30 Jan 2010

Pulsed Power Inertial Fusion Energy

Presented to the NAS Committee on the Prospects for ICF Energy Systems

January 29-31, 2011 San Ramon, California

Keith Matzen, Mark Herrmann, Michael Cuneo, *et al*
in collaboration with colleagues at the
Pulsed Power Sciences Center, Sandia National Laboratories

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Outline

- Matzen (Opening remarks and vision)
- Cuneo (Introduction)
- Herrmann (Targets)
- Cuneo (Drivers, Coupling, Chambers)
- Cuneo (The Road Ahead)

What are the unique aspects of pulsed power IFE?

- Z can efficiently couple 2 MJ’s of energy to fusion targets
- Refurbished Z was inexpensive (~$4/Joule)
- New pulsed power architectures based on Linear Transformer Drivers (LTD’s) are rep-rateable, efficient, and low cost
- Targets directly driven by magnetic fields are a new idea we are exploring
- Our pulsed power IFE concept uses large yields, low rep-rates, and thick liquid walls

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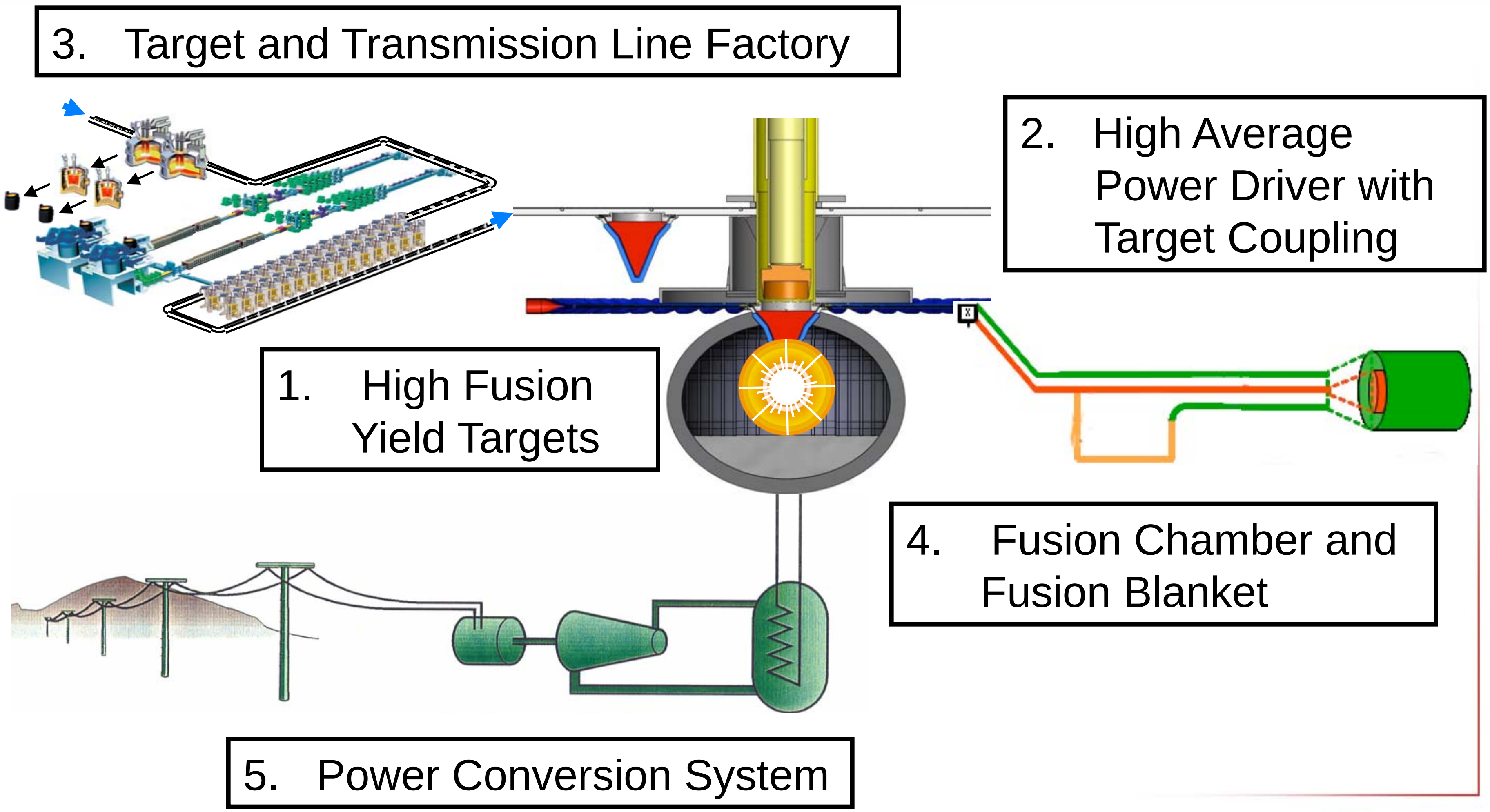
At a high level, all IFE power sources have five major elements



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The diversity of drivers, targets, coupling methods, chamber technologies requires *close scrutiny* of systems interface/integration issues

Drivers
Pulsed power magnetic pressure Pulsed power x-rays Fast Ignition Laser Heavy Ion Accelerator DPSSL Laser KrF Laser

Coupling
Conductor transport-conductor recycling Beam transport-inverse diode Beam transport-space-charge-neutralization Photon transport-target-injection-tracking

Targets
Direct-drive fast-ignition Direct-drive hot-spot ignition Indirect-drive fast-ignition Indirect-drive hot-spot ignition Other advanced concepts

Chamber and Blanket
Thick liquid wall Vaporizing blanket Wetted wall Dry wall with gas fill

- IFE has separability built into it from the start (attractive compared to MFE)
- *But*, system integration is not trivial
- It is imperative to optimize at a system level, *not just* at a sub-system level
- Efficient coupling needs to be demonstrated and is hard for all options

Pulsed power concepts allow thick liquid wall for long lifetime but require recyclable transmission lines

Drivers
Pulsed power magnetic pressure
Pulsed power x-rays
Fast Ignition Laser
Heavy Ion Accelerator
DPSSL Laser
KrF Laser

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Conductor transport-conductor recycling
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Photon transport-target-injection-tracking

Targets
Direct-drive fast-ignition
Direct-drive hot-spot ignition
Indirect-drive fast-ignition
Indirect-drive hot-spot ignition
Other advanced concepts

Chamber and Blanket
Thick liquid wall
Vaporizing blanket
Wetted wall
Dry wall with gas fill

- Direct connection of driver-target
  - simple in concept for low rep-rate, can it be engineered, can yield be high enough?
  - needs to be economic, thus recyclable, is this feasible?
  - longer lifetime chamber designs with larger yields?

This system of systems must meet a large number of demands

Performance	Cost/Schedule	System Engineering	Policy and Politics
Energy rich	Low cost	Reliability	Ease of licensing
High gain	Credible, rapid, development path	Availability	Public acceptance
Efficient	Affordable development path	Maintainability	Acceptabilty of local or global environmental impact
Scalable/flexible	Credible, rapid, deployment path to mass production	Inspectability	No evacuation plan
Robust	Affordable deployment path to mass production	Manufacturability	No high-level waste
Closed, on-site fuel cycle	Management of R and D risk	Disposability	Financing
Sufficient rep-rate		Usability	Safety analysis
Handling of high fusion yields		Mass-producability	Infrastructure development
		Suppliability	

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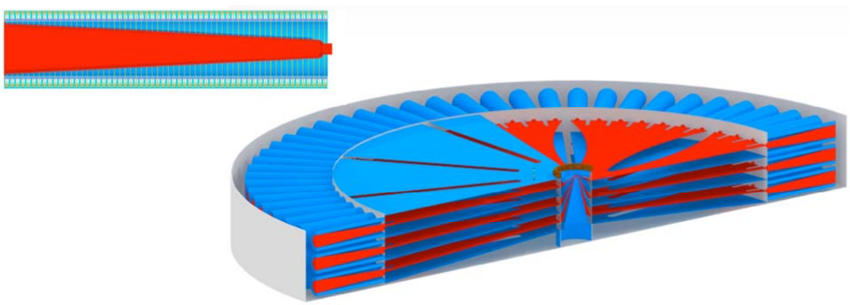
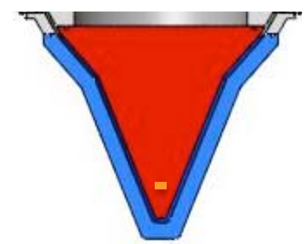
The main areas we will cover today

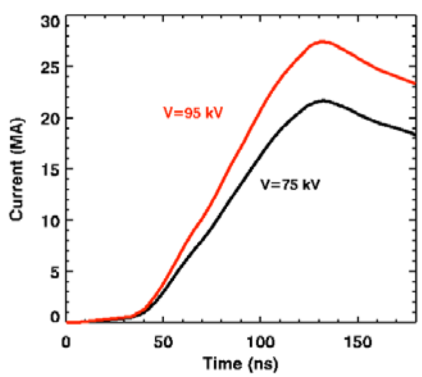
Rep-rate Linear Transformer Drivers (LTD)

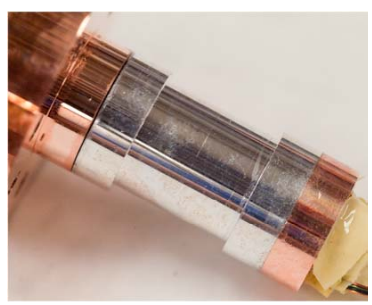


Coupling
Recyclable Transmission Lines (RTLs)

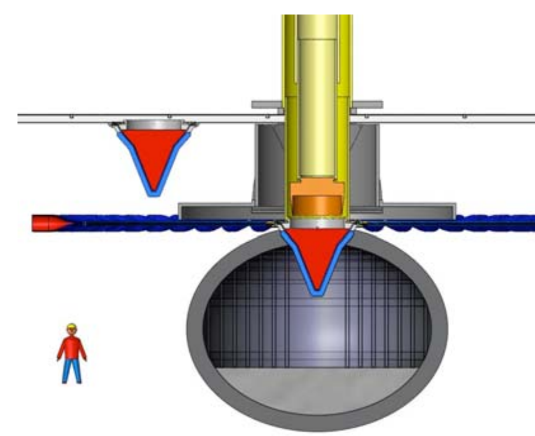


Direct Drive Target Physics





Thick Liquid Wall (TLW)
Fusion Chambers



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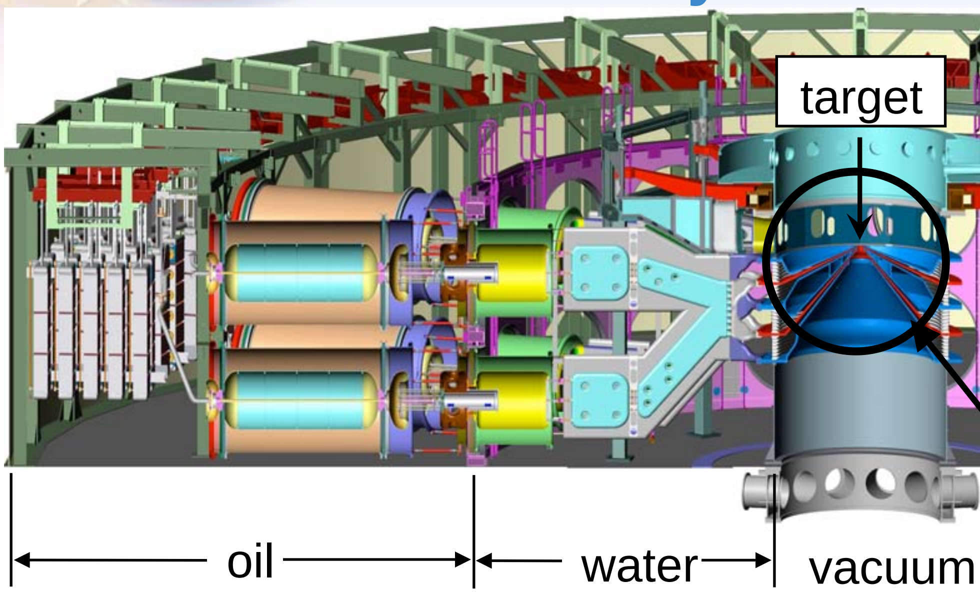
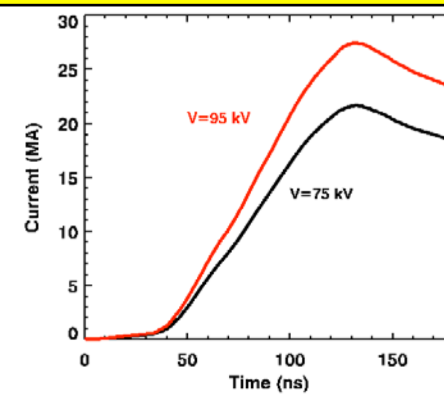
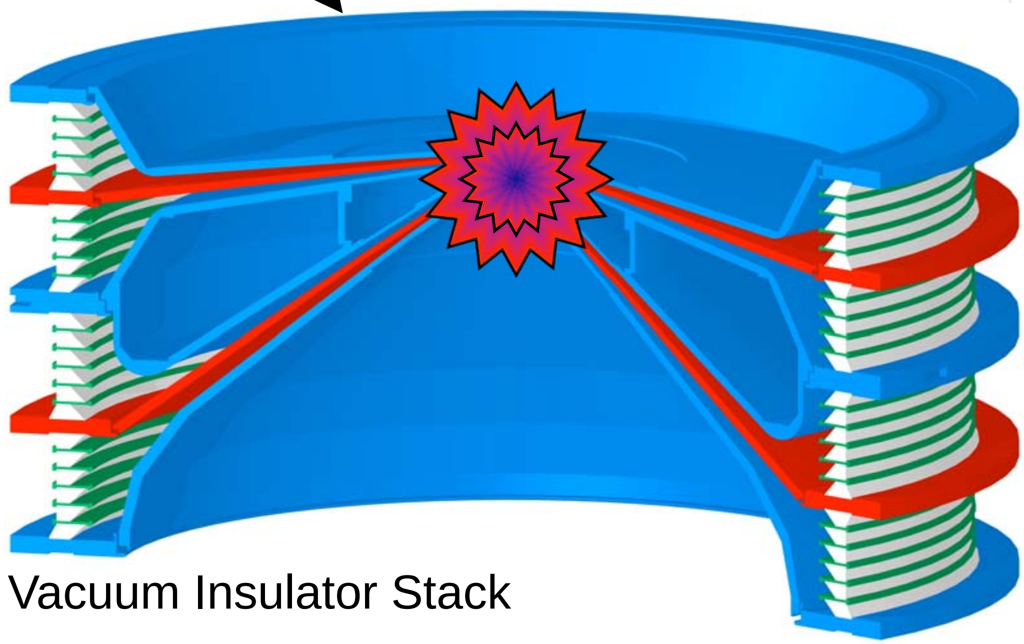
What is a Recyclable Transmission Line (RTL) and why do we need one?



Conductors carry current pulse to target



- Under normal single shot operations the middle 30 cm is replaced every shot
- With high yield single shot operation more of the center would have to be replaced
- With repetitive high yield an automated replacement of the transmission line is needed
- For economic fusion power generation the part has to be recyclable

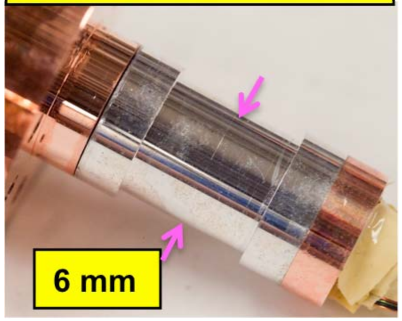


Vacuum Insulator Stack

Direct-drive fusion with magnetic pressure is 25*X* more efficient than indirect-drive with x-rays

- **Simple, robust, efficient, cylindrical targets**
  - Stamp robust and inexpensive targets with at -hand technology and fill with liquid DT
  - High magnetic pressure (>5 GBar) produced by a 60 MA current pulse delivers 10 MJ to targets to generate high yields (G~1000)
  - Minimal energy to ignite and attain high yields is far from clear – being able to provide a lot more energy is a significant advantage for pulsed power

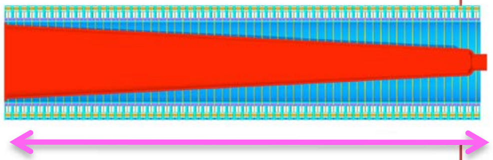
> 8600 targets/day



- **Efficient, inexpensive, drivers (Linear Transformer Drivers)**
  - Inexpensive (prototype ~11$/Joule)
  - Efficient (70%, 2*X* ZR architecture)
  - Achieved rep-rate (0.1 Hz)
  - 1 TW, 125 kJ module test planned
  - Economies of scale through mass fabrication

0.2 TW, 25 kJ

60 cavity 6 TW module



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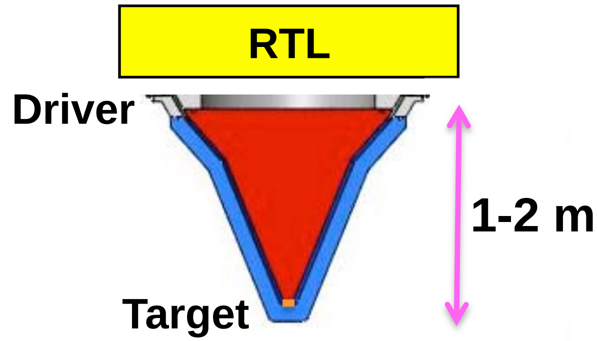
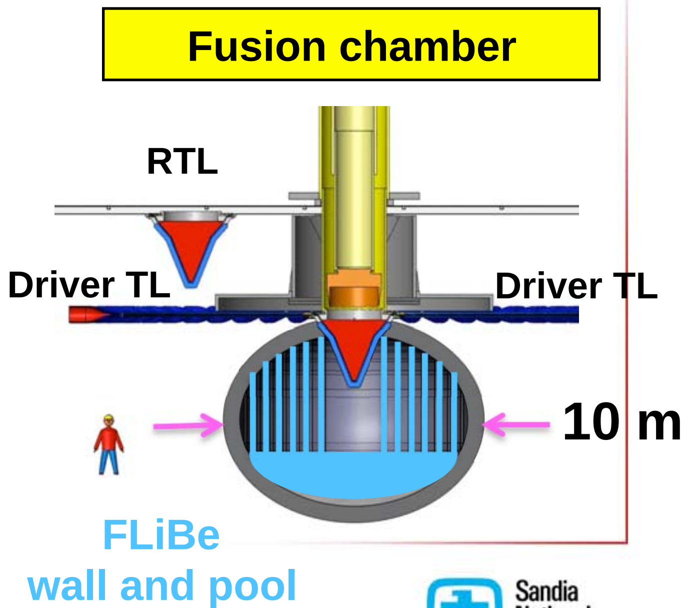
Large yields and low rep-rates may be an attractive path for IFE

- **Recyclable Transmission Lines (RTL) directly connect driver to target repetitively**
  - Mass produced by on-hand technology (stamping or casting)
  - Economics improves at lower rep-rate and higher yield
  - Clears high yield fusion blast debris
  - Shaped to shield driver from direct-line-of-sight
- **Liquid walls could drastically reduce materials issues**
  - Low rep-rate (> 0.1 Hz)
  - Compatible with high pulsed power driver energy coupled to the target (10 MJ)
  - Thick liquid walls (TLW), made possible by RTL, provide operational lifetime for chamber and driver of 40 years
  - RTL provides coupling of driver and target even with chamber debris from previous event; chamber clearing not required





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Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- Compact, efficient, low cost, long-lifetime, repetitive driver
- Advanced, efficient, low cost, robust targets that are simple to fabricate
- $\Longrightarrow$ Very large absorbed target energies
- $\Longrightarrow$ Very large fusion yields
- $\Longrightarrow$ Allows low rep-rate
- $\Longrightarrow$ RTL coupling is feasible, engineering development required
- $\Longrightarrow$ RTL provides vacuum for power flow, clears chamber debris
- $\Longrightarrow$ RTL permits a thick-liquid-wall chamber
- $\Longrightarrow$ Thick-liquid-wall & vaporizing blanket provide long lifetime chamber
- $\Longrightarrow$ Long inter-pulse interval clears chamber
- $\Longrightarrow$ RTL can shield line of sight to the driver

Key enabling physics: magnetically-driven-targets
Key enabling technologies: LTD's and RTL's

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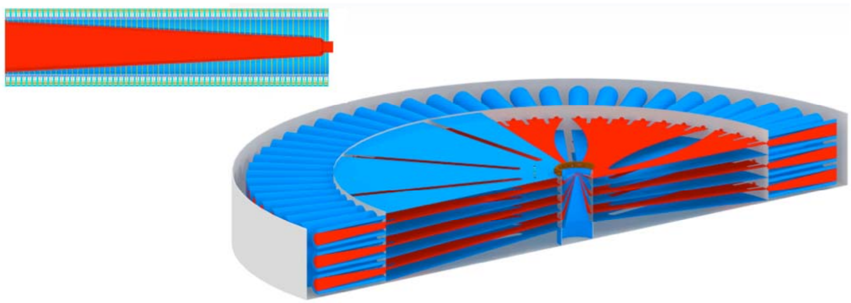
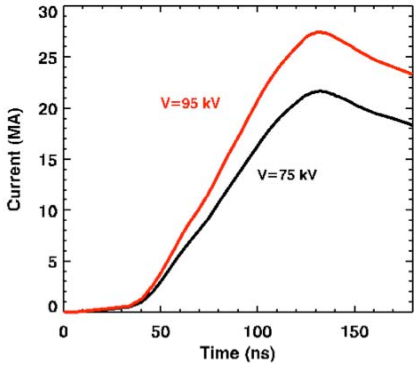
The main areas we will cover today

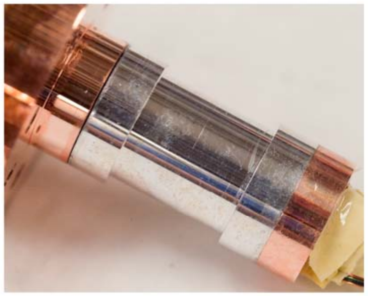
Rep-rate Linear Transformer Drivers (LTD)



Coupling
Recyclable Transmission Lines (RTLs)

Direct Drive Target Physics





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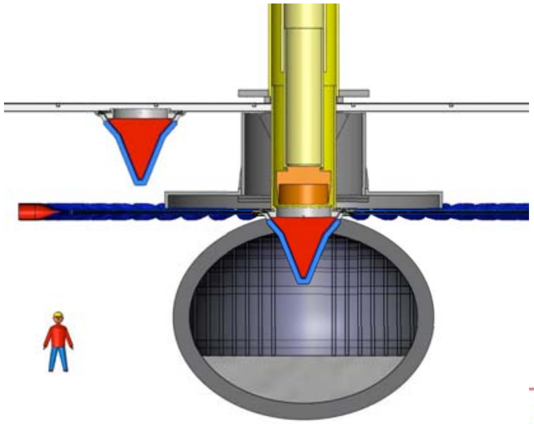
Fusion Chambers



See target talk by Mark Herrmann

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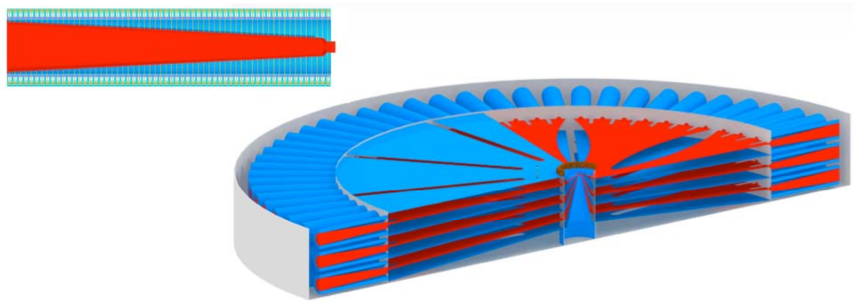
Rep-rate Linear Transformer Drivers (LTD)



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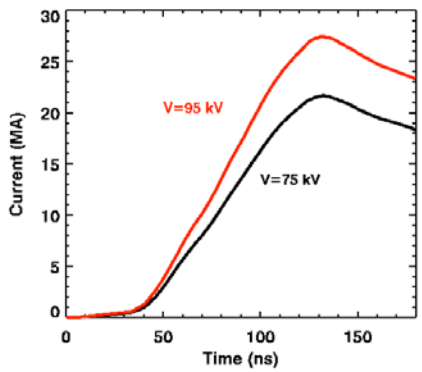

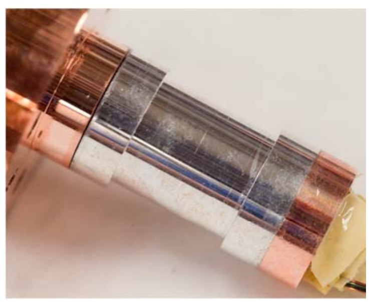

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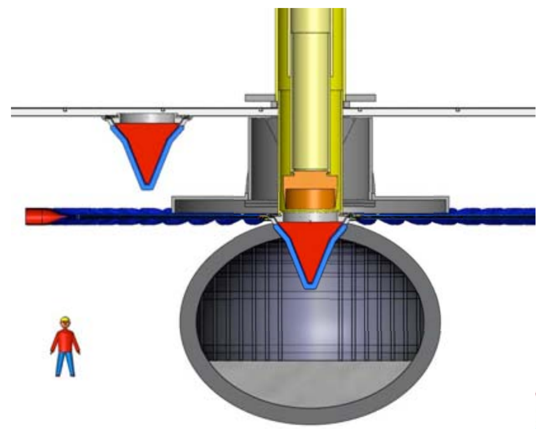

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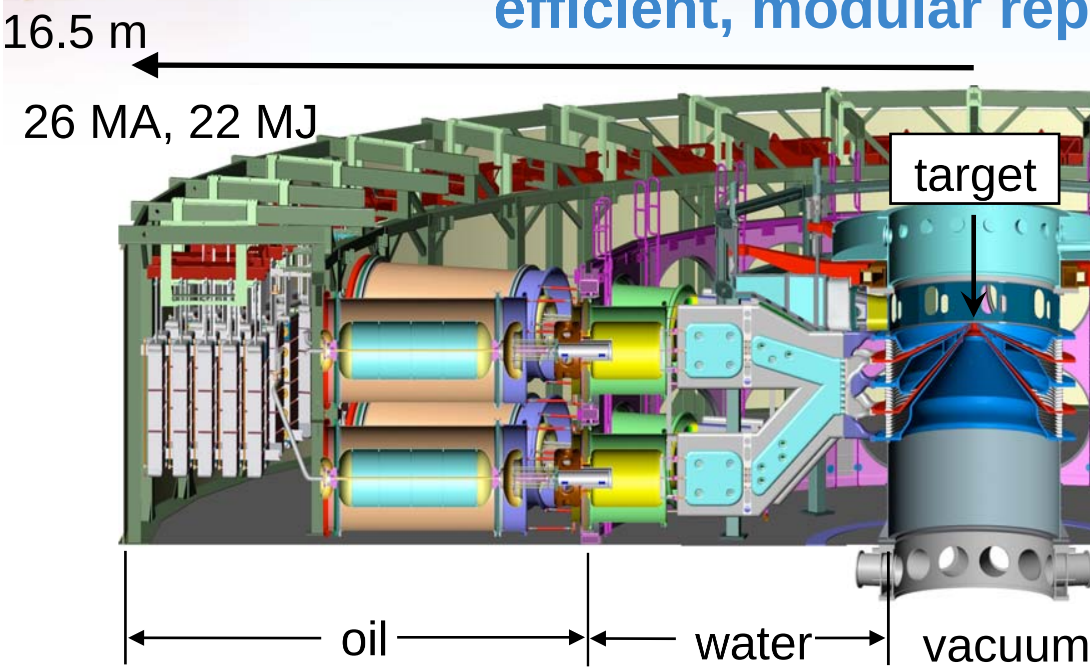
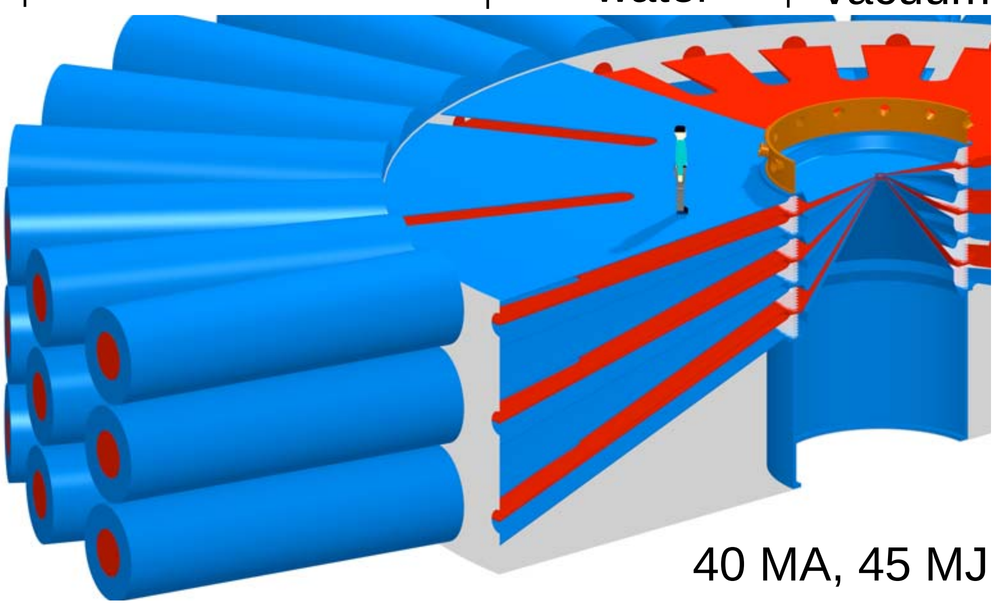
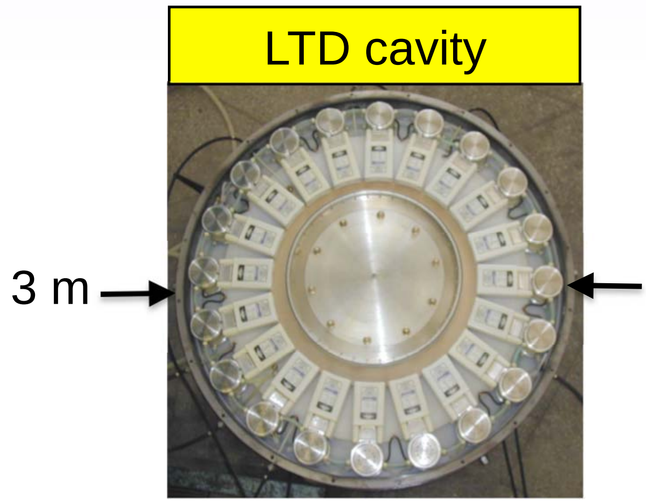
W. Stygar, M. Mazarakis *et al.*, (2011)

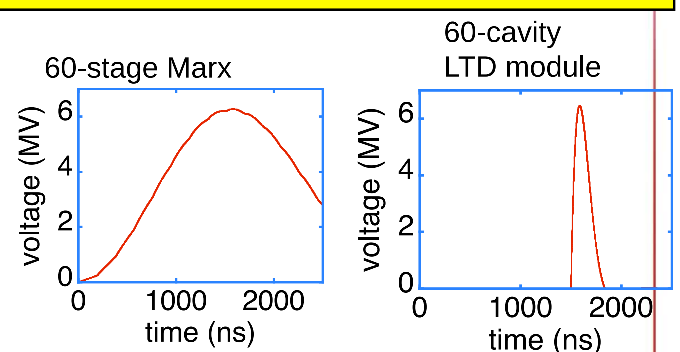
LTDs (Linear Transformer Drivers) offer a simple, reliable, and efficient, modular repetitive IFE driver







Single step pulse compression



Doubles electrical efficiency

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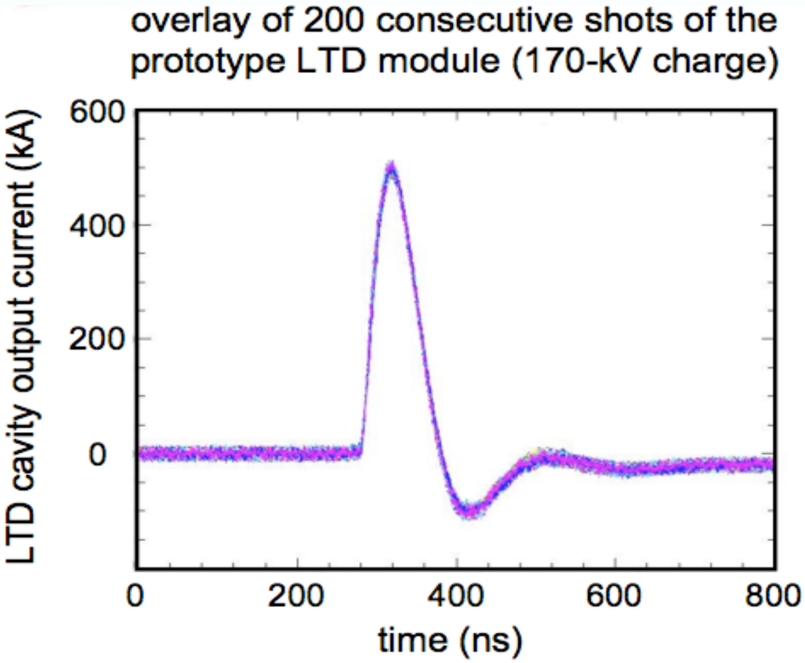
We have demonstrated successful operation of an LTD cavity on over 12,000 shots and bricks to 37,000 shots at 0.1 Hz

The LTD cavity includes 40 capacitors and 20 switches.



- timing jitter = 2 ns (1σ)
- voltage and current reproducibility = 0.3% (1σ)
- peak power = 0.05 TW
- output energy = 6 kJ
- electrical efficiency = 70%
- random switch failure < 7×10^{-6}

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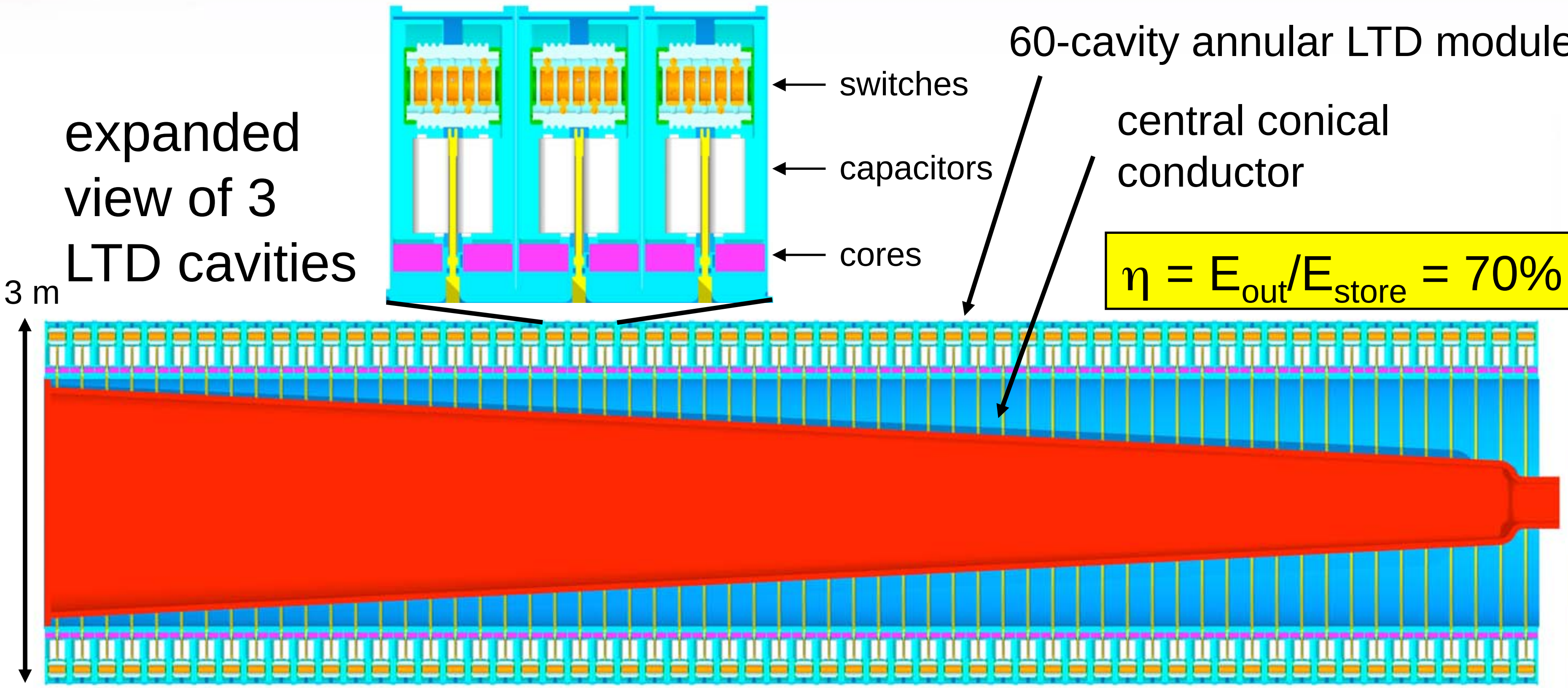
W. Stygar *et al.*, (2007)

Rep-rate generator designs with Linear Transformer Driver (LTD) modules have economy of scale mass production



$\eta = E_{out}/E_{store} = 70\%$

- Impedance matched so no reflected power
- Double electrical efficiency of conventional architecture (70%)

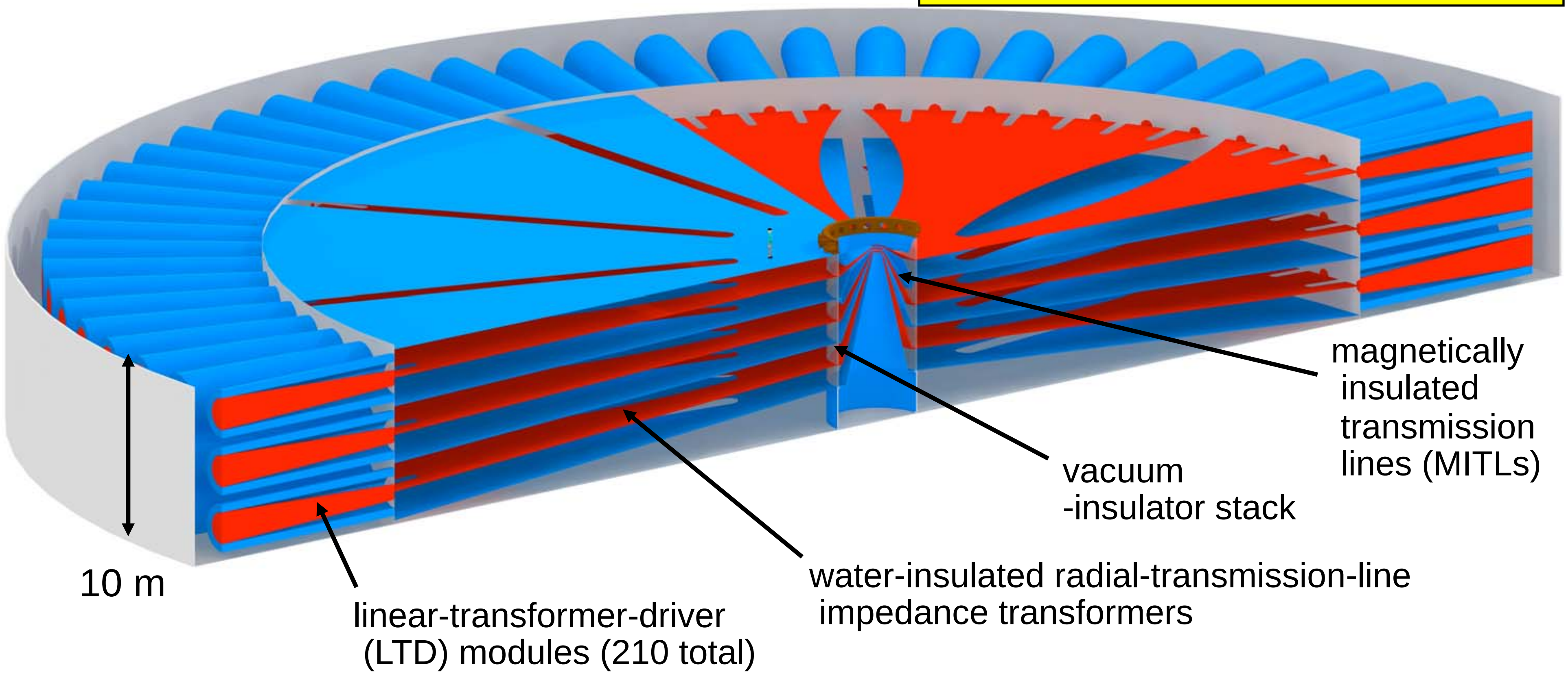
W. Stygar *et al*., Phys. Rev. ST– AB (2007)

LTD modules are integrated into efficient architectures that produce 1 PW and drive high yield fusion targets

P_g = 1200 TW V_{stack} = 24 MV I_{load} ~ 68 MA $E_{radiated}$ = 20 MJ

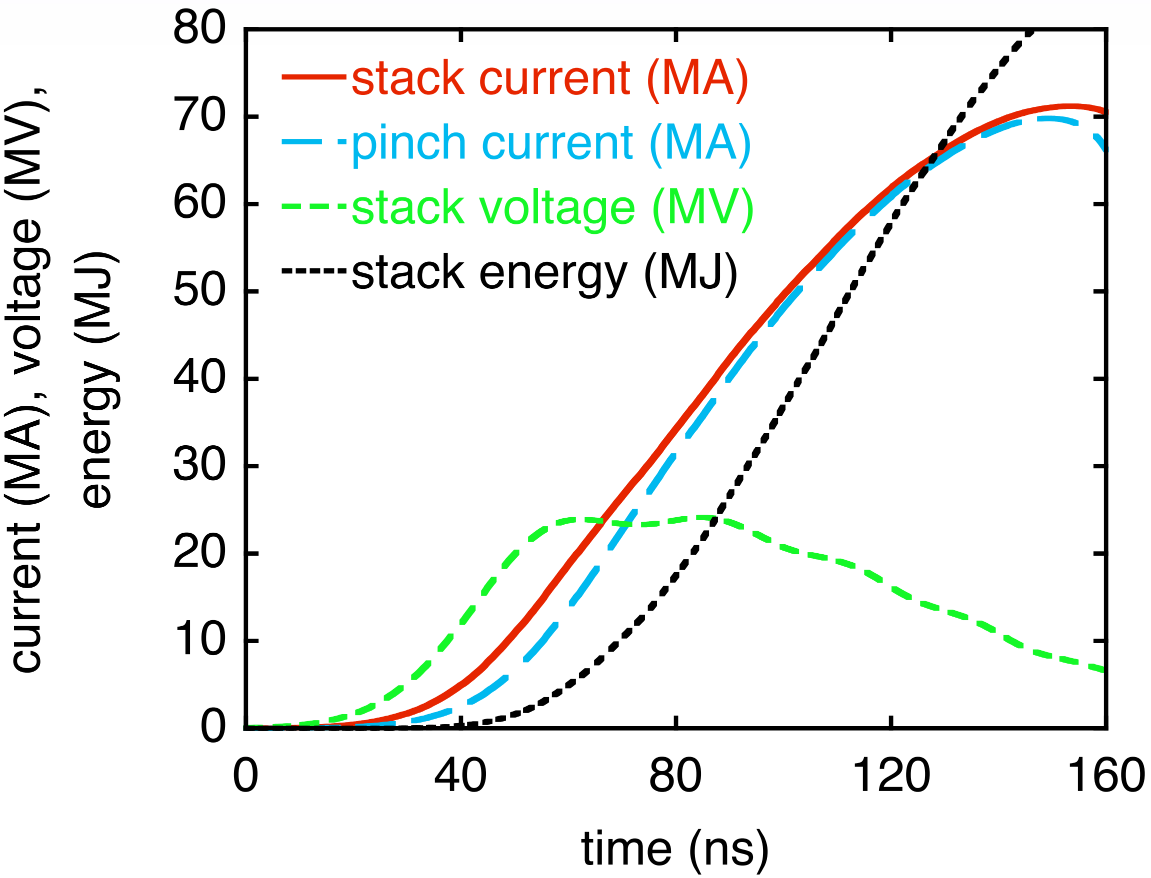
E_g = 180 MJ L_{vacuum} = 29 nH $\tau_{implosion}$ = 100 ns   diameter = 104 m

Patent: US 7,679,297 B1 Stygar *et al.*



This accelerator would deliver a fusion yield > 2 GJ, and achieve engineering Q's of > 10

This system will deliver more than 80 MJ to the vacuum power flow section (transmission line/target) in 100 ns



- Coupling efficiencies of magnetic energy to the load region of 15% have been demonstrated
- Our goal is to increase coupling efficiencies to the load region up to > 30%

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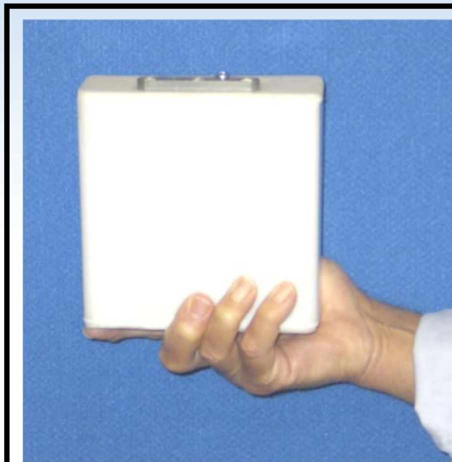
The technology to build high-yield-scale LTD-driven accelerators exists today

The 1000-TW (1-PW) machine would require:

- 1,000,000 capacitors
- 500,000 switches
- 25,000 magnetic cores



The rest of the machine would consist of water, plastic, and stainless steel.

M. Mazarakis, W. Stygar *et al.*, (2010)

Tests of a 0.2 TW rep-rate module are being performed at 0.1 Hz at the required energy and technology scale

LTD Test Module (125 kJ)

Prototype costs are: $11/Joule
~10^{-4} cents/peak watt

80-85% Learning curves: <$2 to 4/Joule

- 1 MA, 1 TW, 125 kJ, 10 cavity test planned to follow
- Fire 40,000 shots (= *1,600,000 switch firings*) at 0.1 Hz with resistive load
- Engineer and test a replaceable transmission line system
- ZR was built for 4$/J. This technology scales more favorably.
- Gen 3 LTD designs have 80% peak current with 50% cavity radius

Several hundred shots are performed every day

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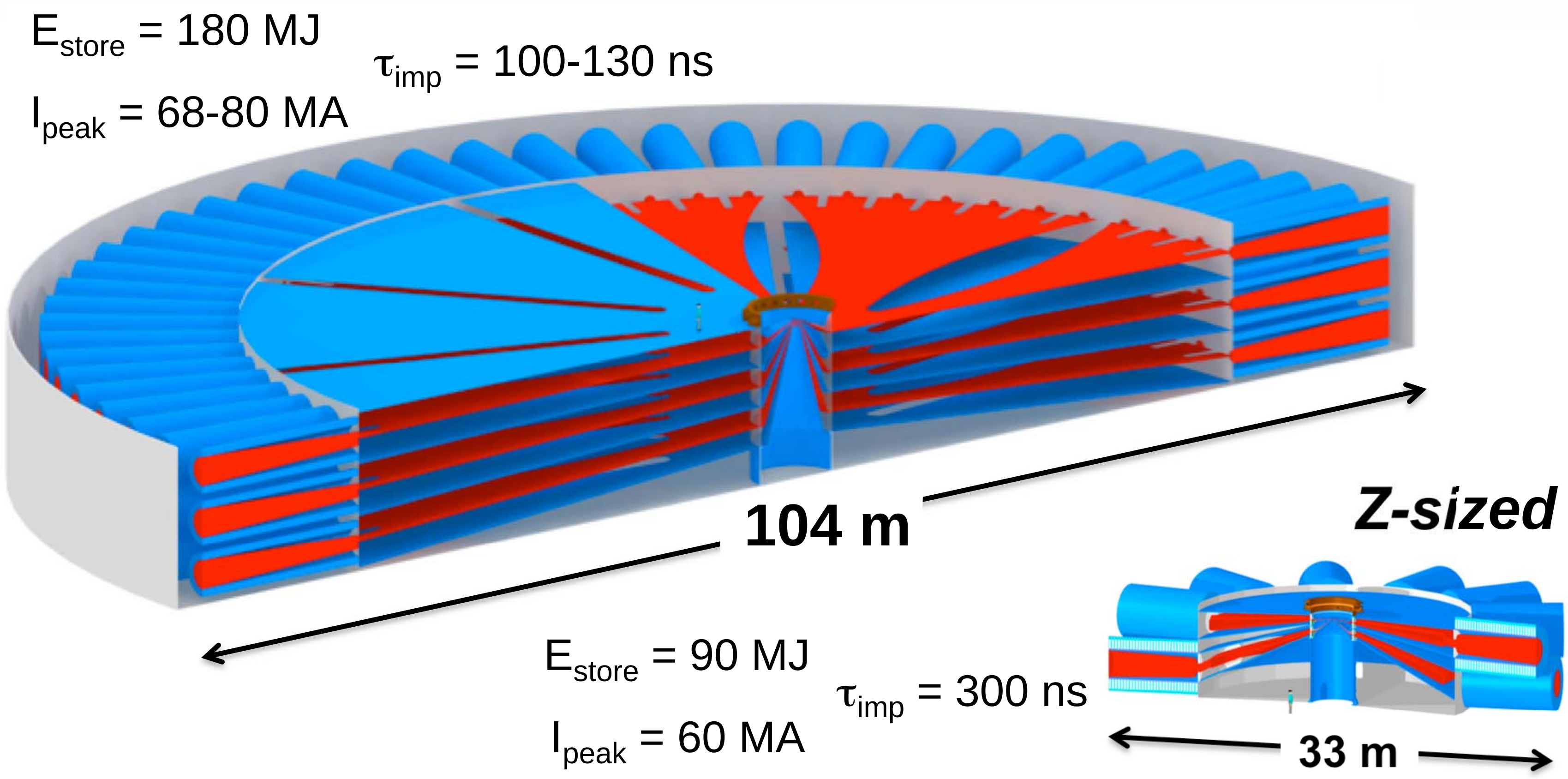
W. Stygar *et al*., Phys. Rev. ST– AB (2007)

At longer pulse lengths (300 ns) Z-sized facilities could deliver 60 MA and 10 MJ to fusion targets

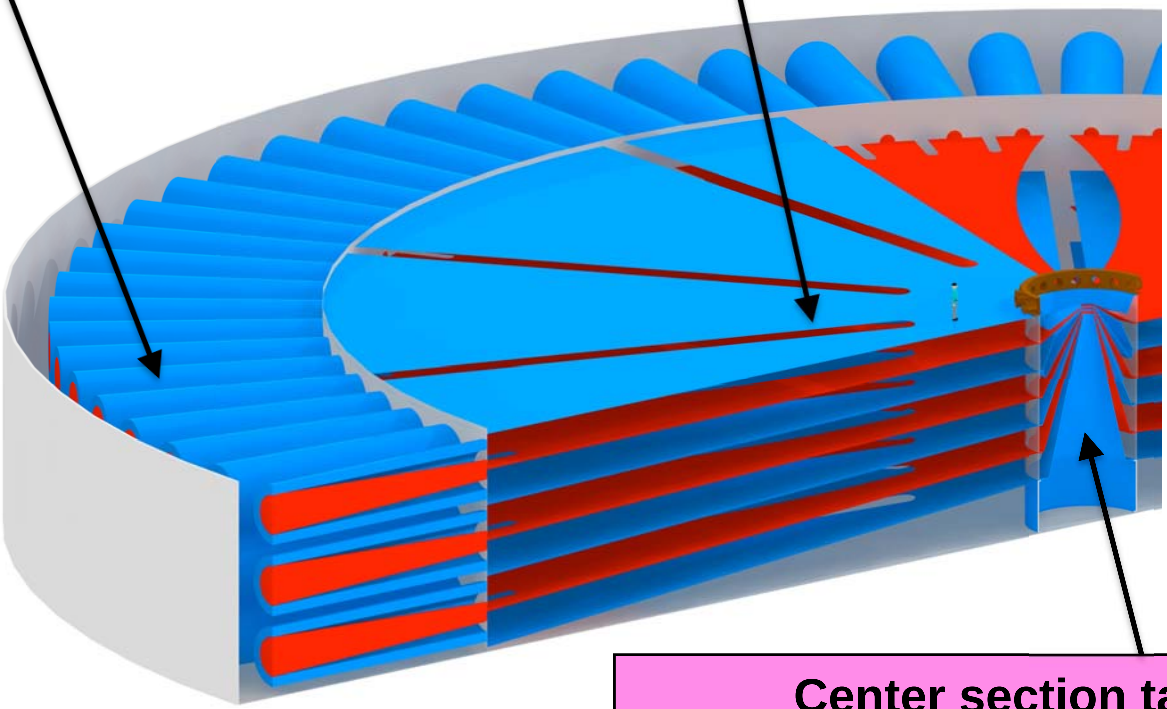


Targets physics experiments will consider performance of longer drives

The "center section" needs to be re-engineered for both single shot high yield and repetitive high yields

Module Section
210 to 500 modules
Low radiation area

40 m Water Section
Passive pulseshaping & symmetrization
Radiation shield



Center section target chamber
Replaceable/Recyclable Transmission Lines
Liquid wall
Vaporizing blanket

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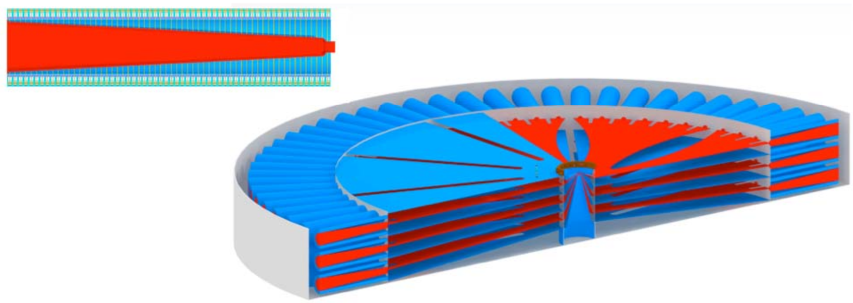

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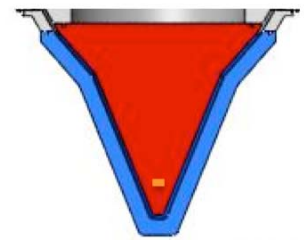
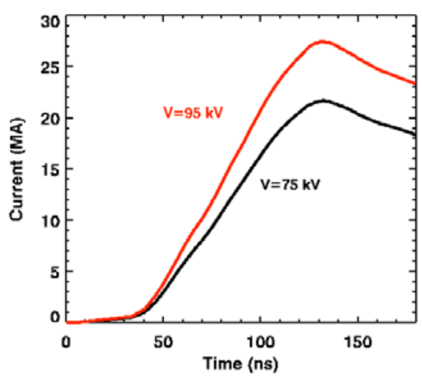
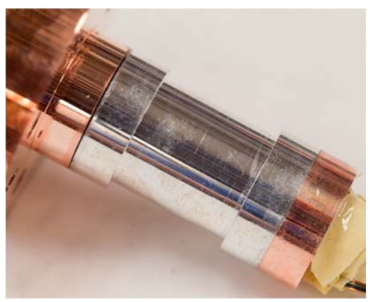


Direct Drive Target Physics





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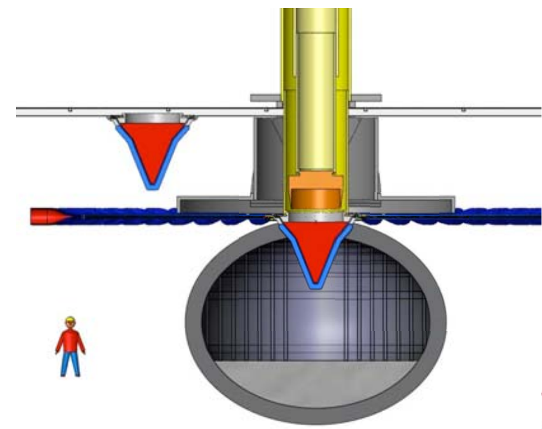

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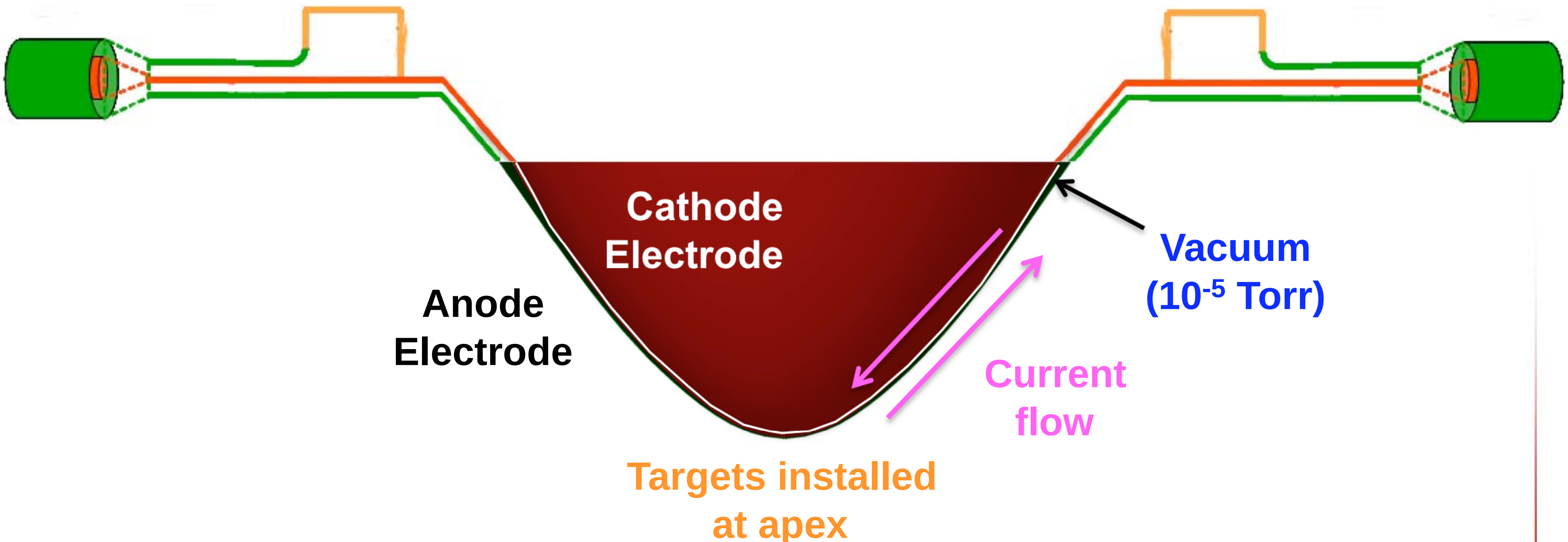
S. Slutz *et al.*, Phys. Plas. (2003) and C. Olson *et al.*, FST, (2005)

Repetitive connection of driver and target is achieved by replacing a Recyclable Transmission Line (RTL) electrode at 0.1 Hz



- RTL and the targets are a low mass (<50 kG), low cost, portable vacuum system
- Recyclable so the process can be economic.
- RTL provides coupling of driver and target even with chamber debris from previous event; chamber clearing not required
- RTL can be shaped to shield direct line of sight to driver

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There are a number of science and engineering challenges for RTL driver-target coupling

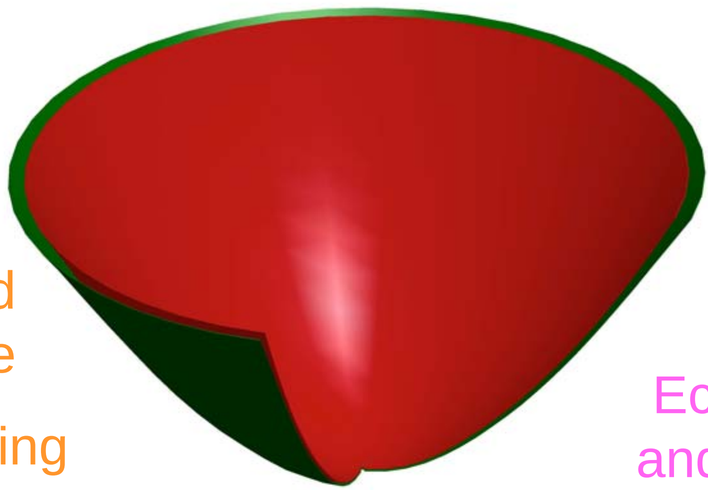
Inductance

RTL recovery and waste handling

Electron flow

Assembly, staging, and operational issues

Ohmic dissipation



Mechanical integrity

Plasma formation and gap closure

Economic recycling and mass fabrication

Driver shielding from blast

Driver/RTL pulsed power integration

Driver/RTL engineering repetitive connection

- An applied science and technology R and D program is needed
- The "ilities": manufacturability, maintainability, reliability, affordability, disposability, usability, availability

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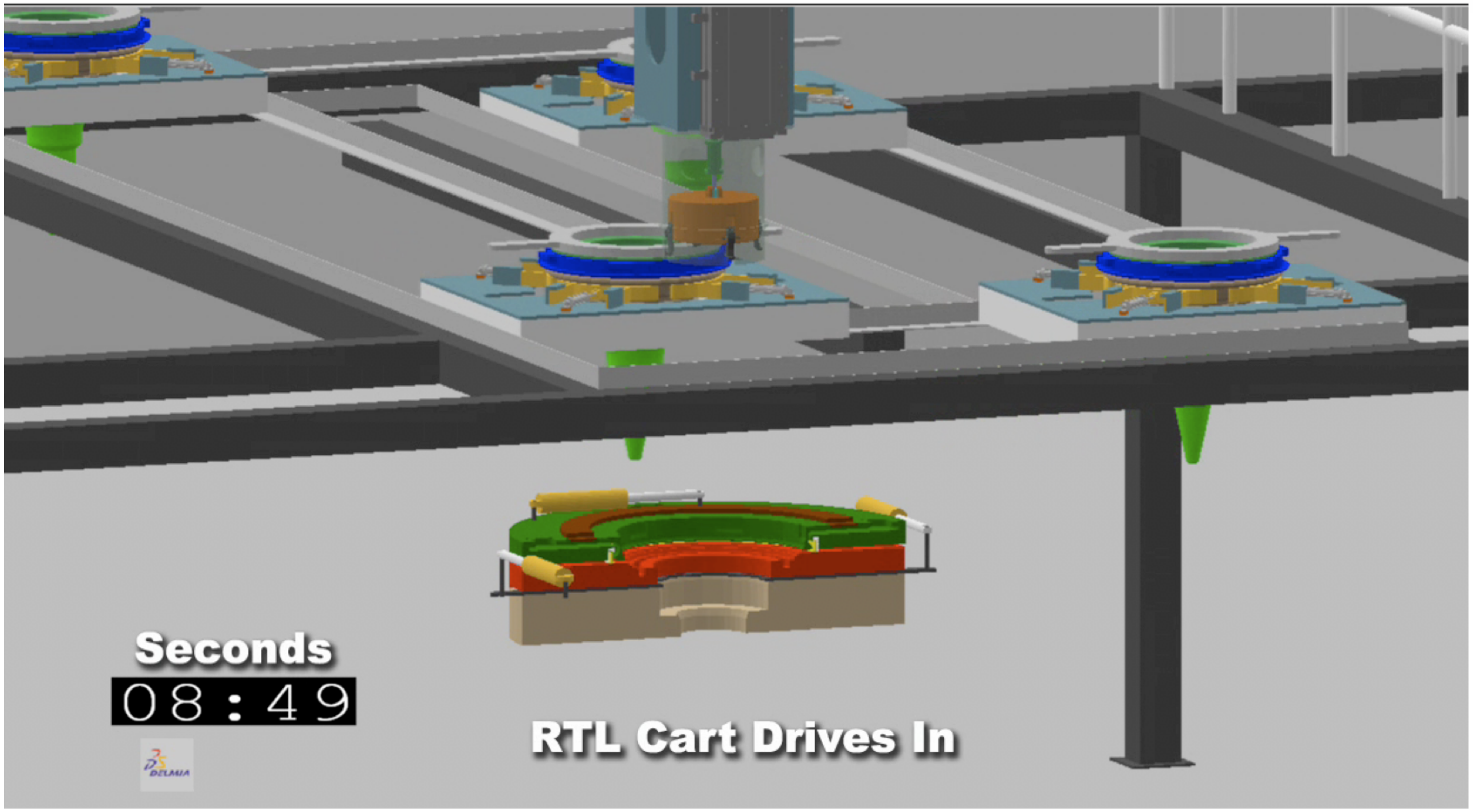
J. Jones, R. McKee et al (2006)

A replaceable transmission line demonstration experiment was designed in 2005-2006



- **RTL movie 1**
  This system could be built with automation technology available in 2006

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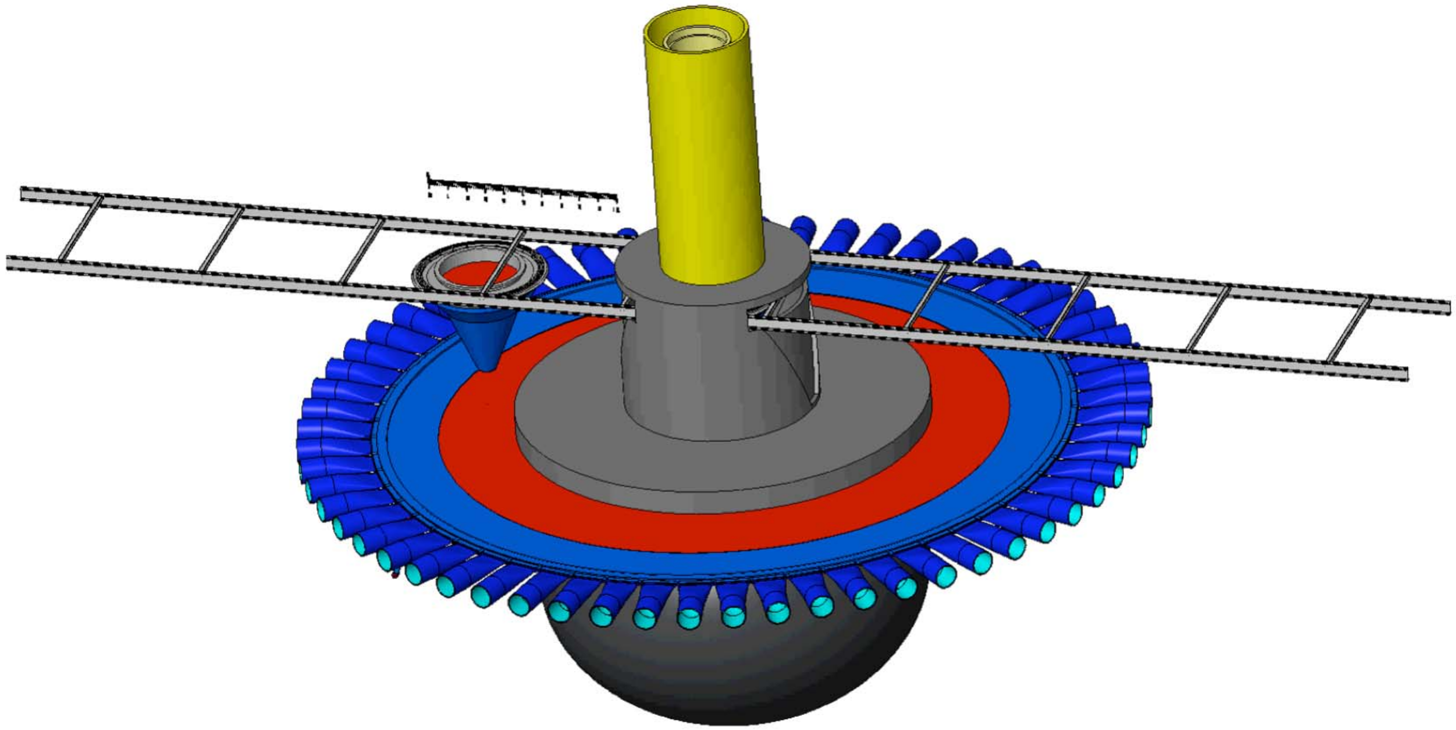
Similar ideas were applied to full scale pre-conceptual design

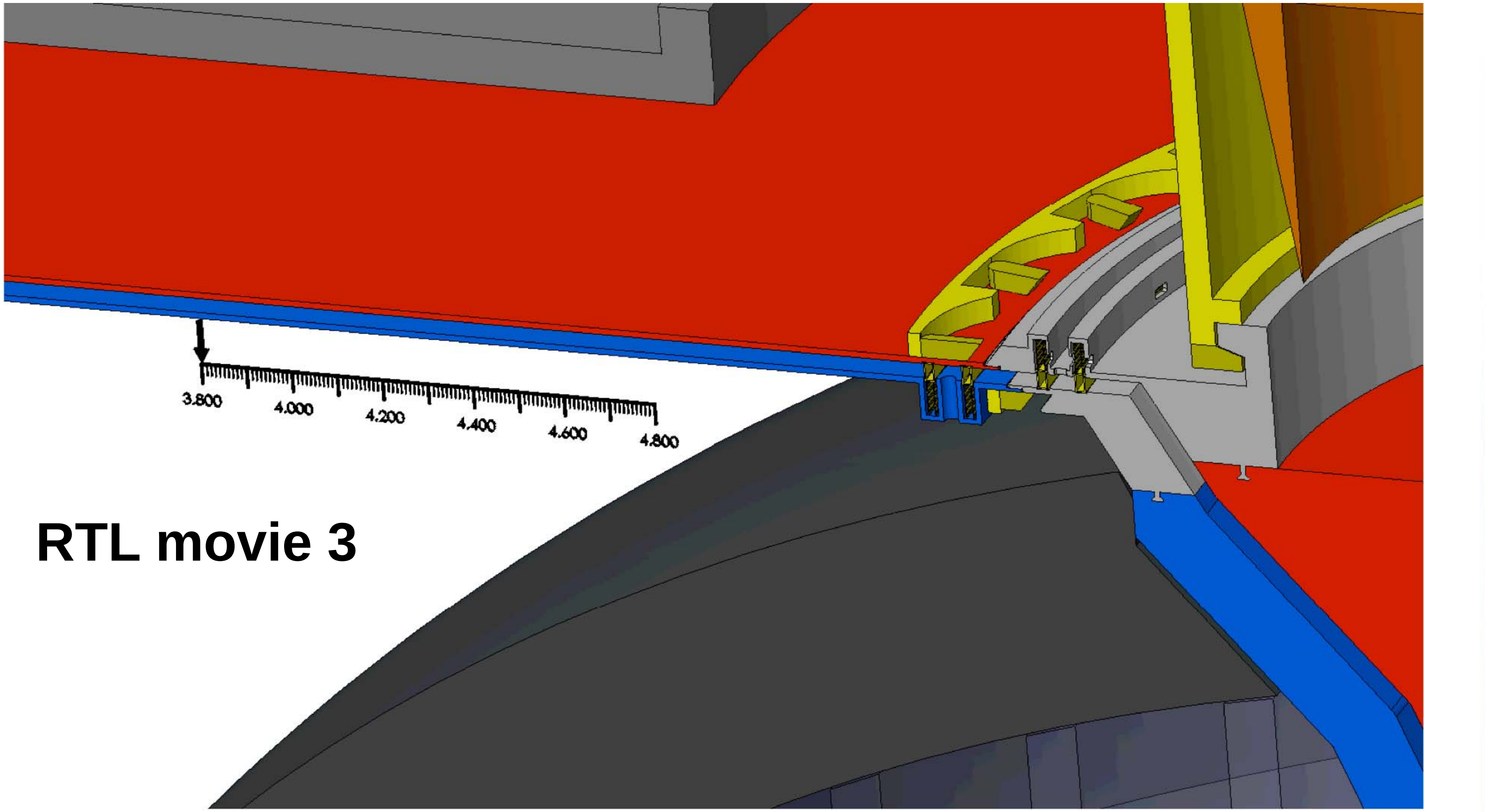


RTL movie 2

Need to engage industry on automation, fast and robust closure valves

G. Rochau et al. (2006)

Similar ideas were applied to full scale pre-conceptual design

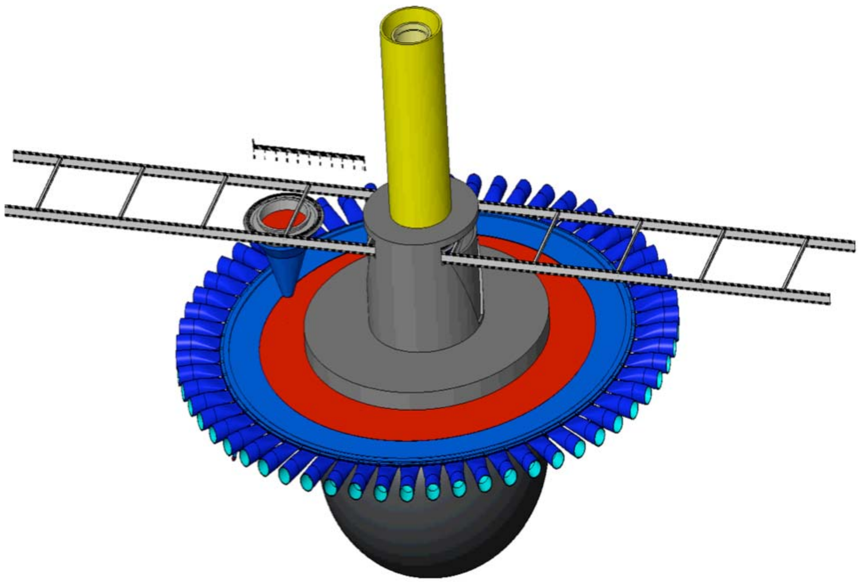


RTL movie 3

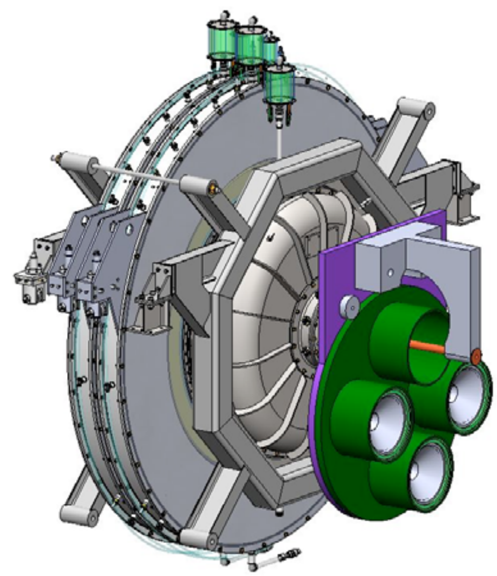
We've begun an LDRD project to design a replaceable transmission line system for the LTD test module

- "New Strategies for Pulsed Power Transmission Lines: From Repetitive to Replaceable to Recyclable"
- $600 K/year for 3 years
- Goal is to deploy a system that addresses, at a small inexpensive scale
  - repetitive driving of small RTL's
  - required automation
  - specialized vacuum valves and vacuum pumping
  - current contacts
  - integrated system control with fault detection
- Concepts may lead to higher repetition rate than 0.1 Hz

Pre-conceptual design of a replaceable transmission line system for LTD test module

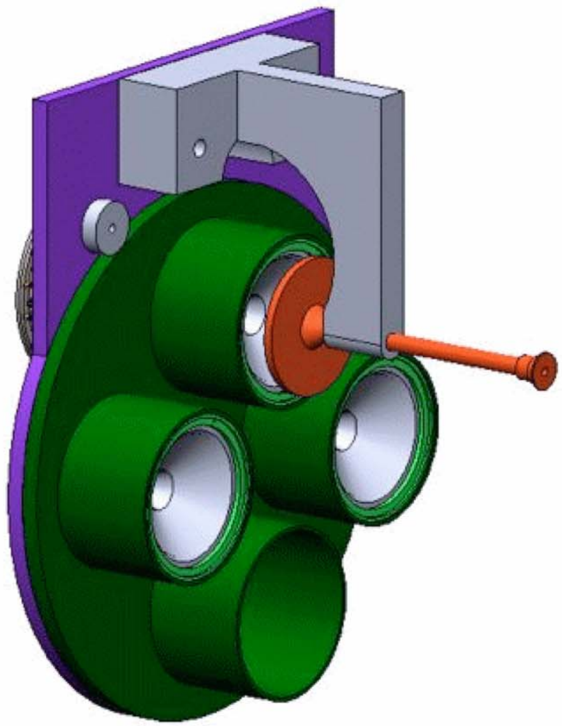


“Muzzle-loader”



“Four-shooter”

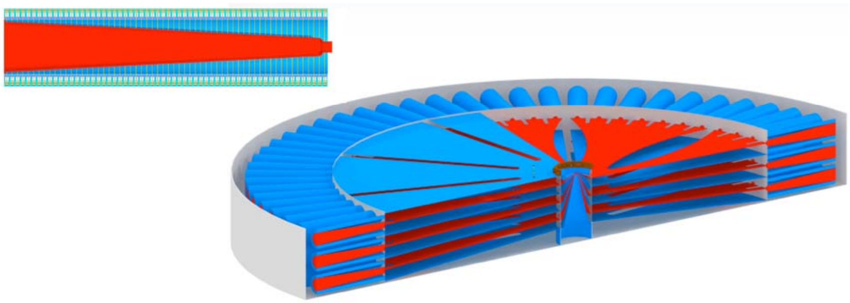
The new concept may allow a higher repetition rate



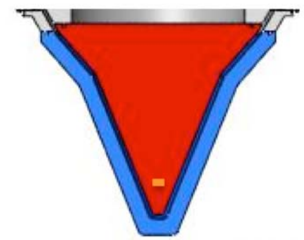
RTL movie 4

The main areas we will cover today

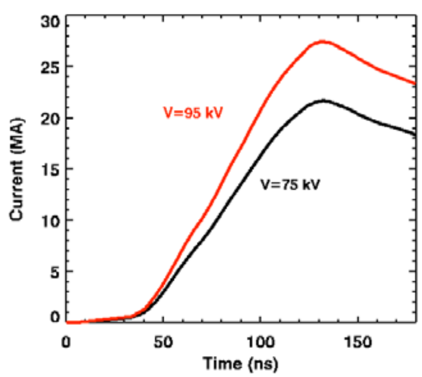
Rep-rate Linear Transformer Drivers (LTD)

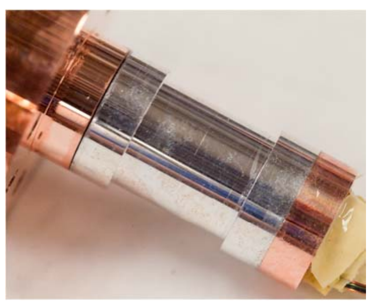


Coupling
Recyclable Transmission Lines (RTLs)

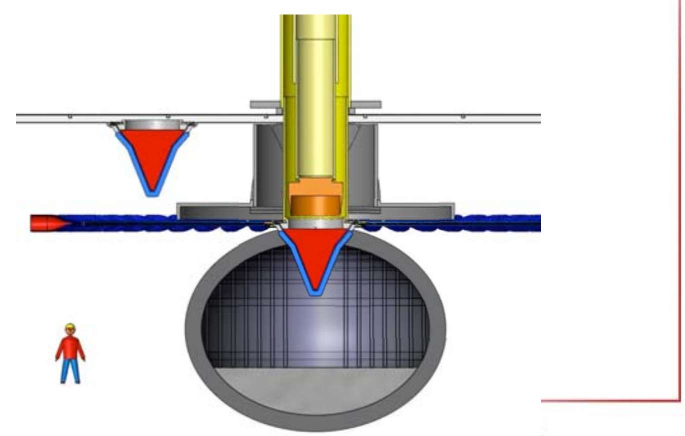


Direct Drive Target Physics





Thick Liquid Wall (TLW)
Fusion Chambers



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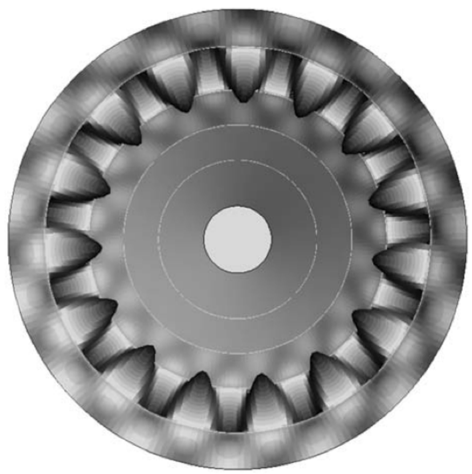
Prototype RTL's were manufactured by metal spinning and buckling strengths were measured and modeled

Prototype

ASTM 1008 low carbon steel
Thickness = 0.620 ± 0.02 mm (25 mils)
Buckling ~ 8.3 psi

Simulation



Experiments

Buckling ~ 26 psi

- Outer RTL electrode is susceptible to the buckling instability
- Stiffening rings increase buckling pressure by 3X
- Thicker RTL's for higher gain and lower rep-rate
- Other materials, other fabrication techniques

The cost of the RTL (and the target) can be thought of as a fuel cost and must be economic

$$\frac{cost}{MWh_e} = 3.6\,\frac{RTL\,cost \bullet RR}{P_{e[GW]}}$$

- $Cost/MWh_e$ is reduced with
  - Lower RTL unit cost (economies of scale help)
  - Fewer RTL's (lower rep-rate at constant power output)
  - Constant power output at lower rep-rate requires higher yield per shot

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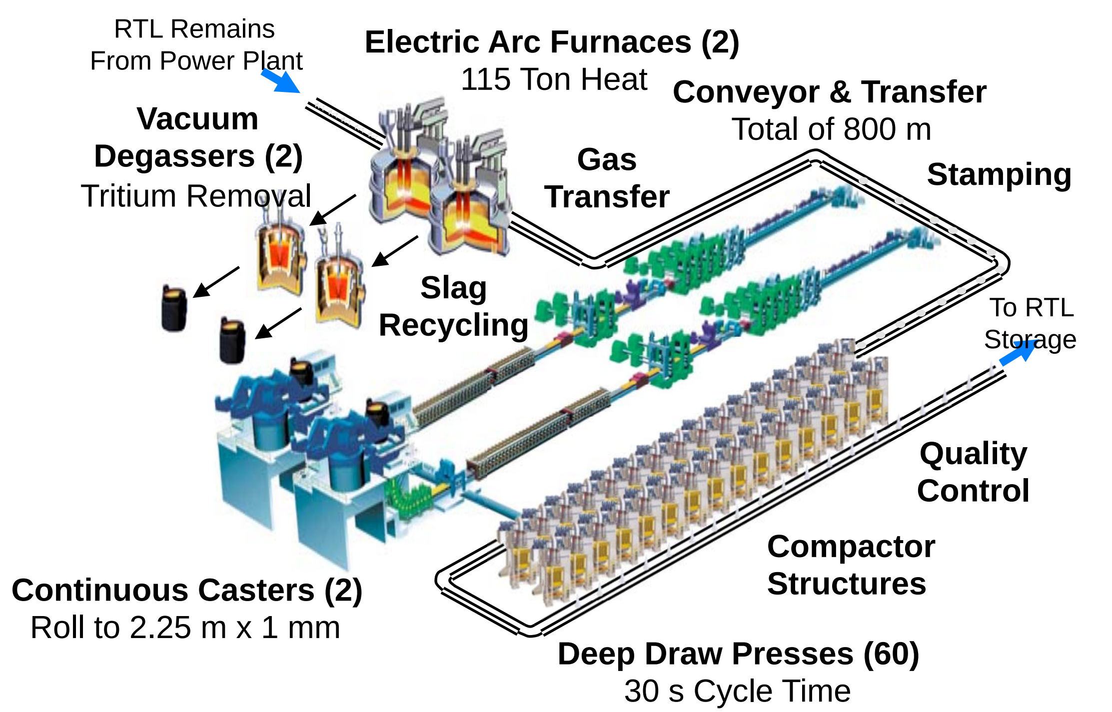
B. Cipiti *et al*. SAND-2006-7399P (2006)

Existing technologies can be integrated to produce RTL's from recycled low-carbon steel

OCC RTL recycling and stamping plant: $160 million



- Highly efficient electric arc furnace, automated continuous sheet casting, automated stamping and transfer press, automated RTL assembly with targets, vacuum pumping and storage, post shot automated steel recovery and de-tritiation systems
- Need to develop design of full scale production line with industry

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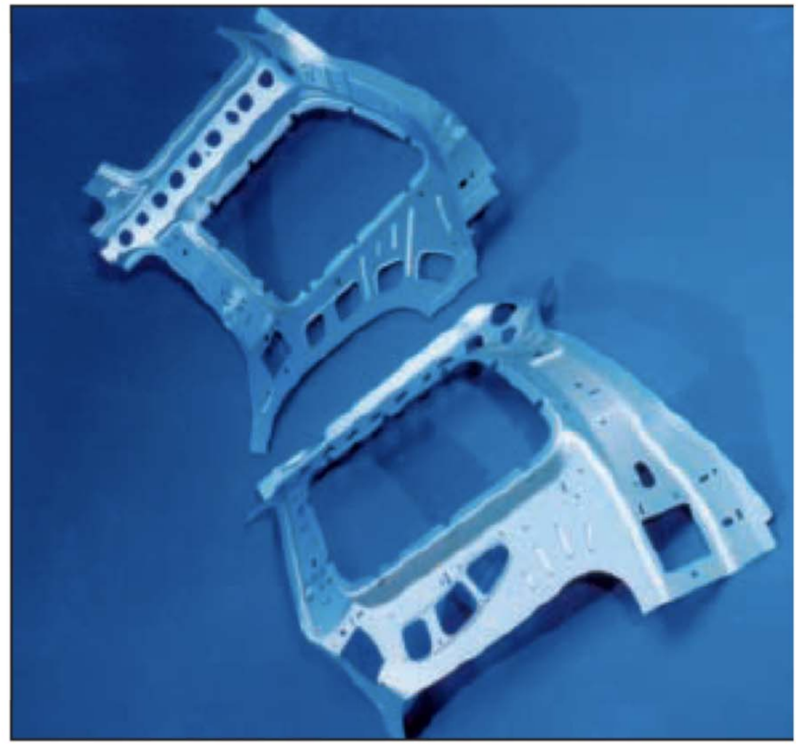
Automated Schuler tandem stamping and transfer press produces 300 metric tons of complex steel parts per day

38 ft



- Supervised by 1 person
- Automatic loading of sheet steel
- Automatic transfer between 5 stations for stamping and cutting
- Accurate to 10 mil
- Produces two Ford F150 doors every 5 seconds

B. Cipiti *et al*. SAND-2006-7399P (2006)

At 0.1 Hz, up to $24/shot can be spent on RTL's and targets at 1 GWe and 8.5 ¢/kW-hour

RTL Type	RTL unit cost ($)	Rep-rate (Hz)	Units per year	Cost/MWhr$_e$ ($)
Stamped steel (50 kG)	5.00	1	31e6	18
Stamped steel (25 kG)	5.30	0.1	3.1e6	**1.90**
Cast FLiBe (76 kG)	0.80	1	31e6	**2.88**
Cast FLiBe (76 kG)	1.00	0.1	3.1e6	**0.36**

- Nuclear plants raw fuel costs ~ $3.50 to $5.50 per MWhr$_e$
- Coal ~ $10 to $13.20 $/MWhr$_e$
- Only 5 to 10% of COE results from RTL and target costs
- 3 to 7 day inventory (1300 to 3000 metric tons) recycled ~50-120X/year for a yearly throughput <160,000 metric tons
- No limit on number of times steel can be recycled – small amount of make up steel added to offset losses for each melt
- Cast LiSn is a possible RTL and liquid wall

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Neil Alexander, Dan Goodin, General Atomics

Economic mass production of cylindrical Al direct -drive targets is feasible with deep draw process

http://www.deepdrawnenclosures.com/standard_round_cases.html

GA deep drawn Pb cylinders

Notional process

1. Die cut a disk of aluminum out of a spooled ribbon of aluminum
2. Deep drawn an can (seamlessly closed at one end). Aluminum 1100 can be deep drawn.
3. Die cut a smaller disk of aluminum for the can lid, in the same progressive press die-cut a small hole in the middle (for a fill tube).
4. Stamp ledge to align to can
5. Cut a fill tube from a length of aluminum tubing
6. Fabricate foam and place in cylinder
7. Laser weld fill tube to lid
8. Laser weld lid to can
9. Place in RTL assembly
10. Fill with DT and pinch fill tube

- At 0.1 Hz, Al targets can be made for ~$0.66/each
- At 1 Hz, Al targets can be made for ~$0.09/each
- Inclusive of material, labor, repair, maintenance and capital costs
- Capital costs amortized over 30 years life of plant

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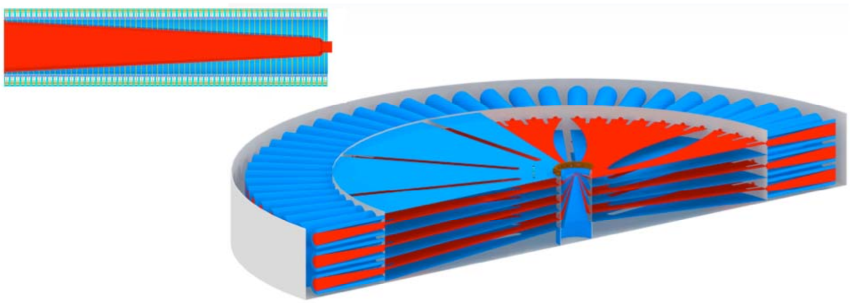
The main areas we will cover today

Rep-rate Linear Transformer Drivers (LTD)



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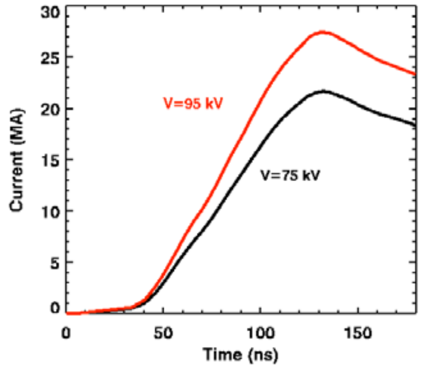
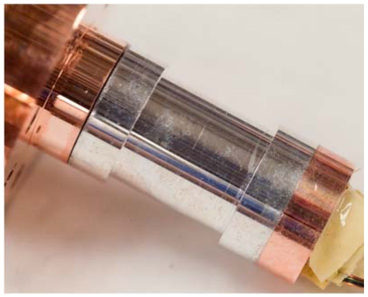
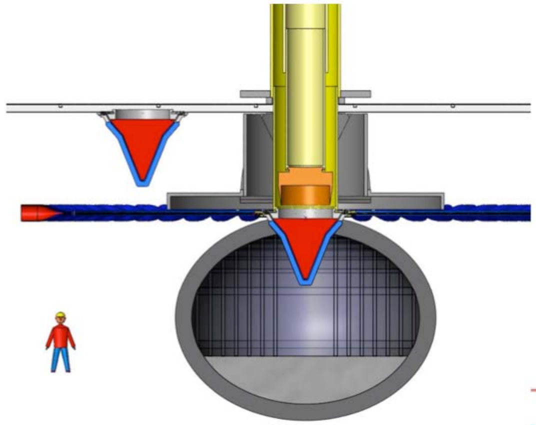


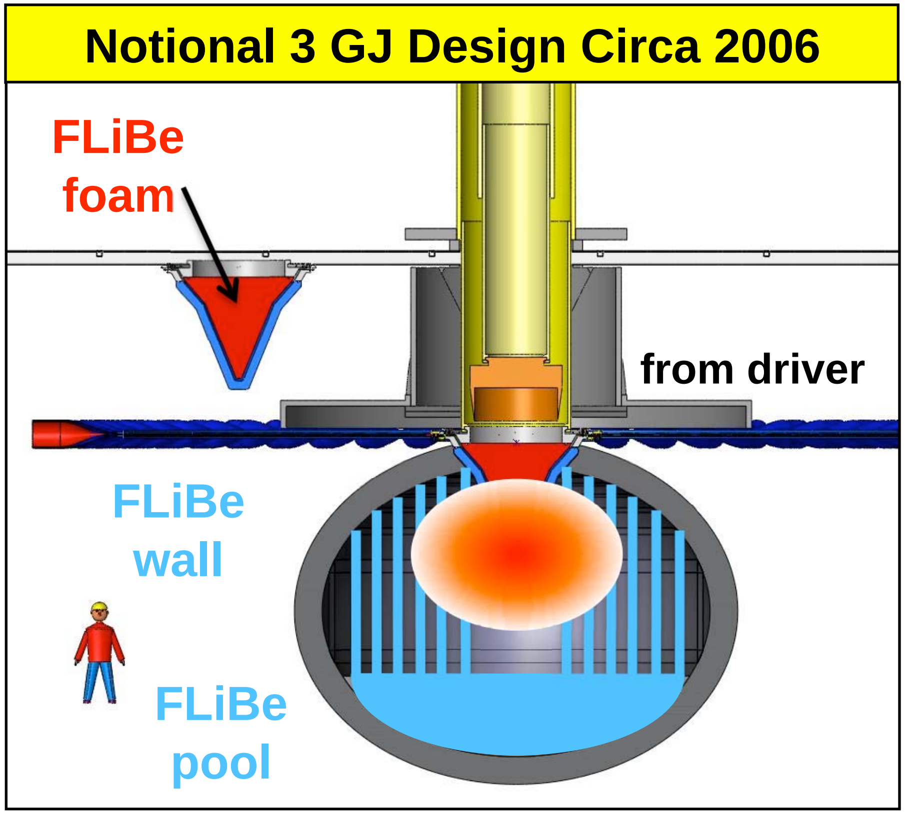


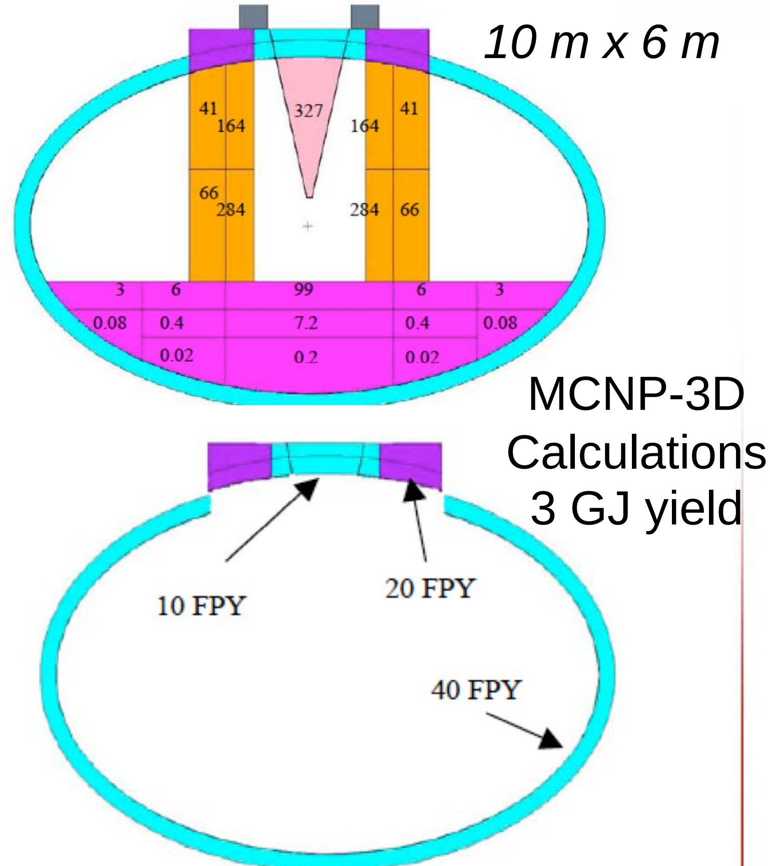
Thick Liquid Wall (TLW)
Fusion Chambers



M. Sawan, L. El-Guebaly *et al.*, FST (2007)

Thick liquid walls (TLW) and vaporizing blankets could drastically reduce the materials issues that a fusion power plant will face





- Direct connection with pre-pumped, mechanically-rigid RTL allows thick liquid wall
- Ongoing calculations to determine optimal shielding configuration
- Neutronics: 40 year lifetime chamber
- Initial point design: cyclic material fatigue: 7 year lifetime

Roadmap

Normative goals for Pulsed-Power IFE

- Single shot ignition
- Single shot higher yields/higher gain
- Rep-rate high power driver
- Rep-rate driver-target coupling
- Rep-rate high yields/high gain

Normative stages and timescales

- Science, Technology, and Engineering (ST&E) Development (5 to 10 years)
  - Sub-scale and full-scale module design, construction, evaluation

- ST&E Integration (5 to 10 years)
  - Design and build a pilot plant at smallest scale that permits evaluation of the issues
  - Integrate various technologies at a pertinent scale subjected to realistic environments
  - Build a plant at a small scale to permit inexpensive solution of issues
  - Small scale to permit inexpensive iterations
  - First adopters have a number of advantages: learning by doing/using, learning about payoffs and costs

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Normative stages and timescales

- ST&E Maturation (5 to 10 years)
  - After pilot start up, operate for 5 -10 years to overcome setbacks and reach full function operability
  - Pilot plant operation increases confidence of public, governmental agencies, and utilities in the technology
  - J. Holdren: "Pushing hardest on the [obvious candidates] today may not represent the shortest path to a technologically and commercially workable reactor" Science, 200, 168 (1978)

- Technology Scale Up

- Market Penetration (25 to 50 years)
  - Technology scale up
  - Build out commercial fleet
  - Full scale adoption

- Long development times and technical uncertainties underscore importance of pursing many paths
  - Want to avoid decisions that might lead to technology lock-in on solutions which may not be optimal in the long run

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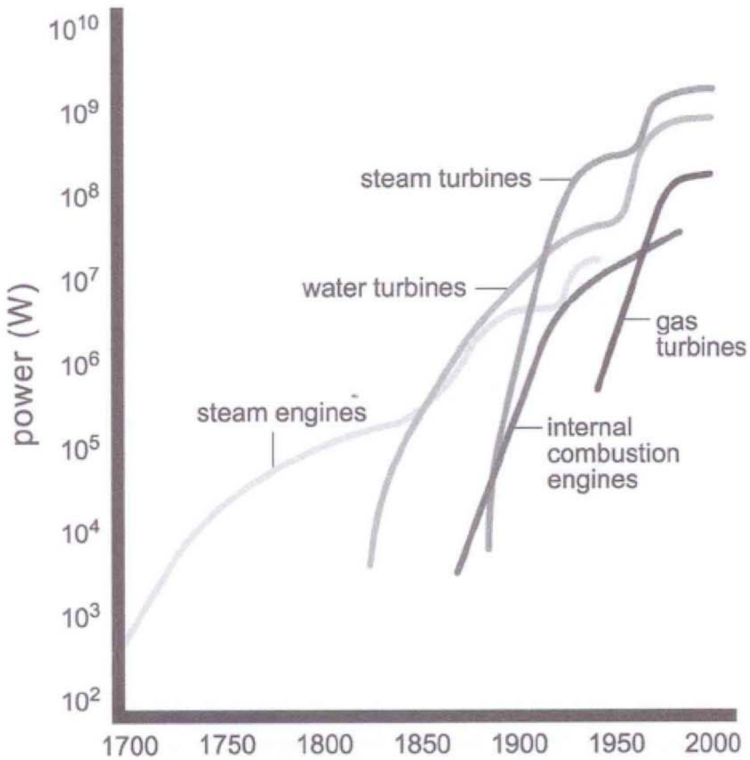
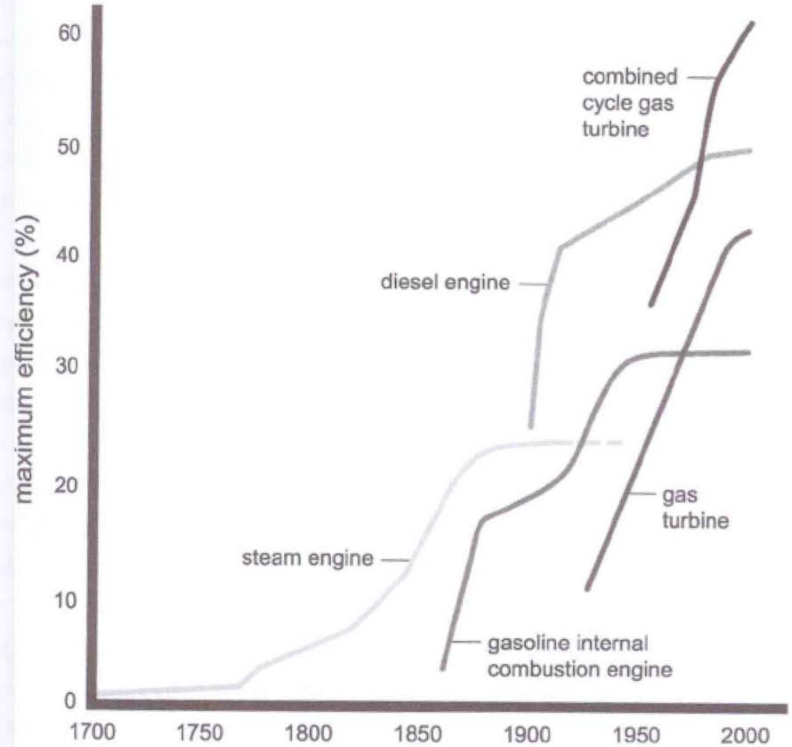
V. Smil, “Energy Transitions”, Praeger (2010)

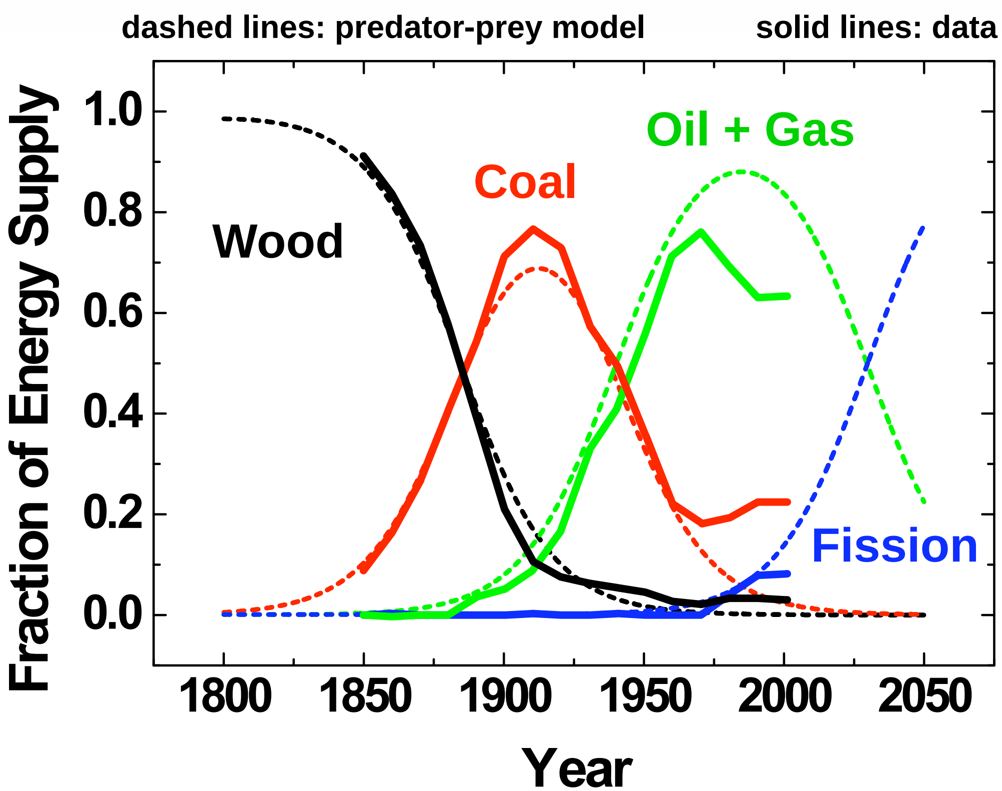
Technology scale up can take decades





C. Marchetti, various see http://cesaremarchetti.org/, C. Jennings (2010)

Energy market penetration rates are well fit by a logistic substitution model (predator-prey) through 1975



$$\frac{dA}{dt} = \alpha A(1 - A - B) - A\beta B$$

$$\frac{dB}{dt} = \beta B(1 - B)$$

- Logistic curves: early exponential growth is replaced by a linear growth
- Development and penetration of new energy sources is a multi-generational issue
- Simple model extrapolations fail

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V. Smil, “Energy Transitions”, Praeger (2010)

Historical examples of the slow pace of energy transitions abound

Market Fraction	1-5 %	5-10 %	10-15 %	15-20 %	20-25 %	25-33 %	33-40 %	40-50 %
	Time interval in years							
Coal	>40 (1840)	15	10	5	5	10	10	5
Oil	30 (1915)	10	10	10	5	15	5	
Nat. gas	35 (1930)	20	10	10	5			
Fission	15 (1998)							
%/year	0.12%	0.3%	0.5%	0.6%	1%	0.6%	0.9%	

- Time scales involved highlights importance of options
- Fission was much faster than all others (145 B (1998)$ investments by AEC)
- Rapid worldwide deployment of LWR/PWR fission reactors shut out alternate designs optimized for inherent safety, waste management, low cost, public acceptance

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Proposed high-level roadmap

- Technology scale up and market penetration can take decades, but sometimes can proceed in parallel (e.g. wind).
- The basic technology needs to be brought to adequate TRL before integration
- The development of fusion is worthwhile even if it is hard - there are just not that many options for clean base load power
- It will require patient work for the long run – even solutions that work after 2040 will help

Proposed high-level roadmap

- **Technology Development Phase 2011-2017**
  - LTD test module demonstrations including RTL tests
  - Design and demonstration of an LTD module with 10.e6 shot lifetime
  - Design 1-PW rep-rate high yield facility with TLW protection systems for single/multiple high yield fusion events
  - Validate target physics on Z

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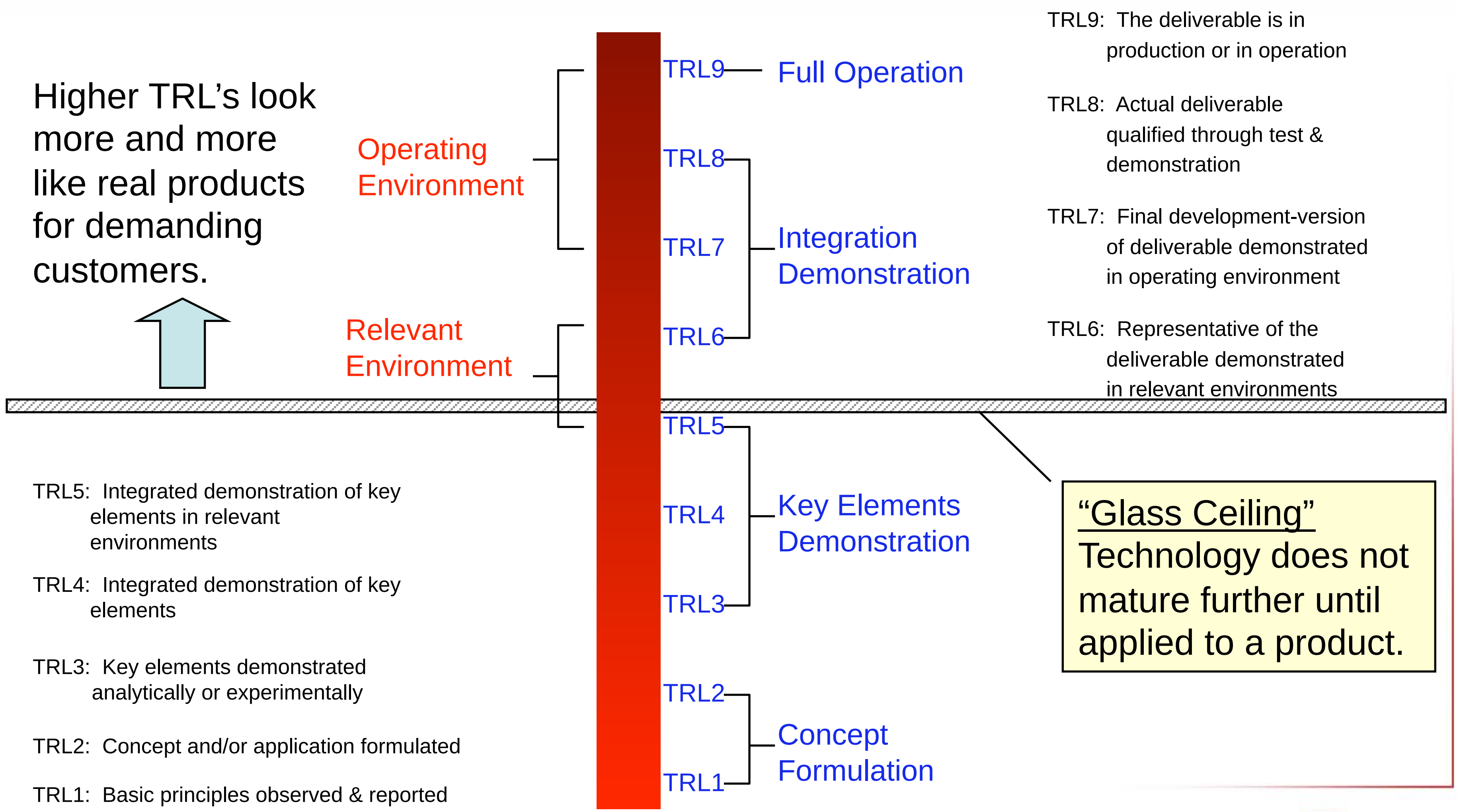
Technology Readiness Levels (TRL's) clarify risk & maturity issues for developers and customers



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We will manage risk using TRL levels - we devised a high level plan based on the consensus phases to bring the system to a TRL of 5-6

System	Current TRL level (2011)	TRL level (2014)	TRL level (2017)
LTD Cavity	4	5	6
Switches	4	5	6
Driver Module	3	5	6
RTLs	2	4	6
Target	3	5	6
Chamber	2	4	6
Breeding	2	3	5
Balance of Plant	4	5	6
"Net TRL"	3	4.5	5.9

- A TRL of 5 to 6 is sufficient to build a pilot plant
- Need detailed design, cost, and schedule estimates
- Such a rate of progress is necessarily linked to funding and personnel

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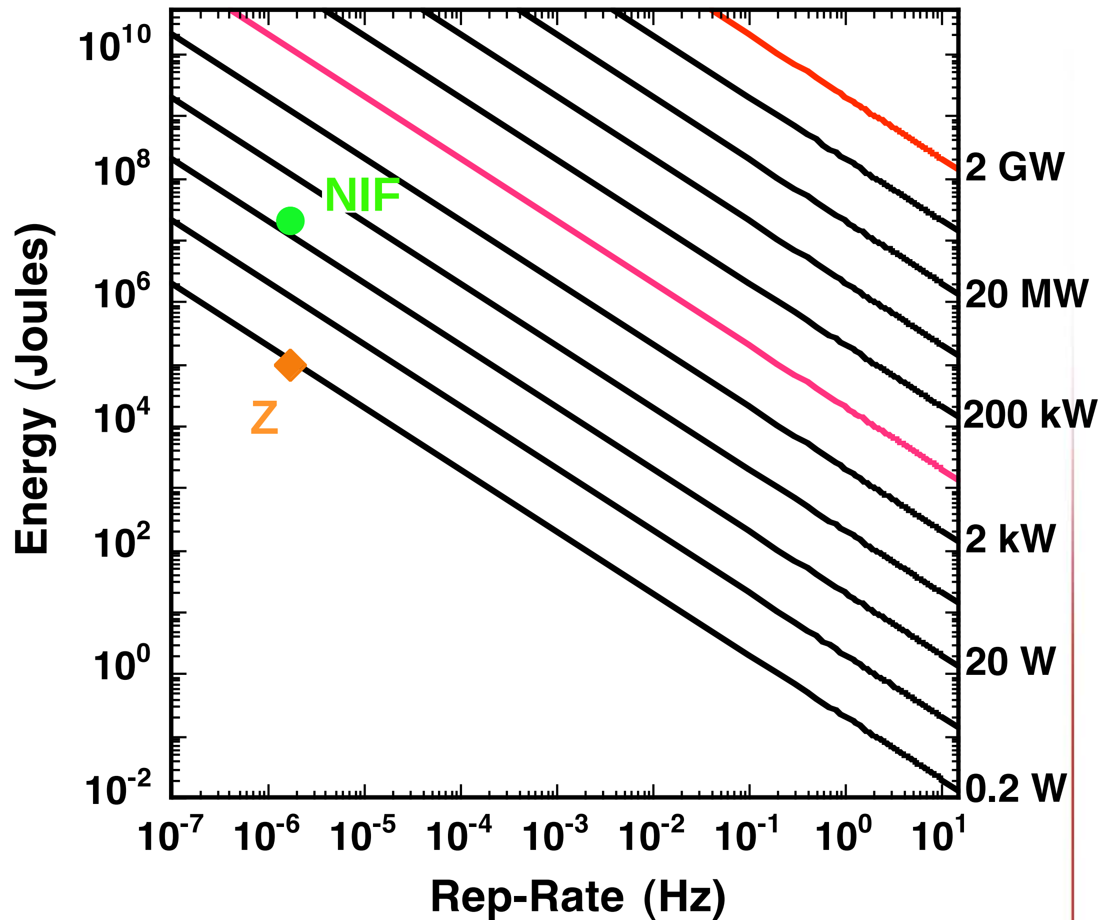
Development of key sub-scale science and technology

System	TRL level completed	Achievement (by 2017)
LTD Cavity	6	100 ns and 300 ns LTD modules with plan to meet cost targets (2-4$/Joule)
Switches	6	10,000,000 to 30,000,000 shot lifetime (3 to 10 years)
Driver Module	6	6 TW full-scale module testing complete at 6 shots/min 121,000 shots with no failure (2 weeks)
RTL's	6	Prototype system demonstrated on full-scale module at speed for 5 days Scaled tests of performance on Z at operating conditions Full scale validated models Final design of full-scale RTL production unit
Target	6	Q ~ 1 to 10 with DT implosions and cryogenics High gain target designs (> 5 GJ) and validated simulations Final design of full scale target production unit
Chamber	6	Preliminary and final designs of full scale liquid wall systems Scaled hydrodynamic shielding experiments Prototype thick liquid wall cassette validated on Z
Breeding	5	Final designs of full-scale tritium extraction system Laboratory scale tritium extraction from molten salt
Balance of Plant	6	Final design of full-scale Brayton cycle system for fusion reactor Scaled laboratory demonstration of Brayton cycle with molten salt primary heat exchanger loop
Net TRL	5.9	

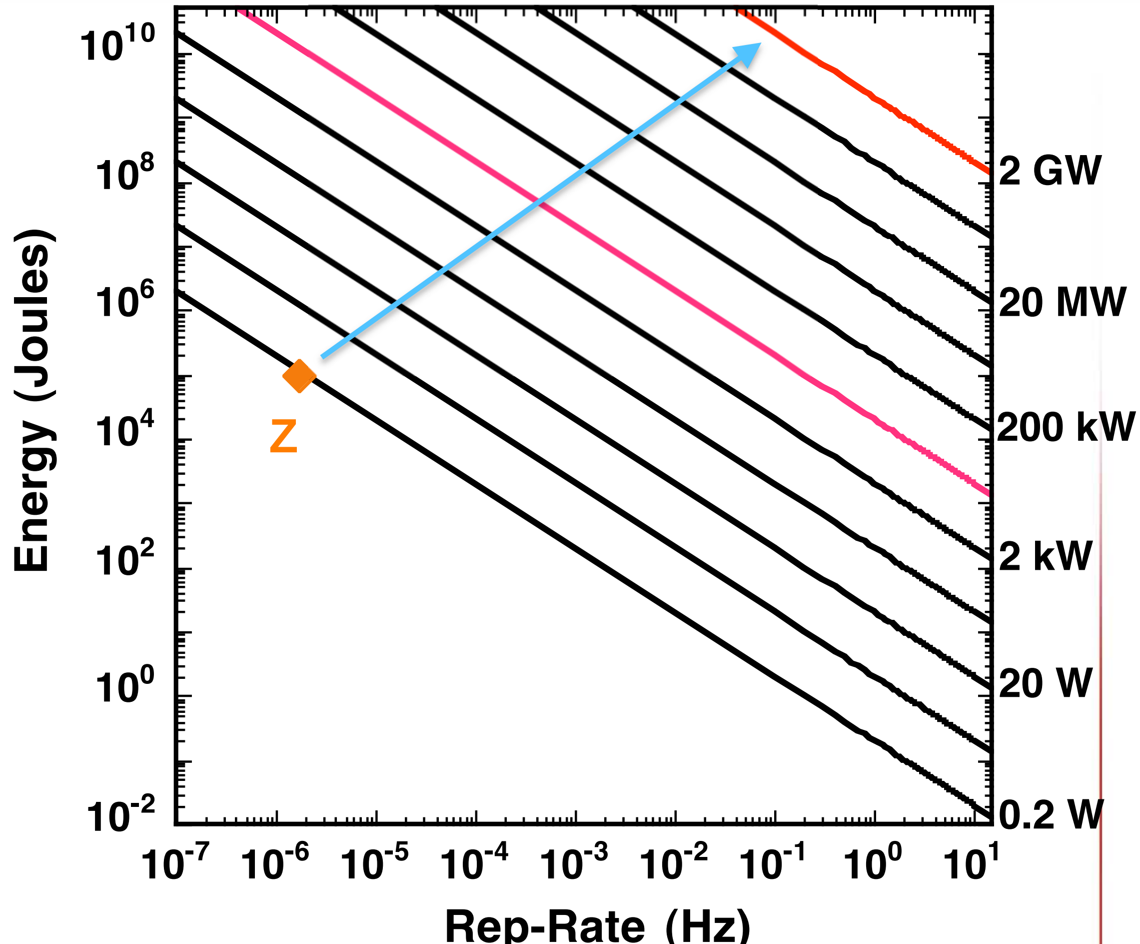
IFE has a vast gulf to cross to achieve the required high average fusion power generation (1-3 GW_{th})

- Our goal on Z is a DT yield of 100 kJ once per week
- This goal is a factor of 10^{10} from economic power generation for pulsed-power
- What is the optimal path to 1-3 GW_{th}?



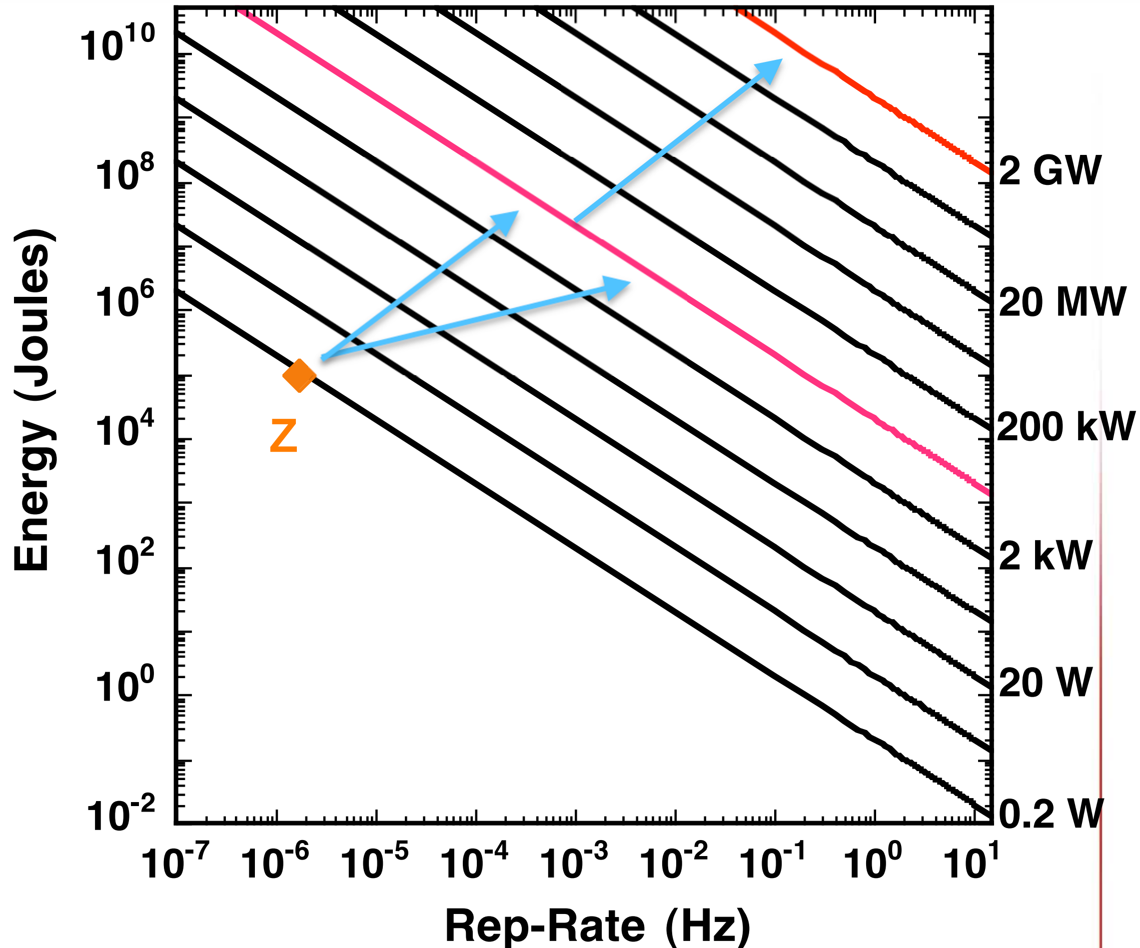
What is the optimal path to 1-3 GW_{th}?

- A straight line in a single step?
- This is unrealistic.



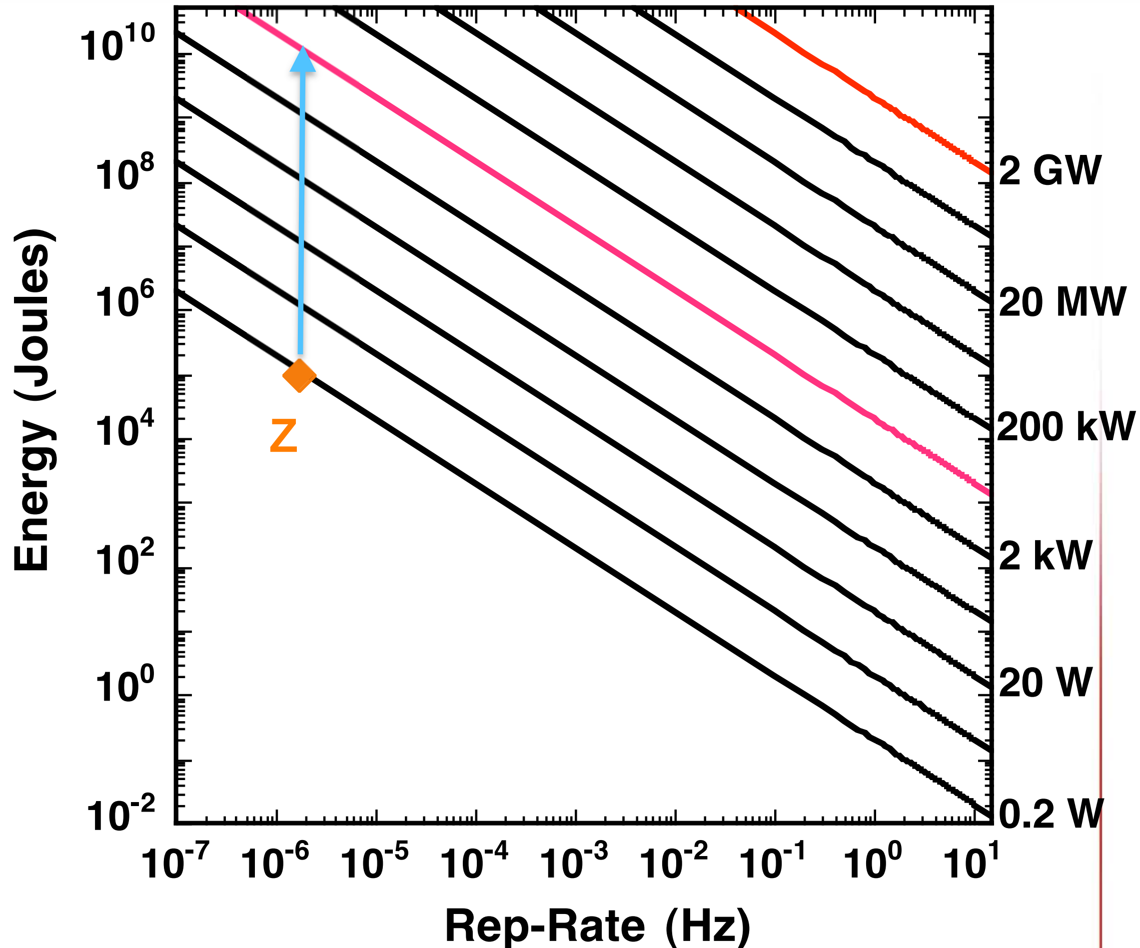
What is the optimal path to 1-3 GW_{th}?

- Stop at a power of 20 kW which is logarithmically spaced for Z?
- This intermediate jump gets neither the yield or pulse rate right, so can't be optimal.



What is the optimal path to 1-3 GW_{th}?

- Increase yield at single shot (NNSA), then solve rep-rate problem?
- This would be of great utility to NNSA mission and would teach us what is required to get high yields and handle high yields often. The machine might be built with the ability to be rep-rated.
- A goal could be “robust ignition” per Crandall perhaps ignition 10 X per day.



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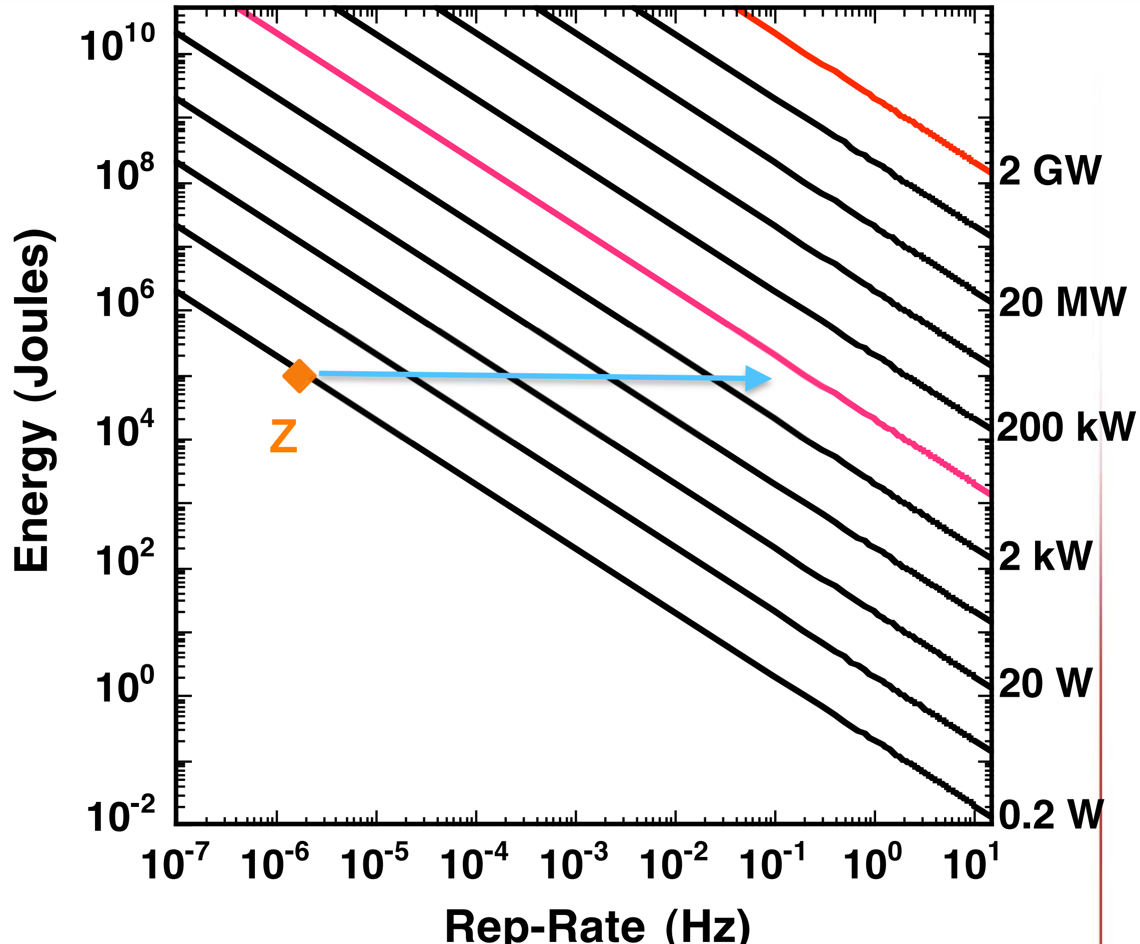
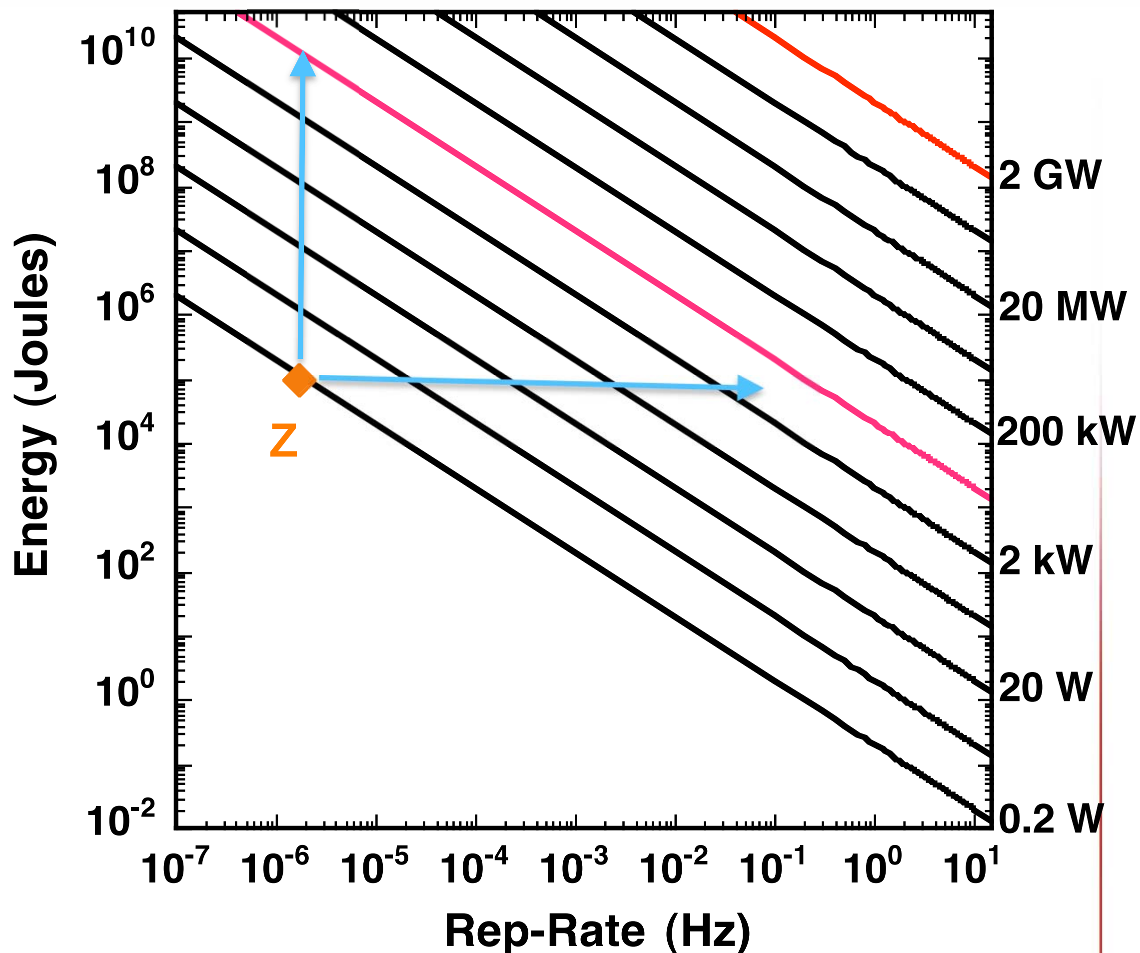
What is the optimal path to 1-3 GW_{th}?

- Stay at low yields and solve rep-rate problem at small scale and cost, then scale up yield?
- Such a facility could be built at Sandia with LTD technology in the foot print of the Saturn accelerator.



What is the optimal path to 1-3 GW_{th}?

- Do both of these last two steps and then to press onward to 1 GWe?
- This might actually be the lowest cost, shortest time path
- We prefer this as an optimal solution but getting the resources for two facilities is likely unrealistic, unless support comes from two different funding sources.
- Coincidentally, both facilities would be at an average power of ~20 kWth, each increase by a factor of 10^5 in different ways



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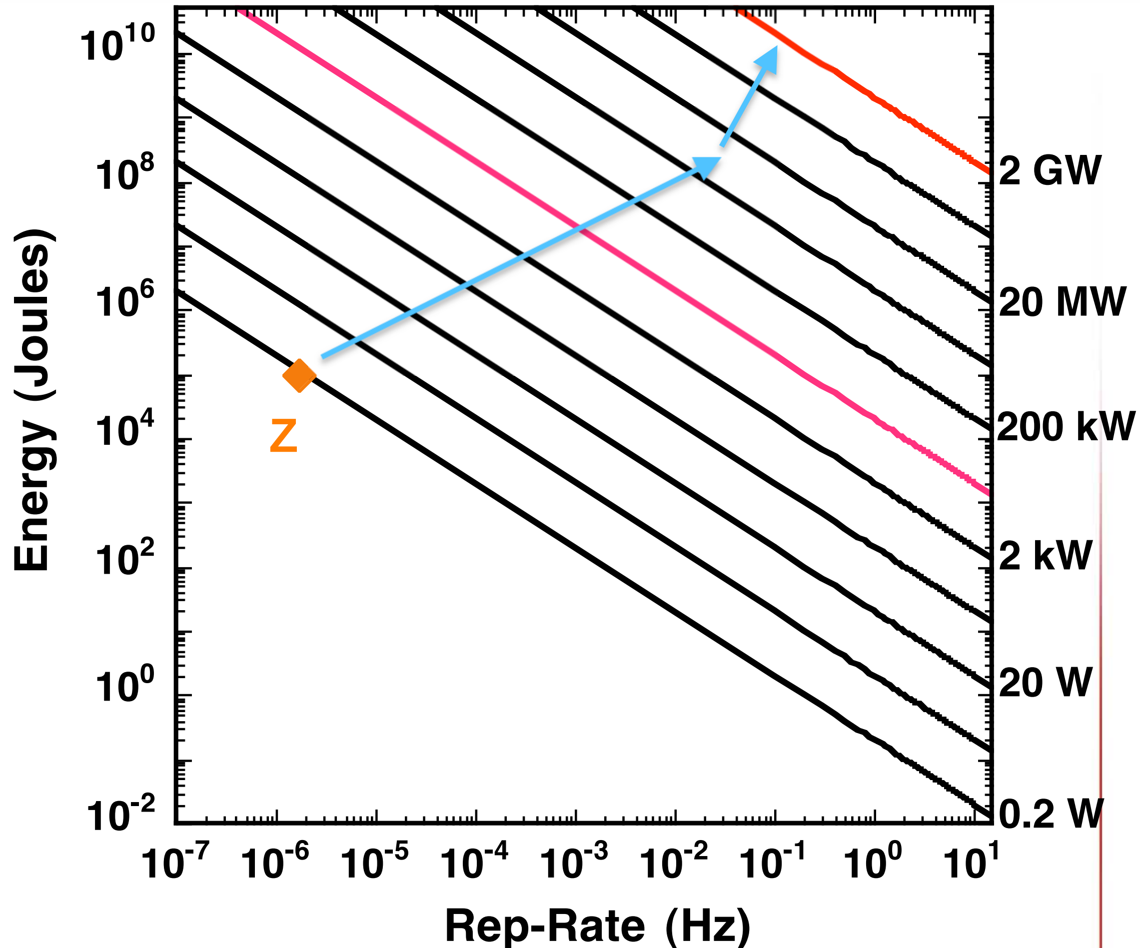
What is the optimal path to 1-3 GW_{th}?

- Make a 10^7 jump (2 to 20 MWth at 0.03 to 0.1 Hz)
- The last factor of 10^3 requires another technology scale up step
- A challenging step.



Proposed high-level roadmap

- **Technology Integration Phase 2020-2030**
  - Build 1-PW rep-rate high yield facility (a fusion pilot plant)
    - Burst-mode: 100-400 MJ every 10-30 seconds for up to 1 hour
    - Single-shot mode: 1 - 5 GJ yields
  - This would be the first device to demonstrate *engineering gains of* > *10*; i.e., a fusion yield greater than 10*X* the energy initially stored in the LTD capacitors.

Proposed high-level roadmap

- **Technology maturation phase 2030-2040**
  - Evaluate burst mode operation at fusion powers of 3 to 40 MW_{th} ~ (2-25% Shippingport)
  - Gradually extend period of burst operation to 1 hour and beyond
  - Demonstrate management of very high fusion yields (> 1-5 GJ)
  - Design 1 GW_e facility based on operating experience

What would our critics say are the biggest challenges?

- We need a validated high gain target design at affordable driver energy.
- We need an RTL scheme that allows adequate coupling efficiency and is manageable and affordable at the desired rep-rate.
- We need an engineering solution to high yield chamber and driver wear and tear at large yields.
- We need a pulsed power technology with a demonstrated 1 to 10e6 shot lifetime.
- We need an integrated plant design and concept of operations

We agree that these are challenges and are planning our research program to address them

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What would proponents say are the potential advantages?

- The minimum energy to ignite and attain high fusion yields is far from clear – being able to provide 10*X* more energy to the target is a significant advantage for pulsed power.
- Efficiency of delivery of energy to the fuel is significantly larger than for other target approaches – up to 3% may be possible in an IFE scale system.
- The cost per joule of energy delivered to the target is at least 10 times smaller than other technologies.
- Very low rep-rates may offer system engineering advantages.
- Use of an RTL is compatible with a thick liquid wall for chamber protection, reducing "first-wall" materials issues – a miracle free materials approach.

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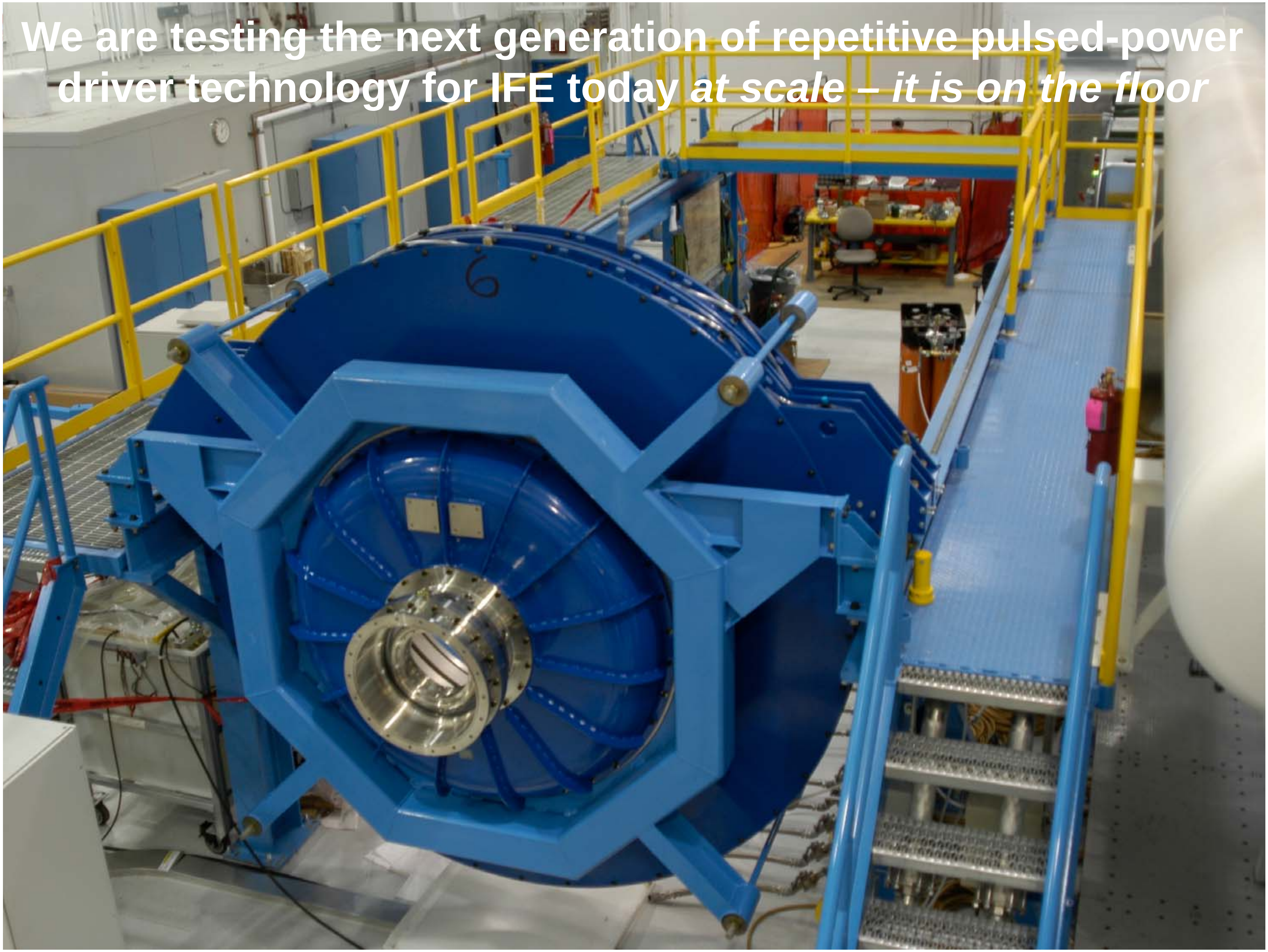
IFE diversification

Drivers	Coupling
Pulsed power magnetic pressure Pulsed power x-rays Fast Ignition Laser Heavy Ion Accelerator DPSSL Laser KrF Laser	Conductor transport-conductor recycling Beam transport-inverse diode Beam transport-space-charge-neutralization Photon transport-target-injection-tracking

Targets	Chamber and Blanket
Direct-drive fast-ignition Direct-drive hot-spot ignition Indirect-drive fast-ignition Indirect-drive hot-spot ignition Other advanced concepts	Thick liquid wall Vaporizing blanket Wetted wall Dry wall with gas fill

- Many possible IFE systems is an advantage
- Don't up-select too early:
  - Magnetically-driven implosions and pulsed power could be a game-changer
  - Diversify the risk portfolio for national IFE plan.
  - Diversification is in the national interest.
- Diversification, formally: for a given level of expected return, a portfolio minimizes total variance by diversifying amongst assets with poorly correlated risks. The risks of pulsed power are orthogonal to the other approaches: different driver, different delivered energy, different target and implosion physics, different coupling technique, different rep-rate and yield, different chamber.
- Long time scales for energy solutions doesn't mean to give up or try and rush to a solution.
  - "Someone is sitting in the shade today because someone planted a tree a long time ago" Warren Buffett.

We are testing the next generation of repetitive pulsed-power driver technology for IFE today *at scale – it is on the floor*



Summary

- Pulsed power technology offers an attractive option for IFE
  - We showed you the unique benefits in driver efficiency, delivered and absorbed energy
- We have concrete ideas for reactors based on hardware that exists today
  - We showed you several reactor pre-conceptual designs
  - We showed you some of the existing hardware and how it might be extended for a reactor
- We have identified in considerable detail the remaining issues and approaches for moving forward
- Immediate near-term opportunities/needs were identified
  - Target physics validation through experiments and modeling
  - RTL proof of principal engineering and science experiments
  - Integrated designs of drivers, RTL's, target chambers for producing and handling high yields

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Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- Compact, efficient, low cost, long-lifetime, repetitive driver
- Advanced, efficient, low cost, robust targets that are simple to fabricate
- $\Longrightarrow$ Very large absorbed target energies
- $\Longrightarrow$ Very large fusion yields
- $\Longrightarrow$ Allows low rep-rate
- $\Longrightarrow$ RTL coupling is feasible, engineering development required
- $\Longrightarrow$ RTL provides vacuum for power flow, clears chamber debris
- $\Longrightarrow$ RTL permits a thick-liquid-wall chamber
- $\Longrightarrow$ Thick-liquid-wall & vaporizing blanket provide long lifetime chamber
- $\Longrightarrow$ Long inter-pulse interval clears chamber
- $\Longrightarrow$ RTL can shield line of sight to the driver

Key enabling physics: magnetically-driven-targets
Key enabling technologies: LTD's and RTL's

The ICF community has a common viewpoint (Hockaday et al. GA, LLNL, NRL, LANL, SNL, UR)

- Demonstration of laboratory ignition will establish that the physics underpinning IFE is fundamentally sound.
- IFE is a field in which the US is a clear world leader – academically, technologically and industrially.
- We have an opportunity to capitalize on this leadership position over the next few years, and will leverage prior substantial defense program investment.
- Recent action by the DOE to propose a new IFE development program and secure a stable home for IFE is timely and very welcome.
- Moving forward, the IFE program needs to focus on the requirements of an operating power plant, with design choices managed at a systems-level.
- The inherent modularity and separability of IFE provides significant benefits when considering power plant development, operations, and evolution.
- Taking advantage of significant prior research, future development activities in this program need to include IFE scale science and technology development and demonstration.
- IFE is a national scale program requiring a coordinated effort by academic, laboratory, and industrial partners.
- A phased program with competition and unambiguous selection criteria is needed

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