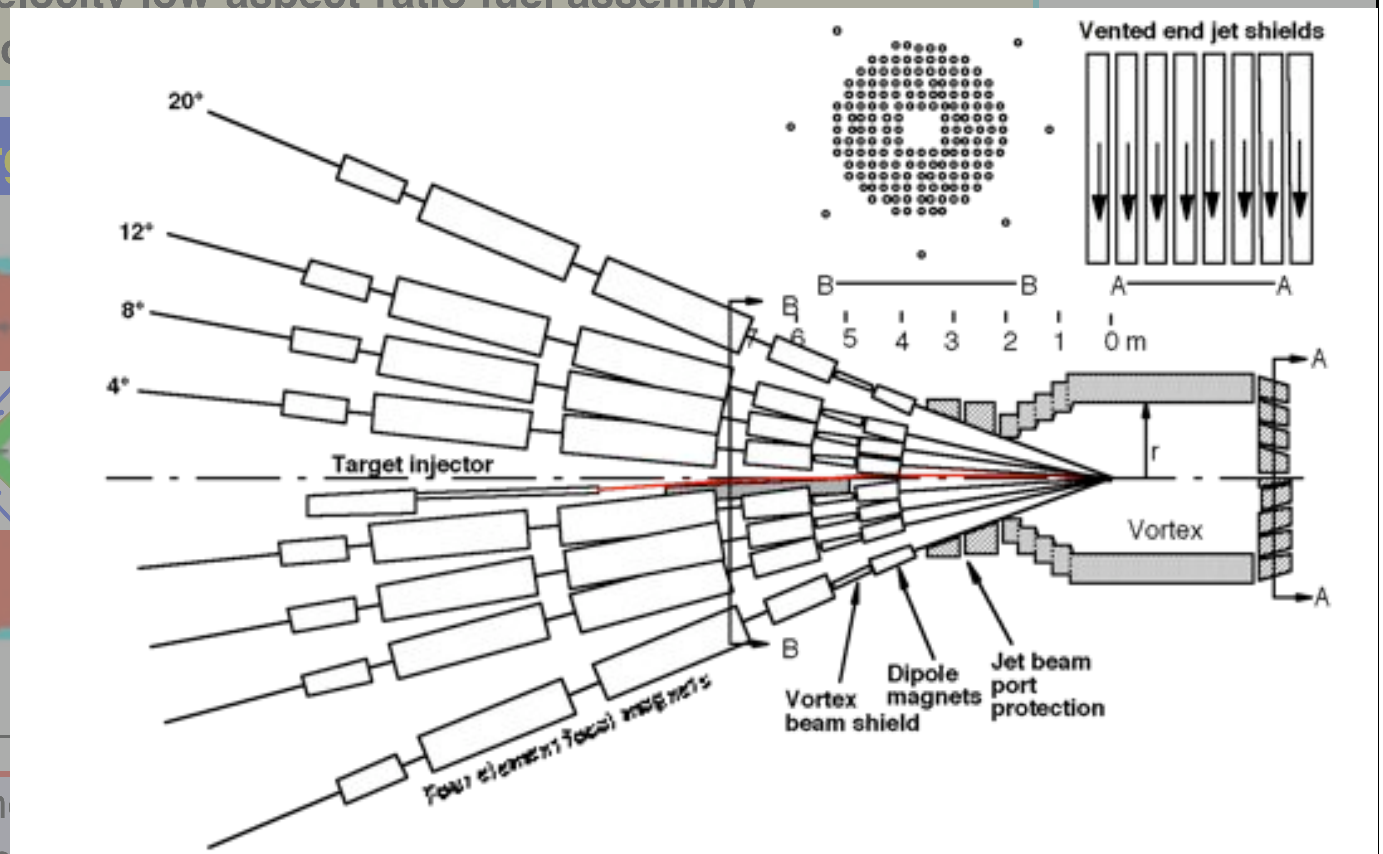
- High gain requires med-high density quasi-spherical assembly → 2D hydro optimization
- Requires efficient ignition source → Hollow-beam fast ignition
- Effect of high-Z scrape mix in ignition region? → High-mode mix studies
- Which range-1.3gcm²-ions? (e.g. 20GeV Cs...) → HI driver design confirmation

Heavy Ion Targets: The X-target:
Potential for one-sided drive and high gain/yield

- Potential one-sided drive (⇒thick liquid wall chambers)
- Large fuel masses, high gains/yields (>1GJ)
- Low-velocity low-aspect-ratio fuel assembly
- More r

X-Targ

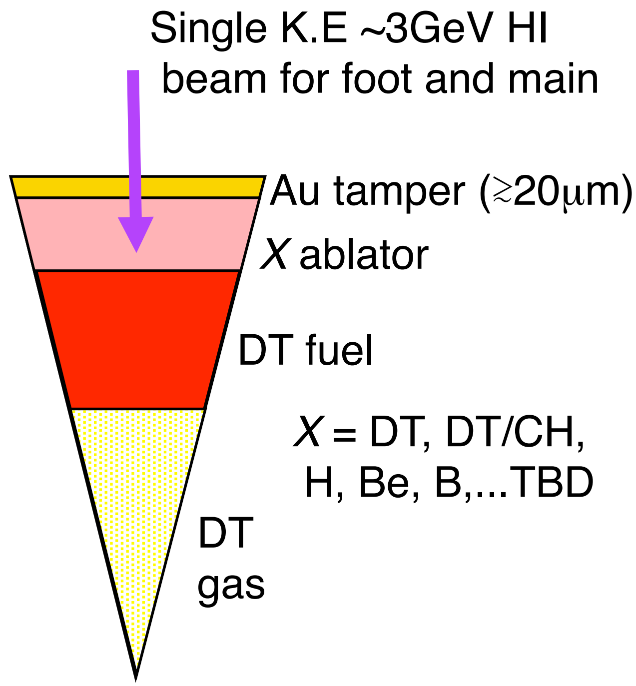




- High gain requires m
- Requires efficient ign
- Effect of high-Z scrape mix in ignition region? → High-mode mix studies
- Which range-1.3gcm²-ions? (e.g. 20GeV Cs...) → HI driver design confirmation

Heavy Ion Targets: A solution to the low ion kinetic energies req'd for HI direct-drive may be found in tamped "cannonballs"

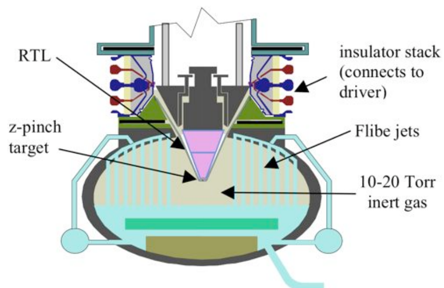
- **Tamped cannonballs (TCs) can be driven with a single high-energy (~2-10GeV) ion species**
- **TCs have high hydro efficiency ≤20% (combination of direct and radiation) that compensates for energy loss in tamp**
- **Addition of shock ignition may enable gains ~100 at ≥1MJ**
- **Further gain increases in gain are possible with zooming**



- Optimum ion species and kinetic energies TBD → Tradeoff between tamp thickness and drive efficiency
- Stability to be confirmed → Ion-driven instability (but low velocity, fat shells with high ablative ion-range/radiation smoothing)
- Two-sided polar drive geometry to be established → Will leverage NIF PPD optimization studies (but heavy-ions don't refract)

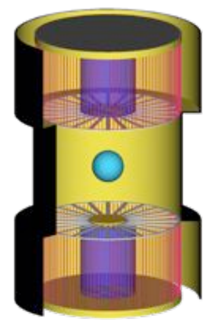
Pulsed Power: Efficient driver/target coupling (and low cost drivers)

Pulsed Power IFE favors large yields and low rep-rates



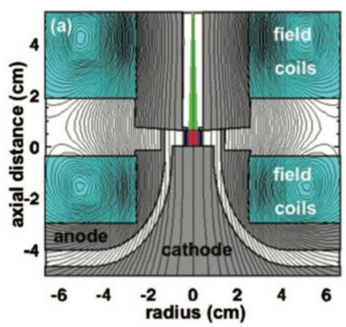
- Yield ~GJ's
- Rep-rates <1Hz
- Driver costs ~$'s/J
- Recyclable transmission lines
- Liquid walls

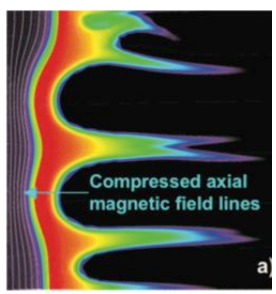
Point-of-departure target designs: Double ended hohlraums



- Indirect drive (NIF implosion physics)
- ~18MJ into x-rays
- ~1.2MJ absorbed (η_{abs}~7%)
- ~500MJ yields
- Gains ~10

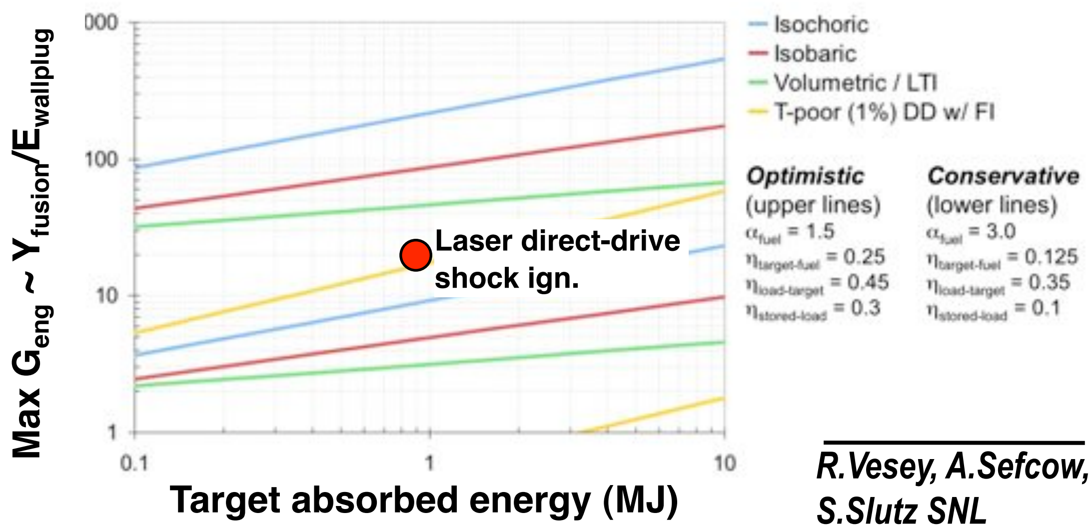
Promising current direction: Direct-magnetic drive





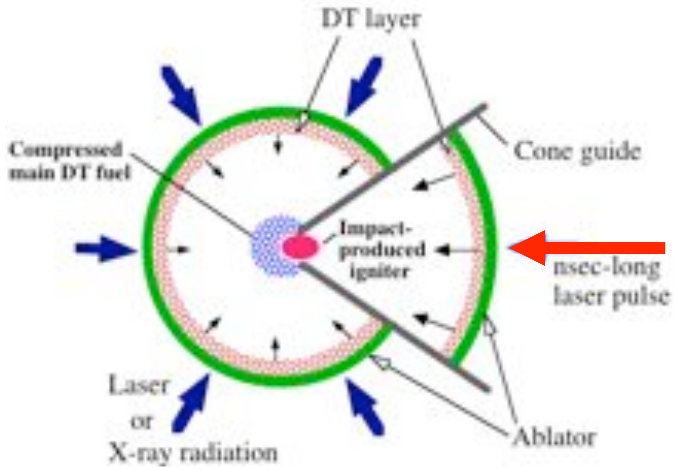
- ~20-30% of the driver energy can end up in the target/fuel at stagnation
- ≥20-X more efficient than indirect drive
- Major issue: mageto-Rayleigh-Taylor

(S.Slutz et al, Phys Plasmas 2010)



R.Vesey, A.Sefcow, S.Slutz SNL

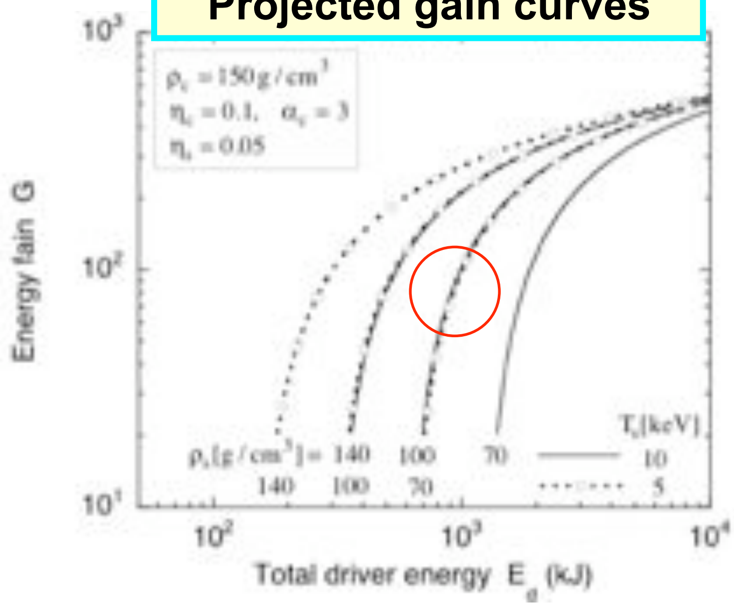
Impact (fast) ignition: predicts gains >100 at 1MJ (and like regular fast ignition may alleviate symmetry/stability constraints)



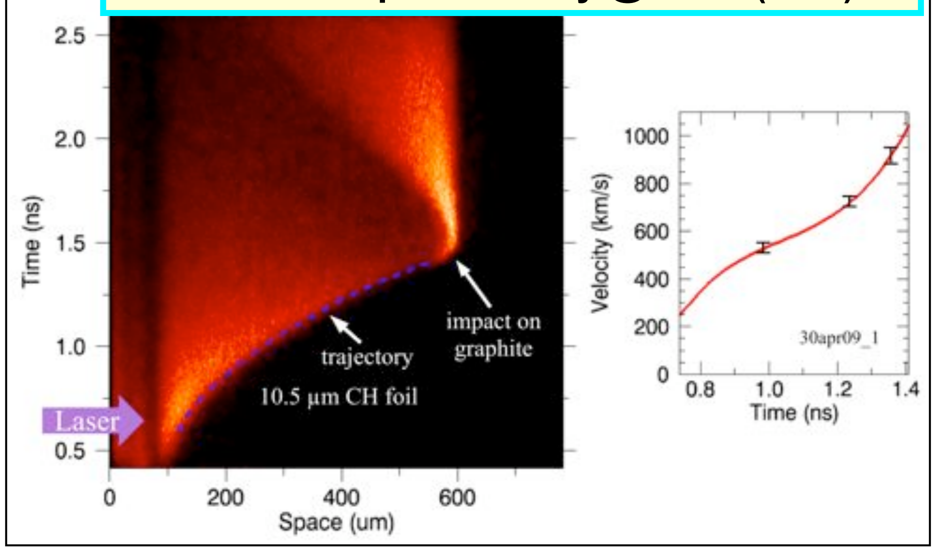
Impactor - Requirement for Ignition

- Kinetic energy → Thermal energy
  1/2 m.v² → 2nkT (T~10keV)
  ⇒v = ~10^8cm/s
- Momentum→ stagnation pressure
  $\rho . v^2 \rightarrow P_{core}$
  ($P_{core} = 2.2\alpha\rho_{core}^{5/3}$, $\alpha = 3$, $\rho_{core} = 200$ g/cc)
  ⇒ρ = 5 g/cc

Projected gain curves

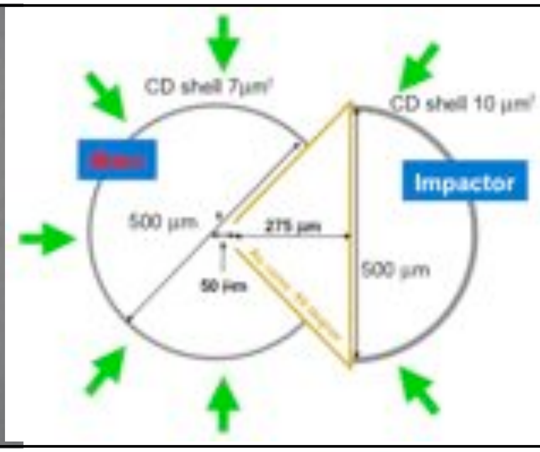


~10^8cm/s flyer plate velocities have been obtained experimentally @ NIKE (NRL)



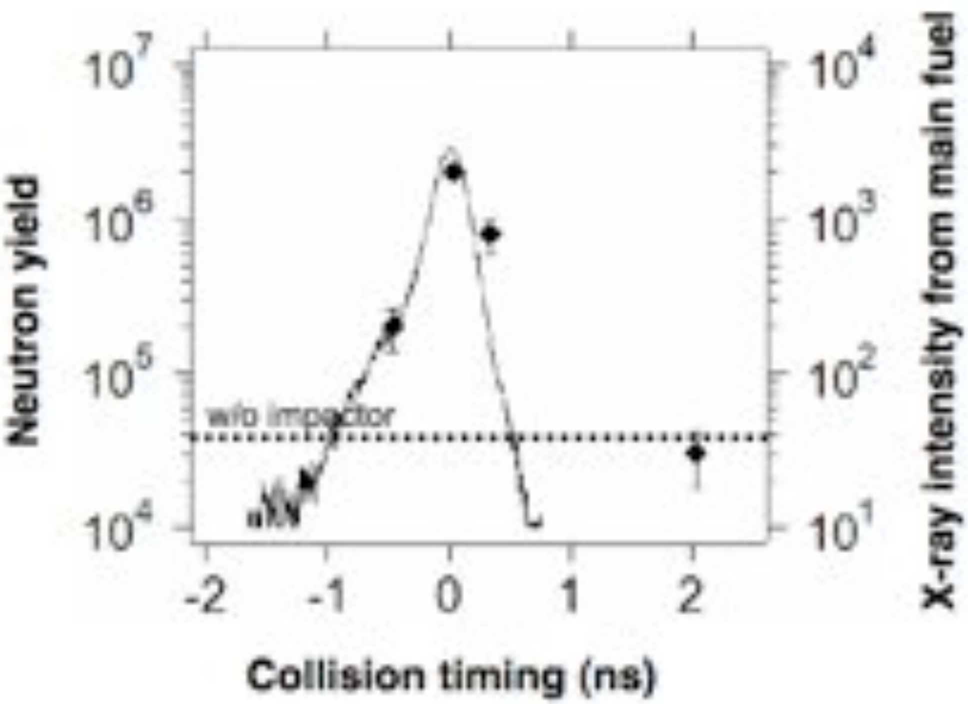
M.Murakami ILE/Osaka, M.Karasik NRL

Impact (fast) ignition: With the impact effect, neutron yield has been enhanced by a factor of about 100

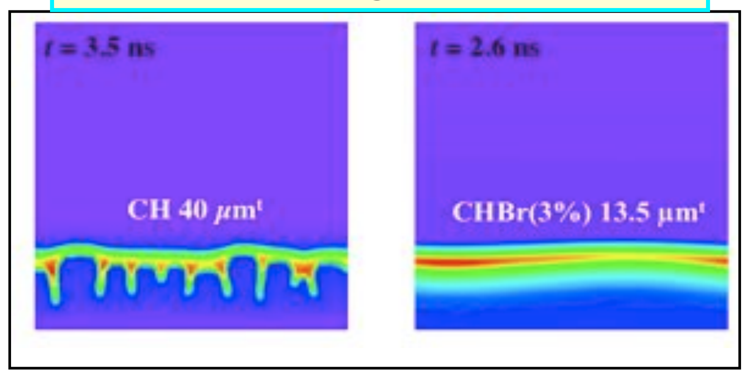


Main fuel:
Laser: 2ω, E = 3 kJ, 1.3 ns
Target: CD shell 7 μm^t, 500 μm$^\phi$

Impactor:
Laser: 2ω, I ~ 200 TW/cm^2 , 1.3 ns
Target: hemispherical CD 10 μm^t, 500 μm$^\phi$



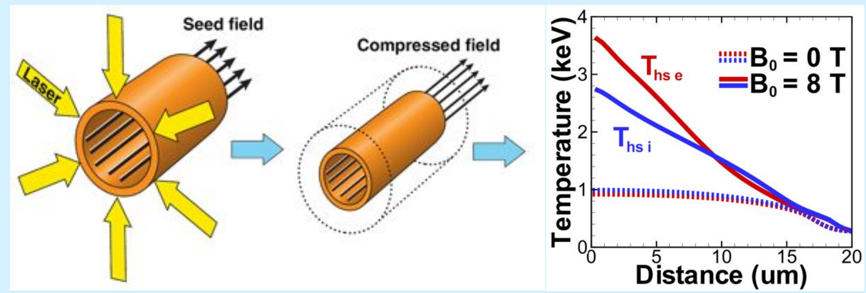
RT growth can be suppressed by radiation from high-z dopant



M.Murakami ILE/Osaka

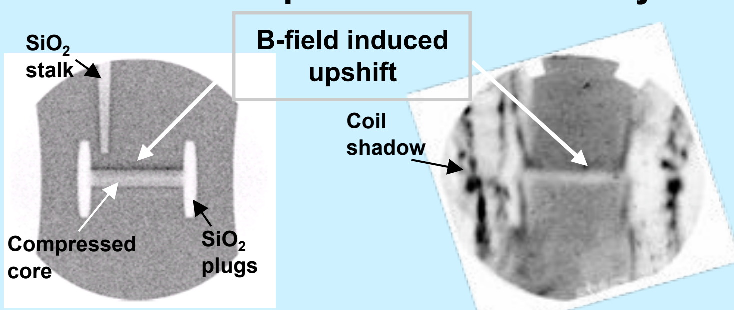
Magnetically-insulated ICF: Laser-compressed magnetic fields could thermally insulate the hot spot of an ICF target

- Electron heat conduction $\kappa \sim T_e^{5/2} \sim \frac{1}{B^2 T_e^{1/2}}$
- α-particle range ~ 1/B
- Thus ignition conditions on ρR_{HS} and T_{HS} could be relaxed ($\Rightarrow$ higher gains)



Imploding a magnetized ICF target results in higher hot-spot temperatures

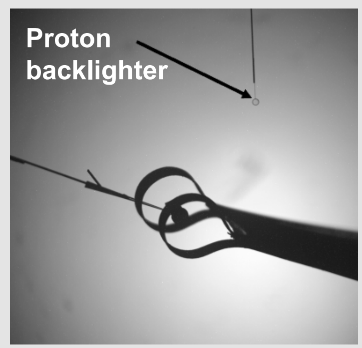
The compressed fields within the dense core were measured via proton deflectometry

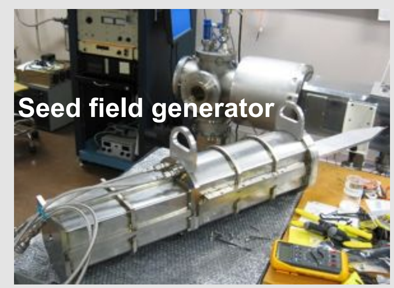


Simulated proton density map at the detector surface

Proton density map at the detector surface

(Orlin, Knauer LLE/U,Rochester)

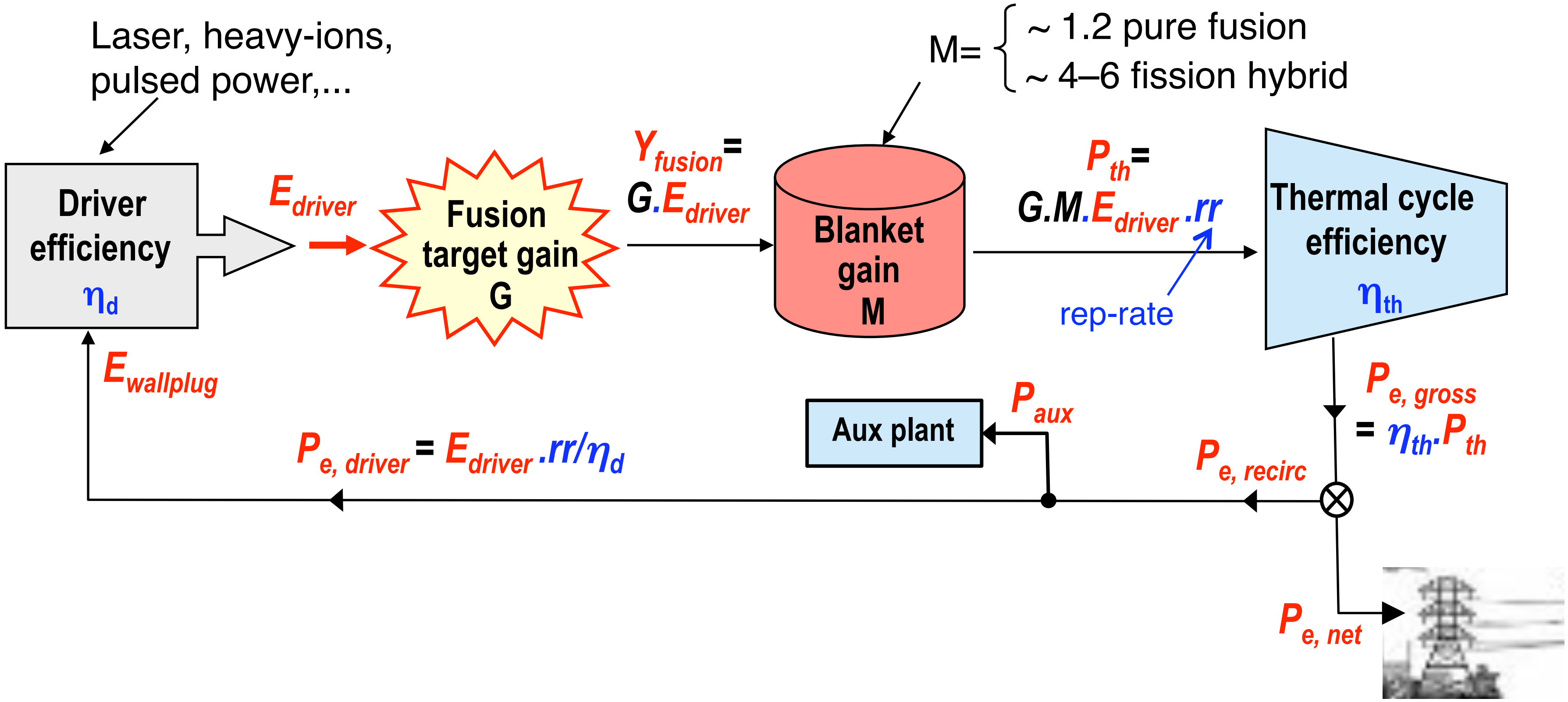




Initial OMEGA experiments on compression of 0.05 MG field, seeded in cylindrical targets by a coil, show fields compressed to > 10 MG.

Verification of yield enhancement will be the first stage of an experimental campaign to measure thermal insulation of ignition-scalable hot spots.

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



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