Z-Pinch IFE Program

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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:

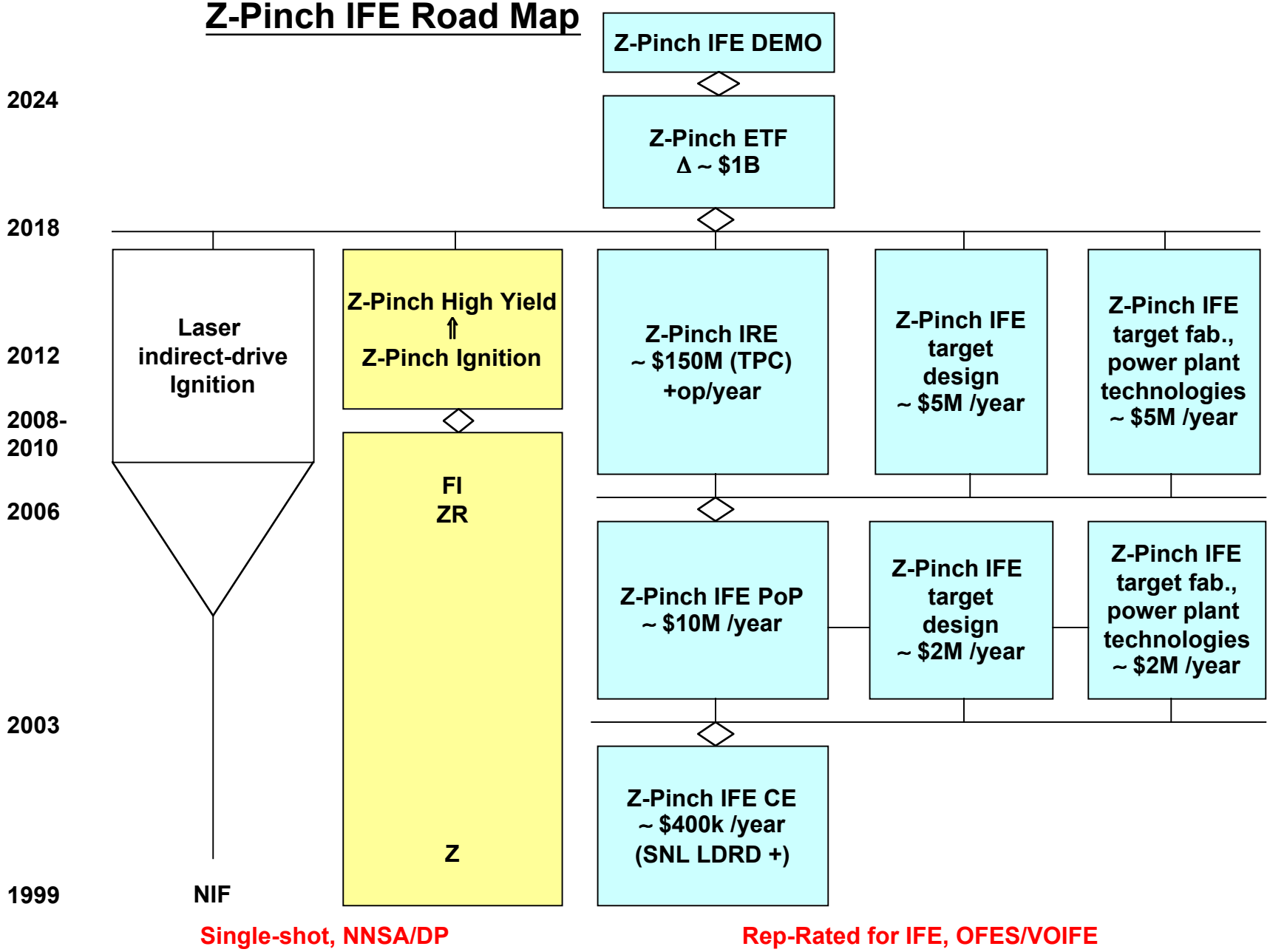
Direct-drive Indirect-drive

Fast Igniter option (major driver + PW laser)

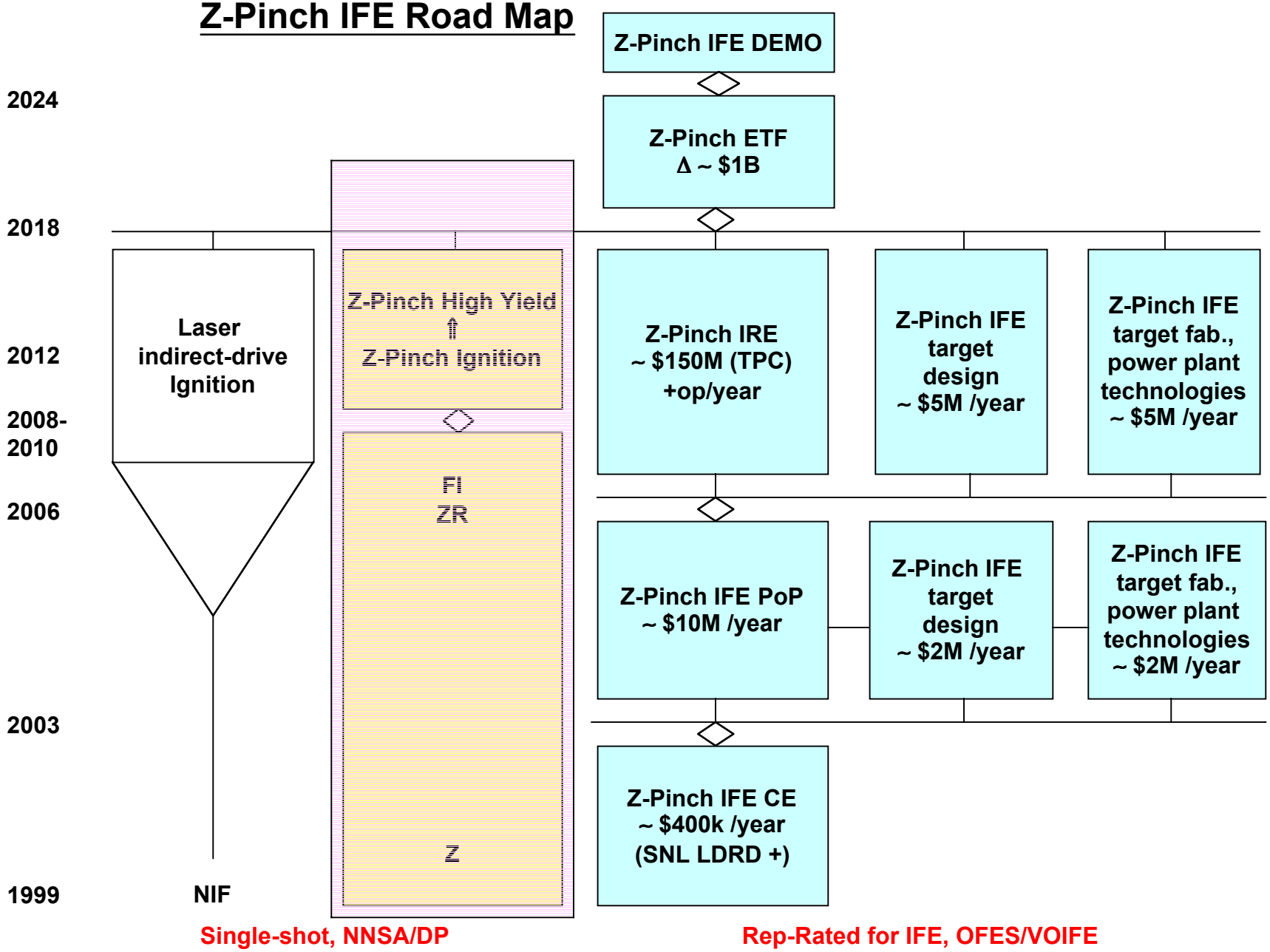
Chambers:

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

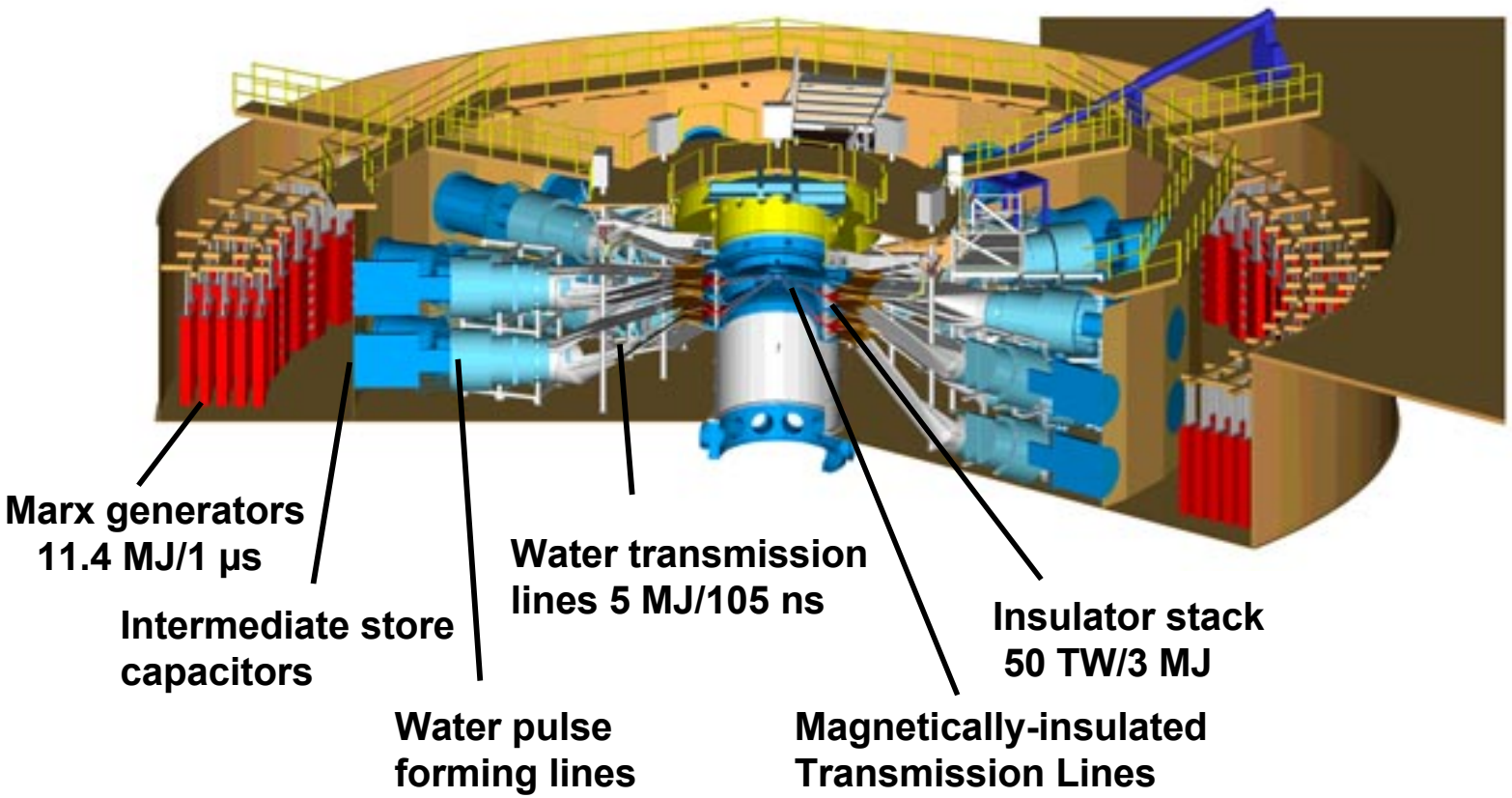
Z-Pinch IFE Road Map



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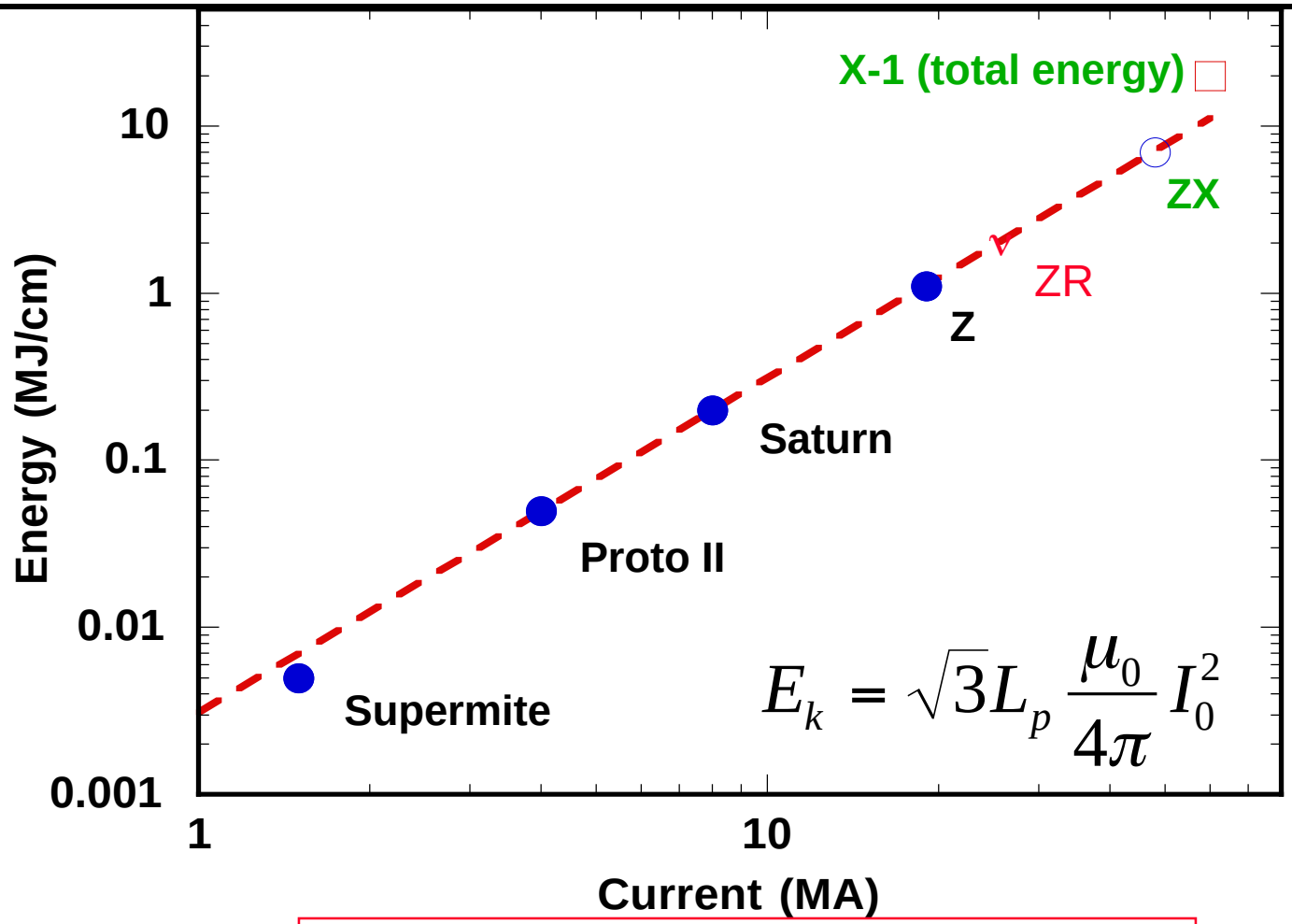
Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE



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

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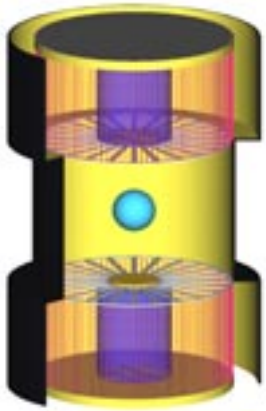
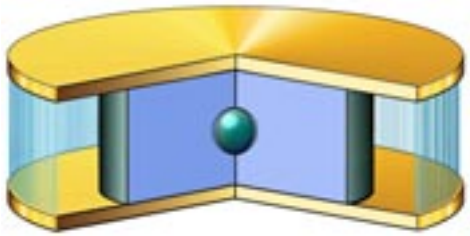
Two complementary Z-pinch indirect drive concepts for high-yield ICF and IFE are being explored

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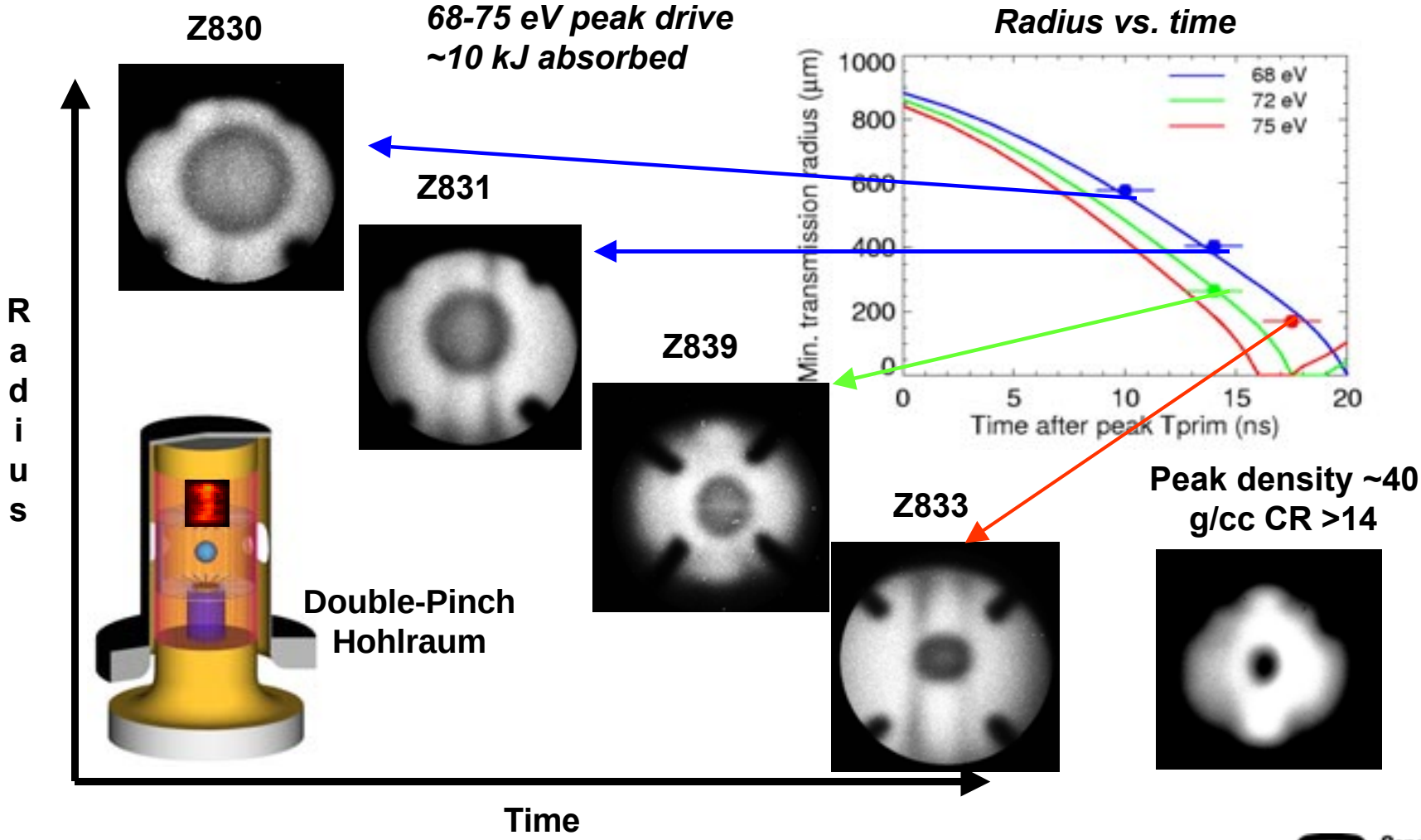
Double-pinch hohlraum on Z; capsule compression experiments demonstrate convergence ratio above 14; backlit capsule images agree with simulations



G. Bennett, M. Cuneo, R. Vesey

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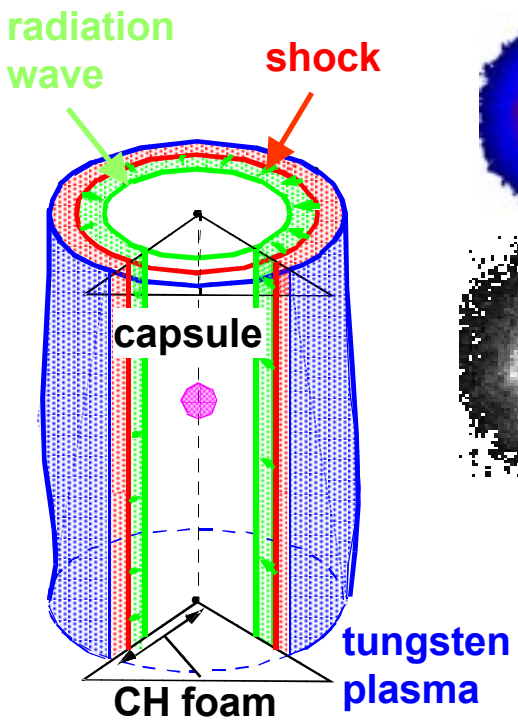
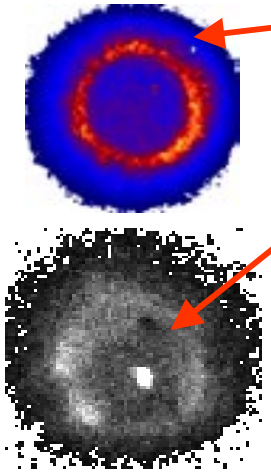
Dynamic hohlraum on Z; capsule compression experiments show convergence ratio of ~10; core image and argon spectra from capsule absorbing 20 kJ of x-rays are shown

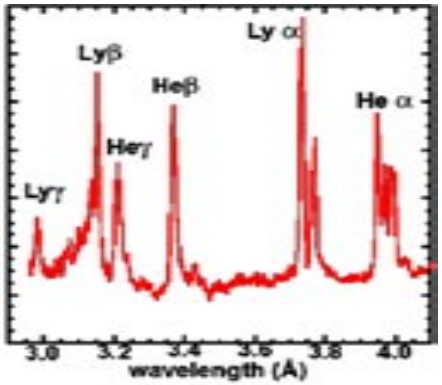




Shock emission width (~250 μm) is consistent with low levels of pinch RT

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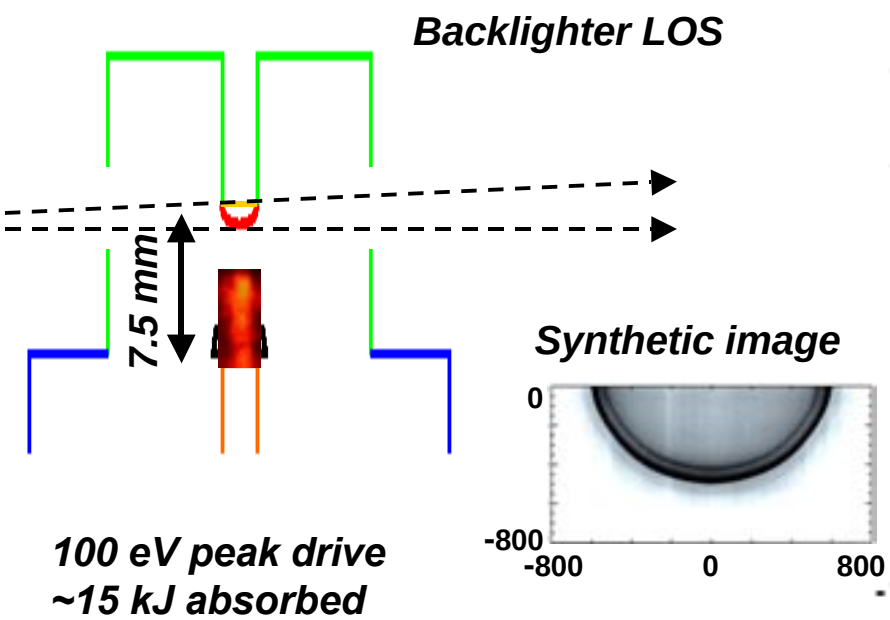
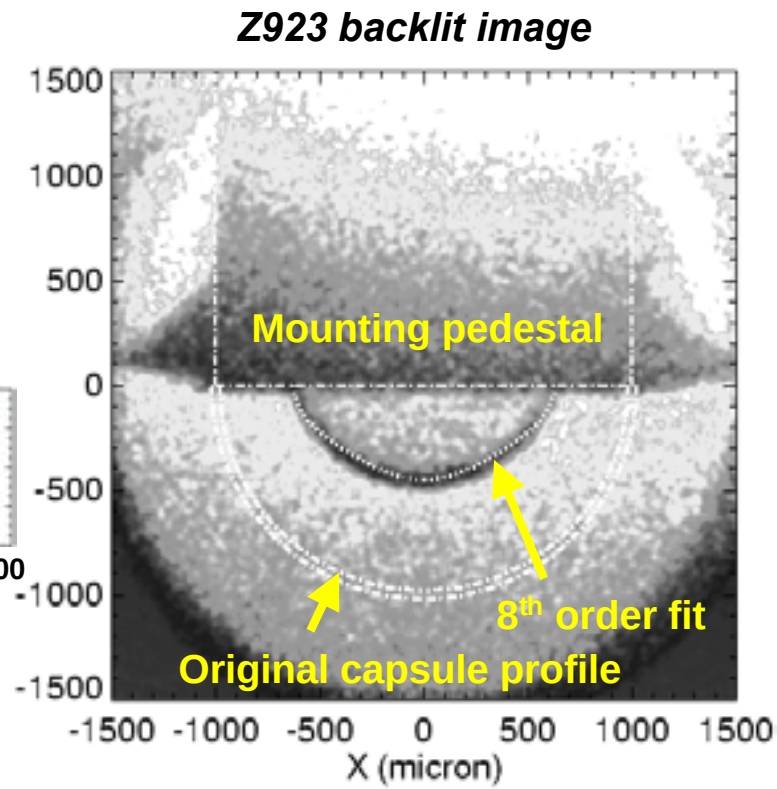
Cone-focused capsule implosions on Z: testing potential fast ignition compression schemes





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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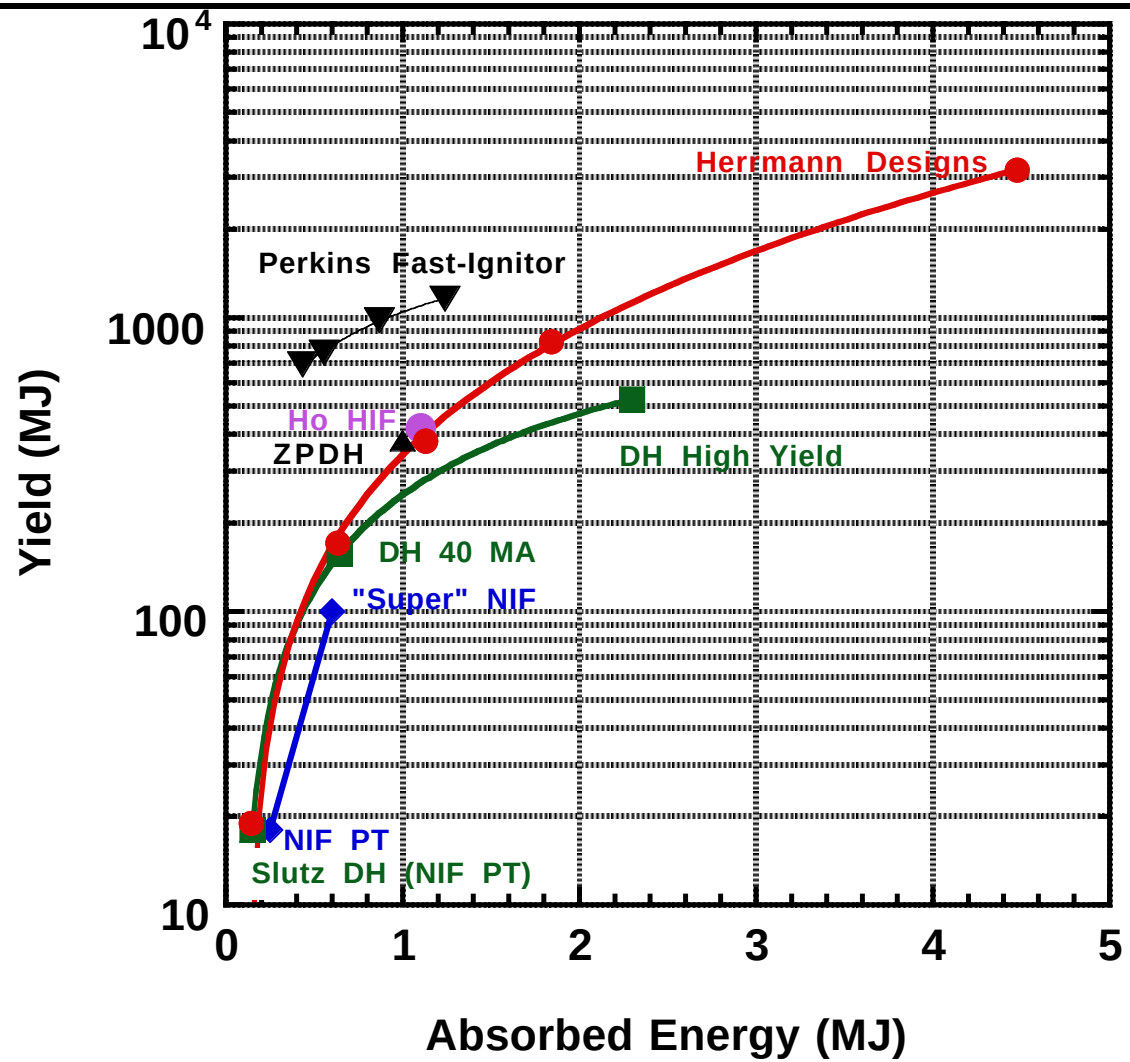
Targets with higher gain are more highly optimized, but could be less robust to variable operating conditions

ICF Capsule Design Scaling



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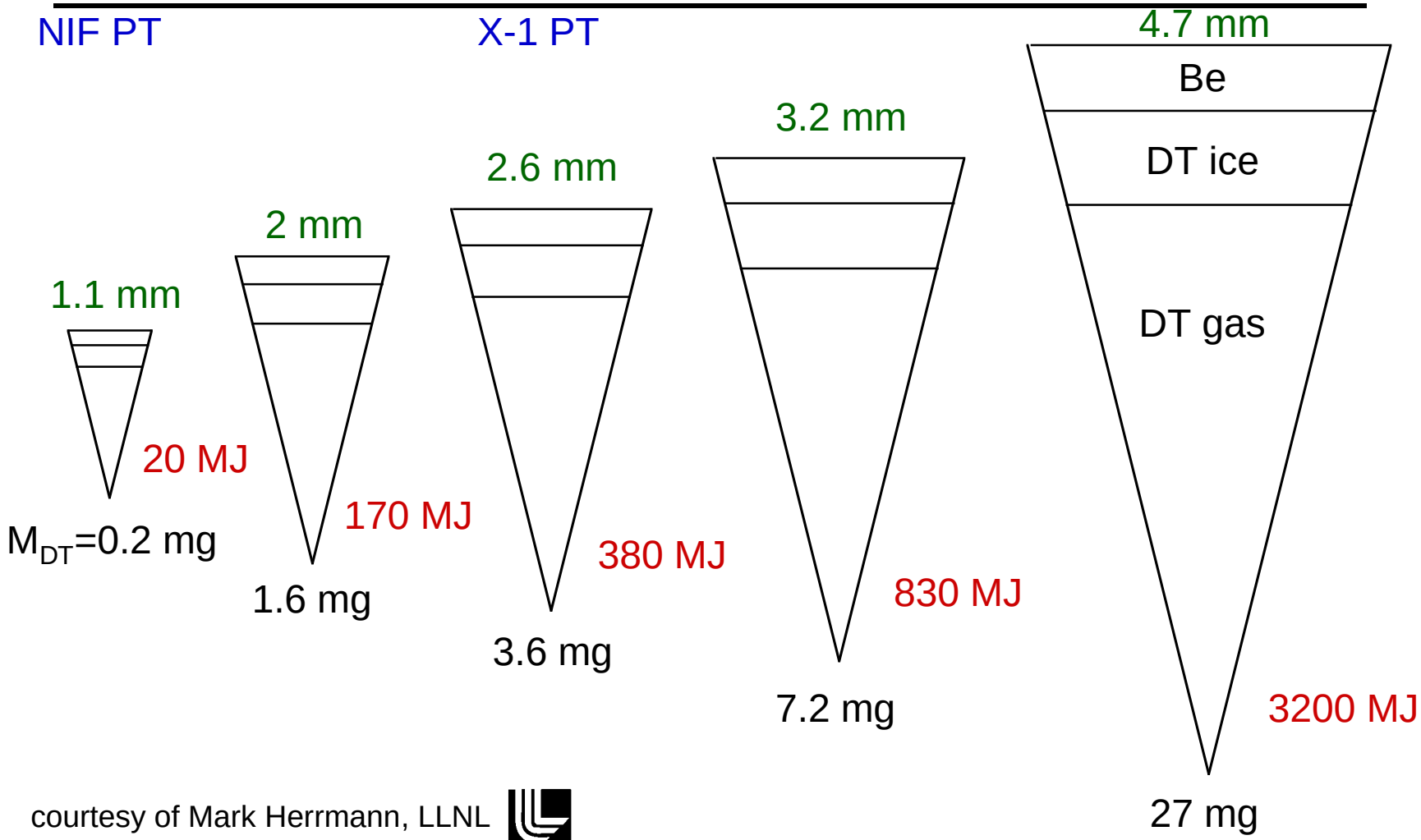
A scaled ZPDH high yield capsule (scaled from NIF PT design) is predicted to achieve sufficient yield for IFE



courtesy of Mark Herrmann, LLNL

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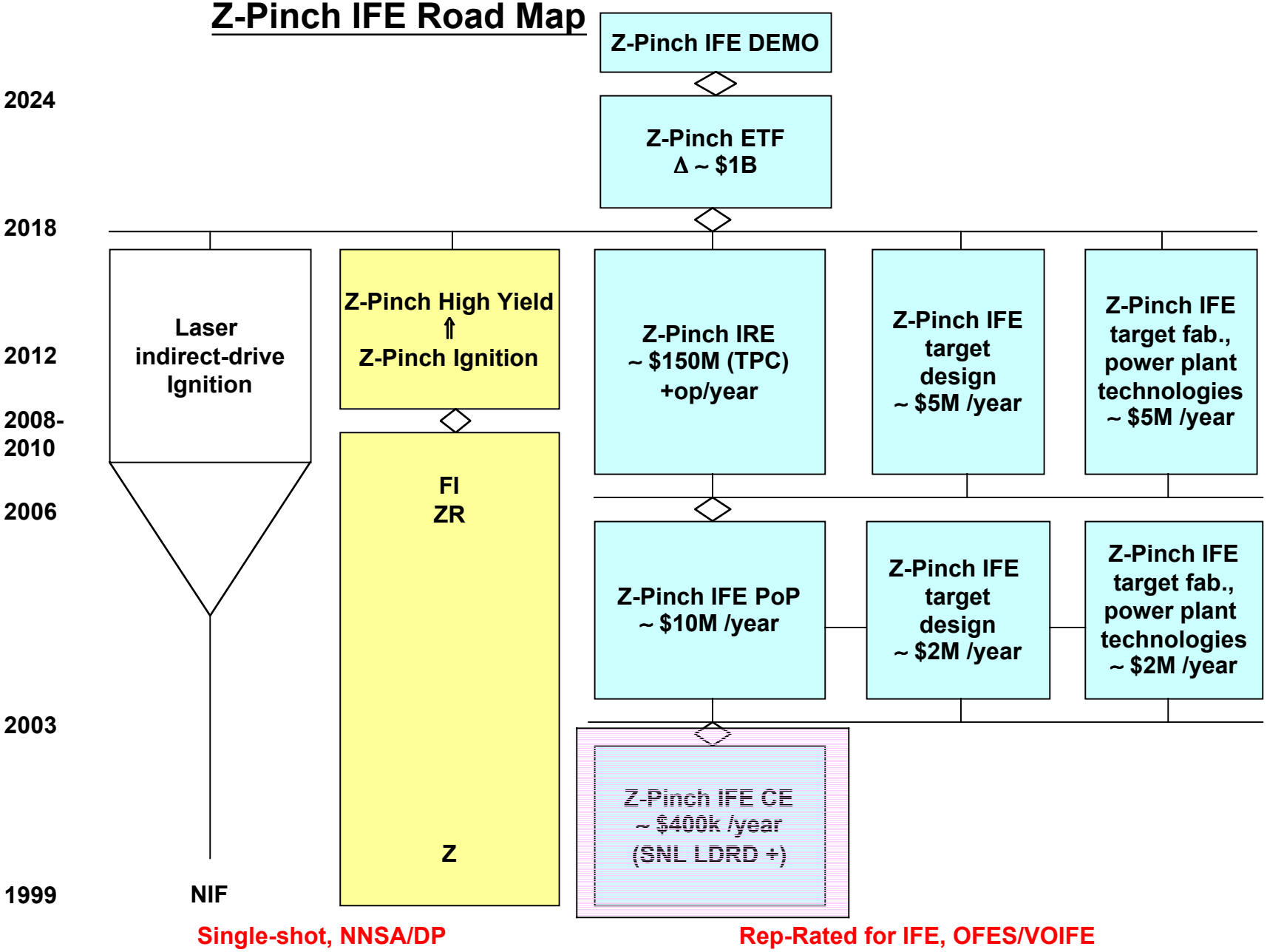
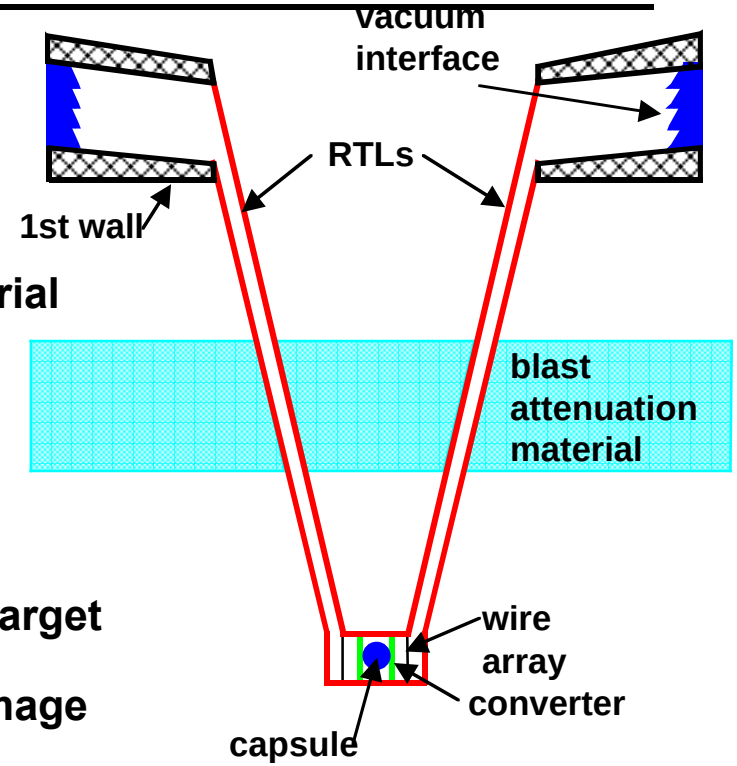
Z-Pinch IFE Road Map



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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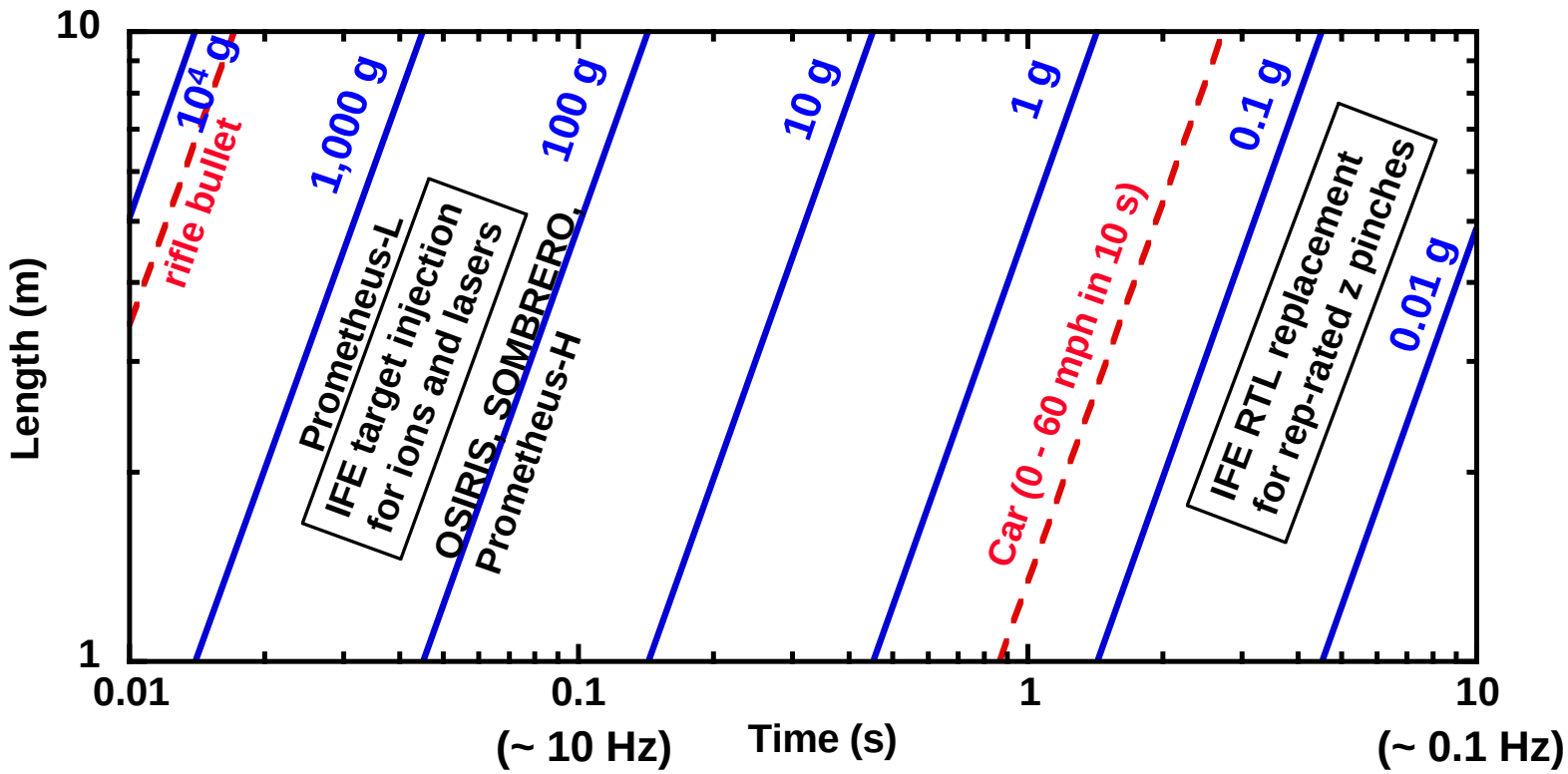
RTL replacement requires only modest acceleration for IFE

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

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



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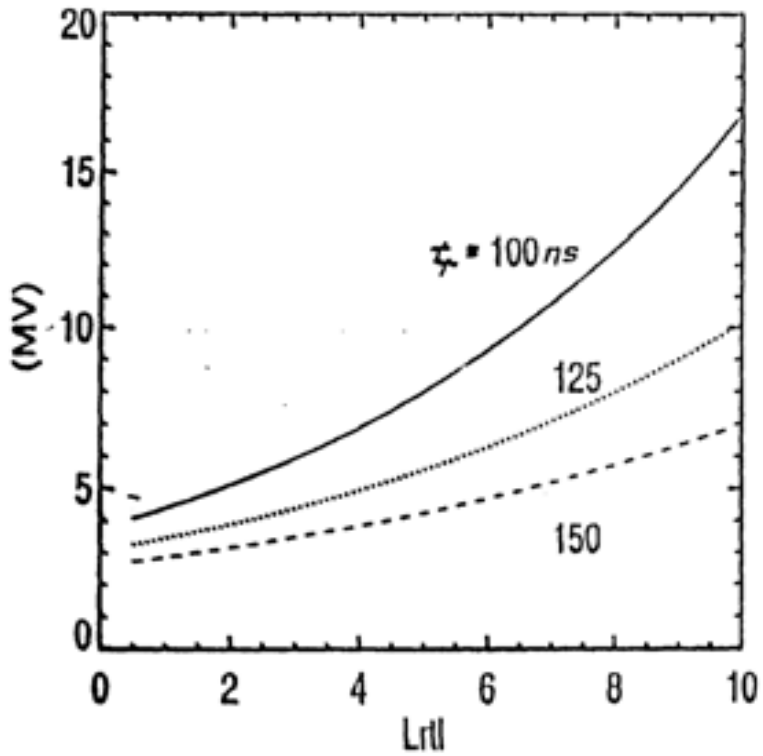
The driving voltage increases with the length of the RTL, and decreases with increasing current risetime



- 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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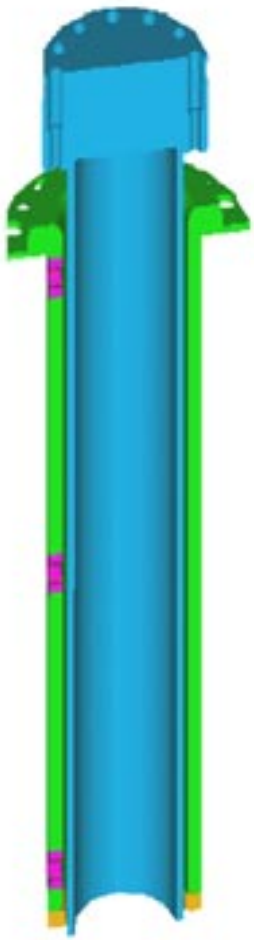
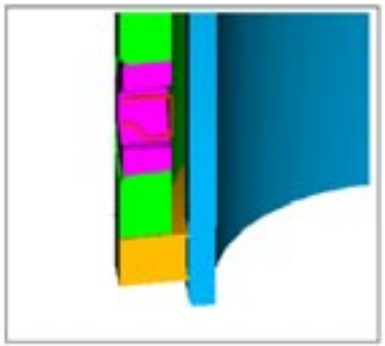
Saturn experiments to test RTL materials have been performed successfully

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

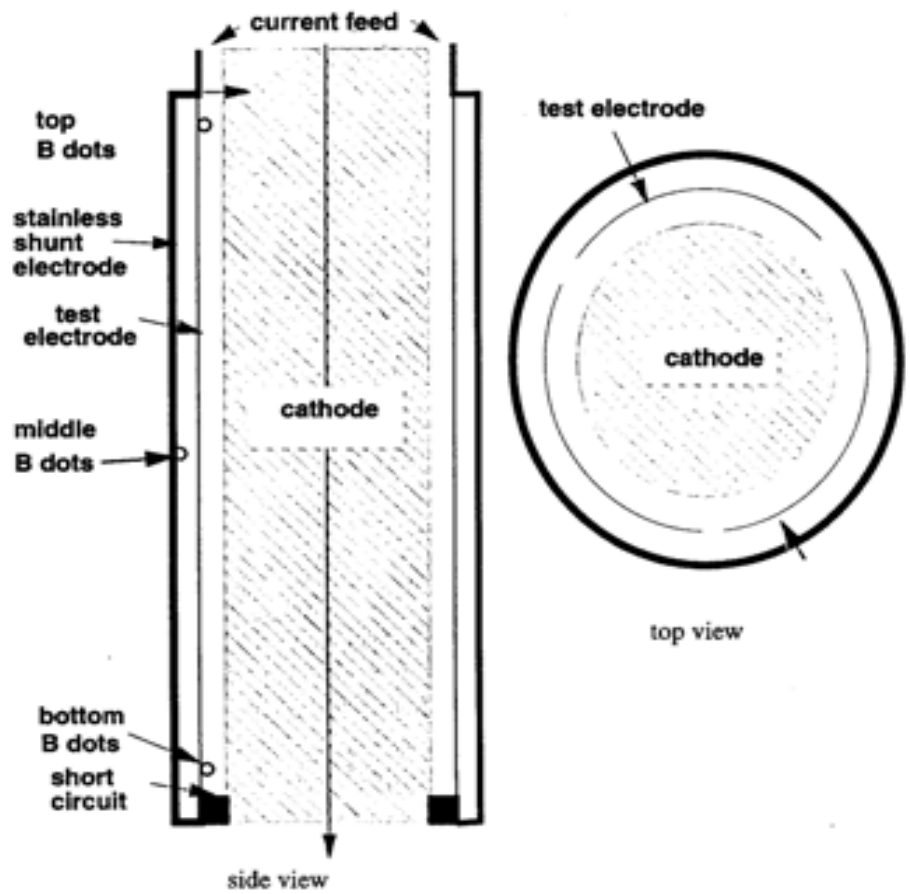
Saturn experiments have been performed at the 10 MA level to measure the electrical conductivity properties of such low-mass RTL electrode materials:

25 μ mylar

50 μ carbon steel

100 μ carbon steel

250 μ carbon steel



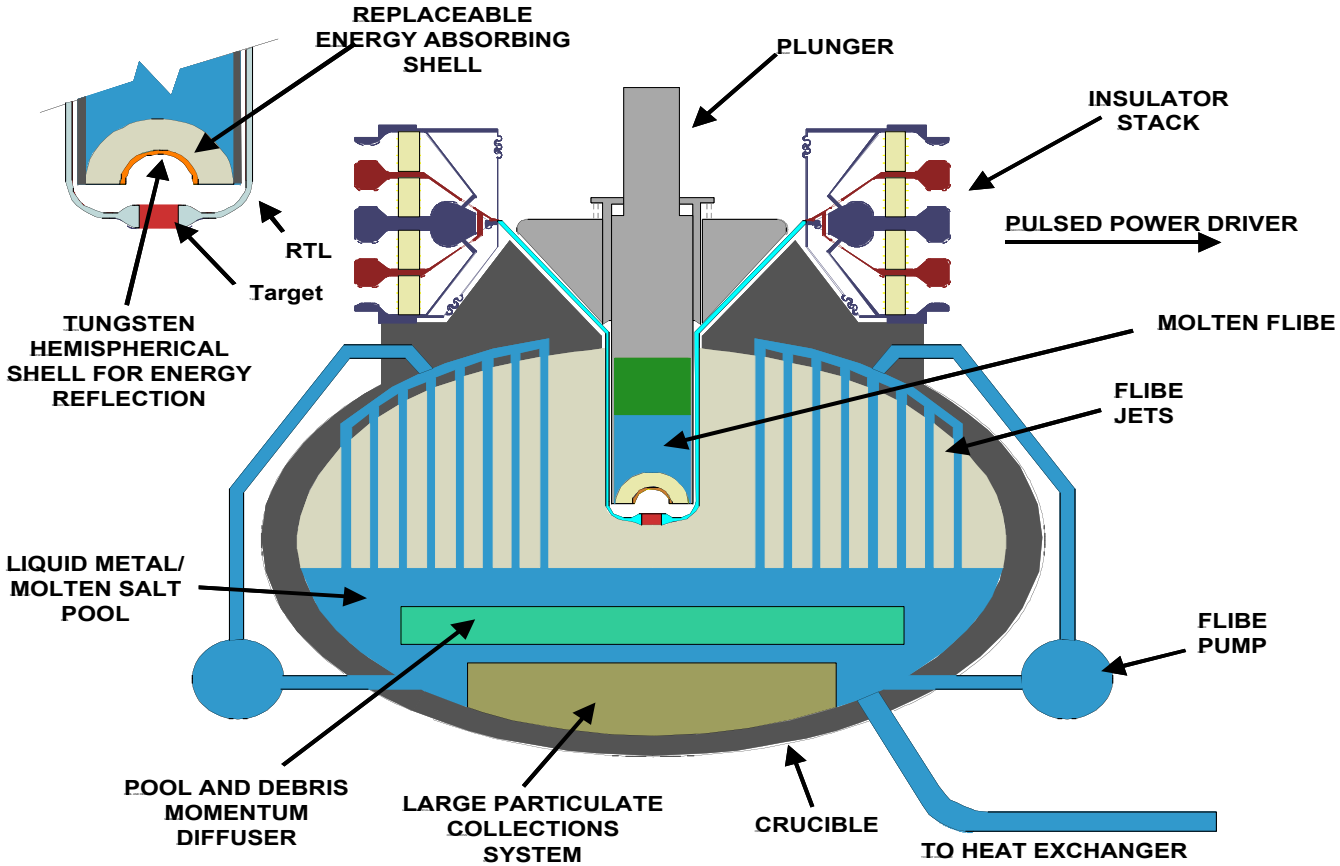
Saturn low-mass RTL experimental results have been used to estimate the total mass and electrical efficiency of a power-plant-scale RTL (R = 4 meters).

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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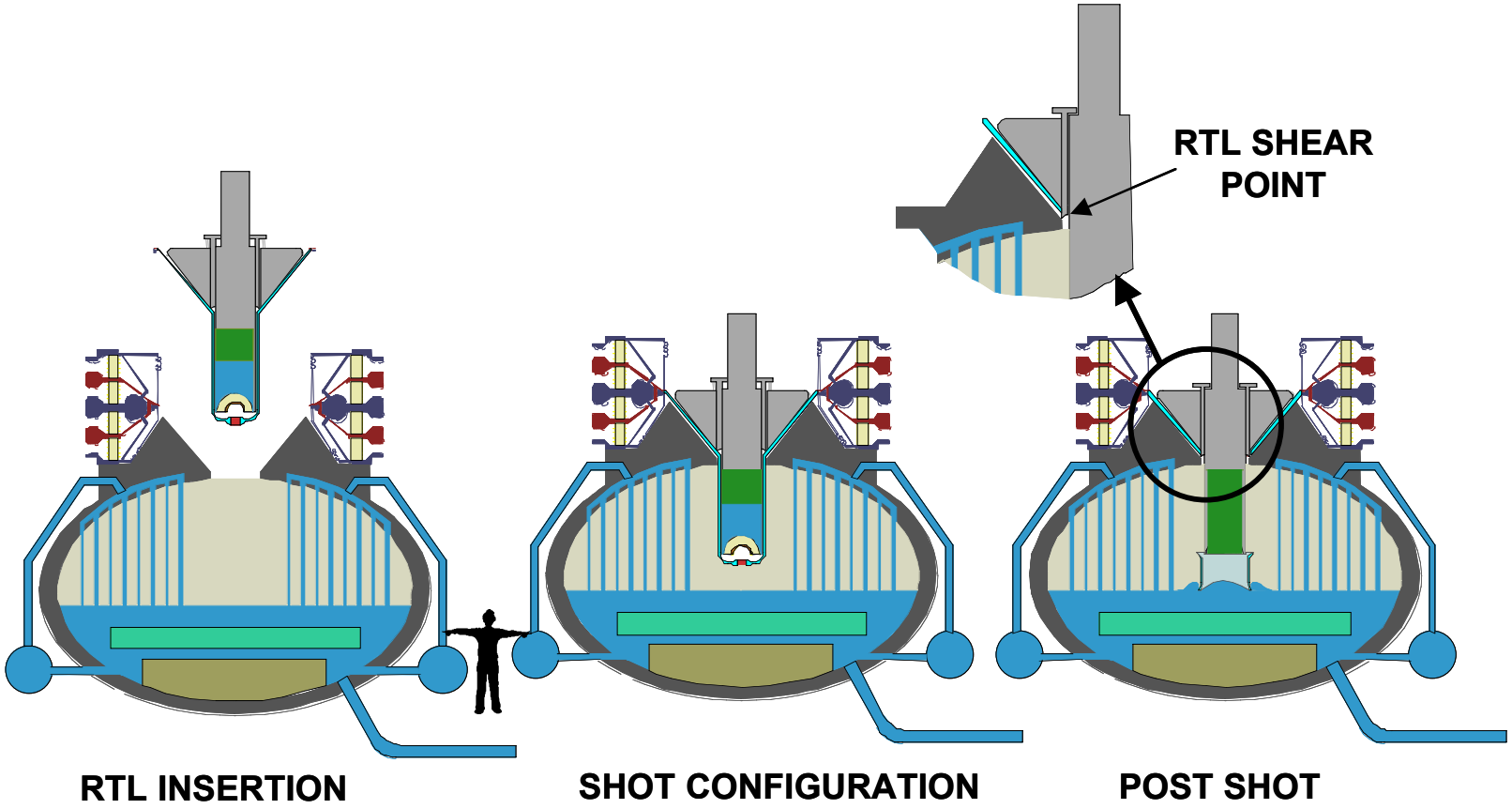
Z-Pinch Power Plant
Proposed Cartridge Cycle



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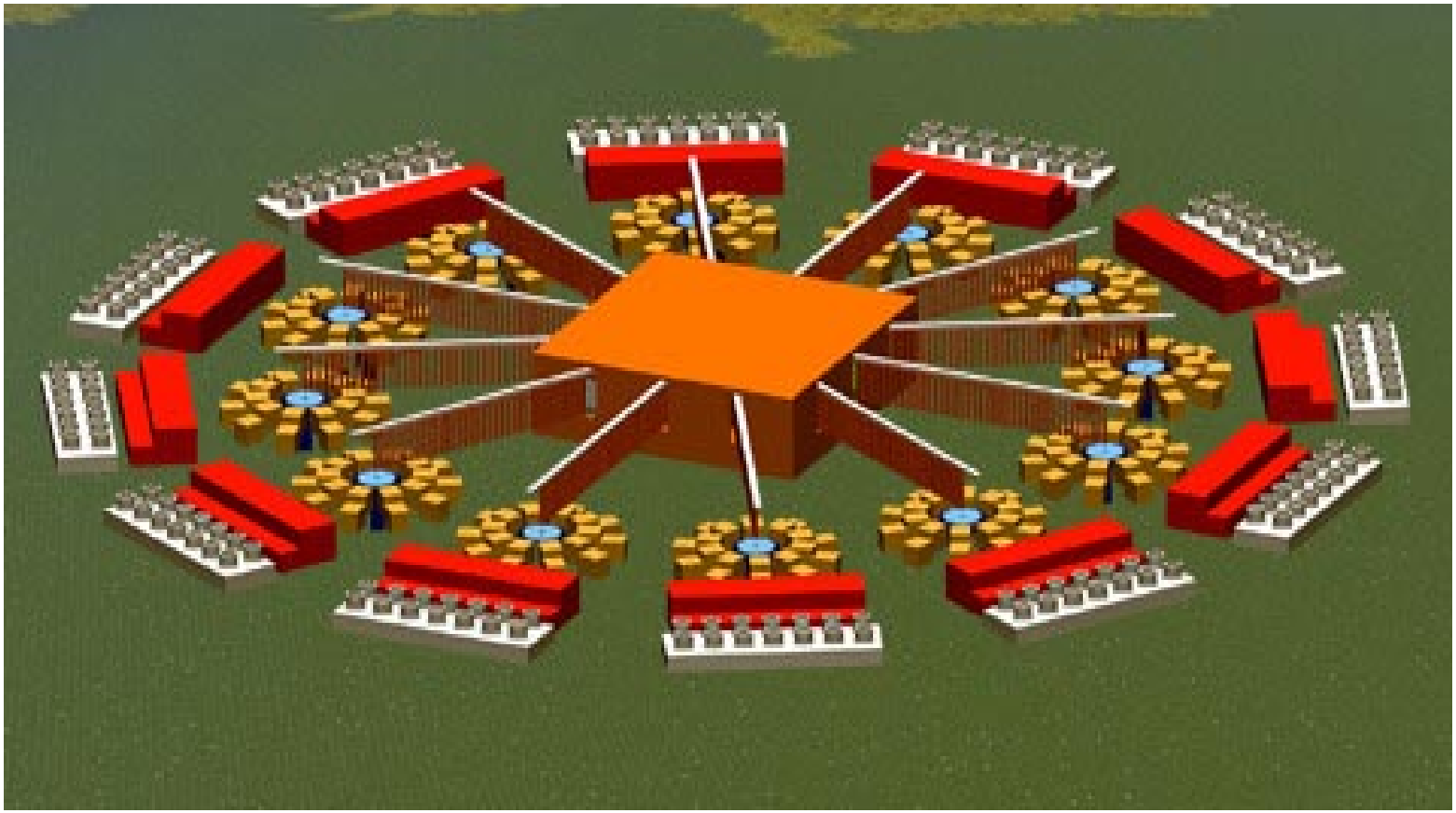
Z-Pinch Power Plant would produce Electricity



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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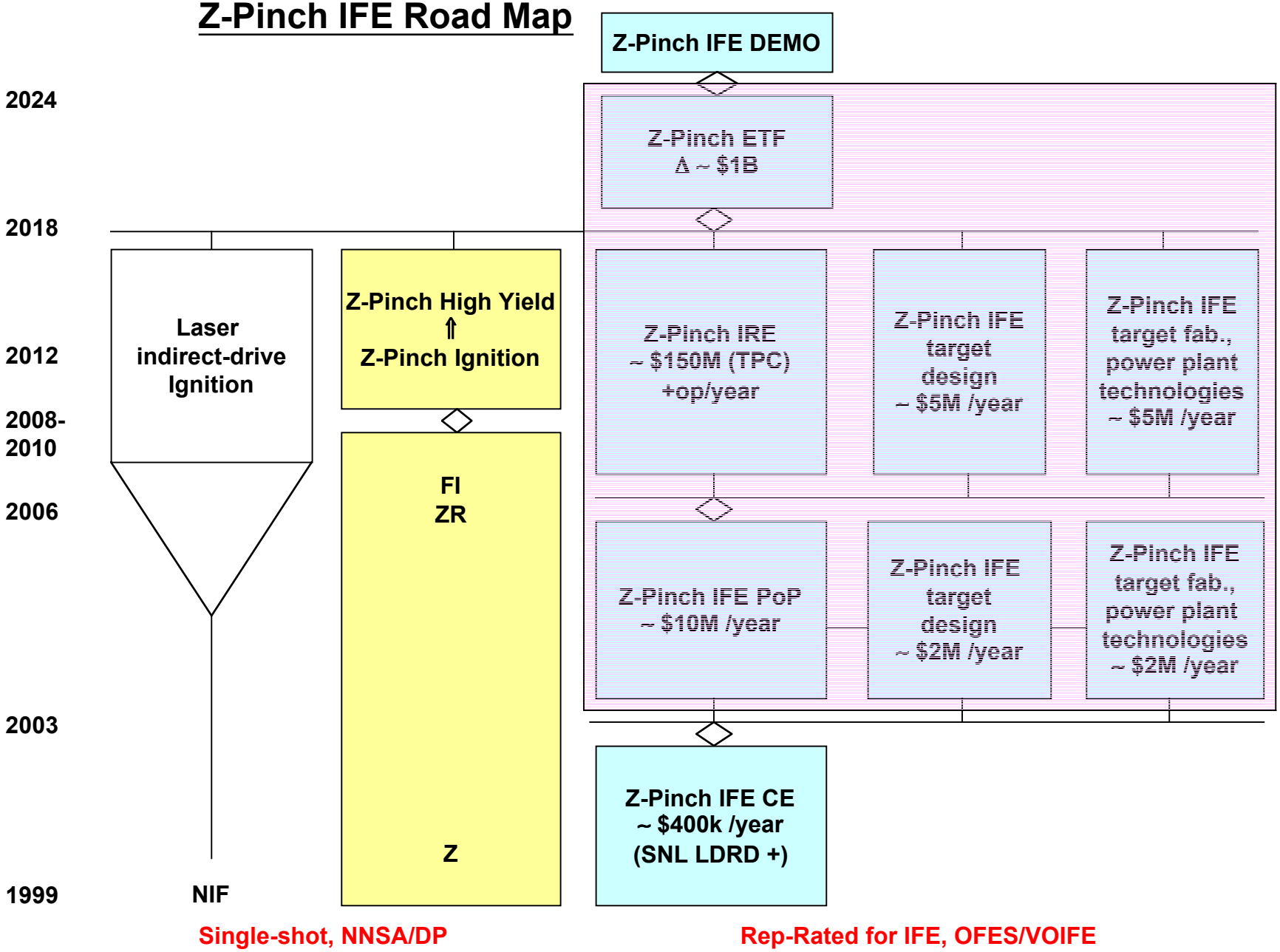
Z-Pinch IFE Road Map



Single-shot, NNSA/DP

Rep-Rated for IFE, OFES/VOIFE

Z-Pinch IFE Questions

What do code calculations predict for z-pinch driven high yield targets?
What are the driver parameters needed for z-pinch IFE GJ yield targets?
Where do z-pinch capsule compression experiments stand relative to other IFE approaches?
Can GJ yield explosions be adequately contained?
What shock mitigation techniques might be used to protect the first wall?
Is there a rep-rated pulsed power approach for the driver at 0.1 Hz?
Is the pulsed power modular?
Can the insulator stack be adequately shielded? Can the insulator stack be removed?
What is the optimal power flow scenario (coax, triax, convolute,…)?
Are there any power flow limits that may become important for z-pinch IFE drivers?
What is the optimal RTL configuration (shape, inductance, shielding,…)?
What are the optimal RTL materials (electrical, low mass, structural,…)?
What are the RTL chamber interface issues (electrical, vacuum, remnant removal,…)?
Are the mechanical accelerations for RTL replacement at 0.1 Hz reasonable?
What are the projected manufacturing techniques and costs for the RTL/z-pinch /target?
What highly automated metal refining and fabrication methods are needed?
What FLIBE coolant processes must be understood (chemical composition and control)?
What z-pinch/target fabrication development is needed?
What scaled rep-rated RTL experiments would make sense?
Is there a first conceptual z-pinch IFE RTL power plant scenario?
When does direct conversion become possible and desirable?
What studies are needed to optimize a z-pinch RTL power plant?
Is the projected COE competitive with other IFE approaches & commercial power?

Z-Pinch IFE Development Areas (PoP)

- RTL optimization
- rep-rated pulsed power
- containment/shock mitigation
- scaled RTL cycle experiments at 0.1 Hz
- 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

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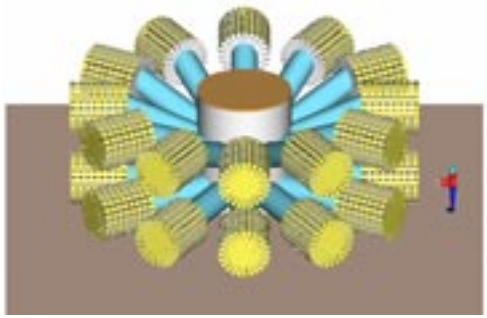
Comparison of Existing Saturn Assembly with the Proposed New LTD (Z-Pinch IRE will be this scale)

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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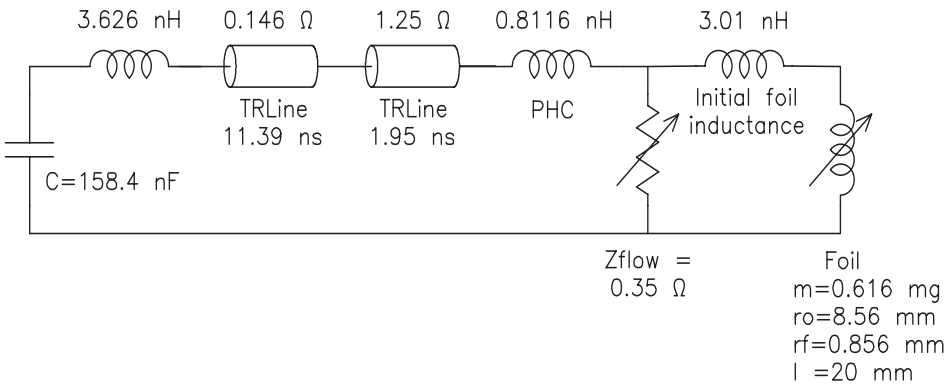
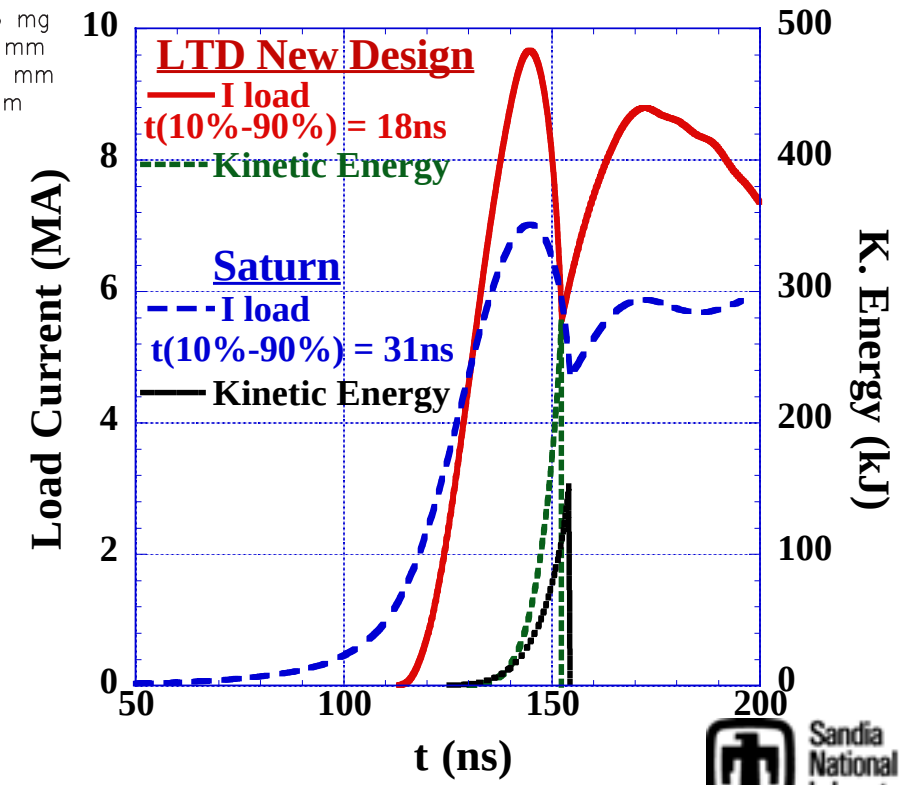
New LTD Driver Performance with Z-pinch Load (Z-Pinch IRE will be this scale)



Comparison of the present with the new design performance. Load is a wire array with the following parameters: Initial radius r_0= 8.56mm, total wire mass m= 0.616mg, final radius r_f=0.856mm, and array length 20mm.



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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

Shock mitigation studies:

- experiments with explosives and water hydraulic flows
- properties of expected coolants, such as EOS
- code modeling studies of chamber flow dynamics

Containment of GJ class yields:

- directed impulse loading
- innovative concepts for shock absorption
- structural analysis of chamber, and effects of shocks

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 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 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 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), FI cone compression

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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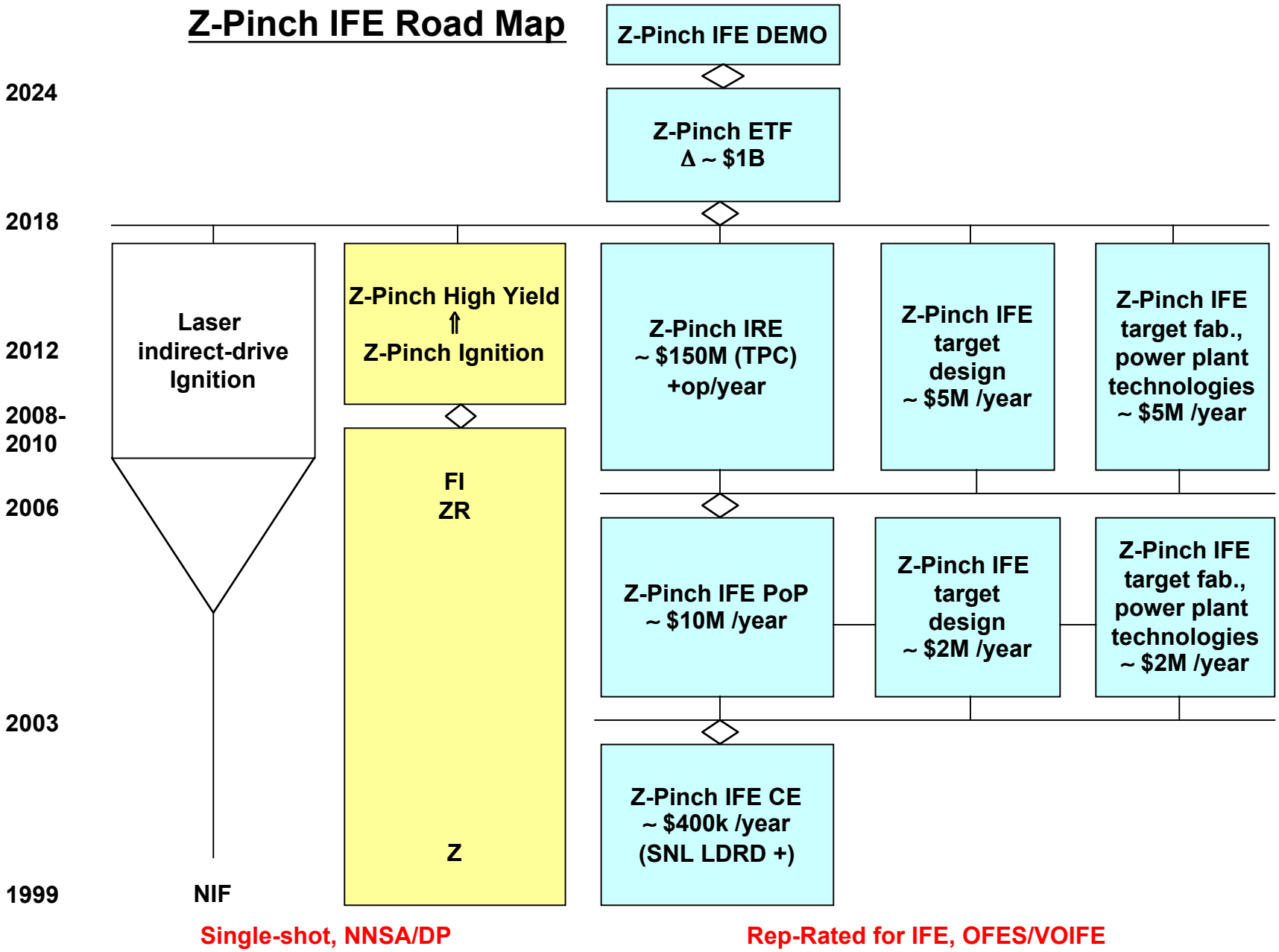
Z-Pinch IFE Road Map