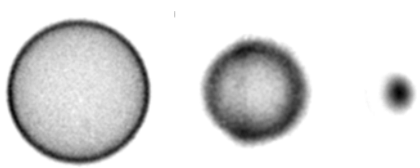
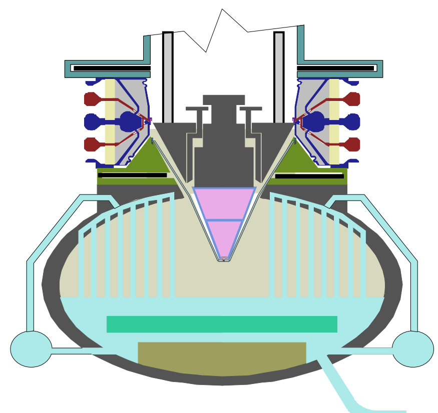
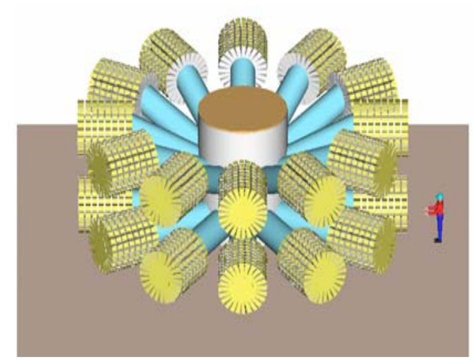
Z-Pinch Inertial Fusion Energy



Capsule compression experiments on Z



Z-Pinch Power Plant Chamber



Repetitive Driver
LTD Technology

Craig L. Olson
Sandia National Laboratories
Albuquerque, NM 87185

RCM on “Elements of Power Plant Design for IFE”
IAEA headquarters
Vienna, Austria
November 4-7, 2003

Why Z-Pinch IFE?

x-rays: **1.8 MJ of x-rays on Z (demonstrated) available now**

low cost: **$30/J for ZR (demonstrated cost)**
$17/J goal for X-1 high yield study (1999)

high efficiency: **wall plug to x-rays: ~15% on Z (demonstrated)**
can be optimized to: ~25% or more

capsule compression experiments on Z: **(demonstrated)**
double-pinch hohlraum[1]: Cr ≈ 14-20, symmetry ~3%
dynamic hohlraum[2]: ~ 24 kJ x-rays absorbed, Cr ≈ 10, DD neutrons
hemisphere compression for fast ignition[3]: Cr ≈ 2
([1]Cuneo, et al.; [2]Bailey, Chandler, Vesey, et al.; [3]Slutz, et al.)

repetitive pulsed power:
RHEPP magnetic switching technology:
2.5 kJ @ 120 Hz (300 kW ave. pwr. demonstrated)
LTD (linear transformer driver) technology:
being developed (compact, direct, simple)

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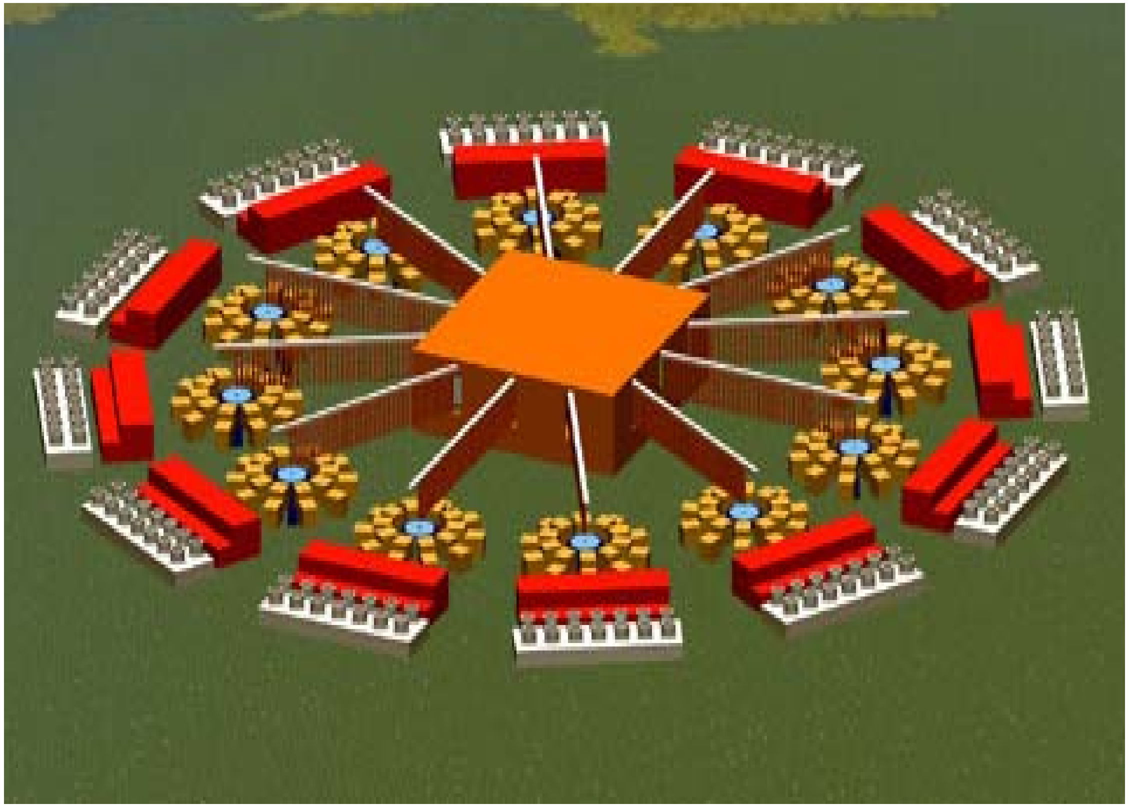
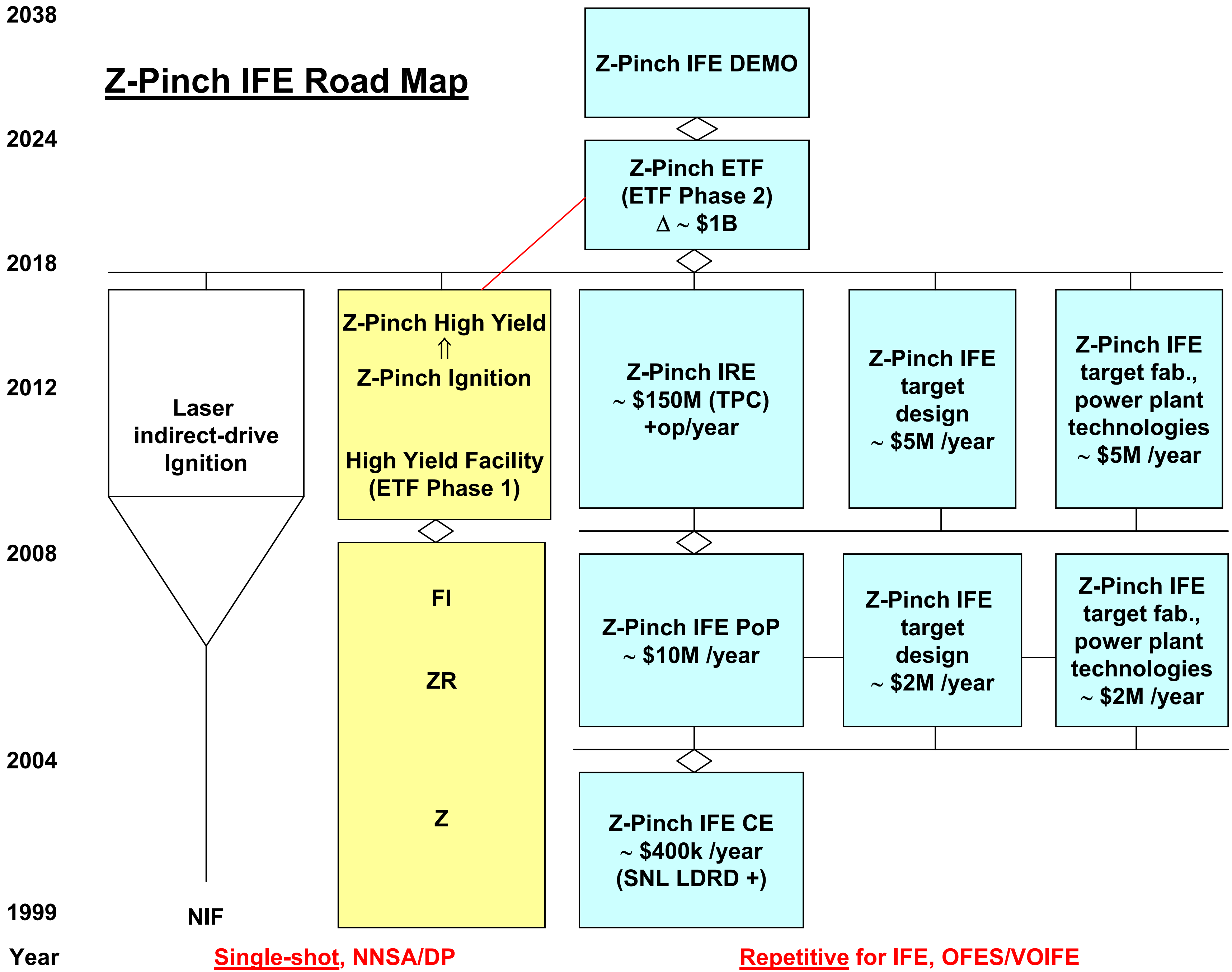
The long-range goal of Z-Pinch IFE is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate (~0.1 Hz)



Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe


2038
Z-Pinch IFE Road Map
Z-Pinch IFE DEMO
2024
Z-Pinch ETF
(ETF Phase 2)
Δ ~ $1B
2018
Z-Pinch High Yield
⇑
Z-Pinch Ignition
High Yield Facility
(ETF Phase 1)
Z-Pinch IRE
~ $150M (TPC)
+op/year
Z-Pinch IFE
target
design
~ $5M /year
Z-Pinch IFE
target fab.,
power plant
technologies
~ $5M /year
2012
Laser
indirect-drive
Ignition
2008
FI
ZR
Z
Z-Pinch IFE PoP
~ $10M /year
Z-Pinch IFE
target
design
~ $2M /year
Z-Pinch IFE
target fab.,
power plant
technologies
~ $2M /year
2004
Z-Pinch IFE CE
~ $400k /year
(SNL LDRD +)
1999
NIF
Year
Single-shot, NNSA/DP
Repetitive for IFE, OFES/VOIFE

Z-Pinch IFE Matrix of Possibilities

(choose one from each category)

Z-Pinch Driver:

- Marx generator/ water line technology
- magnetic switching (RHEPP technology)
- linear transformer driver (LTD technology)

RTL (Recyclable Transmission Line):

- Flibe/electrical coating
- immiscible material (e. g., low activation ferritic steel)

Target:

- double-pinch
- dynamic hohlraum
- fast ignition

Chamber:

- dry-wall
- wetted-wall
- thick-liquid wall
- solid/voids (e. g., Flibe foam)

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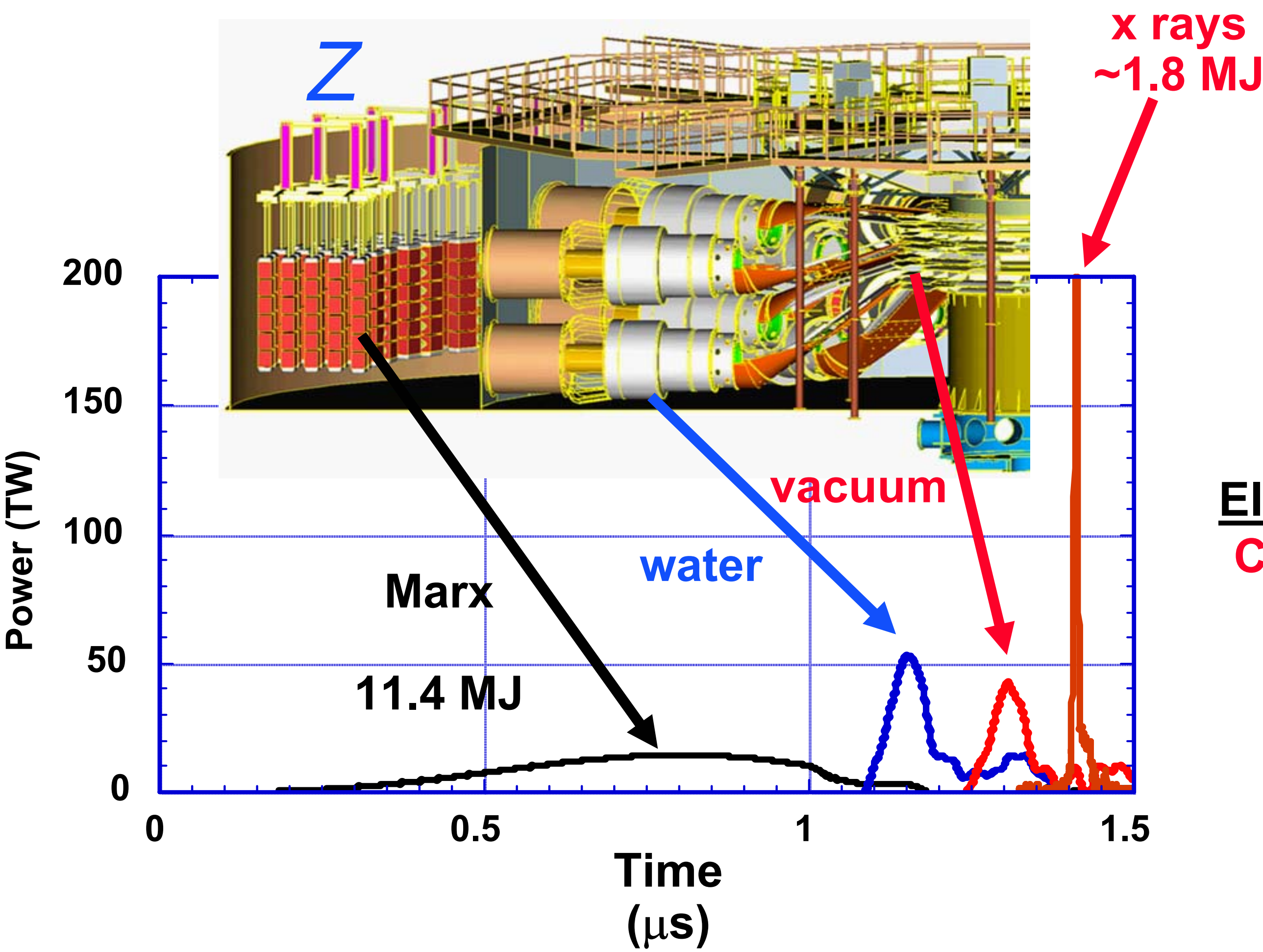
Z-Pinch Driver

Pulsed-power provides compact, efficient time compression and power amplification



<u>Electrical to x-ray energy</u>

Conversion efficiency > 15%

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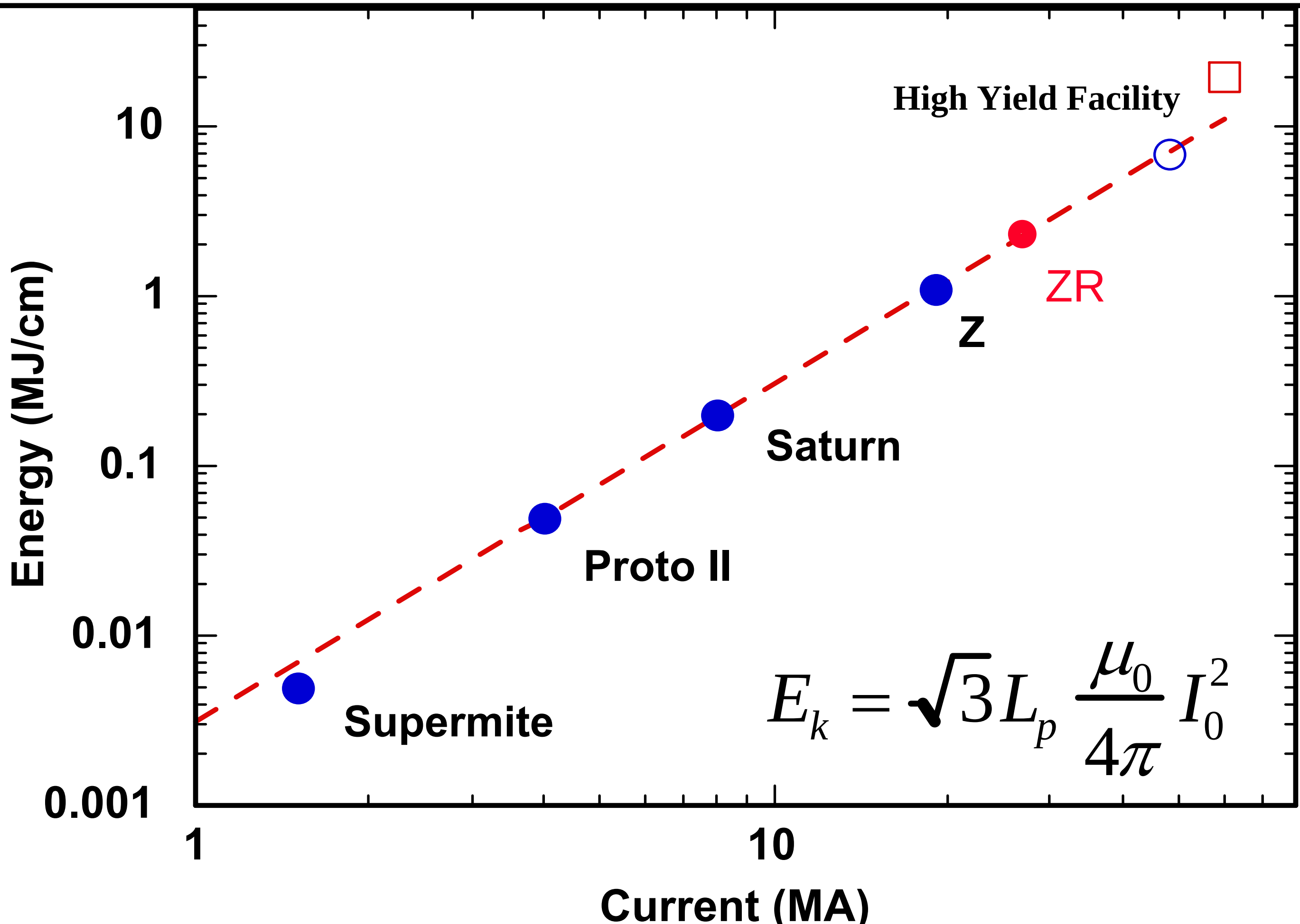
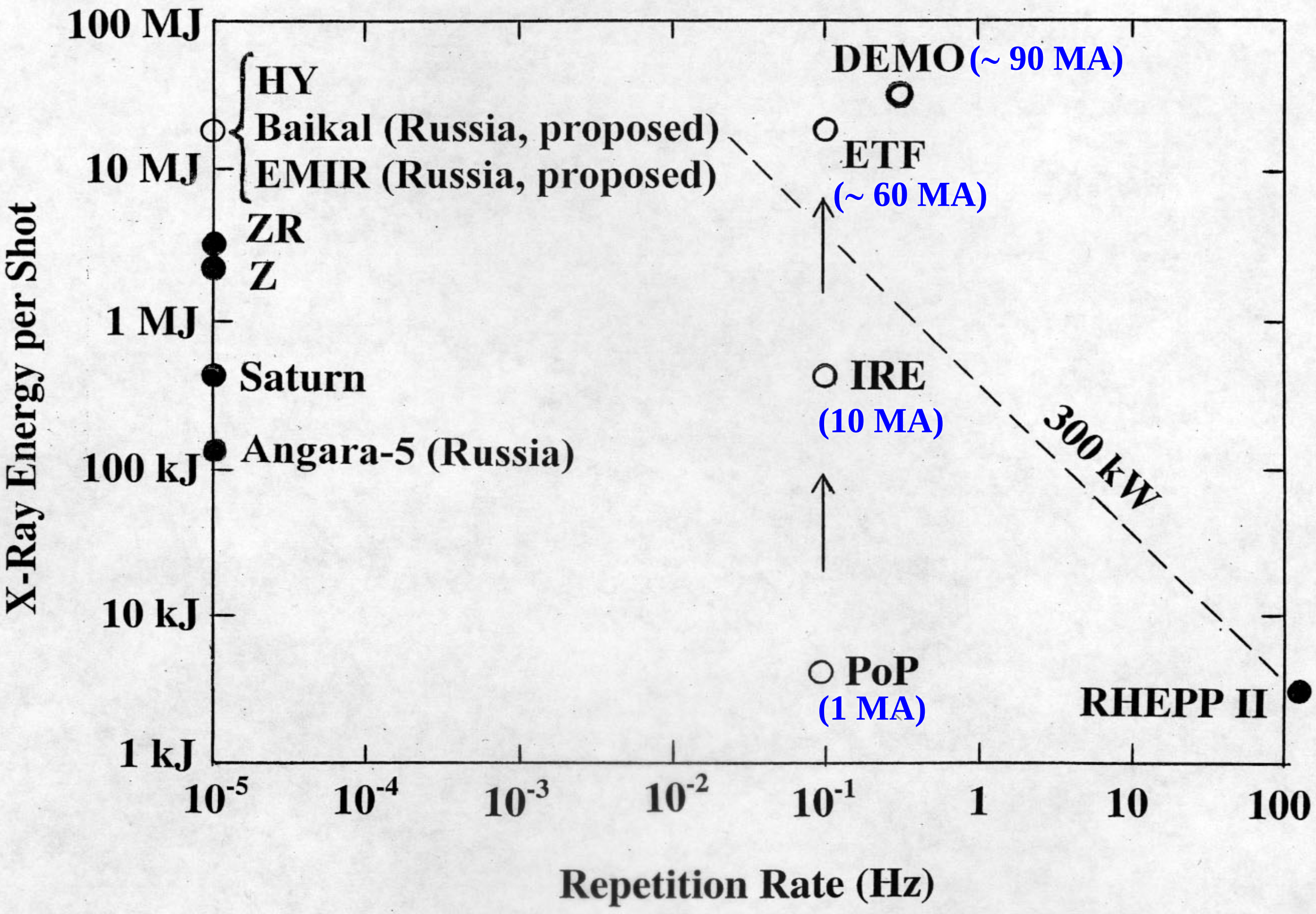
Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE



$$E_k = \sqrt{3} L_p \frac{\mu_0}{4\pi} I_0^2$$

ZR will be within a factor of 2-3 in current (4-9 in energy) of a High Yield driver.

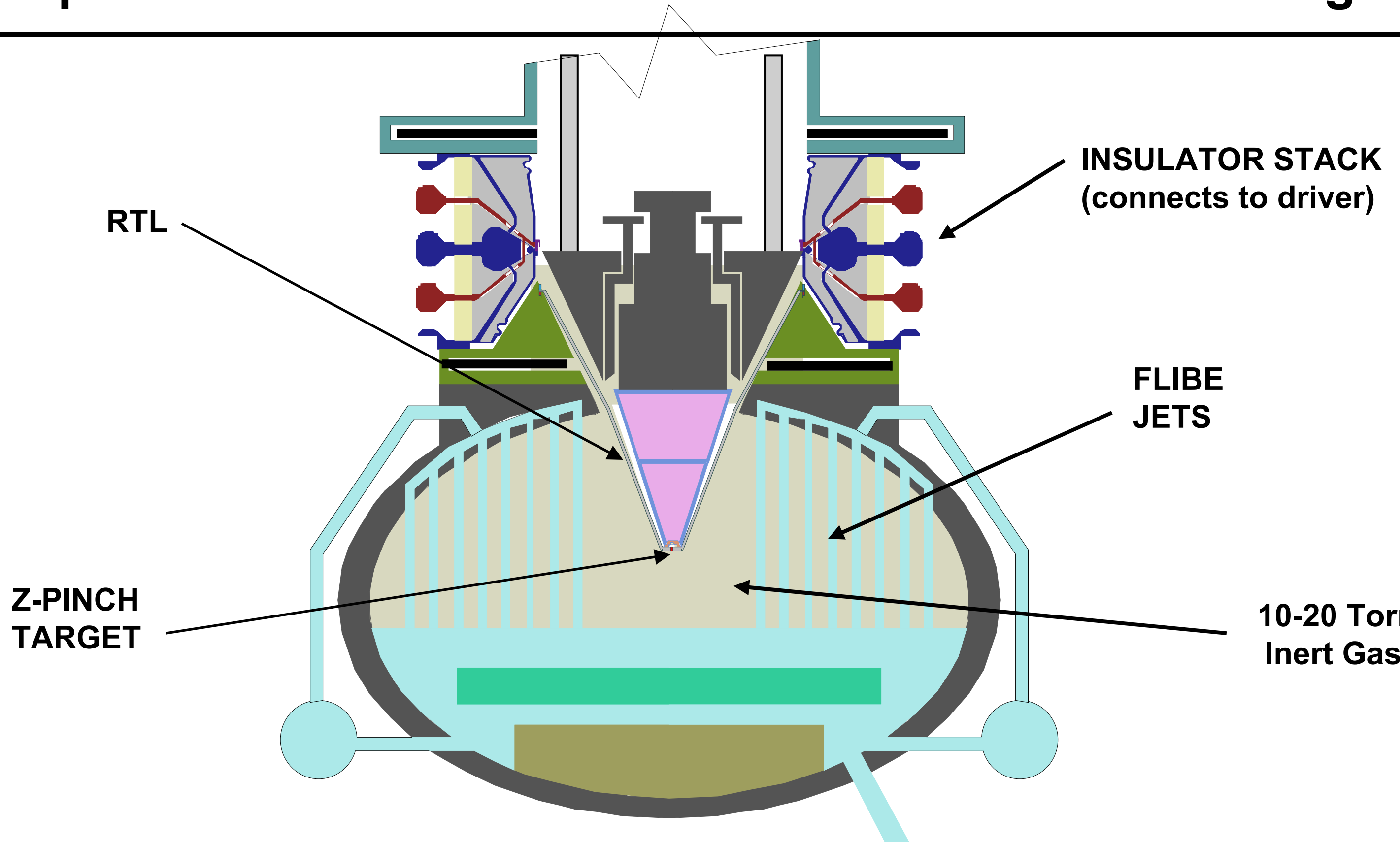
Z-Pinch IFE Development Path *Facilities*



RTL

(Recyclable Transmission Line)

Z-pinch power plant chamber uses an RTL (Recyclable Transmission Line) to provide the standoff between the driver and the target



Yield and Rep-Rate: few GJ every 3-10 seconds per chamber (0.1 Hz - 0.3 Hz)
Thick liquid wall chamber: only one opening (at top) for driver; nominal pressure (10-20 Torr)
Flibe absorbs neutron energy, breeds tritium, shields structural wall from neutrons
Eliminates problems of final optic, pointing and tracking N beams, high speed target injection
Requires development of RTL

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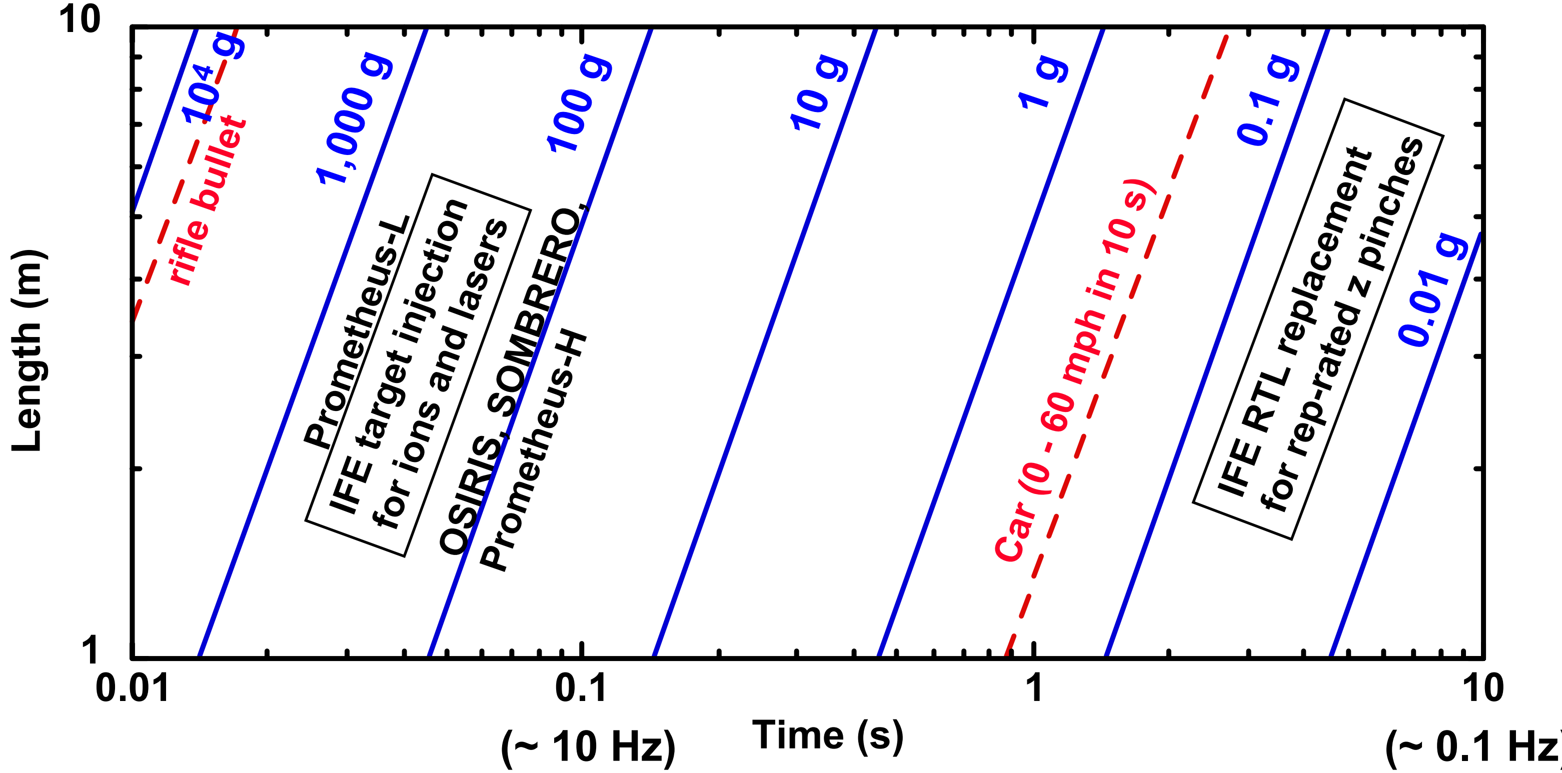
RTL replacement requires only modest acceleration for IFE

$L = 0.5\ a\ t^2$, or $a \sim 1/t^2$

Acceleration is 10^4 less than for IFE target injection for ions or lasers



RTL Research in last 3 years

RTL electrical turn-on	**<u>Saturn experiments</u> (2000)** **tin, Al, stainless-steel all show negligible losses**
RTL low-mass and electrical conductivity	**<u>Saturn experiments</u> (2001)** **20μ mylar; 50μ, 100μ, 250μ steel** **RTL mass could be as low as 2 kg** **RTL mass ~ 50 kg has low resistive losses**
RTL structural	**Calculations (U. Wisconsin) (2002)** **full-scale RTL (~50 kg) of 25 mill steel ok for background pressure ~ 10-20 Torr**
RTL manufacturing	**(allowed RTL budget is a few $ for 3 GJ)** **Flibe casting (~$0.70/RTL)** **ferritic steel stamping (~ $1.20-3.95/RTL)**

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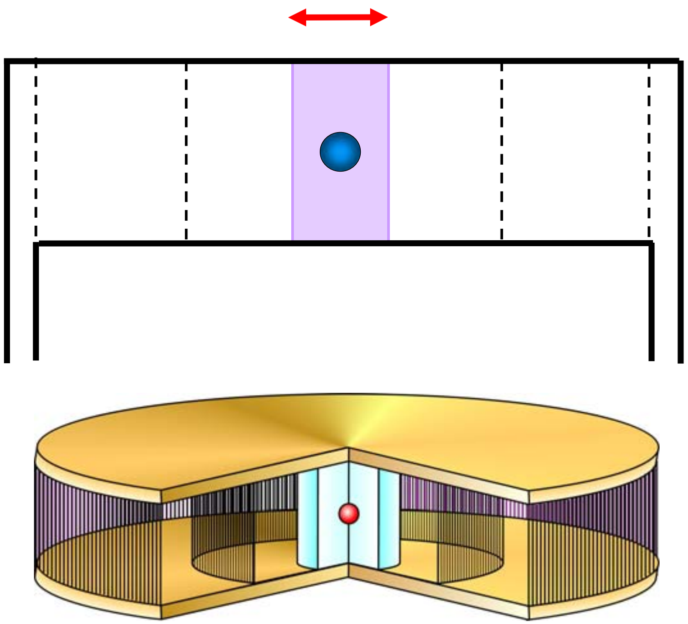
Targets

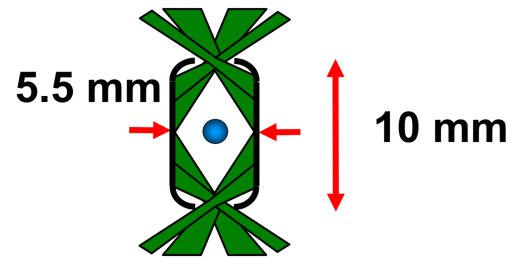
Z-pinch-driven-hohlraums have similar topology to laser-driven-hohlraums, but larger scale-size

Double ended hohlraum

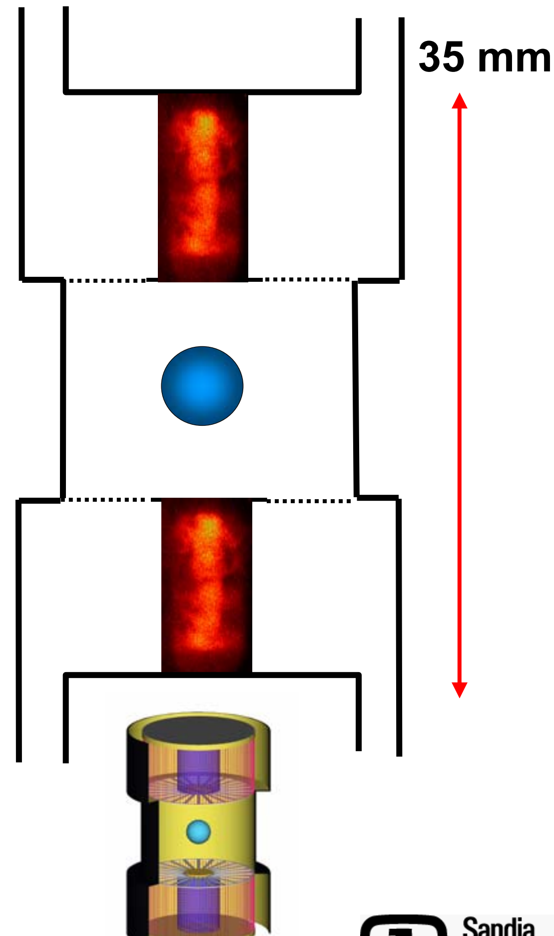
Dynamic hohlraum

Laser Source Cones





NIF Scale



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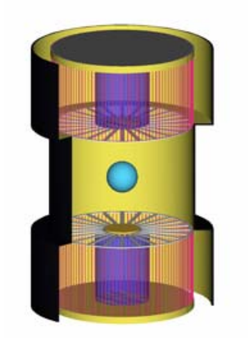
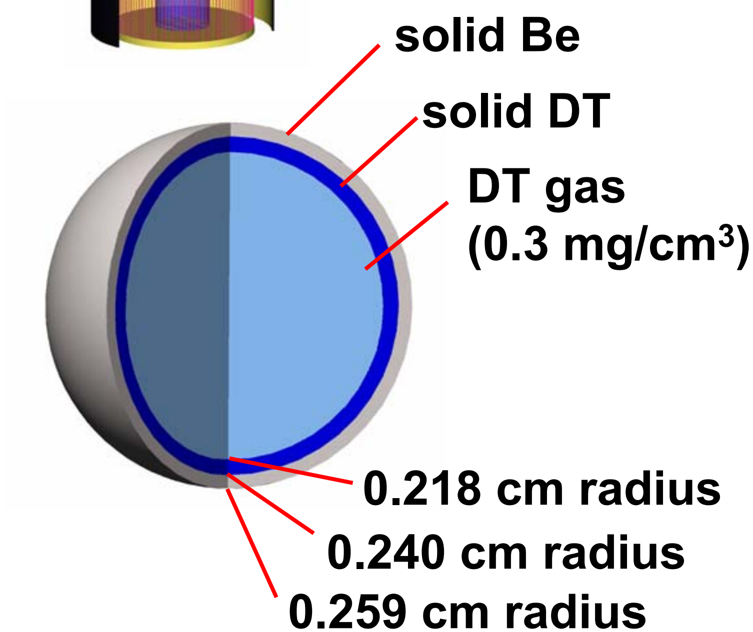
The baseline DEH capsule yields 380 MJ with an ignition margin similar to a NIF capsule





Capsule Performance Parameters

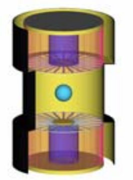
Peak drive temperature	223 eV
In-flight aspect ratio	37
Implosion velocity	2.9×10^7 cm/s
Convergence ratio	36
Total RT growth factor	420
Peak density	750 g/cm^3
Total ρr	3.15 g/cm^2
Driver energy	16 MJ
Absorbed energy	1.12 MJ
Yield	380 MJ
Burnup fraction	31%

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

Summary – Double-ended hohlraum ICF status

- Simulation codes and analytic modeling have been validated by measurements of time-dependent z-pinch x-ray production, z-pinch hohlraum temperatures, and capsule hohlraum temperatures
- A reproducible, single power feed, double z-pinch radiation source with excellent power balance has been developed for ICF capsule implosion studies
- The Z-Beamlet Laser (ZBL) is routinely used as an x-ray backlighter at x-ray energies up to 6.75 keV
- Capsule symmetry (P2 and P4) in double-pinch hohlraums on Z can be systematically controlled with demonstrated time-integrated symmetry of ≤ 3%
- Optimum hohlraums on Z should produce time-integrated radiation symmetry of ≤ 1% for 5 mm diameter capsules and absorbed energies of 25 kJ
- P4 shimming shots are scheduled in collaboration with LLNL and LBL HIF program

Double-Ended Hohlraum Concept Publications



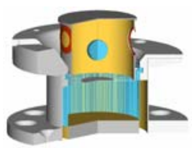
Concept

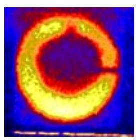
Hammer, Tabak, Wilks, et. al., Phys. Plasmas, 6, 2129(1999)

Hohlraum energetics

Cuneo, Vesey, Porter et al., Phys. Plas. 8, 2257 (2001)

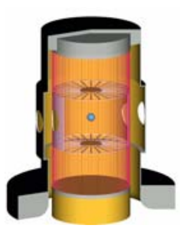
Cuneo, Vesey, Hammer et al., Laser Particle Beams, 19, 481 (2001)





Foam ball radiation symmetry

Hanson, Vesey, Cuneo et al., Phys. Plas. 9, 2173 (2002)



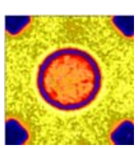
Double pinch performance

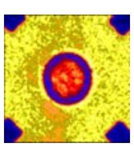
Cuneo, Vesey, Porter et al., Phys. Rev. Lett. 88, 215004 (2002)

Symmetric capsule implosions

Bennett, Cuneo, Vesey et al., Phys. Rev. Lett. 89, 245002 (2002)

Bennett, Vesey, Cuneo et al., Phys. Plasmas (in press)

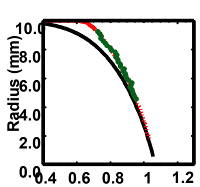


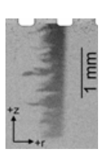


Symmetry control

Vesey, Cuneo, Bennett et al., Phys. Rev. Lett. 90, 035005 (2003)

Vesey, Bennett, Cuneo et al., Phys. Plasmas 10, 1854 (2003)





Pinch physics

Sinars, Cuneo, Bennett et al., Rev. Sci. Instrum., 74, 2202 (2003)

Stygar, Ives, Fehl, Cuneo et al., submitted to Phys. Rev. E

Cuneo, Chandler, Lebedev et al., submitted to Phys. Rev. Lett.

Waisman, Cuneo, Stygar et al., in preparation for Phys. Plasmas

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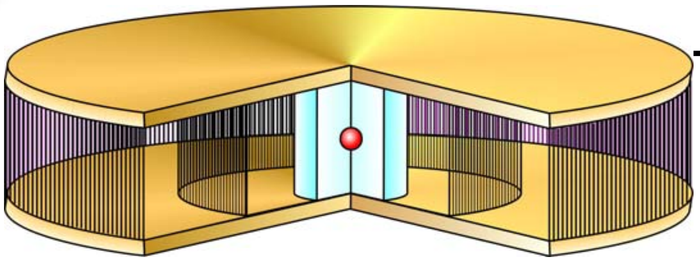
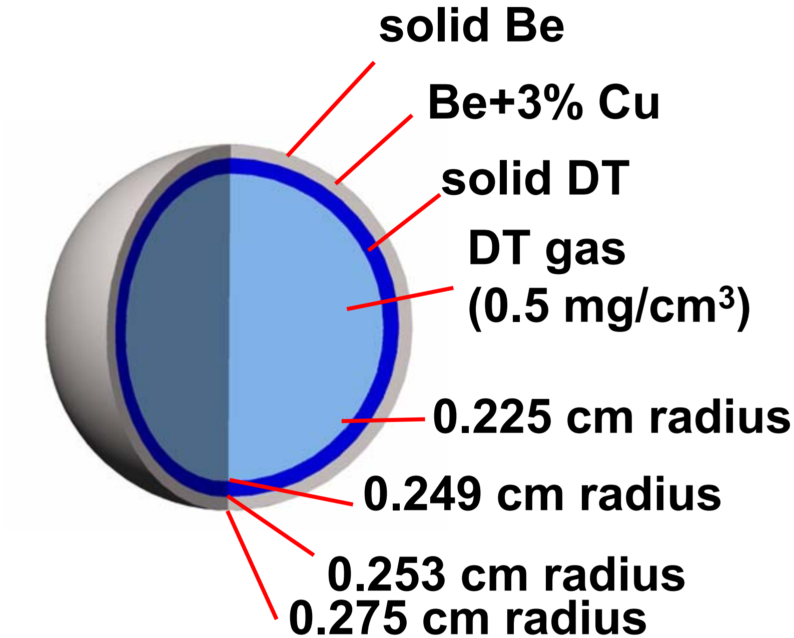
The initial dynamic hohlraum high yield integrated target design produces a 527 MJ yield at 54 MA





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

Summary – Dynamic Hohlraum ICF status

- The primary radiation source is a thin radiating shock in the foam converter
- Demonstrated >200 eV x-ray drive temperatures in dynamic hohlraums on Z
- Measured T_e~1 keV, n_e~1×10^{23} from Ar K-shell spectra from imploded capsules
- Measured $2.6 \pm 1.3 \times 10^{10}$ thermonuclear D-D neutrons from ICF capsules absorbing >20 kJ

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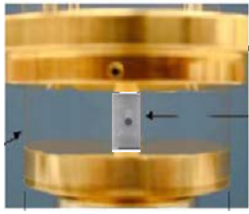
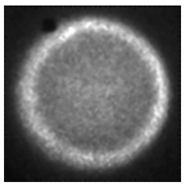
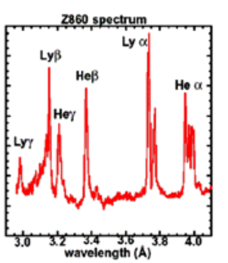
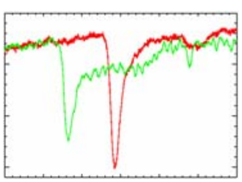
Dynamic Hohlraum Concept Publications









- Concept
  - Lash IFSA publication
- Energetics
  - publication on shock and temperature
- Temperature of imploded capsule core
  - publication on Ar spectra and temperature
- Neutron production
  - publication on neutron yield

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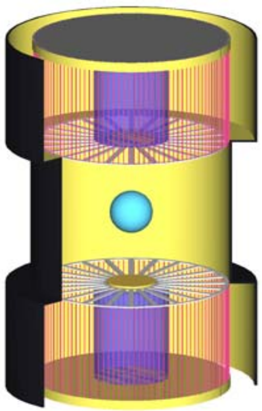
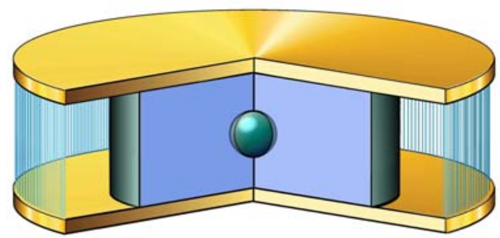
Code calculations and analytic scaling predict z-pinch driver requirements for IFE DEMO

Double-Pinch Hohlraum	current /x-rays E_{abs} / yield	Dynamic Hohlraum	current /x-rays E_{abs} / yield
	2 x 62-68 MA 2 x (16-19) MJ 1.3 – 2.6 MJ 400 – 4000 MJ		54 – 95 MA 12-37 MJ 2.4 – 7.2 MJ 530 – 4400 MJ

Based on these results, an IFE target for DEMO will require:

<u>double-pinch hohlraum</u>	<u>dynamic hohlraum</u>
36 MJ of x-rays (2x66MA)	30 MJ of x-rays (86 MA)
3000 MJ yield	3000 MJ yield
(G = 83)	(G = 100)

J. Hammer, M. Tabak, R. Vesey, S. Slutz, J. De Groot

Chambers/Power Plant

Z-Pinch IFE and Heavy Ion IFE use thick liquid walls

Z-Pinches use simple waterfalls with a pressure requirement of 10-20 Torr

Major drivers:

Laser	Heavy ion	Z-pinch
(KrF, DPSSL)	(induction linac)	(pulsed power)
	GeV, kA	MV, MA

Targets:

Direct-drive	Indirect-drive	Fast Igniter option
		(major driver + PW laser)

Chambers:

Dry-wall	Wetted-wall	Thick-liquid wall	Solid/voids

Thick liquid walls essentially alleviate the "first wall" problem, and can lead to a faster development path

Z-IFE DEMO produces 1000 MWe

DEMO parameters:

yield/pulse:	3 GJ
driver x-rays/pulse (86 MA)	30 MJ
energy recovery factor:	80%
thermal recovery/pulse:	2.4 GJ
time between pulses/chamber:	3 seconds
thermal power/unit	0.8 GWt
thermal conversion efficiency	45 %
electrical output/unit	0.36 GWe
number of units	3
total plant power output	1.0 GWe

Major cost elements:

LTD z-pinch drivers (3)	$900 M
RTL factory	$500 M
Target factory	$350 M
Balance of Plant	$900 M
Total Cost	$2.65 G

ZP-3 (the first study) used 12 chambers, each with 3 GJ at 0.1 Hz

Z-Pinch power plant studies: G. Rochau, et al. : ZP-3
J. De Groot, et al.: Z-Pinch Fast Ignition Power Plant

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Z-Pinch IFE near-term plans

Z-IFE PoP is a set of four experiments (shown here) plus IFE target studies plus IFE Power Plant studies

RTL experiments

- issues: shape, inductance, mass, electrical/structural, manufacture, cost
- power flow: limits, optimal configuration, convolute location
- chamber/interface issues: vacuum/electrical, debris removal, shielding
- RTL experiment test on Z

Repetitive driver- LTD (Linear Transformer Driver) experiment

- 1 MA, 1 MV, 100 ns, 0.1 Hz driver design/construction/testing
- LTD is very compact (pioneered in Tomsk, Russia) no oil, no water
- LTD technology is modular, scalable, easily rep-ratable
- 1 MA, 100 kV cell is being developed this year (SNL/Tomsk)

Shock mitigation scaled experiments

- 3 GJ yield is larger than conventional IFE yields of 0.4-0.7 GJ
- coolant streams, or solids/voids, may be placed as close to target as desired
- shock experiments with explosives and water hydraulic flows
- validate code capabilities for modeling full driver scale yields

Full RTL cycle @ 0.1 Hz experiment

- integrated experiment (LTD, RTLs, z-pinch loads, 0.1 Hz)
- demonstrate RTL/z-pinch insertion, vacuum/electrical connections, firing of z-pinch, removal of remnant, repeat of cycle
- z-pinches have 5 kJ x-ray output per shot

Cost: $14M/year for 3-5 years, $5M for FY04 to start

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