SAND2011-3568C

Sandia National Laboratories

16 May 2011

Pulsed-Power Inertial Fusion Energy

ICENES-2011 Conference

May 16-19, 2011 San Francisco, CA

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

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

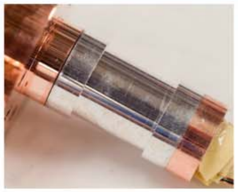
Sandia National Laboratories

Inertial fusion energy systems require integrated progress in four technical areas

NNSA

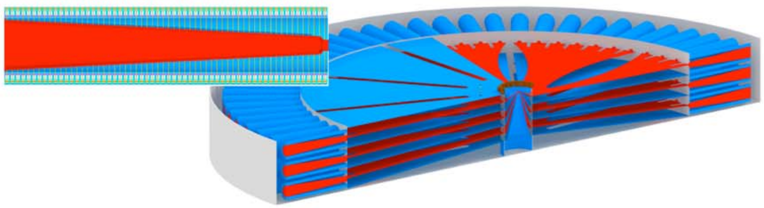
Target physics

- Ignition and high gain
- Validated models



Driver science and engineering

- Repetitive, low cost, driver modules
- Module integration into low cost drivers



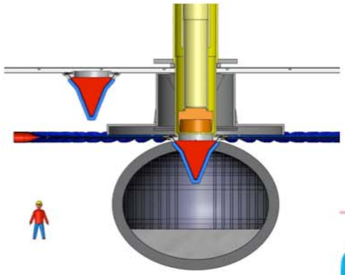
IFE

IFE pulsed power technology (IFET)

- Driver-target coupling and repetitive effective standoff from large fusion events
- Long lifetime modules

Fusion nuclear science (FNS)

- Blankets, tritium breeding and recovery, first wall shielding, nuclear waste
- Handling large yields



A simple scaling relationship gives insight into the requirements for fusion energy production

$$P_e = (1 - f_r)\eta_t M \eta_D E_{store} RG - P_{recirc}$$

$$P_e \propto \eta_D E_{store} RG$$

η_D	E_{store} (MJ)	R (Hz)	G	$2RE_{store}$ (GW_e)	$\eta_D E_{store} RG$ (GW_t)
18	15	16	60	0.48	2.6
7	30	5	250	0.30	2.6
15	250	0.1	690	0.10	2.6

- Trade η_D, E_{store}, R, G against each other

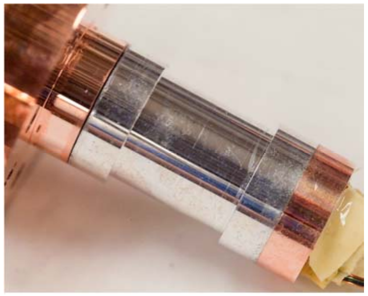
- For pulsed power
  - increase E ~ 10-20X
  - increase G ~4-10X
  - decrease R ~ 50-200X

- What are the system requirements and challenges?

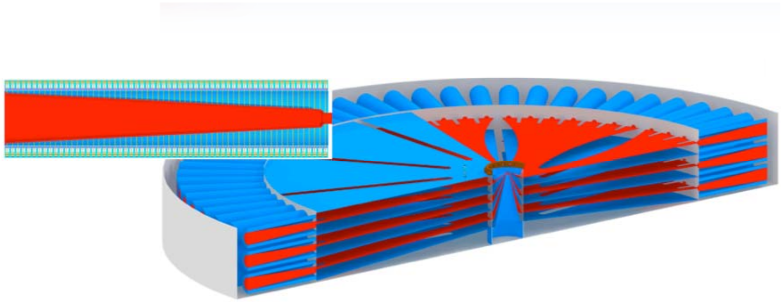
Sandia National Laboratories

Inertial fusion energy systems require integrated progress in four technical areas

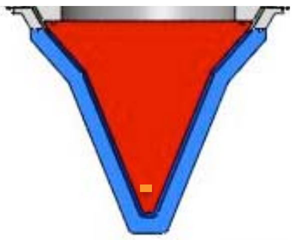
Target Physics



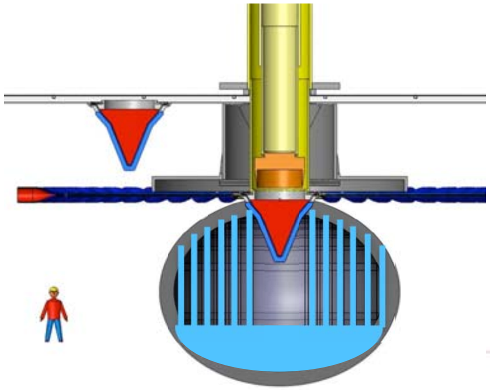
Driver Science and Engineering



IFE Pulsed Power Technology

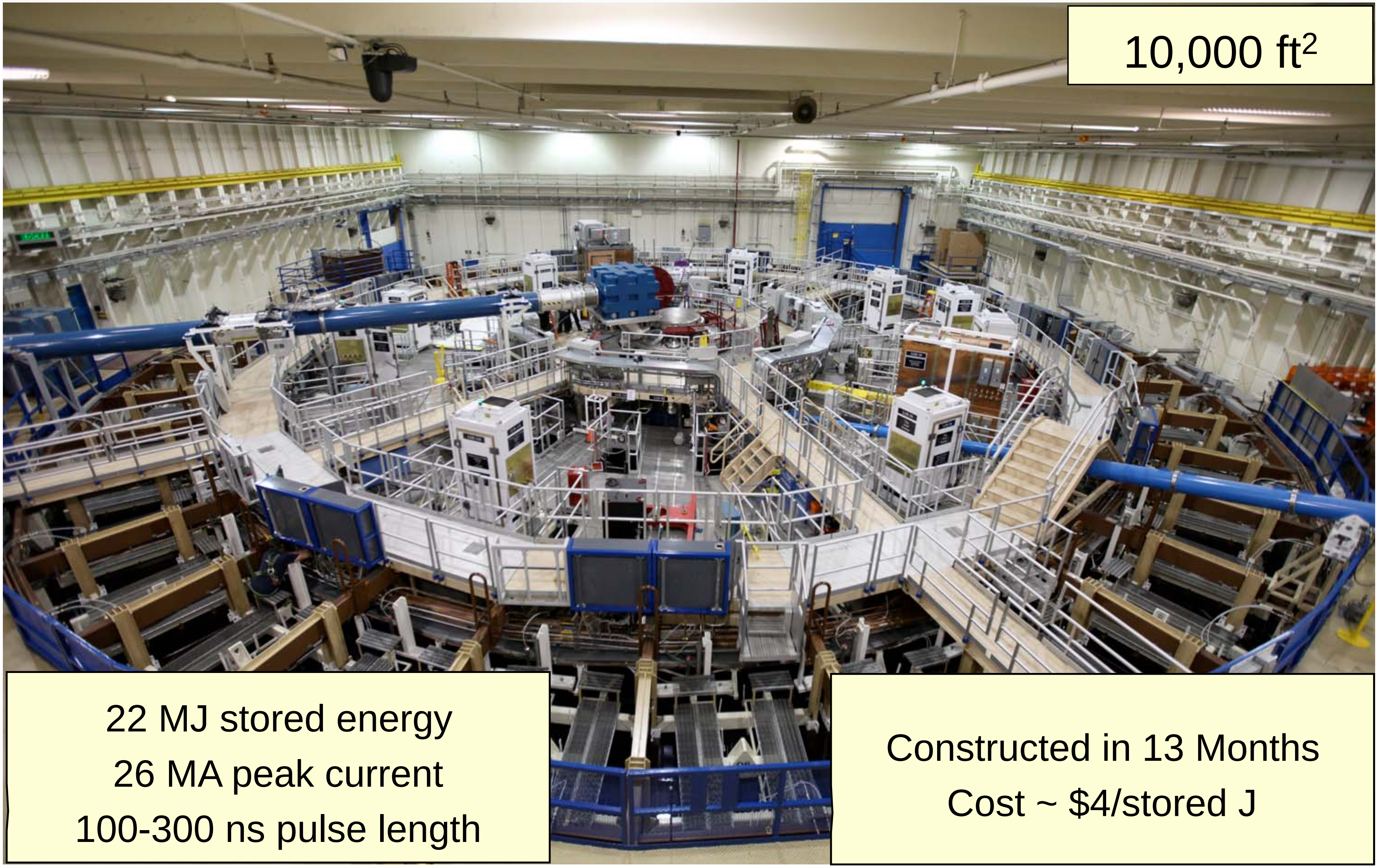


Fusion Nuclear Science



Sandia National Laboratories

The Z pulsed power generator provides a compact MJ-class fusion target physics platform



10,000 ft^2

22 MJ stored energy
26 MA peak current
100-300 ns pulse length

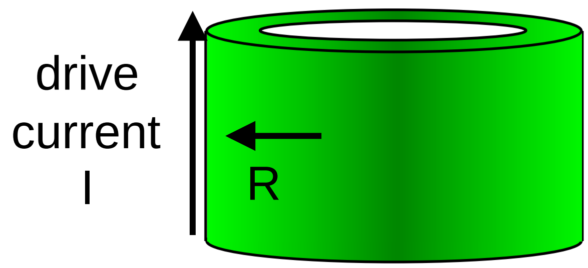
Constructed in 13 Months
Cost ~ $4/stored J

Large currents and the corresponding magnetic fields can efficiently create high energy density matter

Magnetic fields and currents can push conductors around:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P = \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

Magnetically-Driven Implosion



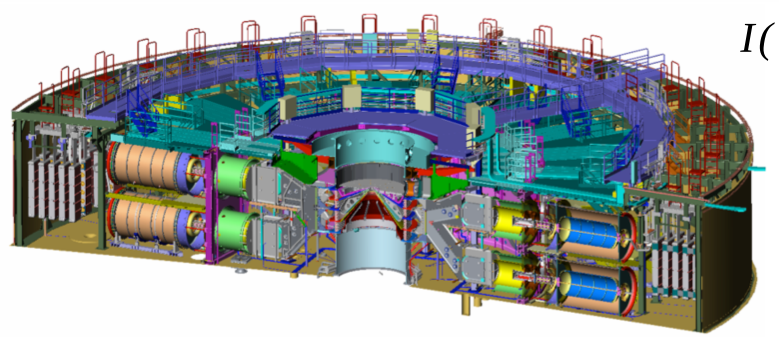
$$B \sim \frac{I}{R} \qquad P \sim B^2 \sim \left(\frac{I}{R}\right)^2$$

100 MBar at 26 **MA and 1 mm**

- Magnetic drive can reach very high drive pressures if current reaches small radius
- Magnetic drive is very efficient at coupling energy (no energy wasted on ablation)

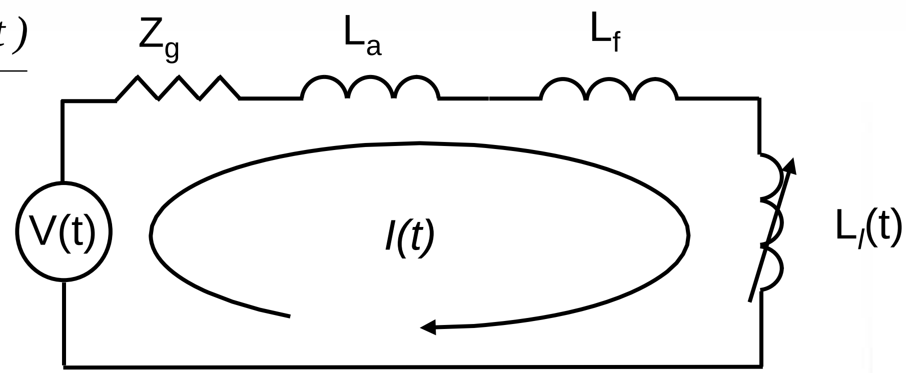
Sandia National Laboratories

Z-pinch implosions efficiently deliver kinetic and magnetic energy to small volumes in short pulses

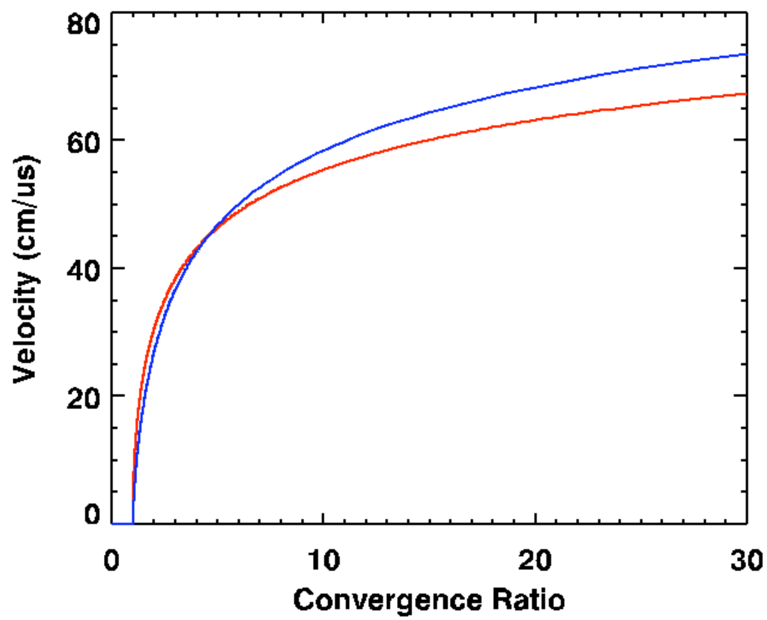


$$I(t) = \frac{\int V(t)}{L}$$

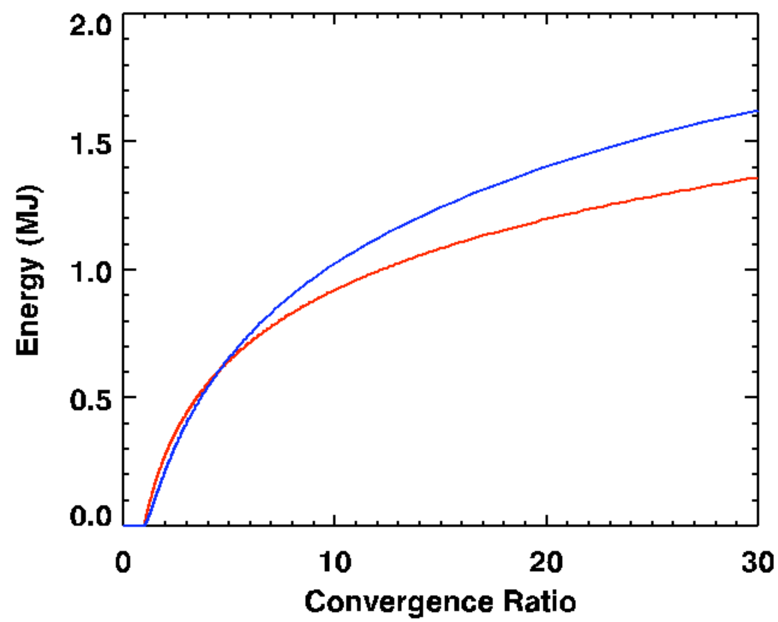
≡



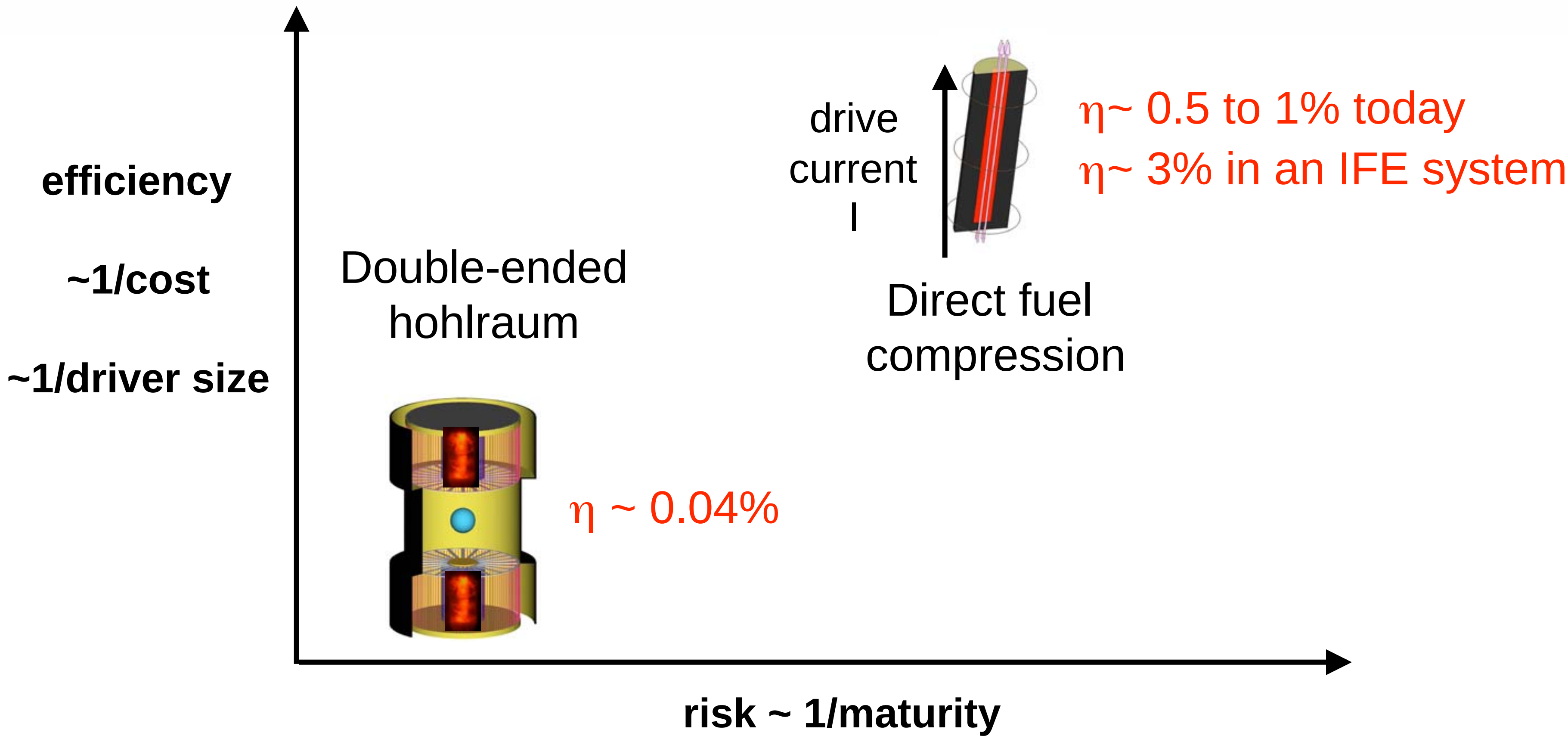
Velocity



Energy



Direct fuel compression and heating with the magnetic field could be 25X more efficient than indirect-drive



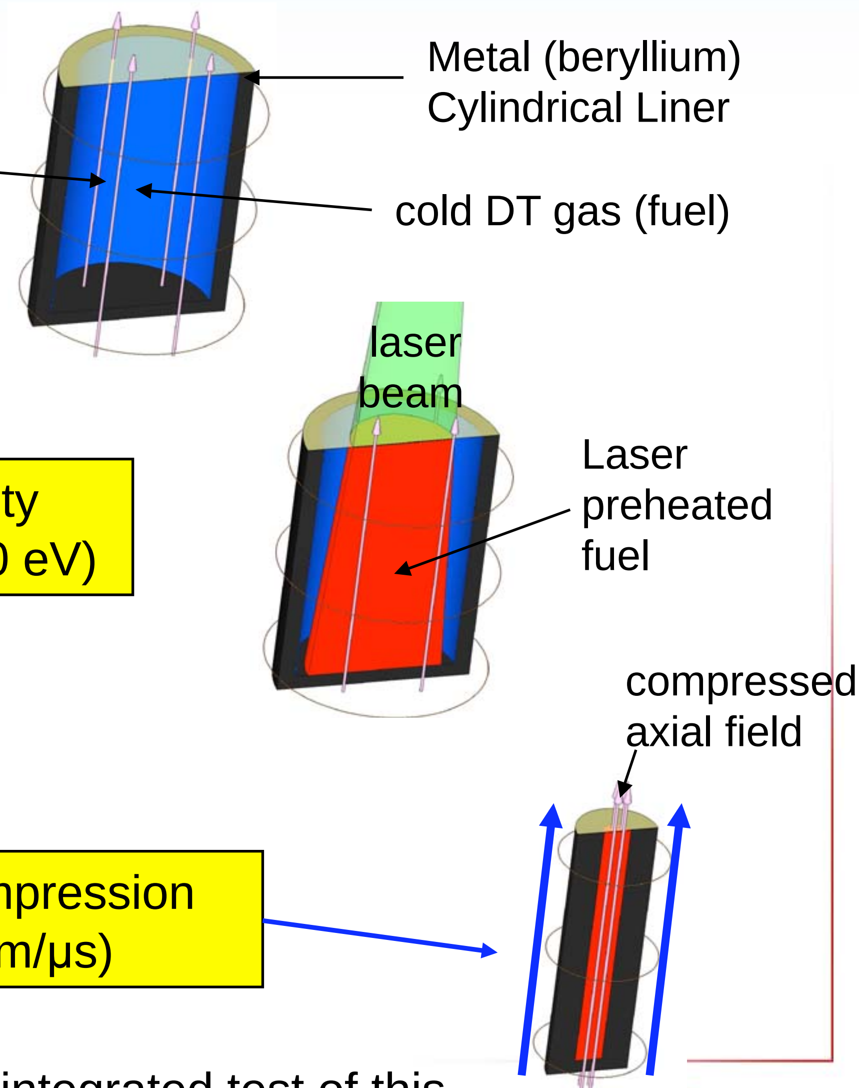
- A near term directly driven concept we can test is Magnetized Liner Inertial Fusion
- Other High Yield/ High Gain concepts are also being explored

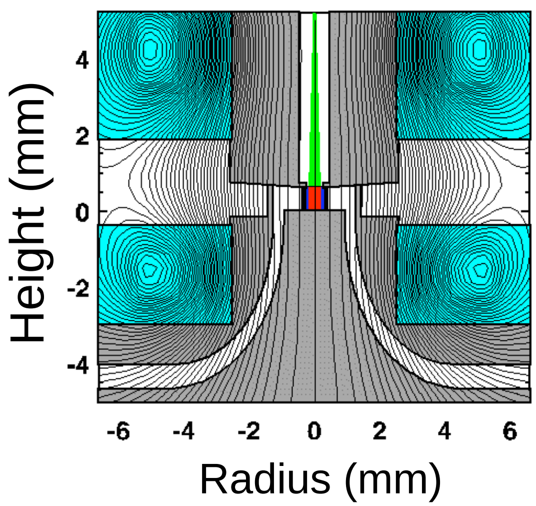
Sandia National Laboratories

* S. A. Slutz *et al*., Physics of Plasmas 17, 056303 (2010)

The Z facility provides a unique opportunity to test the Magnetized Liner Inertial Fusion (MagLIF) concept

Axial pre-magnetization (10-30 Tesla)





Z Beamlet facility preheat (100-1000 eV)

Z liner compression (~10 cm/μs)

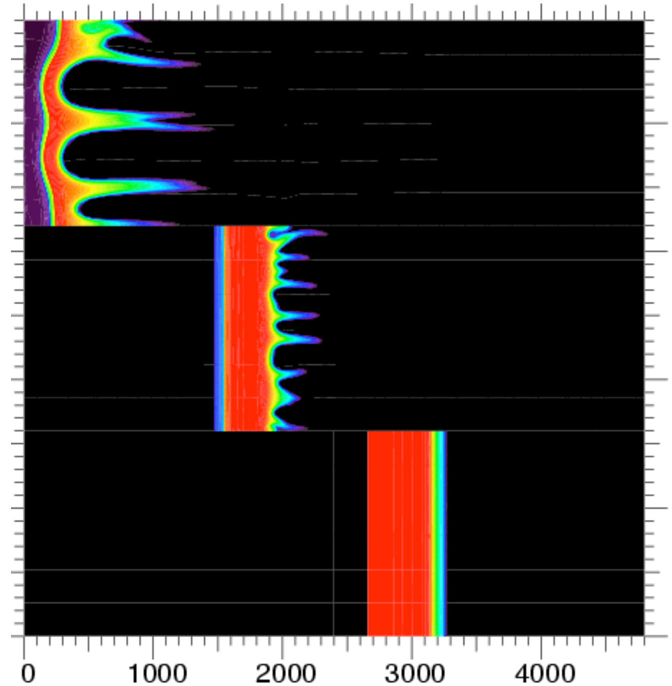
- We are building towards the first integrated test of this concept over the next one to two years

Sandia National Laboratories

Simulations indicate scientific breakeven (fusion energy out = energy deposited in fusion fuel) *may* be possible on Z

INITIAL CONDITIONS	
Peak Current:	27 MA
Be Liner R0:	2.7 mm
Liner height:	5 mm
Aspect ratio (R0/ΔR):	6
Initial gas fuel density:	3 mg/cc
Initial B-field:	30 T
FINAL CONDITIONS	
Energy in Fusion Fuel	~200 kJ
Target Yield:	500 kJ
Convergence ratio (R0/Rf):	23
Final on-axis fuel density:	0.5 g/cc
Peak avg. ion temperature:	8 keV
Final peak B-field:	13500 T
Peak pressure:	3 Gbar

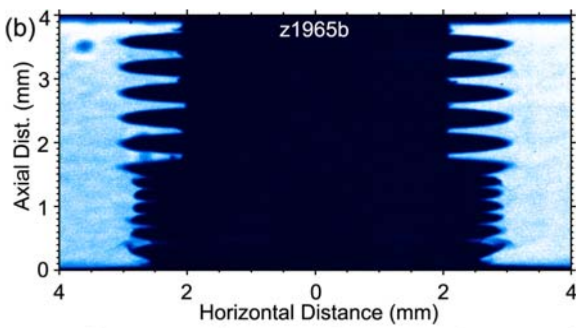
60 nm surface roughness
80 (μm) waves are resolved

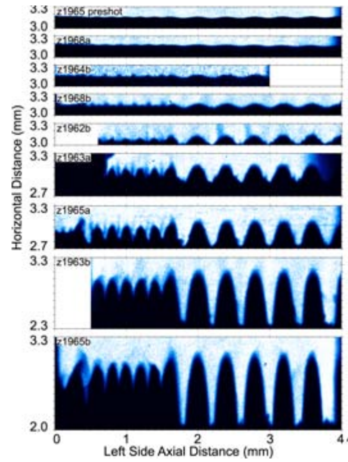


- The magneto-Rayleigh Taylor instability is one of the biggest concerns for this concept
- 2D yield for a DT target ~ 350 kJ (70% of 1D)

We see excellent agreement between theory and experiments for single and multi-mode MRT growth during liner implosion

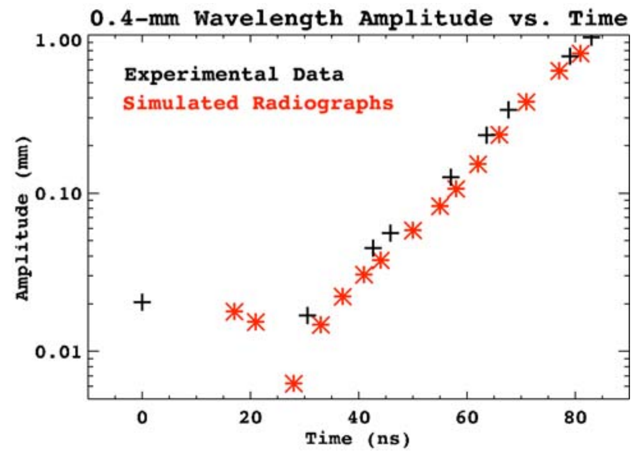
Single-mode Experiments





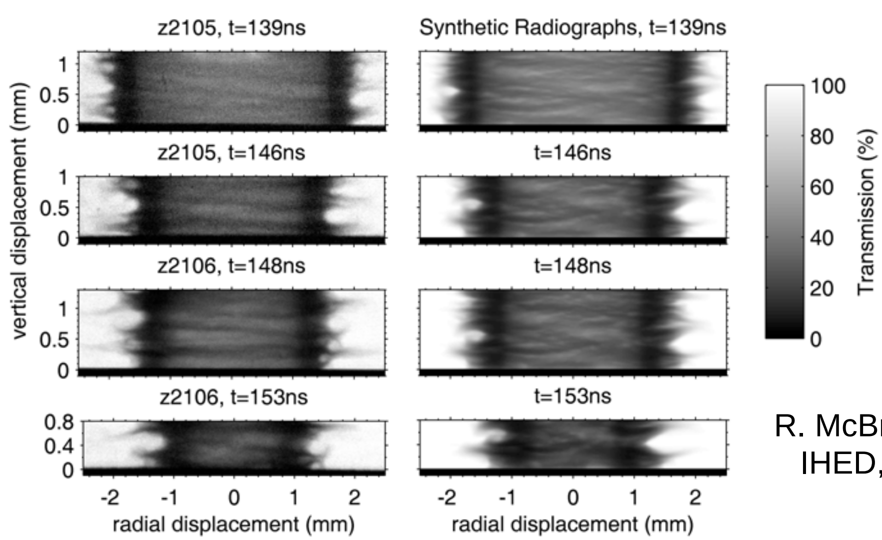
D. Sinars *et al.*, Phys. Rev. Lett. (2010), Phys. Plasmas (2011)

Single-mode 2D Simulations



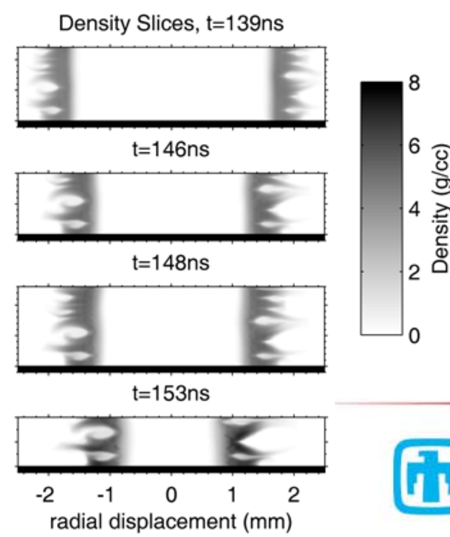
Multi-mode Experiments

Gorgon 3D Simulations



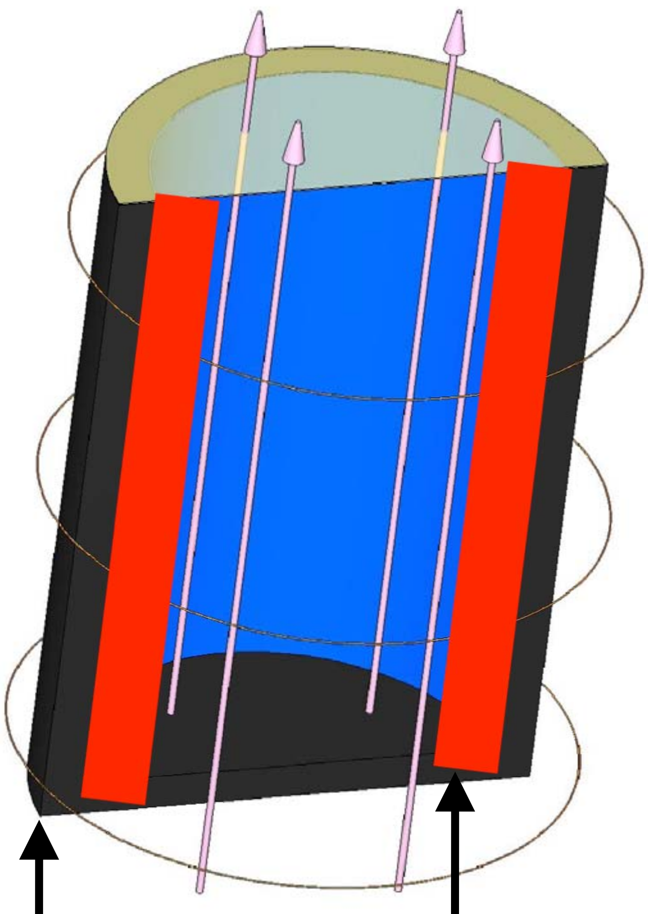
R. McBride *et al.* IHED, (2011)

Gorgon 3D Simulations



Sandia National Laboratories

A levitated shell version of MagLIF could give radially propagating burn, high yield and high gain on a larger facility

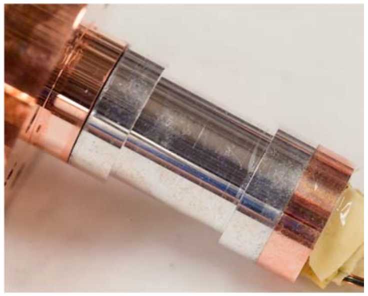


INITIAL CONDITIONS	
Peak Current:	61 MA
Al Liner R0:	4.4 mm
Liner height:	10 mm
Aspect ratio (R0/ΔR):	6
Initial gas fuel density:	10 mg/cc
Initial B-field:	10 T
FINAL CONDITIONS	
Target Yield:	3.0 GJ
Target Gain:	500
Convergence ratio (R0/Rf):	22
Final on-axis fuel density:	9.3 g/cc
Final peak B-field:	12500 T

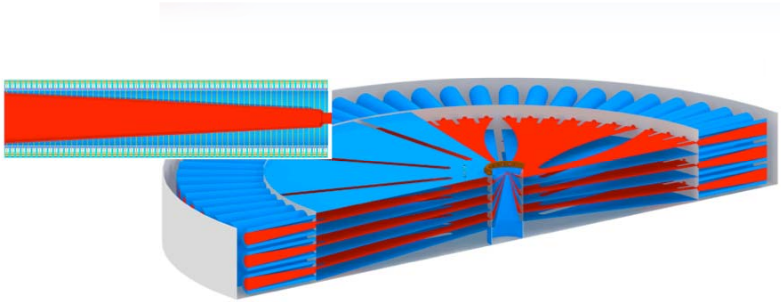
Sandia National Laboratories

Inertial fusion energy systems require integrated progress in four technical areas

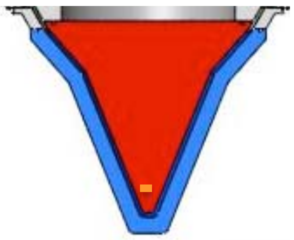
Target Physics



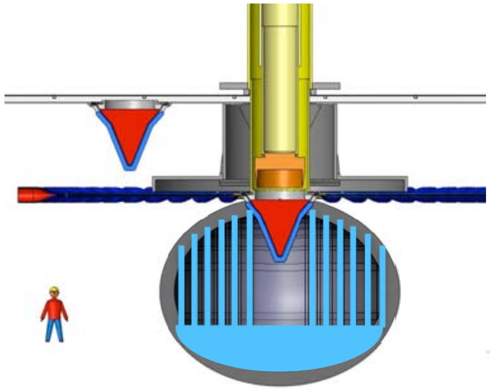
Driver Science and Engineering



IFE Pulsed Power Technology



Fusion Nuclear Science



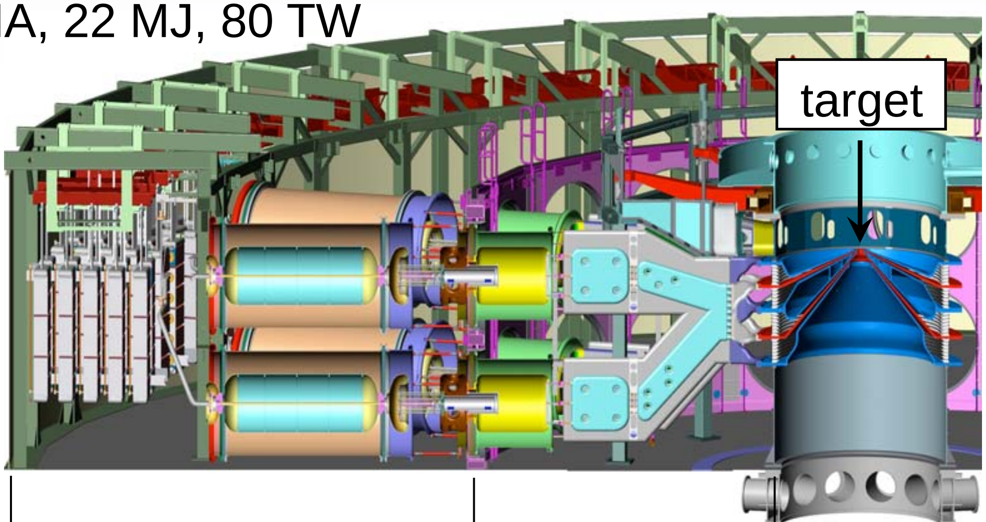
Sandia National Laboratories

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

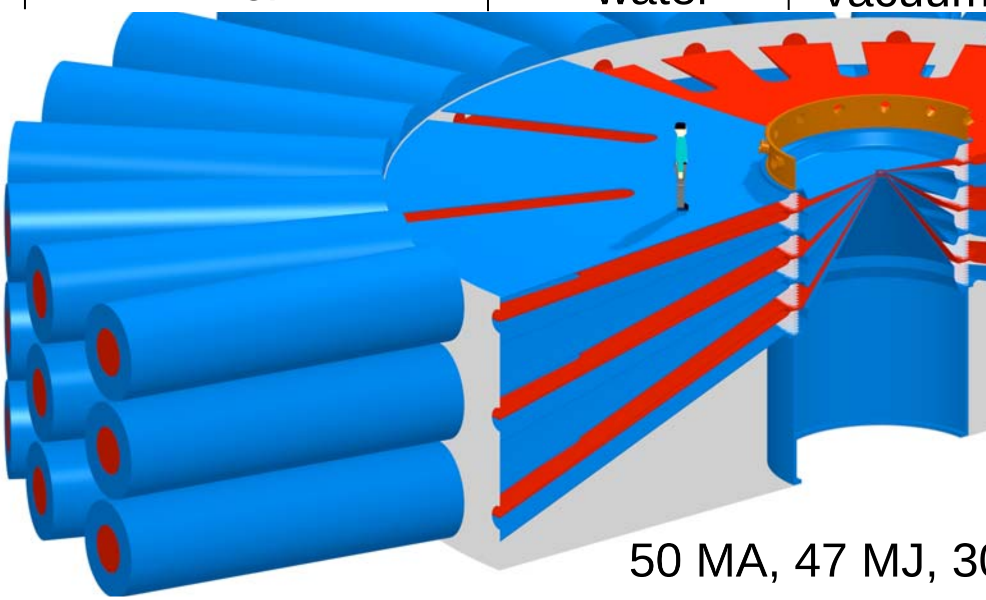
LTDs (Linear Transformer Drivers) offer a simple, reliable, and efficient, modular repetitive IFE driver

16.5 m

26 MA, 22 MJ, 80 TW



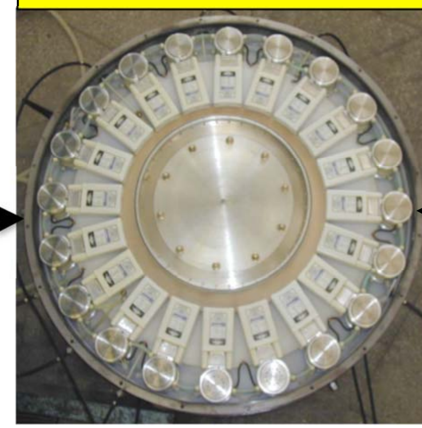
oil | water | vacuum



50 MA, 47 MJ, 300 TW

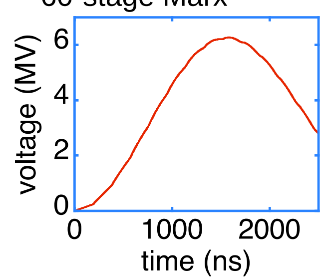
LTD cavity

3 m

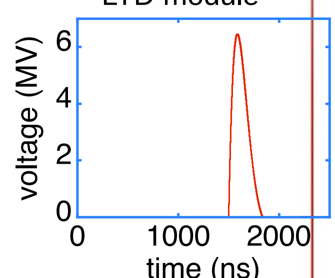


Single step pulse compression

60-stage Marx



60-cavity LTD module

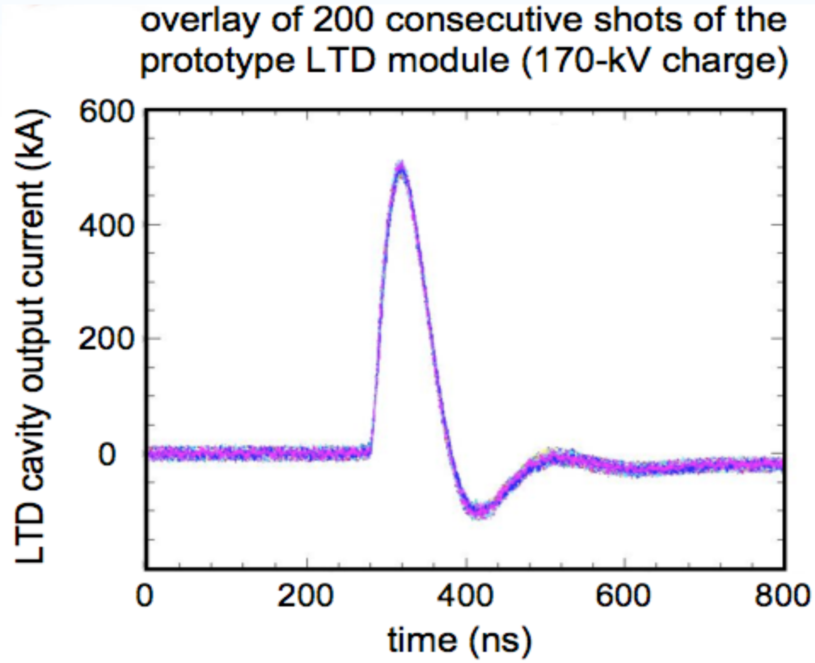


Doubles electrical efficiency

Sandia National Laboratories

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.

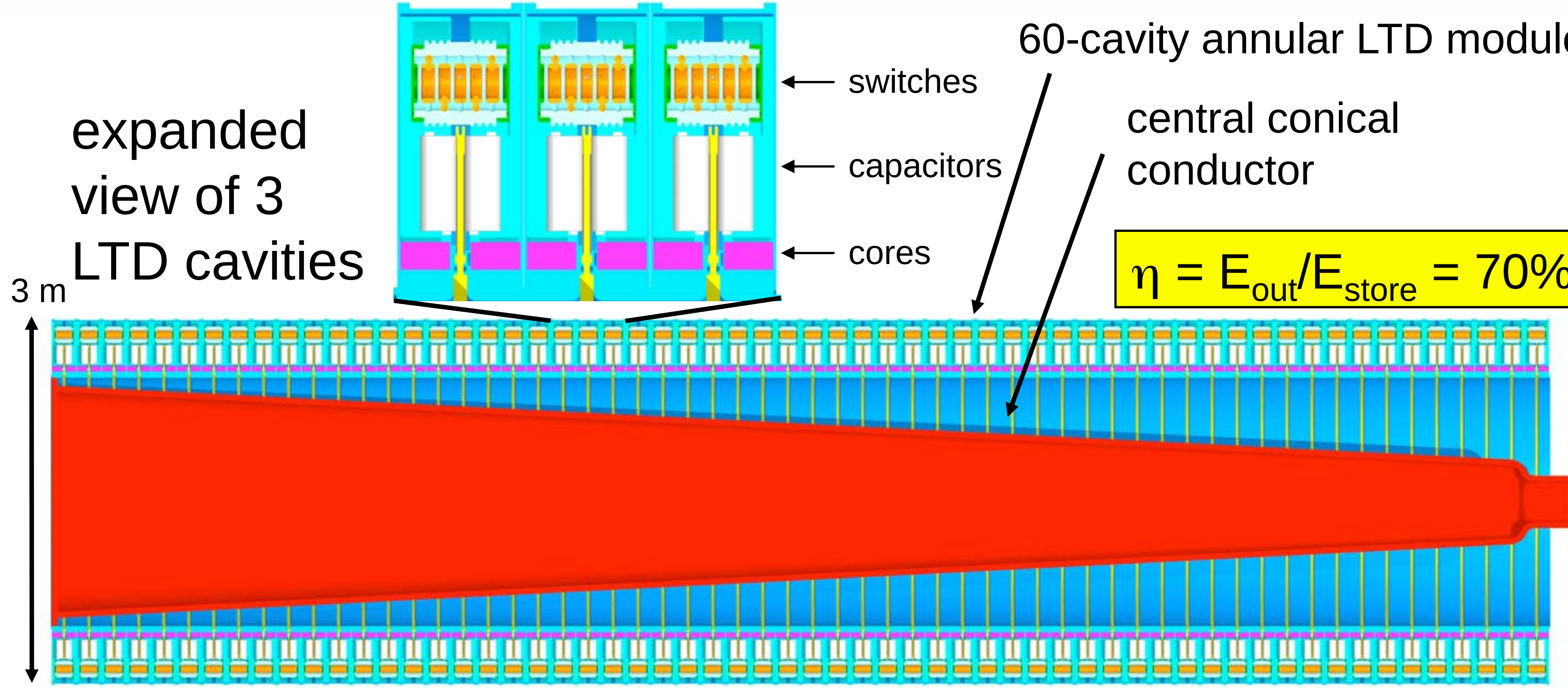


- timing jitter = 2 ns (1σ)
- voltage and current reproducibility = 0.3% (1σ)
- peak power = 0.05 TW
- output energy = 6 kJ
- electrical efficiency = 70%
- random switch failure < 7×10^{-6}

Sandia National Laboratories

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%)

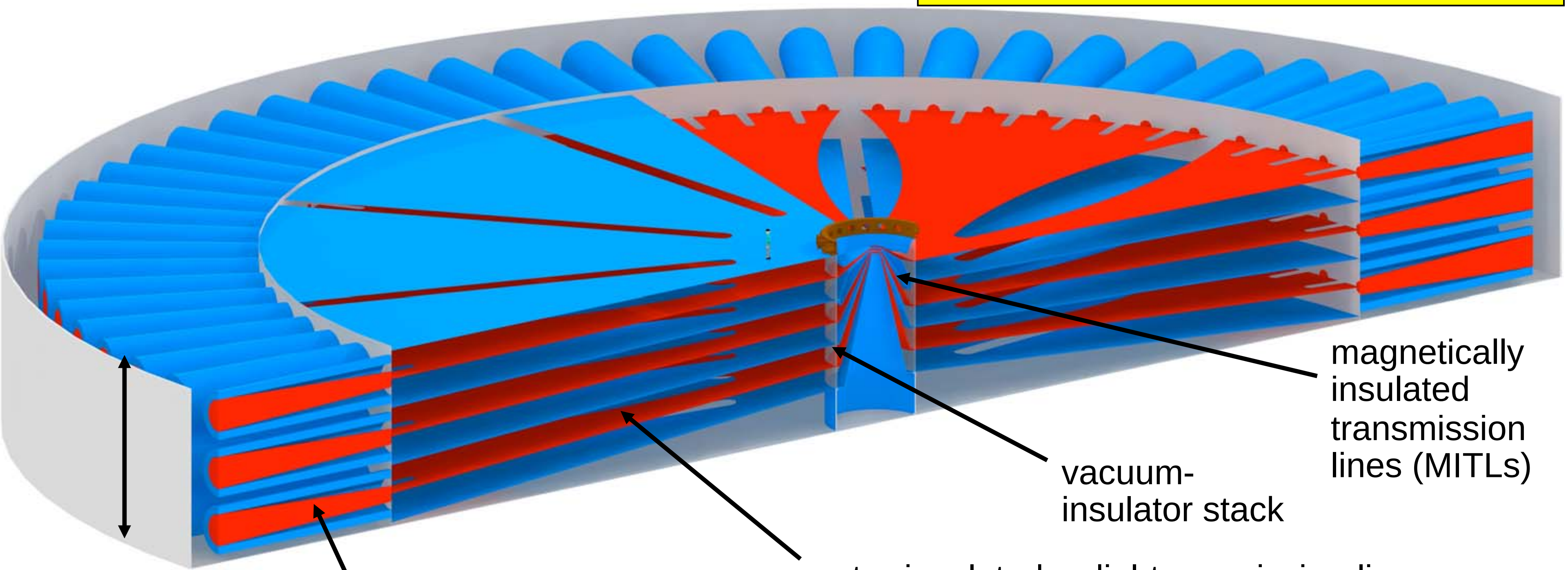
W. Stygar *et al*., Phys. Rev. ST– AB (2007)

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

P_g = 1200-2000 TW V_{stack} = 24 MV I_{load} ~ 70-100 MA $E_{radiated}$ = 20-44 MJ

E_g = 180-360 MJ L_{vacuum} = 29 nH $\tau_{implosion}$ = 100 ns diameter = ≤104 m

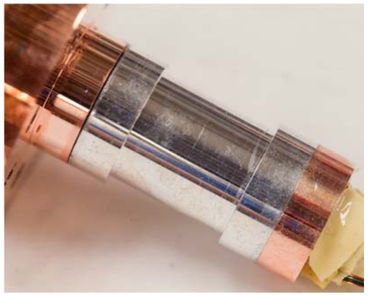
Patent: US 7,679,297 B1 Stygar *et al.*



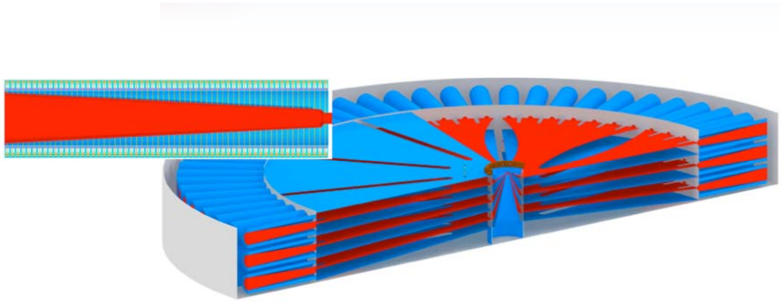
This accelerator would deliver a fusion yield > 2 GJ, and achieve engineering Q's of > 10

Inertial fusion energy systems require integrated progress in four technical areas

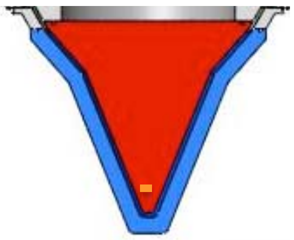
Target Physics



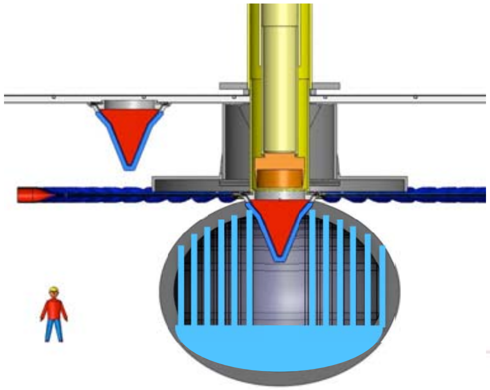
Driver Science and Engineering



IFE Pulsed Power Technology

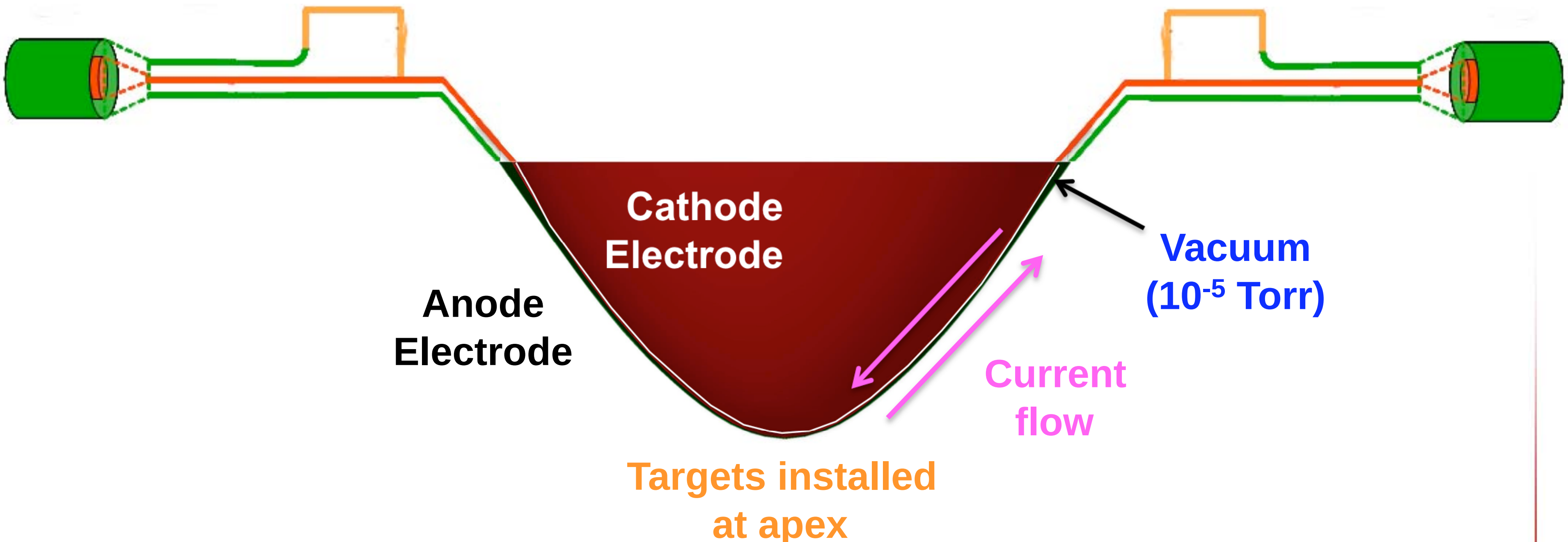


Fusion Nuclear Science



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

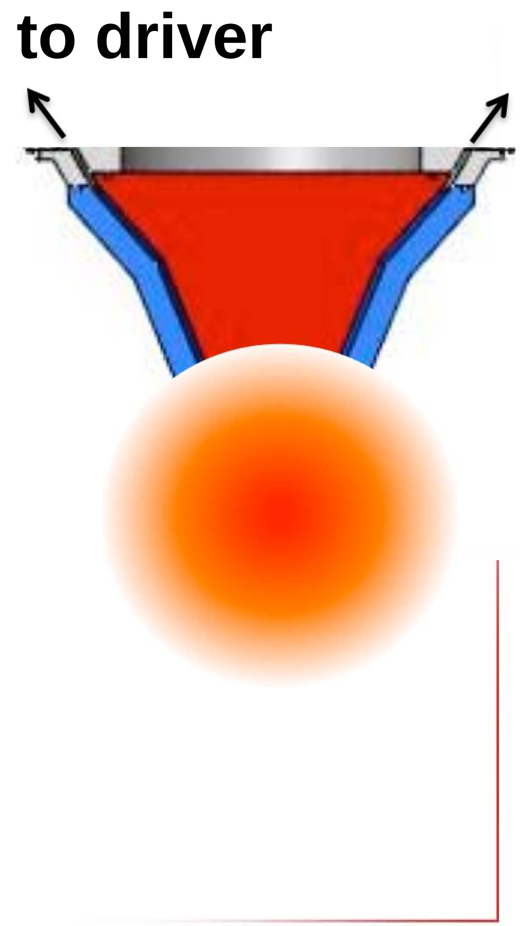
Repetitive connection of driver and target is achieved by replacing a Recyclable Transmission Line (RTL) electrode at 0.1 Hz



- 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

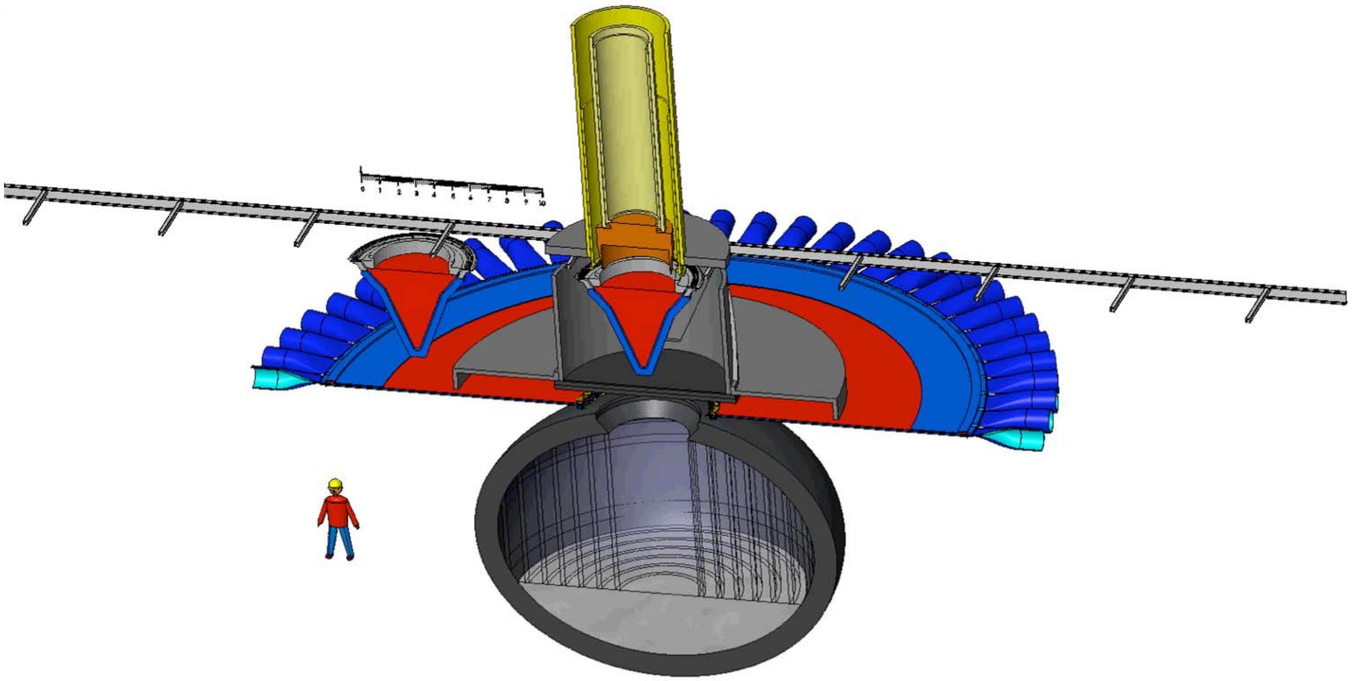
Engineering approaches to issues for repetitive coupling of pulsed-power drivers and high gain targets

Issue	Approach
Standoff or separation of high yields from sensitive driver components	• Long radial or axial vacuum transmission lines • Multiple fast closing valves
Refurbishment or replacement	• Periodically on a maintenance schedule
Shock and blast mitigation	• Recycling and replacement of final section of transmission line (RTL) • Vaporizing or liquid blanket to shield axially • RTL shaped to deflect blast downward • Fast shearing of RTL
Debris mitigation	• RTL shaped to deflect debris downwards • No LOS between driver, driver connection, and target • Self-closing RTL's • Fast closure valves
First wall shielding	• Thick liquid walls • RTLs



Sandia National Laboratories

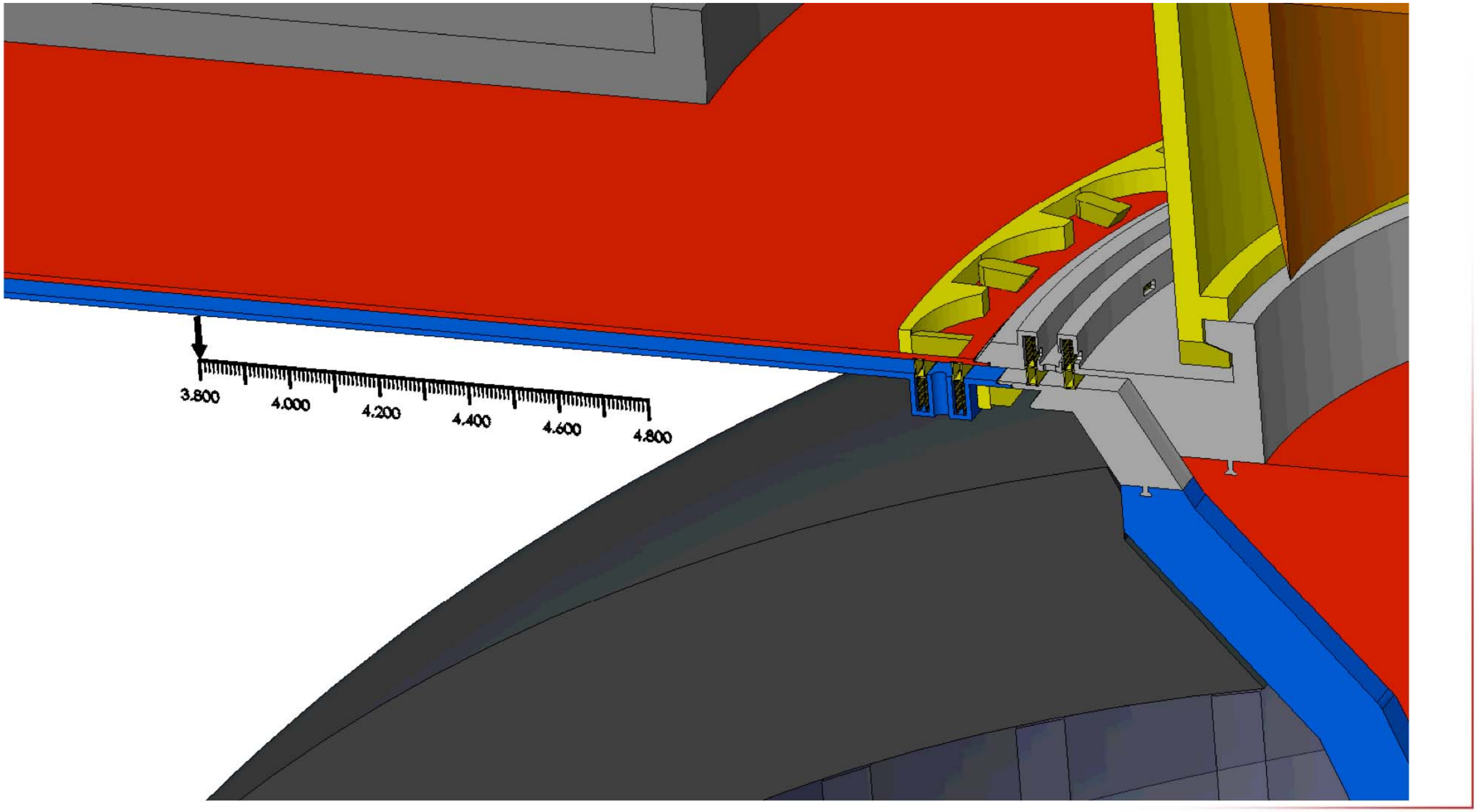
A pre-conceptual design for RTL-fusion chamber system



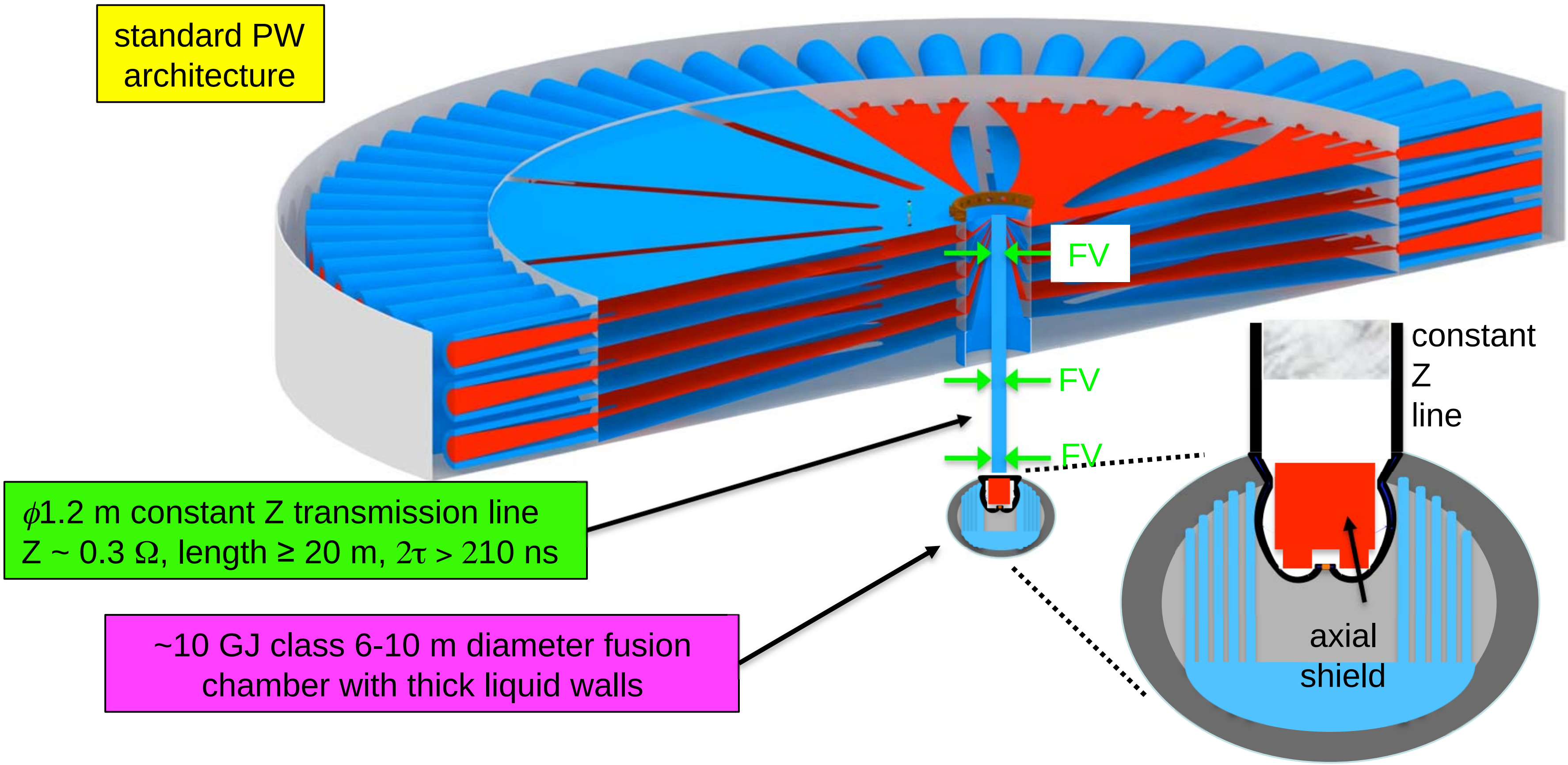
This design employed a number of features to provide RAMI:

1. Recyclable Transmission Line
2. A rapid shear and closure for isolation
3. Four additional annular fast closure valves
4. Long radial transmission lines with gaps > 1 cm
5. Thick liquid walls
6. Vaporizing blanket for axial shielding

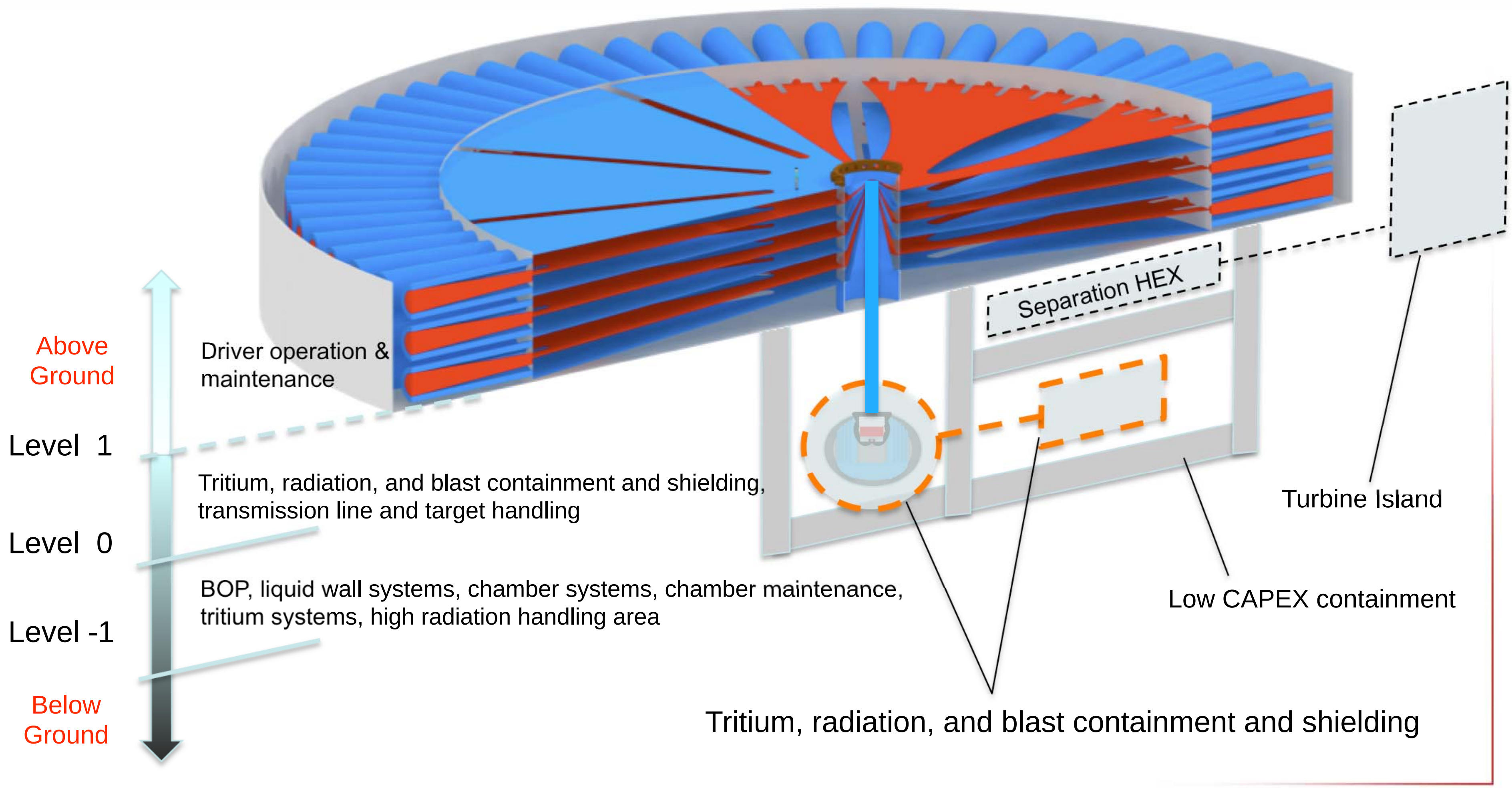
A pre-conceptual design for RTL-fusion chamber system



One idea uses long *axial* standoff and is compatible with the new PW facility architecture



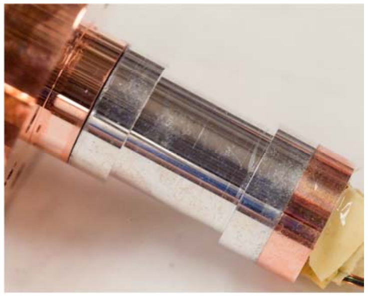
Plant functions are segregated on different levels to provide "defense in depth" and inherent safety



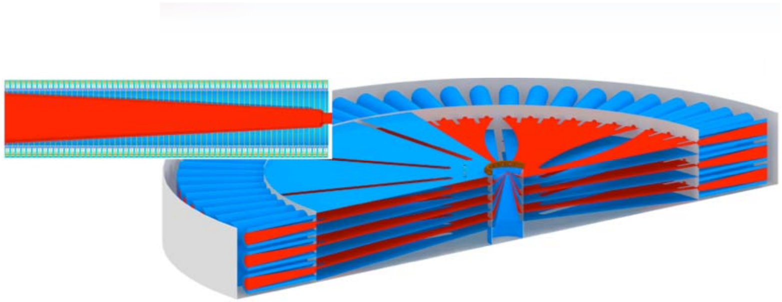
Sandia National Laboratories

Inertial fusion energy systems require integrated progress in four technical areas

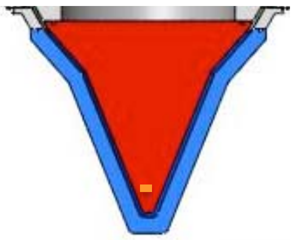
Target Physics



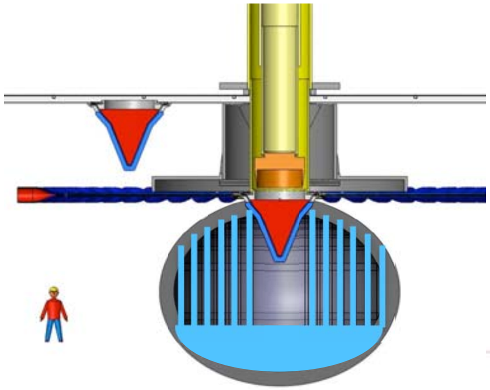
Driver Science and Engineering



IFE Pulsed Power Technology



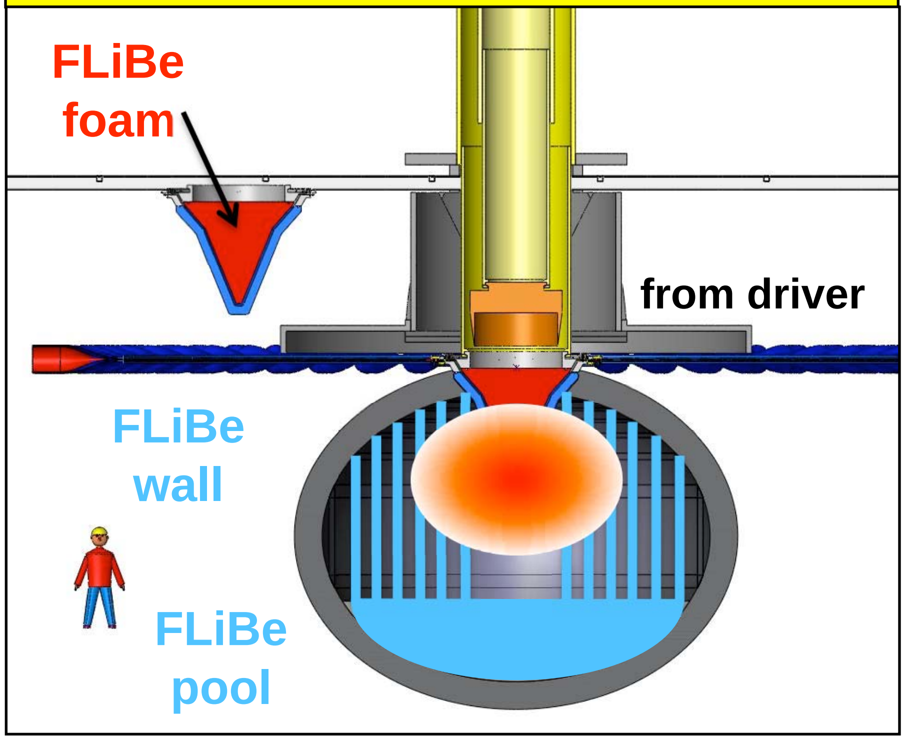
Fusion Nuclear Science



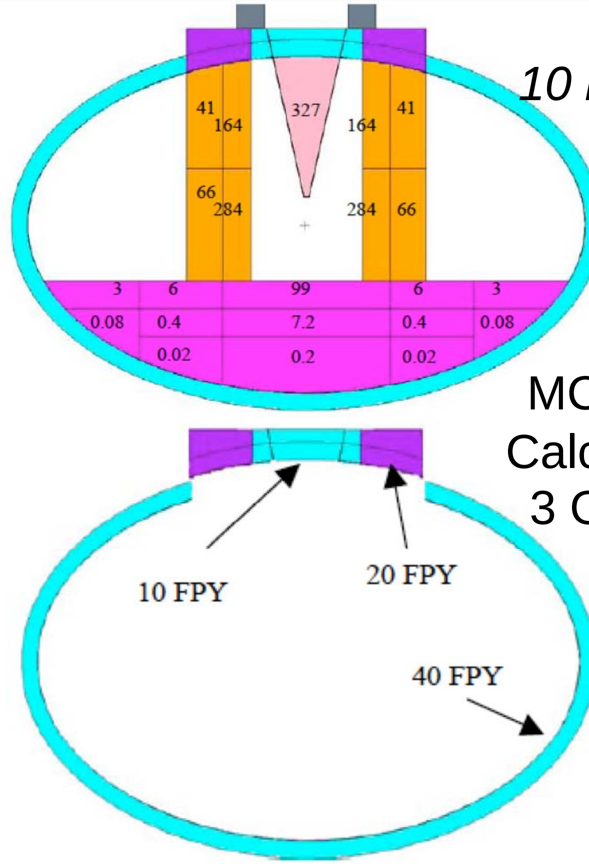
Sandia National Laboratories

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

Notional 3 GJ Design Circa 2006



10 m x 6 m

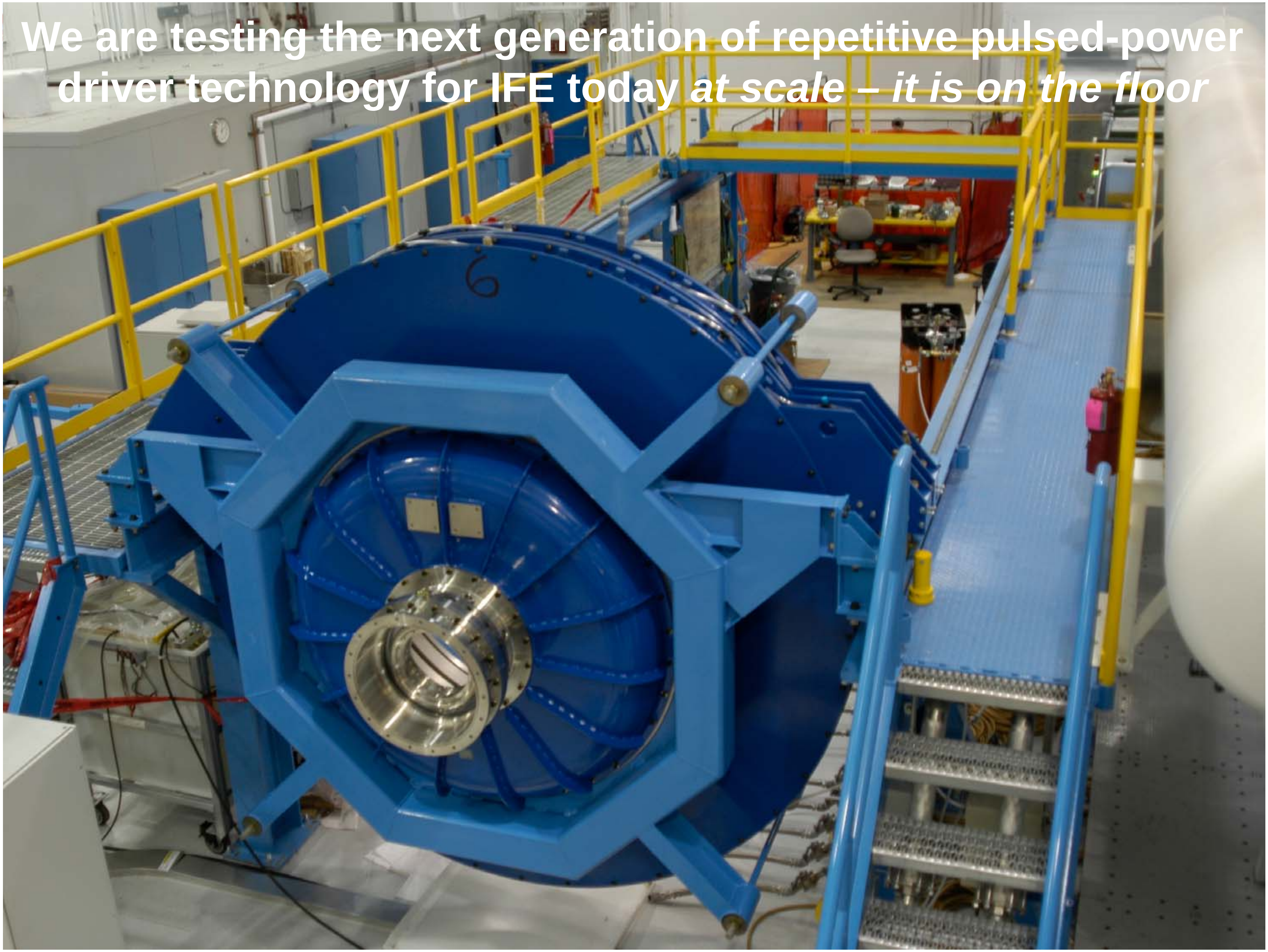


MCNP-3D Calculations 3 GJ yield

- Direct connection with pre-pumped, mechanically-rigid RTL allows thick liquid wall
- Thick liquid wall is a coolant-breeder-HeatEx material (FLiBe, Li, LiPb, LiSn, LiXX)
- Neutronics: 40 year lifetime chamber
- Thick wall/chamber is not very sensitive to details of fusion target output spectrum

Sandia National Laboratories

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



The logic of the pulsed power approach to IFE

- We have large stored energy (100 – 360 MJ) at potentially low cost (costs are under development)
- We could deliver large energy to targets (≥10% efficiency, 10 MJ, 10X other approaches)
- Large energy, larger target size may reduce target risk for high yields if convergence of targets is sufficient
- Natural geometry for target is cylindrical.
- Large yields implies can use a low rep-rate but still achieve high fusion power
- Use a direct connection of driver and target with a low cost, low mass recyclable transmission line
- RTL compatible with low rep-rate, thick liquid wall chambers for long chamber lifetime

Backup

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

Summary

Pulsed power is an efficient, inexpensive way to create matter at high energy densities

Magnetically driven implosions offer a path to coupling much higher fractions of the driver stored energy to fusion fuel

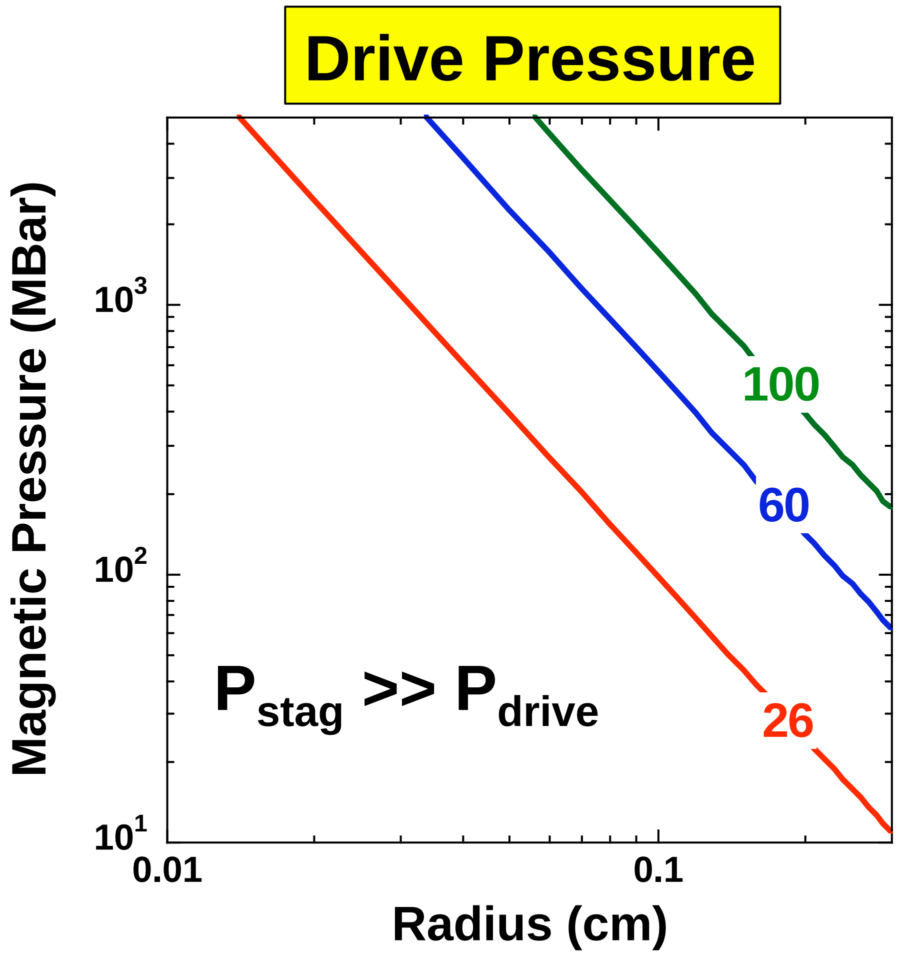
Magnetized Liner Inertial Fusion (MagLIF) offers a near term chance for testing our understanding of magnetically driven implosions. If successful, would lead to breakeven with DT.

Experimental data on the Magneto-Rayleigh Taylor instability is promising, we hope to do an integrated MagLIF test in 2012.

A high-yield (GJs), high-gain (>500) MagLIF design is under development. Much of the relevant physics can be tested on Z.

Sandia National Laboratories

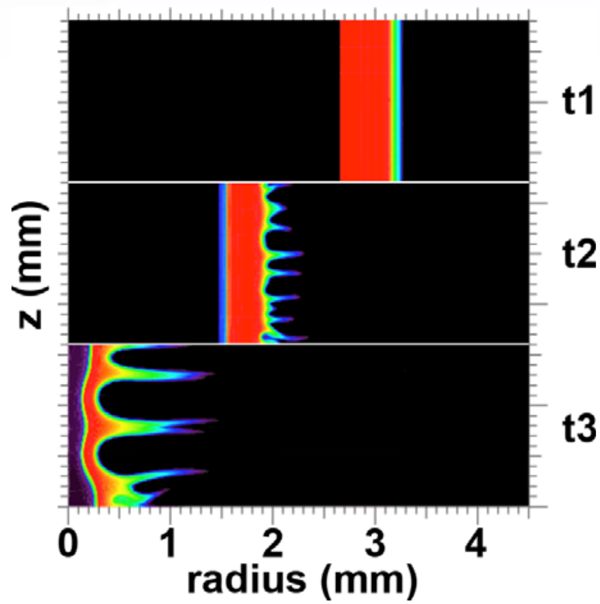
Multi-mega-Ampere currents produce high drive pressures and stagnation pressures

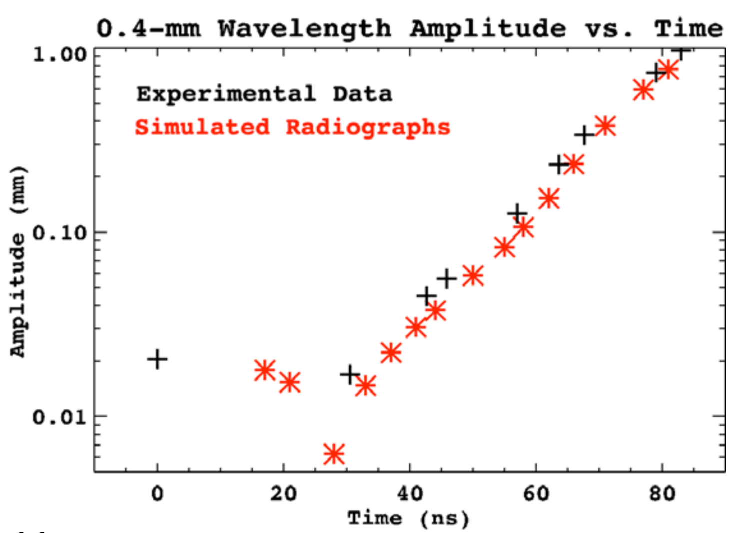


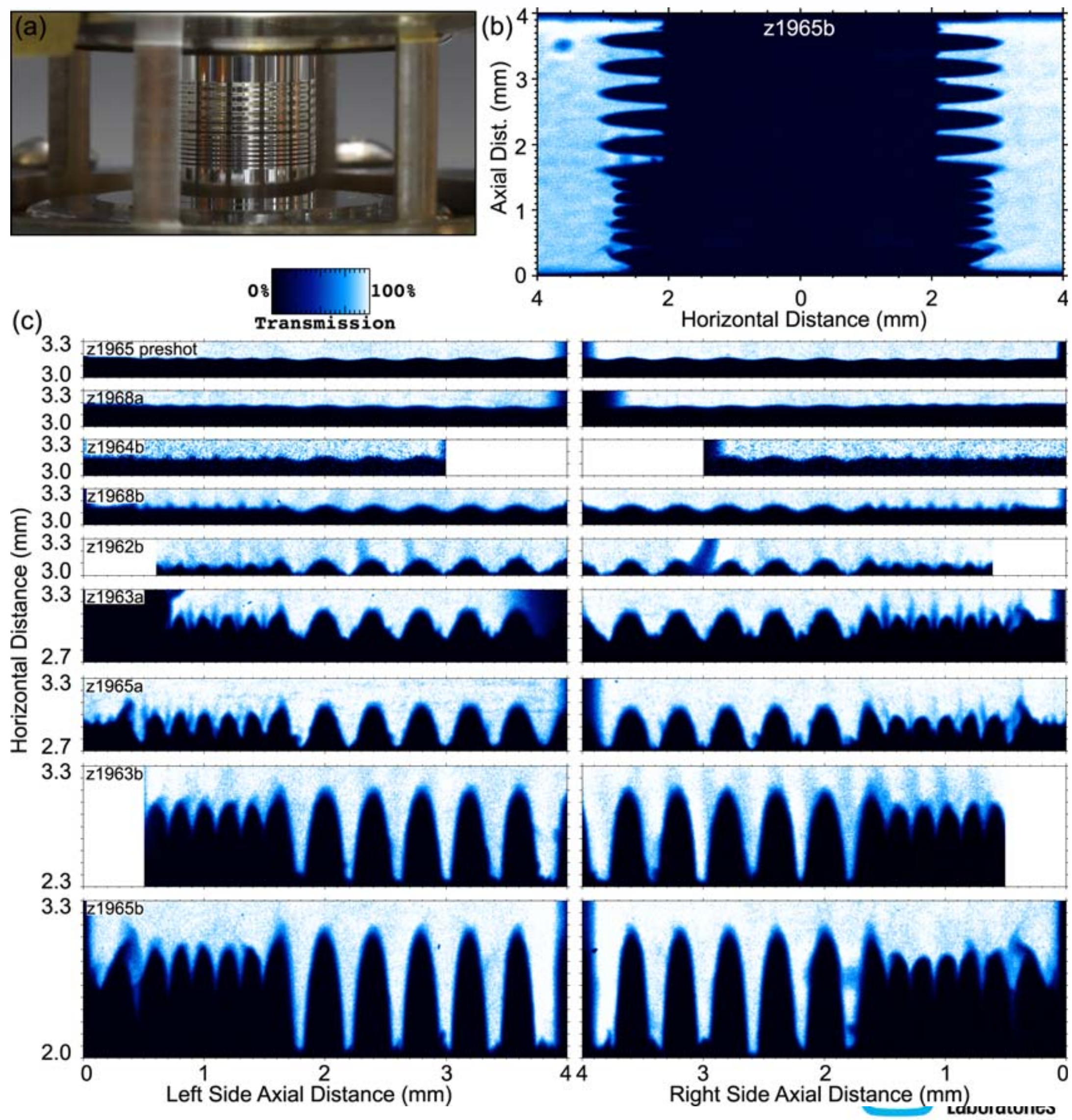
Sandia National Laboratories

D. Sinars *et al.*, Phys. Rev. Lett. (2010)
D. Sinars *et al.*, Phys. Plasmas (2011)

We observe excellent agreement between theory and experiment for single-mode MRT growth experiments

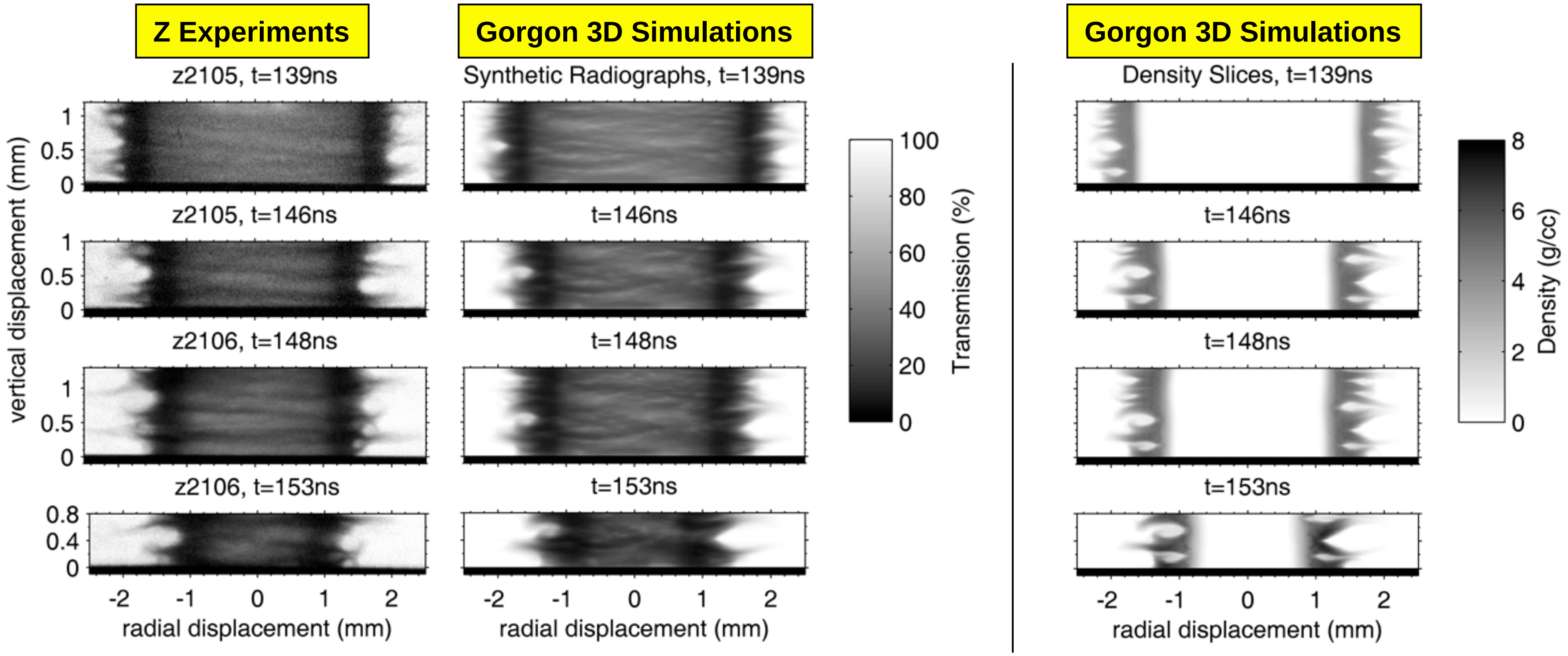






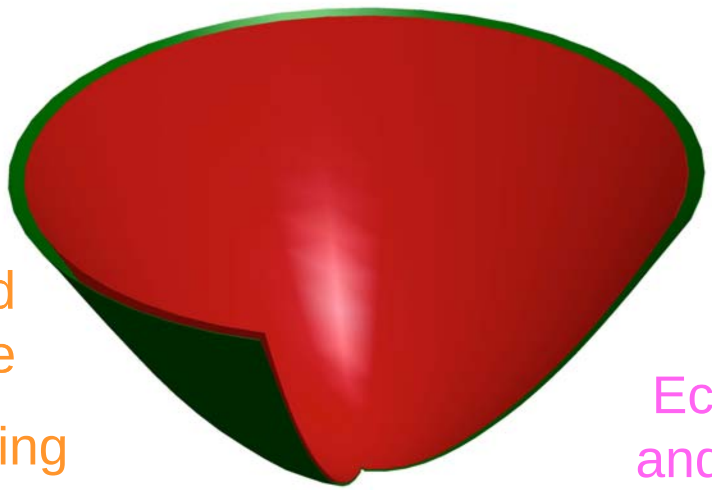
R. McBride *et al.*, IHED, (2011)

We see excellent agreement between theory and experiments for multi-mode MRT growth experiments



Sandia National Laboratories

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



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

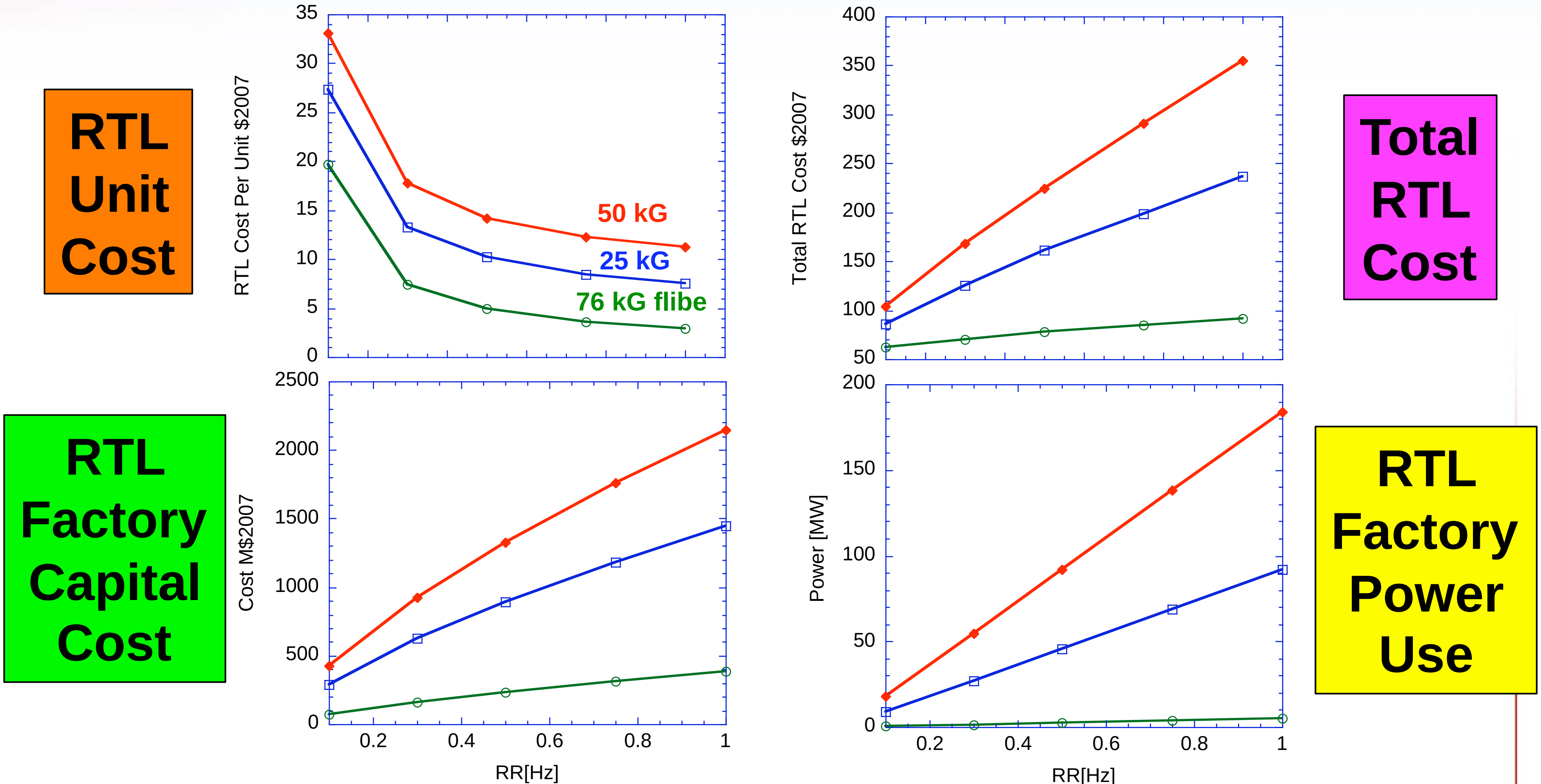
The cost of the RTL (and the target) can be thought of as a fuel cost and must be economic

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

- At 1 GJ_e/pulse, 8.5 ¢/$kWhr_e$, up to 25$/pulse can be spent on "consumables" (10% of value of electricity)
- Example "fuel" costs
  - Stamped steel RTL's at 25 - 50 kG and 0.1 Hz = $2-4/$MWhr_e$
  - Nuclear plants raw fuel costs ~ $3.50 to $5.50 per $MWhr_e$
  - Coal ~ $10 to $13.20 $/$MWhr_e$

Sandia National Laboratories

The optimal rep-rate R for a pulsed power system is determined by a number of factors



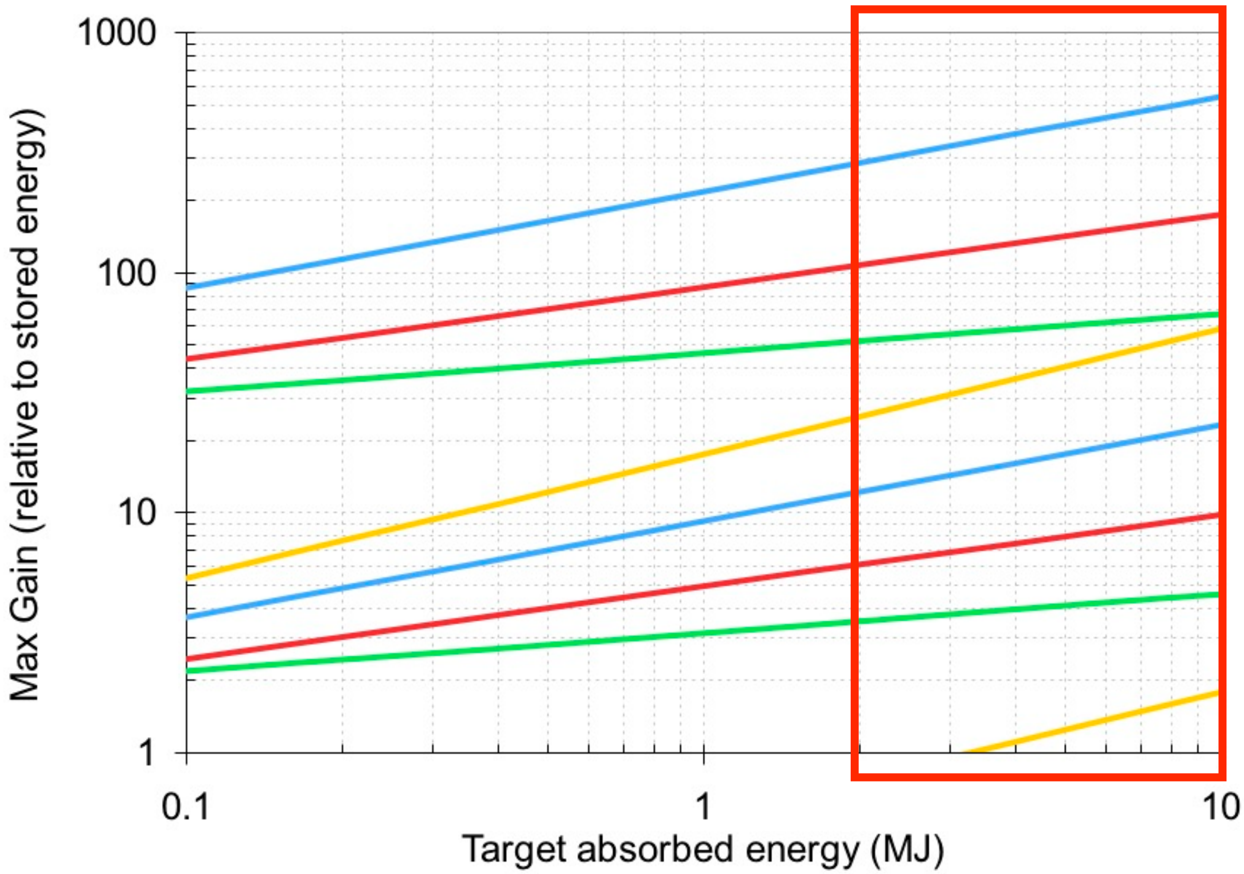
- Target gain – favors higher rep-rate
- Rate of feasible installation – favors 0.1 Hz, but new ideas may increase
- Total mass throughput and rate of mass throughput – favors 0.1 Hz
- Waste production – favors fewer units, 0.1 Hz

Sandia National Laboratories

High gain pulsed-power-driven IFE targets will absorb > MJ by design

$E_{storage}=$			
	57.1 MJ	285.7MJ	Conservative
	14.8 MJ	74.1 MJ	Optimistic

$Q_{facility}$

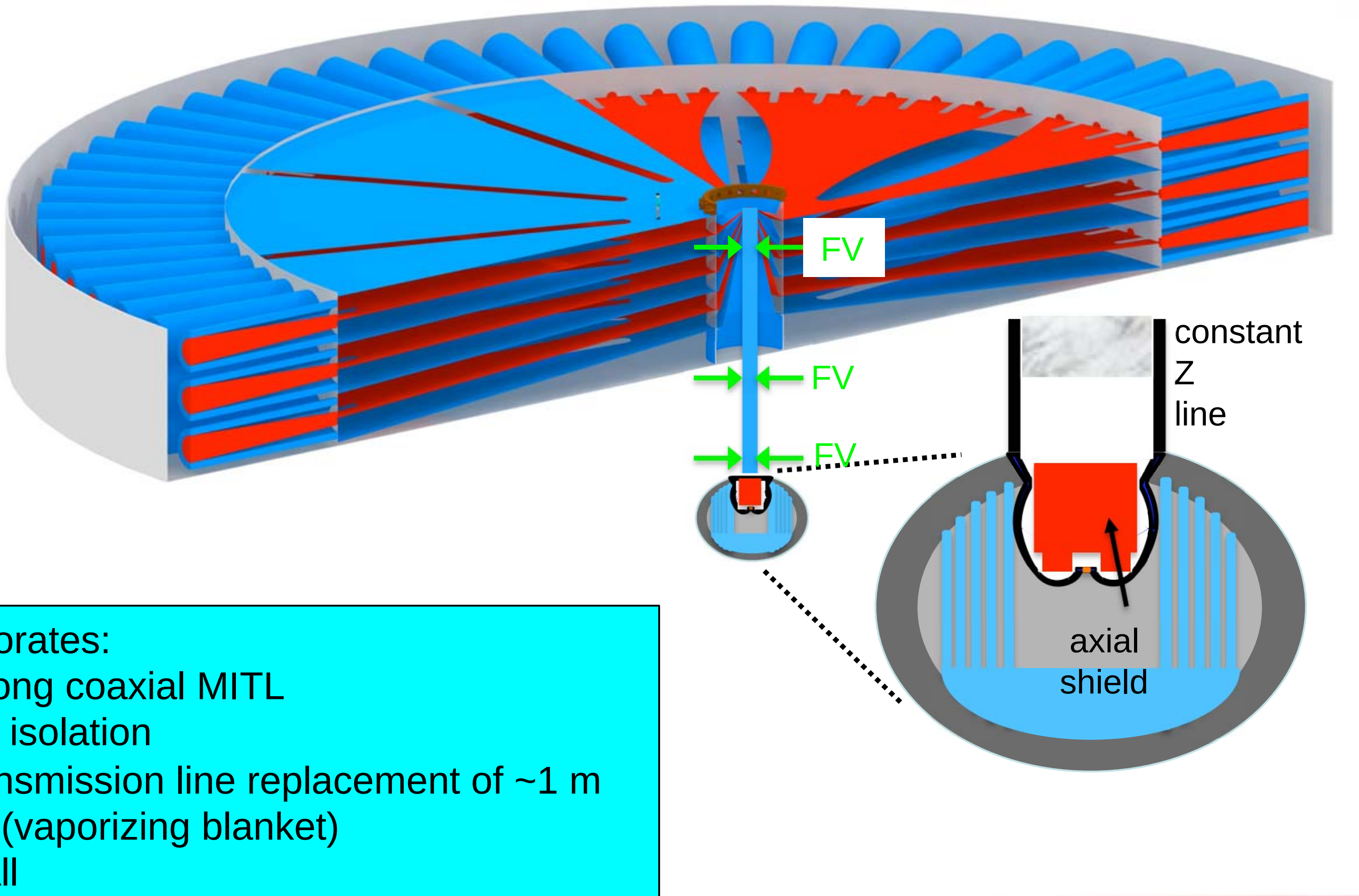


Optimistic
(upper lines)
$\alpha_{fuel} = 1.5$
$\eta_{target\text{-}fuel} = 0.25$
$\eta_{load\text{-}target} = 0.45$
$\eta_{stored\text{-}load} = 0.3$
$\eta_{total} \sim 0.0338$

Conservative
(lower lines)
$\alpha_{fuel} = 3.0$
$\eta_{target\text{-}fuel} = 0.125$
$\eta_{load\text{-}target} = 0.35$
$\eta_{stored\text{-}load} = 0.1$
$\eta_{total} \sim 0.0044$

Sandia National Laboratories

One idea uses long *axial* standoff and is compatible with the new PW facility architecture



System incorporates:
Standoff with long coaxial MITL
Fast valves for isolation
Recyclable transmission line replacement of ~1 m
Axial deflector (vaporizing blanket)
Thick liquid wall
Target is shielded from a direct line of sight to driver

The physics issues for direct magnetic-drive targets are similar to those for other inertial fusion concepts

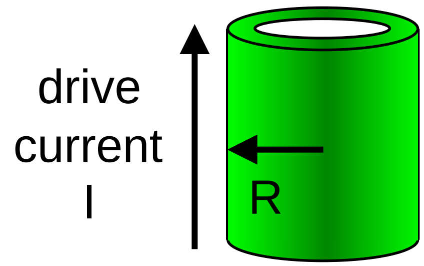
Stabilization techniques

Instability growth

Fuel Preheat

Convergence ratio

Fuel Premagnetization



Implosion time and velocity

Driver coupling

Pusher-fuel mix

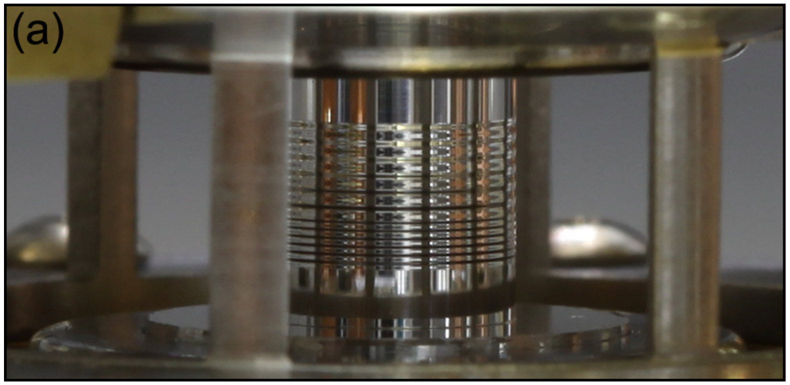
Pusher adiabat

r-θ symmetry

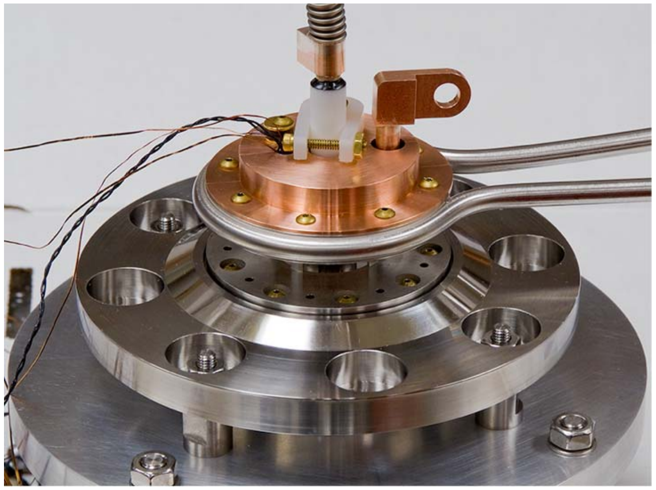
- We are conducting a vigorous research program to validate the general class of magnetically-driven targets on the Z facility at the MJ target scale

Sandia National Laboratories

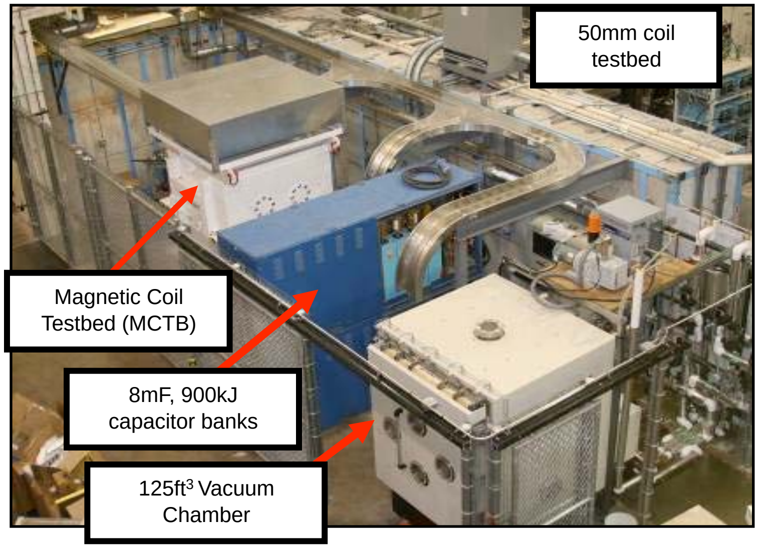
We have already developed most of the capabilities required to test MagLIF on the Z facility, rest are imminent



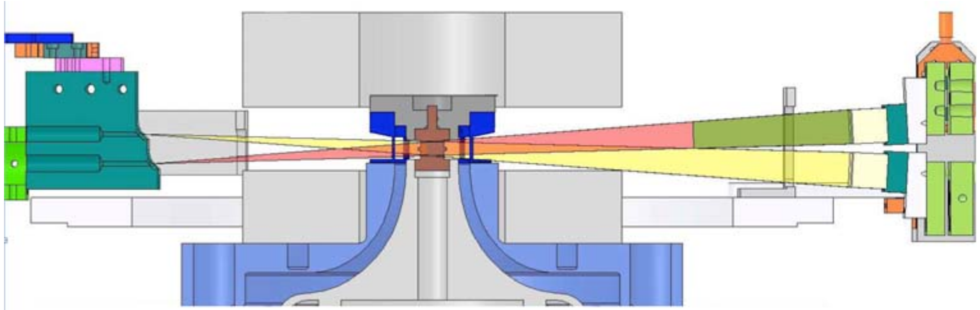
High-quality target fabrication on site



Cryogenic cooling of liner targets has been demonstrated (liquid D2)



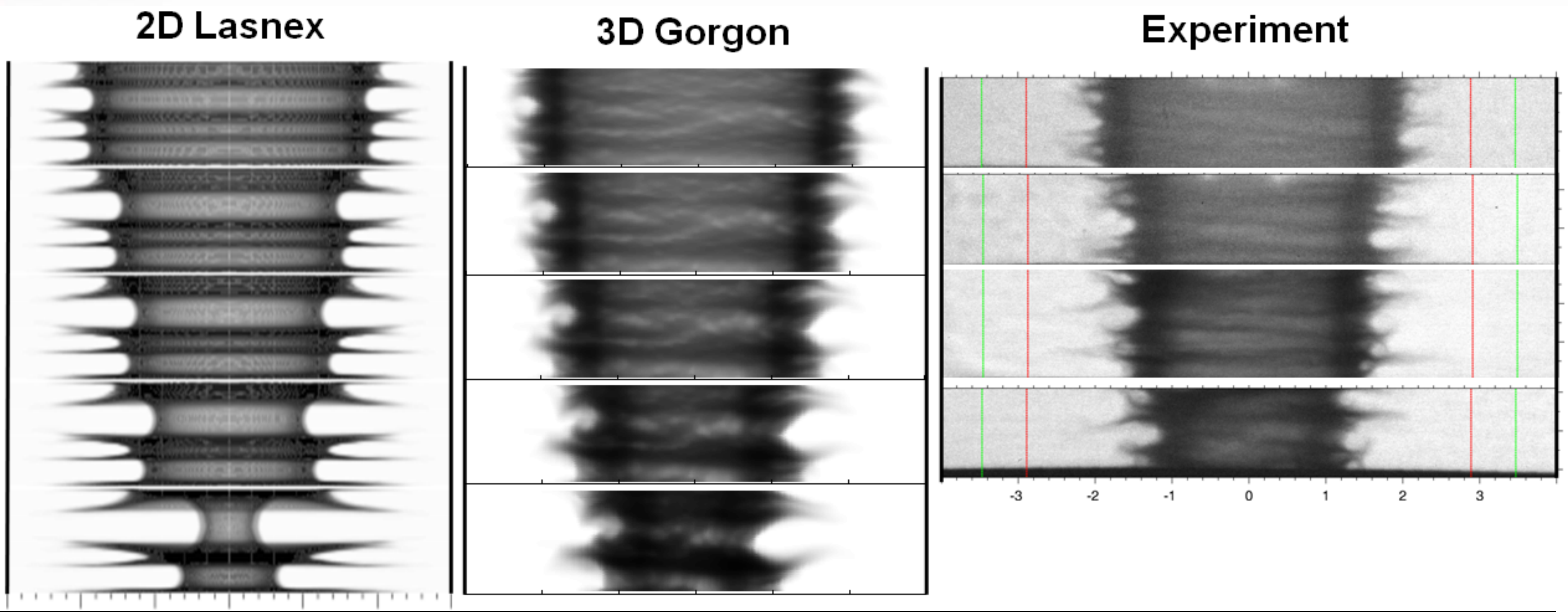
Test facility for coil development on site



10 T coil designs allowing diagnostic access on Z will be tested

Sandia National Laboratories

3D simulations show a lower growth rate than 2D simulations



- 2D calculations of wire-array z-pinch implosions overestimate growth rates for MRT instability not seen in 3D calculations and experiments [e.g., Yu *et al.*, Phys. Plasmas 15, 056301 (2008).]
- 2D calculations of liner z-pinch implosions likewise overestimate MRT growth compared to 3D simulations and experiments
- 2D calculations tend to predict extreme on-axis conditions (as in 1D)

Sandia National Laboratories

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

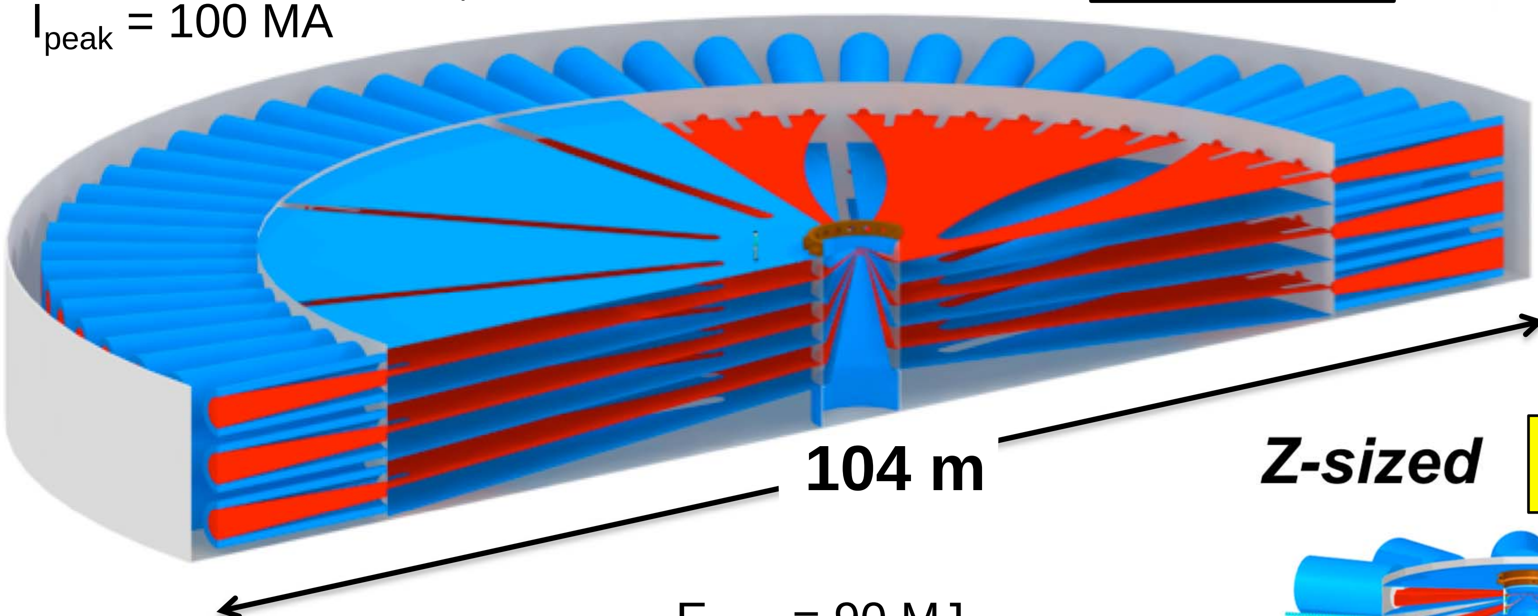
If targets can be driven at lower electrical power the facility size can be decreased significantly

E_{store} = 360 MJ

I_{peak} = 100 MA

τ_{imp} = 100-130 ns

2000 TW

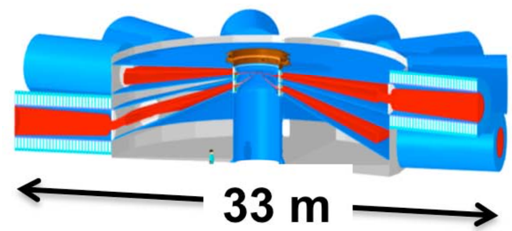


Z-sized **130 TW**

E_{store} = 90 MJ

I_{peak} = 60 MA

τ_{imp} = 300 ns

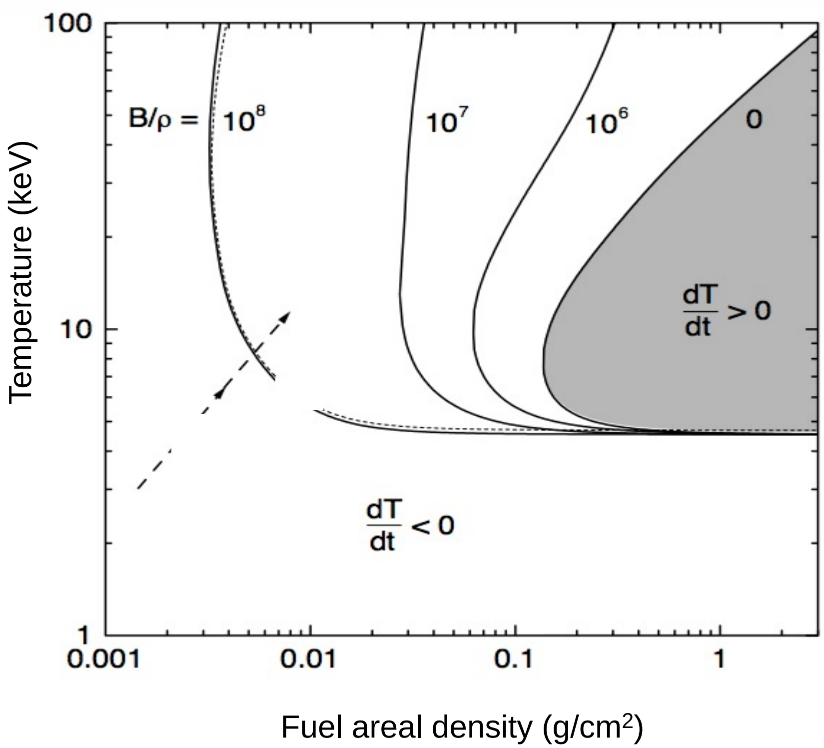


Targets physics experiments will consider performance of longer drives

Sandia National Laboratories

A large, embedded magnetic field significantly expands the space for fusion self heating

*Basko et al. *Nuc. Fusion* 40, 59 (2000)



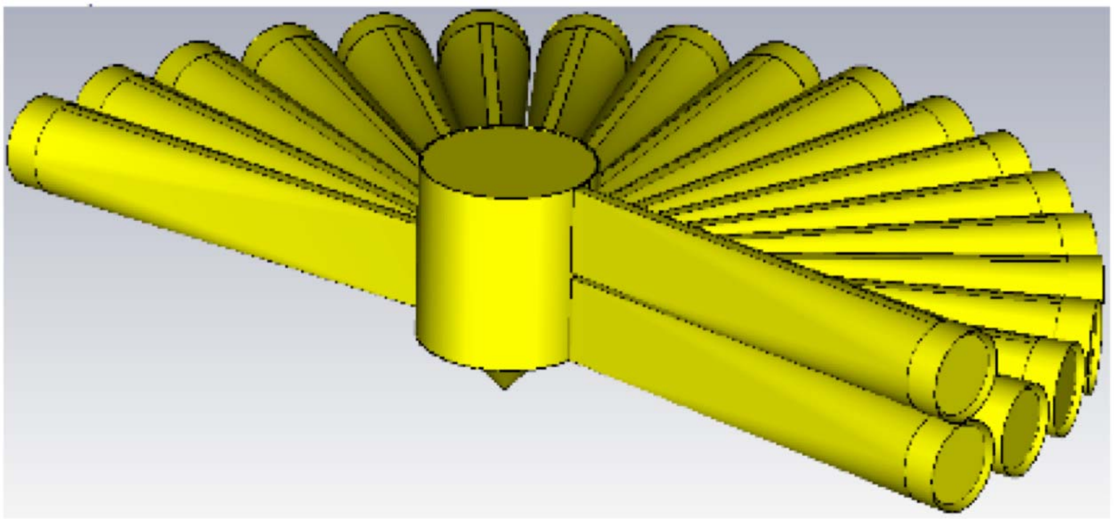
The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field

- inhibits electron conduction
- enhances confinement of alpha particles

Lower ρr means low densities are needed (~1 g/cc << 100g/cc)

Pressure required for ignition can be significantly reduced to ~5 Gbar
(<< 500 Gbar for hotspot ignition)

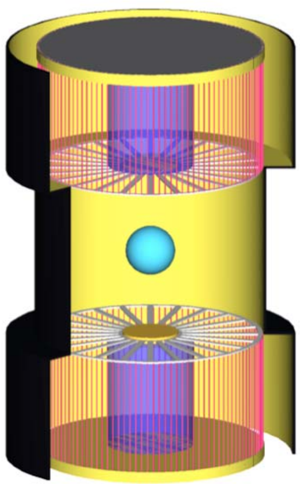
Other module addition methods could prove more robust

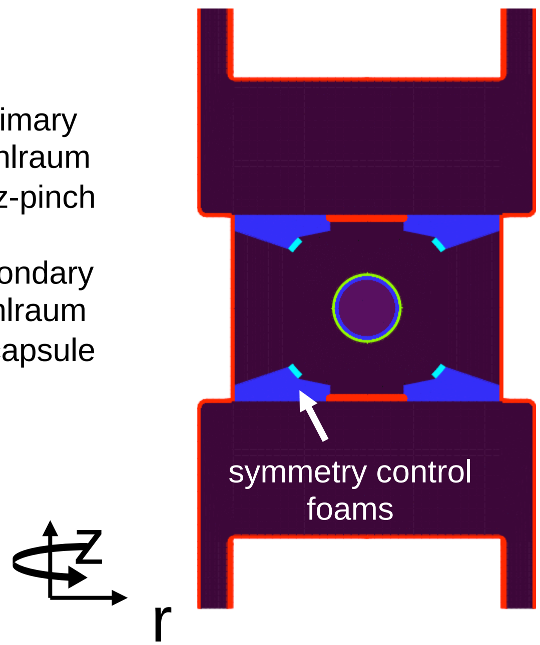


Integrated LASNEX simulations demonstrate 400+ MJ fusion yield in a pulsed-power z-pinch driven hohlraum

Double z-pinch hohlraum fusion concept

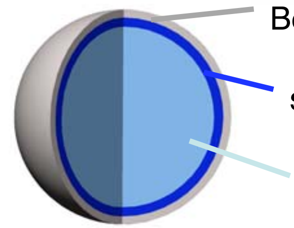
R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)



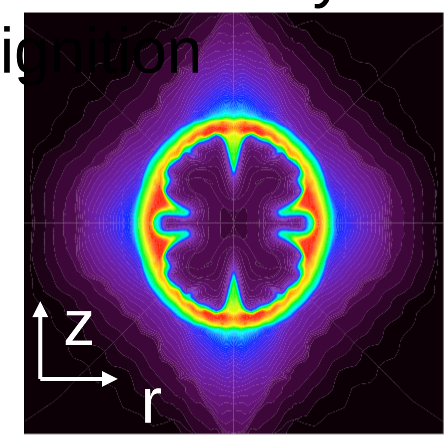


Inefficiencies lead to only 0.04% of the driver wall plug energy in the fusion fuel

High yield capsule design



Fuel density at ignition



1D capsule yield 520 MJ
2D integrated yield 470 MJ

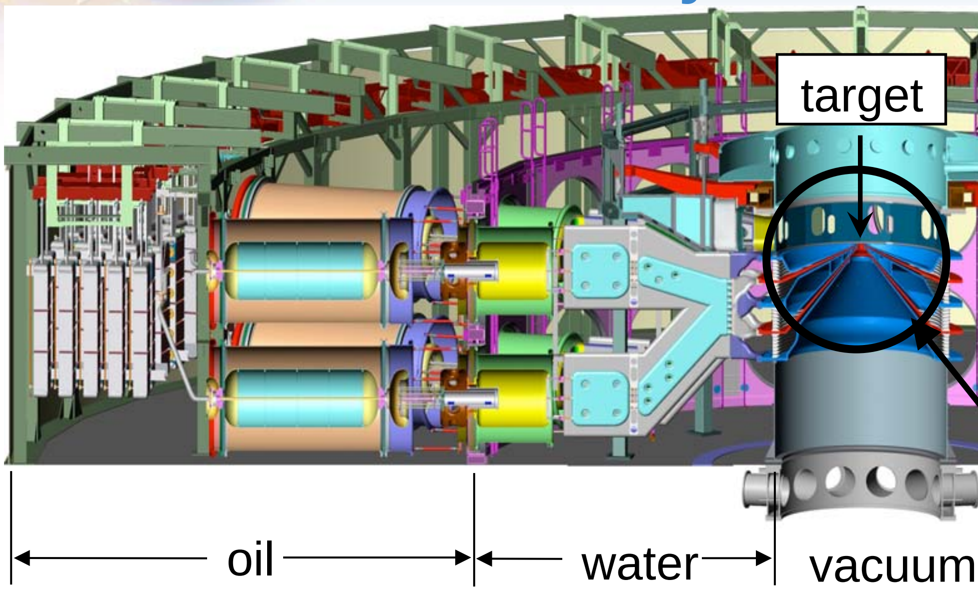
Sandia National Laboratories

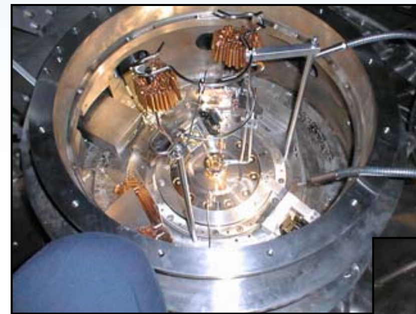
What are the unique aspects of pulsed power IFE?

- Z is a robust technology that can efficiently couple 2 MJ's of energy to fusion targets
- Refurbished Z was cost effective (~$40/Joule at the load)
- New pulsed power architectures based on Linear Transformer Drivers (LTD's) are rep-rateable, efficient, and cost effective
- Targets directly driven by magnetic fields are a new idea we are exploring that improves the efficiency of coupling energy to the fuel by up to 50X
- It is feasible that pulsed power can deliver 10X the total energy to the fuel as other concepts
- Our pulsed power IFE concept uses large yields, low rep-rates, and thick liquid walls

Sandia National Laboratories

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

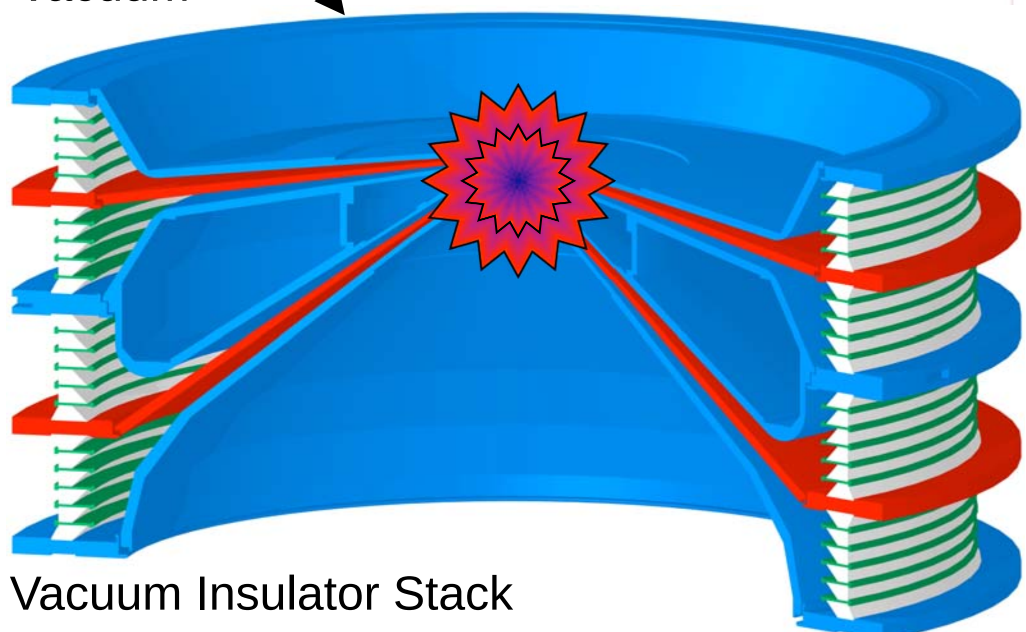




Before

After 2 MJ

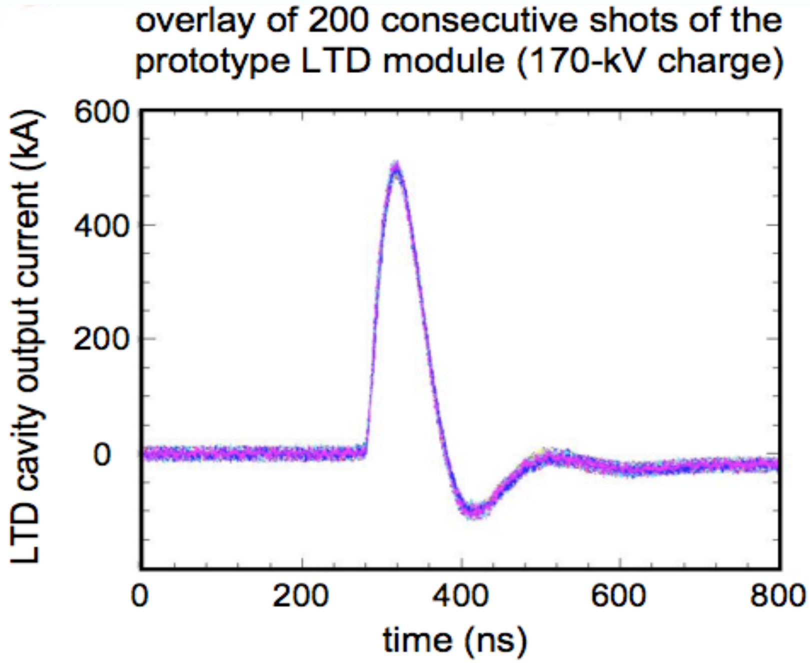
- Under normal single shot operations the middle 30 cm is replaced every shot – some parts are refurbished and reused
- With high yield single shot operation more of the center would have to be replaced
- With repetitive high yield an automated replacement of the these target and transmission line components is needed
- For economic fusion power generation the part has to be recyclable



Vacuum Insulator Stack
(sensitive component)

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.

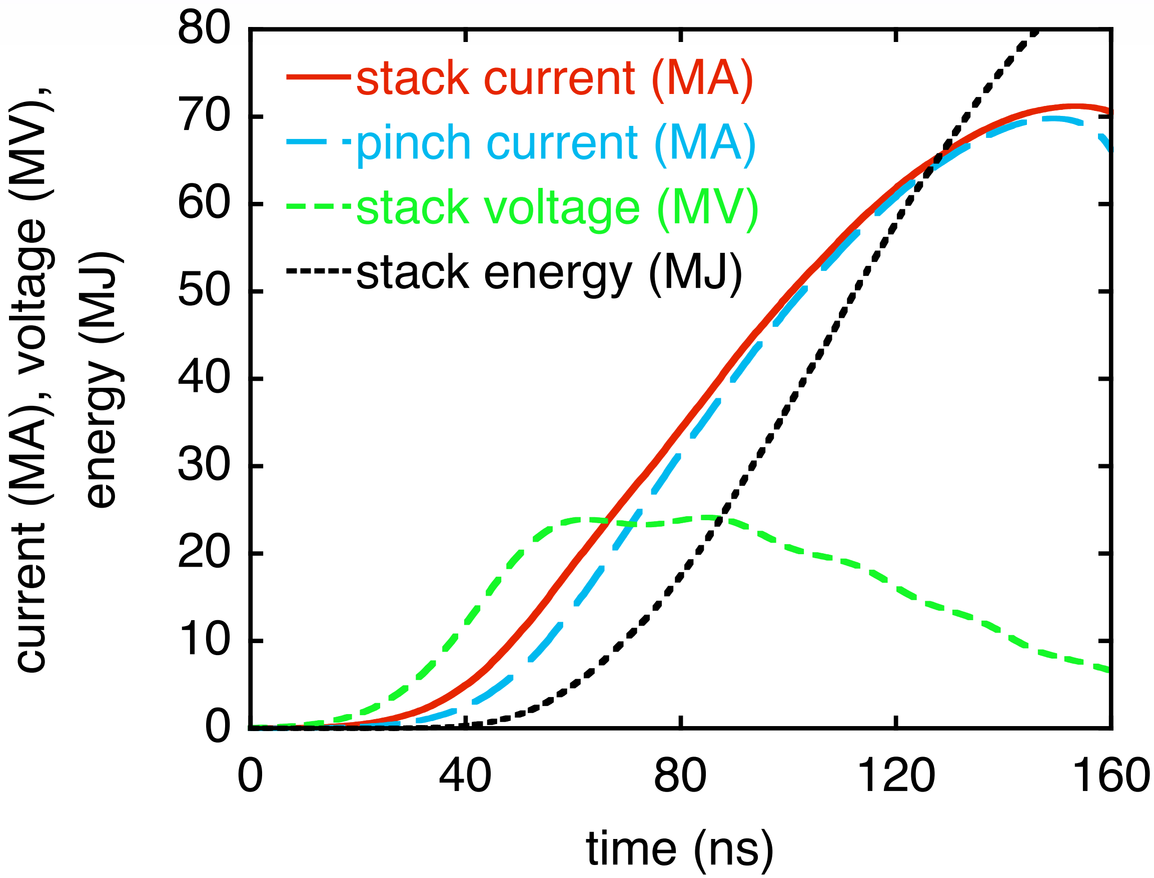


- timing jitter = 2 ns (1σ)
- voltage and current reproducibility = 0.3% (1σ)
- peak power = 0.05 TW
- output energy = 6 kJ
- electrical efficiency = 70%
- random switch failure < 7×10^{-6}

Sandia National Laboratories

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

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



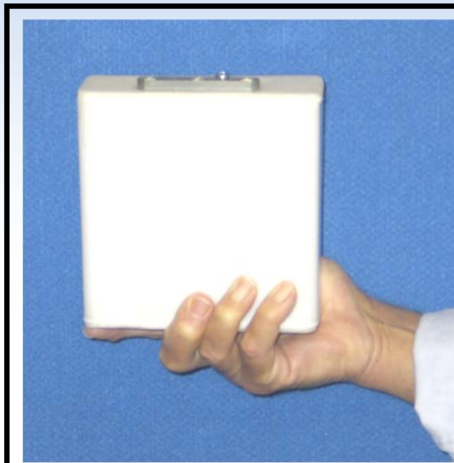
- Coupling efficiencies of magnetic energy to the load region of 15% have been demonstrated
- Our goal is to increase coupling efficiencies to the load region up to > 30%

Sandia National Laboratories

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

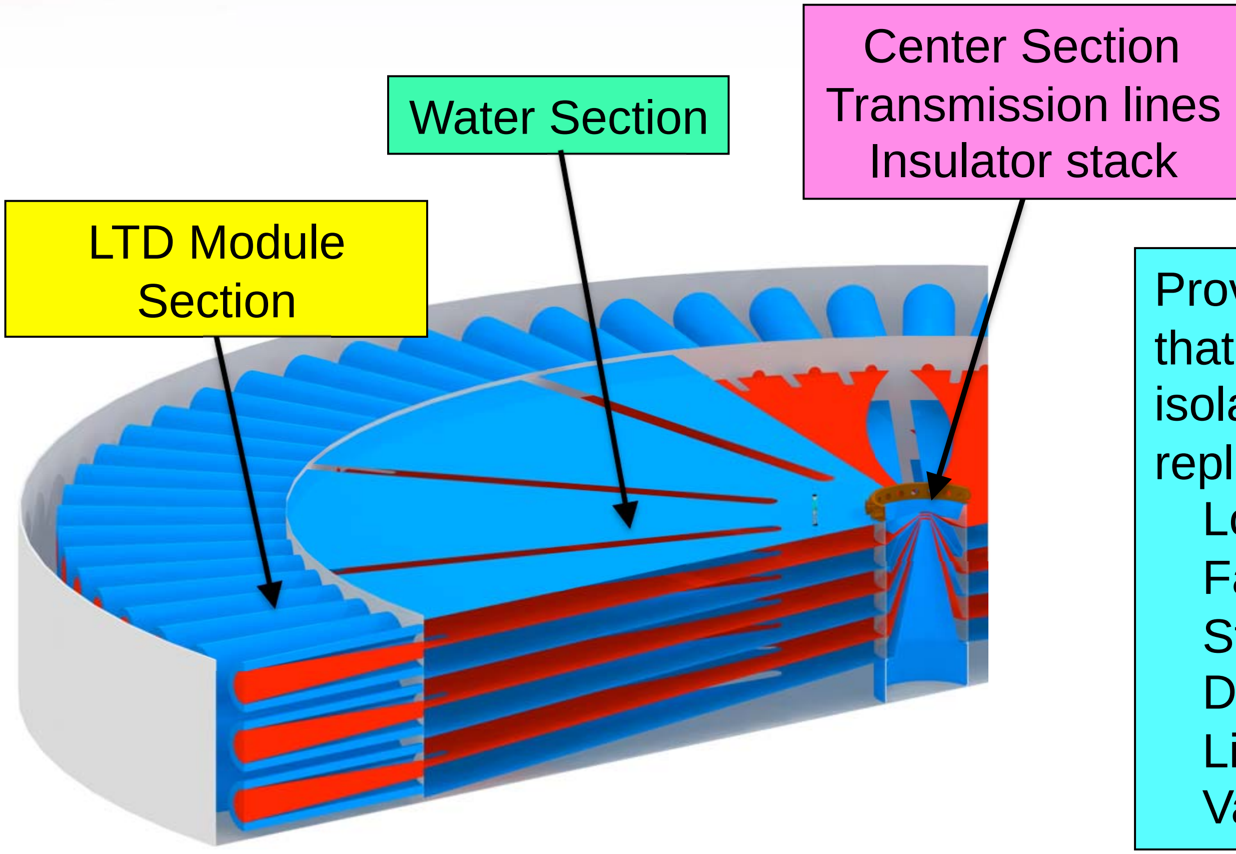
80-85% Learning curves: <$2 to 4/Joule

- 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 on given days

Sandia National Laboratories

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



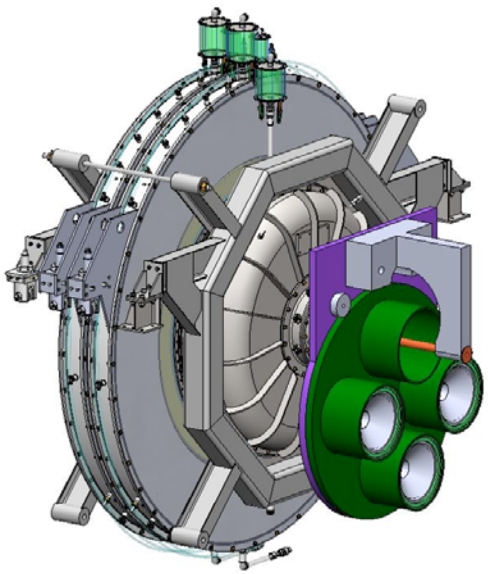
Provide RAMI with systems that have standoff and isolation, and that are replaceable and recyclable:

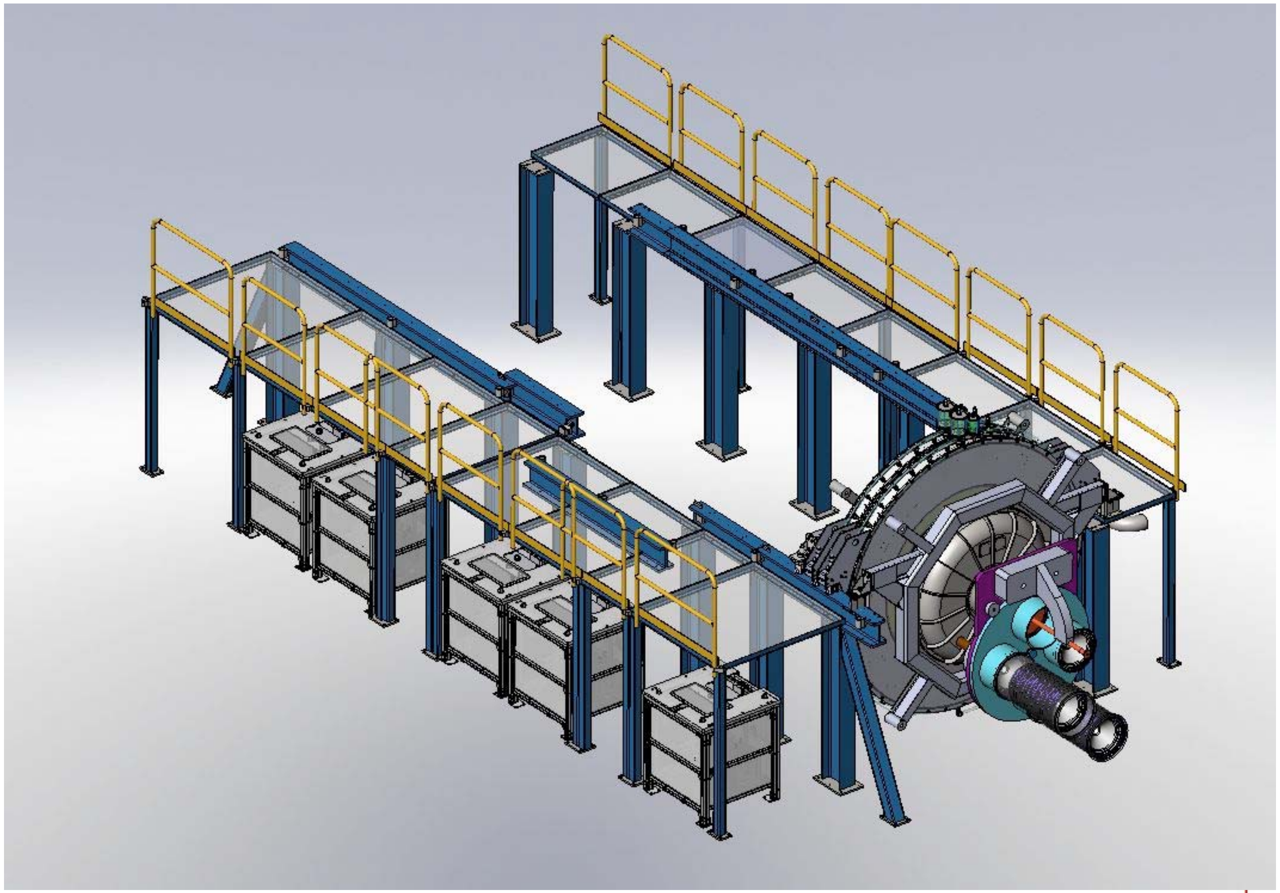
- Low cost, low mass RTLs
- Fast closures or valves
- Standoff
- Deflection
- Liquid wall
- Vaporizing blanket

- Highly modular driver architecture optimized for single shot NNSA missions
- We will build on solid pulsed power science and technology foundation to develop integrated architectures tolerant of GJ yield events

Sandia National Laboratories

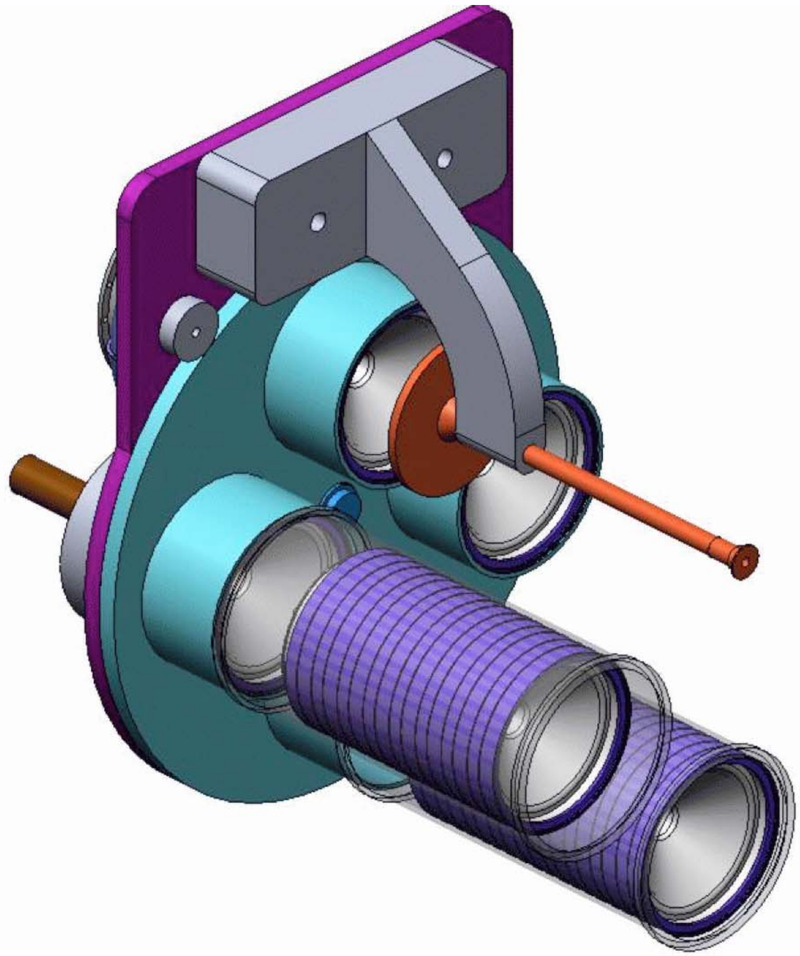
Pre-conceptual design of a replaceable transmission line system for LTD test module





"Four-shooter"

The new concept may allow a higher repetition rate



The MYKONOS LTD module demonstration experiment has several goals

- Can we demonstrate a rep-rated driver-target coupling with an RTL on any scale?
- New physics for repetitive MITL's – cleaning and conditioning will allow improved power flow performance by reducing plasma formation
- What are the system integration issues?
  - power flow, current contacts at scaled conditions
  - automation and control systems
  - installing and removing low mass RTLs
  - manufacturing low mass RTL's
  - fast closing valves (~ 0.1 – 1 ms for 1 cm gaps)
  - fast vacuum pumping and staging requirements
- Develop annular fast closing valves of different designs with industrial partners
- What is the fastest rep-rate that current technology can support?
- Are there new approaches that can increase the rep-rate by factors of 2-3?

Sandia National Laboratories

Experiments on LTD test bed, Z, and a full size mechanical laboratory demonstration can test the physics and engineering scaling of RTLs adequately

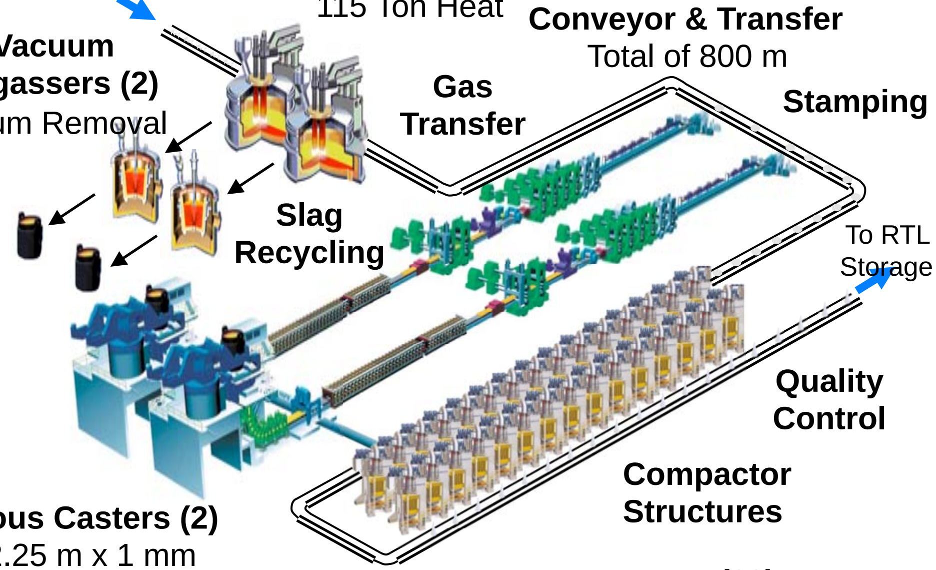
Facility	Magnetic Energy (MJ)	Peak Current (MA)	Diameter (cm)	Linear Current Density (kA/cm)	Rep-rate
LTD test bed	0.05	1	46	1 – 7	**0.03 – 0.1**
Z	2	25	30	**150 – 250**	Sequential single shots
Full size mechanical mock up	NA	NA	100 – 200	NA	**0.1 –0.3**
Requirement	10 – 20	60 – 100	100 – 200	**100 – 320**	**0.1**

Sandia National Laboratories

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

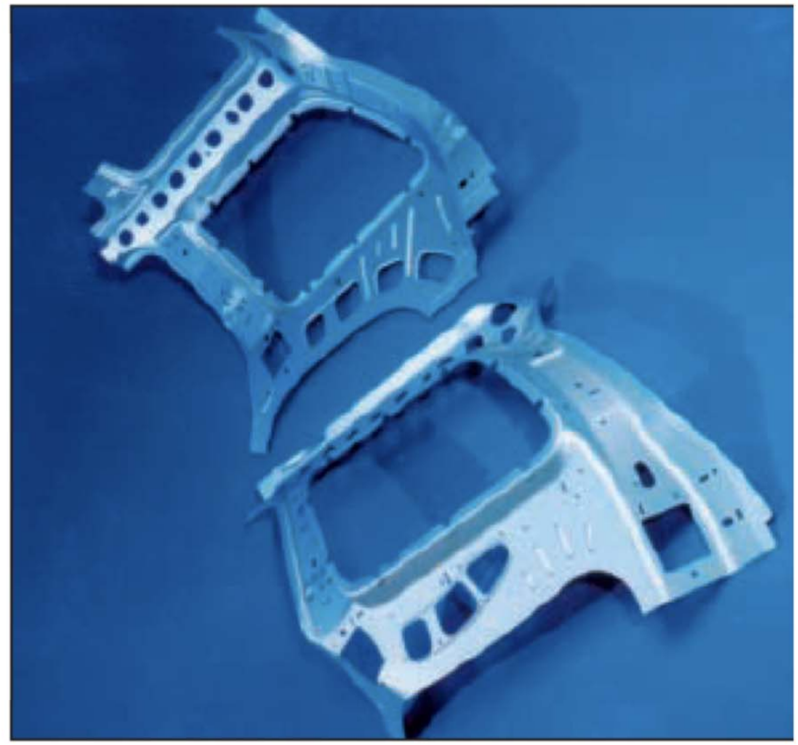


- Highly efficient electric arc furnace, automated continuous sheet casting, automated stamping and transfer press, automated RTL assembly with targets, vacuum pumping and storage, post shot automated steel recovery and de-tritiation systems
- Need to develop design of full scale production line with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

MetalForming (2000)

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

Sandia National Laboratories