Z-Pinch Driven Inertial Confinement Fusion Program at Sandia National Laboratories: Double Pinch Hohlraum approach [1]

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Seminar in the Physics Department of Universidad Carlos III

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[1]Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

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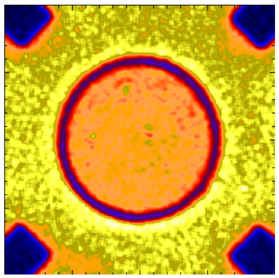
SAND2006-0923P

Outline

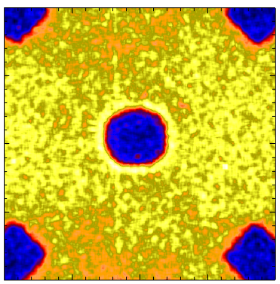
- ICF Double Pinch Hohlraum Concept
- Z-Pinches the Z-machine at SNL
- Requirements
- Some aspects of wire ablation physics
- Discussion

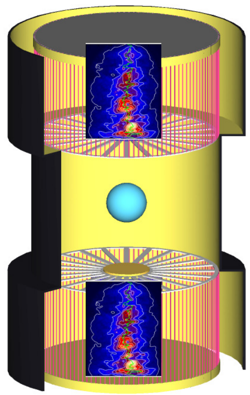
Inertial Confinement Fusion with Z-Pinches

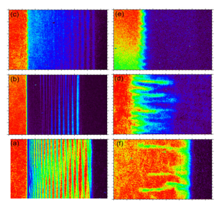
$C_r = 2.5$
3% asymmetry

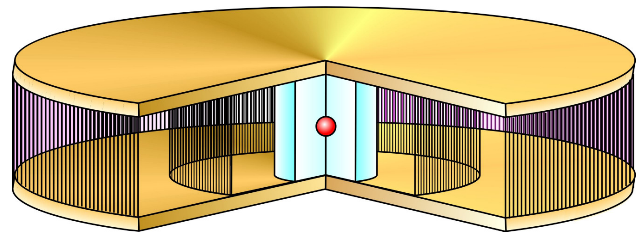


C_r ~13-20, ~40 g/cc

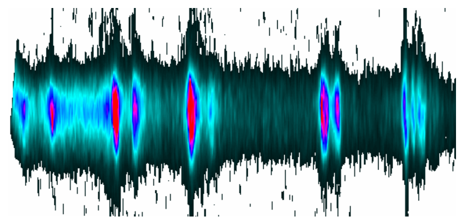






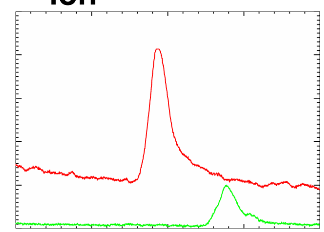


$T_{electron}$ ~ 1.5 keV



hot core

T_{ion} ~ 4.5 keV



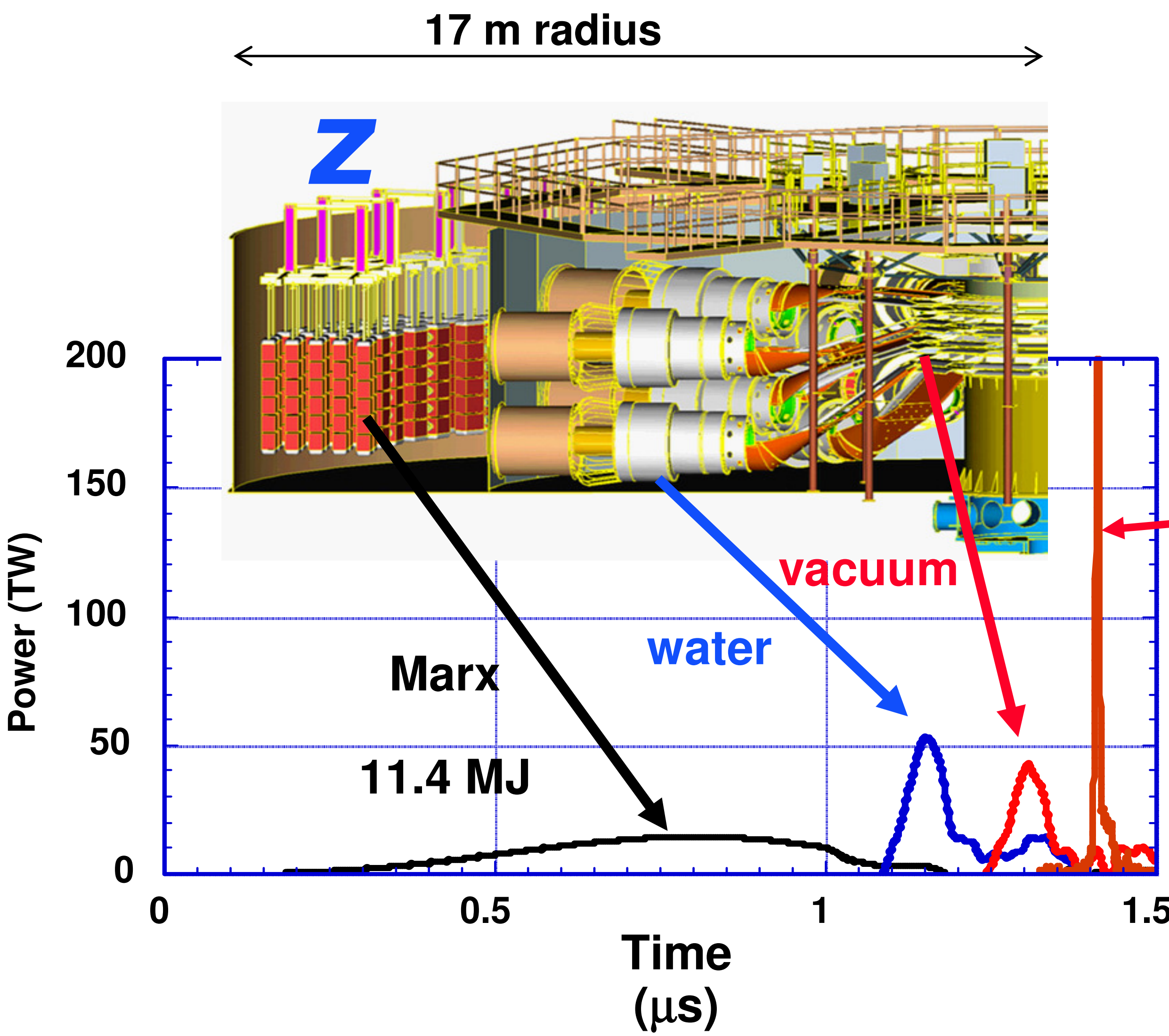
neutrons

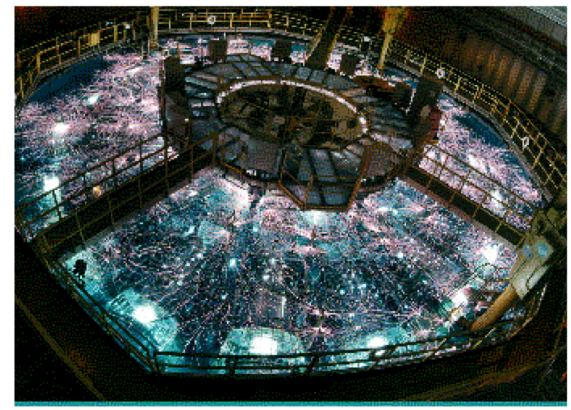
Michael Cuneo

With thanks to: Roger Vesey, Guy Bennett, Dan Sinars, Jim Bailey, Carlos Ruiz, Steve Slutz, Rick Olson, Tom Sanford, Dave Hanson, John Porter, Keith Matzen, Ray Leeper, Jim Hammer, Debbie Callahan, Mark Hermann, Steve Haan, Mordy Rosen, John Lindl

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Pulsed-power provides compact, efficient, power amplification





x ray output
~1.6 MJ
~200 TW

Electrical to x-ray energy
Conversion efficiency ~ 15%

Efficiency ⇒ Low Cost

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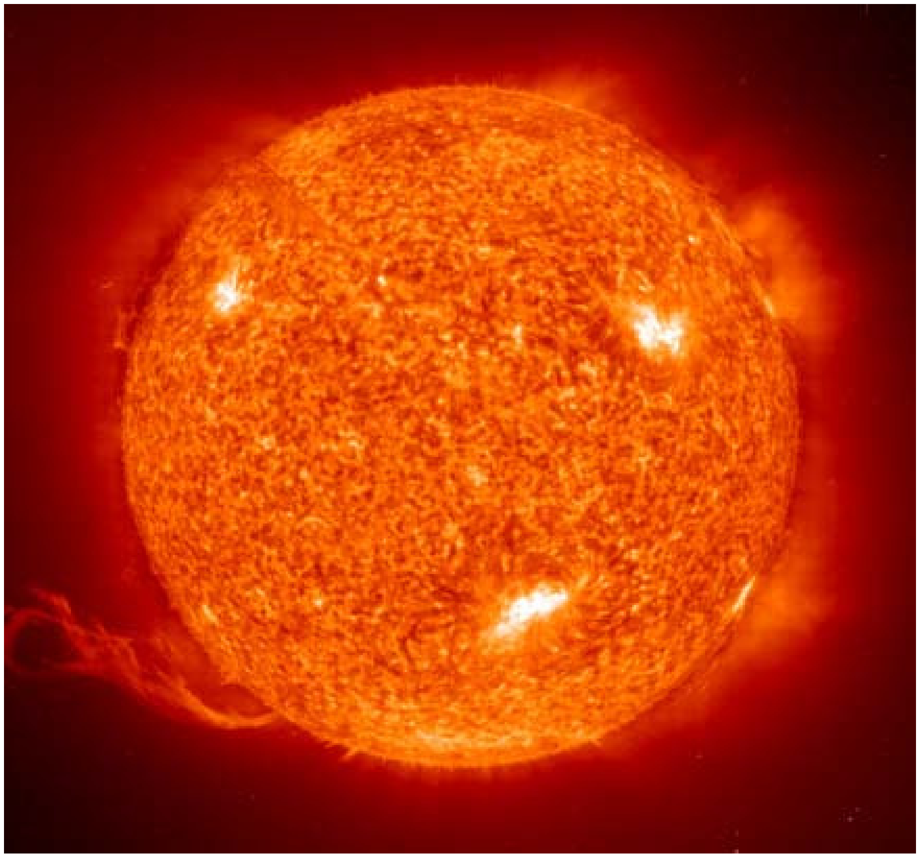
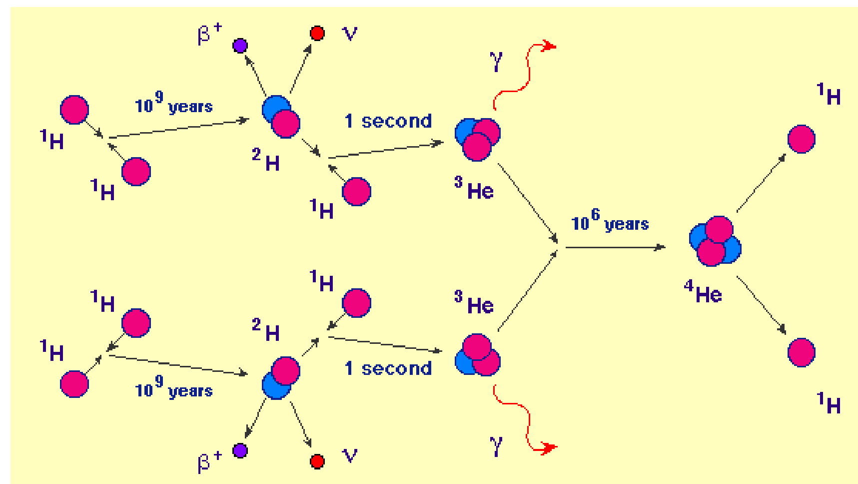
Our local steady-state controlled fusion reactor



Gravity balances thermal energy produced by fusion reactions



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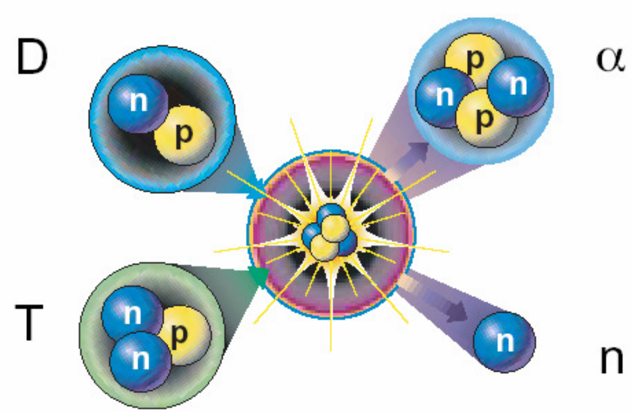
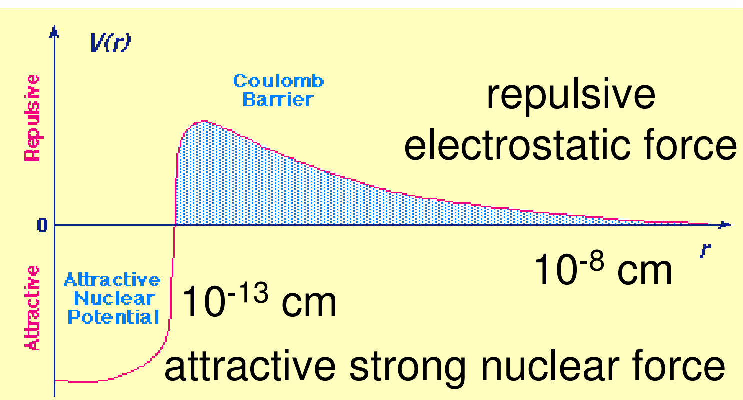
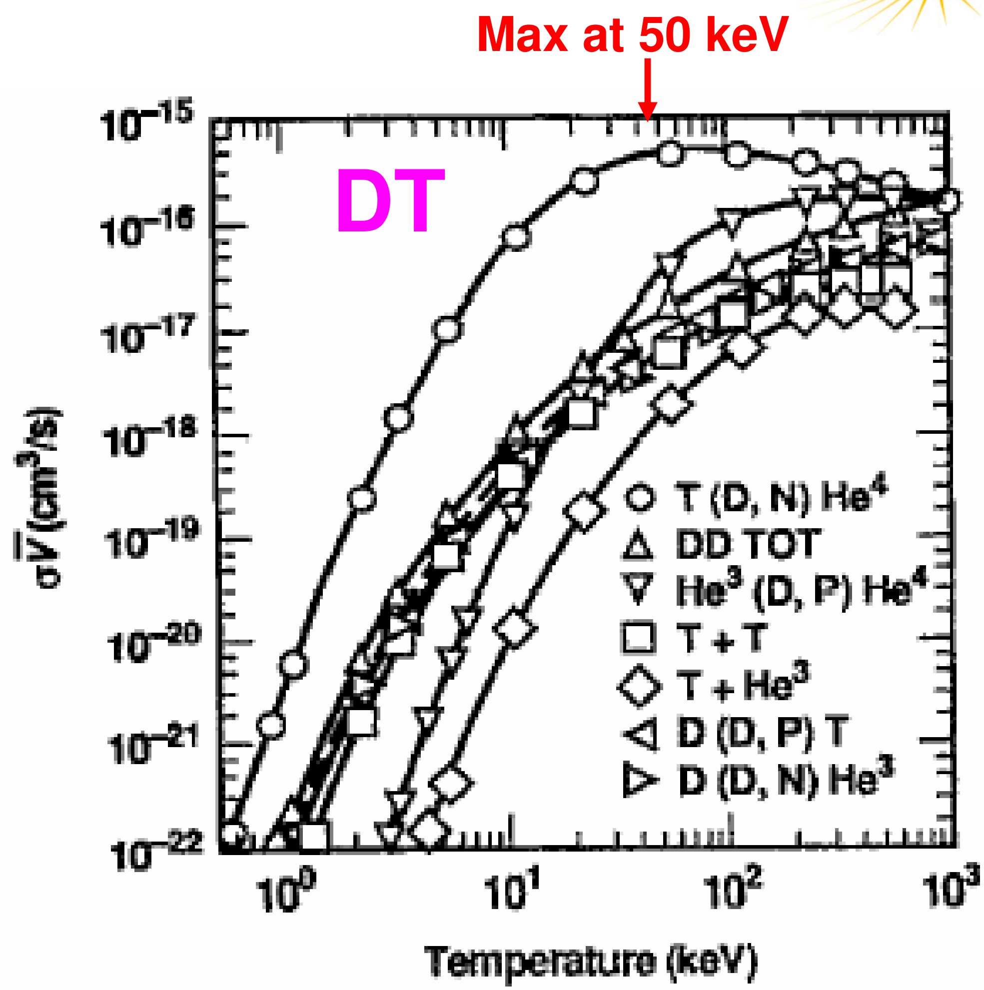
Thermonuclear fusion requires high temperatures to overcome the Coulomb barrier



$$D + T \rightarrow \alpha + n$$

3.5 MeV 14.1 MeV

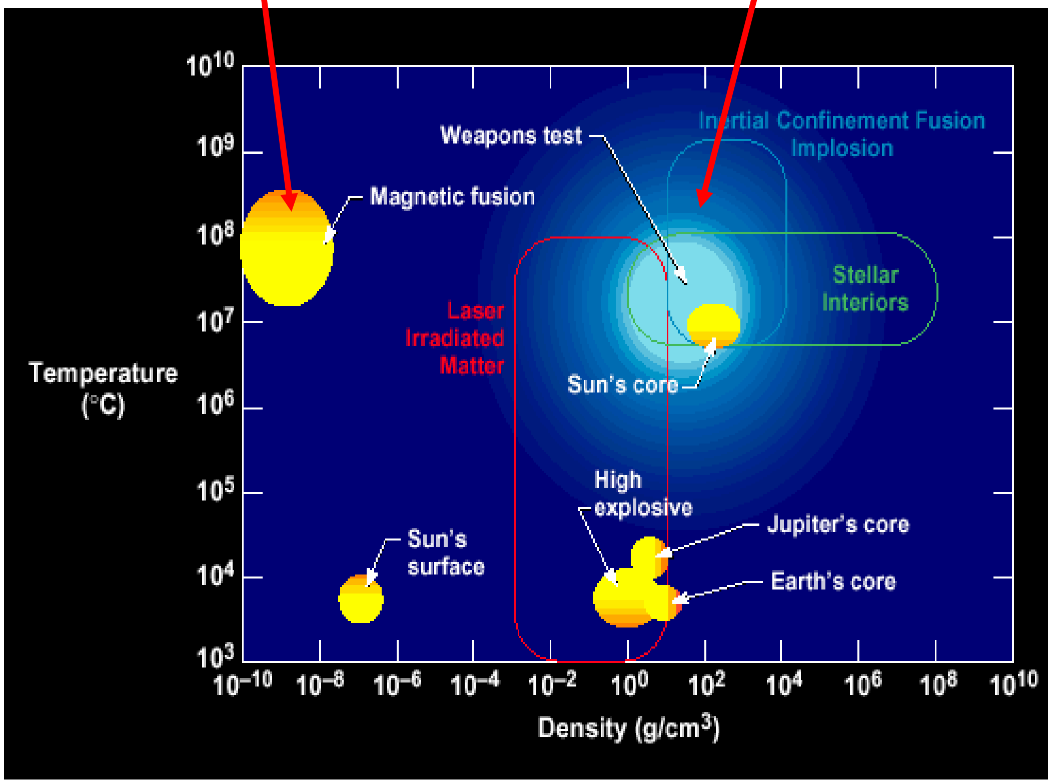




- $Q_{DT\ fusion}$ = 17.6 MeV/5 AMU = 3.3 x 10^{11} J/g

Fusion can produce net energy with sufficient plasma density and confinement time at temperatures > 10 keV

≈ second confinement   ≈ 40-100 ps confinement

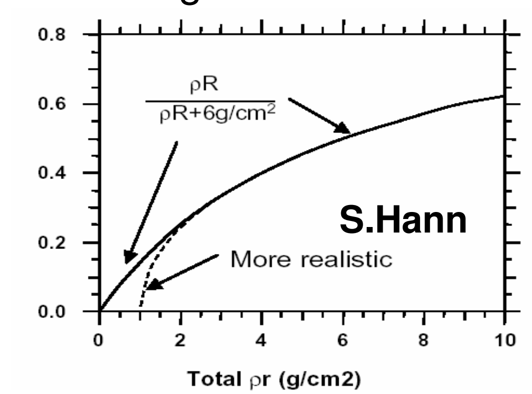


J. D. Lindl, Phys.Plasmas, 2, 3933 (1995)
M.D. Rosen, Phys. Plasmas, 6, 1690 (1999)

$$\frac{dn_T}{dt} = -n_T n_D \langle \sigma v \rangle_{DT}$$

f_b = "burn-up fraction"

$$f_b = \frac{\rho r}{\rho r + 6_{g/cm^2}} = \frac{n\tau}{n\tau + 5\times 10^{15}}$$



- $n\tau > 2.e14\ cm^{-3}s^{-1}$ at T~20 keV for magnetic confinement (Lawson criterion)
- $\rho r > 0.3\ gcm^{-2}$ for ignition of ICF hot spot, equivalent to $n\tau > 2.5e14\ cm^{-3}s^{-1}$
- $\rho r > 3.0\ gcm^{-2}$ for ~30% fuel burn-up at 30 keV, equivalent to $n\tau > 2.5e15\ cm^{-3}s^{-1}$

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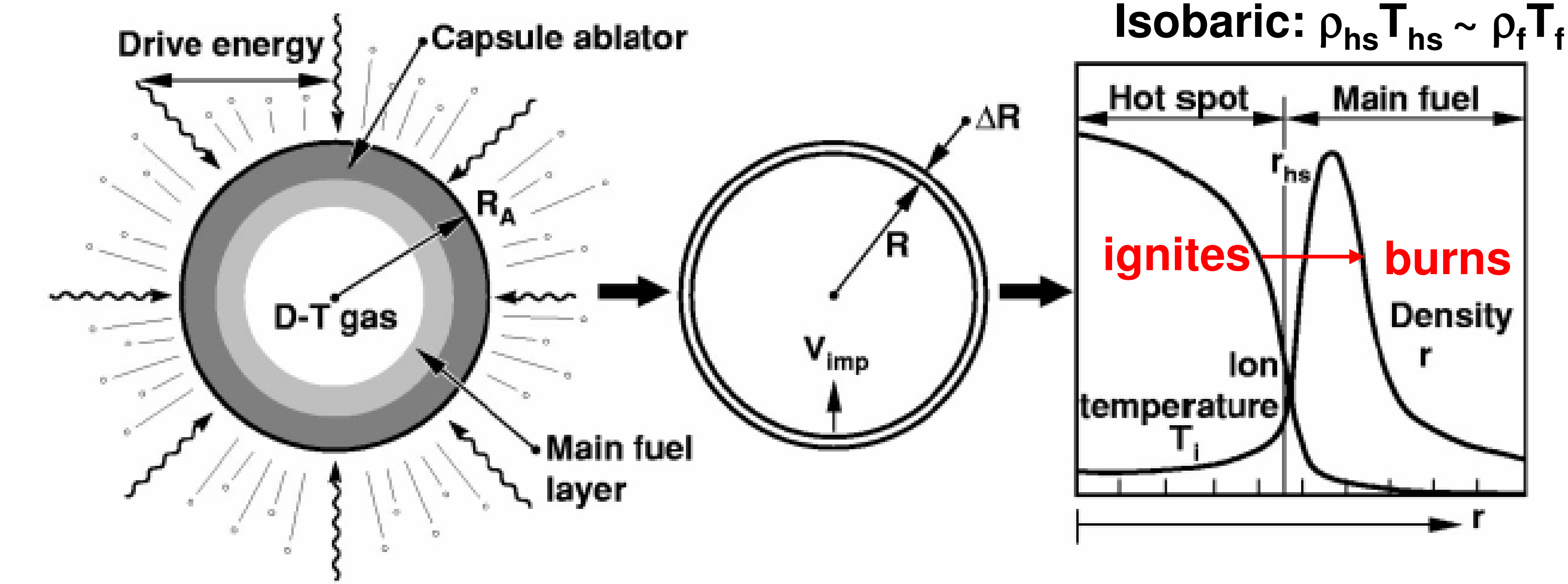
High fuel density and efficient fuel burn (high ρr) may be achieved with spherical compression

J. D. Lindl, Phys.Plasmas, 2, 3933 (1995)



Hot-spot ignition minimizes investment in heating DT

Symmetry: R_A/r_{hs} = convergence = 25-45

Stability: $R/\Delta R$ = in-flight aspect ratio < 30-40

Ignition:
$T_{ion,hs}$ = 10 kV
ρr_{hs} = 0.3 g/cm^2

There are two basic methods for spherical implosion

- Direct drive: lasers (visible photons), ions, or magnetic fields
- Indirect-drive: laser, ion, or z-pinch produced soft x-rays

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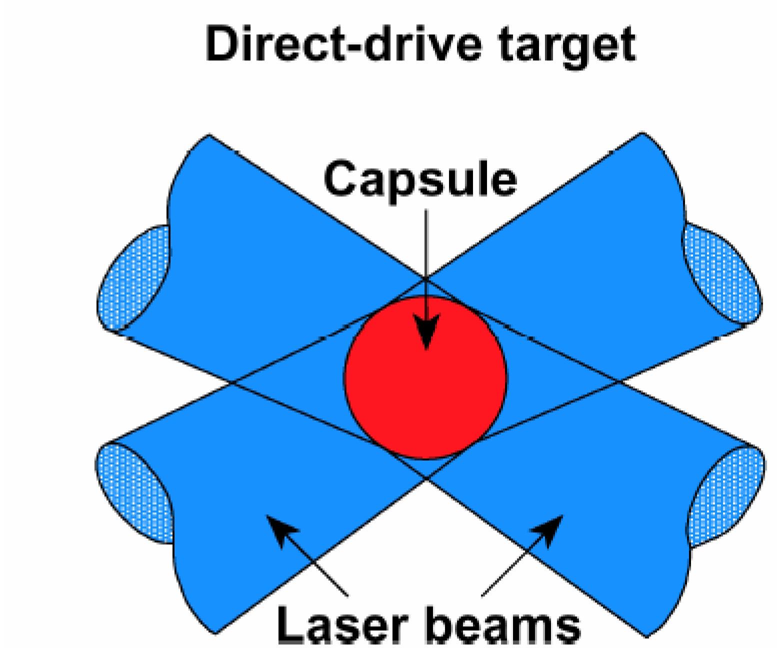
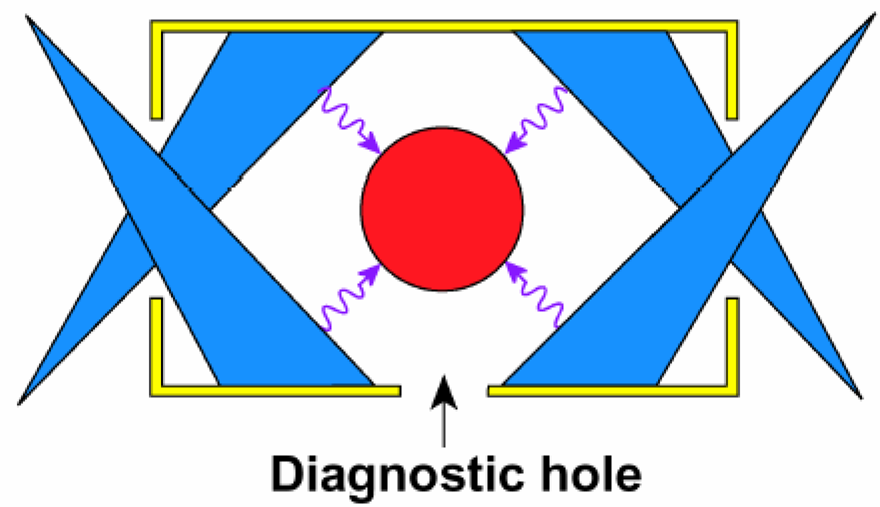
Soft x-rays generated in a hohlraum implode the capsule in the indirect-drive approach





For indirect-drive:

- Soft x-rays couple to the capsule ablation front
- X-ray re-emission from the walls symmetrizes drive
- Symmetry can be tuned geometrically
- Hohlraums amplify radiation flux using wall re-emission by a factor of $1/(1-\alpha) \sim 5$, where $\alpha \sim 0.8$ is the wall albedo

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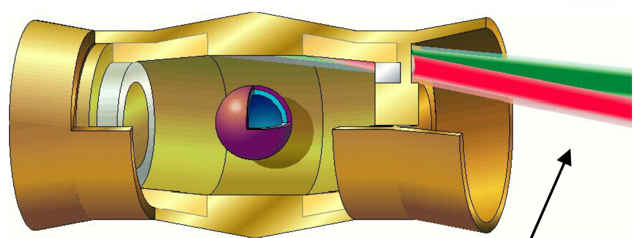
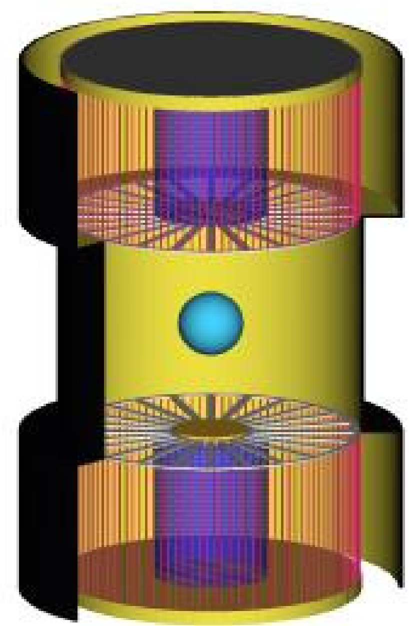
Hohlraums can be driven with a variety of x-ray sources, including lasers, ion beams, and now z-pinches

NIF glass laser
Ignition hohlraum

Heavy Ion Beam
Distributed radiator



Double-ended Z-pinch



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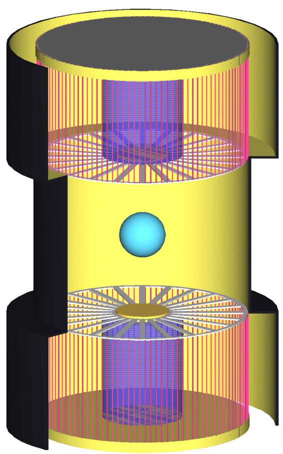
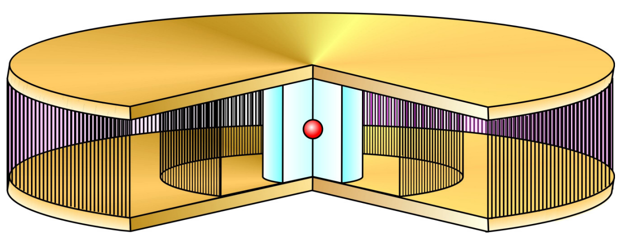
Double-pinch and dynamic hohlraums bound the spectrum of risk and coupling efficiencies for z-pinch indirect drive

	ICF – IFE	Features/Issues
Double-Pinch Hohlraum 	Z-pinch Drive: 2 x 62 MA Eabs: 1.3 – 2.6 MJ Yield: 400 – 3000 MJ	Capsule isolated from z-pinches Symmetry via hohlraum design demonstrated on Z (2x16 MA) Low coupling (η_{hohl} ~ 8-16 %) implies large stored energy required
Dynamic Hohlraum 	54 – 95 MA 2.4 – 7.2 MJ 530 – 4500 MJ	Capsule inside pinch and converter, high coupling η_{hohl} ~ 20 % Core T_e > 1 keV, dopant x-ray spectra measured on Z (20 MA) Control of symmetry needed

Capsule designs by J. Hammer, M. Tabak, R. Vesey, J. Lash, S. Slutz

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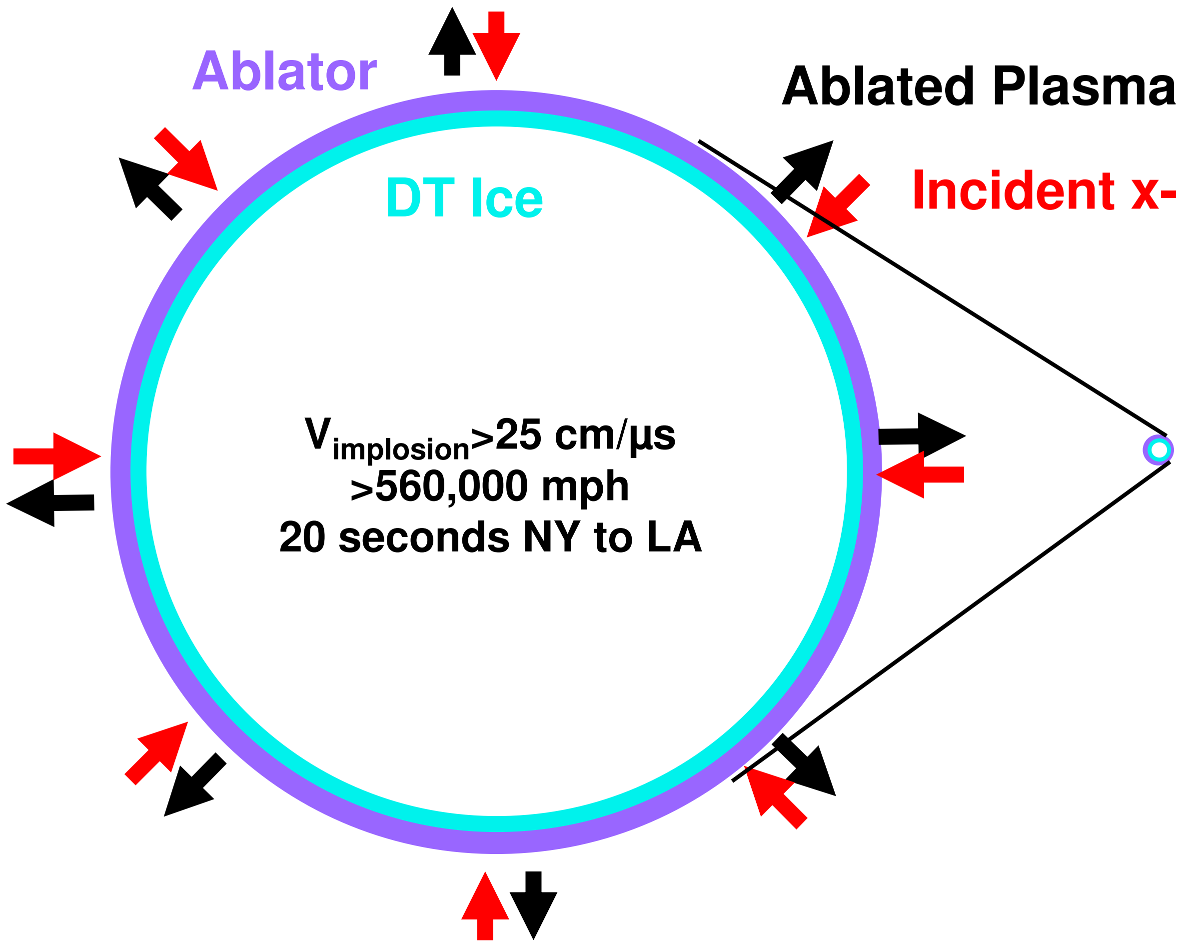
ICF capsules are spherical rockets



$P = 3T^{3.5}$ MBar

50-150 Mbar

≈1e9 psi

at 220 to 300 eV

30:1 compression ratio shown

High convergence implosions require excellent radiation symmetry

- Yes "ICF *is* rocket science" (Mordy Rosen)

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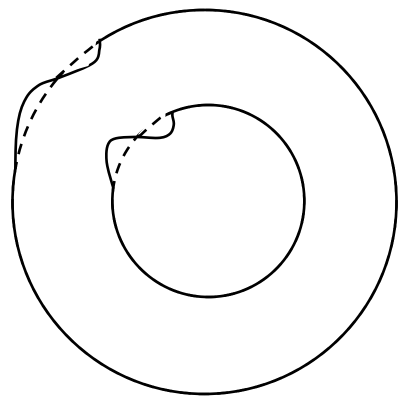
A simple derivation from Lindl is helpful to understand the 1% requirement

$$R = R_o - \frac{1}{2} g t^2$$

$$\delta R = \frac{1}{2} \delta g t^2$$

$$R_f = R_o - \frac{1}{2} g t_{final}^2$$

$$t_{final}^2 = \frac{2(R_o - R_f)}{g}$$



$$\delta R = \frac{1}{2}\frac{\delta g}{g}(R_o - R_f)$$

$$\delta R = \frac{1}{2}\frac{\delta g}{g} R_f \left(\frac{R_o}{R_f} - 1\right)$$

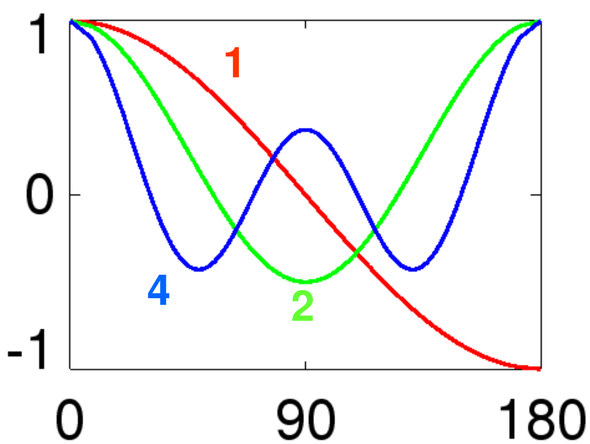
$$\frac{\delta R}{R_f} = \frac{1}{2}\frac{\delta g}{g}(Cr - 1)$$

so if $\delta R/R_f$ <25% (mix!), and Cr ~30 – 40:

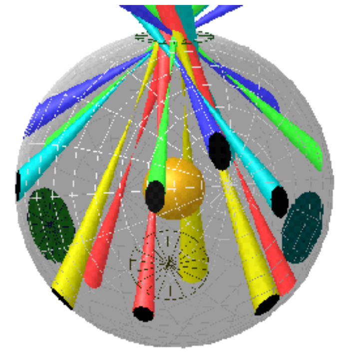
$$\frac{\delta g}{g} \sim \frac{\delta v}{v} < \frac{1}{4(Cr - 1)} \sim 1\%$$

Controlling drive symmetry to <1% is a goal common to all central hot-spot ignition indirect-drive ICF approaches

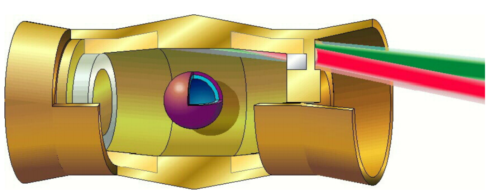
Low order Legendre modes P_ℓ



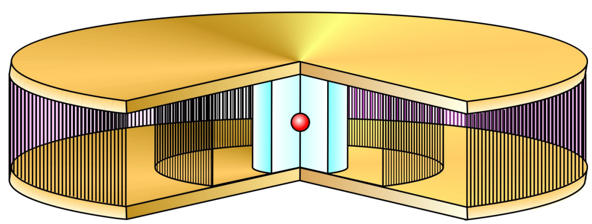
NIF hohlraum
multiple cones
beam phasing
gas fill



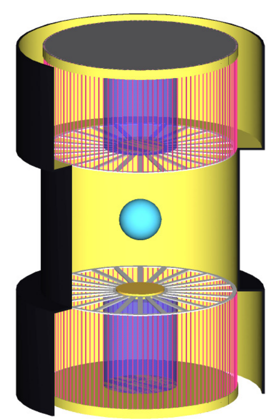
tetrahedral hohlraum
source placement
beam phasing



heavy ion hohlraum
multiple beams
tailored converters



dynamic hohlraum
tailored converters
shine shields
shims



double z-pinch hohlraum
hohlraum geometry
albedo tailoring

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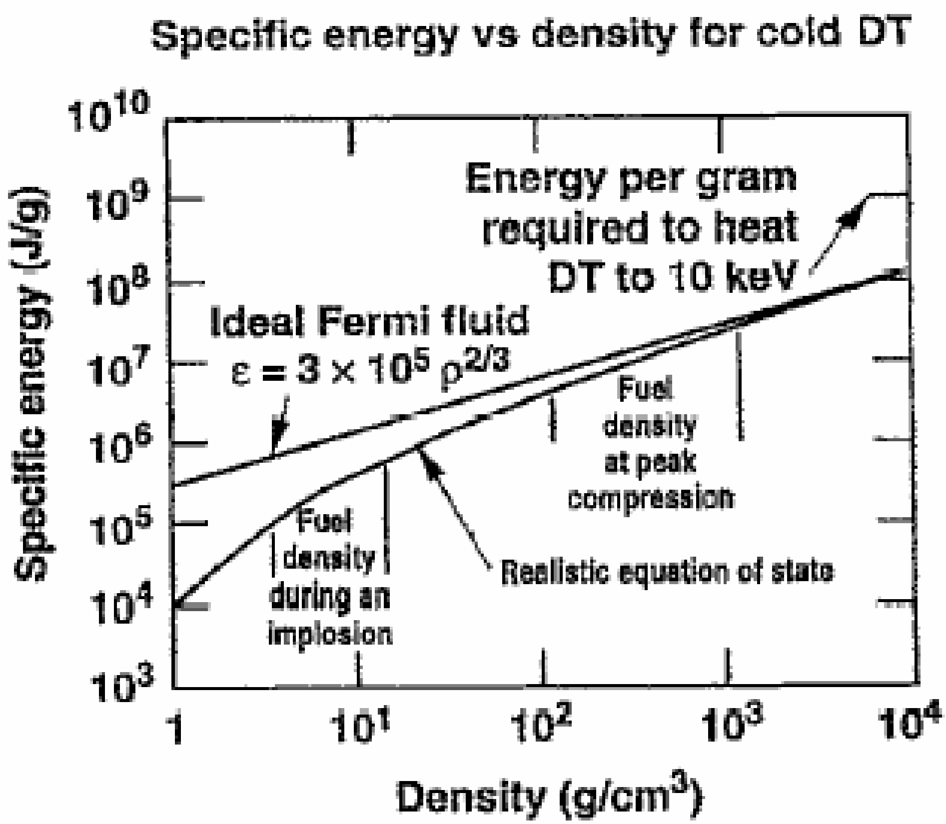
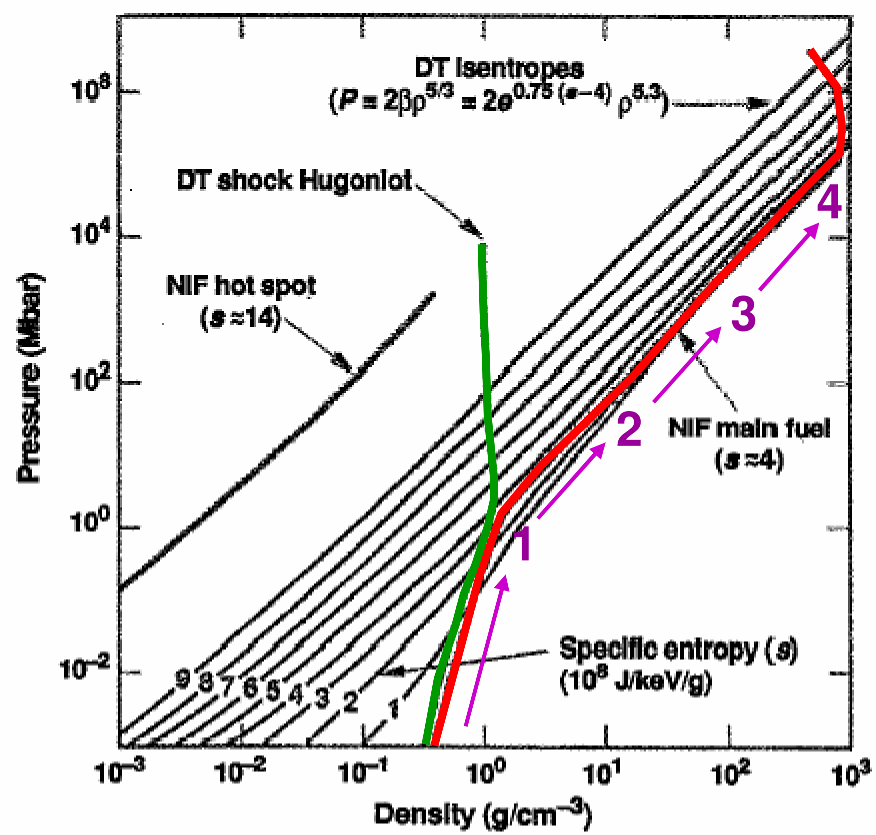
High gain requires a minimum investment of energy to compress the fuel

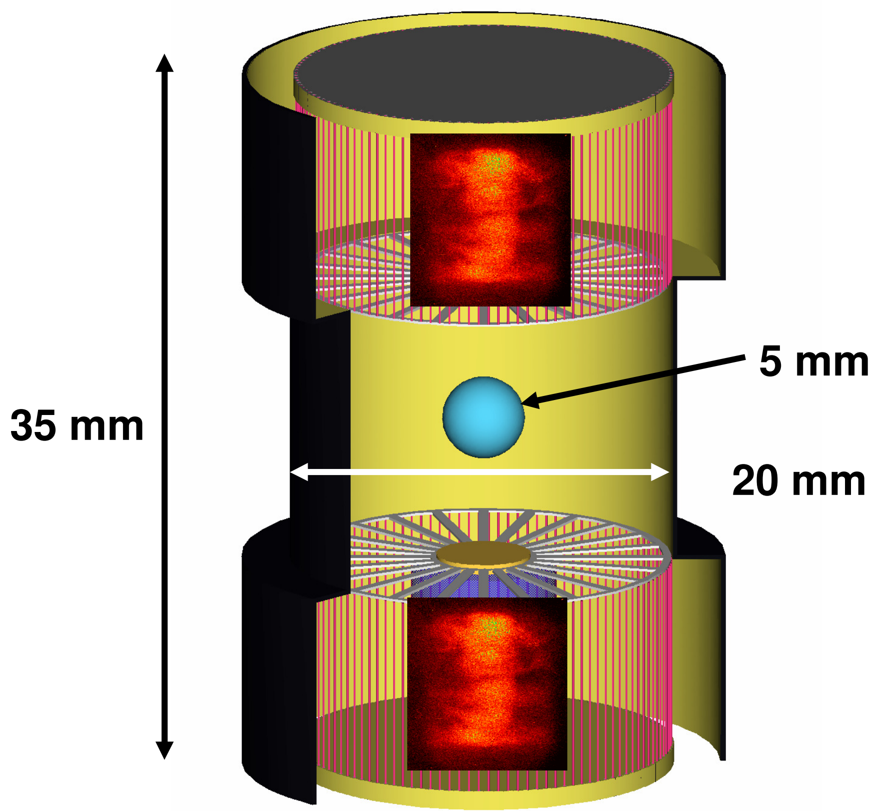




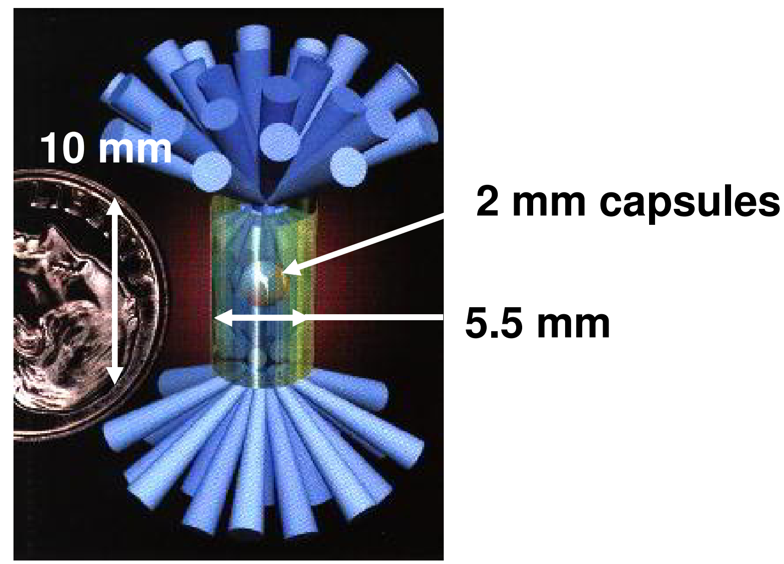
J. D. Lindl, Phys.Plasmas, 2, 3933 (1995)

- Compression of DT fuel with lowest energy investment requires radiation pulse shaping (1st shock = 1 Mbar, then 2 or 3 successive smaller shocks)

Z-pinch driven hohlraums are compatible with the size and cost requirements for high fusion yield and energy



Z-pinch driven hohlraum (2 Z-pinches)
Z: 1-2 MJ X-ray source
ZR: 3.5 MJ X-ray source
50-150$ capital/x-ray joule



NIF Laser (192 laser beams)
1-2 MJ X-ray source
2000-4000$ capital cost/x-ray joule

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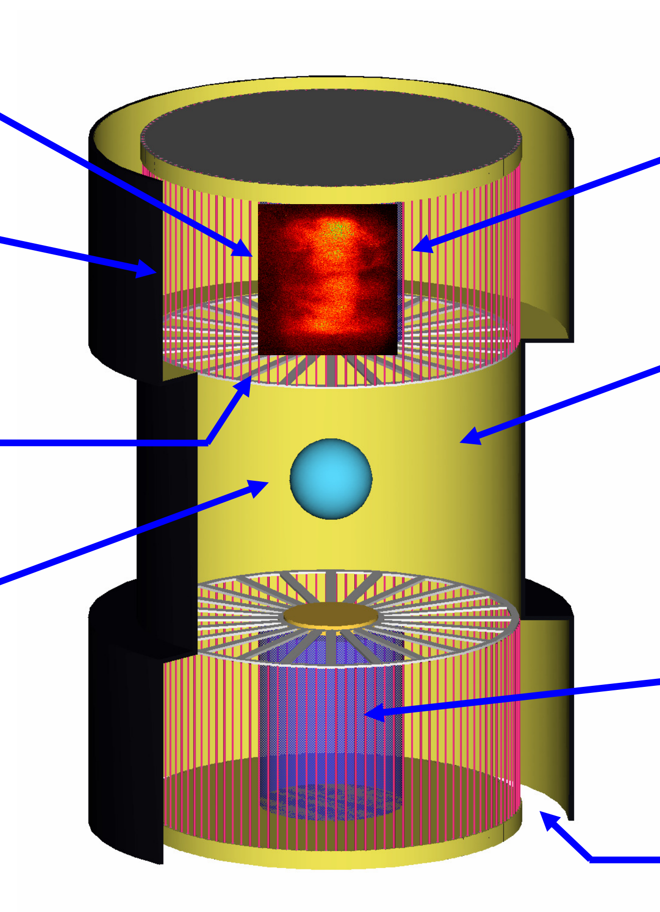
The double-ended-hohlraum (DEH) high yield concept separates capsule and z-pinch physics issues

JH Hammer et al., Phys. Plasmas 6, 2129 (1999)



This work builds directly from the laser indirect-drive program

Double-ended hohlraum concept resources: hohlraum physics and capsule implosion symmetry

J.H. Hammer et al., Phys. Plasmas, 6, 2129 (1999)

M.E. Cuneo, et al., Phys. Plasmas, 8, 2257 (2001)

M.E. Cuneo, et al., Laser and Particle Beams, 18, 481 (2001)

W. A. Stygar, et al., Phys. Rev. E, 64, 026410 (2001)

D.L. Hanson, et al., Phys. Plasmas, 9, 2173 (2002)

M.E. Cuneo, et al., Phys. Rev. Lett., 88, 215004 (2002)

G.R. Bennett, et al., Phys. Rev. Lett., 89, 245002 (2002)

R.A. Vesey, et al., Phys. Rev. Lett., 90, 035005 (2003)

R.A. Vesey, et al., Phys. Plasmas, 10, 1854 (2003)

G.R. Bennett, et al., Phys. Plasmas, 10, 3717 (2003)

M. K. Matzen, et al., Phys. Plasmas, 12, 055503 (2005)

D. A. Callahan et al., Nucl. Inst. Meth. A, 544, 9 (2005)

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Double-ended hohlraum concept resources: pinch physics, power scaling and radiation pulse shaping

W.A. Stygar et al., Phys. Rev. E, 69, 046403 (2004)

E.M. Waisman, et. al., Phys. Plasmas, 11, 2009 (2004)

D.B. Sinars, et al., Phys. Rev. Lett., 93, 145002 (2004)

M.E. Cuneo, et al., Phys. Rev. E, 71, 046406 (2005)

D.B. Sinars, et al., Phys. Plasmas, 12, 056503 (2005)

M.E. Cuneo, et al., Phys. Rev. Lett., 94, 225003 (2005)

W.A. Stygar, et al., accepted, Phys. Rev. E (2005)

M.E. Cuneo, et al., Phys. Rev. Lett., submitted (2005)

D. B. Sinars, et al., in preparation for Phys. Plasmas (2005)

E.M. Waisman, et al., in preparation for Phys. Plasmas (2005)

Other relevant pinch physics:

T.J. Nash, et al., Phys. Plasmas, 11, L65, (2004)

T.J. Nash, et al., Phys. Plasmas, 11, 5156 (2004)

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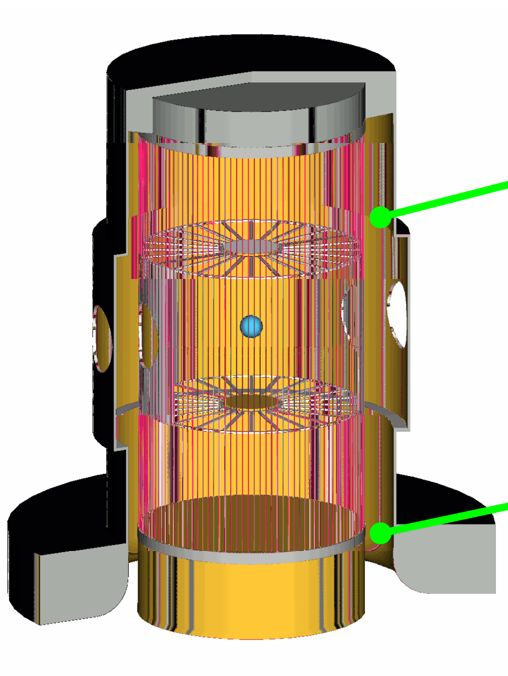
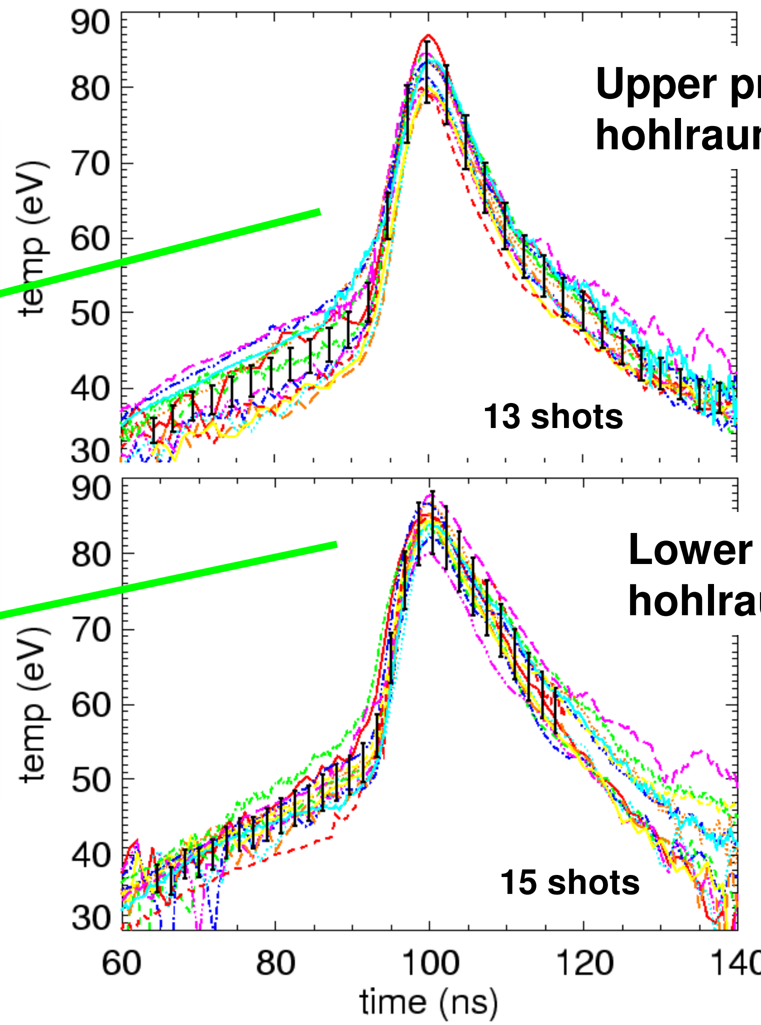
Capsule implosion experiments enabled by the development of a single-sided power feed, double-pinch for Z

M. E. Cuneo et al., Phys. Rev. Lett. 88, 215004 (2002)

Wire array hardware

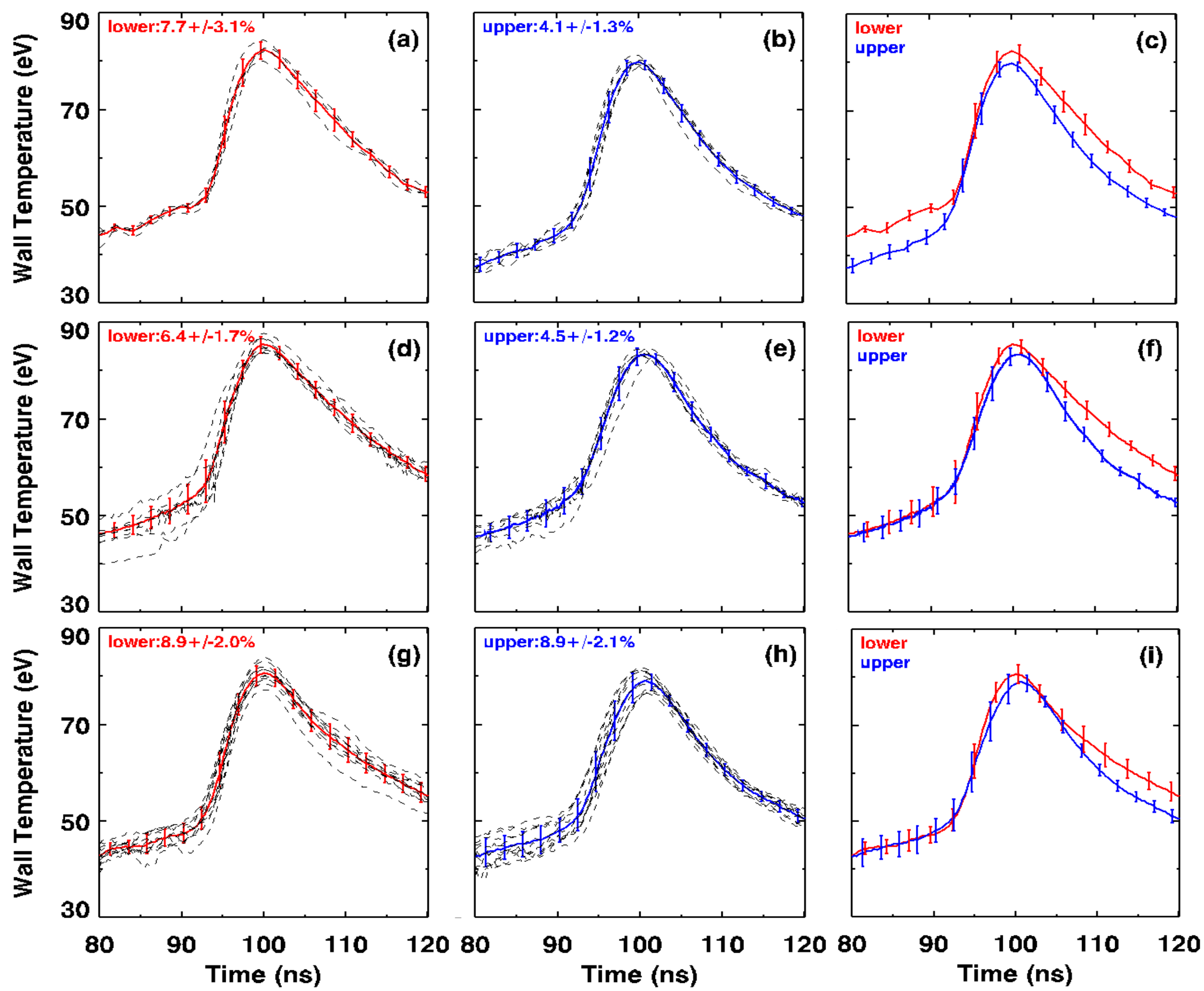




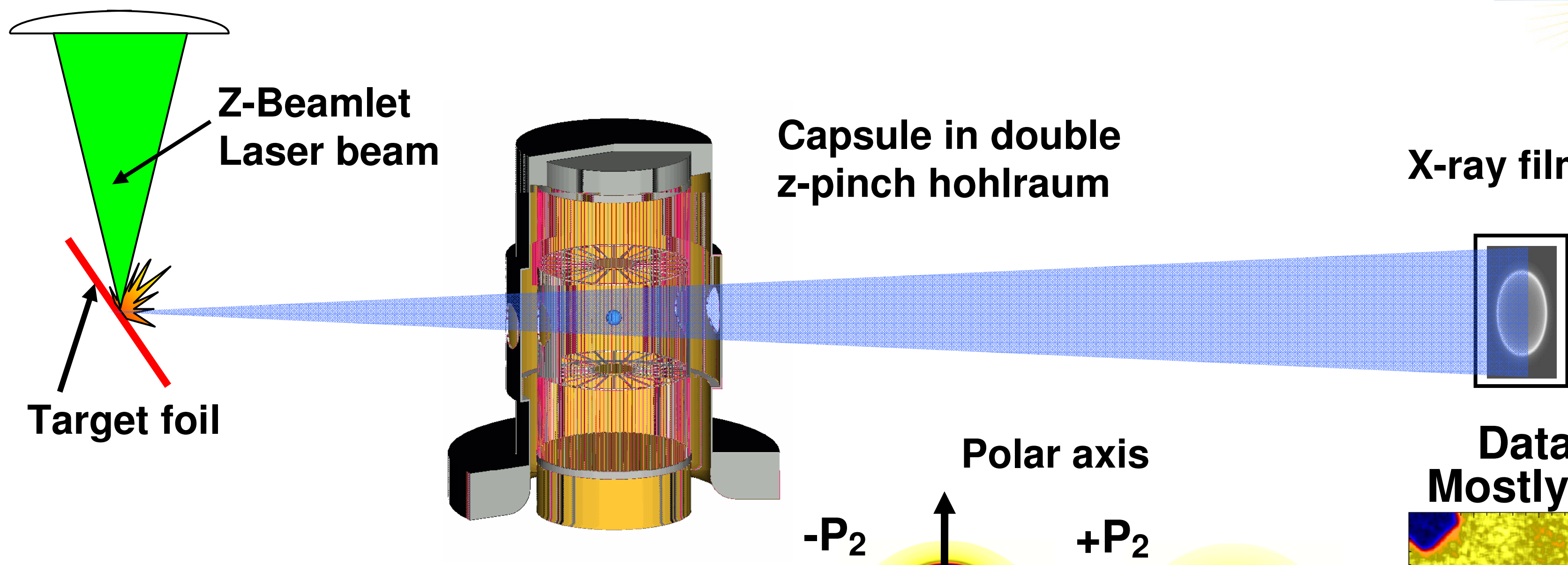
Shot-to-shot variation in peak hohlraum T_r is less than ± 5% instrumental error

The shot-to-shot x-ray power variation is 5.3±0.4 % from a weighted average over 62 hohlraum experiments

M. E. Cuneo et al., to be submitted

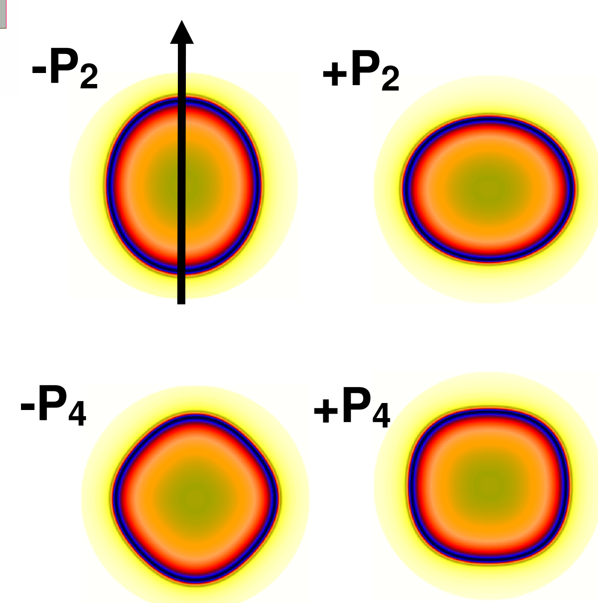


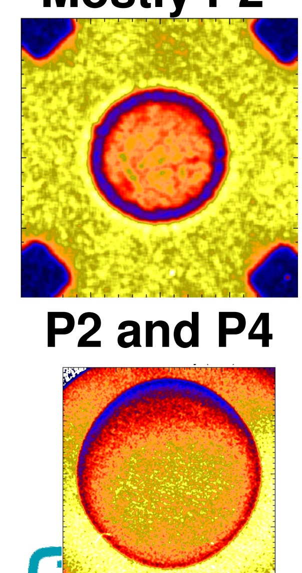
We diagnose radiation asymmetry on Z with x-ray point-projection backlighting of an imploding capsule



Capsule drive asymmetry expressed in terms of low-order Legendre modes P_ℓ

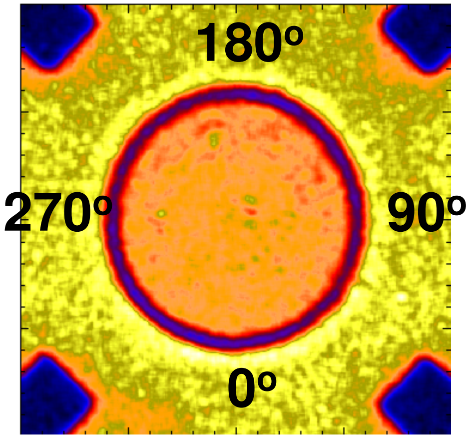
Example in-flight backlit images of capsules driven by dominant modes:





ZBL images have confirmed time-integrated asymmetry as low as 3.0 ± 0.7 % in double-pinch hohlraums on Z

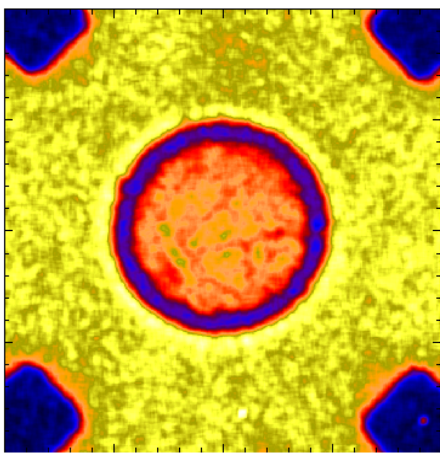
Experimental image



$\frac{\delta r}{r} = 1.8 \pm 0.4\ \%$

$C_r = 1.85$

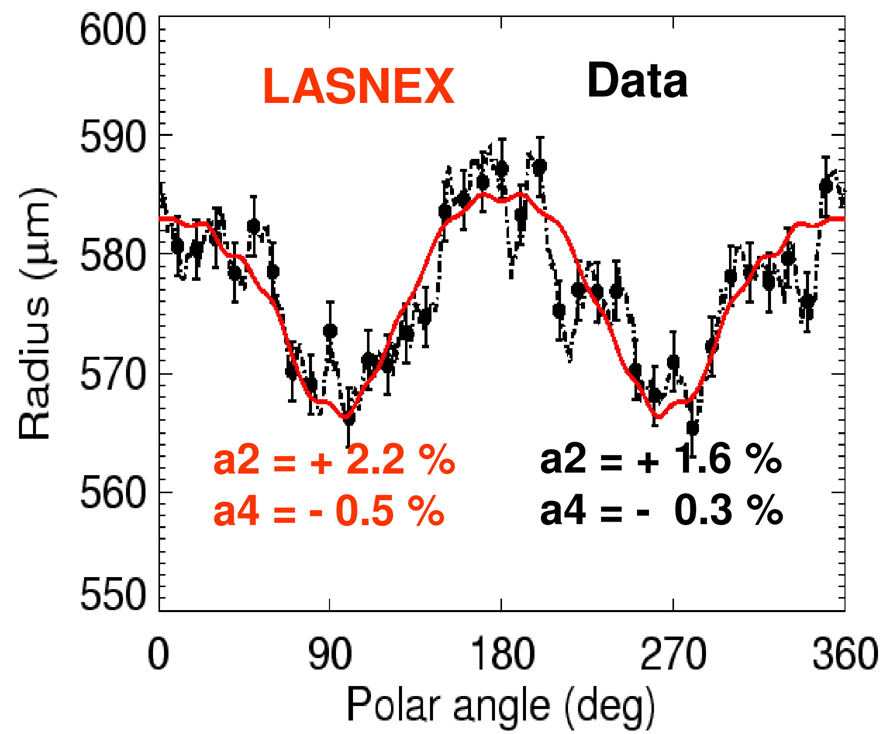
$\frac{\delta I}{I} = 2.8 \pm 0.6\ \%$



$\frac{\delta r}{r} = 3.5 \pm 1.2\ \%$

$C_r = 2.48$

$\frac{\delta I}{I} = 3.1 \pm 1.6\ \%$



G. R. Bennett, et al., Phys. Plasmas, 10, 3717 (2003)

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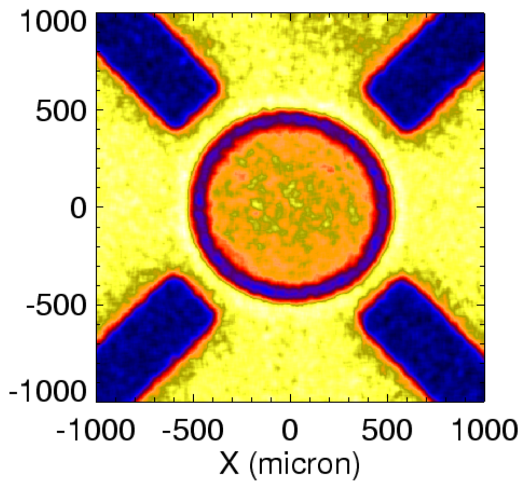
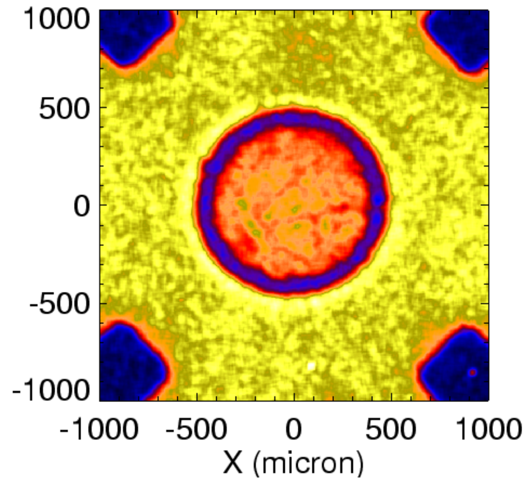
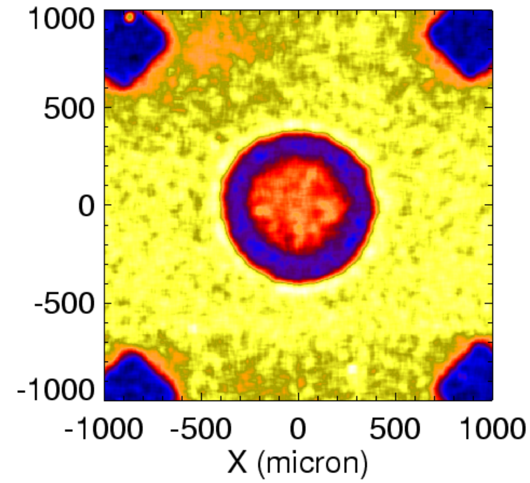
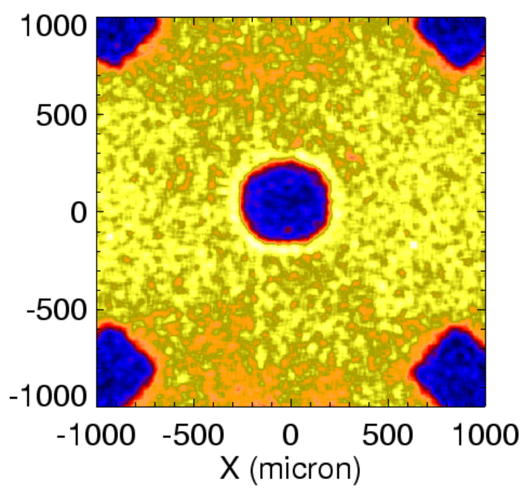
Implosion history confirms hohlraum energetics models and shows high convergence >10-13

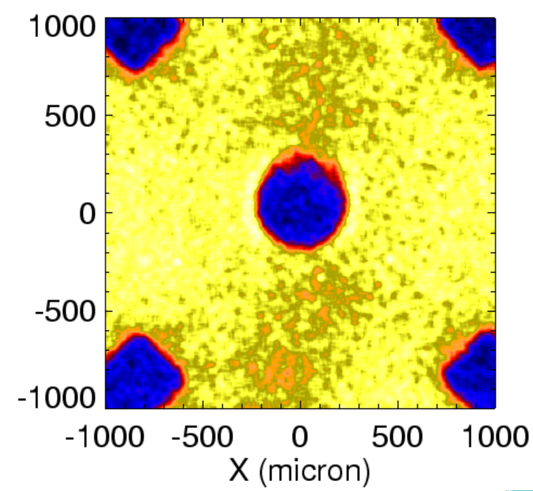






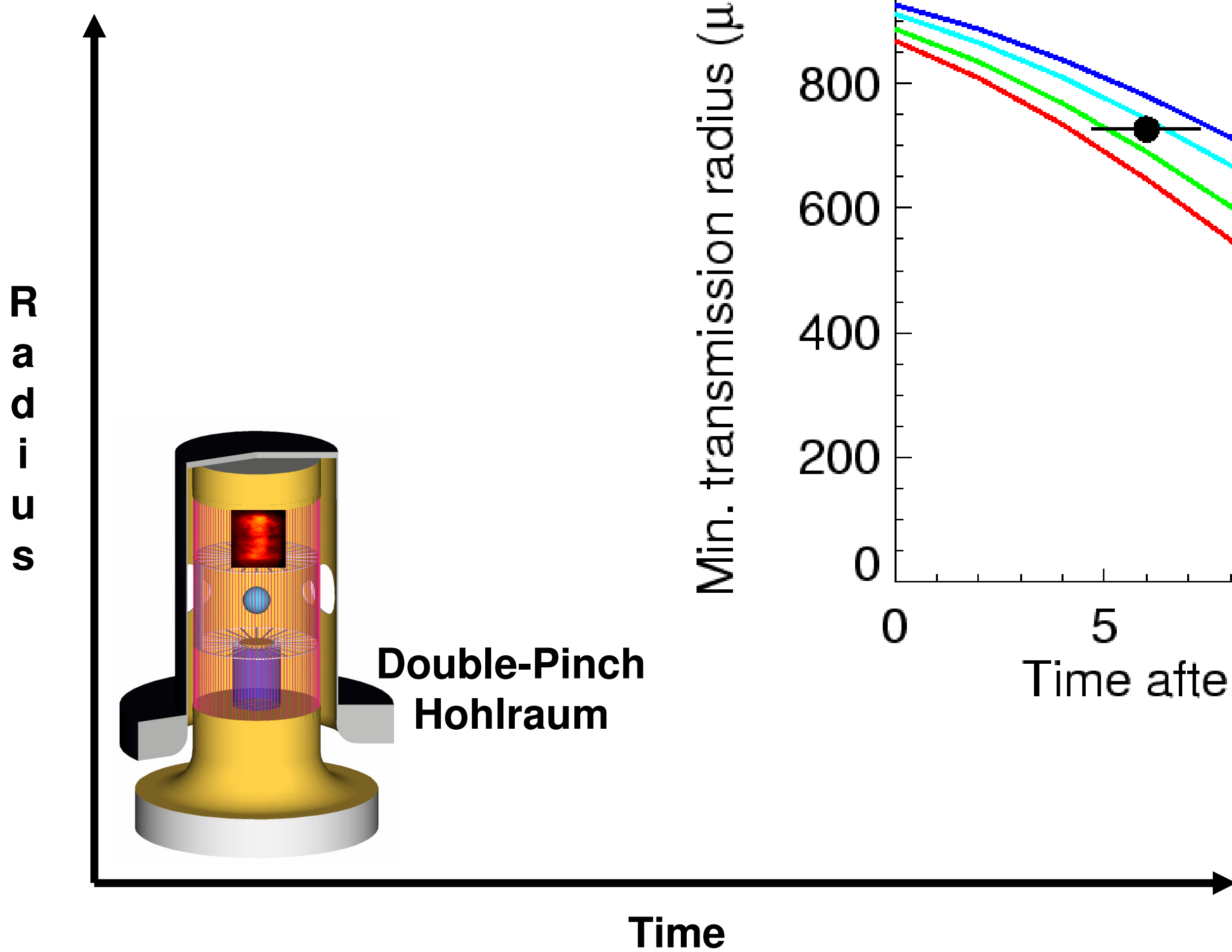


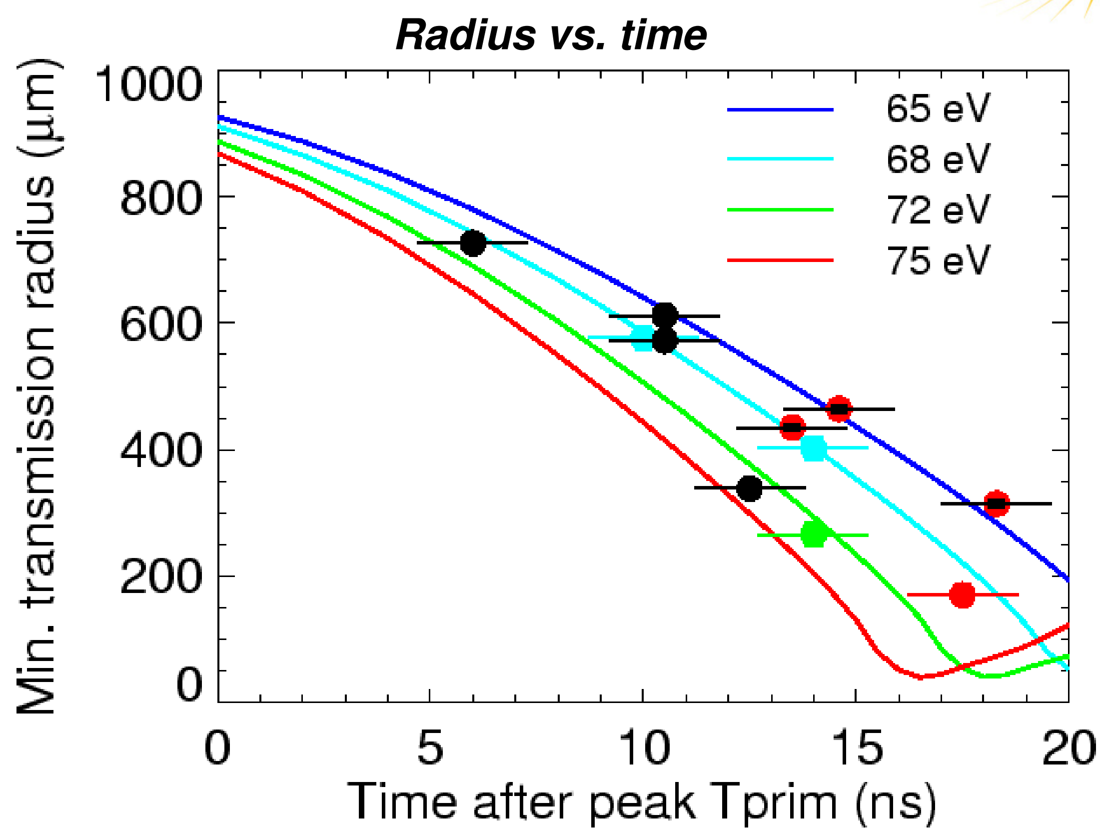
near peak CR
absolute transmission
~ 0 near center



Double-pinch hohlraum backlit capsule images agree with simulated capsule trajectory

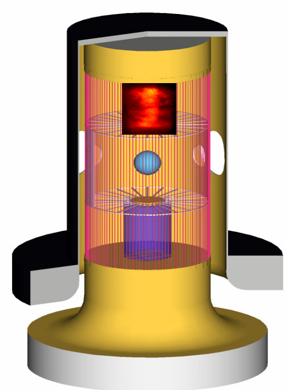
65-75 eV peak drive
6.8 – 8.7 kJ absorbed



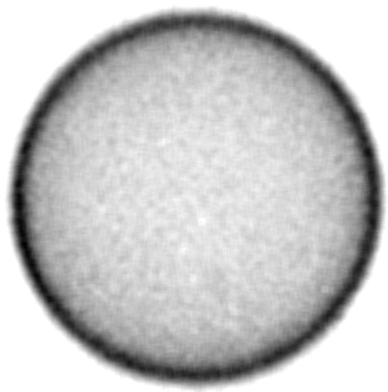


Capsule convergence of 14-21 has been observed in a double-*z*-pinch

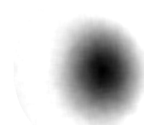
G. R. Bennett, et al., Phys. Rev. Lett., 89, 245002 (2002)



Pre-shot

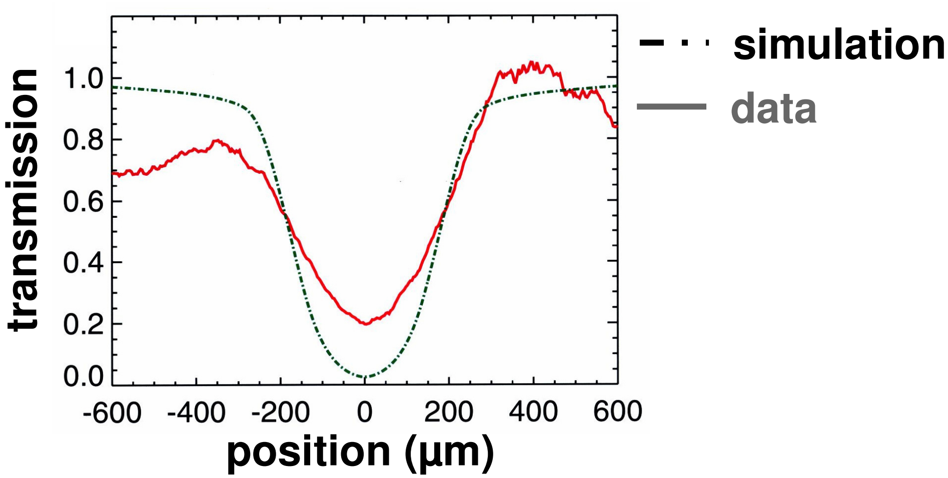


Z837
t = 22.5 +/- 1.3 ns
T_r = 68 eV

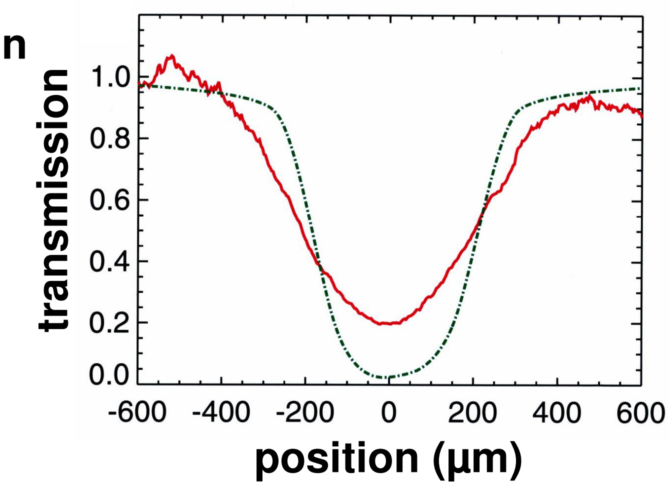


Simulated density in 2D rad-hydro of ~ 16 to 35 g/cc

Horizontal lineout



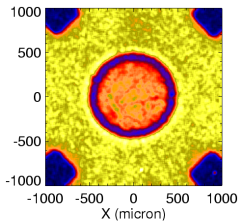
Vertical lineout



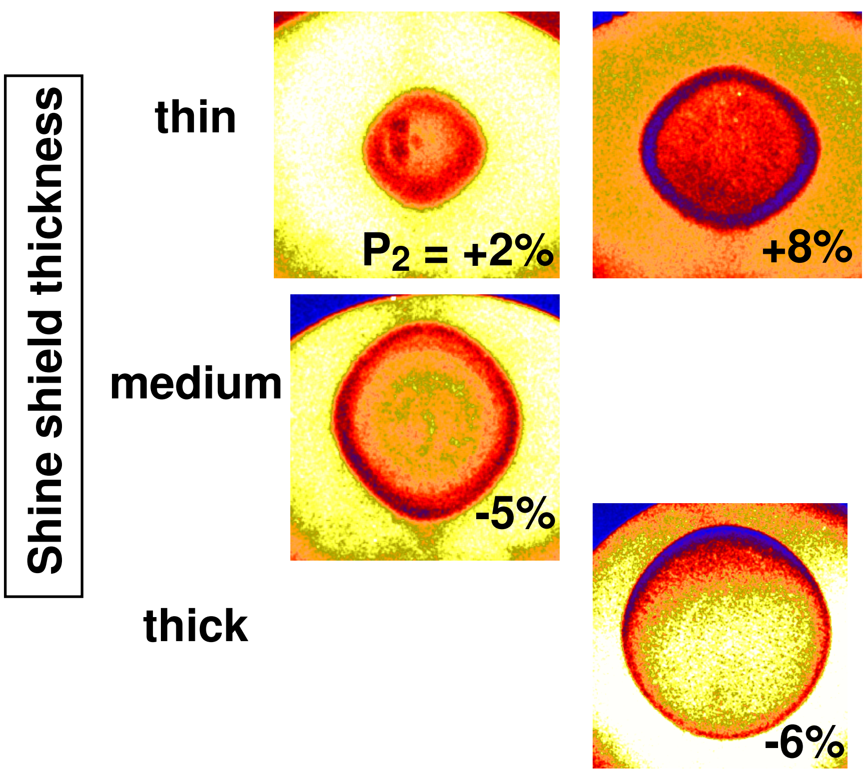
- capsules

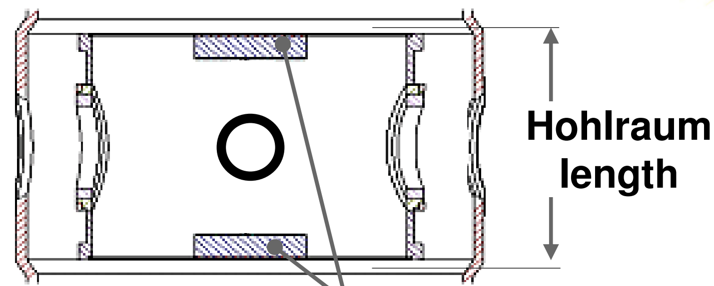
Larger 4.7-mm diameter capsules test symmetry control at HY-relevant case-to-capsule ratios of ~ 4

r_o = 1.05 mm



r_o = 2 .35 mm





- Capsules show a range of P2 from +8% through –6%
- P2 controlled by hohlraum length and shine shield thickness
- P4 for all these large capsules ranges from -3% to -8%
- Experiments varying primary wall radius for control of P4 planned

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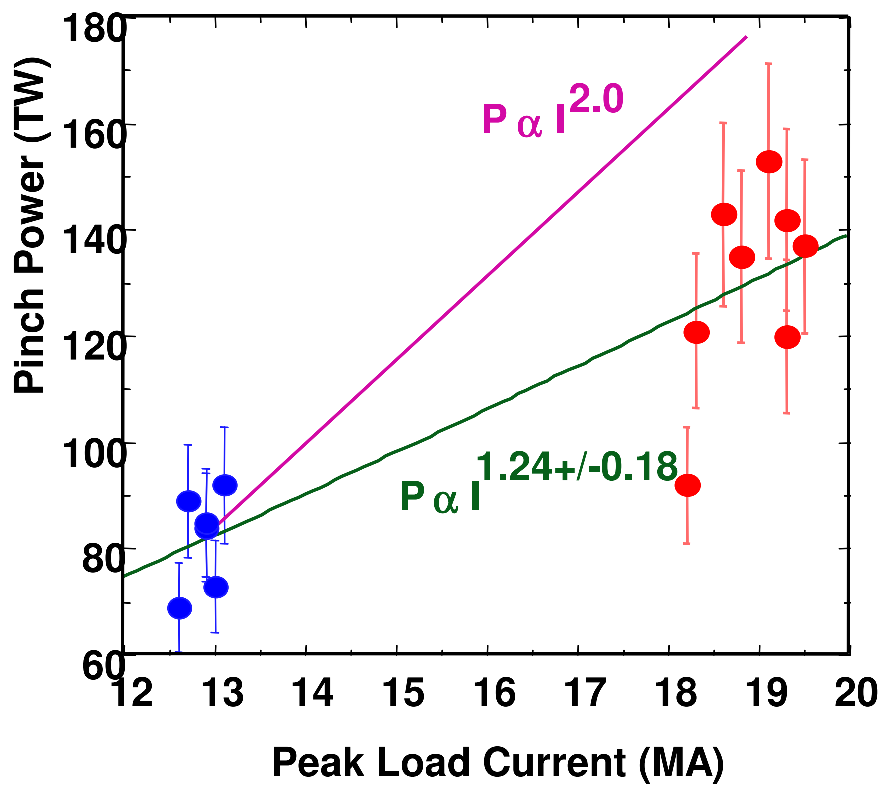
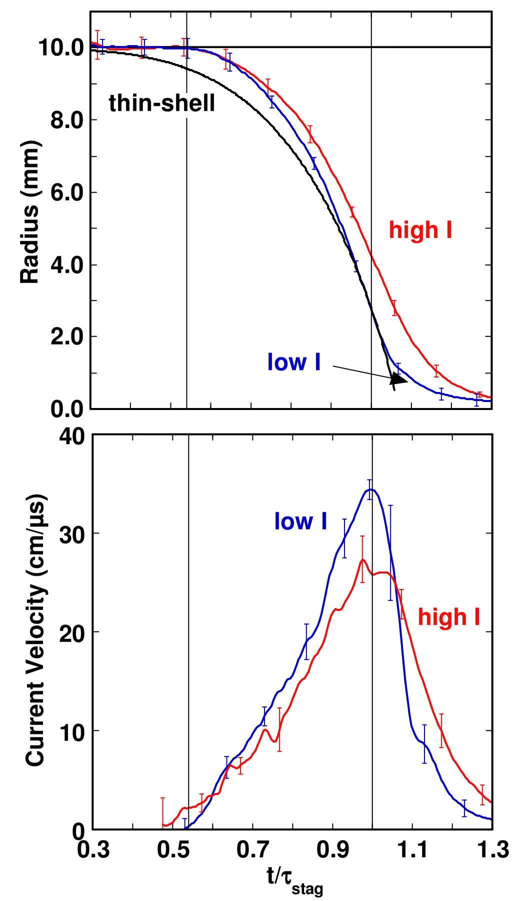
Sub-quadratic power scaling with current correlates with smaller convergence and peak velocity of current

W. A. Stygar, et al., Phys. Rev. E, 69, 046403 (2004)



P

M. E. Cuneo, et al., Phys. Rev. E, 71, 046406 (2005)
E. M. Waisman, et al., Phys. Plasmas, 11, 2009 (2004)



- Different implosion velocities confirmed with pinhole cameras
- Mazarakis et al. show I^2 scaling with 80 ns implosion times

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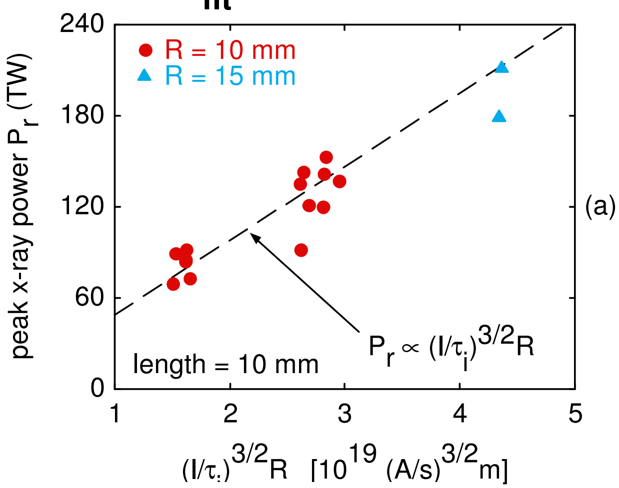
Pinch power scaling with current may be the most important issue for the double pinch

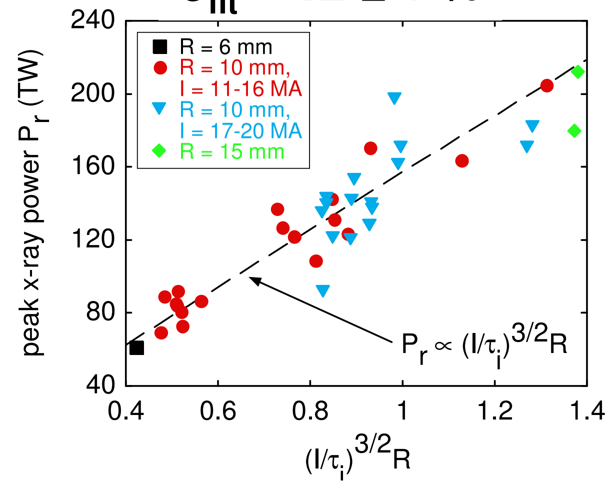
W. A. Stygar, et al., Phys. Rev. E, 69, 046403 (2004)
W. A. Stygar, et al., accepted, Phys. Rev. E, 69, (2005)

M. E. Cuneo, W. A. Stygar, et al., unpublished

σ_{fit} = 13 ± 2 %

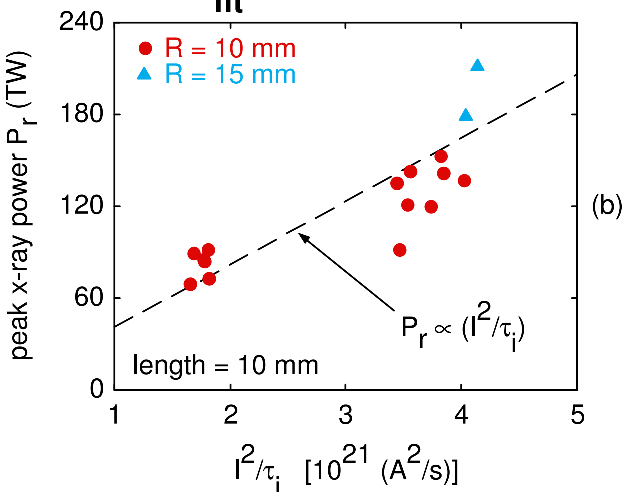


σ_{fit} = 12 ± 1 %

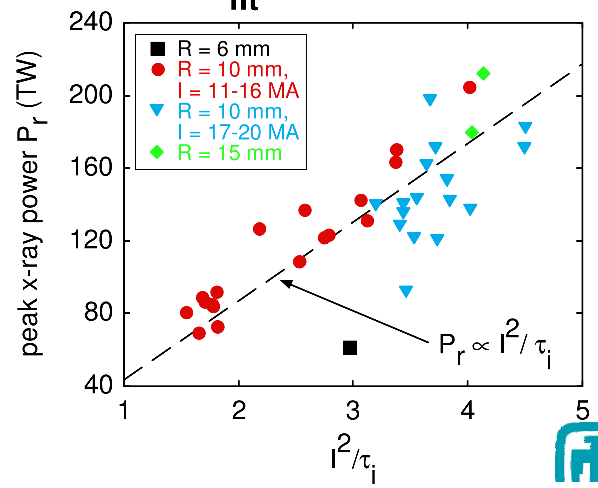


New datasets from: Cuneo Sinars, Mazarakis

σ_{fit} = 18 ± 3 %



σ_{fit} = 18 ± 2 %



- **Much more theoretical and simulation work is required**

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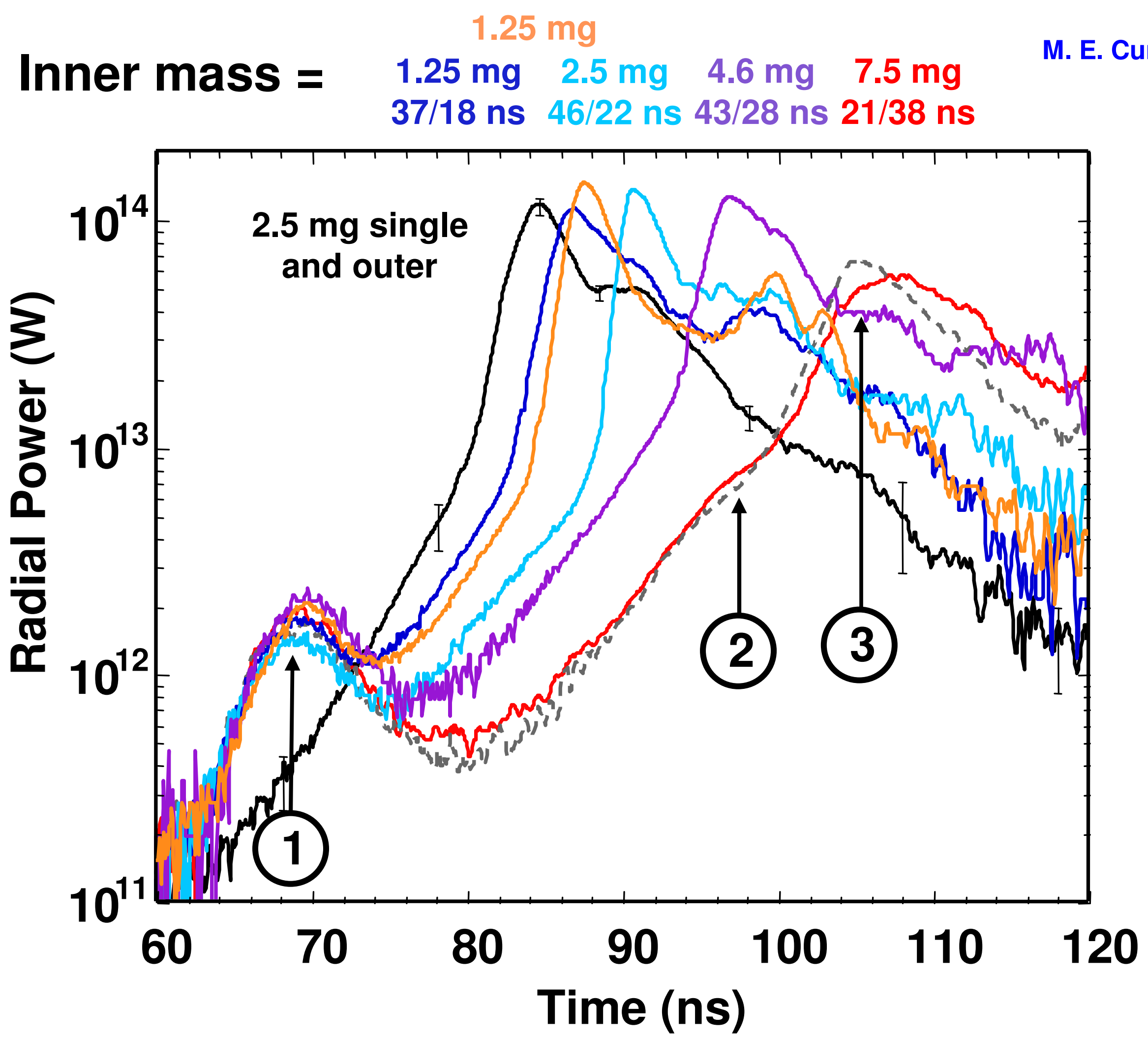
Nested wire arrays show systematic, controllable, and reproducible radiation pulseshaping

M. E. Cuneo, et al., to be submitted to Phys. Rev. Lett. (2005)



- 1st pulse: outer array interaction with inner
- 2nd step: inner interaction with foam target or precursor plasma
- 3rd step: inner array stagnation

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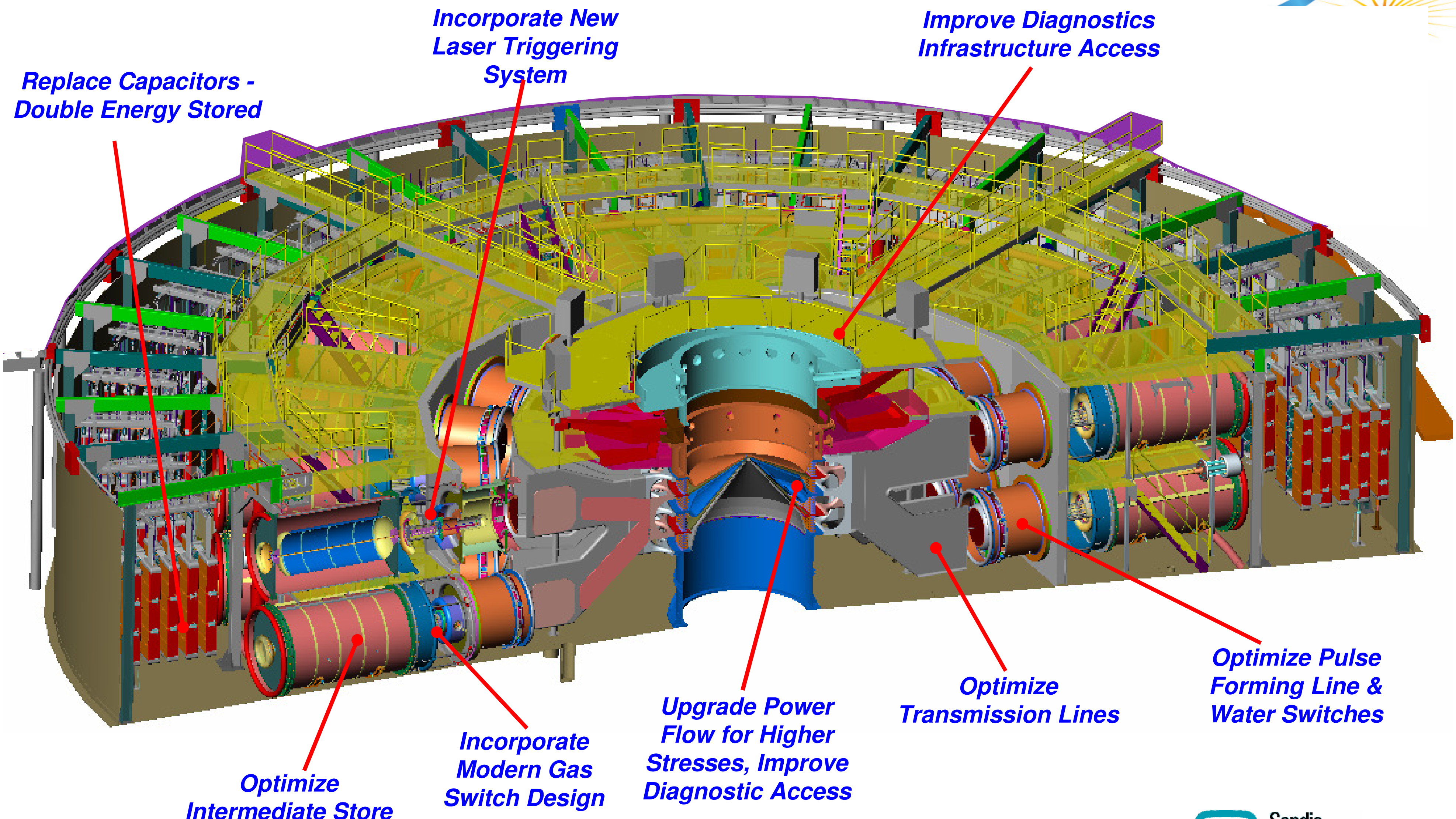
ZR - Refurbishing the ***Z*** pulsed power facility



26 MA, 3 MJ x-ray source

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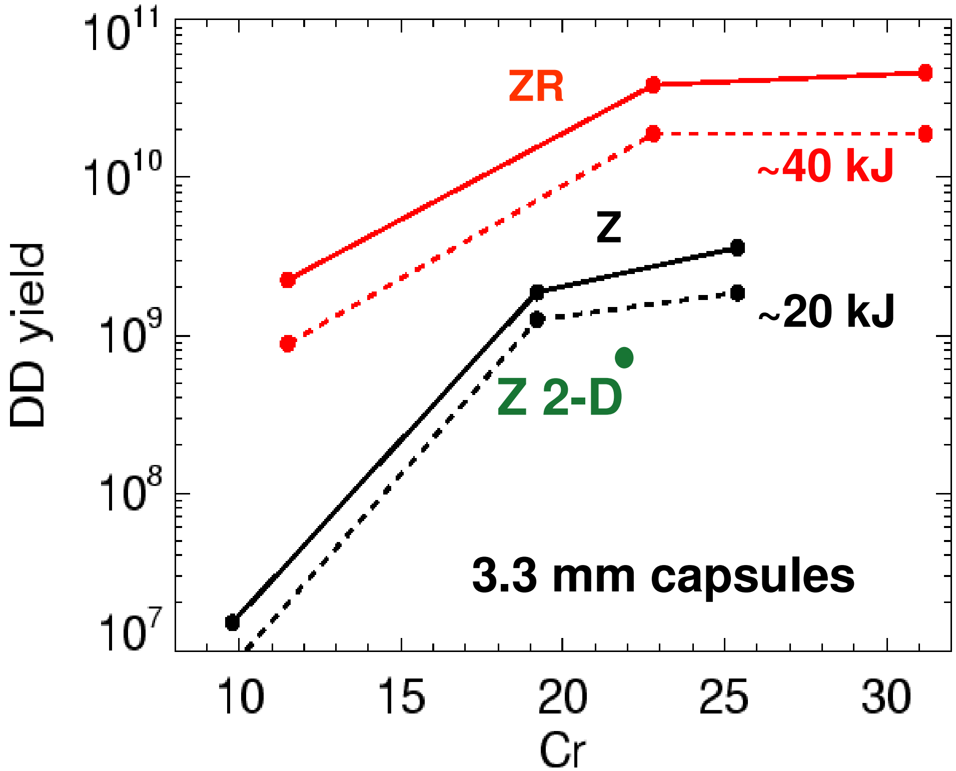
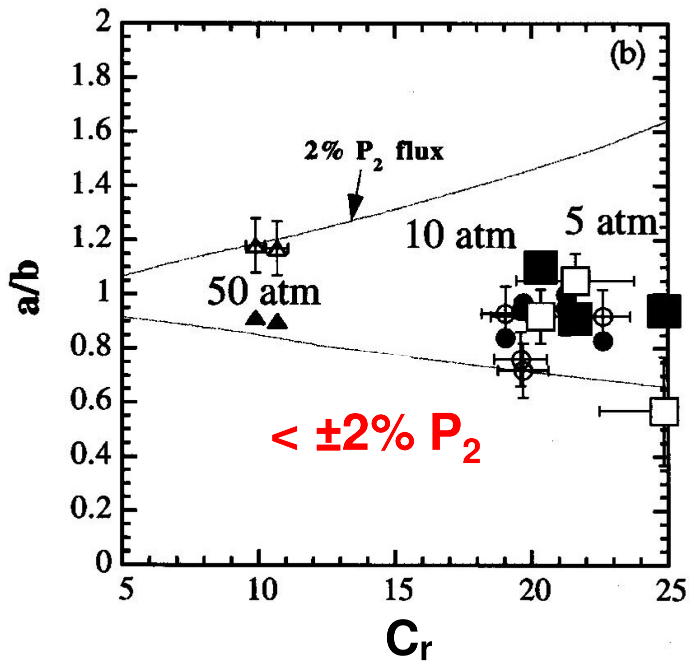
1% asymmetry with double-ended hohlraum allows high-performance implosions with Cr~20 on Z and ZR

1D Yield DD neutrons vs. C_r



Comparable to best laser-driven implosions possible now

P. Amendt et al., Phys. Rev. Lett., 89, 165001 (2002)



- We are developing advanced neutron diagnostics

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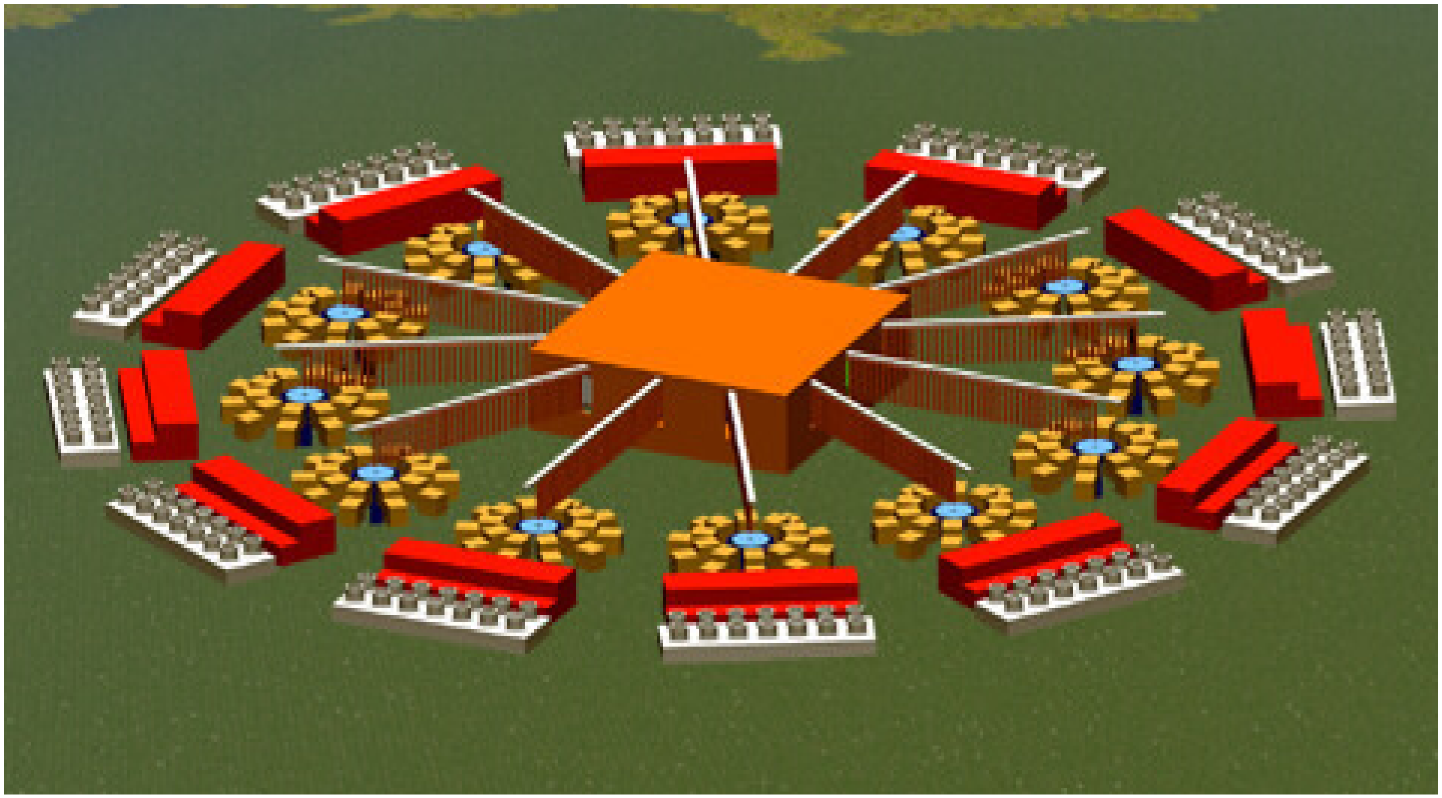
Conceptual *z*-pinch Inertial Fusion Energy (IFE) power plant

C.L. Olson, et al., Fusion Technology, 47, 633 (2005)



Cartridges (RTL, target assembly, blanket) are cast from recycled material and distributed to each module (1 GWe, 12 units, 3 GJ/pulse, 10 seconds between pulses in each module)

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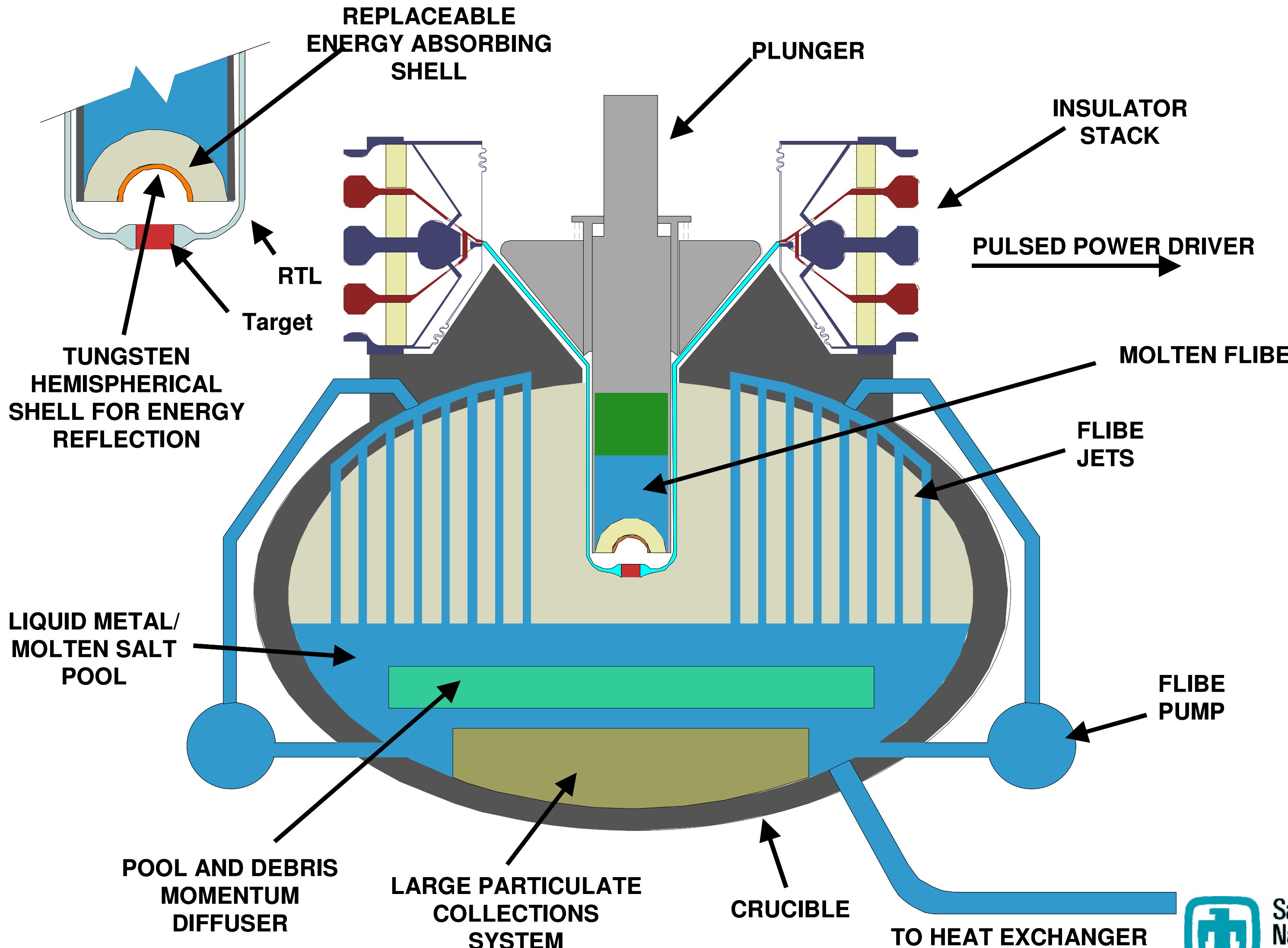
A *z*-pinch power plant chamber is based on the concept of a recyclable transmission line

C.L. Olson, et al., Fusion Technology, 47, 633 (2005)



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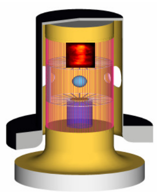
Future goals for dynamic-hohlraum and double-ended-hohlraum on the ZR accelerator



Double-Ended Hohlraum:

- Continue to study pinch physics and power scaling for the double-pinch
- How fast will the power scale with current for z-pinch loads that are optimized and pulse shaped?
- Achieve 1% time-integrated radiation asymmetry with 3-5 mm capsules at absorbed energies of up to 65 kJ
- Measure time-dependent symmetry swings with multiple frame backlighting
- Integrate pulse shaping and symmetry control on ZR
- Develop advanced, higher temperature compact double pinch loads, with short pulse, low mass, high dI/dt single and nested arrays

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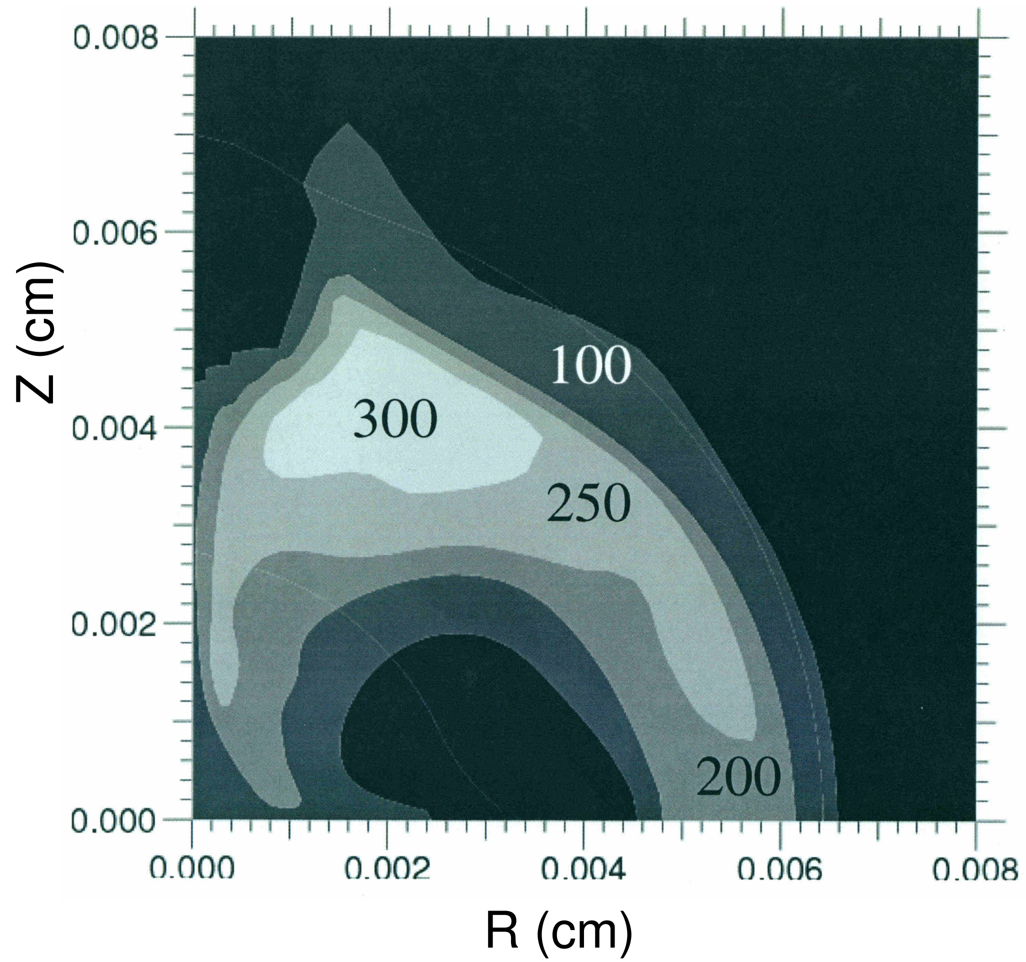
High DT fuel densities obtained with ZR parameters



Simulations yielded

$\rho r > 1$ g/cm^2 , $\rho > 300$ g/cc

Slide surface simulations need to be performed

The geometry as not yet been optimized!

S. A. Slutz

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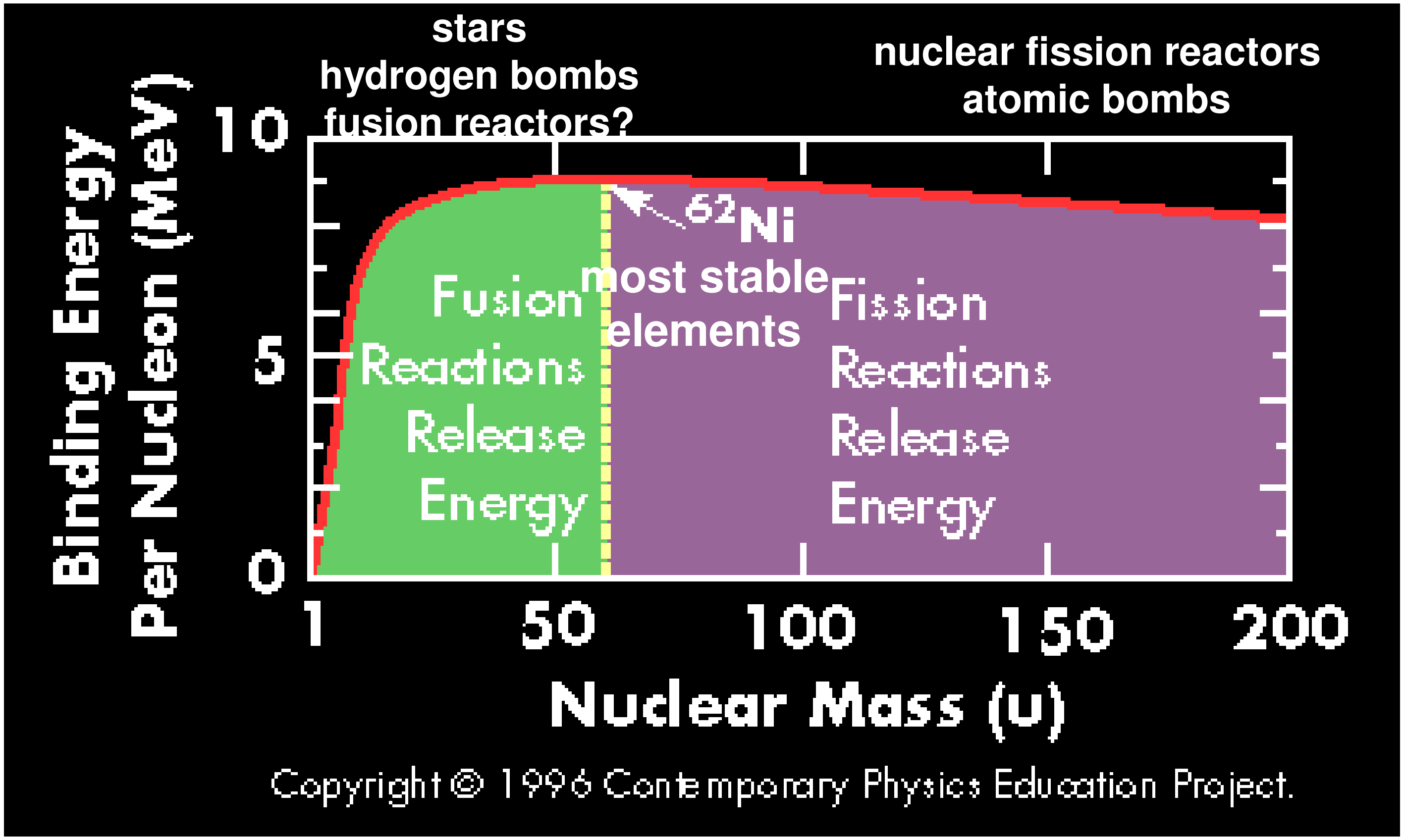
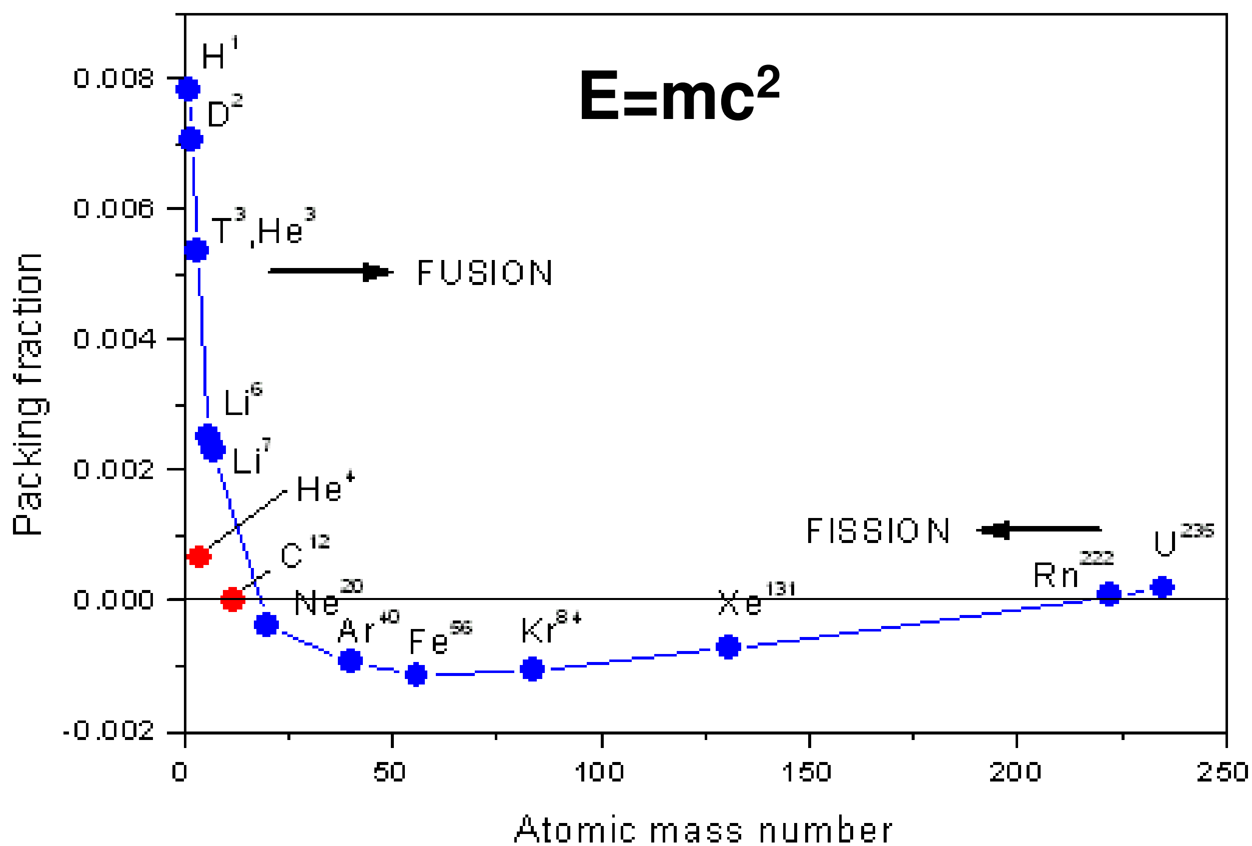
Conversion of mass into energy ($E=mc^2$) can proceed by (at least) two methods



Total mass is less after fusion or fission reaction than before
“Excess mass” is converted to energy

The excess mass/nucleon can be converted to energy

“Extra mass per nucleon”



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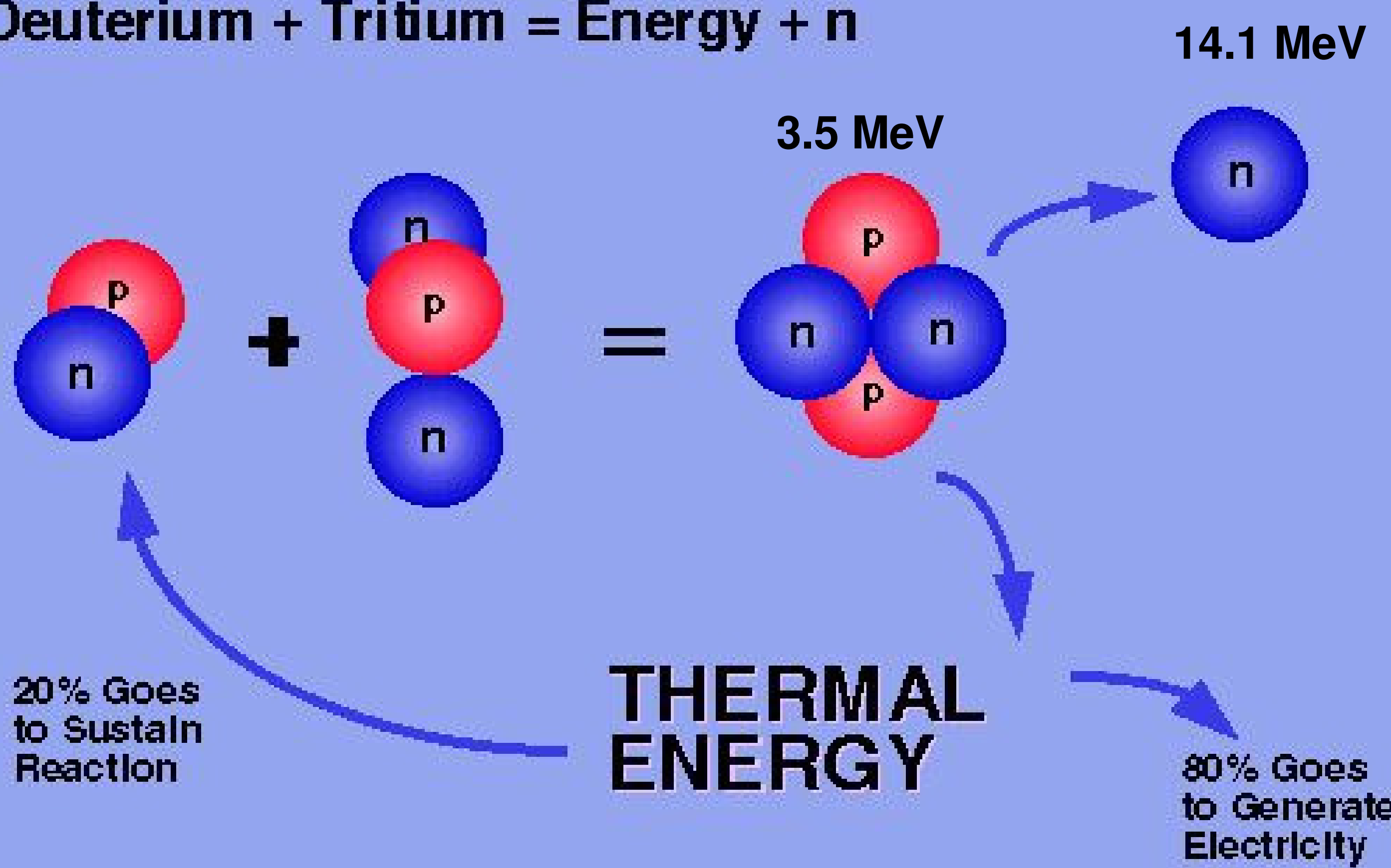
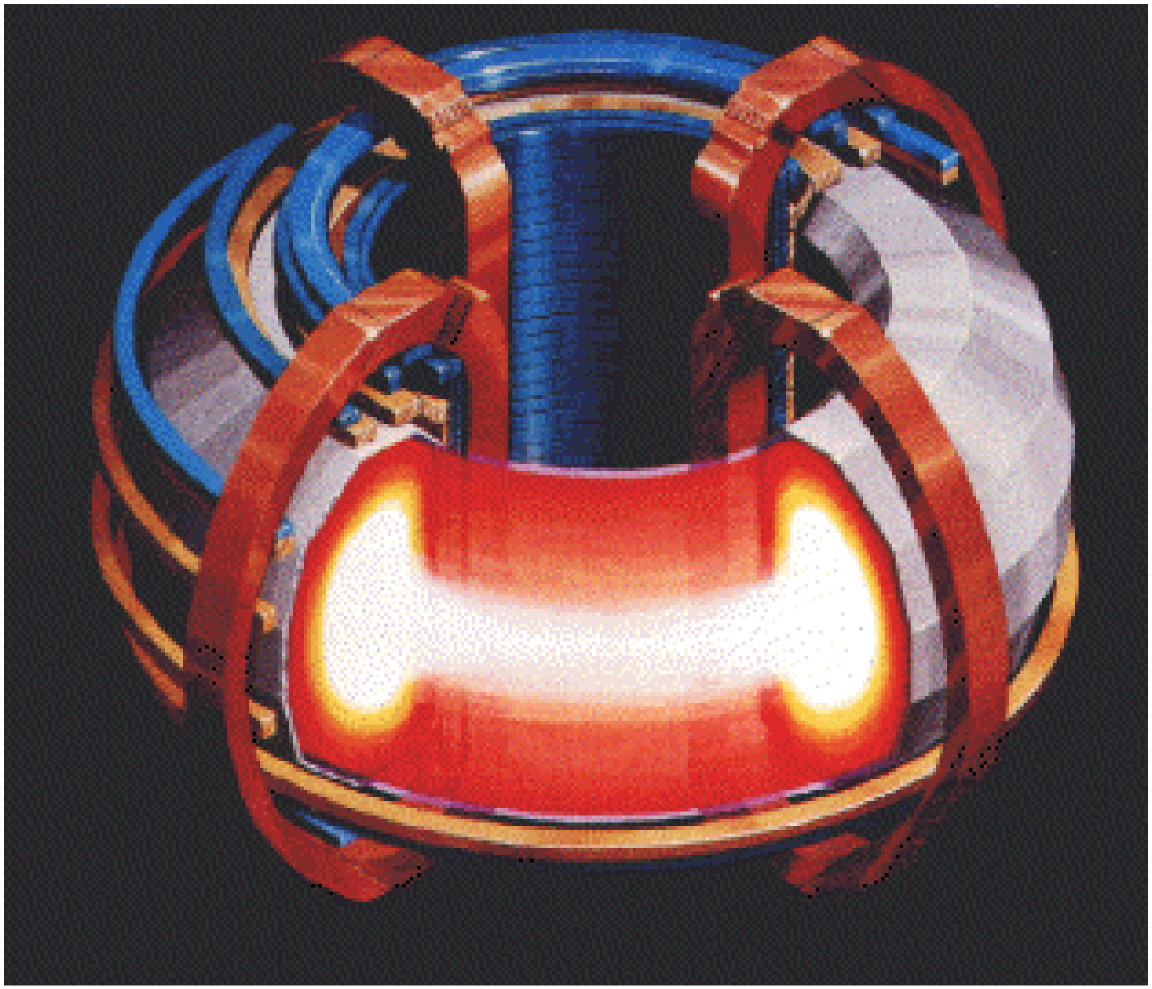
Fusion energy appears as the kinetic energy of the resultant particles

Deuterium + Tritium = Energy + n



Magnetic fields can confine hot plasmas (10 keV) for a long time (>2 sec) at lower densities (10^{14} cm^{-3})



Tokamak Plasma Confinement Method

Heating Techniques

Ohmic

EM waves

Neutral beams

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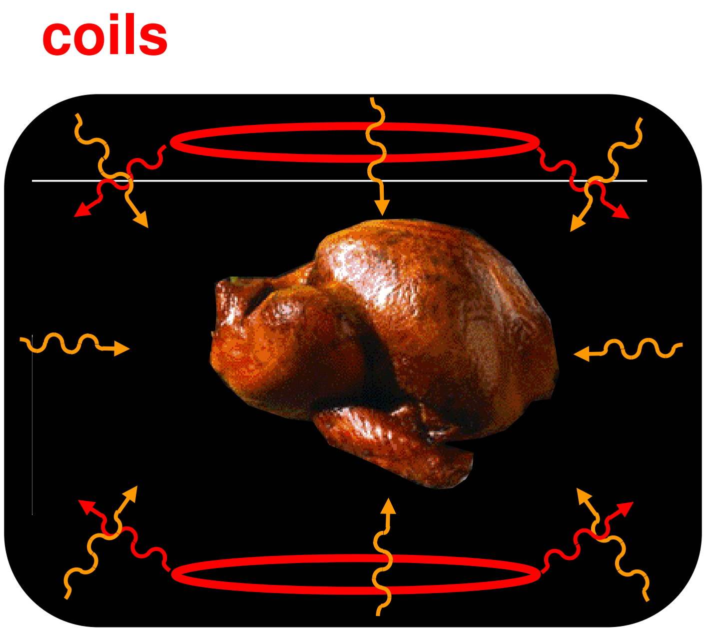
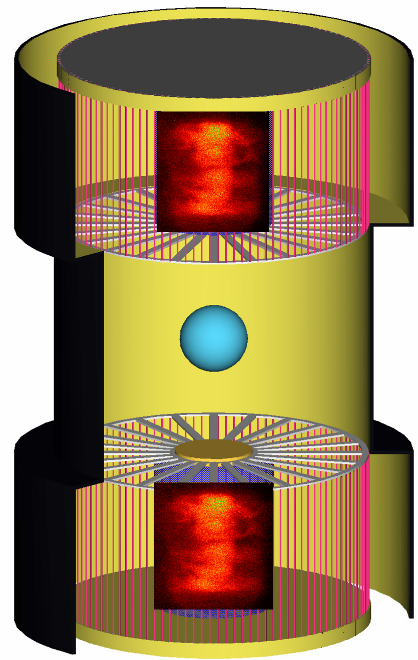
X-ray radiation uniformity must be within 1% to compress the capsule

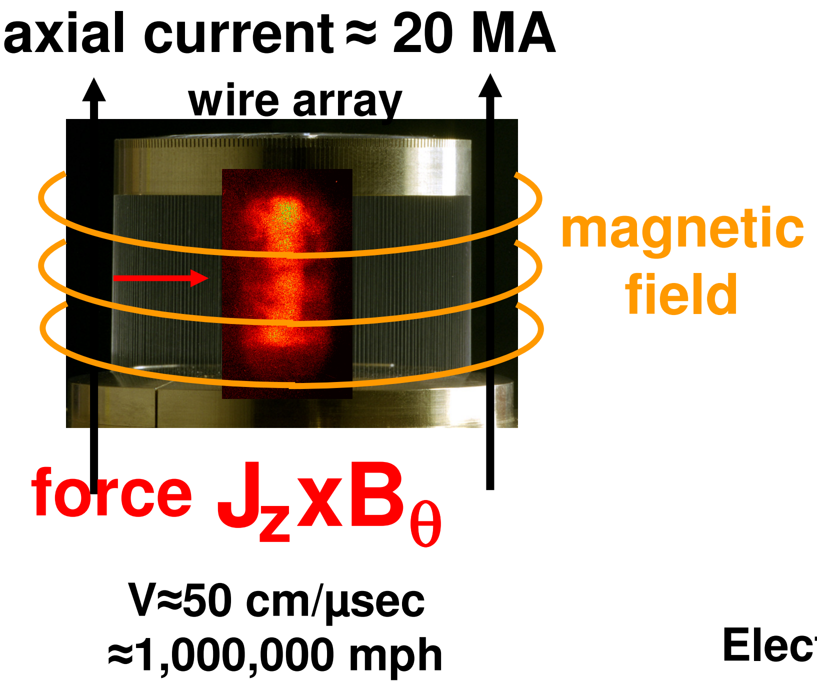


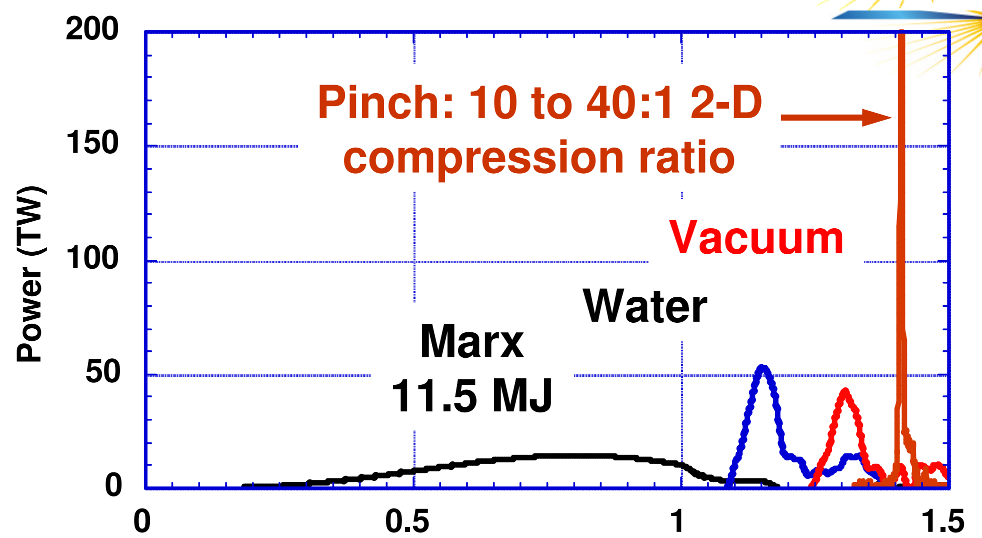
Oven: 350 °C
infra-red-radiation cavity
walls reflect radiation



Hohlraum: >2,500,000 °C
x-ray radiation cavity
walls ionize and re-emit radiation

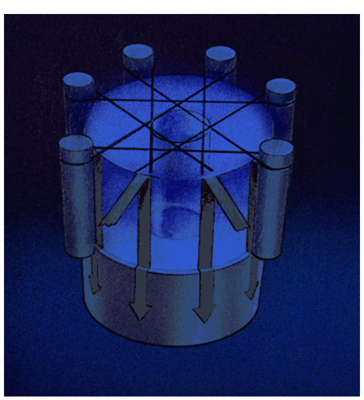
Z pinches are confined and accelerated by the self-B fields generated by an axial current



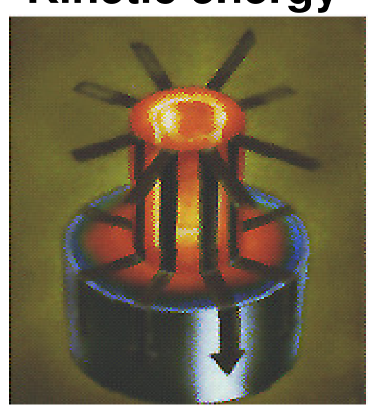


Electrical energy → Kinetic energy

Kinetic and magnetic energy → Internal energy → X-rays



Initiation



Implosion

Stagnation

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There are several power amplification/addition steps

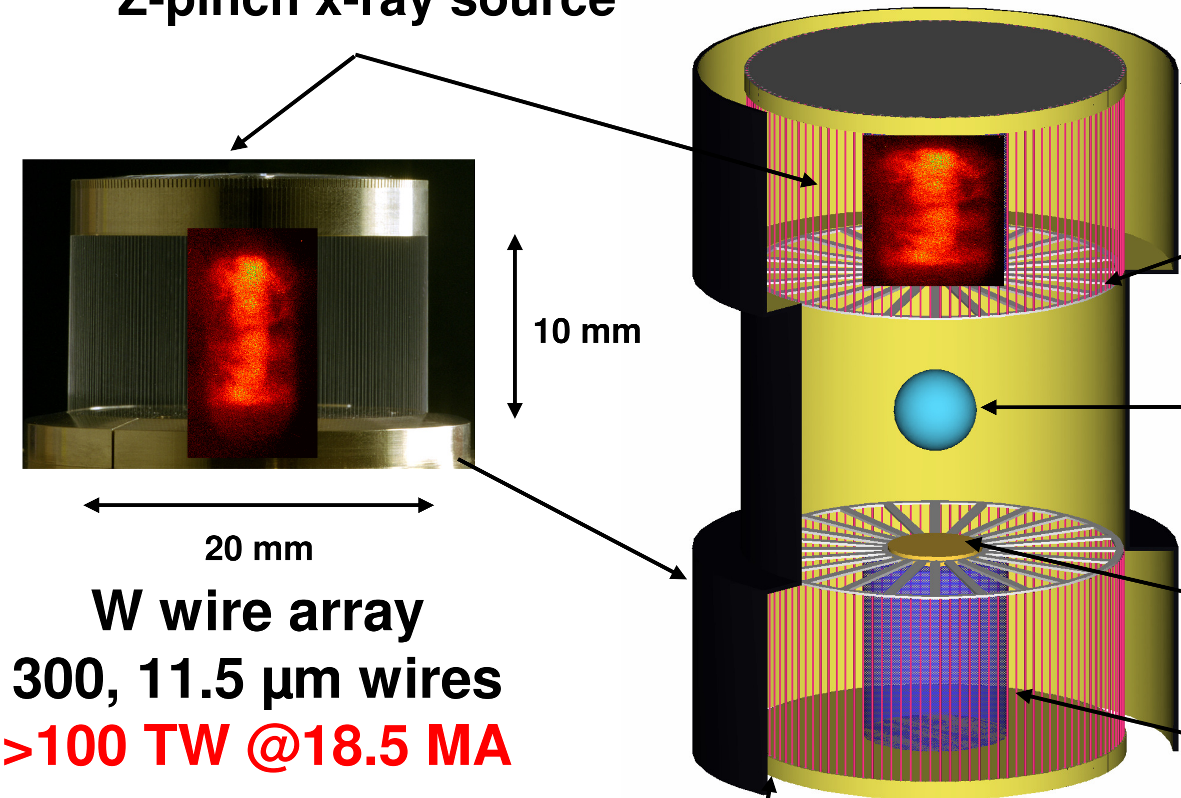
Device	Physics	Factor	Circa
	Wall plug power (110 v x 20 A) =	2200 watts	
Marx generator	Electrical pulse compression	2e8	1950's
Water lines	Electrical pulse compression	4	1970's
Multi-module	Laser Triggering	36	1980's
Low-L MITL	Low-loss transmission	----	1970-90's
Current Convolute	Parallel current addition	0.7	1980-1990's
Wire array Z-pinches	10-20:1 2-D convergence	3 - (6)	late 1990's
Hohlraums	Radiation confinement	5	1970-1990

(need another factor of 20 to get to fusion conditions: from multi-module/fast ignition/Dynamic Hoh)

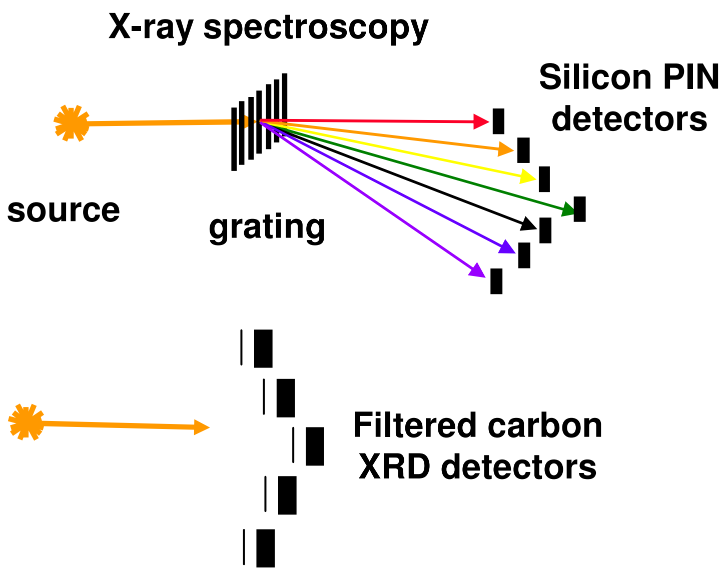
Capsule Implosions	30:1 3-D convergence (hot spot ignition)	>25	2010-25?

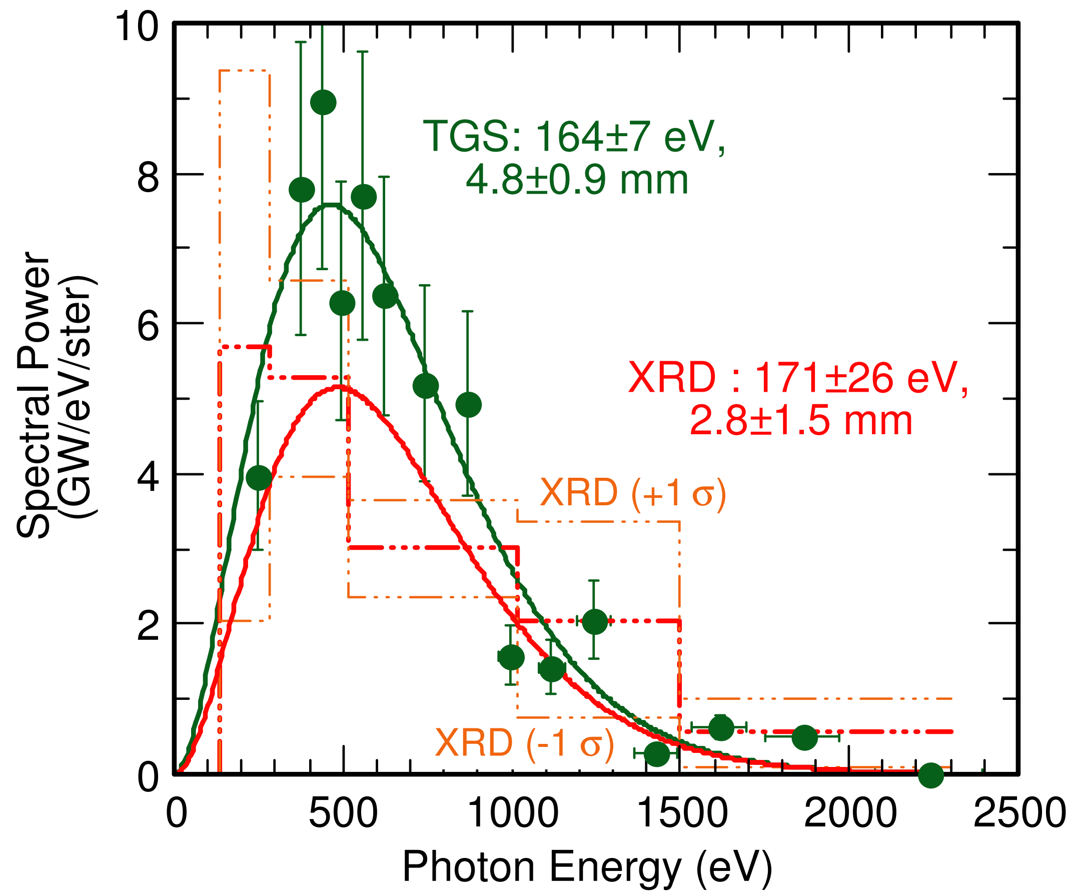
Total power = 2200 x 2e8 x 4 x 36 x 0.7 x 3 x 20 x 25 ≈ 70 petawatts ≈ 70000 TW

Z-pinch-driven-hohlraums show great promise as a driver for high-yield ICF capsules



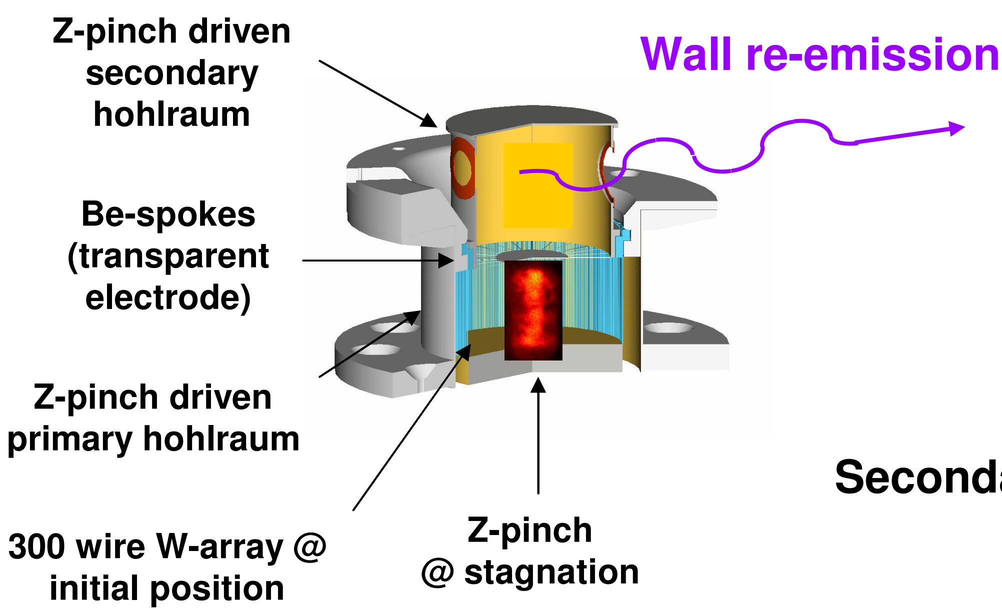
The pinch is a nearly-Planckian radiator

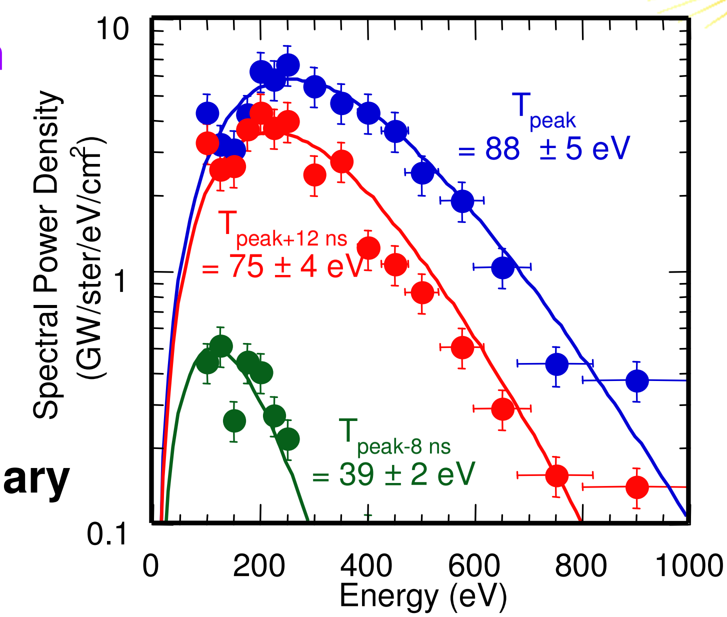


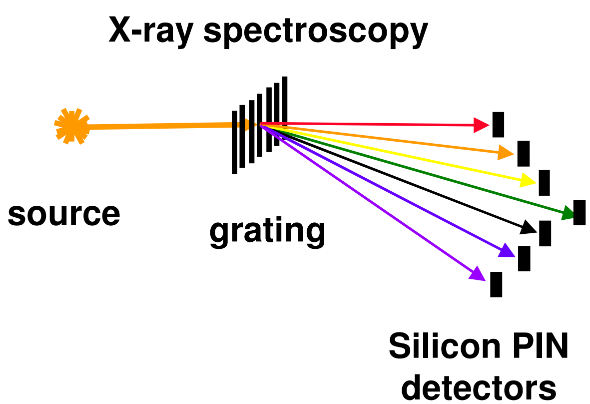


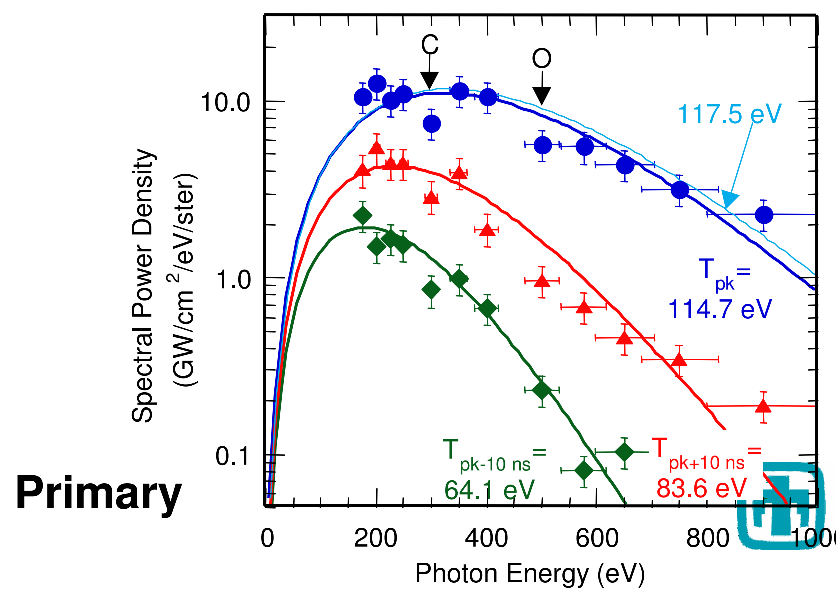
Optical depth in 1-D is about 5-10

Wall re-emission spectrum is Planckian for at least 20 ns in the primary and secondary





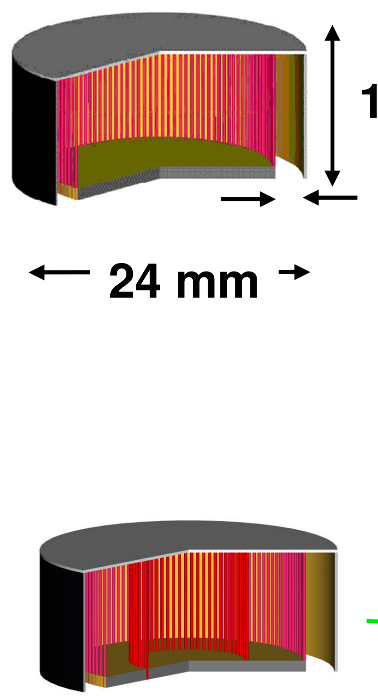


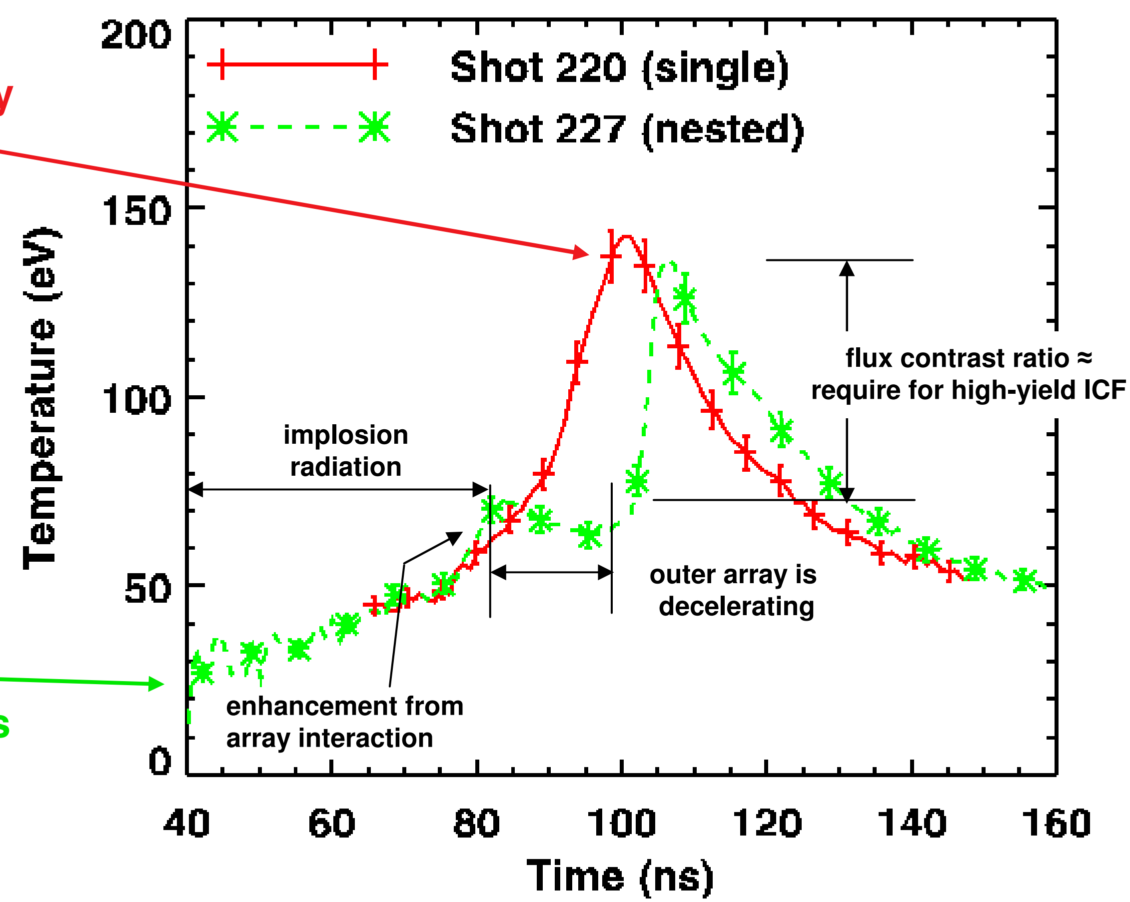


Meets ICF requirements

Nested wire arrays provide one example of a radiation pulseshaping technique

J. L. Porter, Jr. , Bull. Amer. Phys. Soc., 42, 1948(1997)
J. H. Hammer et. al., Phys. Plasmas, 6, 2129(1999)



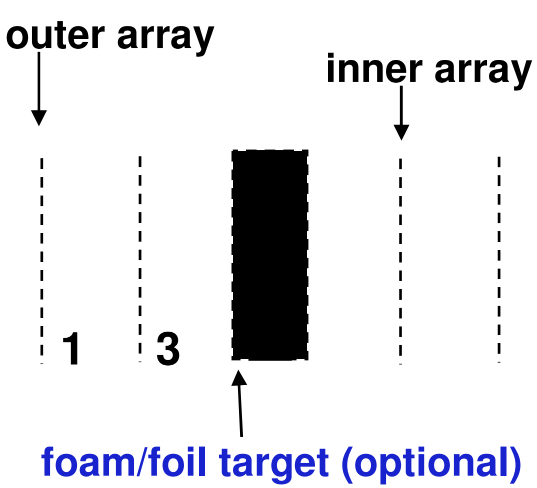


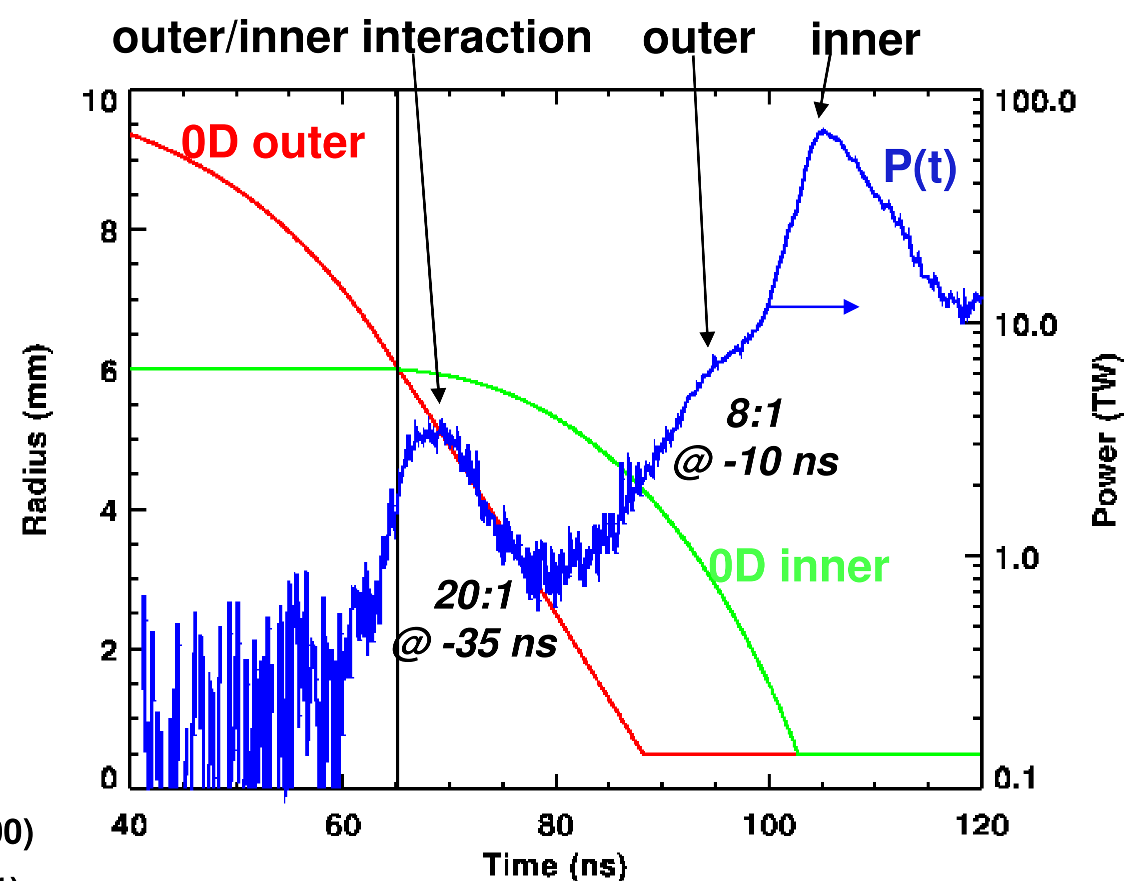
- We are beginning a systematic study of ICF pulseshaping

Laboratories

We are developing 3-shock pulseshapes for high yield capsules with nested arrays

High mass ratio transparent nested arrays*





*Transparent mode wire arrays

Davis et al., Appl. Phys. Lett., 70, 170 (1997)

Lebedev et al., Phys. Rev. Lett., 84, 1708 (2000)

Chittenden et al., Phys. Plasmas, 8, 675 (2001)

Bland et al., prepared for publication

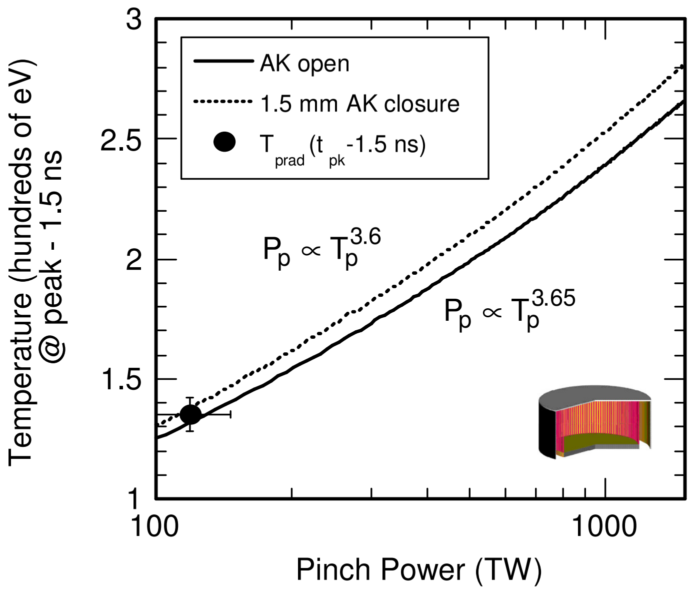
Many other requirements must be satisfied for hot spot ignition

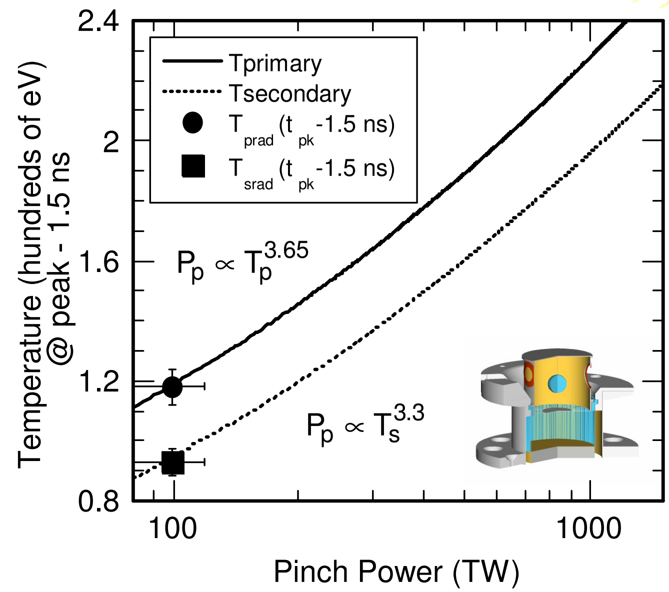
Radiation symmetry
- 1% time integrated over 20 ns pulse
- larger asymmetries can be tolerated over shorter windows
- requirements on shell thickness

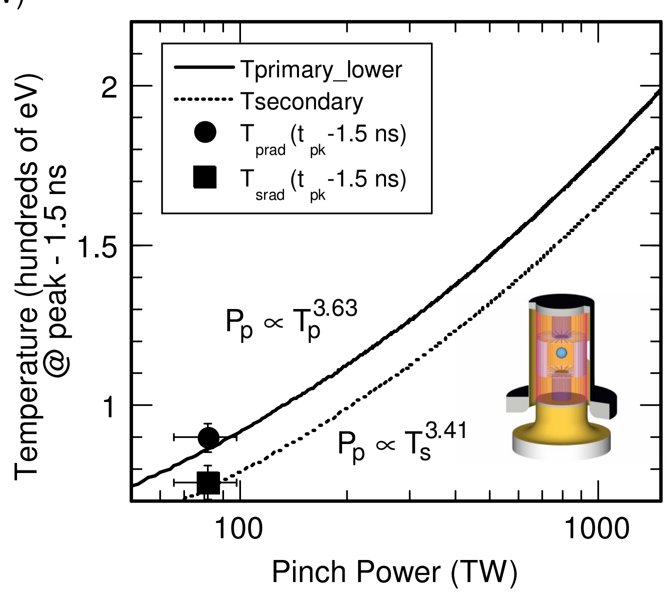
Rayleigh Taylor instability
- requirements on shell radius to shell thickness
- requirements on shell thickness

Minimize capsule preheat to minimize drive energy
- ≤ 1 eV preheat tolerated
- 4 pulses with precise shape and amplitude
  - 100 ps shock timing
  - <2% variation in shock drive temperatures
  - <5% shell thickness variations
- 93±3% ablator burn through fraction

0-d model gives good agreement between measured temperatures and powers







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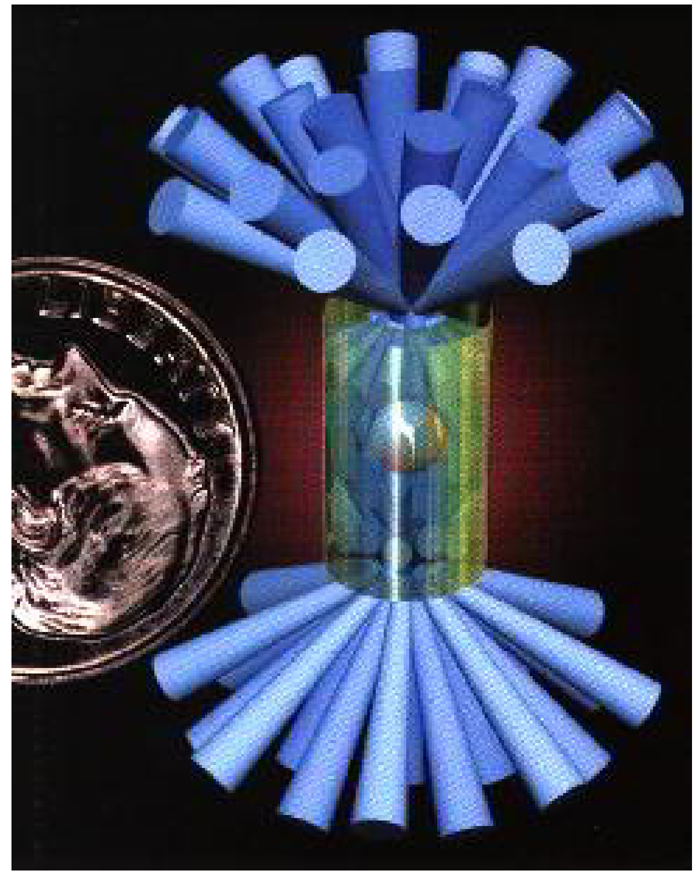
MEC, 10/00

NIF requires a very complex method with 192 laser beams to produce adequate symmetry

NOVA Laser (20 laser beams)

Best convergence ratio on NOVA ≈ 20



NIF Laser (192 laser beams)
2MJ x-ray source/20 MJ Capsule Yield
2000$ capital cost/x-ray joule

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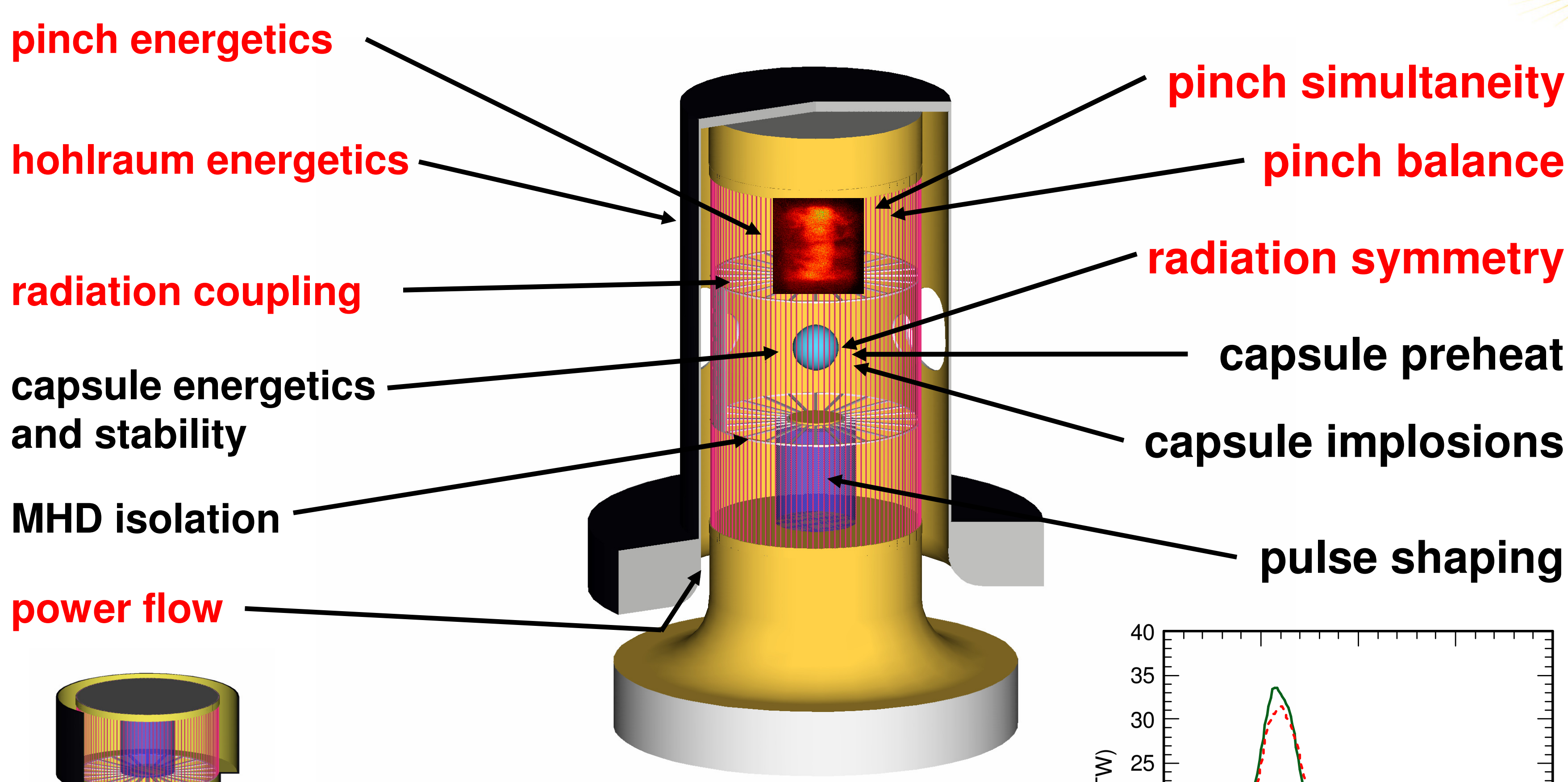
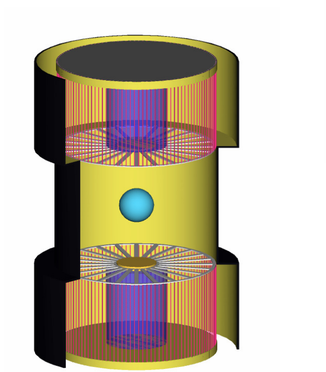
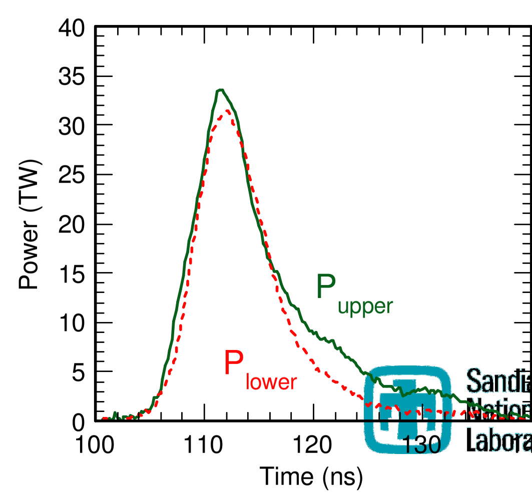
A systematic study of the many outstanding physics issues is proceeding on *Z*



single-sided power feed on *Z*



two-sided power feed



Tools and approach necessary to scale to ZR and beyond

- Hierarchy of tools needed to predict instead of "all or nothing calculational" approach [stay as close as possible to experimental results in "leap frog approach"]:
  - Back of the envelope models
  - Circuit and data analysis
  - 1D RMHD
  - 2D RMHD in x,y and r,z planes
  - 3D RMHD
  - Tensor electrical conductivity representation
  - Turbulent models incorporated in tool kit
  - Beyond MHD

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Approach towards scaling for more powerful pulsed power generators

- The largest paradox in this field is not how complex z-pinches are, how turbulent they are, how unstable, but:

- How reproducible the experimental results are!!!

- Why? How do we resolve this paradox in an useful way towards predictive scaling?

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Wire Array Phases

- At an elementary level we understand (cartoon, simple models, some calculations) the phases of wire array implosion:
  - Initiation (formation of boundary layer and cold core)
  - Ablation
  - Snowplow
  - Stagnation
- We have somewhat adequate descriptions of the Ablation and Snowplow phases if we accept the decoupling approximation of Aleksandrov et al *[however initiation may change mass rate properties]*

A model for ablated plasma width applied to peak X-ray power scaling for z-pinch wire array implosions [1]

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OUTLINE

- 1D radial ablation inflow for wire arrays
- Definition of density distribution width for various models
- Application of width calculation to x-ray peak power scaling on Z
- Conclusions

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1D radial Ablation Model for wire arrays

- During the ablation phase the wire array is considered a mass injecting source
- The momentum generated by the magnetic force at the initial wire position accelerates the injected mass while the dense core is stationary. We can write a dimensional relationship between the mass rate and the magnetic force per unit of axial length: $\dot{\mu}(g/cm)u_a(cm/s) = I^2(A)/100r_0(cm)$
- The character of the flow is determined by what is assumed about the "ablation velocity"
- The fundamental quantities are $\dot{\mu}, I$, in terms of which u_a is defined
- Under conditions relevant to experiments, the flow that develops attains the Alfven speed near the injection point (boundary layer), $u_{Alfven} = -2u_a/3$, and becomes super-Alfvenic in its motion towards the axis[1,2]
- The plasma becomes a perfect conductor experiencing negligible pressure force
- The three equations that apply are: conservation of mass, conservation of flux and the momentum equation containing the $j \times B$ term as the only acting force

[1]V. V. Aleksandrov, et al, Plasma Phys. Rep. **27**, 89, (2001)

[2]J.P. Chittenden, S .V. Lebedev, B.V. Oliver, E.P Yu, and M.E. Cuneo, Phys. Plasmas **11**, 1118 (2004)

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1D radial Ablation Model for wire arrays (Cont.)

- We define the mass weighted width of the density distribution at the end of the ablation phase as:

$$\delta \equiv \sqrt{\langle y^2 \rangle - \langle y \rangle^2}$$

$$\langle y^n \rangle = \langle (r/r_0)^n \rangle = \int_0^{r_0} dr (r/r_0)^n 2\pi r \rho(r) / \int_0^{r_0} dr 2\pi r \rho(r)$$

- This width can be calculated for various relevant cases for super-Alfvenic flow equations

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1D radial Ablation Models considered to compute ablated sheath width

- For super-Alfvenic flow equations:
- Rocket model[3]: assumes, ad-hoc, that the flow velocity is constant in radius and equal to the constant ablation velocity, for arbitrary current
- Steady state[2], constant current and constant ablation velocity. Analytic solution for flow equations has been obtained
- Current exponential in time and constant ablation velocity. Analytic solution for flow equations has been obtained[4]
- Numerical solution[4] of flow equations for $I = \dot{I}\,t,\; u_a(t) = u_R(\dot{I}\,t / r_0)^{\eta} / (I / r)_R^{\eta}$ using code introduced in [1], where R stands for reference value of the quantities

[1] V. V. Aleksandrov, et al, Plasma Phys. Rep. **27**, 89, (2001)

[2] J.P. Chittenden, S.V. Lebedev, B.V. Oliver, E.P Yu, and M.E. Cuneo, Phys. Plasmas **11**, 1118 (2004)

[3] S. V. Lebedev, et al, Phys. Plasmas **8**, 3734 (2001)

[4] To be published by authors of this presentation

1D radial Ablation Model for wire arrays
Properties of super-Alfvenic flow equations

- A remarkable property of super-Alfvenic flow equations is that for:

$$I = \dot{I}\,t,\ \ u_a(t) = u_R(\dot{I}\,t/r_0)^{\eta}/(I/r)_R^{\eta}$$

- The solution, including the Alfvenic boundary conditions, depends solely on:

$$x = u_a(t_a)t_a/r_0 \text{ and parametrically on } \eta$$

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Width depends on dimensionless variable

$$x = u_a(t_a)t_a / r_0$$

Model	u_a	$I(t)$	δ	Method
Rocket	constant	$\dot{I}t$	$0.19x$	Ad-hoc $u(r) = u_a$
Steady State	constant	constant	0.29	Analytic solution
Exponential Current	constant	$I_0 e^{\alpha t}$	$0.19x$ $x \le 0.8$	Analytic solution: $\alpha t_a = 3.0$
"Experiment"	$u_R(\dot{I}t/r_0)^{\eta} / (I/r)_R^{\eta}$	$\dot{I}t$	$0.17x$ $x \le 1.5$	Numerical, only function of x. $\eta = 1/3$

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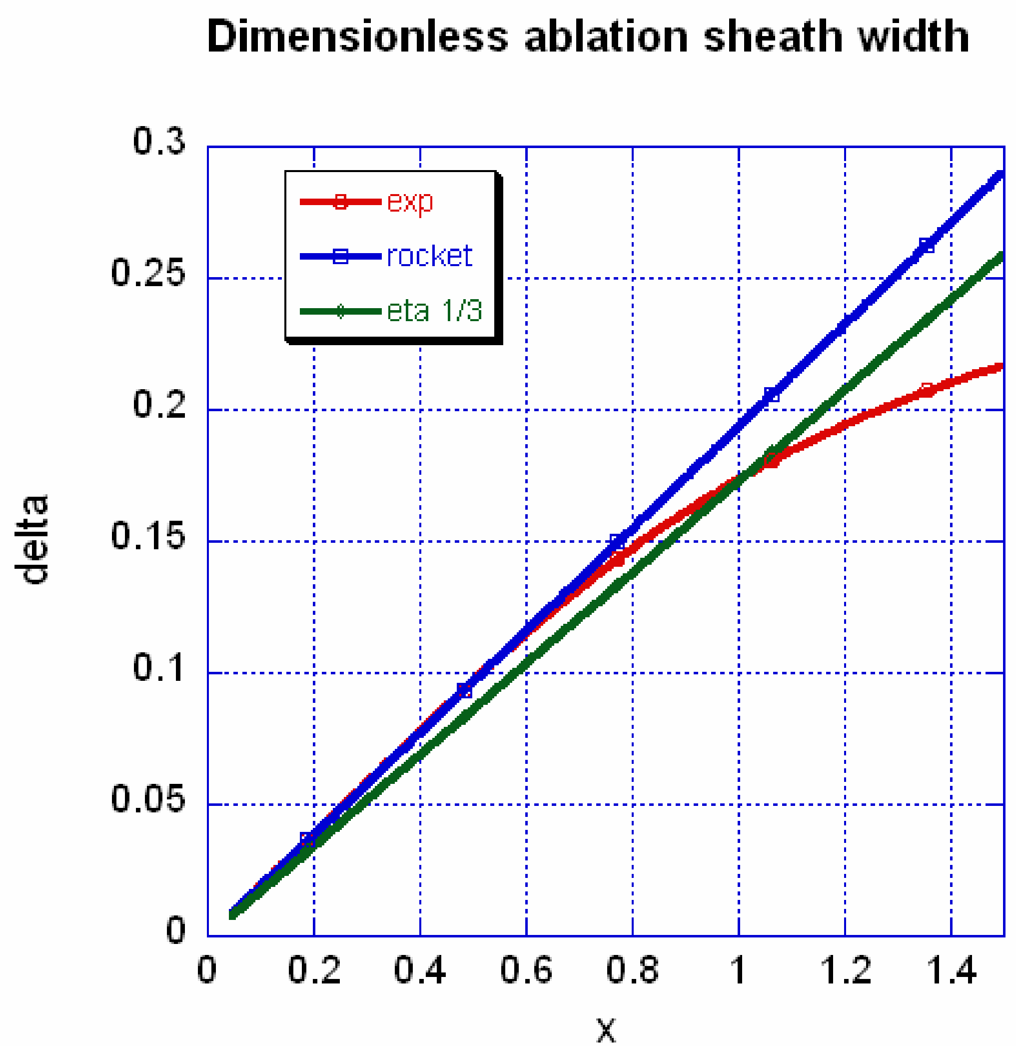
Dimensionless Width as a function of

$$x = u_a(t_a)t_a / r_0$$



Peak X-ray power scaling

- Assuming that the sheath width at stagnation is proportional to the ablation width and that the radiated energy is proportional to I^2 we find[5,6] for the peak x-ray power

$$P \sim I^2 / \tau\delta$$

- For a given generator, such as Z and ZR, and for optimal number of wires the three independent variables of the implosion can be chosen as

$$(\dot{I}, \tau, r_0)$$

[5] W. A. Stygar et al, Phys. Rev. E **69**, 046403 (2004)

[6] W. A. Stygar et al., submitted for publication to PRE (2005)

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Peak X-ray power scaling

- We find the scaling with the peak X-ray power in terms of the implosion variables by using the results of width for super-Alfvenic flow, and implosion and total mass ablation conditions for $\eta = 1/3$

$$\delta \sim u_a(t_a)t_a / r_0 \sim (\dot{I})^{1/3} t_a^{4/3} / (r_0)^{4/3}, \text{ width}$$

$$\mu_0 \sim (\dot{I}/r_0)^2 \tau^4 \sim (\dot{I})^{5/3} (t_a)^{8/3} / (r_0)^{2/3},$$

  Where the last two proportionalities are the implosion and ablated mass conditions, respectively

- To finally obtain

$$P \sim r_0 (I/\tau)^{3/2} (r_0/\tau)$$

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Conclusions

- For $I = \dot{I}t$ the sheath width for super-Alfvenic flow is proportional to $u_a(t_a)t_a / r_0$ assuming $u_a(t) = u_R(\dot{I}\,t / r_0)^\eta / (I / r)_R^\eta$

- This linear dependence holds for the simple "rocket model" and, for small values of $u_a(t_a)t_a / r_0$,for the exponential in time current case

- For $\eta = 1/3$ we obtain $(\dot{I})^{3/2}$ scaling[1] for r_0 *and* τ fixed, by assuming that the sheath width at stagnation is proportional to that of the end of the ablation phase, and that the mass ablated fraction is independent of $\dot{I}$

[1] This result is only the same as the scaling proposed in W. A. Stygar et al, Phys. Rev. E **69**, 046403 (2004), for wire array radius and implosion time fixed

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Conclusions (cont.)

- The relationship between ablation and stagnation sheath width needs to be further tested with RMHD calculations

- RT is expected to dominate for small "ablation widths" and thus I^2/τ scaling to apply[6]

[6] W. A. Stygar et al., submitted for publication to PRE (2005)

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