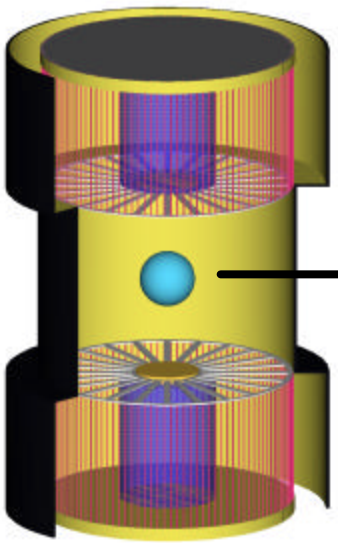
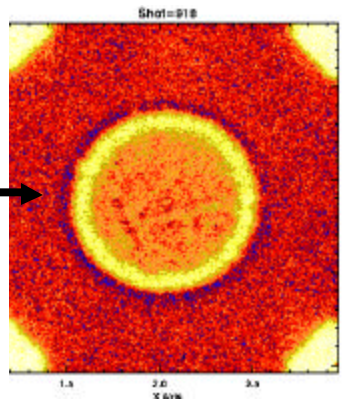
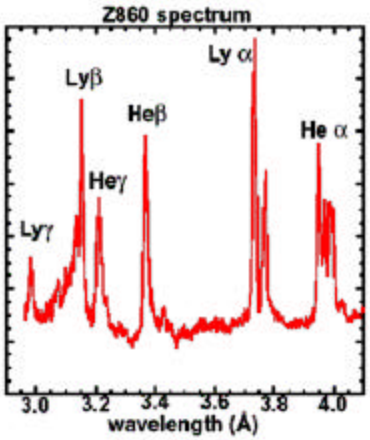
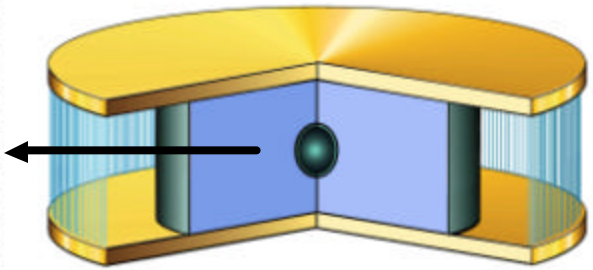
Target Physics Issues for Z-Pinch-Driven Inertial Fusion Energy







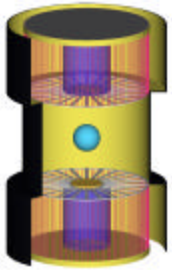


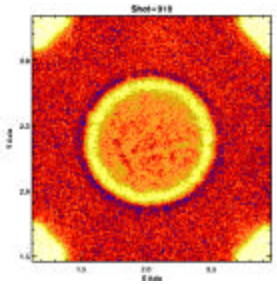
Tom Mehlhorn, Manager
Target & Z-pinch Theory Dept
Sandia National Laboratories

Snowmass Fusion Workshop
Snowmass, CO
July 2002

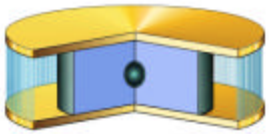
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL84000.

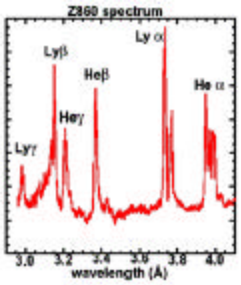
Sandia ICF capsule experiments are laying the target physics foundation for Z-pinch-driven IFE concepts



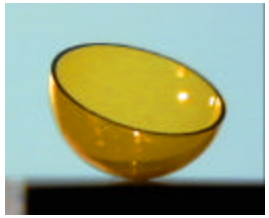


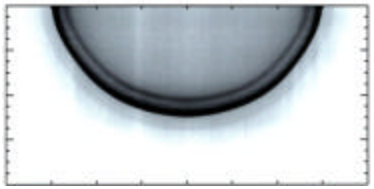
- Successful backlit ICF capsule implosions in double-ended z-pinch hohlraum





- Argon K-shell spectra and core images obtained from ICF capsule implosions in dynamic hohlraum

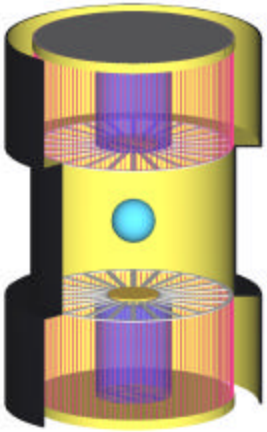
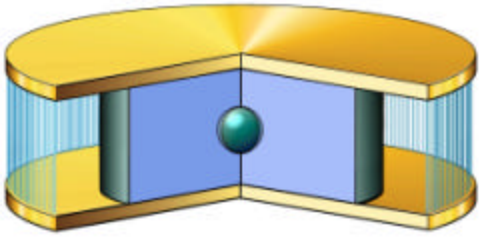




- Exploring possibilities for studying fast ignition physics using ZR + ZBL-PW

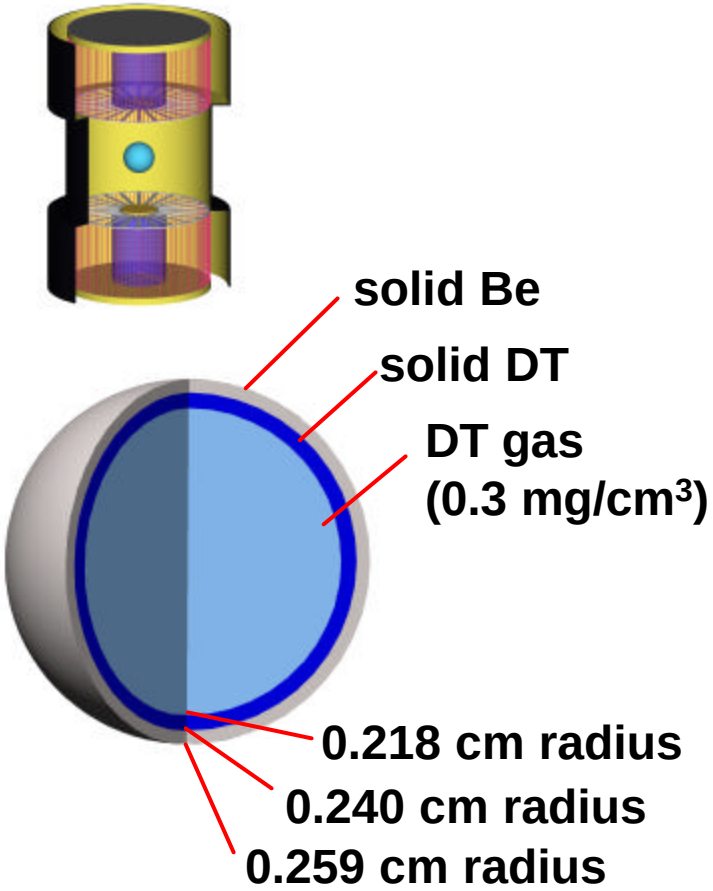
- Studying capsule designs for RTL concept that scale to GJ IFE yields

Two complementary Z-pinch indirect drive concepts for high-yield ICF and IFE are being explored

	ICF – IFE Current / Driver / E_{abs} / Yield	Features
Double-Pinch Hohlraum 	2 x 62 MA 16 MJ 1.3 – 2.6 MJ 400 – 1300 MJ	Dual power feed, double-pinch Capsule isolated from z-pinches Symmetry via hohlraum design demonstrated on Z (2x16 MA) h_{hohl} ~ 8-16 %
Dynamic Hohlraum 	54 – 95 MA 12 – 37 MJ 2.4 – 7.2 MJ 530 – 4400 MJ	Capsule inside single pinch and converter Core T_e > 1 keV, dopant x-ray spectra measured on Z (20 MA) h_{hohl} ~ 20 %

J. Hammer, M. Tabak, R. Vesey, J. Lash, S. Slutz

The baseline ZPDH capsule yields 380 MJ with an ignition margin similar to a NIF capsule



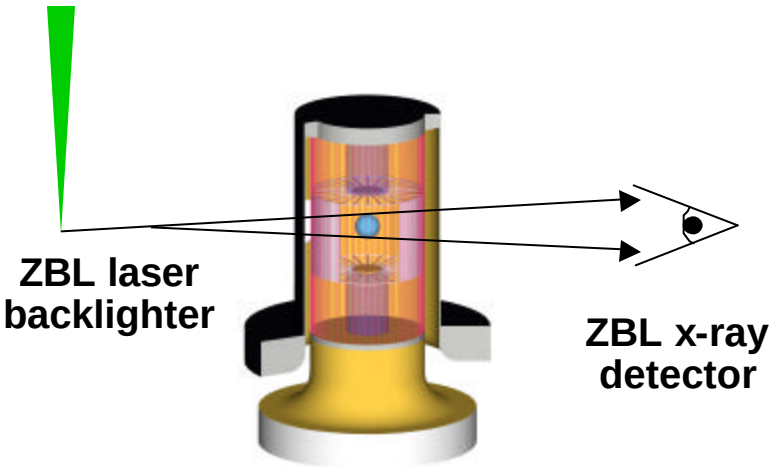
Capsule Performance Parameters

Peak drive temperature	223 eV
In-flight aspect ratio	37
Implosion velocity	2.9×10^7 cm/s
Convergence ratio	36
Total RT growth factor	420
Peak density	750 g/cm^3
Total ρr	3.15 g/cm^2
Driver energy	16 MJ
Absorbed energy	1.12 MJ
Yield	380 MJ
Burnup fraction	31%

J.H. Hammer, et al., Phys Plasmas 6, 2129

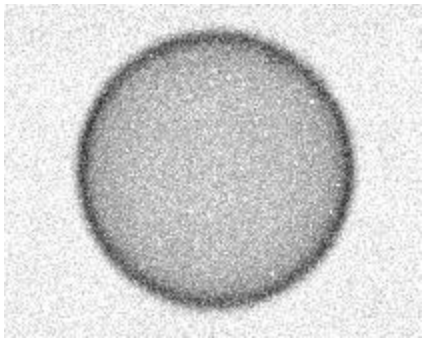
The 2 TW Z-Beamlet laser has enabled the first measurement of polar radiation symmetry on Z

G. R. Bennett et al., submitted to Phys. Rev. Lett. (2002)

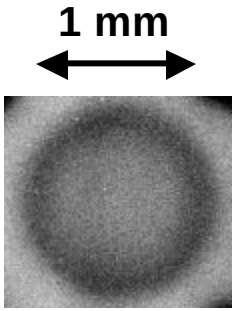


Schematic layout of a Z experiment

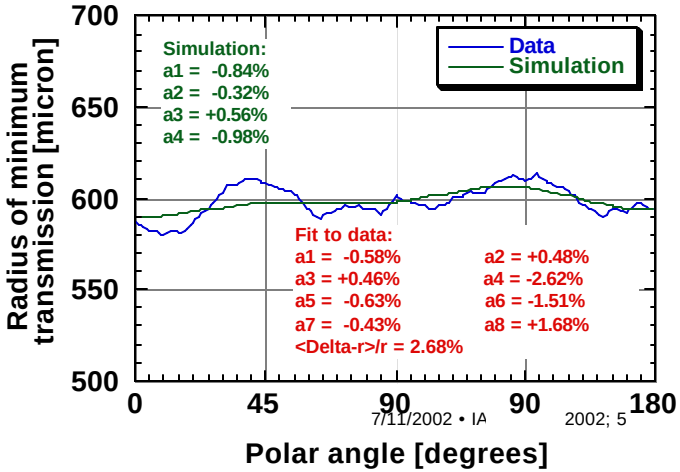
X-ray radiography of double-pinch-driven capsule implosion experiments



Pre-shot



Z830



$DI/I_{total} = 3.8\%$

$DI/I_{even} = 2.8\%$

$DI/I_{HYscale\_total} = 1.8\%$ (3x requirement)

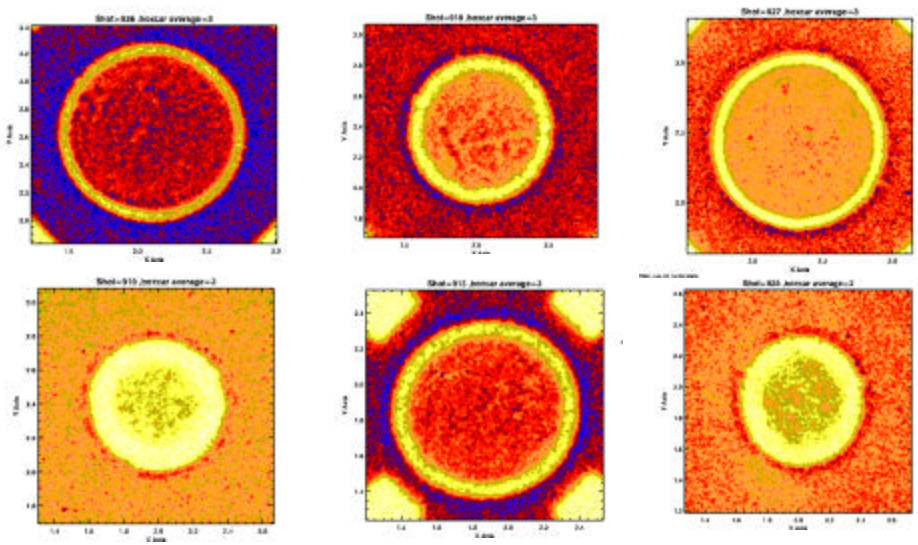
$DI/I_{HYscale\_even} = 1.0\%$ (1.7x requirement)

Preliminary analysis of recent capsule backlighter experiments confirm control of P2 by secondary length

Ls = 17.0
h/v = 1.0638

Ls = 16.25
h/v = 1.0176

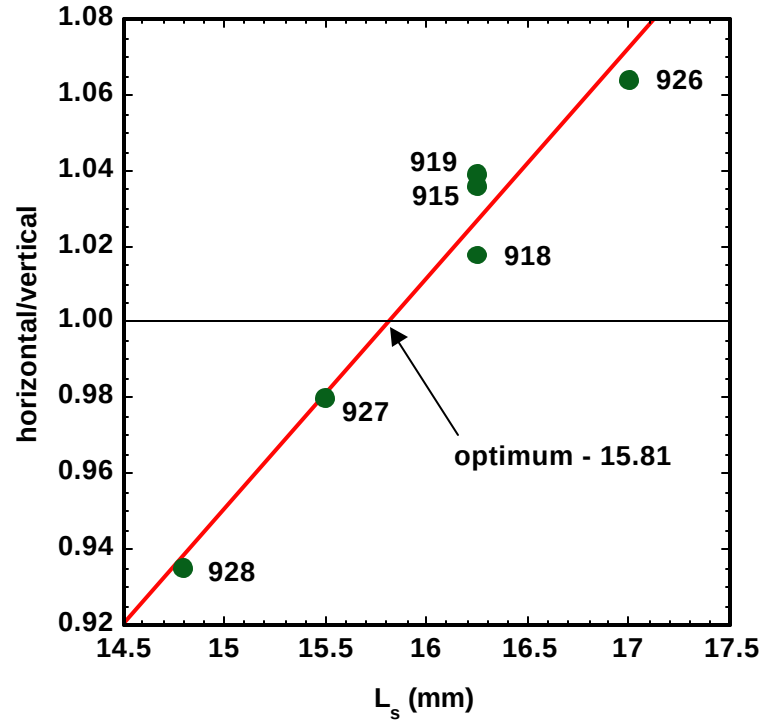
Ls = 15.5
h/v = 0.98



Ls = 16.25
h/v = 1.039

Ls = 16.25
h/v = 1.036

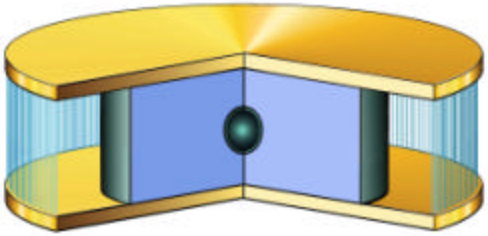
Ls = 14.8
h/v = 0.935

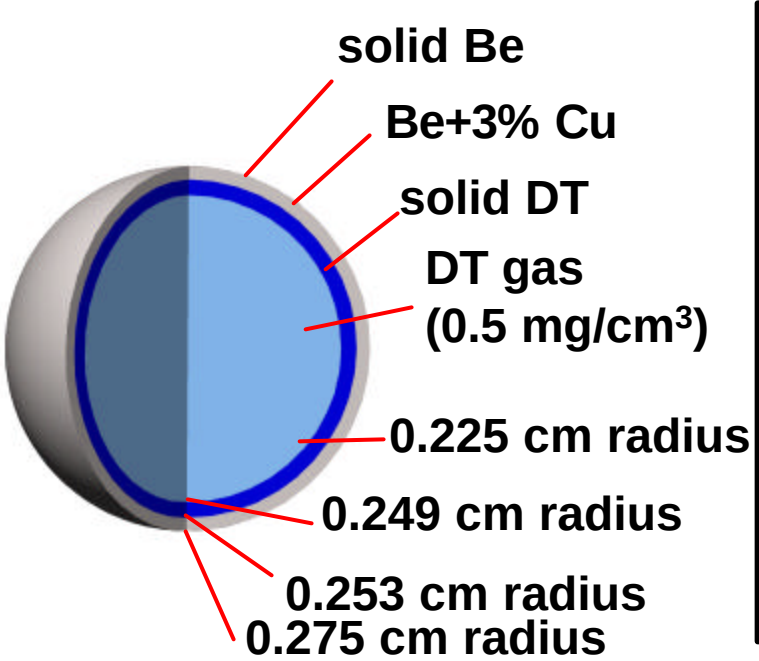


We expect to tune out P2 by choosing a secondary length of ~ 15.8 mm
Experiments in January/Feb will test minimization of residual P2 and P4

M. E. Cuneo, G. R. Bennett, R. A. Vesey, J. L. Porter

The initial dynamic hohlraum high yield integrated target design produces a 527 MJ yield at 54 MA



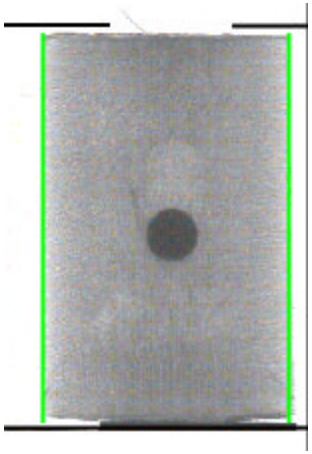


Capsule Performance Parameters

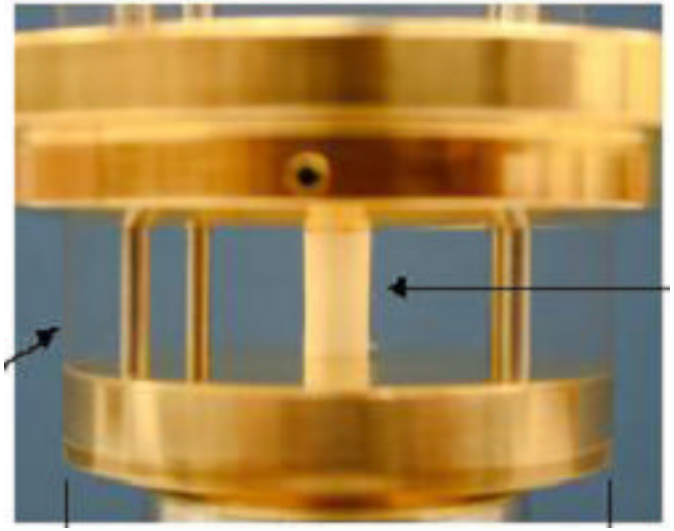
Peak drive temperature	350 eV
In-flight aspect ratio	48
Implosion velocity	3.3×10^7 cm/s
Convergence ratio	27
DT KE @ ignition	50%
Peak density	444 g/cm^3
Total ρr	2.14 g/cm^2
Driver energy	12 MJ
Absorbed energy	2.3 MJ
Yield	527 MJ
Burnup fraction	34%

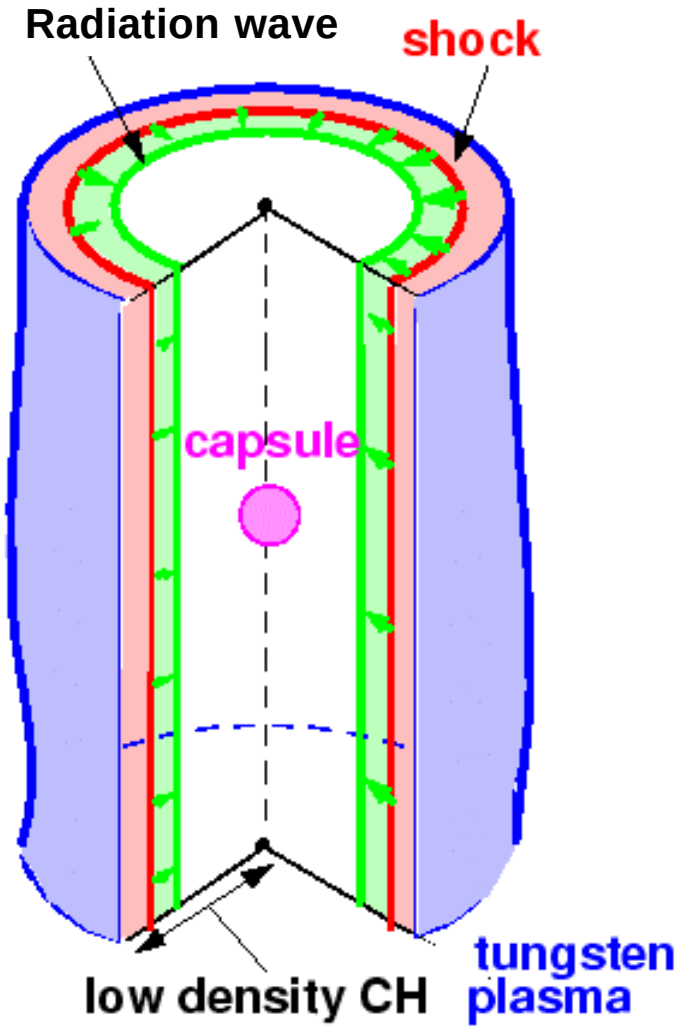
J.S. Lash et al., *Inertial Fusion Sciences & Apps 99*, p583

A dynamic hohlraum is created by impacting a tungsten liner on a low density CH converter

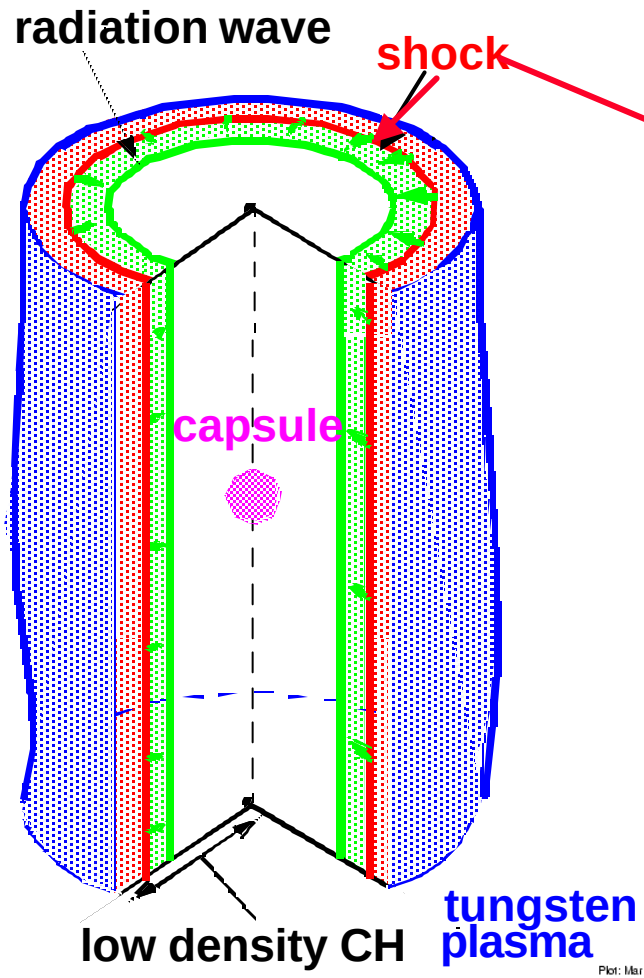


Radiograph:
Capsule in foam

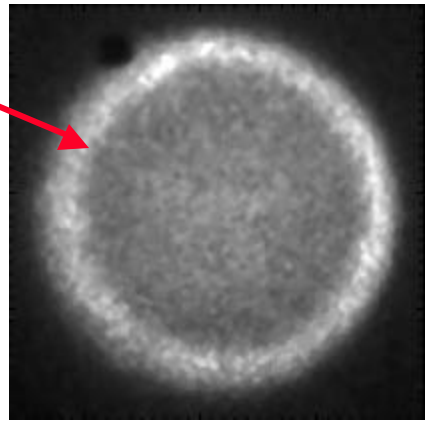




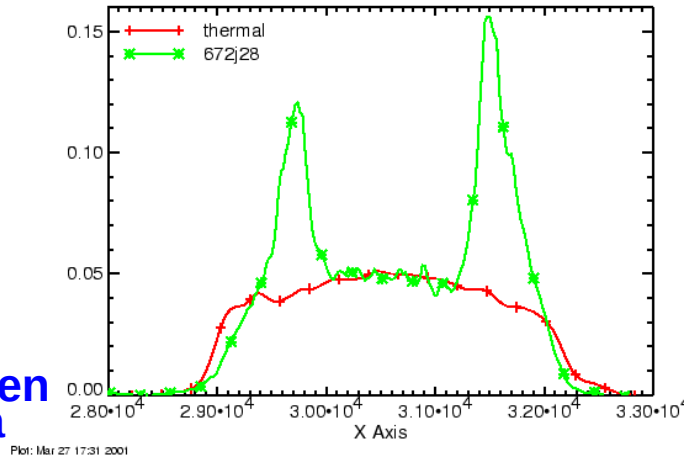
The primary radiation source is a thin radiating shock in the foam converter



Z670

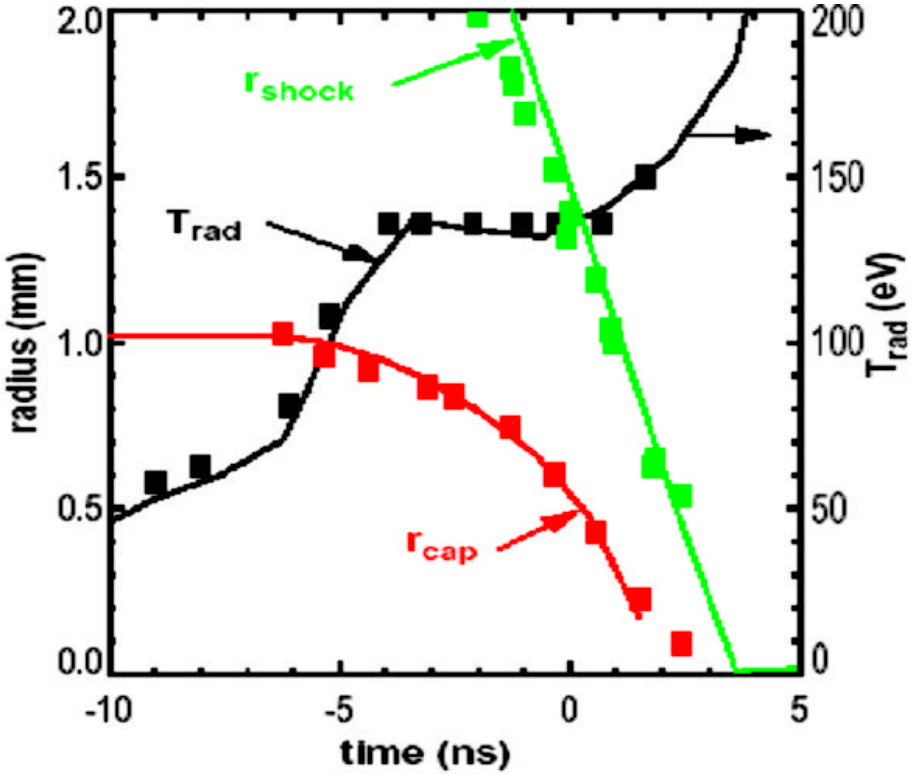


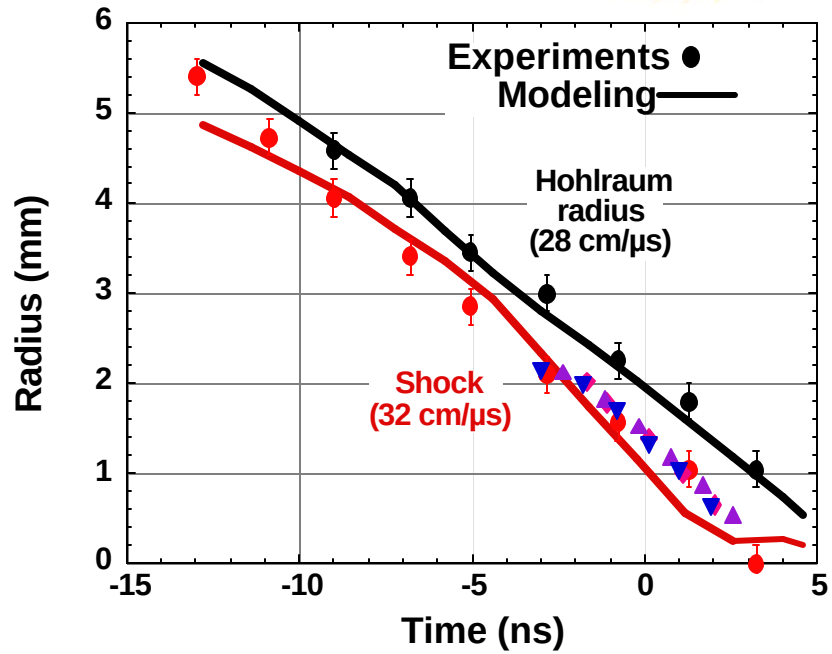
Simulated image



- **Measured shock width shock ~ 400 mm**
- **Deconvolved shock width ~ 250 mm**
- **No evidence of MRT instability imprint on shock**

DH drive temperature, shock position, capsule trajectory, and tungsten trajectory have been successfully modeled



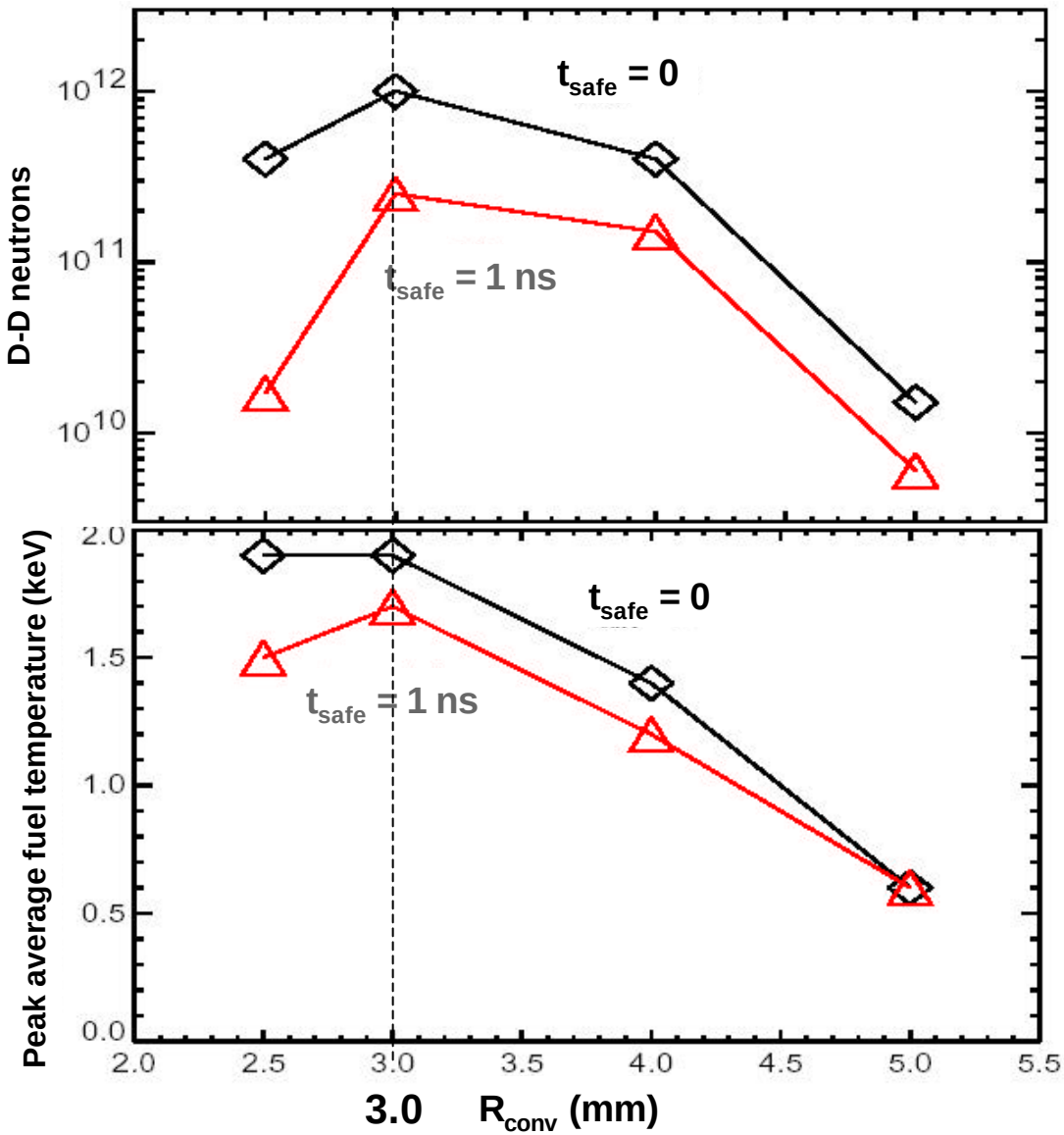


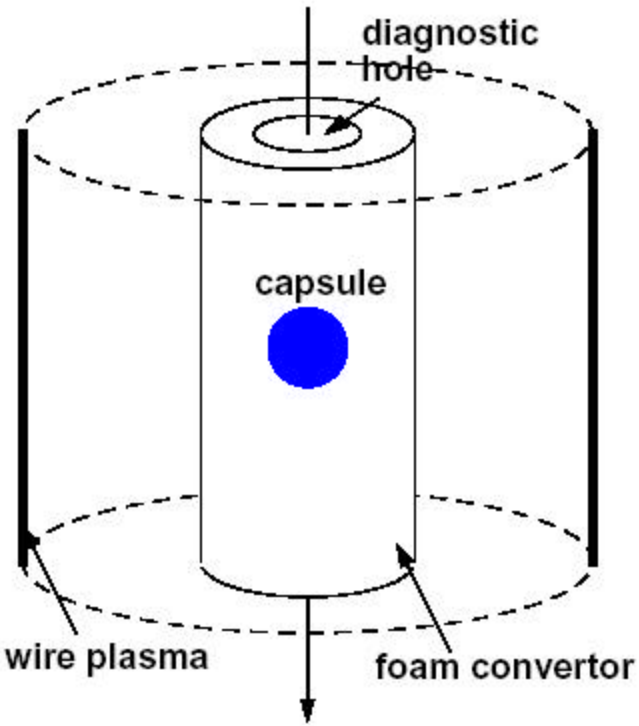
Above pulse shape was sub-optimal for capsule implosions; redesigned convertor & capsule yielded argon spectra

Builds confidence that useful drive pulse shapes for DH (and DPH) capsules can be designed and reproduced in experiment

S. Slutz, J. Bailey

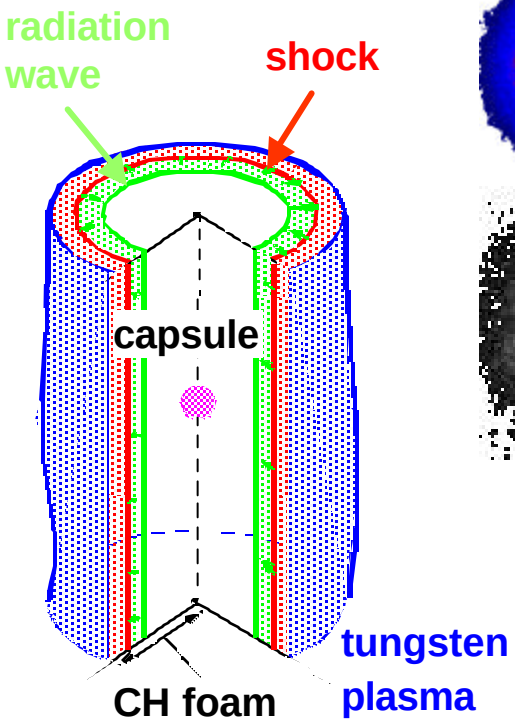
Simulations show largest neutron yield and highest fuel temperature for a 3 mm convertor

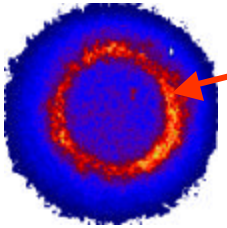




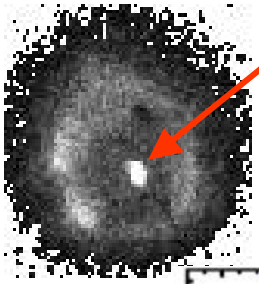
1.6 mm diam capsule
40 or 50 m wall
14 mg/cc CH_2 foam – 3 mm
240/120 wires – 10 mm tall

Dynamic hohlraum experiments obtain core images and argon spectra from capsule absorbing 20 kJ of x-rays



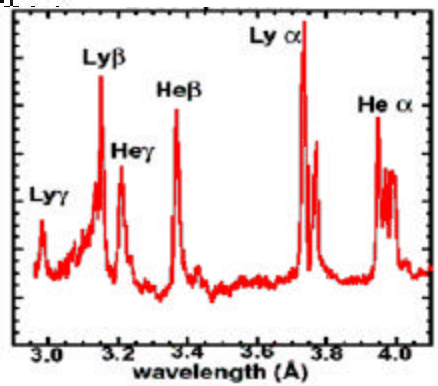


Shock emission width (~250 mm) is consistent with low levels of pinch RT



End-on core x-ray images imply a capsule convergence ratio of ~10

Side-on imaging planned to assess symmetry



Capsule spectra imply core

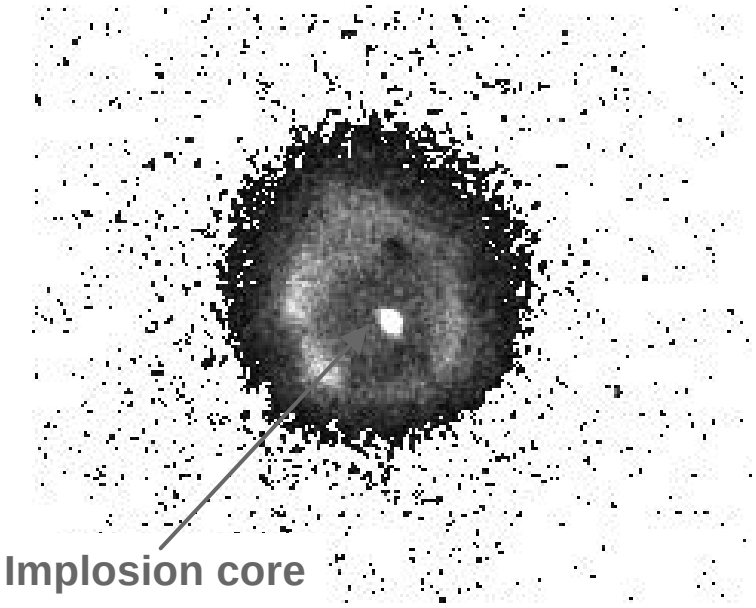
T_e > 1 keV, n_e ~ 2x10^{23} cm^{-3}

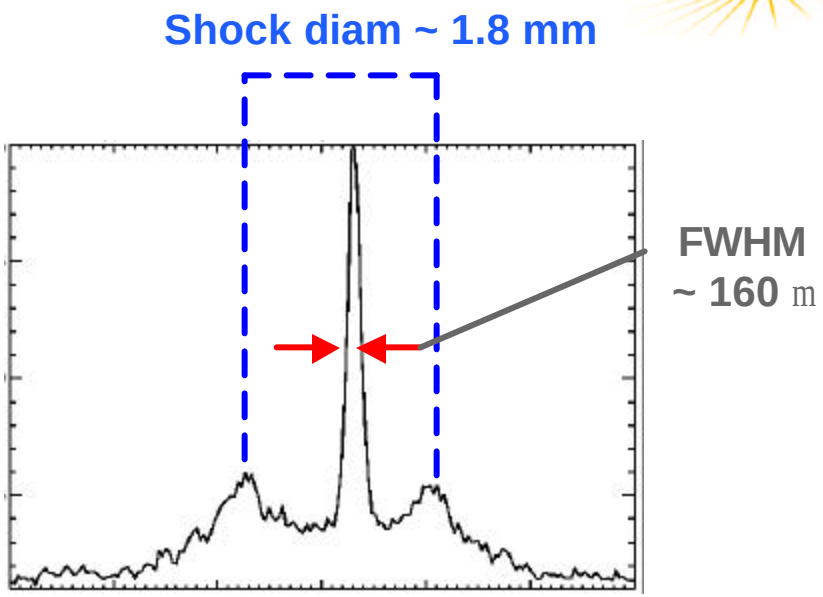
Foam dopants, radiation burnthrough shielding, and converter shaping will be implemented to control pole-equator asymmetry

J. Bailey, G. Chandler, S. Slutz

An image of the x-ray emission from the implosion core implies a convergence ~10

Framing camera – hard channel





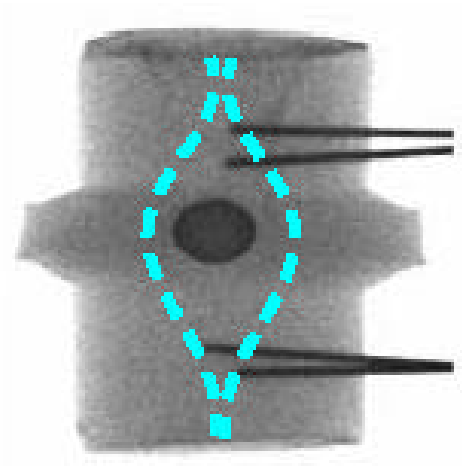
Lineout

The separation between shock and implosion implies that we can drive capsule longer (2-3 nsec), increasing absorbed energy and neutron yield

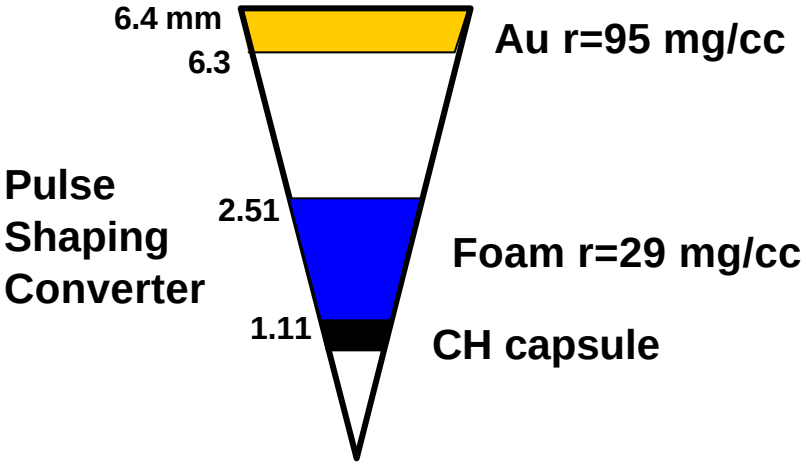
August 2002 implosion series will have neutron yield as a goal:

- **Optimized capsule design**
- **Improved capsule fabrication**
- **Improved neutron diagnostics**

More complex converters can be used to increase standoff and for pulse shaping



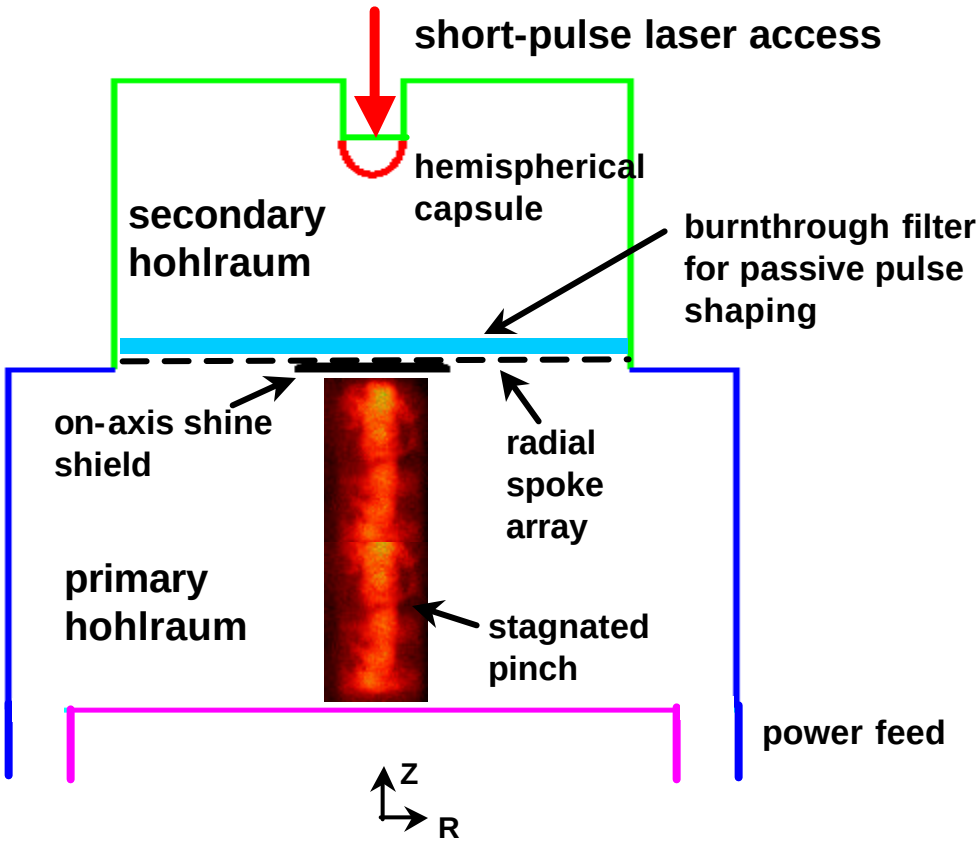
- Shaped converter foams can increase shock standoff time
  - Safety margin increased by 4 ns in this configuration
  - Absorbed capsule energy can increase to >40 kJ
  - Preliminary experiments show expected behavior



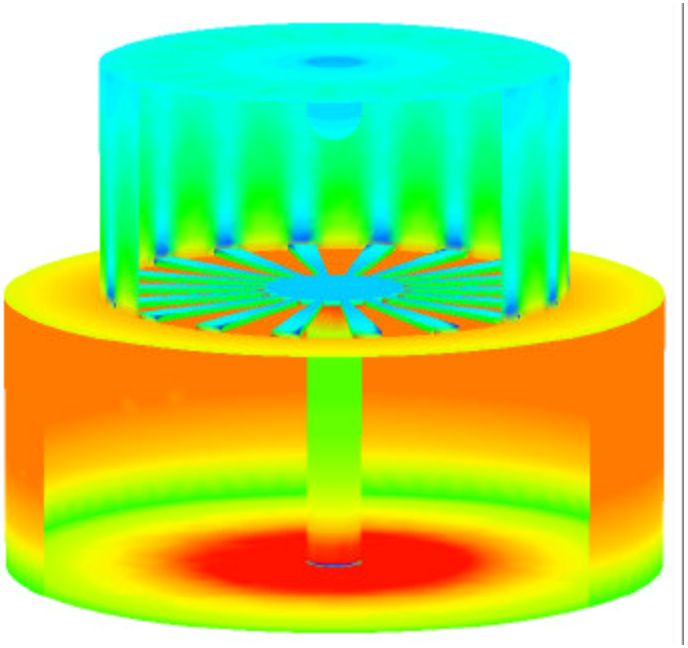
- A NIF-like pulse shape has been calculated using a two-component converter

Initial Fast Ignitor fuel assembly experiments are beginning on Z

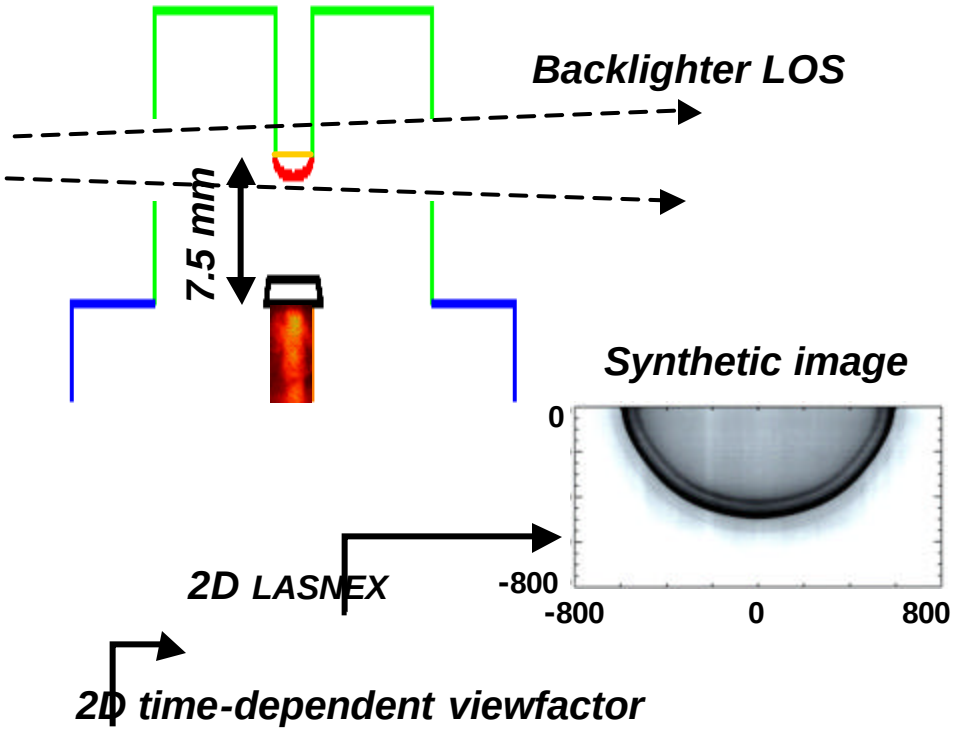
Initial geometry for FI target assembly on Z

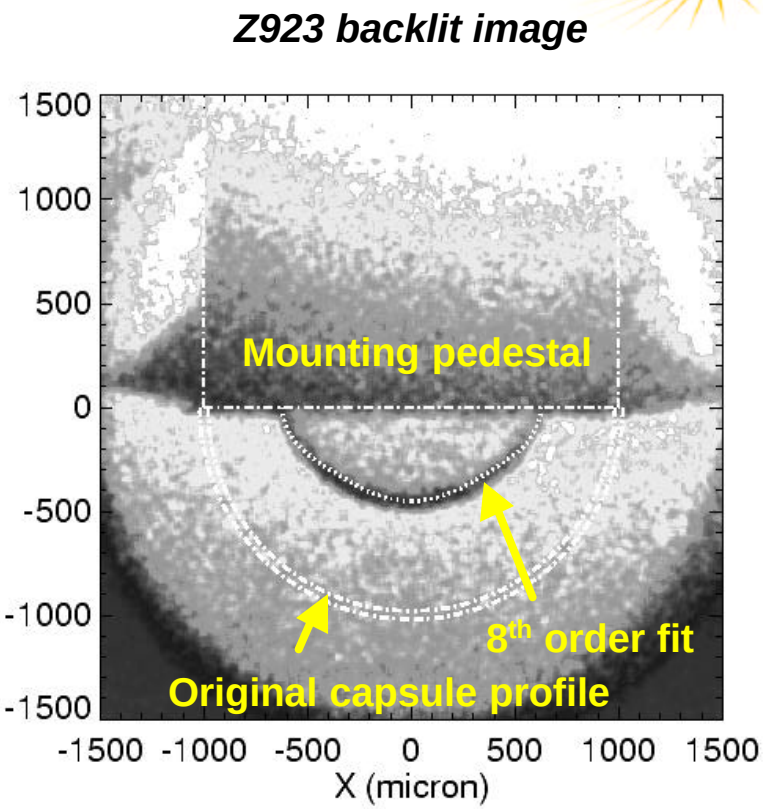


Initial 2D viewfactor and rad-hydro simulations have been performed for these targets



Conservative hohlraum design yielded useful images of imploding hemi shell on Z for model validation





Preliminary image analysis agrees qualitatively with piecewise simulations

2D simulations give polar-averaged peak ρ = 60 g/cc, ρr = 0.3 g/cm² for this case

More optimized Z hohlraum designs should allow ρ = 90-100 g/cc, ρr = 0.4 g/cm²

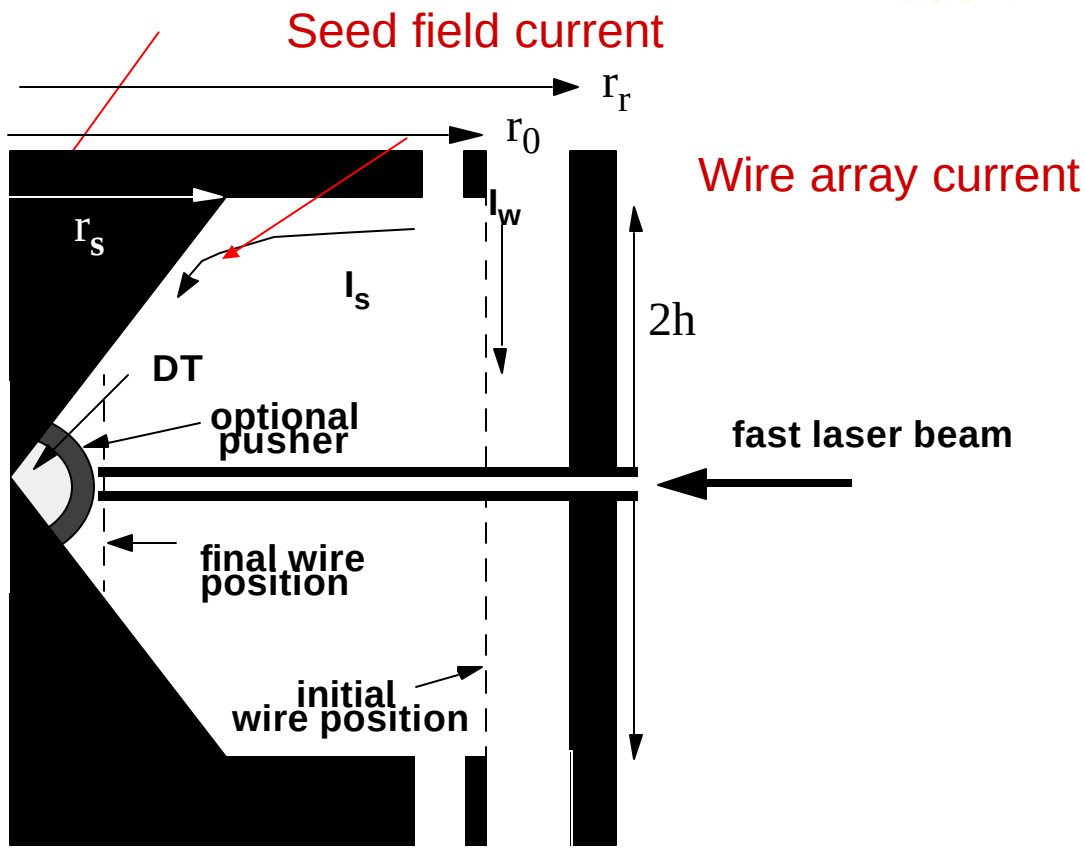
Simulations for ZR with cryo DT capsule give ρ = 160 g/cc, ρr = 0.65 g/cm²

Fast ignition of a quasi-spherical isentropic z-pinch implosion via magnetic flux compression

Peak density ~1500 x solid
E_{las} ~10 KJ
I_w ~ 20 MA
I_{cap} ~ 30 MA

Utilizes flux compression (French/US collaboration)

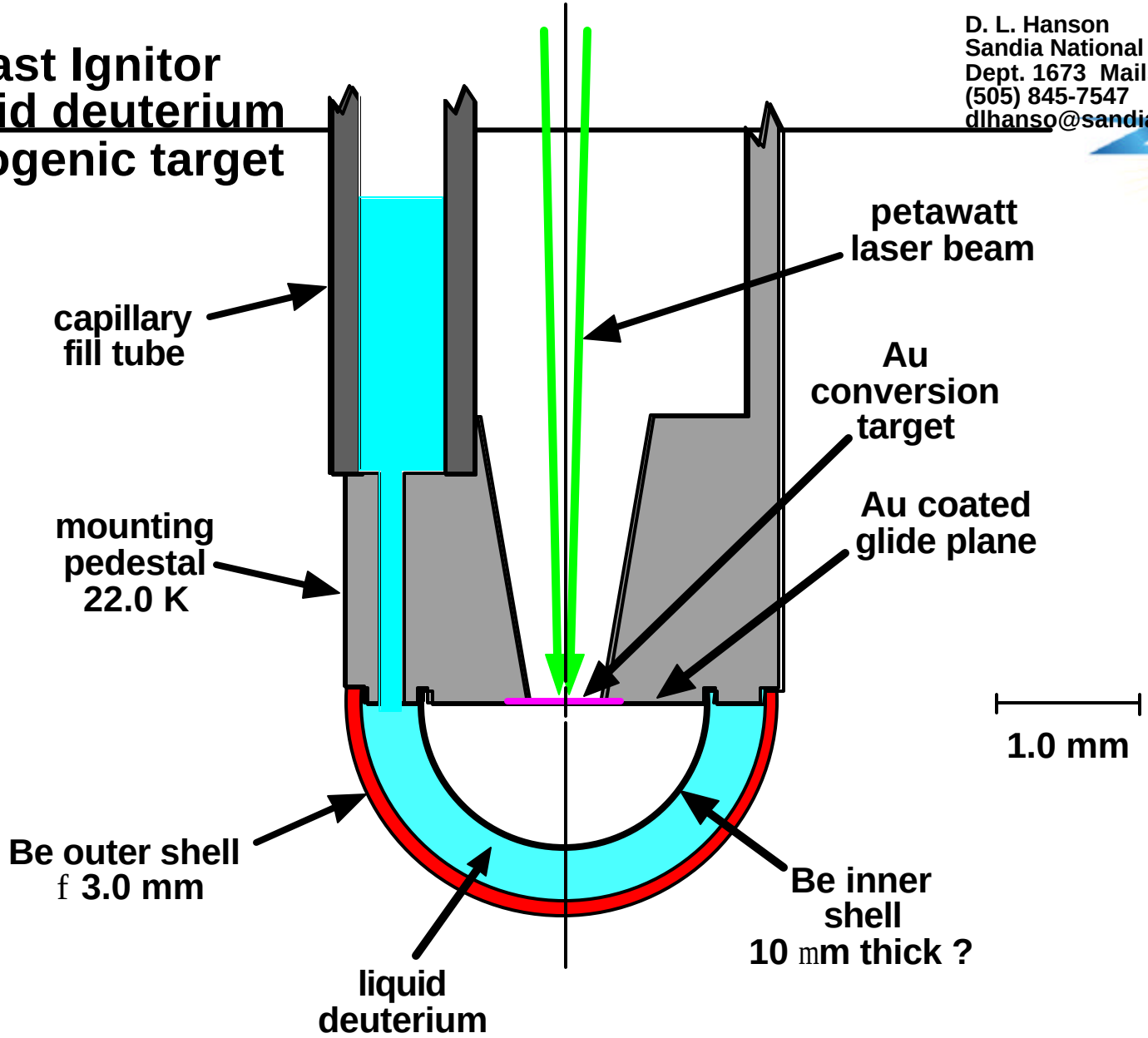
Electrode interactions?
- **Shear**
- **Movement**
- **Mix**



Ref: S.A. Slutz, et al, SAND98-2269, 1999

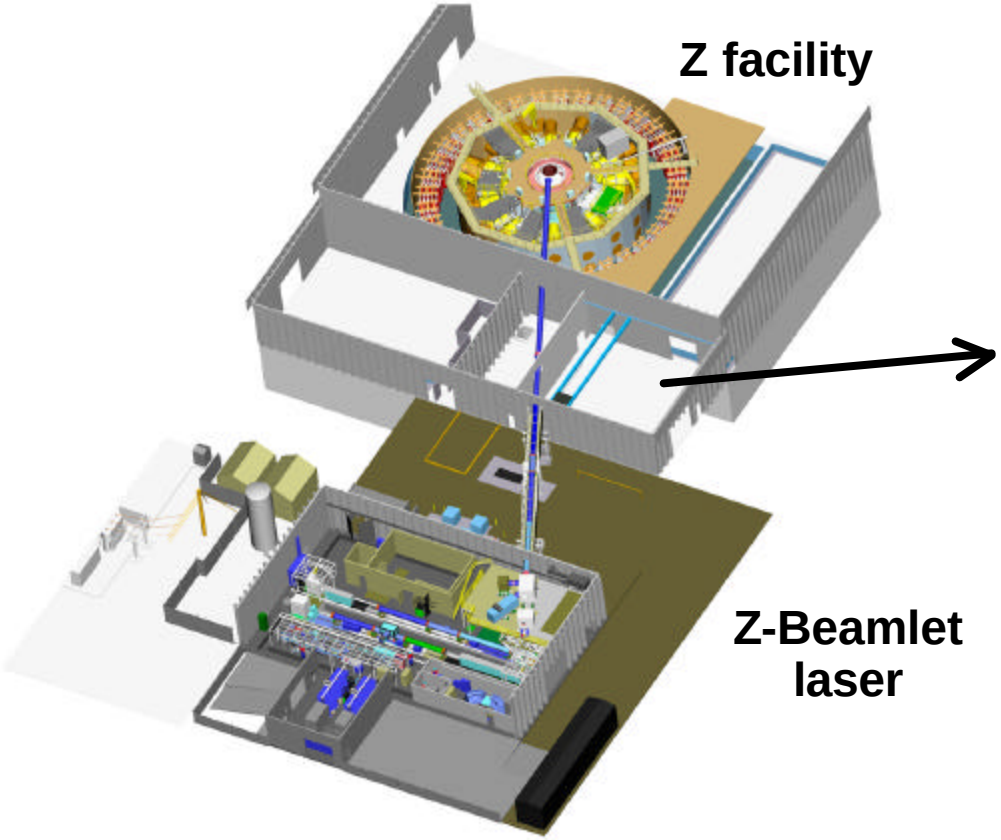
Fast Ignitor liquid deuterium cryogenic target

D. L. Hanson
Sandia National Labs
Dept. 1673 Mailstop 1193
(505) 845-7547
dlhanso@sandia.gov

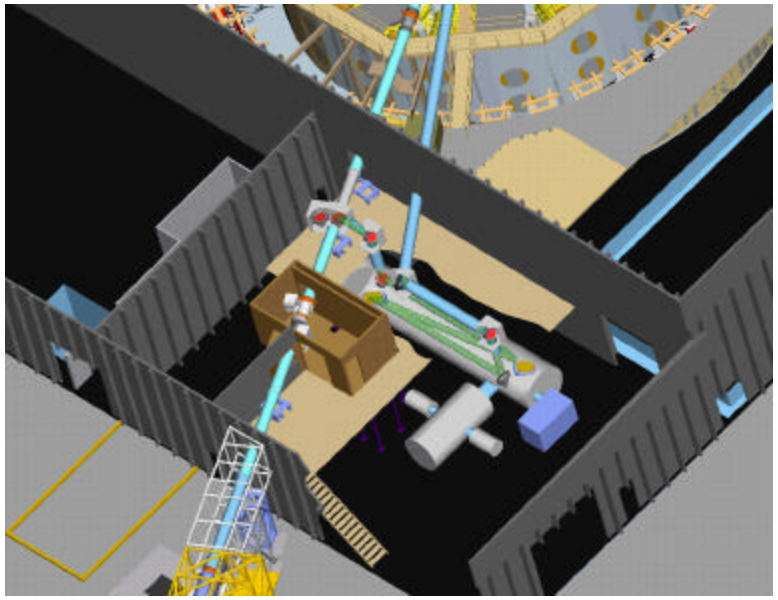


Z-Petawatt can be constructed using existing space

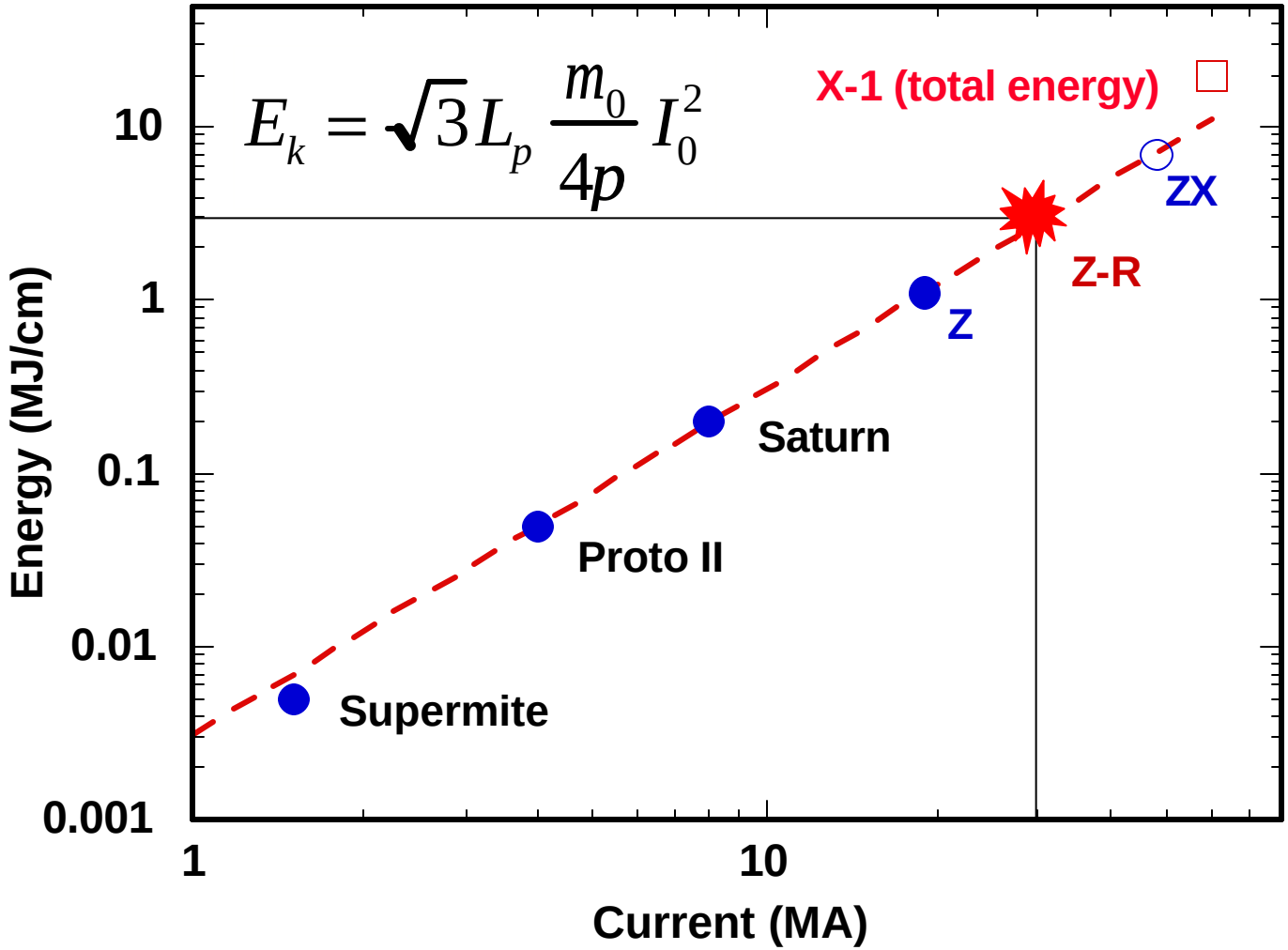
Existing layout of Z-Beamlet laser system and the Z facility



Location of the Z-Petawatt compressor in the Phase C area of the Z facility



The upgraded energy store in *ZR* could deliver up to 30 MA to a pinch radiating 3-4 MJ



Pulsed power ICF Roadmap

FY02 | FY03 | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10

Z — ZR

ZBL — 0.1 PW — 0.5 PW — >1 PW; >1 kJ

NIF — NEL — 1st Cluster — Full NIF

Double-ended hohlraums

Even mode symmetry — meets even mode rqmts

Odd mode symmetry — meets odd mode rqmts

Pulse shaping and pinch energetics — meets pulse shape rqmts

CR > 20
20% clean 1D
$P > I^{1.7}$

Dynamic hohlraums

Imaging & neutron diagnostics — Backlighter, 10 m, yield, bang time, rR

Symmetry — CR~8 — CR~15 — CR~25 — meets rqmts

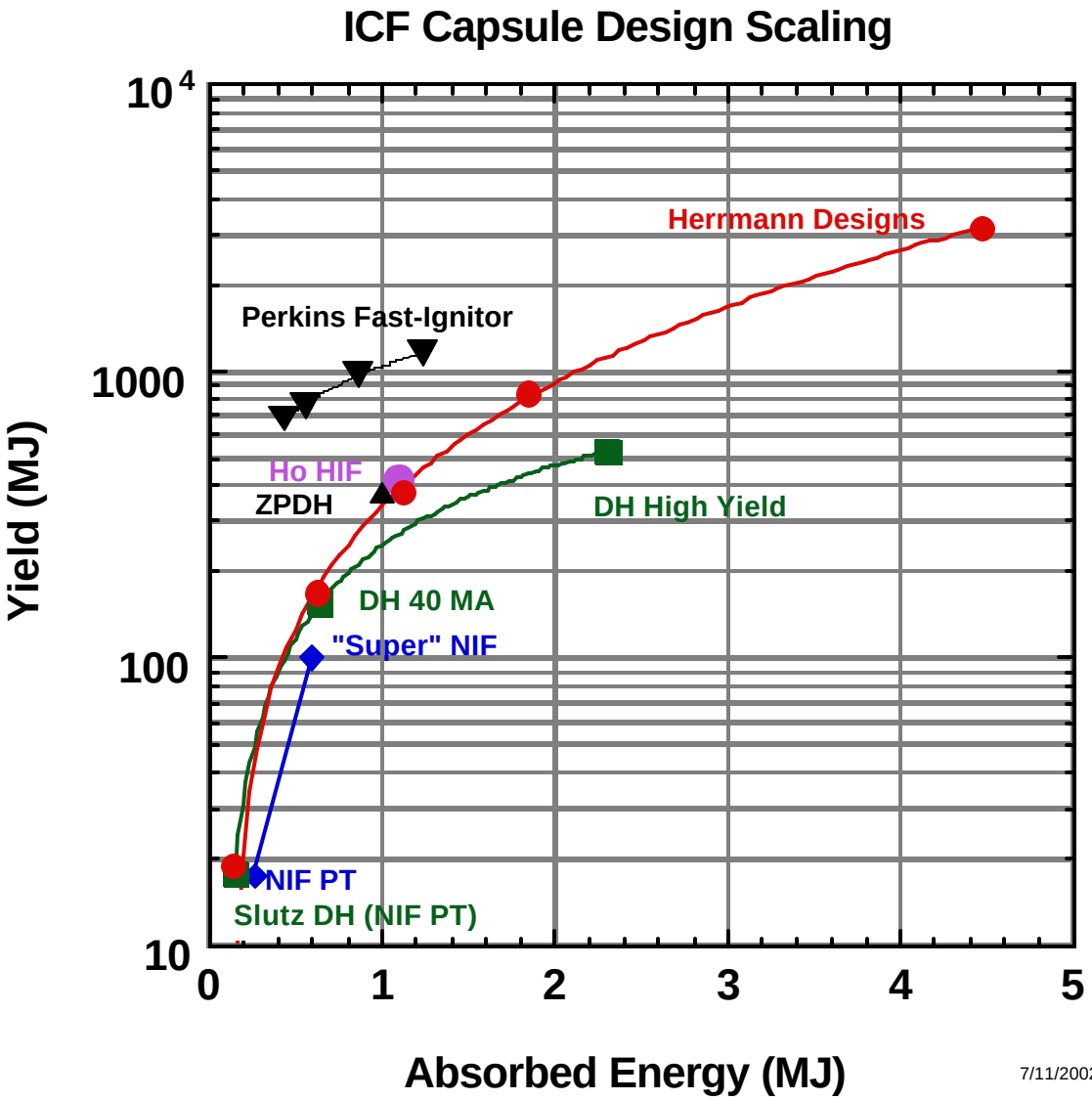
Energetics and integrated design — Validated designs

Fast Ignition

Fast ignition implosions and target coupling experiments

coupling expts
at > 150 g/cc

We are beginning to study ICF capsule designs with higher yield as well as higher gain (fast ignitor)



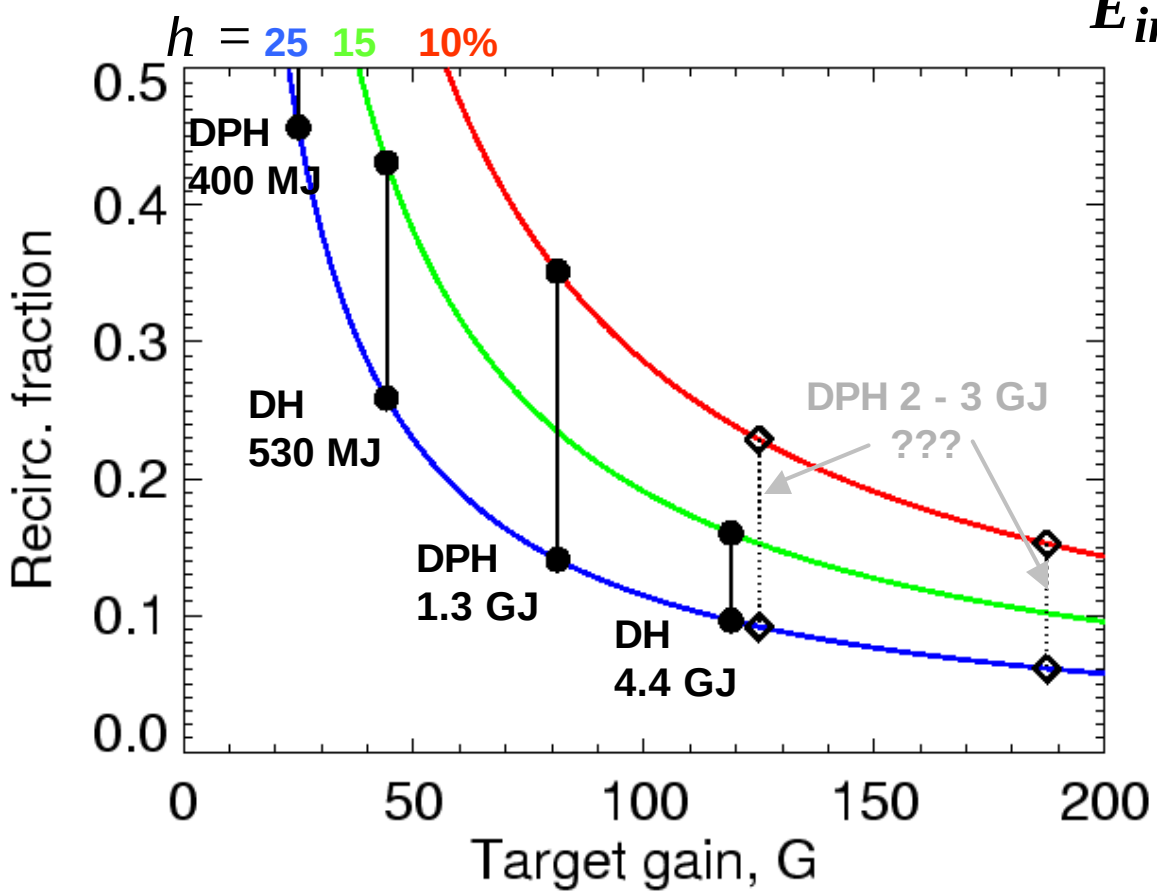
Demonstrated efficiency of pulsed-power z-pinch drivers strongly motivates pursuing these schemes

Recirculating power fraction

$$f_d = \frac{1}{h G Me}$$

$Me =$ 0.35 assumed

$$h = \frac{E_{driver}}{E_{input}} =$$ 10 – 15% routinely on Z now

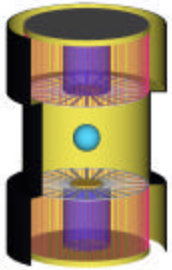


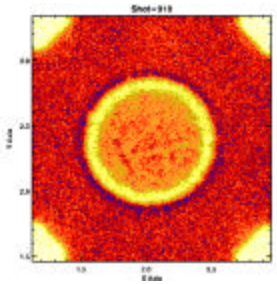
2-3 GJ DPH capsules from 16 MJ driver?

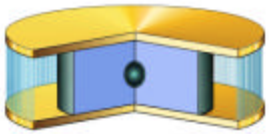
Improvements in h?

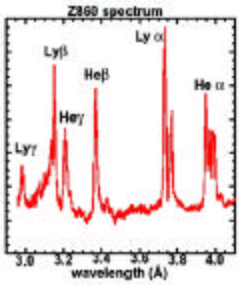
2-4 GJ targets for either DPH or DH look attractive even with today's h

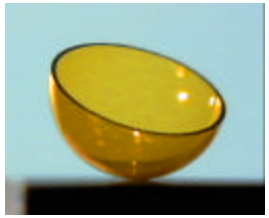
Sandia ICF capsule experiments are laying the target physics foundation for Z-pinch-driven IFE concepts

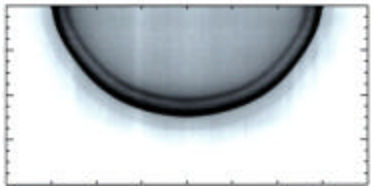












- **Successful backlit ICF capsule implosions in double-ended z-pinch hohlraum**
- **Argon K-shell spectra and core images obtained from ICF capsule implosions in dynamic hohlraum**
- **Exploring possibilities for studying fast ignition physics using ZR + ZBL-PW**
- **Studying capsule designs for RTL concept that scale to GJ IFE yields**