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1 April 2011

Pulsed Power IFE
Background, Phased R&D, and Roadmap

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

April 1, 2011 Albuquerque, New Mexico

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Topics

- Background of pulsed-power IFE concept
- Synergies with NNSA programs
- Answer outstanding questions from San Ramon
- Path forward with phased R&D
- Vision for pulsed power IFE
- Planned phase 1 research and funding needed

Outstanding questions from San Ramon

- How does the target concept work?
- How does the driver-target coupling concept work?
- How will we mitigate and control the impacts of large fusion yields on the driver and coupling (~10 GJ)
  - debris
  - shock or blast
  - neutrons (80% of the energy deposition)
- What is the goal of the small scale LTD test bed experiment?
- How do you propose to demonstrate feasibility and the key science and technology goals?

What are the unique aspects of pulsed power IFE?

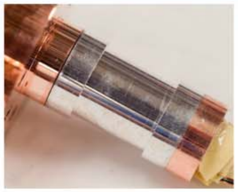
- Z is a robust technology that can efficiently couple 2 MJ's of energy to fusion targets
- Refurbished Z was cost effective (~$40/Joule at the load)
- New pulsed power architectures based on Linear Transformer Drivers (LTD's) are rep-rateable, efficient, and cost effective
- Targets directly driven 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

Progress needs to be made in four technical areas

NNSA

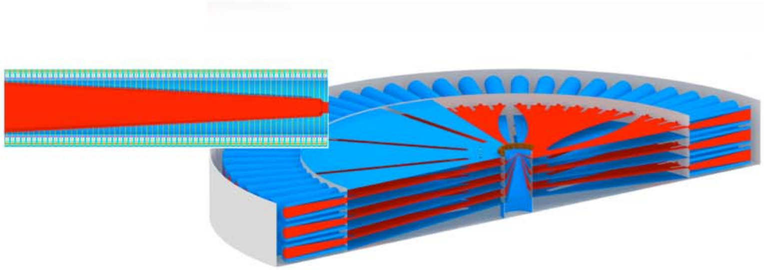
Target physics

- Ignition and high gain
- Validated models



Driver science and engineering

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



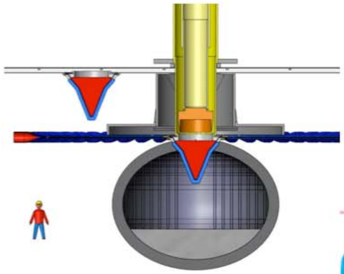
IFE

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



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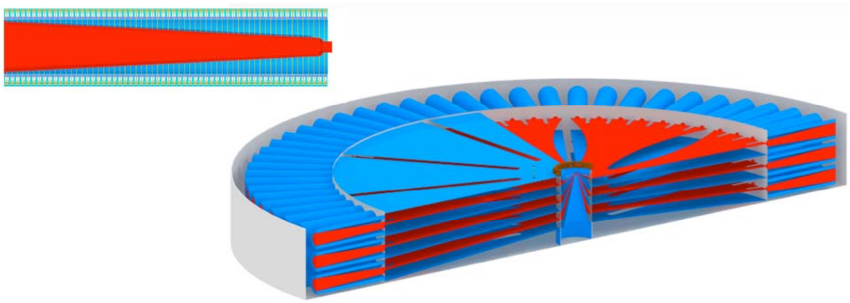
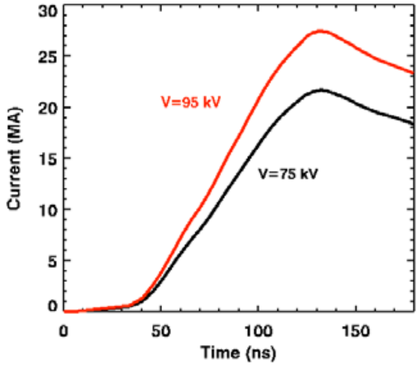
We reviewed these areas at a high level in San Ramon

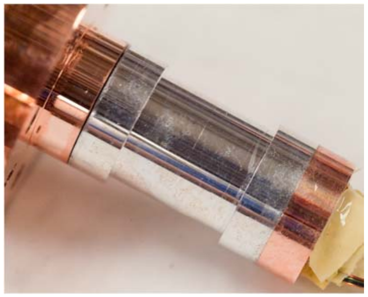
Rep-rate Linear Transformer Drivers (LTD)



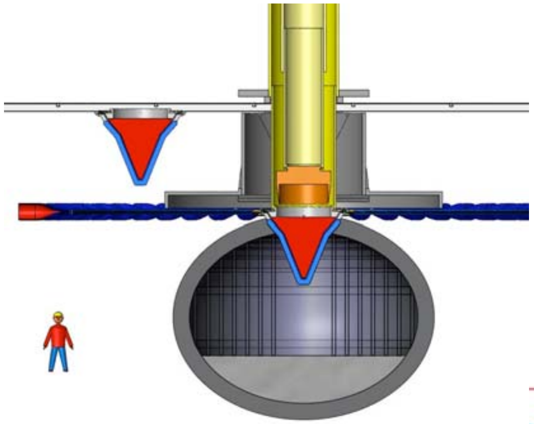
Coupling
Recyclable Transmission Lines (RTLs)

Direct Drive Target Physics





Thick Liquid Wall (TLW)
Fusion Chambers



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NNSA and IFE goals are synergistic in many areas

NNSA

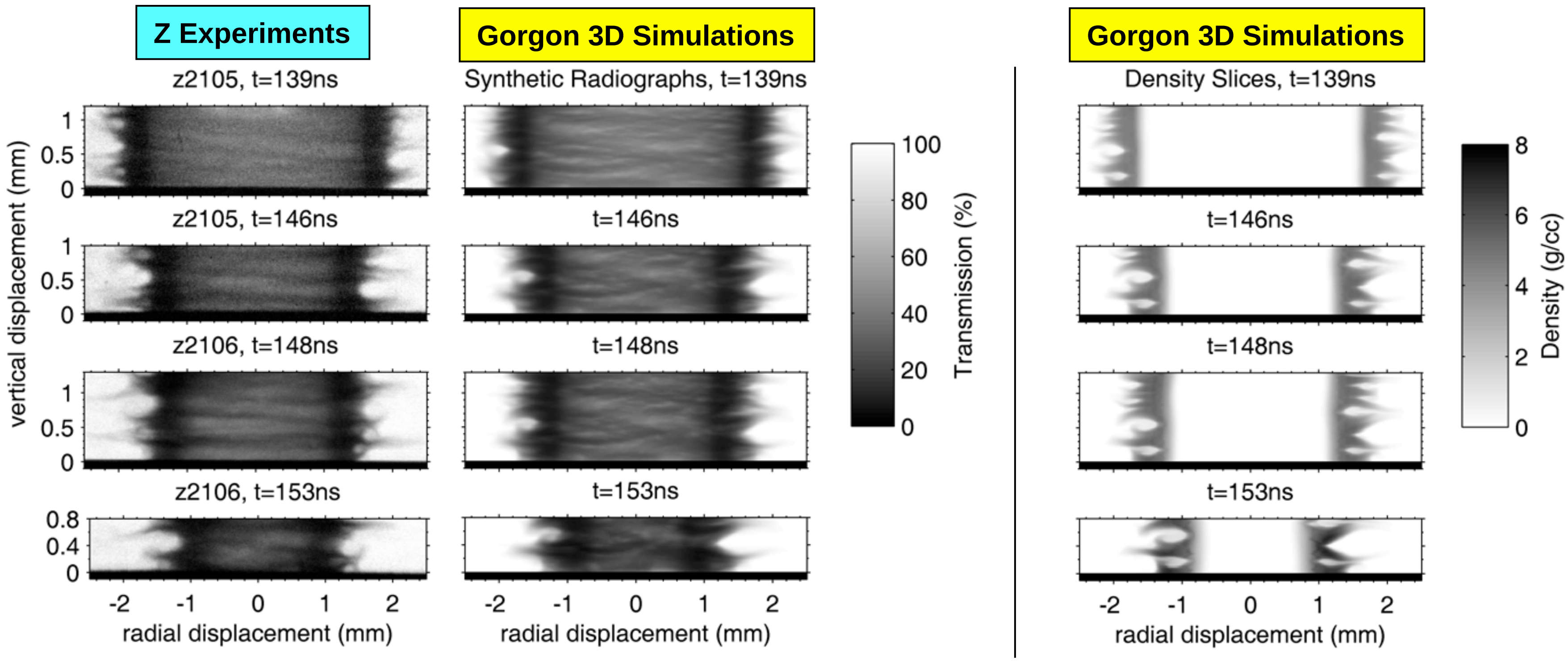
- Ignition
- High fusion yields
- Target physics and drivers
- Low mass RTL for remote handling of high yields
- Pulse shaping
- Multiple missions

IFE

- High fusion yields
- Target physics and drivers
- RTLs for automated, repetitive handling of high yields
- High average power
- High availability and reliability
- Low cost targets/RTLs

Facility and personnel safety
Decrease operational cost
Decrease hazardous waste
Higher shot rate

Direct-magnetic drive is a promising and highly-efficient method for compressing fusion fuel

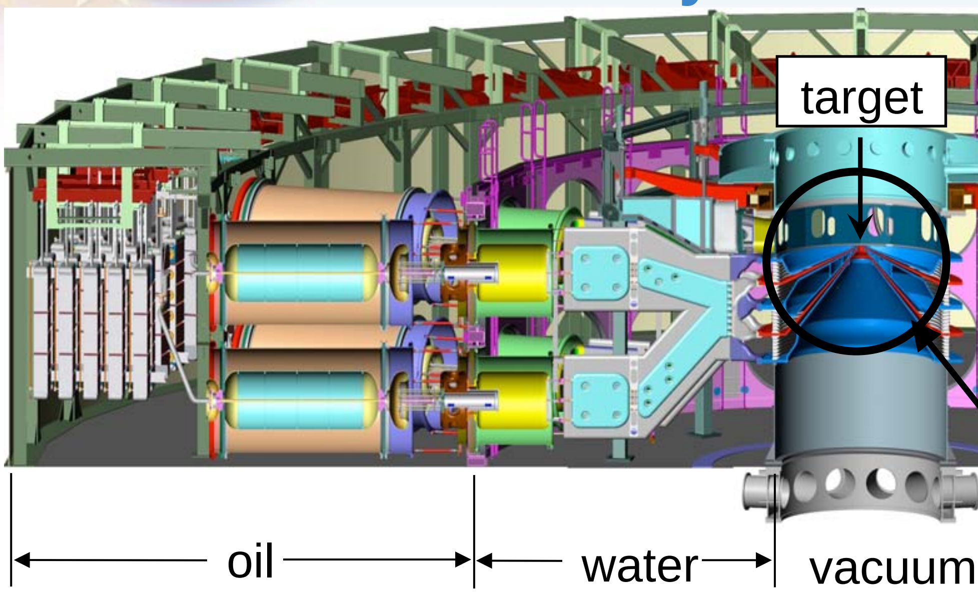


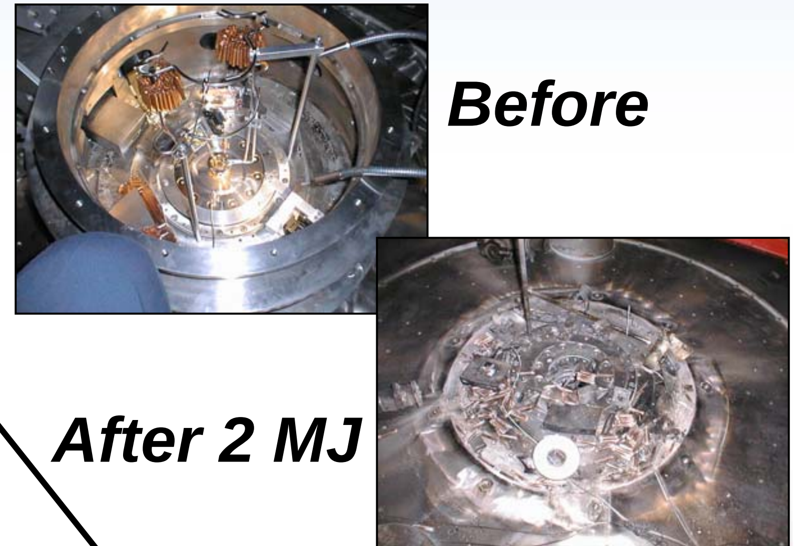
- Liner integrity is critical for the viability of directly-driven z-pinch fusion concepts
- We see excellent agreement between theory and experiments for these multi-mode Magneto-Rayleigh-Taylor (MRT) growth experiments

The logic of the pulsed power approach to IFE

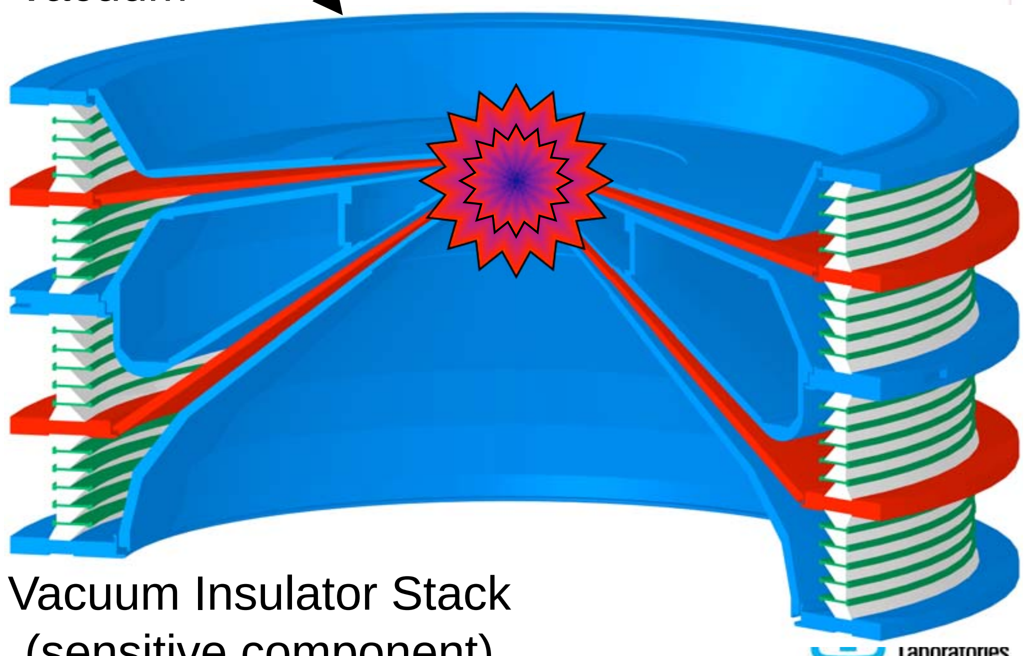
- We have large stored energy (100 – 360 MJ) at potentially low cost (cost are under development)
- We could deliver large energy to targets (≥10% efficiency, 10 MJ, 10X other approaches)
- Large energy may reduce target risk for high yields if convergence of targets is sufficient
- Natural geometry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

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





- 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)

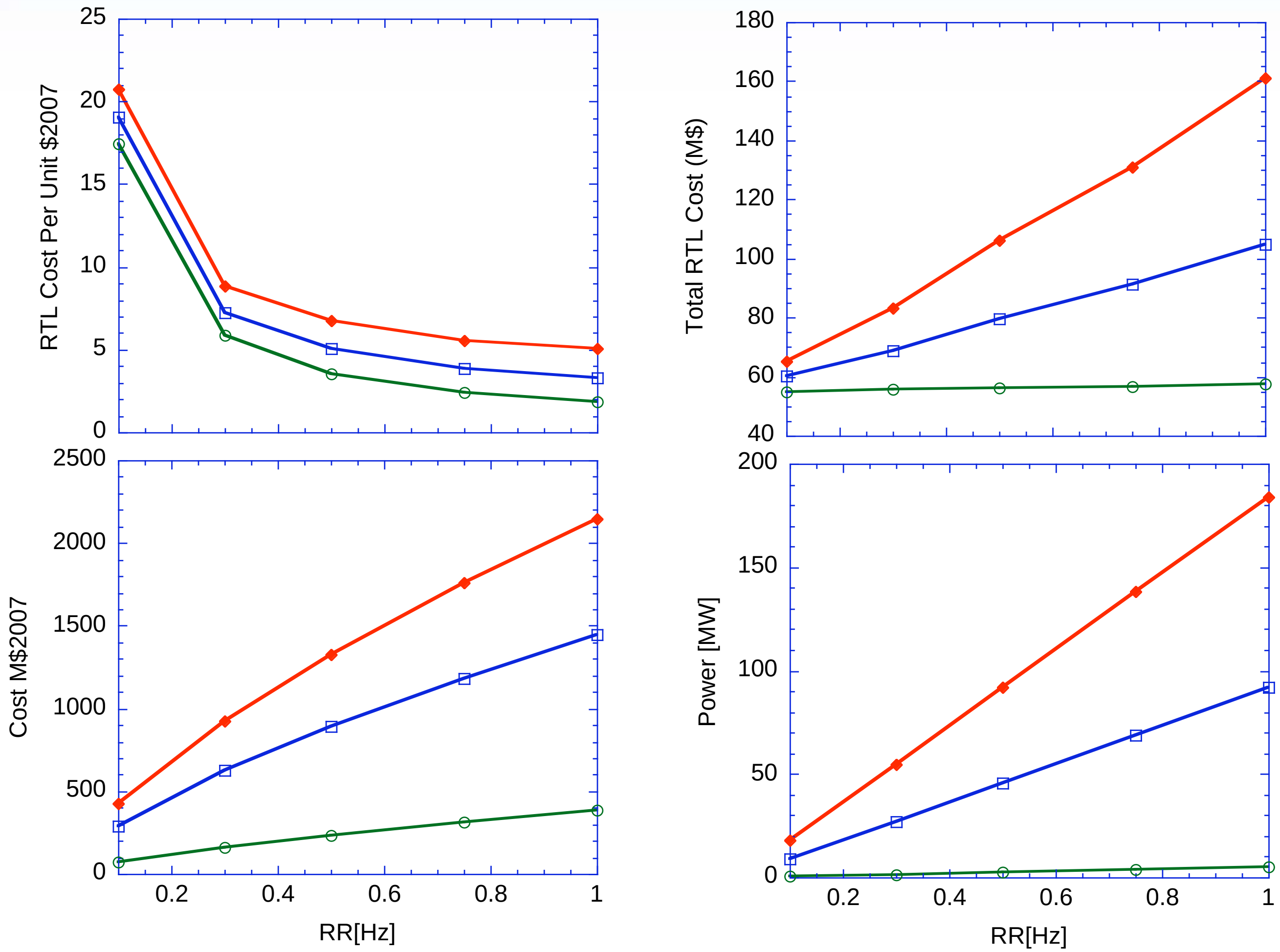
The optimal rep-rate R for a pulsed power system is determined by a number of factors

RTL Unit Cost

Total RTL Cost

RTL Factory Capital Cost

RTL Factory Power Use



- 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

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

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

- 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 \$/$MWhr_e$

A simple scaling relationship gives insight into the requirements for fusion power 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
- Is there an optimal system to produce a given $E_{store}RG$ product
  - of course, we want to make *ergs*…
- What are the system requirements and challenges?

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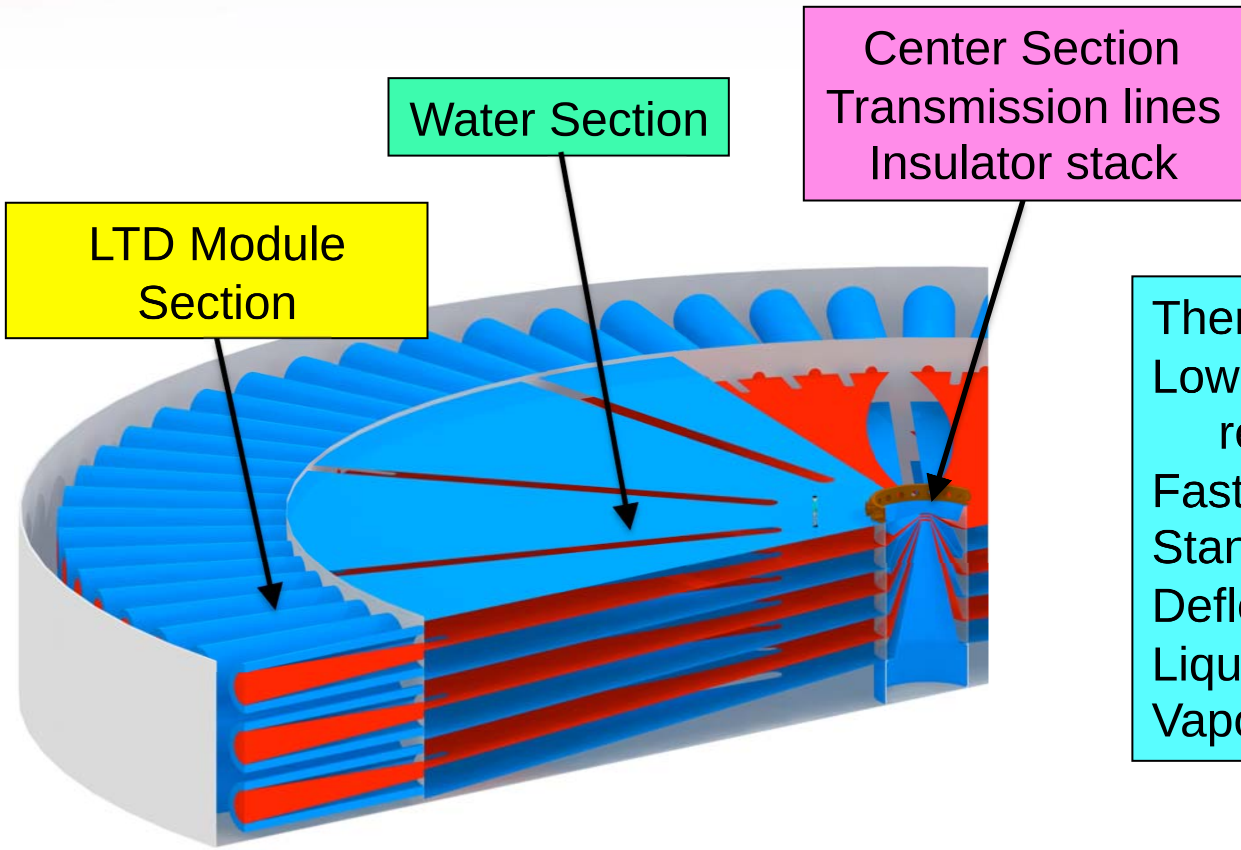
The "center section" needs to be re-engineered for both single shot high yield and repetitive high yields



There are many ideas:
Low cost, low mass RTLs
replaceable/recyclable
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

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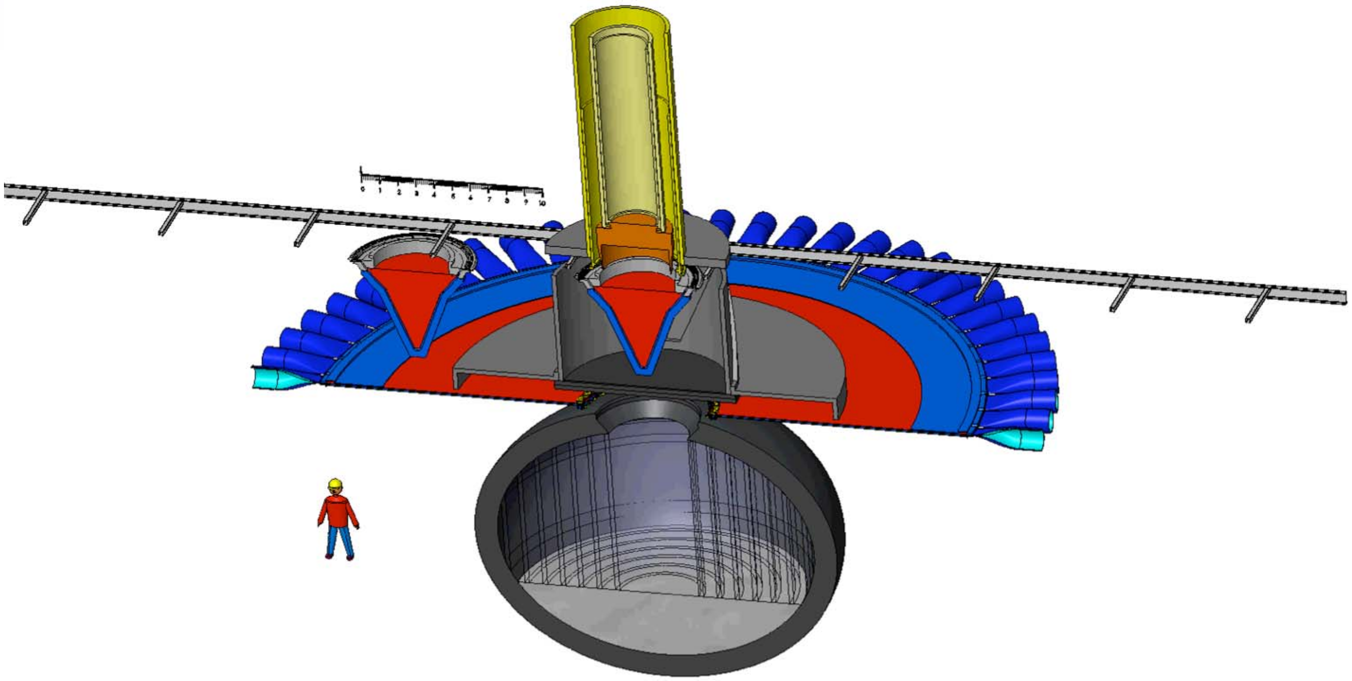
We showed you some pre-conceptual designs for RTLs in San Ramon



This design employed a number of features:

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

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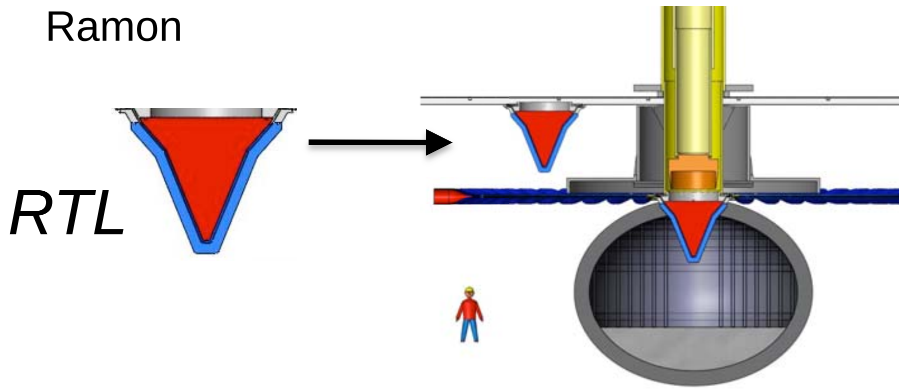
To provide effective standoff between driver and target different approaches need to be developed

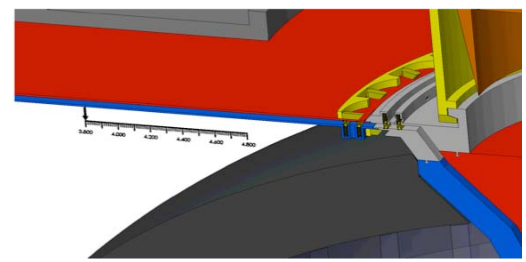
- The Recyclable Transmission Line (RTL) represents the sacrificial central component rapidly replaced following each pulse
  - Recall four animations of three different designs in San Ramon

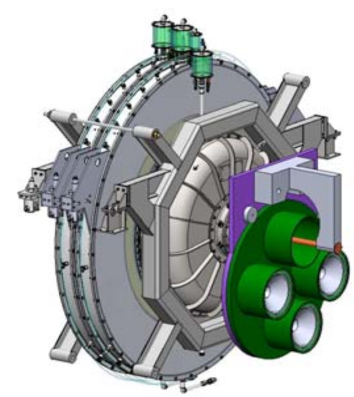


Automated RTL replacement every 10 s

- Facility design integrates rapid and remote refurbishment, maintenance, cleaning of portions of facility that are not sacrificial
- Need to develop, rank, and assess rapid maintenance and reliability to minimize and simplify this portion of the facility

examples of rapid replacement mechanisms under evaluation





There are a number of other approaches to protect the rest of the facility

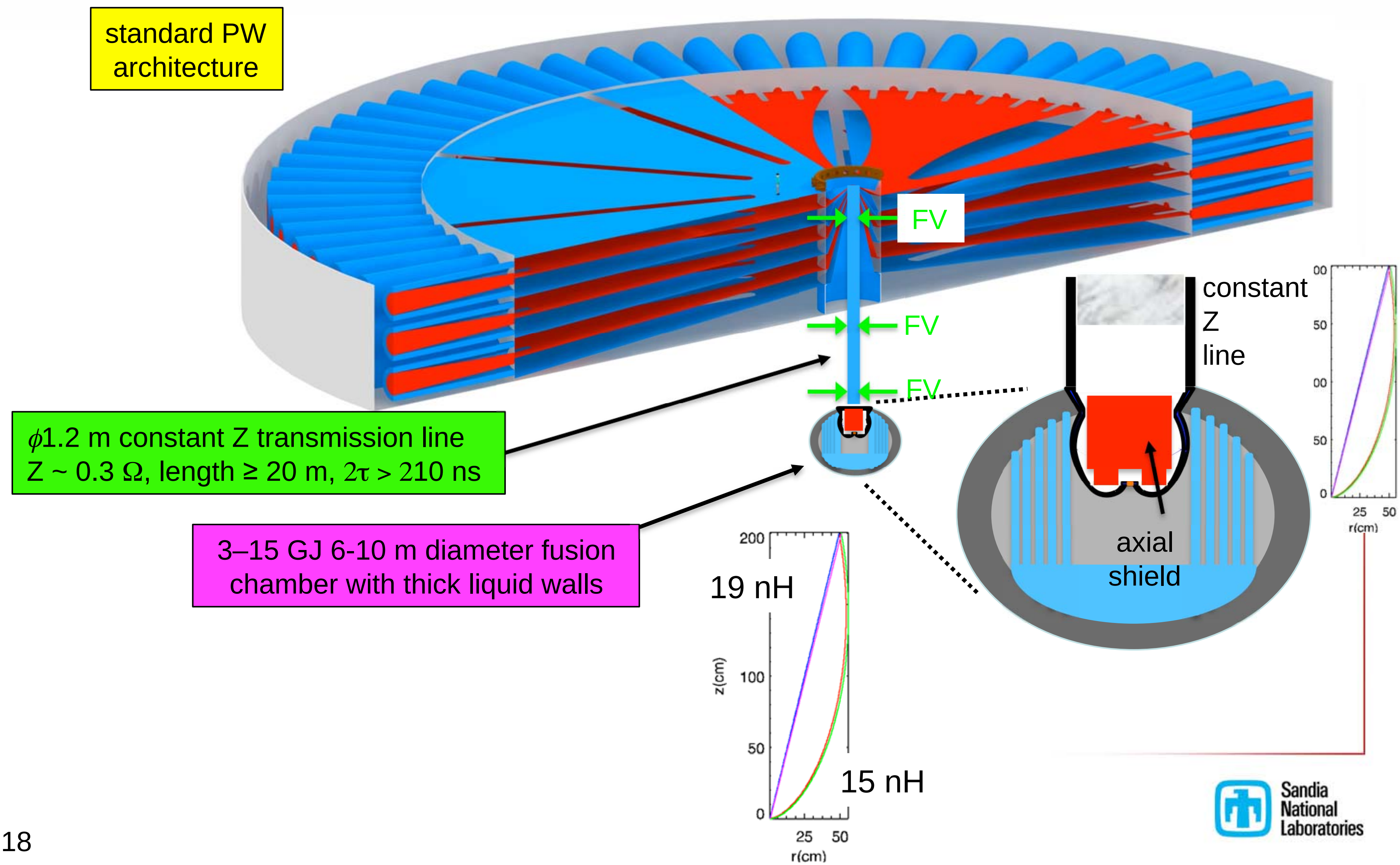
- Employing a long standoff distance either axially or radially between fusion target and the insulators, and other critical driver components
  - Provided by long transmission lines that have larger anode-cathode gaps and are therefore debris tolerant, and are cleaned periodically with low level pulses, or discharges

- Utilizing fast closure valves to close off connection to driver and transmission lines
  - 10 μs to 1 ms closure times for 1 cm gaps
  - High pressure air, shock tube, electromagnetic, current, explosive, fusion blast (self-closing)

- Shaping the transmission line and vaporizing blanket around target to deflect the fusion blast downwards away from transmission line
  - The "deflector" approach

- Conductors can bend around corners
  - No line of sight between target and main driver transmission lines

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



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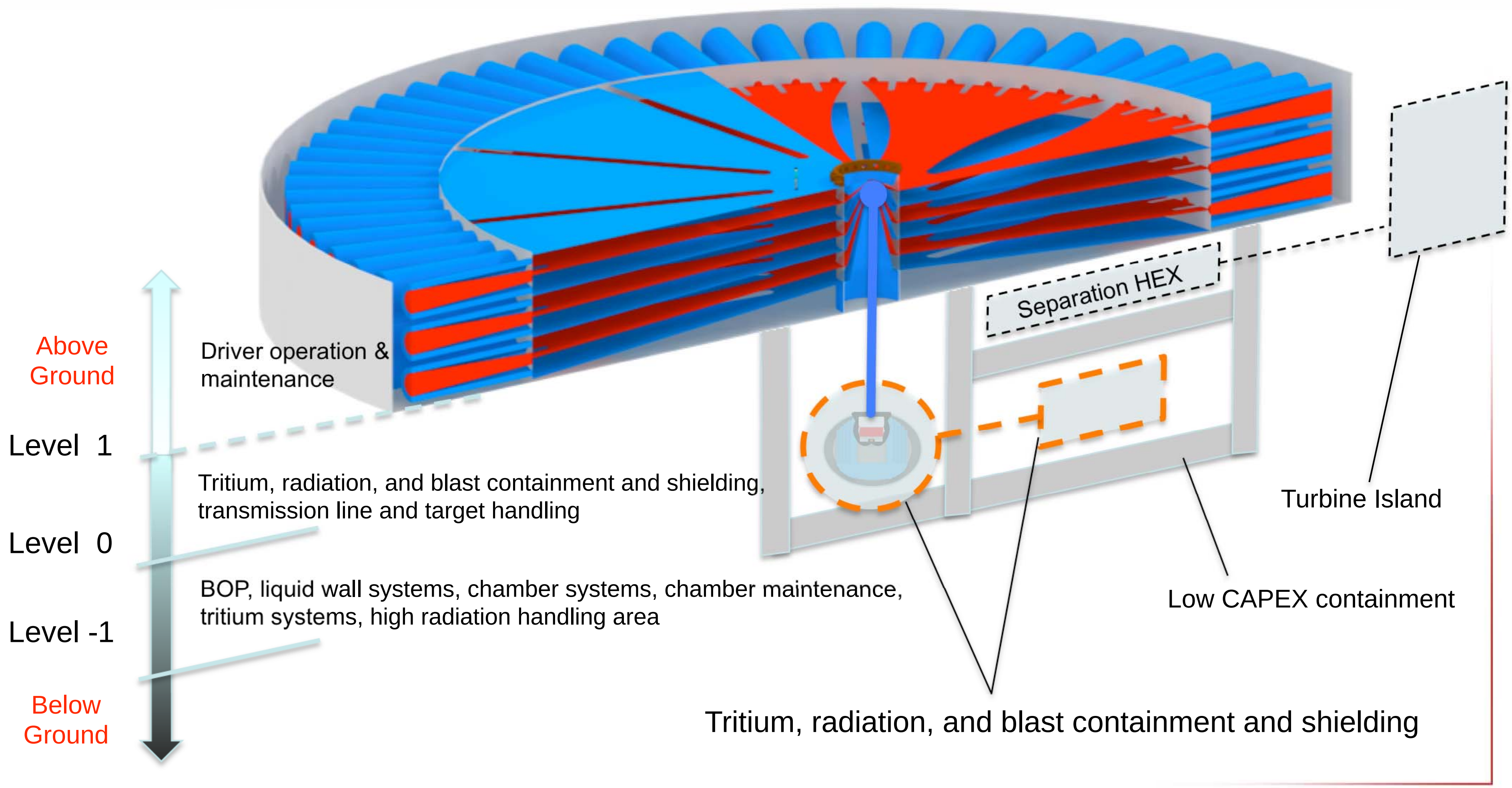
Plant functions are segregated on different levels to provide "defense in depth" and inherent safety



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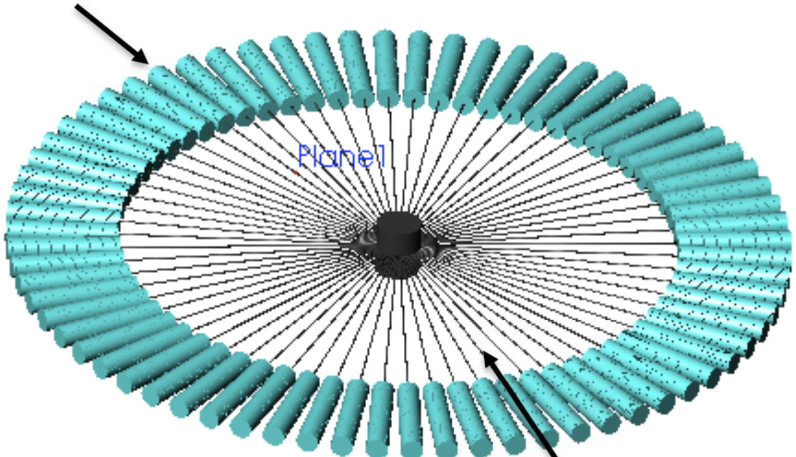
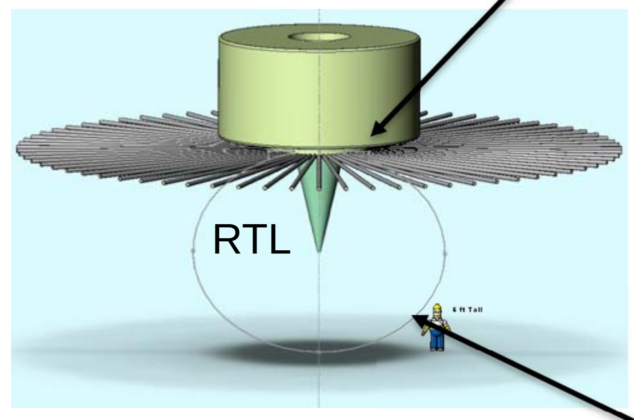
Another idea uses long *radial* standoff with coaxial vacuum transmission lines

Standard LTD modules
water or vacuum insulated

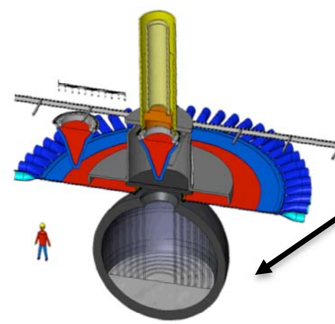


Long coaxial MITL (35 m)

Current addition



Chamber



- Long distance and closure valves at module exit isolate driver in 10 ms
- Several closure valves near chamber isolate transmission lines, large gaps make transmission lines debris tolerant

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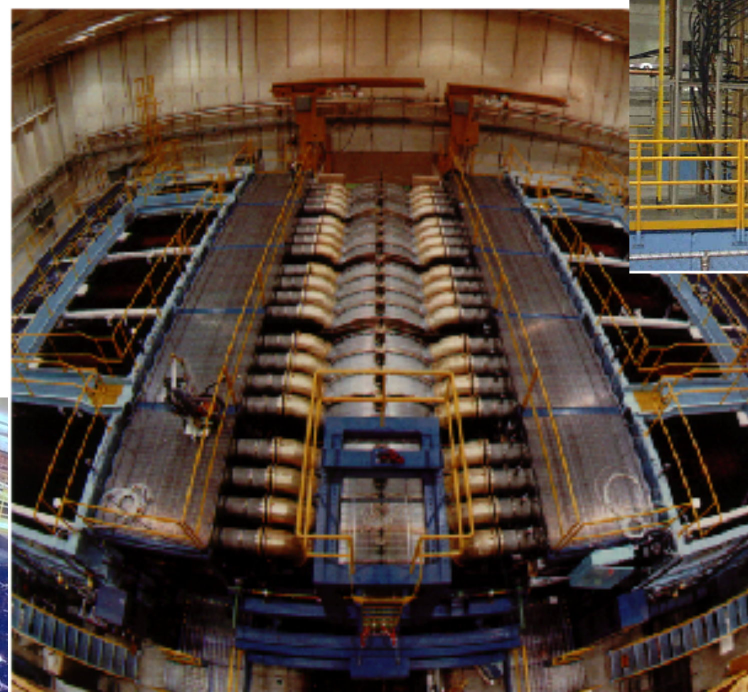
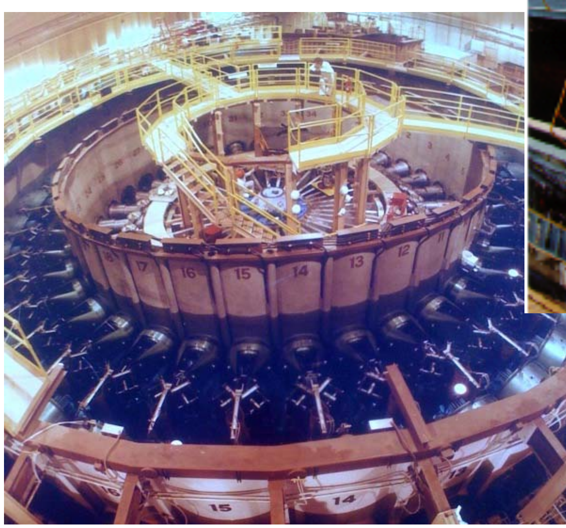
Long Self-Magnetically Insulated Transmission Lines (MITLs) have been proven technology for 30 years

Hermes III, 18 MV, 700 KA
in 1988



RHEPP II, 120 Hz,
in 1993

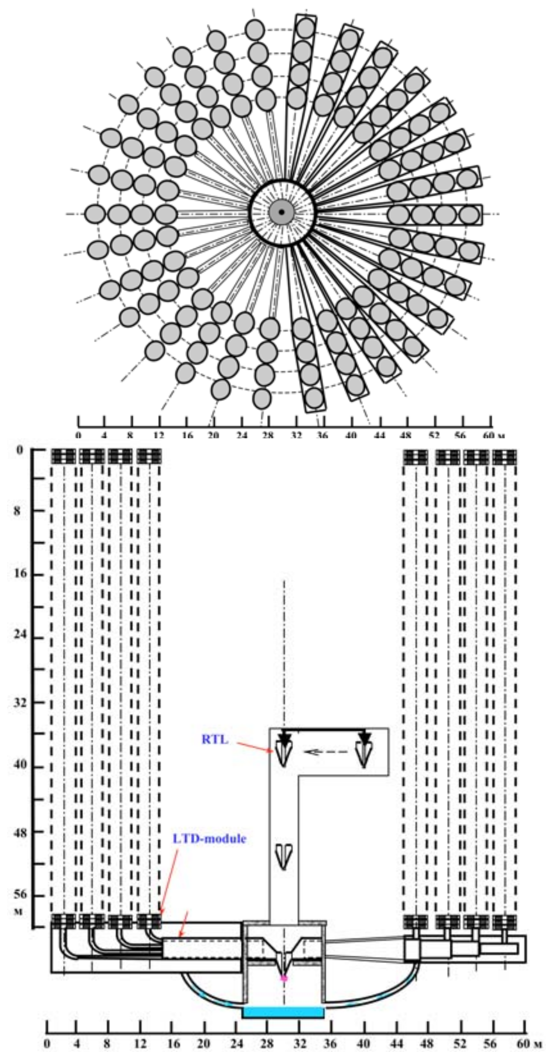
PBFA-I, 2 MV, 12 MA
in 1980



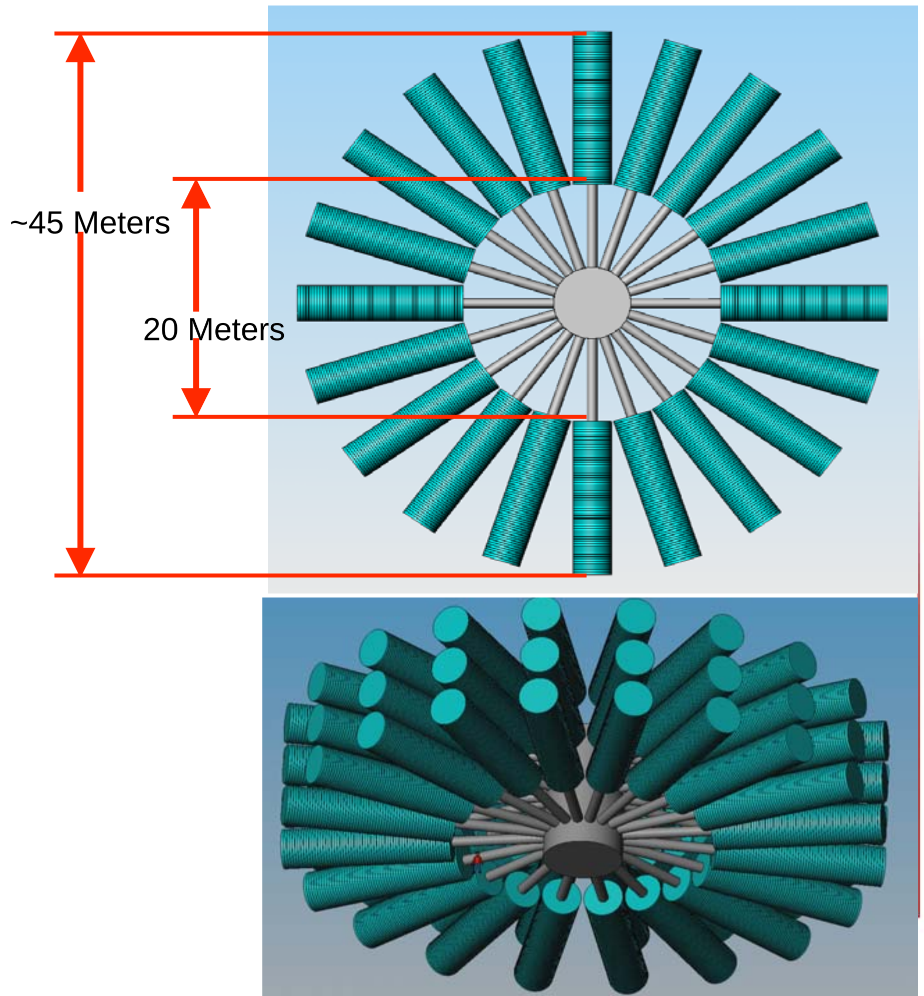
15-m to 22-m long

Other accelerator architectures could provide standoff, reduce driver size, and improve plant layout

Yu. G. Kalinin et al.

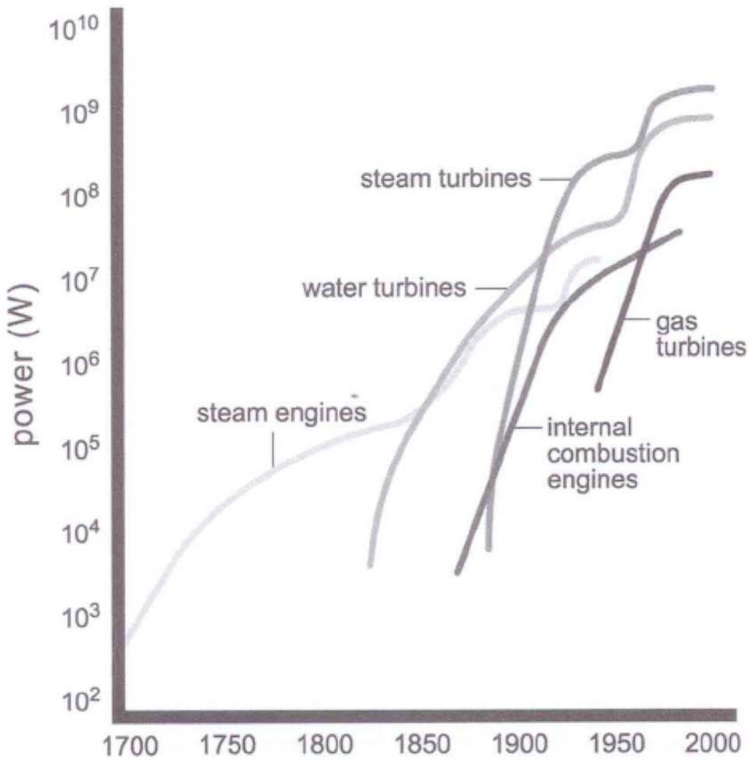


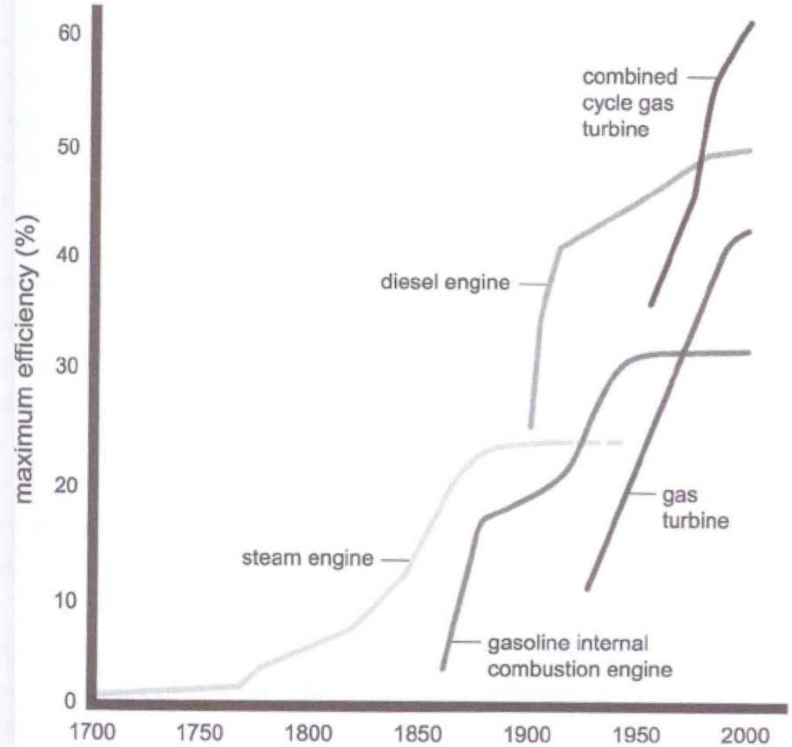
M. G. Mazarakis



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

Technology scale up took decades for technologies we now use everyday – systems progressed in steps



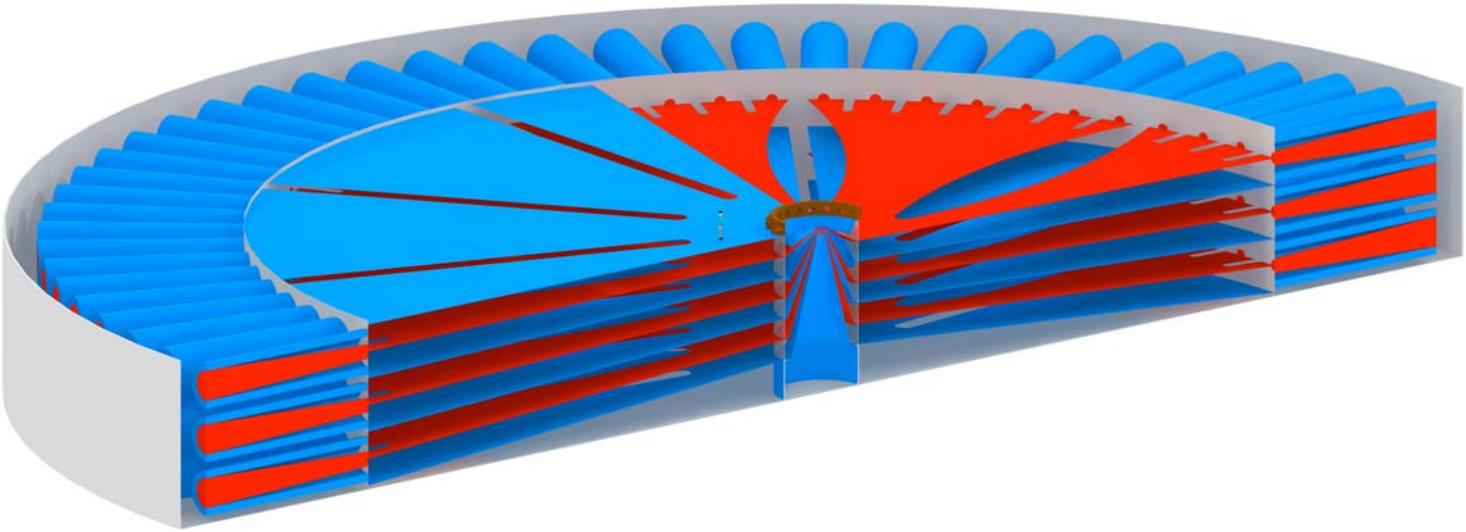


- Difference – these had immediate application at small scale
- Fusion has a certain scale before it is feasible and economic
- Need government interest and investment help to bridge gap
- Philosophy – develop systems at smallest relevant scale to lower costs

A phased R & D program to retire risk and develop complex nuclear systems

- Phase 1 (~6 years): Science, engineering, and technology (ST&E) feasibility and path forward
  - Primary goal of phase 1 is to down-select driver architecture, driver-target coupling technique and design, driver energy, pulse length, peak current, repetition rate, target design, chamber and driver shielding designs and fusion breeder/coolant concepts.
- NNSA
  - Finish sub-scale driver module testing, build and demonstrate full-scale repetitive driver module, and cost engineer driver modules (NNSA).
  - Develop mature target physics and scaling, with validated state-of-the-art models and achieve *scientific breakeven* with DT (0.1 to 0.5 MJ yields) on Z (fusion energy out = energy delivered to fuel), in the next 5 years. The Z facility generates a peak current (Ip) of 25 MA with energy storage of (Estore) 20 MJ (NNSA).
  - Develop costing for full-scale integrated physics and technology demonstration (NNSA).
- IFE (resources for these tasks could make a big difference)
  - Demonstrations of repetitive coupling (IFE) utilizing Recyclable Transmission Lines (IFE).
  - IFE architecture design and demonstration with rearrangement of module cavities (IFE).
  - Chamber/first-wall/fusion-nuclear-science designs (breeding, balance of plant) (IFE/NNSA).
  - Radiation "Life Cycle Analysis" of baseline pulsed power IFE plant (IFE).
  - Integrated designs for facility to handle GJ yields with high availability (IFE/NNSA).

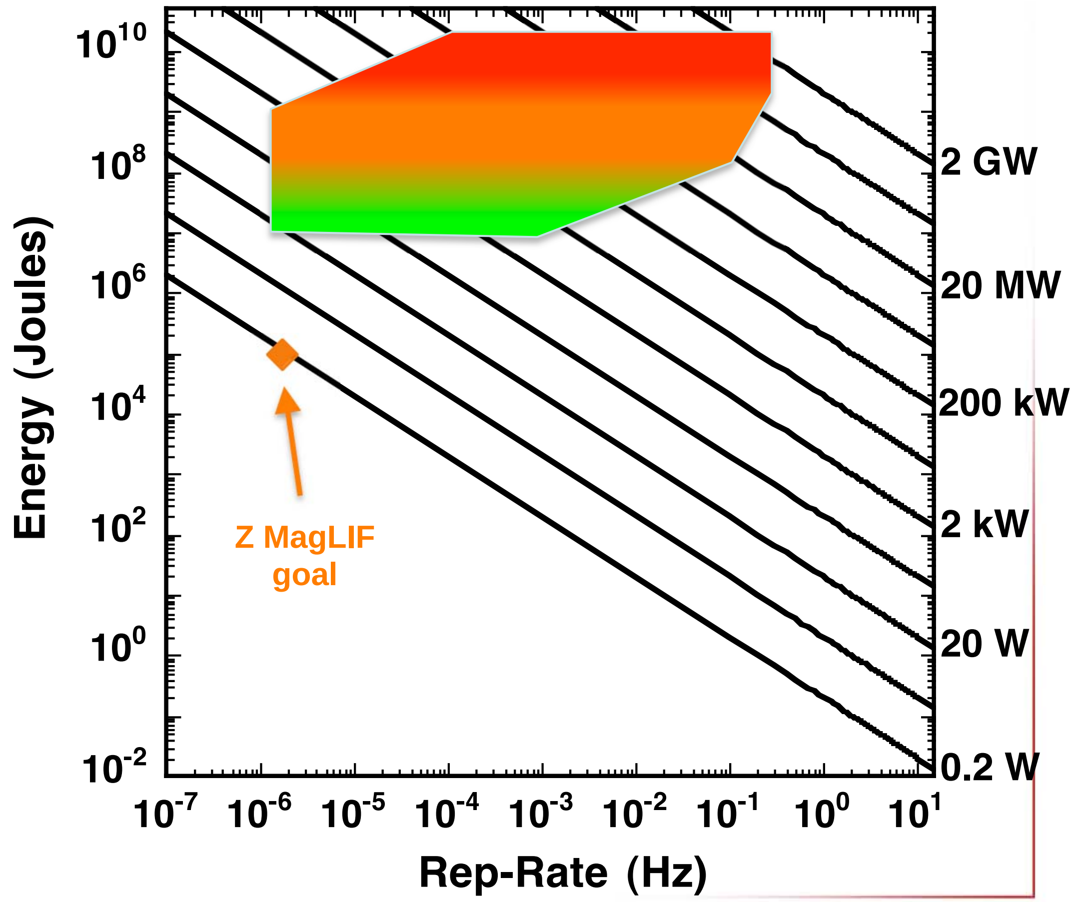
Build a research facility that can be flexibly expanded to develop ignition, propagating burn, high yield for IFE, and approach commercial sustainability



- Build infrastructure (building, tank, cranes) for 1-2 PW facility (tank = 104 m diameter), marginal extra cost gives huge flexibility
- Initial population: 90 modules, each module with 33 cavities
  - 300 TW, 50 MA, 47 MJ
- Final possible configuration: 210 modules, each of which consist of 60 cavities
  - 2000 TW, 100 MA, 360 MJ

The optimal path to an IFE demo for pulsed-power involves an expandable facility

- Z-pinch research needs to demonstrate ignition and propagating burn
- Likely will initially need to be dual use NNSA/IFE
- Initially maximum fusion yields of 100 MJ to minimize costs
- Minimize size and costs of subsystem modifications, iterations, solutions
- Expand numbers and length of modules to meet increased yield requirements for energy, as necessary



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A phased R & D program to retire risk and develop complex nuclear systems

- Phase 2 (>8 years): Integrated ST&E demonstration at smallest surrogate scale for fusion testing relevant to energy
  - *Based on phase 1 work,* design for a maximum yield of 100 MJ to lower cost of nuclear handling and to prove propagating burn
  - Build *ZFIRE – Z-pinch Fusion Ignition Research and Engineering* facility (2–5 x Z)
  - Fill science gaps in the NNSA mission space, if any
  - Facility infrastructure is expandable (add modules, add cavities), flexible since the development of fusion technology will take time
  - Repetitive fusion yields for limited duration
  - Tritium breeding and recovery, not self-sufficiency
  - Operate under DOE
  - Goal bring TRL level of fusion energy to a 7

A phased R & D program with competition to retire risk and develop complex nuclear systems

- Phase 3 (>8 years): IFE demonstration facility
  - Expand facility to achieve goal of facility breakeven and high yield with a facility that is 5–10 x Z, *if necessary*
  - *ZFUSE – Z-pinch Fusion for United States Energy*
  - Breakthroughs in phase 2 targets or driver technology may permit more compact facility
  - Show repetitive facility breakeven and high yields at rep-rates of 10^{-3} – 0.1 Hz, with high driver availability (50%) for limited – to – extended durations.
  - Tritium self-sufficiency and generation of electricity
  - Goal bring TRL of fusion energy to an 8
  - Licensing under NRC
  - Partner with electric utilities in facility development, operation, and licensing, and development of a nuclear fusion safety program.

- Phase 4: Full scale commercial demonstration plant
  - Transfer technology to industry
  - EPC selection

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Phase 1 funding required to make progress

- NNSA support for target research and driver technology development

- Give the likelihood of limited funding we propose to address a selected set of key science and technology challenges for repetitive pulsed-power IFE
  - 31 M total for 6 years to address a selected set of key science and technology challenges for repetitive pulsed-power IFE
  - Funding profile: $3 M, $4.5 M, $7 M, $8 M, $4.5 M, $4 M

- With success or one or more breakthroughs in IFET, a more aggressive development program could be considered

Limited phase 1 go/no-go program to address key science and technology

- A recyclable transmission line (RTL) technology demonstration experiment to show a proof of principle of the concept at 1-TW, 0.1-Hz, 125-kJ experiment ($7 M over 6 years).
- Single shot RTL physics and engineering experiments at 80 TW on Z ($4 M over 6 years).
- Development of a driver architecture with standoff that is compatible with IFE requirements and high fusion yields. ($6.5 M over 6 years).
- Design and operate key components of a 0.5-TW LTD cavity and demonstrate long lifetime (~3×10^6 shots). ($7.5 M over 6 years).
- Designs, large scale simulations, and experiments for driver shielding at high fusion yields. Design affordable RTL concepts compatible with high IFE plant availability and minimal waste, that employ repetitive GJ-level yields. ($6 M over 6 years).

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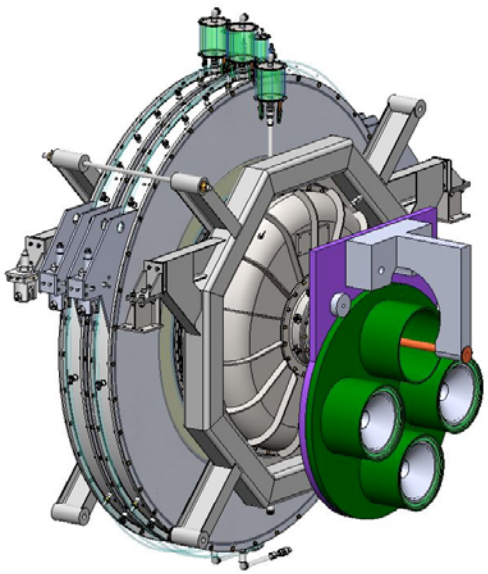
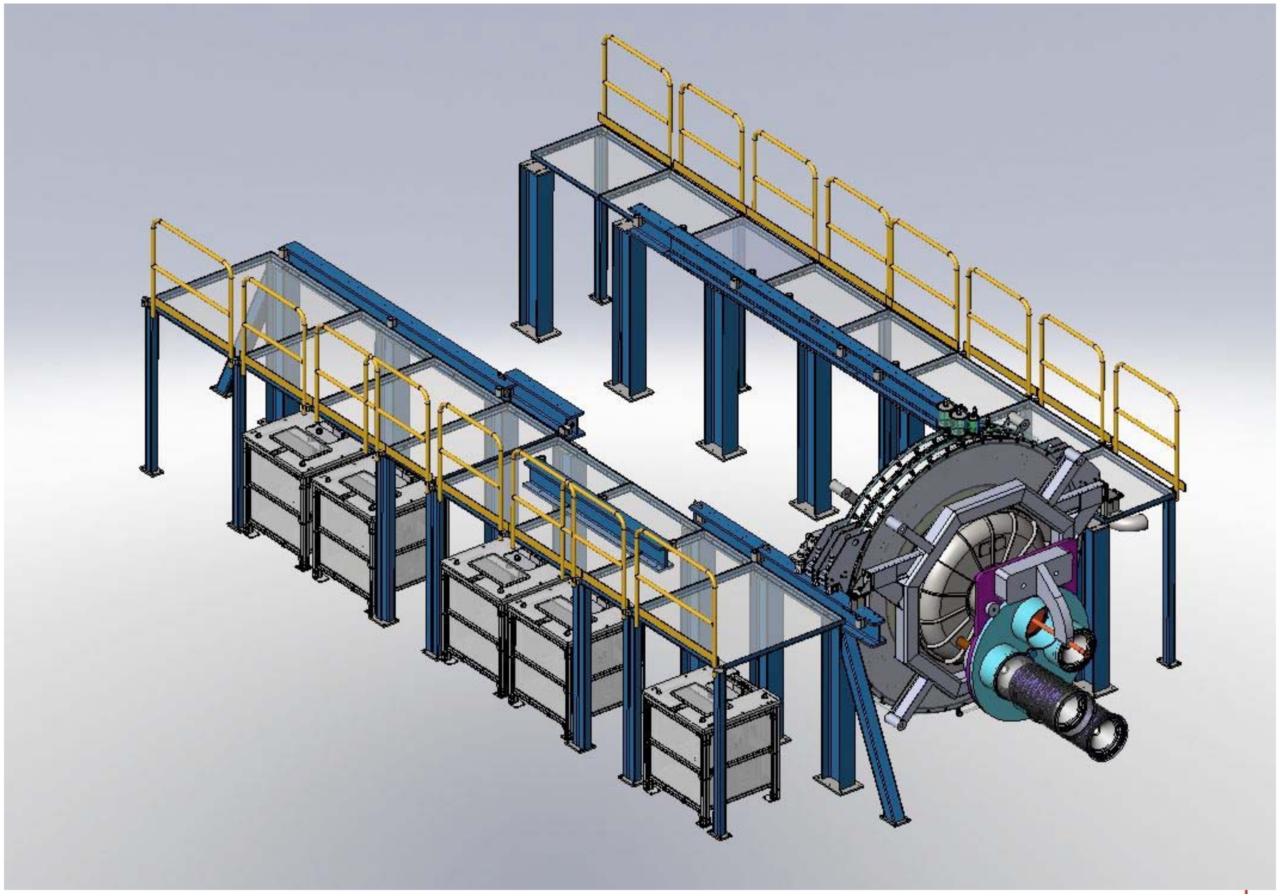
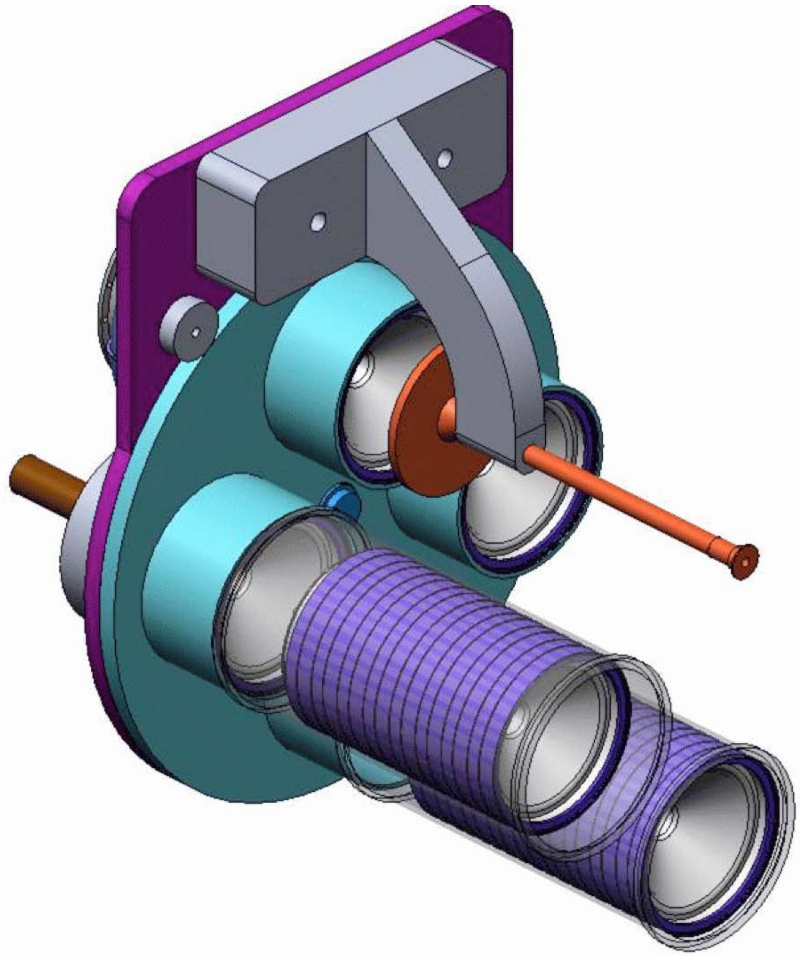
Pre-conceptual design of a replaceable transmission line system for LTD test module





“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?

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**

Success during phase 1 could justify larger investments in all four technical areas in preparation for phase 2

System	Current TRL level (2011)	TRL level (2016)	TRL level (2018)	Full program (over 6 years)
Targets				
Target physics*	3	5	6	10
Cryogenics*	3	5	6	0.5
DT fuel	2	4	6	15
Drivers				
Cavity performance and cost*	4	5	6	5
Driver module*	3	5	6	20
IFET				
Cavity lifetime	4	5	6	10-20
RTLs	2	4	6	10-20
IFE architecture	2	4	6	10
FNS				
Chamber	2	4	6	10-20
Breeding	2	3	5	10-20
Balance of plant	4	5	6	10-20
Systems Integration	2	4	5	6
Net TRL	2.8	4.4	5.8	
Total				~120 – 170
Total (per year)				~20 – 30

Over 6 years

- Targets: $20 M
- Drivers: $25 M
- IFET: $30 – $50 M
- FNS: $30 – $60 M

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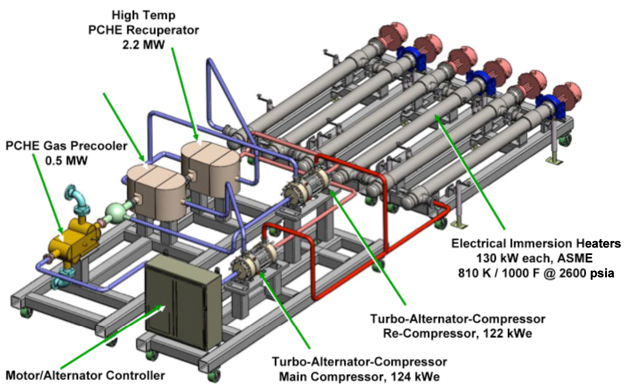
Sandia is a multi-disciplinary engineering laboratory that can tackle the highly integrated systems issues of high fusion yields

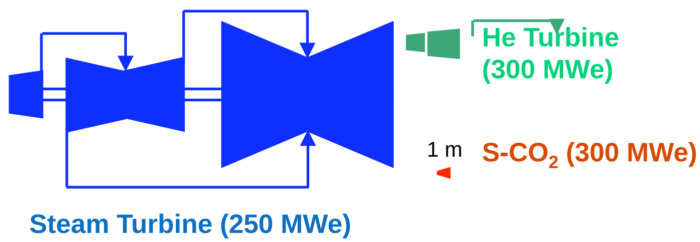
Multiple Applications
Inertial Fusion Energy
Nuclear Weapons Stewardship
NEP design and validation
Weapons effects at threat levels
Fundamental Science
Nuclear Materials

Lab-Wide ST & E Engagement
Multi-disciplinary science & technology advances
High Power Computing
Materials
Nuclear, Mechanical, Electrical Engineering
Robotics and automation
Semiconductors
Nuclear Energy and Advanced Thermal Cycles
Fusion target science & technology
Fusion driver science & technology
Systems Engineering
Tritium handling
Nuclear facility design for large fusion yields
Systems design for handling of activated hardware
Licensing, regulations, waste handling, and mitigation

For example, Sandia has significant programs in nuclear fission energy, advanced thermodynamic cycles and fusion energy technology

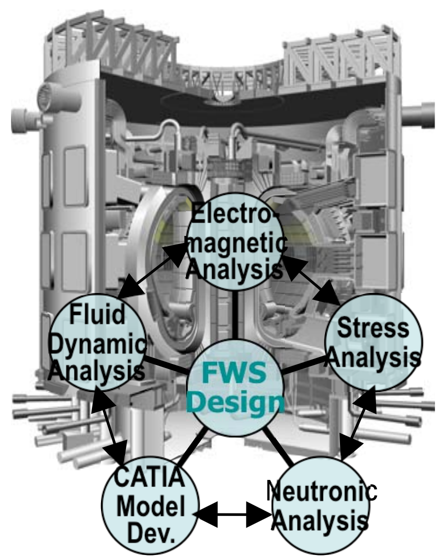
R.A. Wright and G.E. Rochau





- Supercritical S-CO_2 Brayton Cycle
- DOE-Gen IV reactors
- NaK for solar
- FLiBe for Molten Salt Reactors
- Working temperatures up to 700–900 C
- $5-6 M/year program

R.E. Nygren



Plasma Materials Test Facility

heating **cooling**

water - 250C, 8MPa, 2 MW, nuclear-grade

He loop - 500C, 20 Mpa, 220 g/s

LIMITS - 400C moveable liquid lithium loop

- Sandia leads the US technical team designing ITER's enhanced heat load first wall modules and coordinates the international design R&D for half the first wall.
- $5-6 M/year program

Sandia National Laboratories

From SNL high-energy-density environments for NNSA's Stockpile Stewardship Program to Commercial Sustainability

- **Where do we stand?**
  - ☑ Improved reliability and efficiency of Linear Transformer Drivers (LTDs) by factor of 2-3. LTDs may be repetitively pulsed
  - ☑ Developed capability to meet mission needs (close gaps) for NNSA Stockpile Science, and continue to provide data for NNSA mission
  - ☑ Matured technology basis for constructing up to a 2 PW single-shot driver that is rep-rateable
  - ☑ Develop magnetically-driven MagLIF targets for scientific breakeven

- **Outstanding Issues**
  - ❑ Must demonstrate scientific breakeven and validate target approach with simulations
  - ❑ Develop robust high yield targets designs in state-of-the-art 2D and 3D simulations
  - ❑ Demonstrate a repetitive coupling with an RTL system
  - ❑ System design for reliably creating, handling, and utilizing repetitive high fusion yields with high availability
  - ❑ Determine feasibility of a dual-use (NNSA/IFE) expandable facility formed by add-on modules that allow cost-effective upgrades and optimization while increasing fusion yields (all the way to commercial sustainability)

From SNL high-energy-density environments for NNSA's Stockpile Stewardship Program to Commercial Sustainability

- **Short-term Needs**
  - Continue NNSA funded targets and driver developments
  - For phase 1 we need about $5 M/year for 6 years to resolve 5 key science and technology challenges for pulsed-power IFE
  - Supplement the target and driver funding, if possible
- **Long-term Vision**
  - If NNSA/IFE programs are successful the goal is an expandable z-pinch facility that allows ignition and propagating burn
  - Expand the facility, if necessary, to achieve yields required for energy – the goal is to build to demonstration of commercial sustainability in the same facility
  - Transition from a R&D facility under DOE umbrella into a commercially sustainable IFE-based pilot facility that can be approved under NRC guidelines

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