Z-Pinch IFE Program

C. L. Olson,[a] S. A. Slutz,[a] C. W. Morrow,[a] G. E. Rochau,[a] P. S. Pickard,[a] M. S. Derzon,[a] G. A. Rochau,[a] R. E. Olson,[a] A. R. Parker,[a] M. E. Cuneo,[a] D. L. Hanson,[a] G. R. Bennett,[a] T. W. L. Sanford,[a] G. A. Chandler,[a] J. E. Bailey,[a] W. A. Stygar,[a] J. L. Porter,[a] R. A. Vesey,[a] T. A. Mehlhorn,[a] K. W. Struve,[a] M. G. Mazarakis,[a] L. X. Schneider,[a] K. R. Prestwich,[a] G. Benevides,[a] T. J. Renk,[a] T. J. Tanaka,[a] S. T. Eakle,[a] M. A. Ulrickson,[a] D. H. McDaniel,[a] M. K. Matzen,[a] J. P. Quintenz,[a] P. F. Peterson,[b] J. S. De Groot,[c] R. R. Peterson,[d] I. Golovkin,[d] G. L. Kulcinski,[d] E. Mogahed,[d] I. Sviatoslavsky,[d] M. Sawan,[d] C. Gibson,[e] H. Tran,[f] M. S. Tillack,[g] A. R. Raffray,[g] F. Najmabadi,[g] T. R. Knowles,[h] P. Panchuk[i], K. Kasuya[j]

[a]Sandia National Laboratories, Albuquerque, NM USA
[b]University of California, Berkeley, CA USA
[c]University of California, Davis, CA USA
[d]University of Wisconsin, Madison, WI USA
[e]General Atomics, San Diego, CA USA
[f]University of New Mexico, Albuquerque, NM USA
[g]University of California, San Diego, CA USA
[h]Energy Science Laboratories, Inc, San Diego, CA USA
[i]EG&G, Albuquerque, NM USA
[j]Tokyo Institute of Technology, Tokyo, Japan

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Related Z-Pinch Research

Russia (next slide)

LANL

LLNL

Cornell University

Imperial College

Weizmann Institute

University of Nevada, Reno

Naval Research Laboratory

University of Michigan

...

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Russian activity in Z-pinches and beams

- Kurchatov Institute of Atomic Energy (Moscow)
- TRINITY (Troitsk)
- Institute of Nuclear Physics (Novosibirsk)
- Lebedev Institute (Moscow)
- VNIIEPh (Sarov)
- VNIITPh (Snejinsk)
- Efremov Institute (St. Petersburg)
- Institute of High Current Electronics (Tomsk)
- Physical and Technological Institute (Sukhumi)
- Institute of Spectroscopy (Troitsk)
- ITEPh (Moscow)

U.S./Russia Collaboration on Z-Pinch IFE is being initiated

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KURCHATOV INSTITUTE
RUSSIAN RESEARCH CENTRE

IFE Systems (choose one from each category)

Major drivers:

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

Targets:

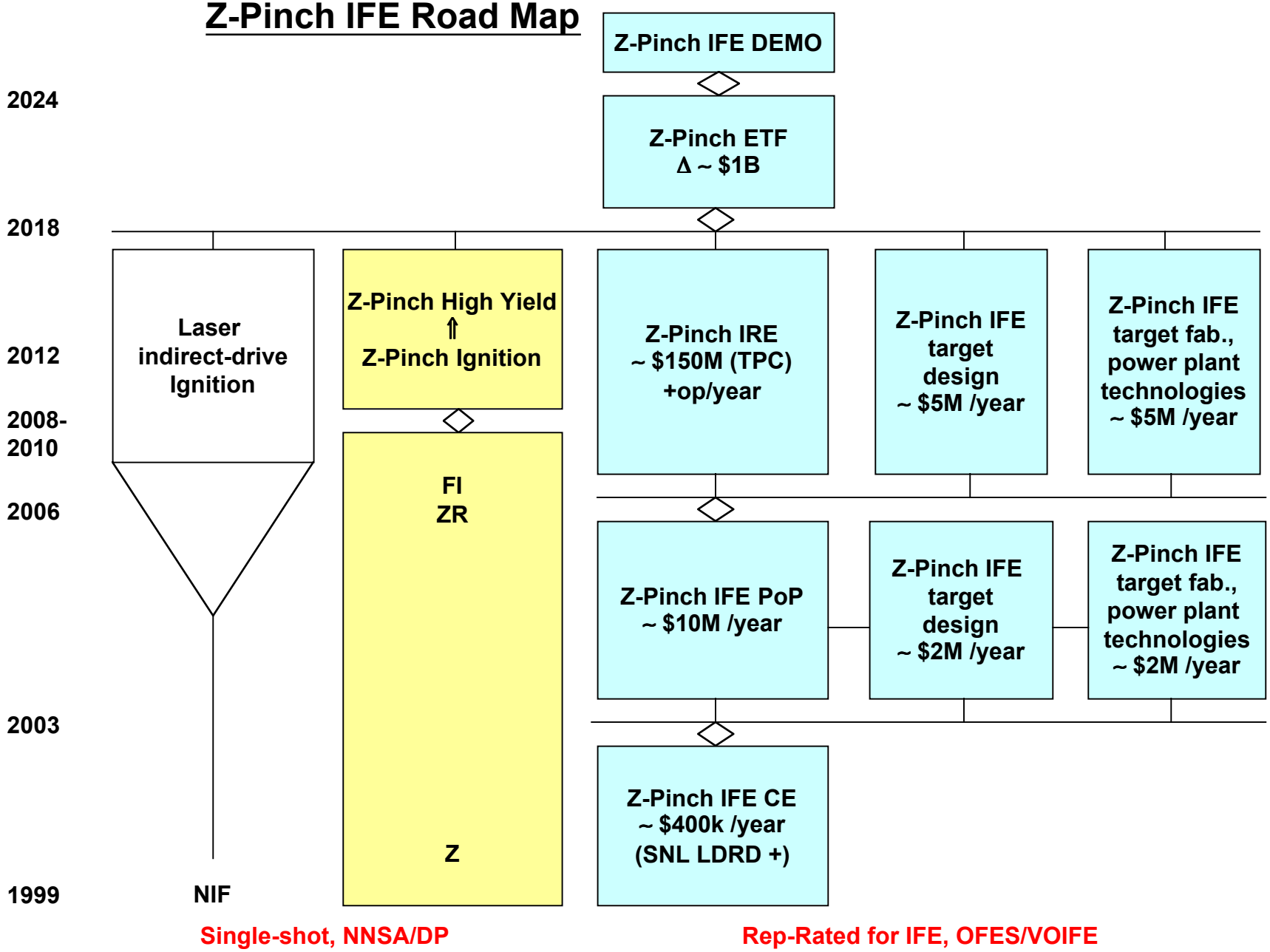
Direct-drive Indirect-drive

Fast Igniter option (major driver + PW laser)

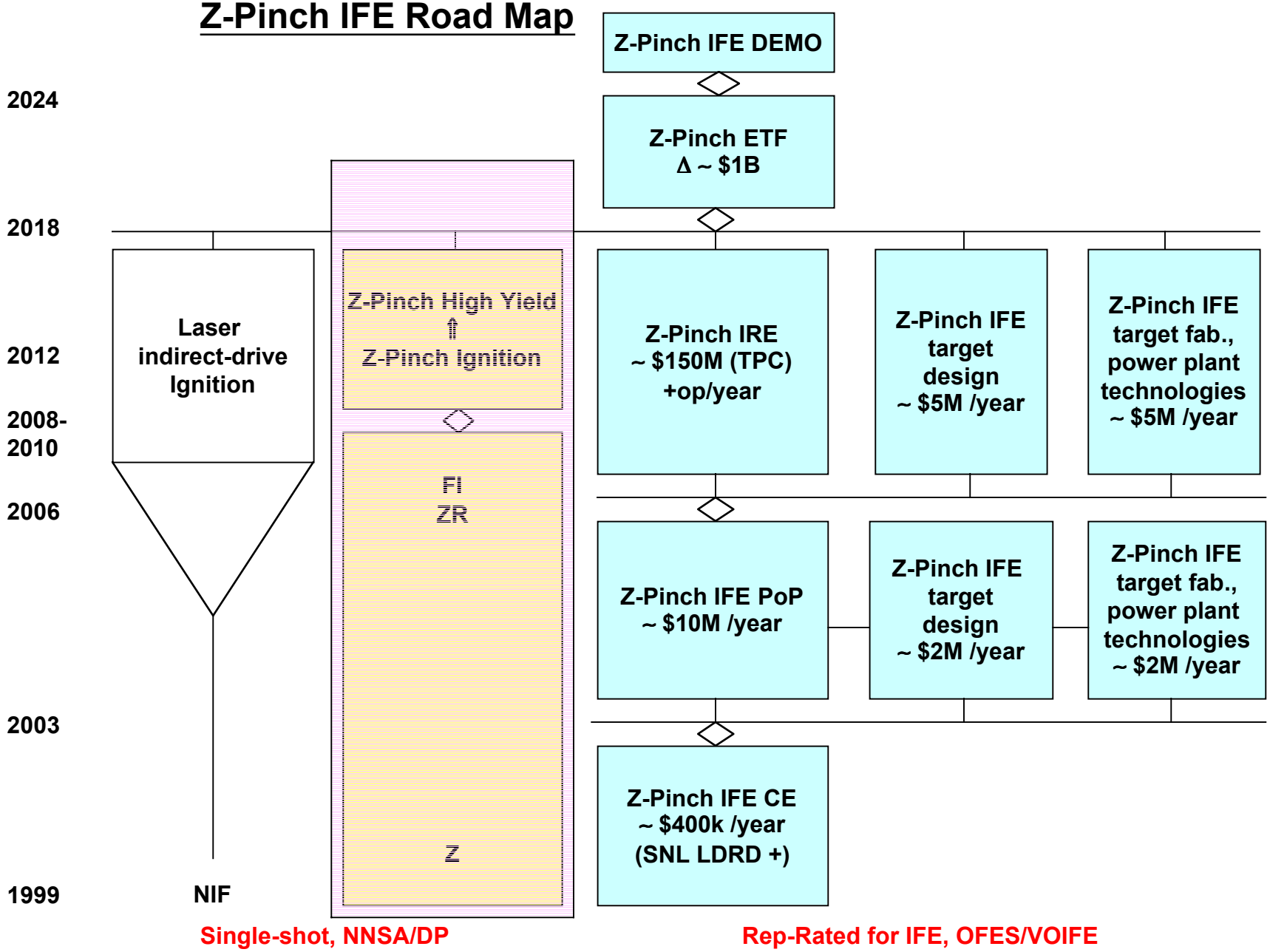
Chambers:

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

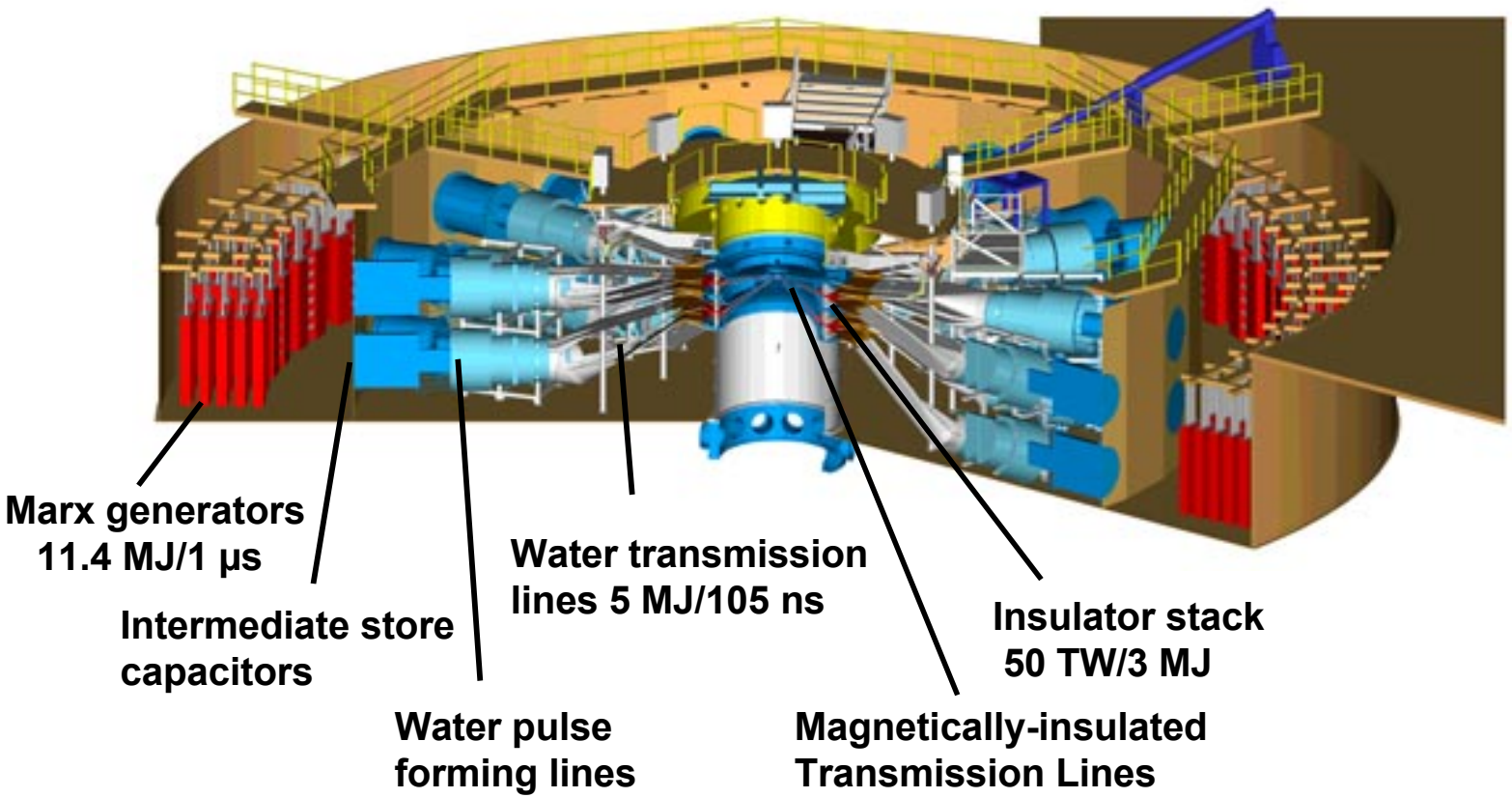
Z-Pinch IFE Road Map



Z-Pinch IFE Road Map



Z, the world's most powerful x-ray source for z-pinch-driven targets, is on the pathway to z-pinch IFE



X-rays from z-pinch wire array: ~ 6 ns, ~ 1.6 MJ, ~ 230 TW
High efficiency (wall-plug to x-rays): ~ 15%

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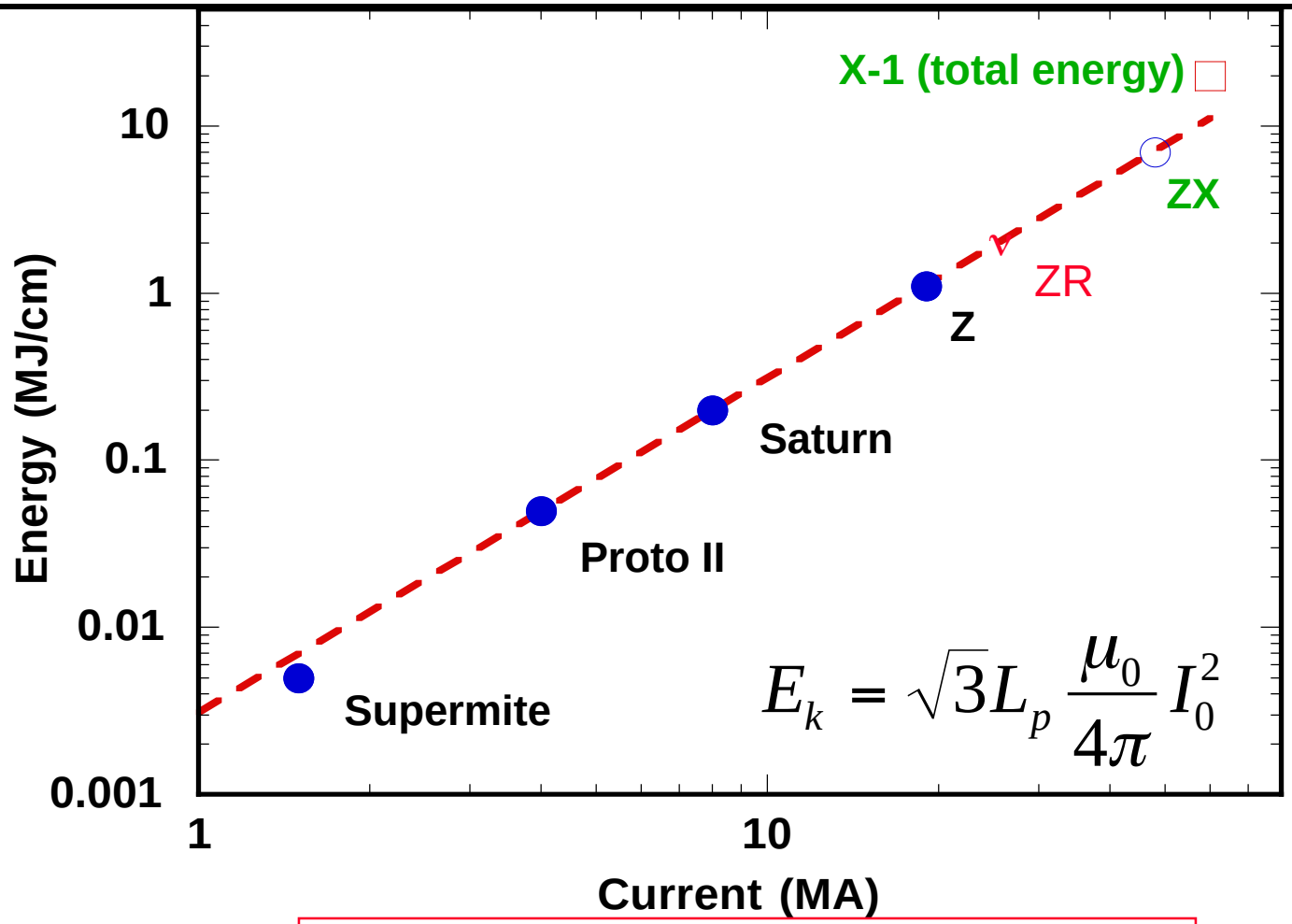
Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE



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

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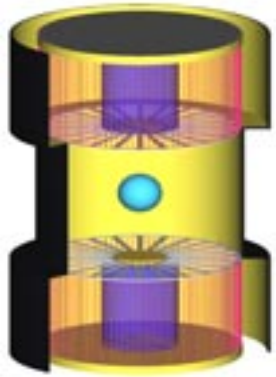
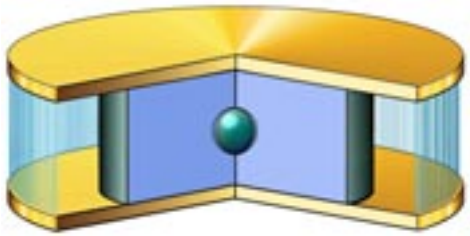
Two complementary Z-pinch indirect drive concepts for high-yield ICF and IFE are being explored

	ICF – IFE Current / E_{abs} / Yield	Features
Double-Pinch Hohlraum 	2 x 62-68 MA 1.3 – 2.6 MJ 400 – 3500 MJ	Dual power feed, double-pinch Capsule isolated from z-pinches Symmetry via hohlraum design demonstrated on Z (2x16 MA) η_{hohl} ~ 8-16 %
Dynamic Hohlraum 	54 – 95 MA 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) η_{hohl} ~ 20 %

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

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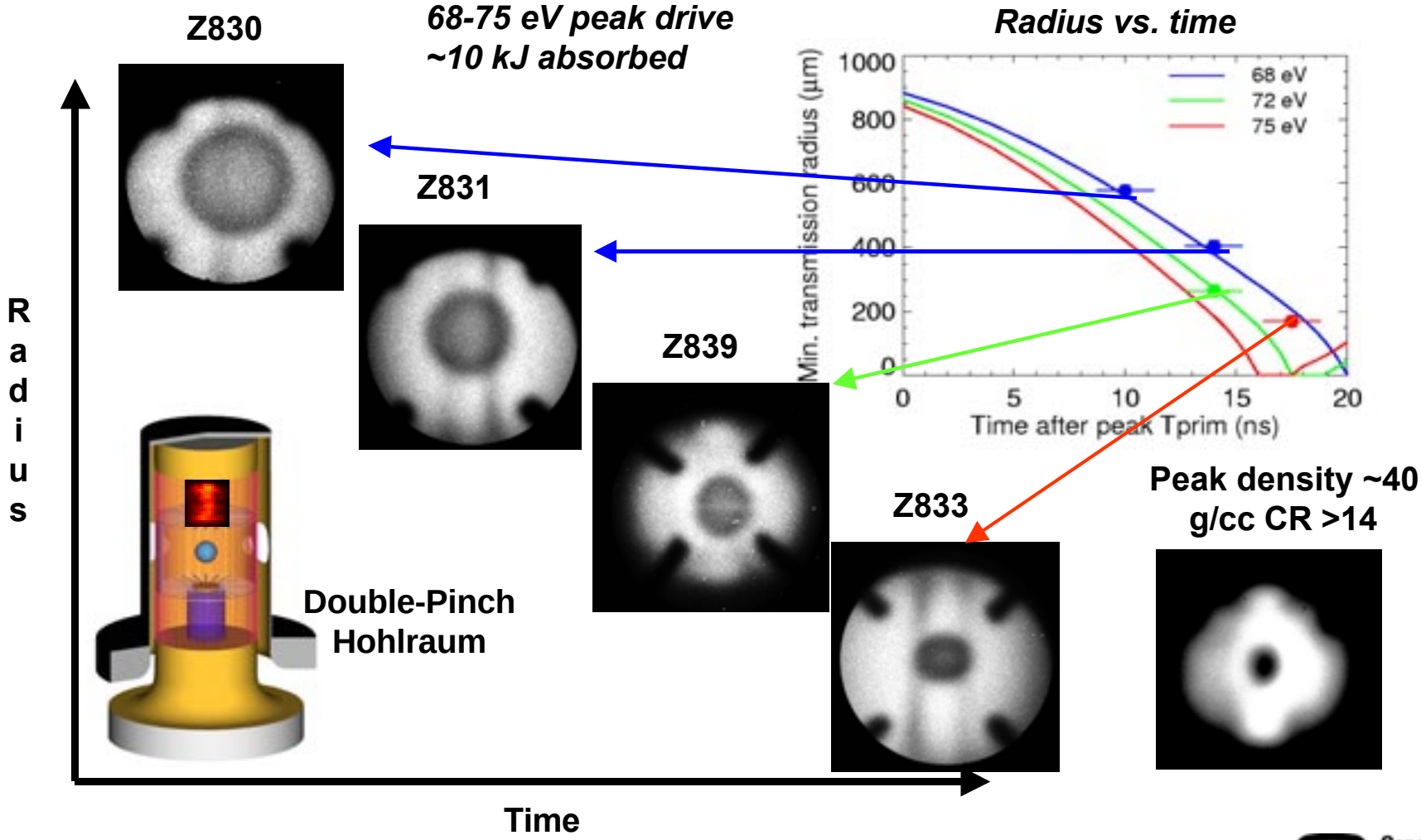
Double-pinch hohlraum on Z; capsule compression experiments demonstrate convergence ratio above 14; backlit capsule images agree with simulations



G. Bennett, M. Cuneo, R. Vesey

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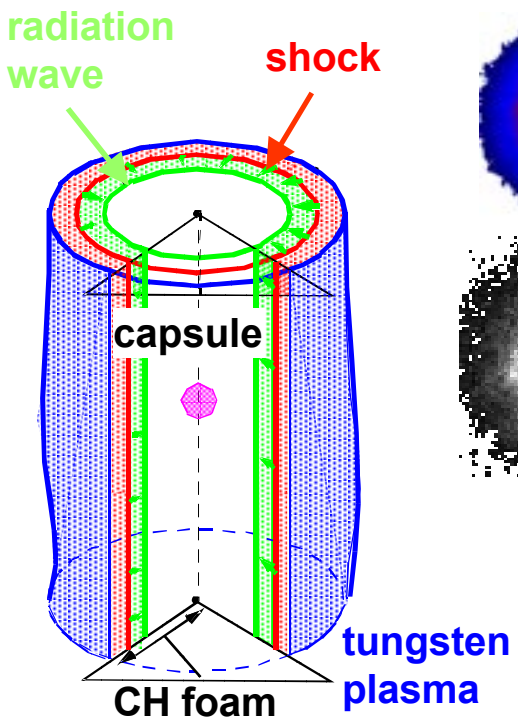
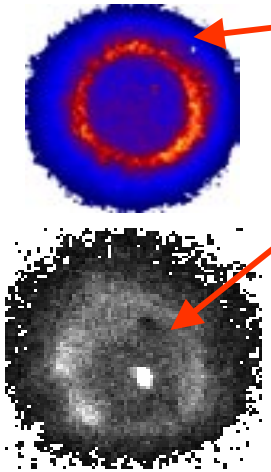
Dynamic hohlraum on Z; capsule compression experiments show convergence ratio of ~10; core image and argon spectra from capsule absorbing 20 kJ of x-rays are shown

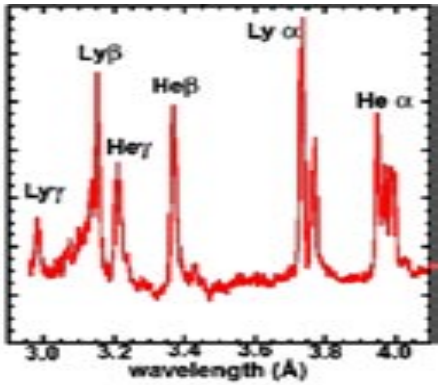




Shock emission width (~250 μm) is consistent with low levels of pinch RT

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, $n_e \sim 2\times10^{23}$ cm^{-3}

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

J. Bailey, G. Chandler, S. Slutz

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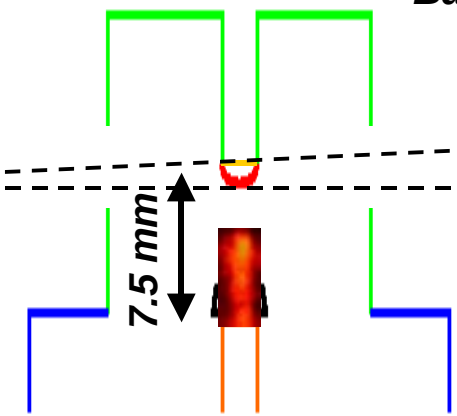
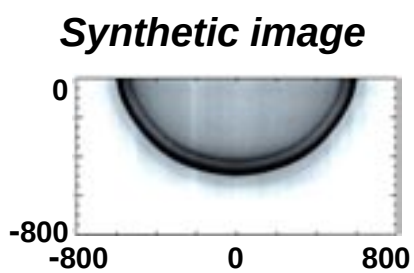
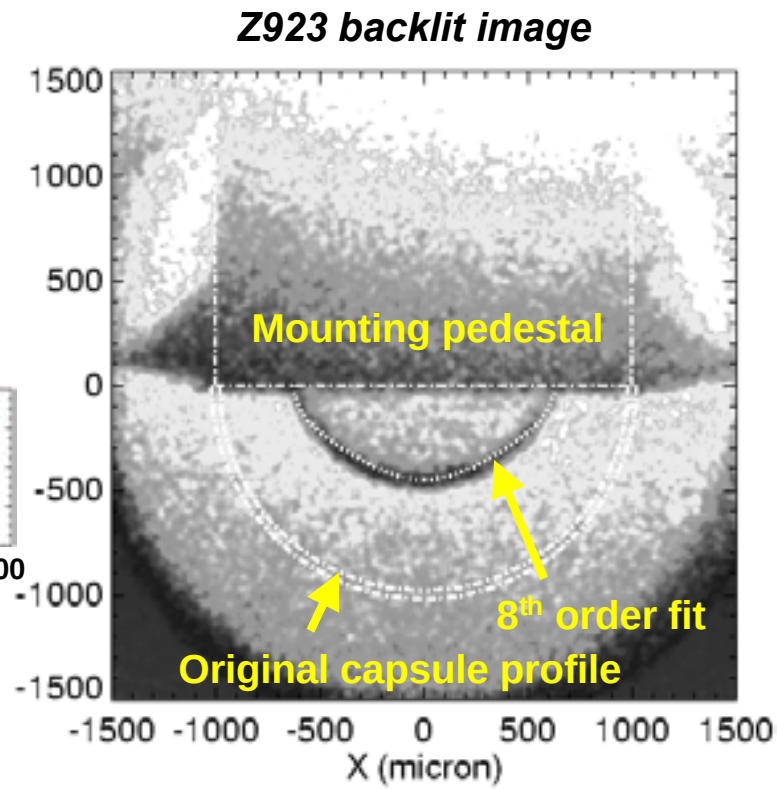
Cone-focused capsule implosions on Z: testing potential fast ignition compression schemes







100 eV peak drive
~15 kJ absorbed

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

More optimized Z hohlraum designs should allow ρ = 90-100 g/cc, ρr = 0.4 g/cm^2

Simulations for ZR with cryo DT capsule give ρ = 160 g/cc, ρr = 0.65 g/cm^2

D. Hanson, R. Vesey, S. Slutz

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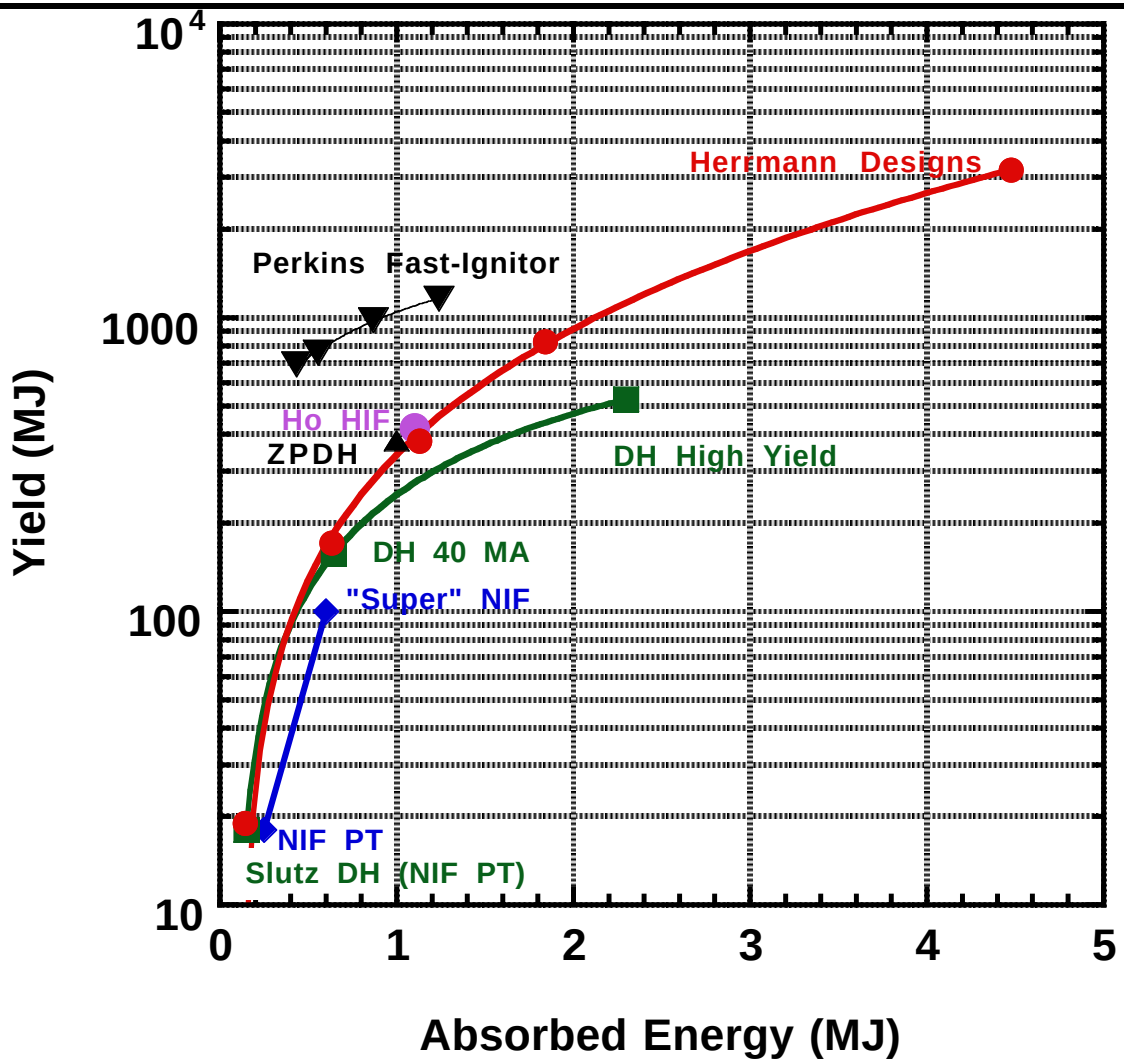
A variety of target concepts (ZPDH, DH, FI) are being investigated for scaling to high yields for Z-Pinch IFE

ICF Capsule Design Scaling



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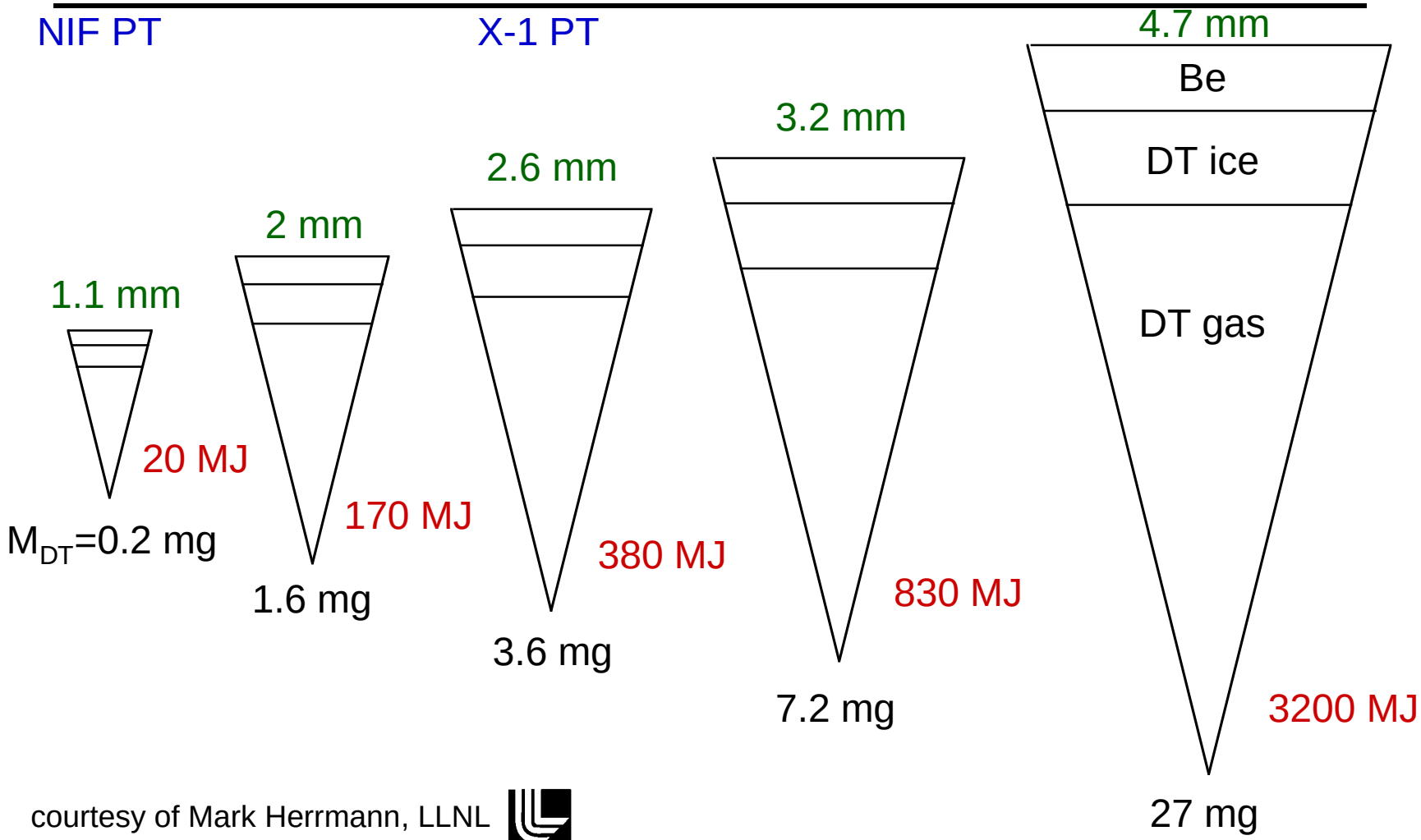
A scaled ZPDH high yield capsule (scaled from NIF PT design) is predicted to achieve sufficient yield for IFE



courtesy of Mark Herrmann, LLNL

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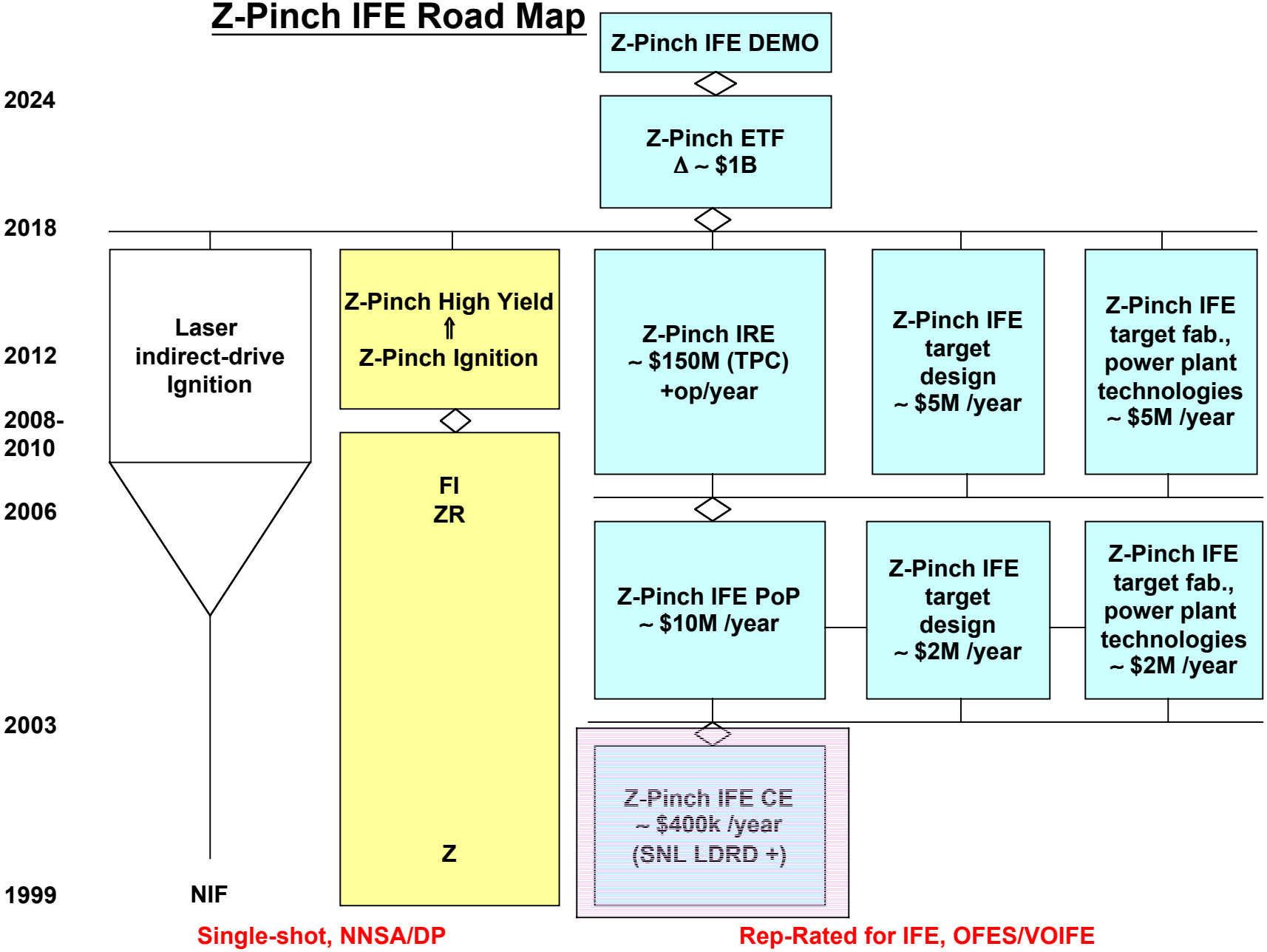
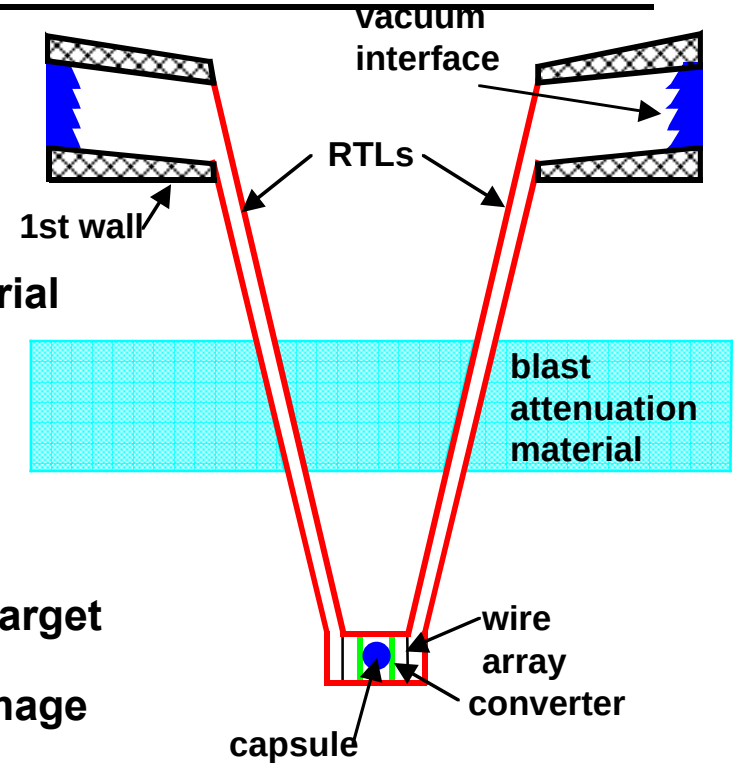
Z-Pinch IFE Road Map



Rep-rated z-pinch power plant concept uses a Recyclable Transmission Line (RTL)

- High yield (~ few GJ), low rep-rate (~0.1 Hz)
- RTL made of solid coolant (e.g., Flibe) or material easily separable from coolant
- RTL's pumped down before loading
- Essentially no chamber vacuum requirement
- Can pack solid or liquid Li or Flibe up next to target
- Wall lifetime limited by shock, not neutron damage
- RTL can bend around corners; can shield convolute
- Works in a robust, dirty environment of metal/plastic



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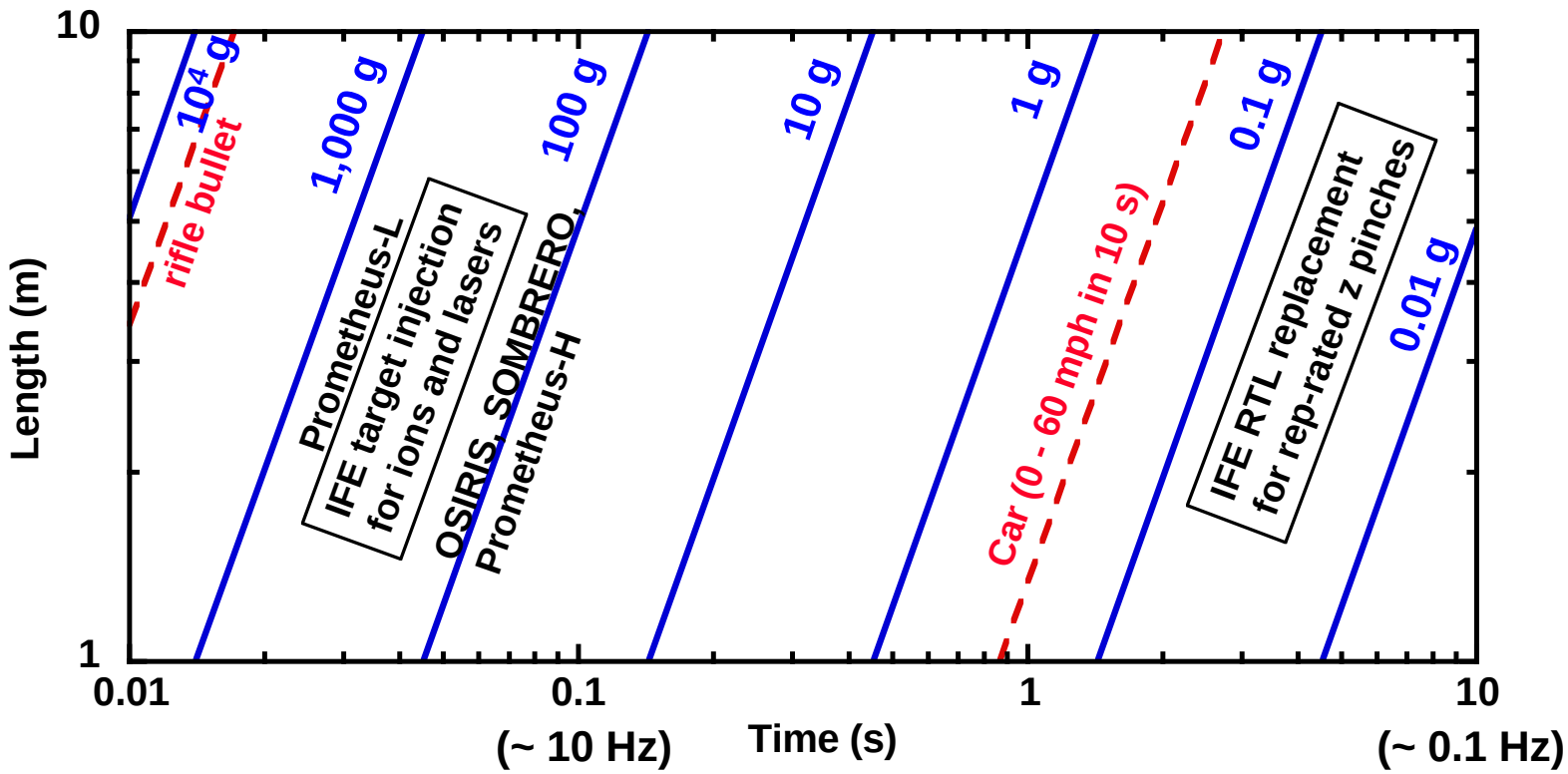
RTL replacement requires only modest acceleration for IFE

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

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



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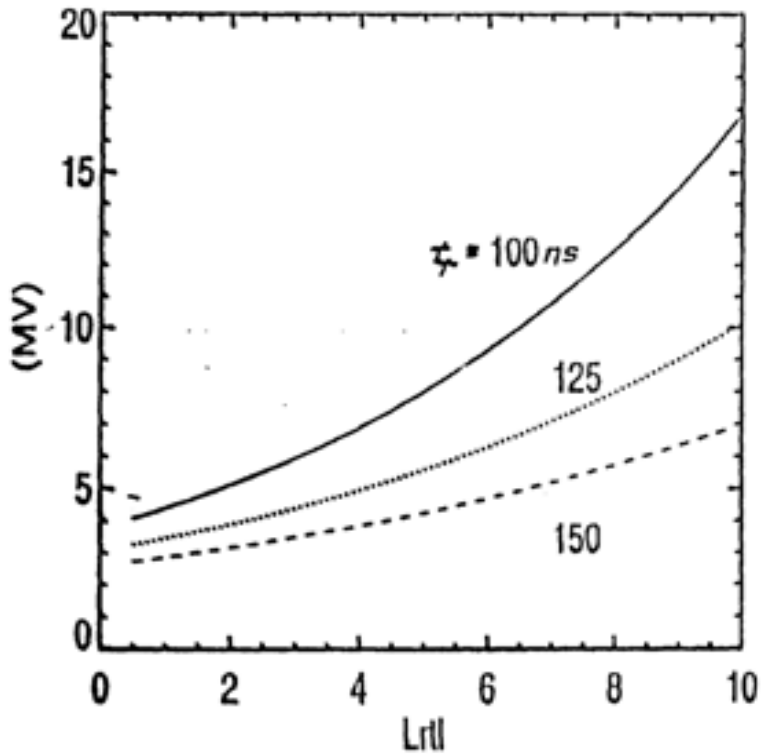
The driving voltage increases with the length of the RTL, and decreases with increasing current risetime



- The RTL dimensions were calculated for self magnetically insulated operation at a peak current of 60 MA
- Per Peterson estimates that 4 m of standoff will be required for GJ yields
- The driving voltage is about 3-4 MV on the Z accelerator with a risetime of 100 ns
- Work on longer pulses is in progress

Z-pinch IFE cost estimates

At 5¢/kWh, typical IFE systems with ~0.4 GJ yield require ~25¢/target

At 5¢/kWh, Z-pinch IFE with 3 GJ yield scales to requiring ~$1.90/shot

SNL Advanced Manufacturing estimate for cast FLIBE 600 lb RTL is	**~ $0.70**
-or-	
Present Z-pinch power plant study for deep-forming ferritic steel RTL is	**≥ $1.20**
SNL Advanced Manufacturing estimate for making wire z-pinch is	**~$0.35**
capsule is	**~$0.25?**
rough total is	**~$1.80**

Present cost estimates are already in an acceptable range

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Rep-rated z-pinch power plant concept: Key advantages and main issues

- Key advantages:
  - Z-pinch target is hard-wired to the accelerator, essentially guaranteeing that it will work
  - Problem of a final optic is completely eliminated
  - Problem of accurately pointing and tracking N beams to accurately hit the target is eliminated
  - Problem of high speed target injection is eliminated
  - Concept is simple, robust, and works in an industrial environment

- Main Issues
  - Find a suitable RTL material and test it on Saturn/Z
  - Investigate the use of tailored-density gradients to mitigate the shock to the first wall
  - Develop a suitable rep-rated pulsed power concept to drive the power plant (draw on existing pulsed power and power plant concept expertise)
  - Refine the overall RTL power plant concept

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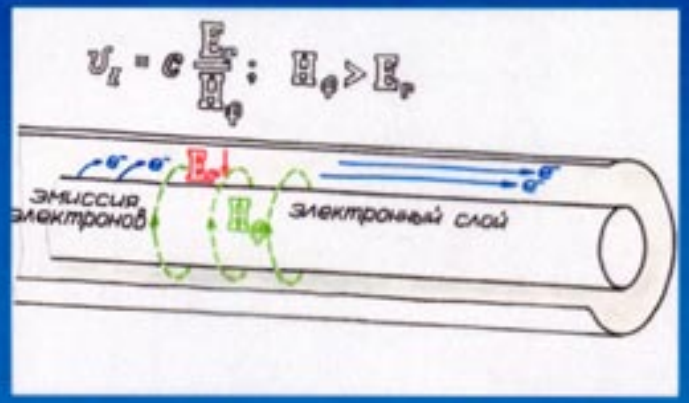
Magnetic Insulation

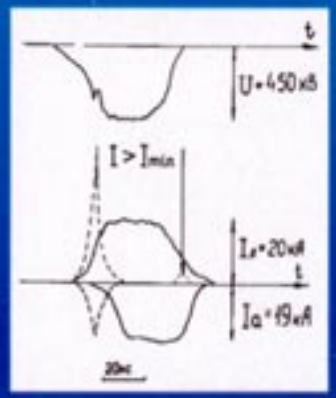
(V.Smirnov et al, 1973)

Magnetic self-insulation of vacuum transmission line

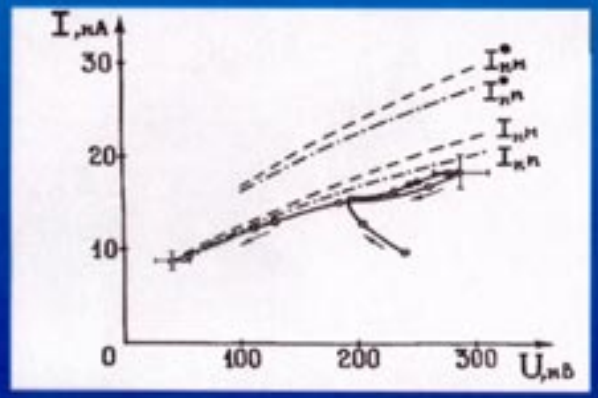


Quasistationary regime ($l<c\tau_f$)

Oscillograms of voltage U, currents I_{into} and I_{out}, leakage currents



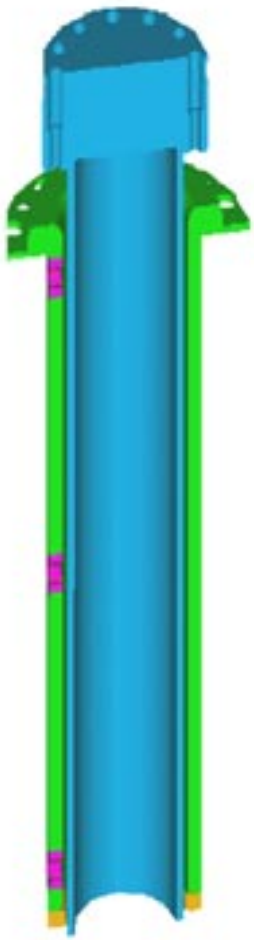
Volt-ampere characteristic

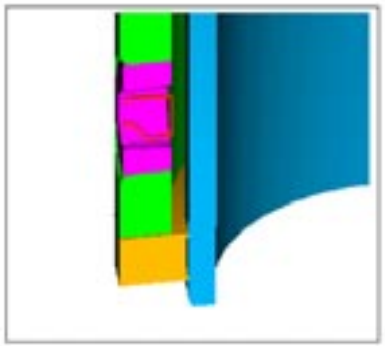


Condition of the magnetic insulation: $I>I_{min}$, where $I_{min}=8{,}5i(\gamma)\ln(r_a/r_c)$

Saturn experiments to test RTL materials have been performed successfully

Height: 30 cm
Diameter: 8 cm
Gap: 3 mm





- **The diameter of the RTL was chosen to provide current density comparable to a reactor system**
- **Power flow within Saturn limits the load inductance to less than 5 nH.**
- **Only nontoxic materials were tested, e. g. tin, aluminum, and stainless steel**
- **Current monitors placed at the top, middle, and bottom of the RTL showed no loss of current for any material**

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Saturn experiments to investigate the low-mass RTL limit have been performed successfully

Based on RTL electrode motion due to the B field, calculations show the RTL mass could be as low as 1 kg (compared to 5 tons for the Z MITL)

Such low-mass RTL electrodes would have a thickness of order of one resistive skin depth or less

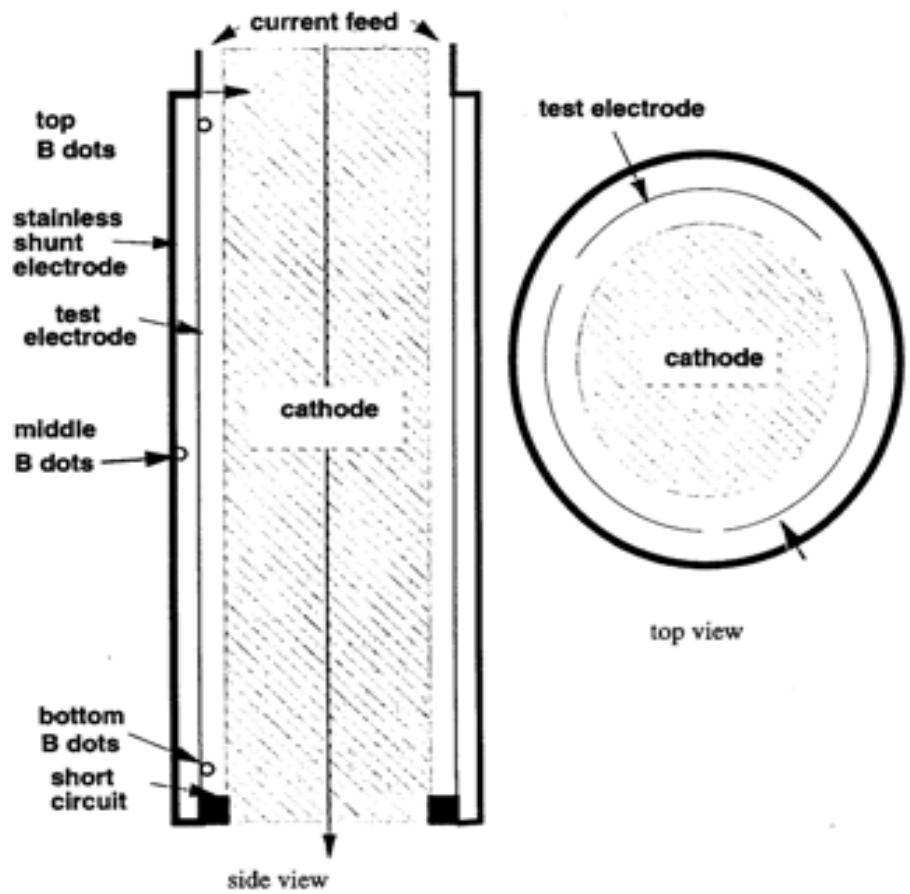
Saturn experiments have been performed at the 10 MA level to measure the electrical conductivity properties of such low-mass RTL electrode materials:

25 μ mylar

50 μ carbon steel

100 μ carbon steel

250 μ carbon steel



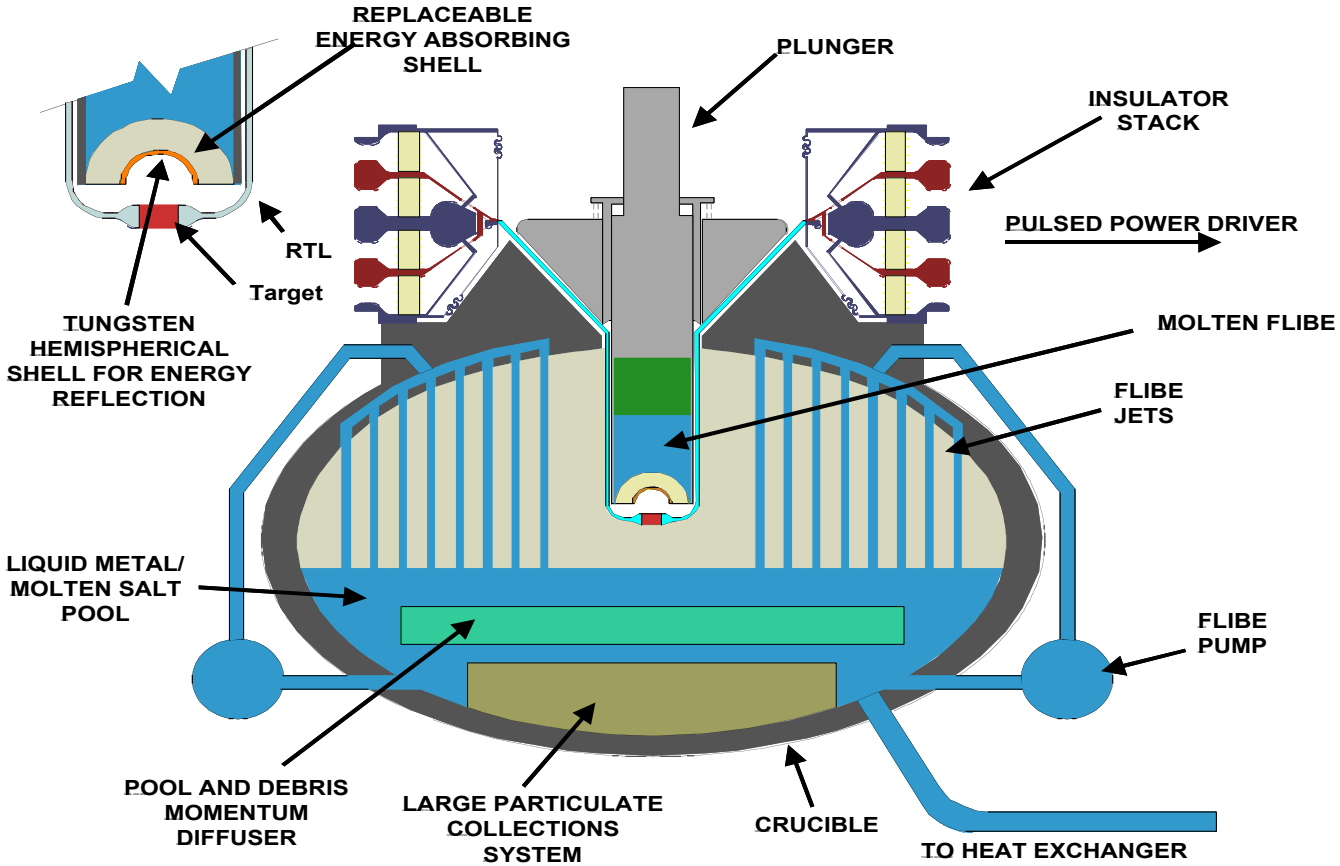
Saturn low-mass RTL experimental results have been used to estimate the total mass and electrical efficiency of a power-plant-scale RTL (R = 4 meters).

electrode	Γ (kg/m^2)	M_{TOT} (kg)	Efficiency%
20 μ mylar	0.02	2.0	45
50 μ steel	0.4	40.0	70
100 μ steel	0.8	80.0	90
250 μ steel	2.0	200.0	98

RTL mass as low as 2 kg could be used

RTL mass of 80 kg has very small resistive losses (~10%)

Z-pinch power plant concept uses an RTL with thick liquid walls



First z-pinch power plant study has produced a plausible scenario for RTL operation, including vacuum and electrical connections to the RTL.

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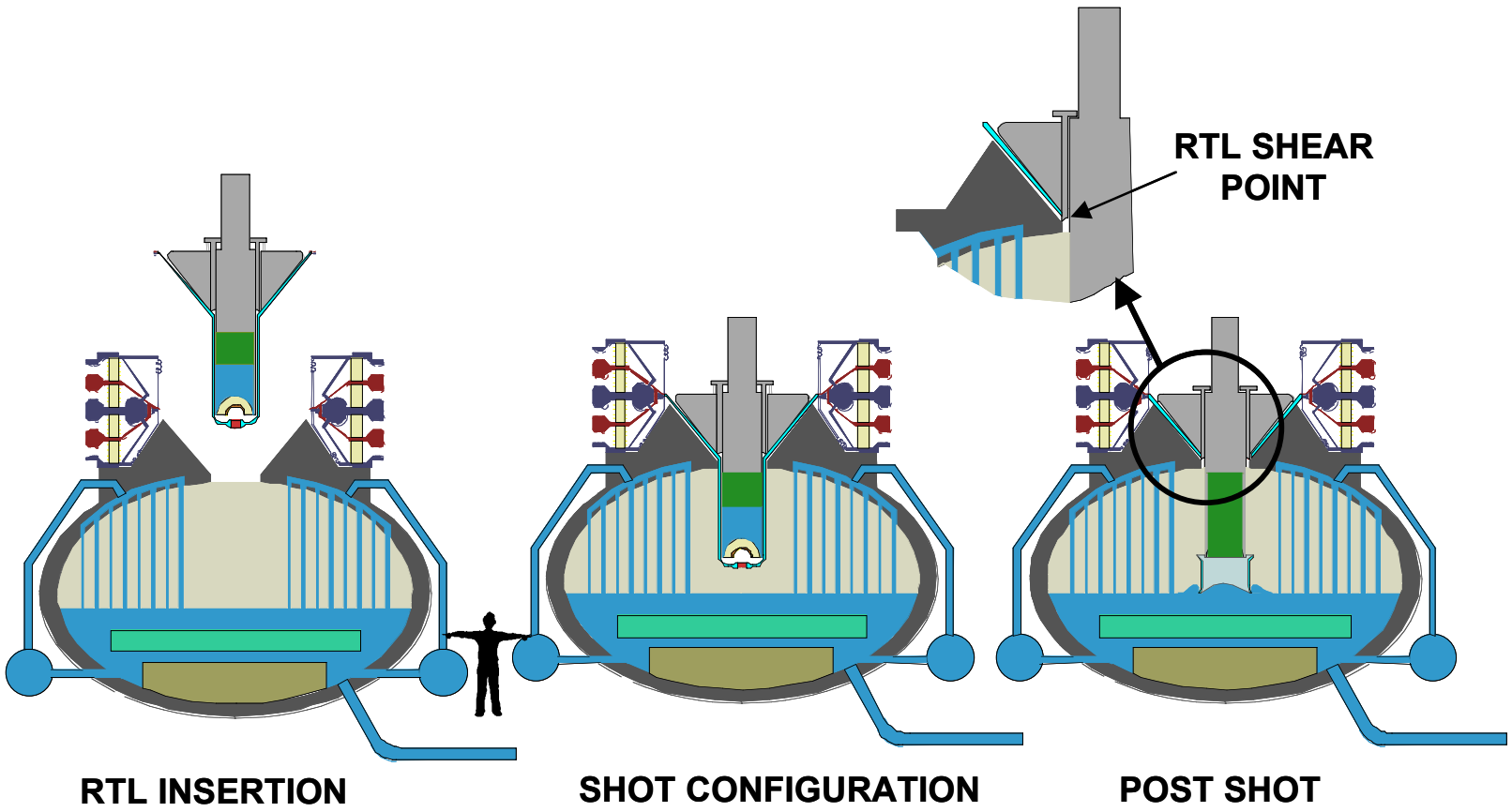
Z-Pinch Power Plant
Proposed Cartridge Cycle



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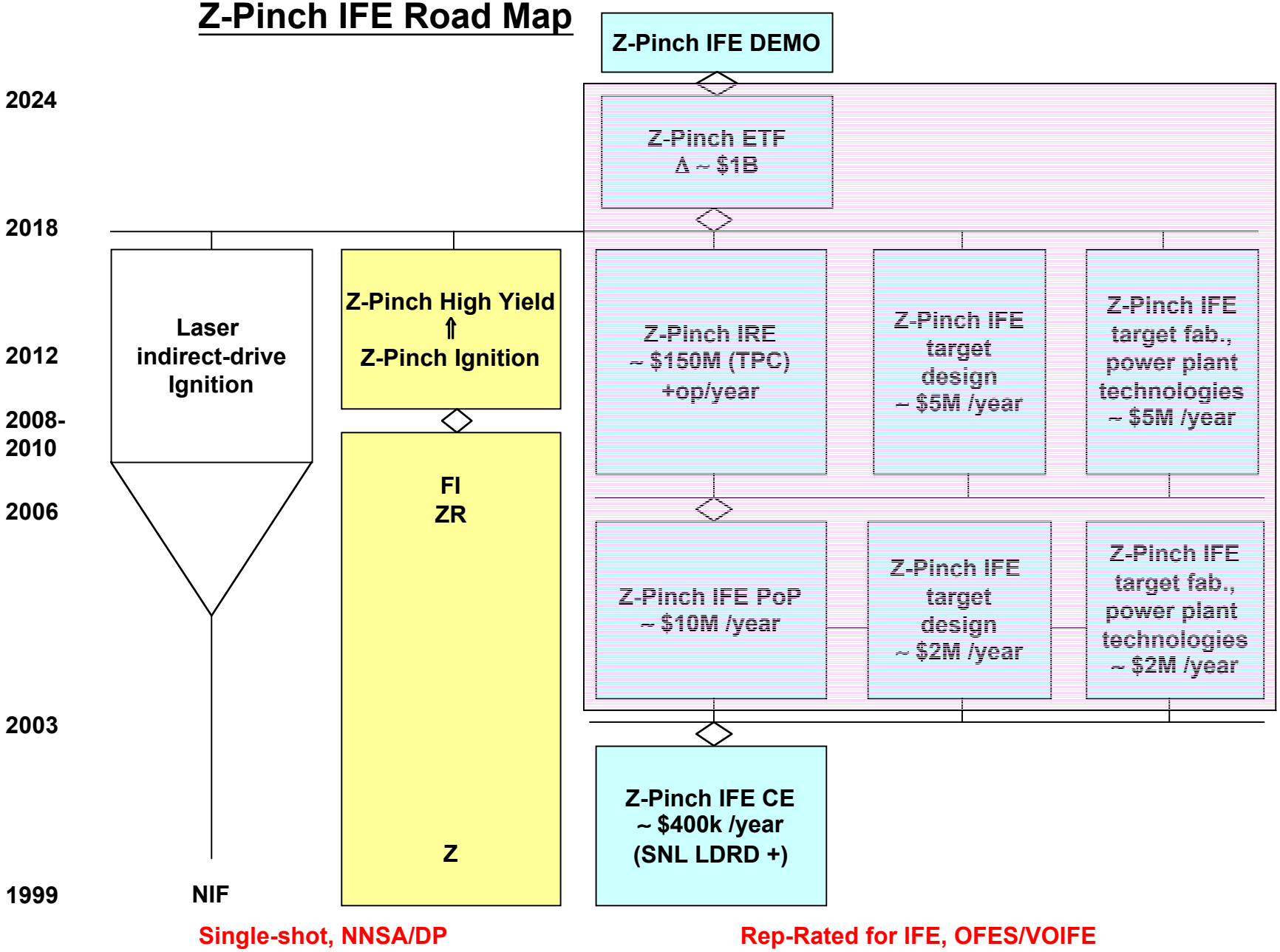
Z-Pinch IFE Road Map



Single-shot, NNSA/DP

Rep-Rated for IFE, OFES/VOIFE

Z-Pinch IFE is being developed as an integrated system

	CE	PoP	IRE
Targets (capsule compression, symmetry experiments, etc. on Z,ZR, etc.) (DP) Z-Pinch Driven Target Dynamic Hohlraum Target Fast Ignition, Advanced Targets	(X)	(X)	(X)
Driver (Rep-Rated) Fast cycling Marx/waterPFL/… RHEPP technology LTD technology		X	X
Standoff (Recyclable Transmission Line - RTL) RTL material choice, optimum shape, low inductance, etc. Electrical turn-on, conductivity, low mass, mechanical strength, etc. RTL/Chamber interface issues, etc.	X	X	X
Chamber and Power Plant Thick liquid walls, solid/voids, containment, etc. Power Plant design Manufacturing, target fabrication, costing, etc.	X	X	X
Integrated, Rep-Rated, Scaled RTL Cycle Experiment @ 0.1 Hz Model RTL cycle Couple with z-pinch load Automated, rep-rated, demonstration experiments		X	X

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Z-Pinch IFE Development Areas (PoP)

- RTL optimization — Experiment
- rep-rated pulsed power — Experiment
- containment/shock mitigation — Experiment
- scaled RTL cycle experiments at 0.1 Hz — Experiment
- Z-Pinch IFE power plant optimization
- Z-Pinch IFE target design
- Z-Pinch IFE target fabrication & power plant technology development

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RTL Optimization (PoP)

RTL issues:

- shape (disc, cone, coax, sheet, etc.,…)
- minimal inductance
- low mass
- electrical properties (turn-on, conductivity, …)
- structural properties
- manufacturing/recycling/cost properties

RTL power flow issues:

- limits for IFE z-pinch driver parameters
- optimal power flow scenarios
- convolute location

RTL/chamber interface issues:

- vacuum connections
- chamber pressure requirements
- electrical connections
- remnant removal
- insulator stack shielding

RTL test on Z with z-pinch load Demonstration Experiment on Z

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Rep-rated pulsed power is being studied for the z-pinch power plant concept

Status: Z (20 MA) at ~ 1 shot/day is ~ 10^{-5} Hz
Z-Pinch IFE needs ~ 1 shot/10 seconds is 0.1 Hz
RHEPP has demonstrated 2.5 kJ at 10^2 Hz (0.25 MW ave. pwr.)

Survey of possible rep-rated pulsed power scenarios for 0.1 Hz :
- fast charging MARX/water PFL/…
- RHEPP (magnetic pulse compression)
- linear transformer driver (LTD)

Tentative choice: LTD
- LTD is very compact, very fast (pioneered in Tomsk, Russia)
- direct charging of compact capacitors
- IVA (inductive voltage adder)
- MITL (magnetically-insulated transmission line)
- modular, scalable, easily rep-rateable

Planned Scaled facilities:
- PoP scale experiment: 1 MA, 1MV, 100 ns, 0.1 Hz
- IRE: 10 MA, 2 MV, 100 ns, 0.1 Hz
- ETF: 60 MA, 5-10 MV, 100 ns, 0.1 Hz

LTD studies for a 1 MA driver (PoP scale) and a 10 MA driver (IRE scale) are in progress

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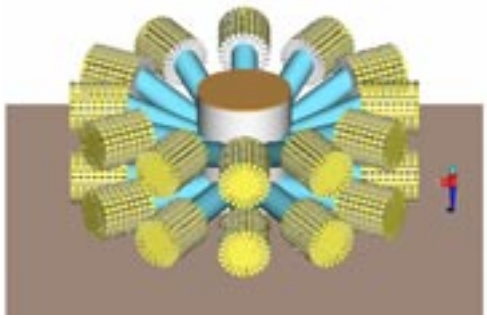
Comparison of Existing Saturn Assembly with the Proposed New LTD (Z-Pinch IRE will be this scale)

Present Device	New Design
30-m diameter.	**14.8-m diameter.**
6 -m height.	**5-m height**
250,000-gallon oil tank.	**None**
250,000-gallon water tank.	**None**
2 m diameter insulating stack.	**None**



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Containment/Shock Mitigation (PoP)

Status:

- 4 GJ (1ton TNT) confined in 8 meter radius chamber with 20 cm thick shells at Russian Academy of Sciences in Moscow
- Present power plant studies for laser IFE and HIF IFE use yields of 0.4-0.7 GJ with a chamber radius of 3-6 meters
- For Z-Pinch IFE, liquid coolant streams, or solids with voids, may be packed as close to the target as desired

Containment of GJ class yields:

- Directed impulse loading
- Innovative concepts for shock absorption
- Structural analysis of chamber, and effects of shocks

Shock mitigation studies:

- Experiments with explosives and water hydraulic flows
- Properties of expected coolants, such as EOS
- Code modeling studies of chamber flow dynamics

Scaling studies for chamber phenomenon

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Scaled RTL Cycle Experiments

PoP (Proof of Principle):

1 MA, ≤ 1 MV, 100 ns, 0.1 Hz
scaled RTL
integrated experiment for N shots
~ 5 kJ x-ray output per shot

IRE (Integrated Research Experiment):

10 MA, 2 MV, 100 ns, 0.1 Hz (rep-rated Saturn scale)
scaled RTL
integrated experiment for N shots
~ 0.5 MJ x-ray output per shot

ETF (Engineering Test Facility):

Extension of Z-pinch HY Facility
~ 60 MA, 5-10 MV, 100 ns, 0.1 Hz
full-scale RTL
~ 0.5 GJ fusion yield per shot

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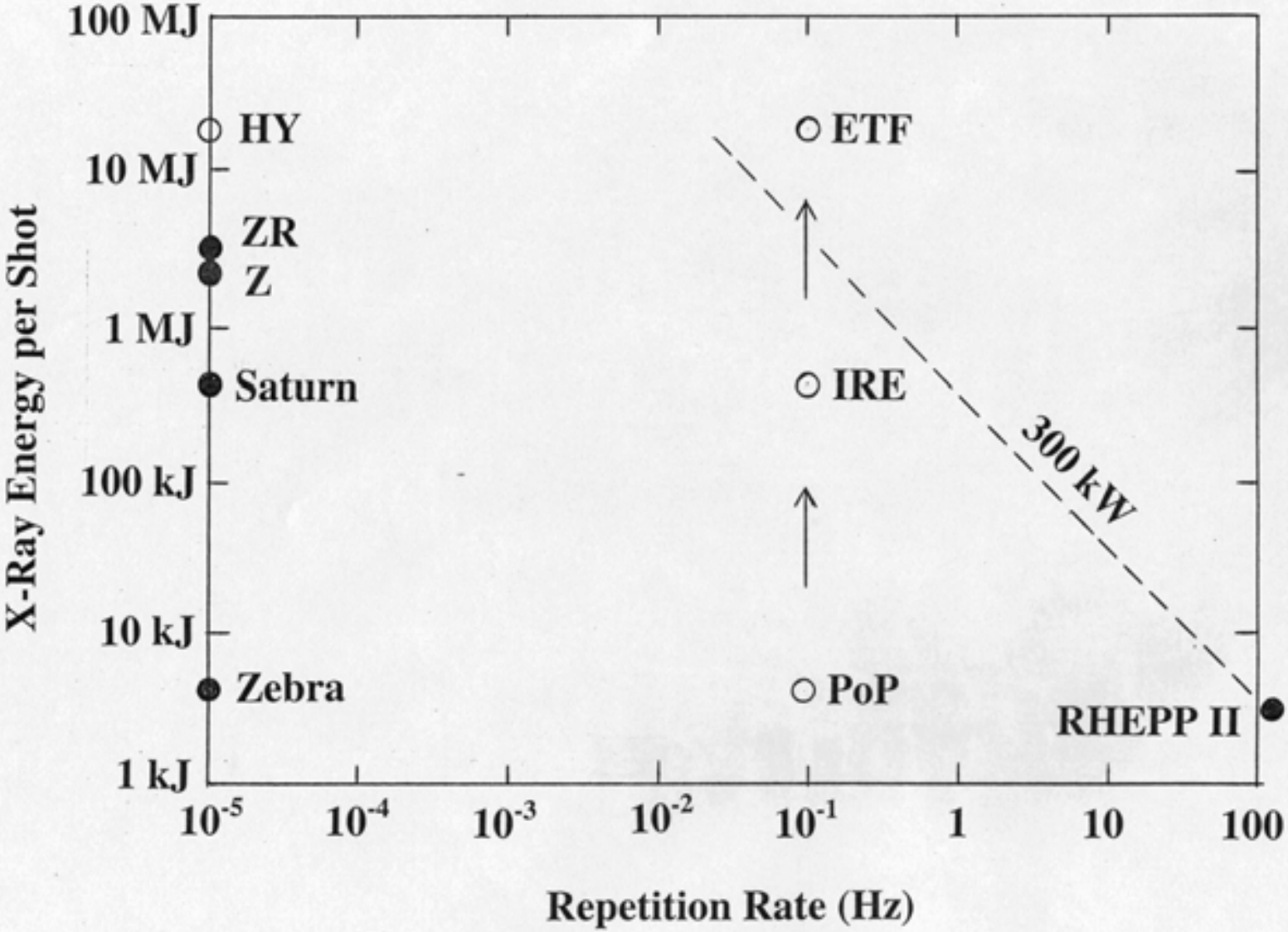
Z-Pinch IFE Development Path



Z-Pinch IFE Program - Conclusions

Z-Pinches have joined lasers in capsule implosion experiments

Z-pinch driven capsule compression experiments on Z

- double-pinch hohlraum (Cr > 14),
- dynamic hohlraum (Cr ~ 10)
- cone compression for fast ignition

High yield target simulations for 0.5 GJ - 3 GJ

- double-pinch hohlraum; dynamic hohlraum; fast ignition

Z-pinch driver development Z ZR High Yield

- ZR will be within a factor of 2-3 in current (4-9 in energy) of high yield

Recyclable Transmission Line (RTL) concept for rep-rated operation

- Saturn RTL experiments at 10 MA successfully completed

Z-pinch power plant (3 GJ @ 0.1 Hz per chamber)

- First integrated design study completed

Rep-rated Z-Pinch driver

- Linear Transformer Driver (LTD) technology (no oil, no water, no insulator stack)

PoP - IRE - ETF

- 1 MA @ 0.1 Hz; 10 MA @ 0.1 Hz; ~ 60 MA @ 0.1 Hz

Z-Pinch IFE Road Map

- Leverages DP investment in Z-Pinches, Merits home in DOE

Z-Pinch IFE ready for PoP level now
Z-Pinch IFE will be ready for IRE decision in 3-5 years

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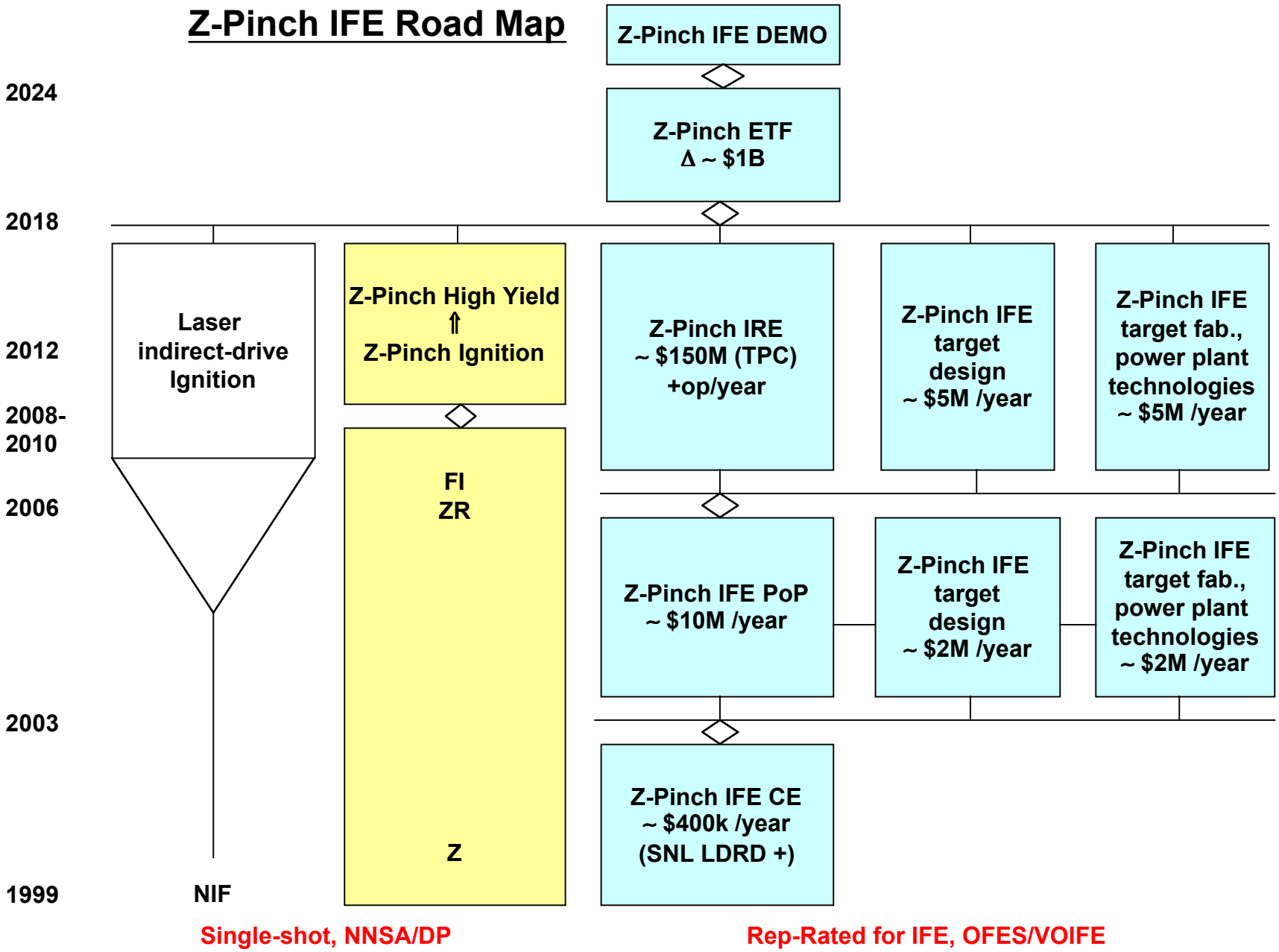
Z-Pinch IFE Road Map