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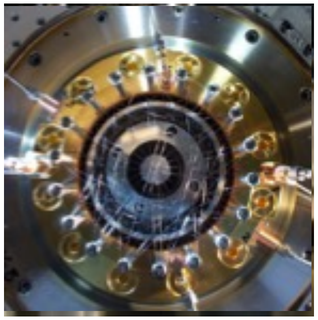

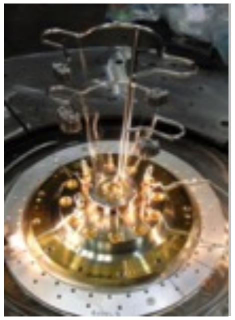

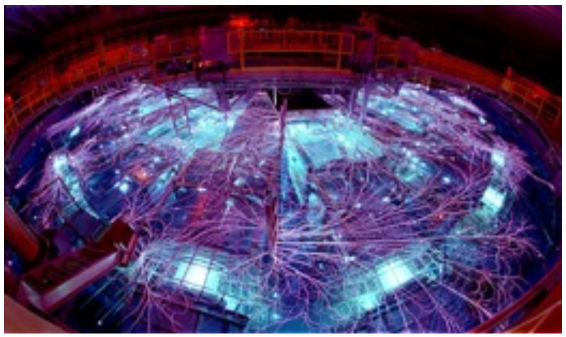

Pulsed Power Accelerators – Engines of Discovery for High Energy Density Physics

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Texas Tech Pulsed Power Group
Lubbock, Texas
Dec. 8th, 2017

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Special thanks to

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[1]*Sandia National Laboratories, Albuquerque, NM*

[2]*Laboratory of Plasma Studies, Cornell University, Ithaca, NY*

[3]*Lawerence Livermore National Laboratory, Livermore, CA*

[4]*General Atomics, San Diego, CA*

[5]*Raytheon Ktech, Albuquerque, NM*

[6]*Naval Research Laboratory, Washington, DC*

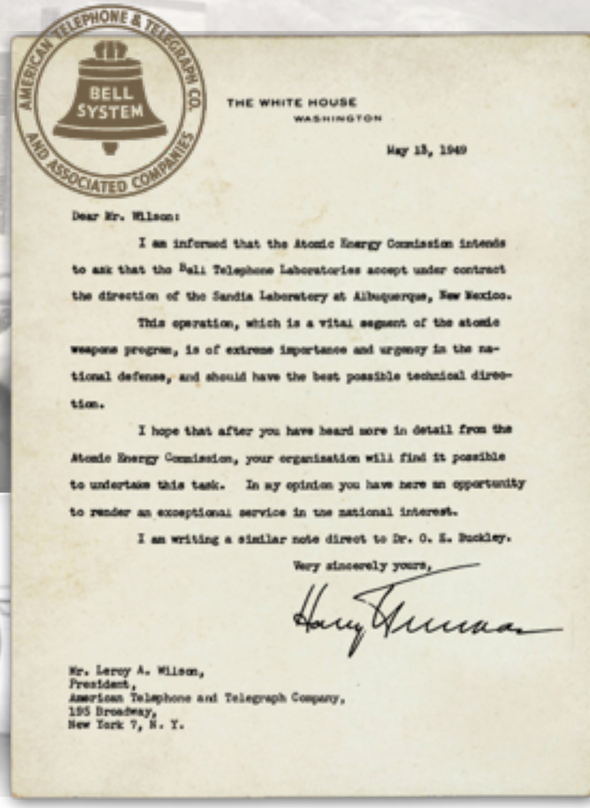
[7] *University of Michiagn, Ann Arbor, MI*

Summary

- Sandia National Laboratories
- The Z facility
- What is High Energy Density or HED?
- Pulsed Power as “Engines of Discovery”
- The future of pulsed power development at Sandia

Sandia National Laboratories' history dates back to World War II

Exceptional service in the national interest



AMERICAN TELEPHONE & TELEGRAPH CO.
BELL SYSTEM
AND ASSOCIATED COMPANIES

THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

- **July 1945:** Los Alamos creates Z Division
  - Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established
- **1949–1993:** AT&T
- **1995–2017:** Lockheed Martin Corporation
- **2017-Beyond:** Honeywell

Sandia has sites across the United States, but the majority of its employees are located in NM

Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

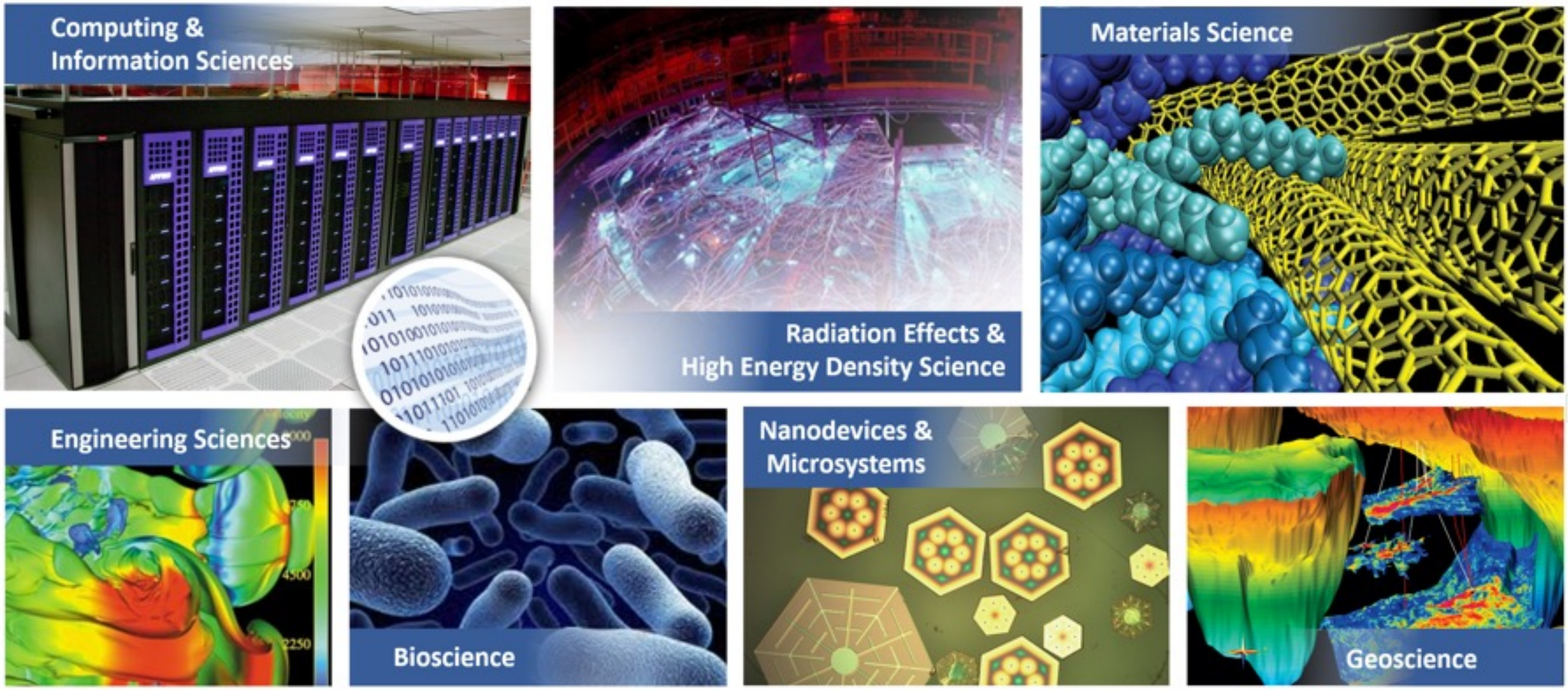
Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas

Tonopah, Nevada

12,500 employees, >$3 B budget

Sandia has "Research Foundations" that span a wide range of science and engineering

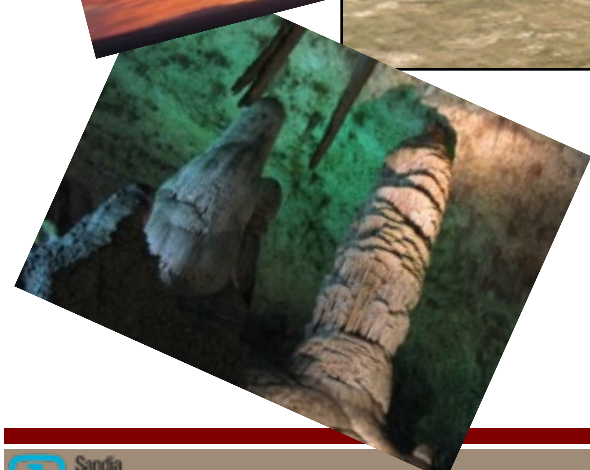


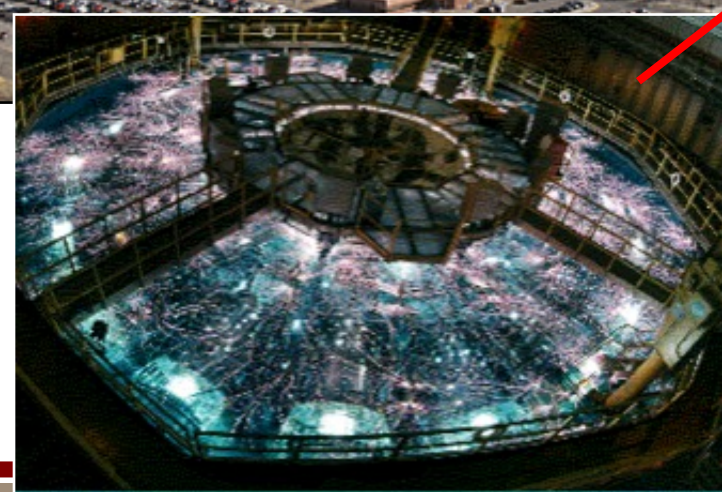
More than 2000 Ph.Ds

6

The “Z” pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

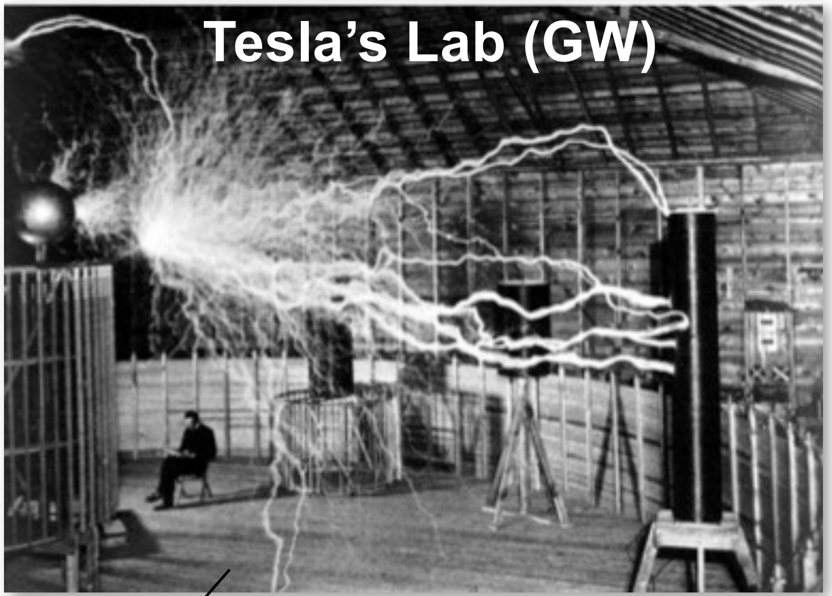
Youtube.com: search for the BBC TV show:
“*Horizon: Can we make a star on earth*?”

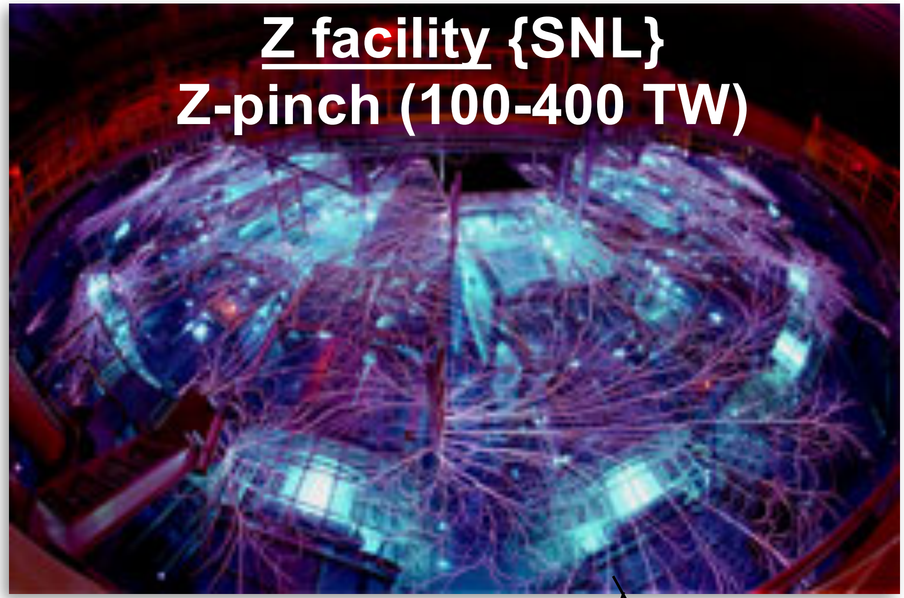


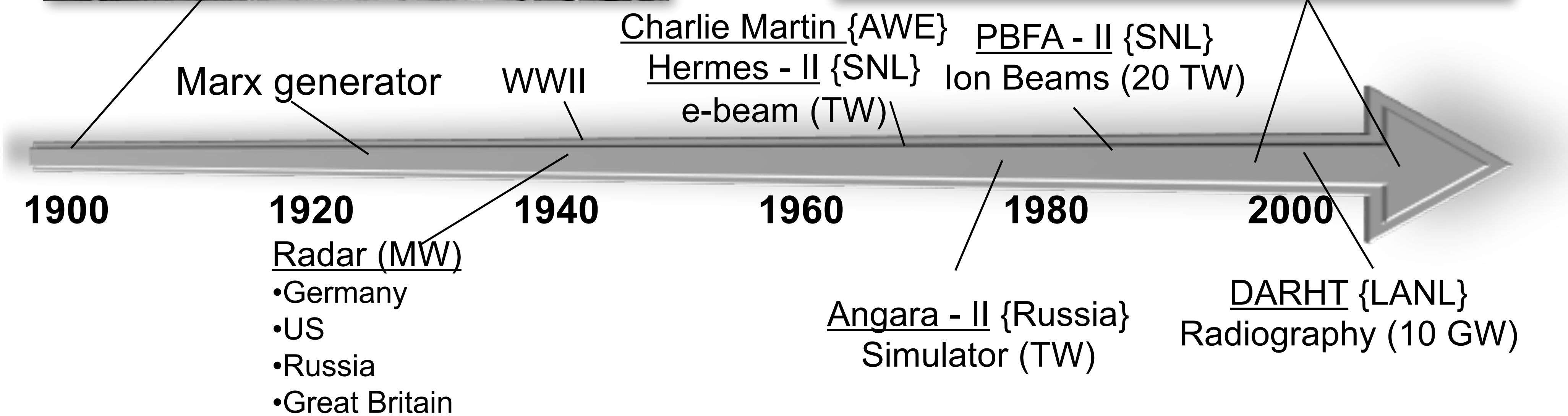


The “Z” pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

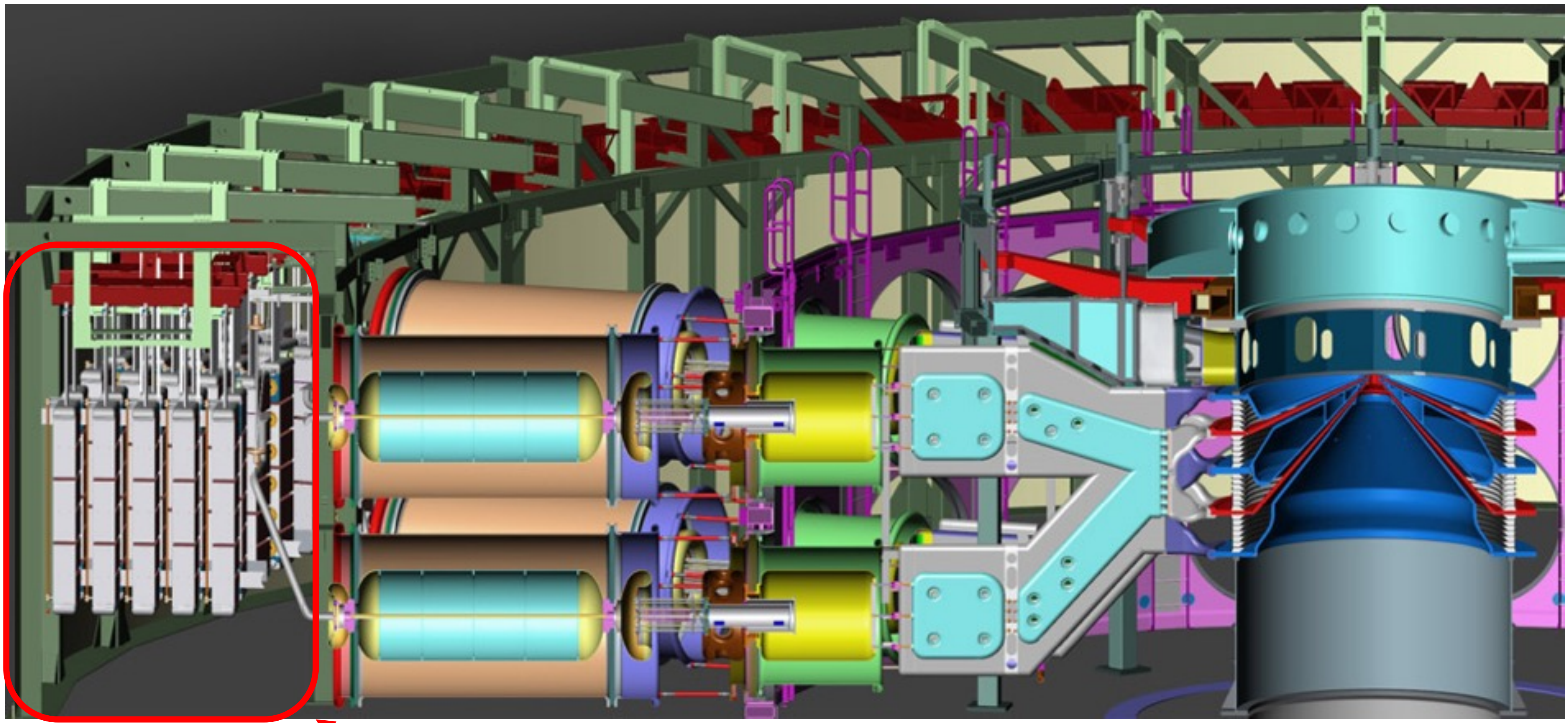
The accumulation and transmission of electromagnetic energy, called "pulsed power", has been investigated for more than a century





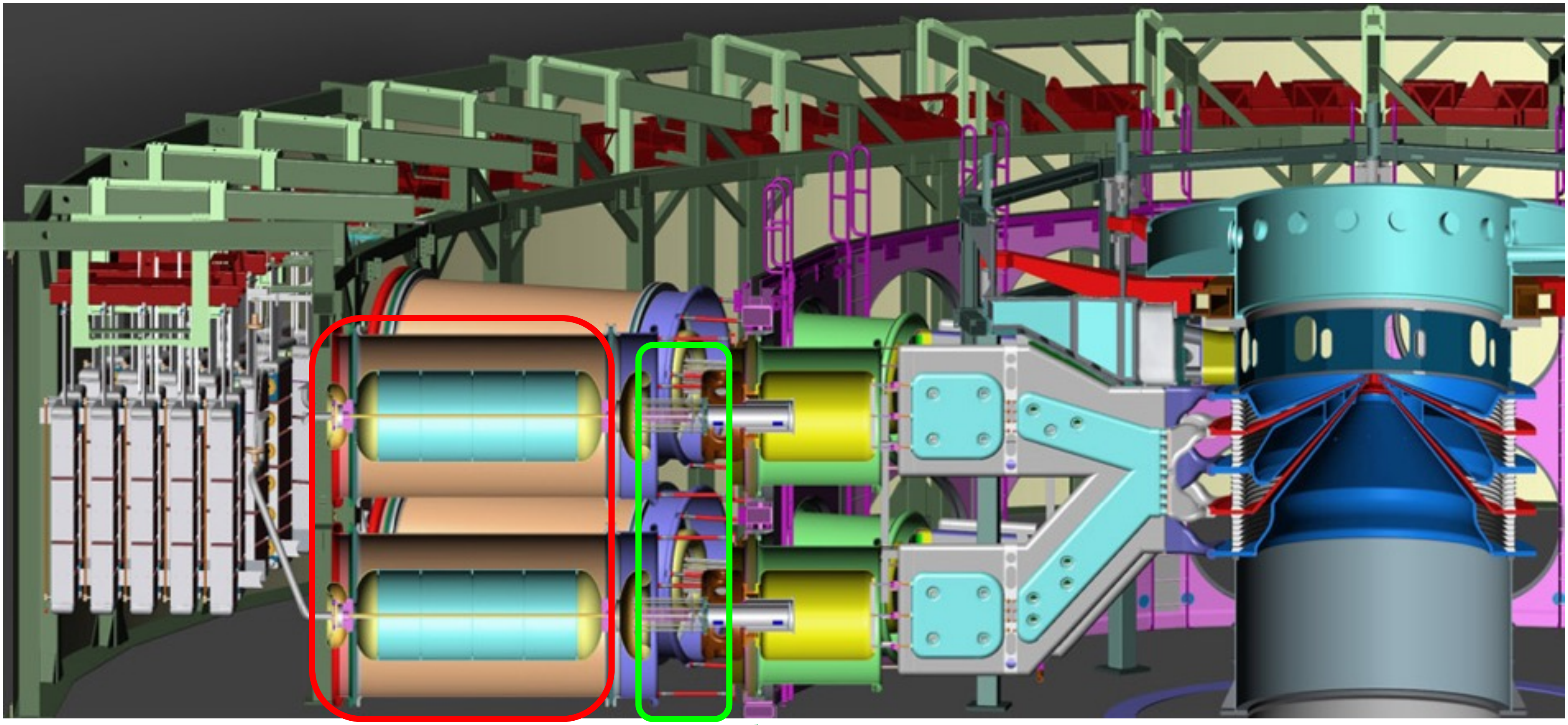


The Z machine uses Marx banks to generate high voltage electrical pulses



36 Marx banks, each with 60 capacitors, charged to 85kV → Output voltage is > 5 MV

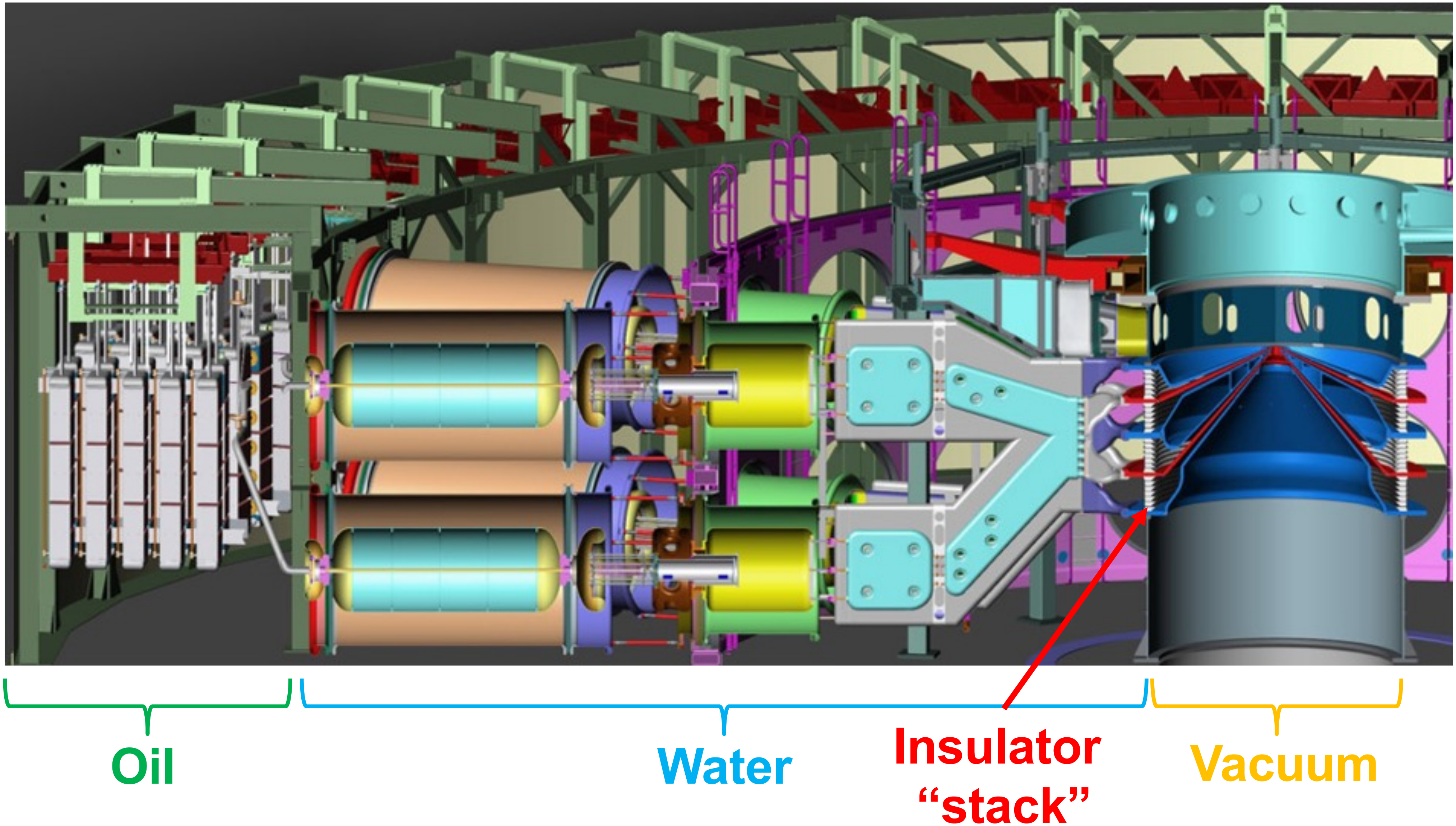
We use pulse compression stages to reduce the rise-time of the current



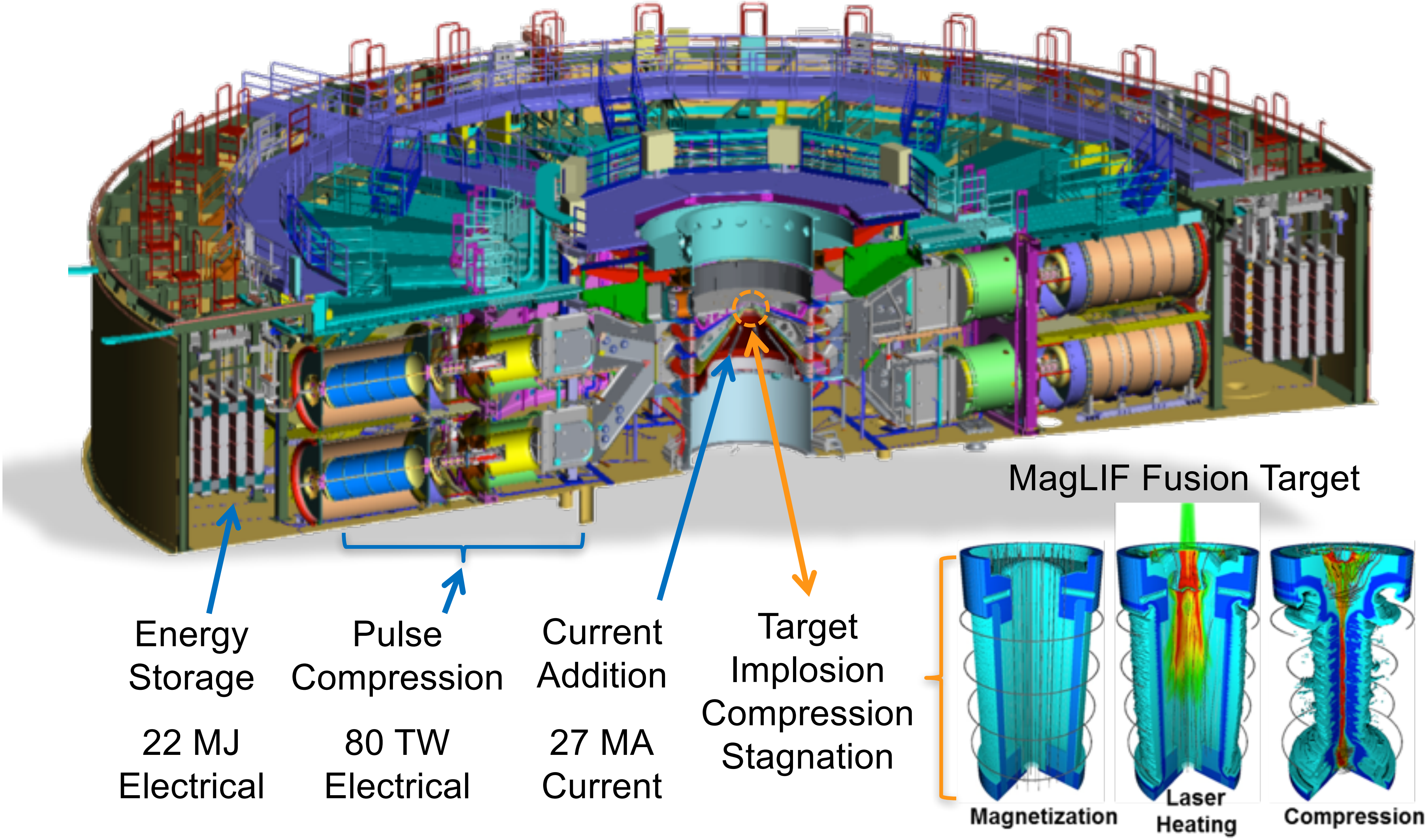
Water capacitor temporarily stores charge (~5MV)

Laser triggered switches release the energy

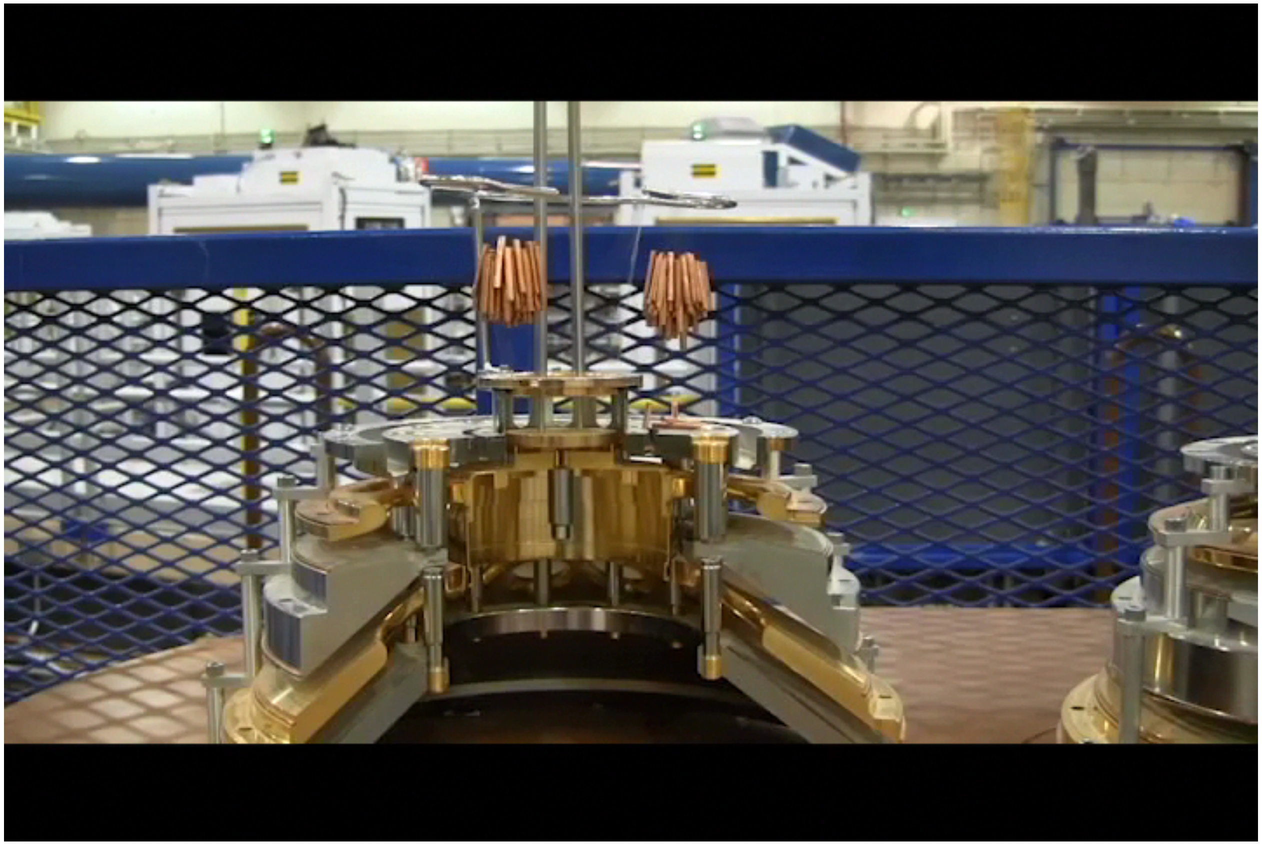
The compressed electrical pulse is transmitted into vacuum through an insulator stack



The Z facility compresses energy in space (>10^9 X) and time (>10^9 X) to generate High Energy Density matter



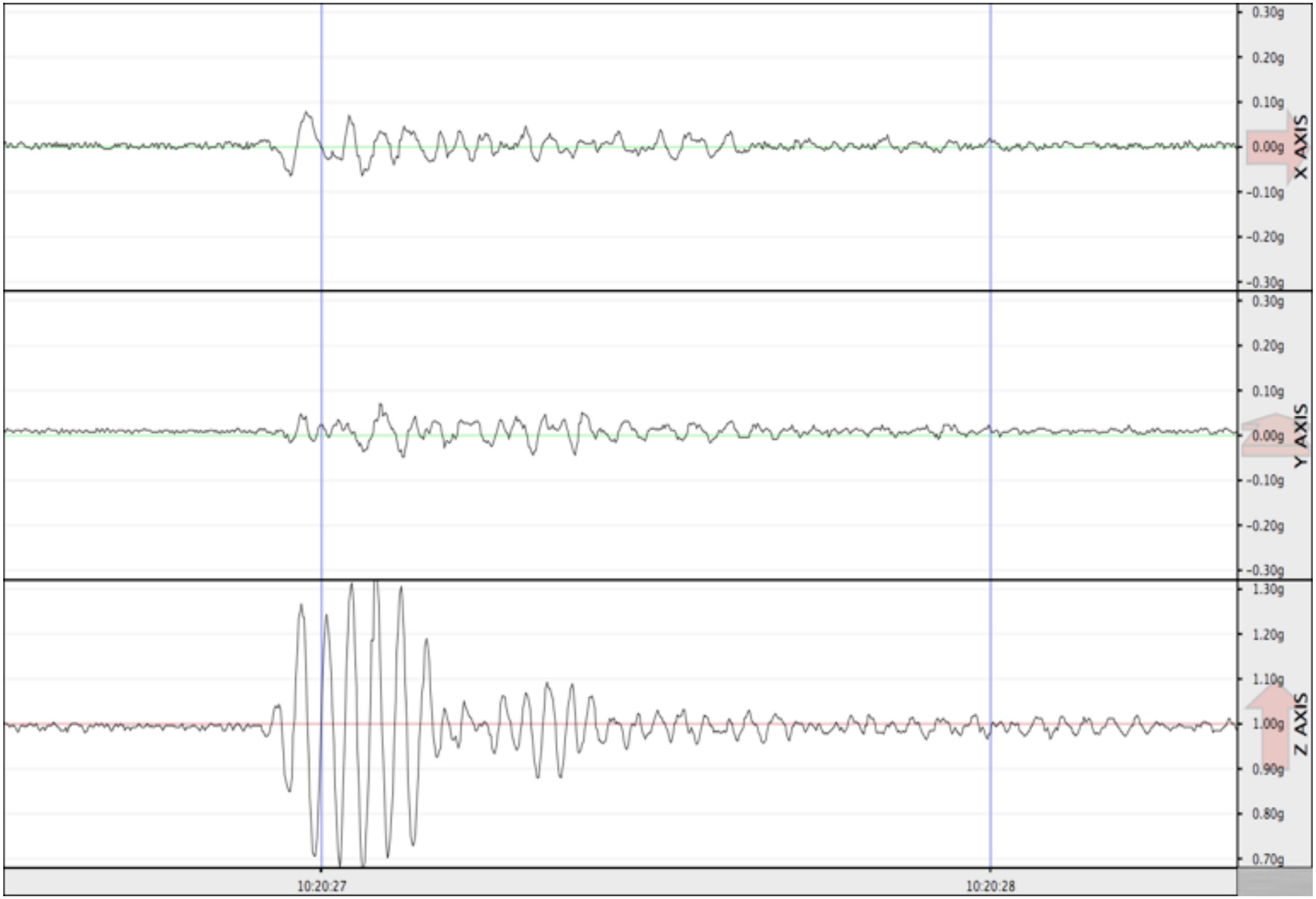
Z poses a challenging environment for experiments



• 30 – 100 g instantaneous shock at center

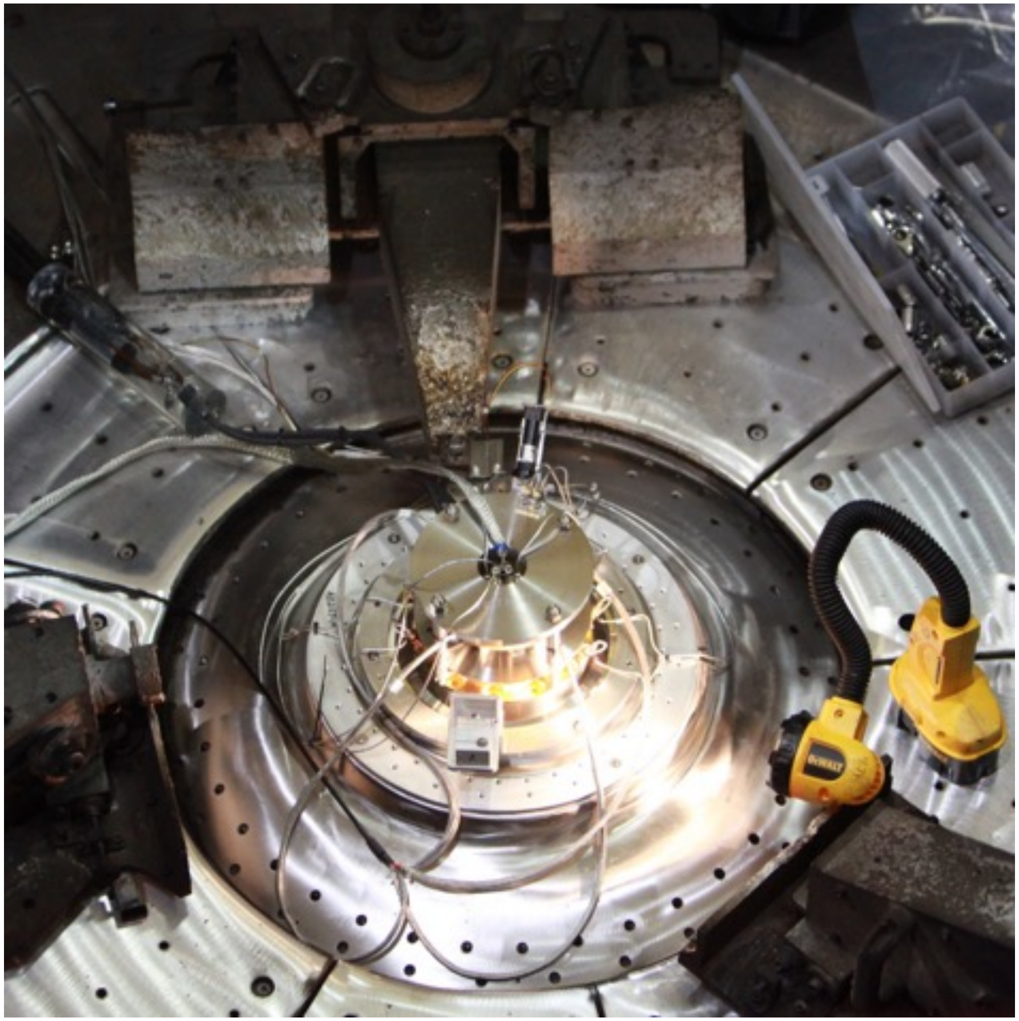
Michael Jones

The ground shock is ±1g of acceleration over 200 ms



Seismac program

Debris from all experiments must be carefully managed (several MJ energy release is equivalent to few sticks of dynamite)



Pre-shot photo of coils & target hardware

Post-shot photo

MagLIF Experiment

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

- High energy density matter is in a state well outside of what we normally experience
- 1 Mbar > 10^6 atmospheres
- 1 Mbar = 100 kJ/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A Toyota 4runner weighs about 4600 lbs
- Traveling at 70 MPH it has a kinetic energy of ~ 1 MJ
- Its volume is ~ 10 million cm^3
- Energy density ~ 0.1 J/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A baseball weighs 0.145 kg
- Traveling at 100 mph it has a kinetic energy of ~ 150 J
- Its volume is ~ 200 cm^3
- Energy density ~ 1 J/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm³

- Burning a match releases about 1 kJ of energy
- The volume of a match is ~ 0.33 cm^3

- Energy density ~ 3 kJ/cm^3

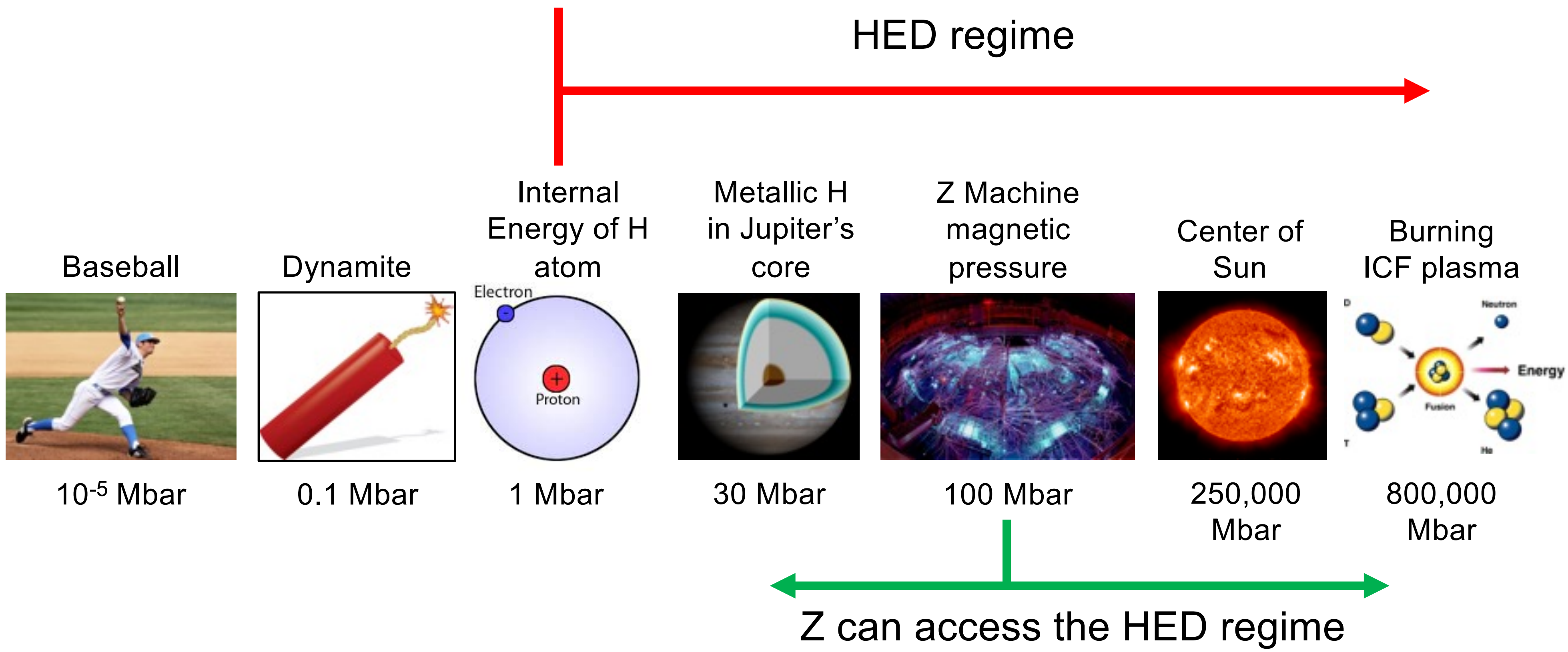
Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A stick of dynamite has a stored energy of about 1-2 MJ
- A stick of dynamite is 20 cm long and 3.2 cm in diameter
  - Volume = 161 cm^3

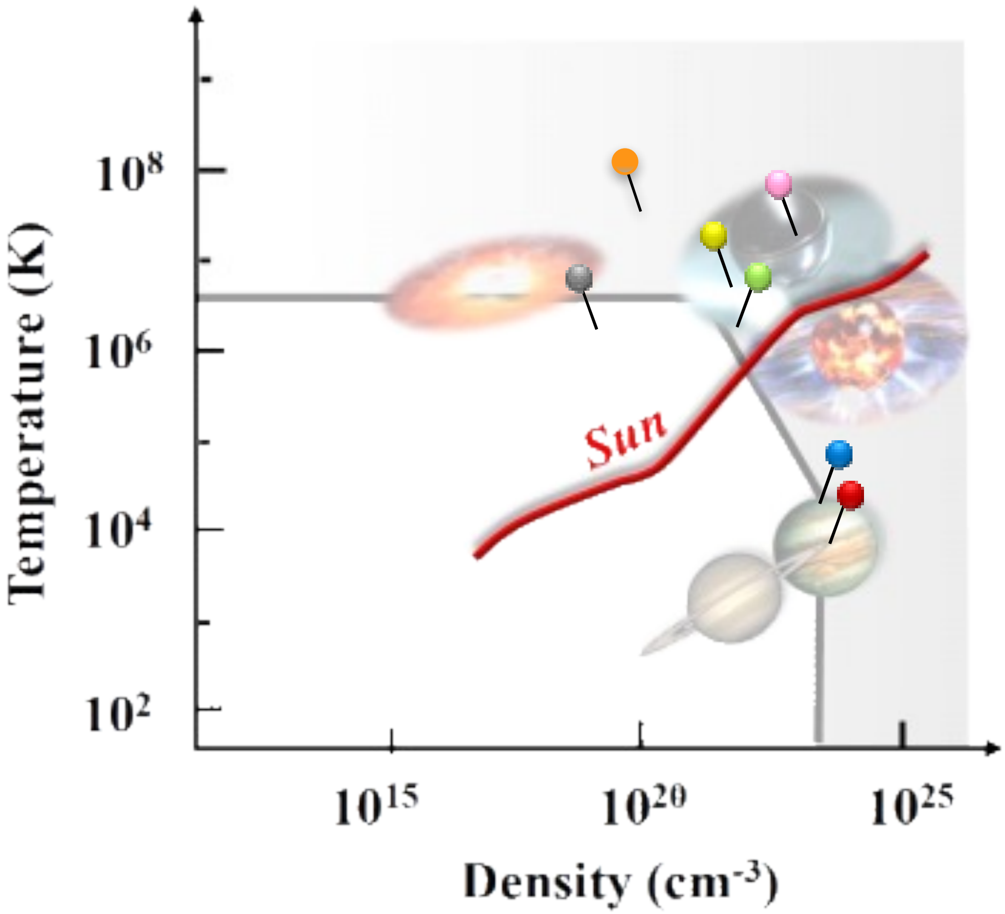
- Energy density ~10 kJ/cm^3

The HED regime is beyond what we normally experience, but common in the universe



The efficient delivery of magnetic energy over large spatial scales on Z has revolutionized HED science

Pulsed Power driven experiments on Z are "engines of discovery" for HED and stockpile stewardship



Diamond at 10 Mbar
Knudson et al., Science 322 (2008)

D_2 EOS at 1 Mbar
Knudson et al., PRL 87 (2001)

Photoionized Plasmas
Foord et al., PRL 94 (2004)

Radiating Shocks
Rochau et al., PRL 100 (2008)

Opacity at T_e > 150 eV
Bailey et al., PRL 99 (2007)

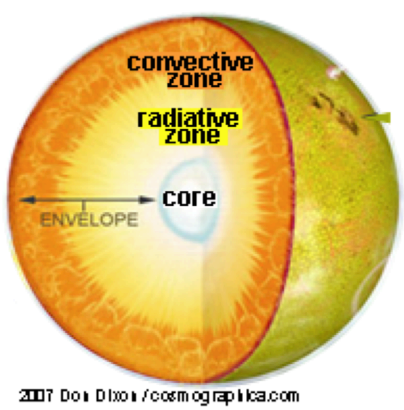
Fusing Plasmas
Bailey et al., PRL 93 (2004)

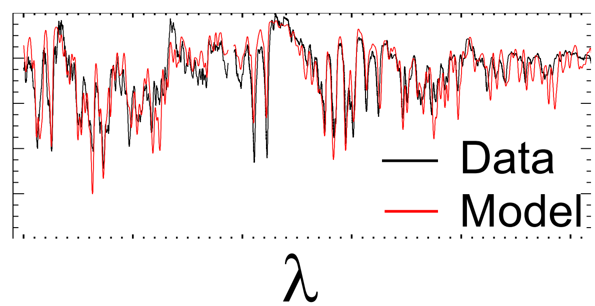
High-Z Ion Radiating Plasmas at 40 Mbar
Ampleford et al.. submitted PoP (2013)

figure courtesy of G. Rochau

Magnetically-driven x-ray sources are being used for a variety of fundamental and applied science applications

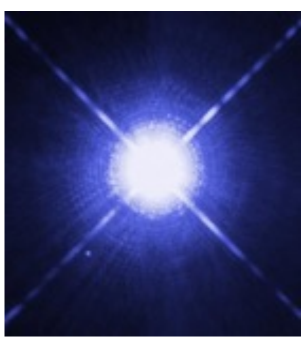
Solar opacity at T_e > 150-170 eV





J. E. Bailey, et al., Nature 517, 7532 p. 56 (2015)

White dwarf physics



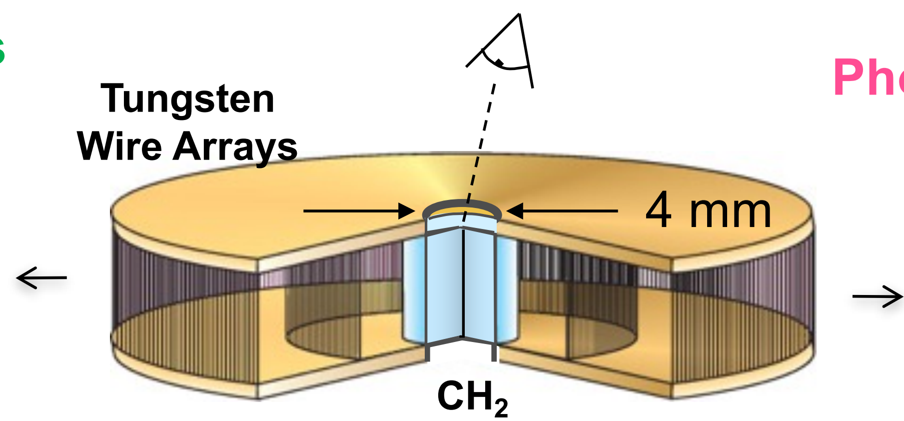
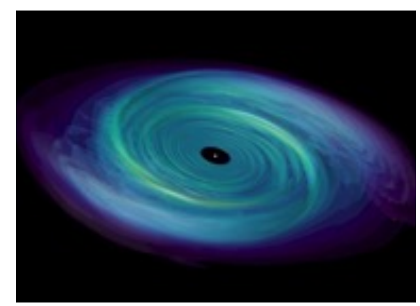


Photo-ionized plasmas

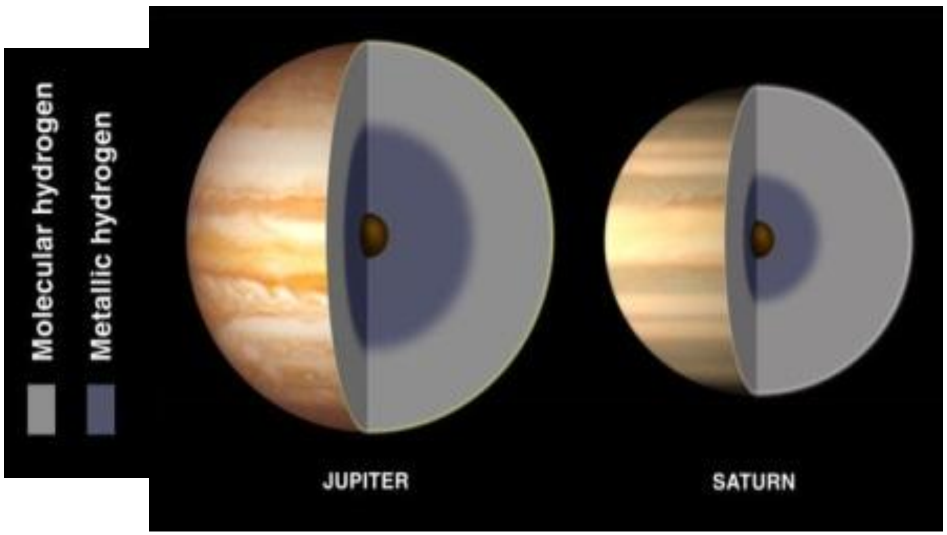


G. P. Loisel, et al., PRL 119, 075001 (2017)

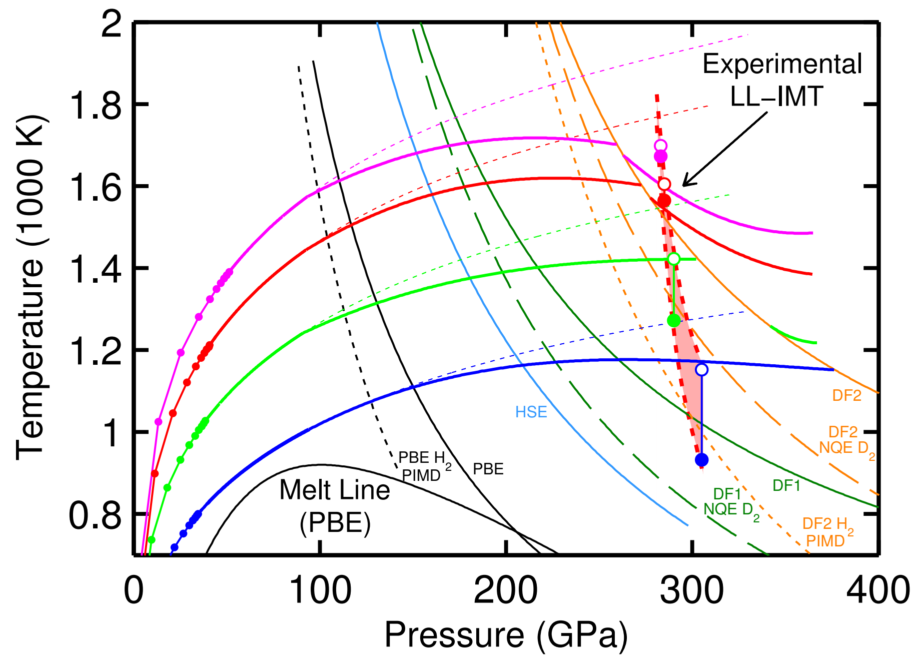
- 1 µg of stellar interior at R ~ 0.7Rsol
- ~0.1 liters of white dwarf photosphere
- 10^{-3} liters of accretion disk at R ~ 100 – 1000 km from black hole
- weapons science

Z produces unprecedented states of matter in the laboratory

Dynamic Material Properties



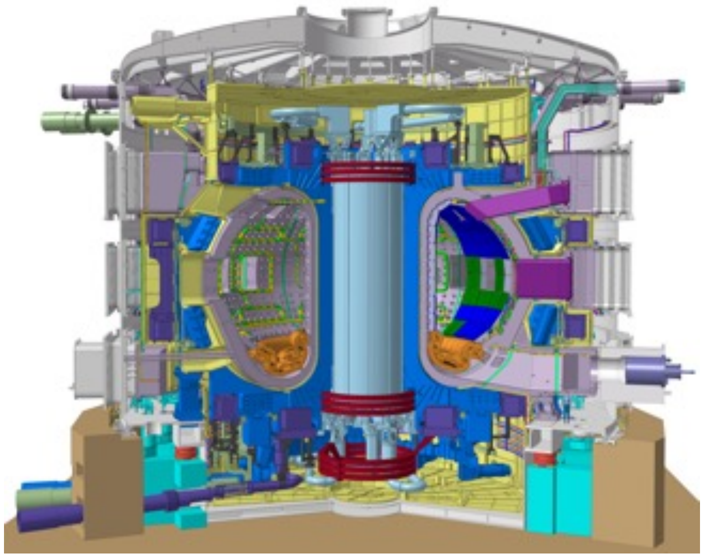
Metallic Hydrogen



M. D. Knudson, et al., Science 348, 6242 p. 1455 (2015)

Magnetic confinement fusion utilizes magnetic fields hold a plasma while fusion reactions occur

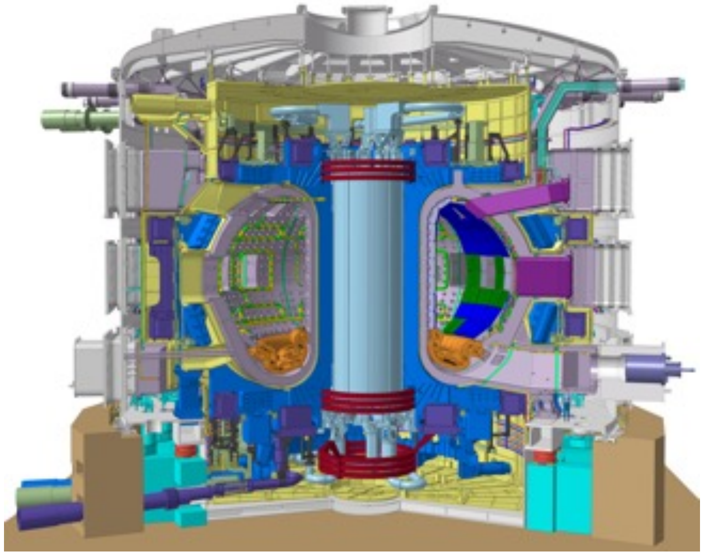
ITER



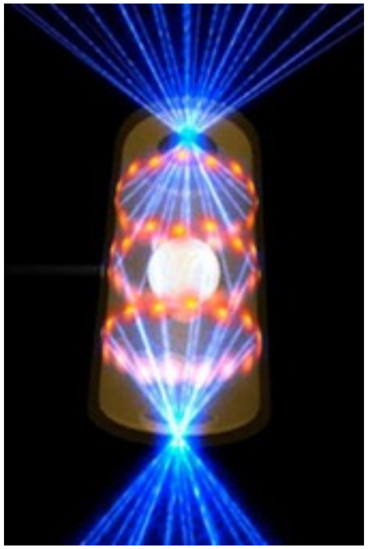
Density	1 x 10^{14} cm^{-3}		
Volume	8 x 10^{8} cm^{3}		
Duration	300-500 s		
Magnetic field	100 kG		

Inertial confinement fusion relies on sufficient fusion reactions occurring prior to falling apart

ITER



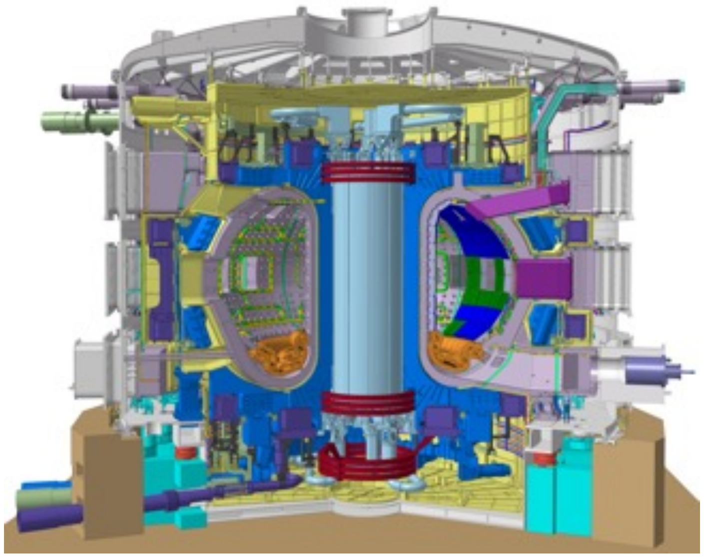
NIF hohlraum



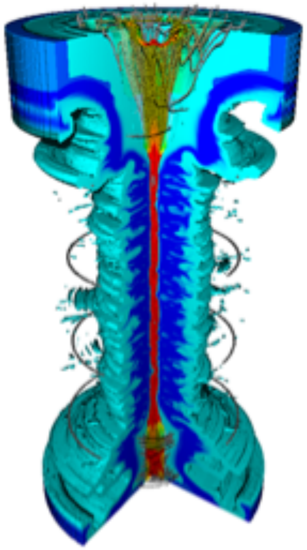
Density	1 x 10^{14} cm^{-3}		2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}		6 x 10^{-8} cm^{3}
Duration	300-500 s		5-10 x 10^{-11} s
Magnetic field	100 kG		0 kG

Magneto-inertial fusion sits in the space between magnetic and inertial confinement fusion

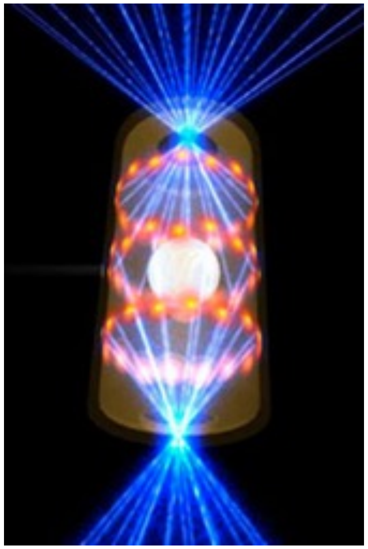
ITER



MIF concept

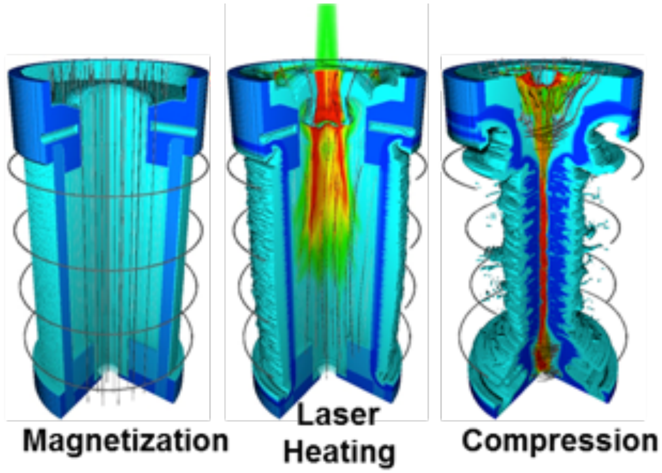


NIF hohlraum



Density	1 x 10^{14} cm^{-3}	1 x 10^{23} cm^{-3}	2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}	8 x 10^{-5} cm^{3}	6 x 10^{-8} cm^{3}
Duration	300-500 s	1-2 x 10^{-9} s	5-10 x 10^{-11} s
Magnetic field	100 kG	50-100 MG	0 kG

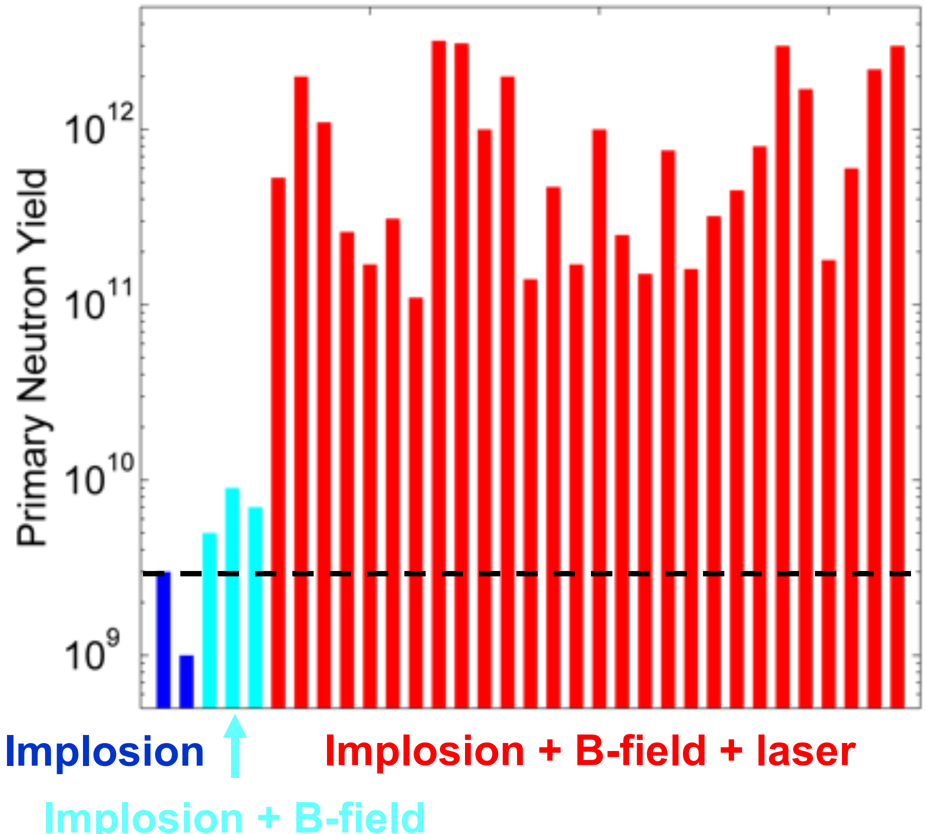
We are developing a magnetic direct drive (MDD) magneto-inertial fusion concept called MagLIF



	No B-field	B-field
No Laser Heating	3×10^{9}	1×10^{10}
Laser Heating	4×10^{10}	3×10^{12}

Inertial Confinement Fusion

Fuel conditions ~ 3 GBar

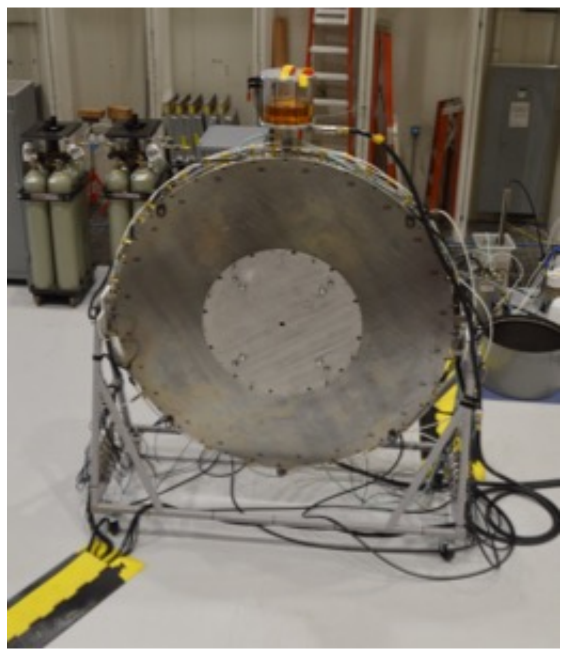


M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014).

Good performance requires both laser pre-heat and pre-magnetization with B-field

We are developing a new generation of pulsed power drivers for the fundamental HED and stewardship experiments of tomorrow

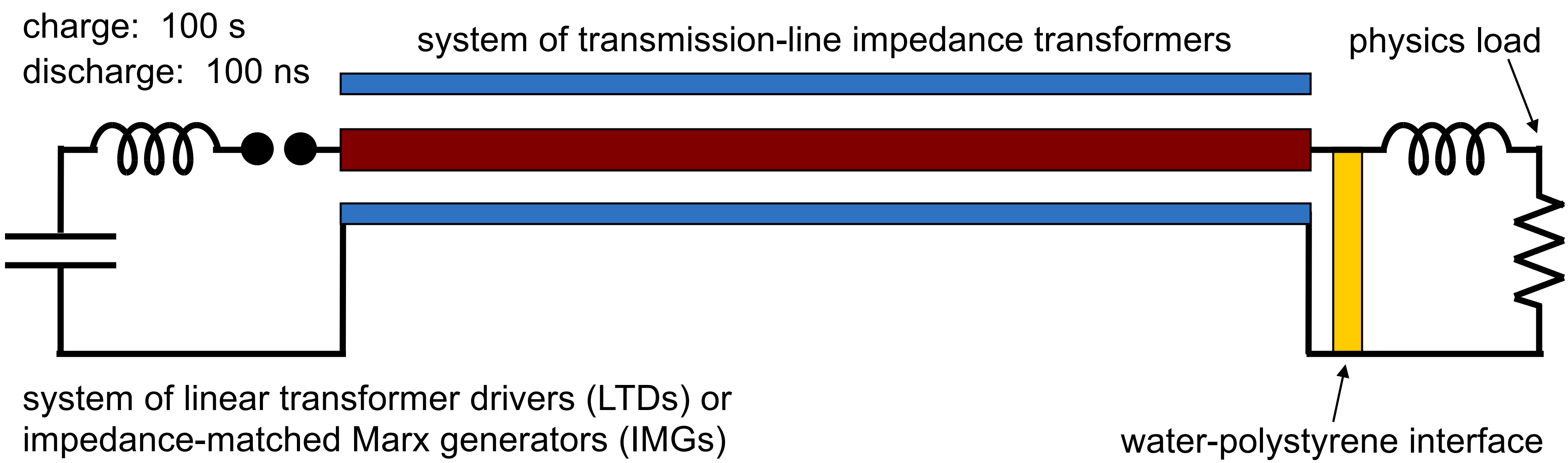
Current Adder	Current and Voltage Adder	Multi-Pulse Voltage Adder
Dynamic Materials Properties with arbitrary loading	Z Next Module	4 pulse technology for radiographic application
Thor – 4 MA (2017)	Z Next Cavity 1 MA, 100 GW LTD (2017)	Centipede 250 kV, 1 GW (2017)



We are developing a new approach to the design of next-generation accelerators

The approach is based on six fundamental concepts:

- Single-stage electrical-pulse compression.
- Low-voltage switching.
- Impedance matching.
- Transit-time-isolated prime power sources.
- Economies of scale.
- Engineered safety.



Thor is a *proof of principle* demonstration of a multi-MA arbitrary waveform generator for Dynamic Materials Properties

Energy storage
• 6 brick towers

Coupling
• 6 cable towers

Coupling
• Central Power Flow Section

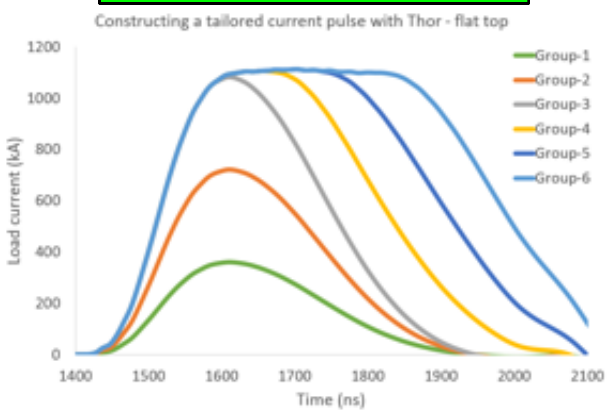
2017 – Thor 48 provides 250 kBar

2018 – Thor 72 provides 600 kBar

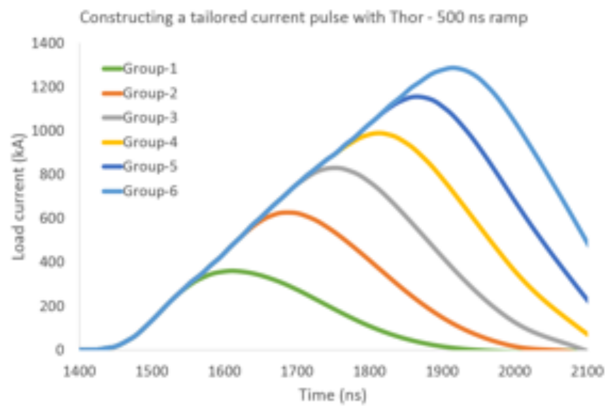
B. Stoltzfus et al. (2017)

Thor is capable of different loading histories, which allows greater flexibility in accessing temperature-density phase space

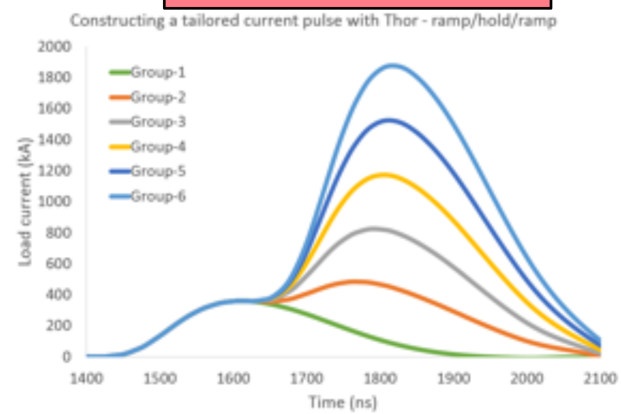
ramp-hold-release



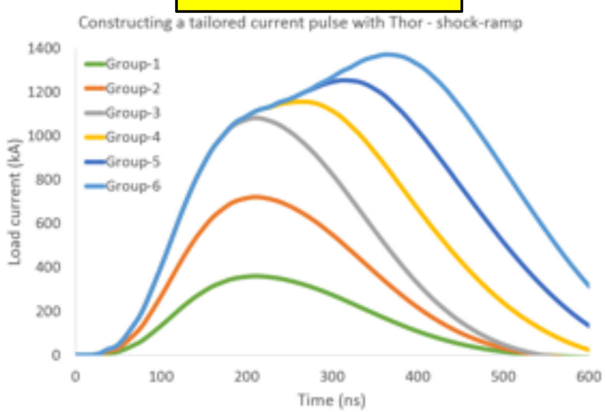
ramp



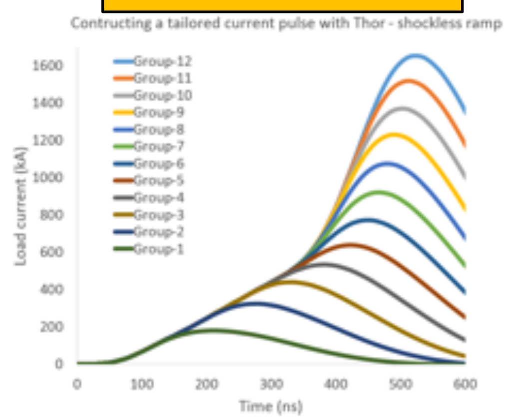
ramp-hold-ramp



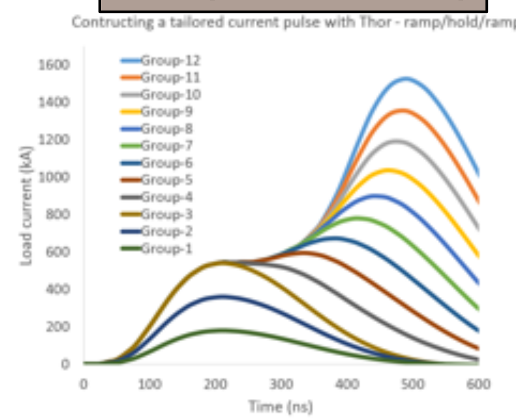
shock-ramp



shockless ramp



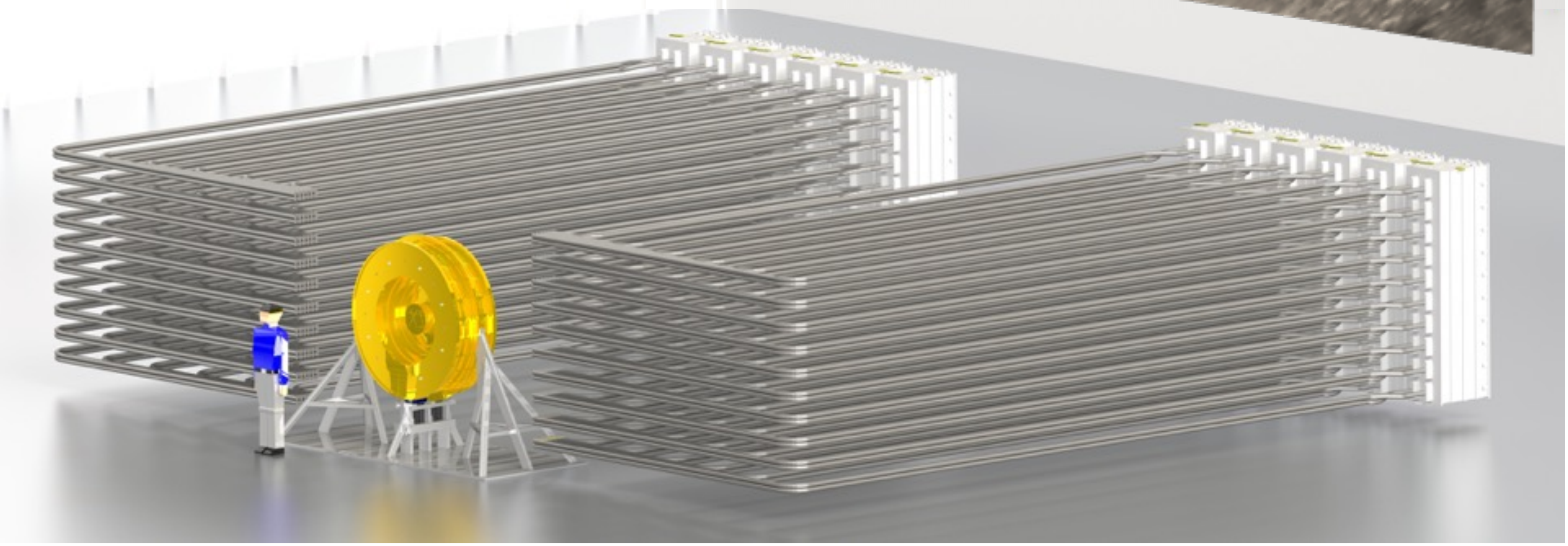
ramp-hold-ramp



Yogi Gupta: “There is no capability like this anywhere.” (May 2017)

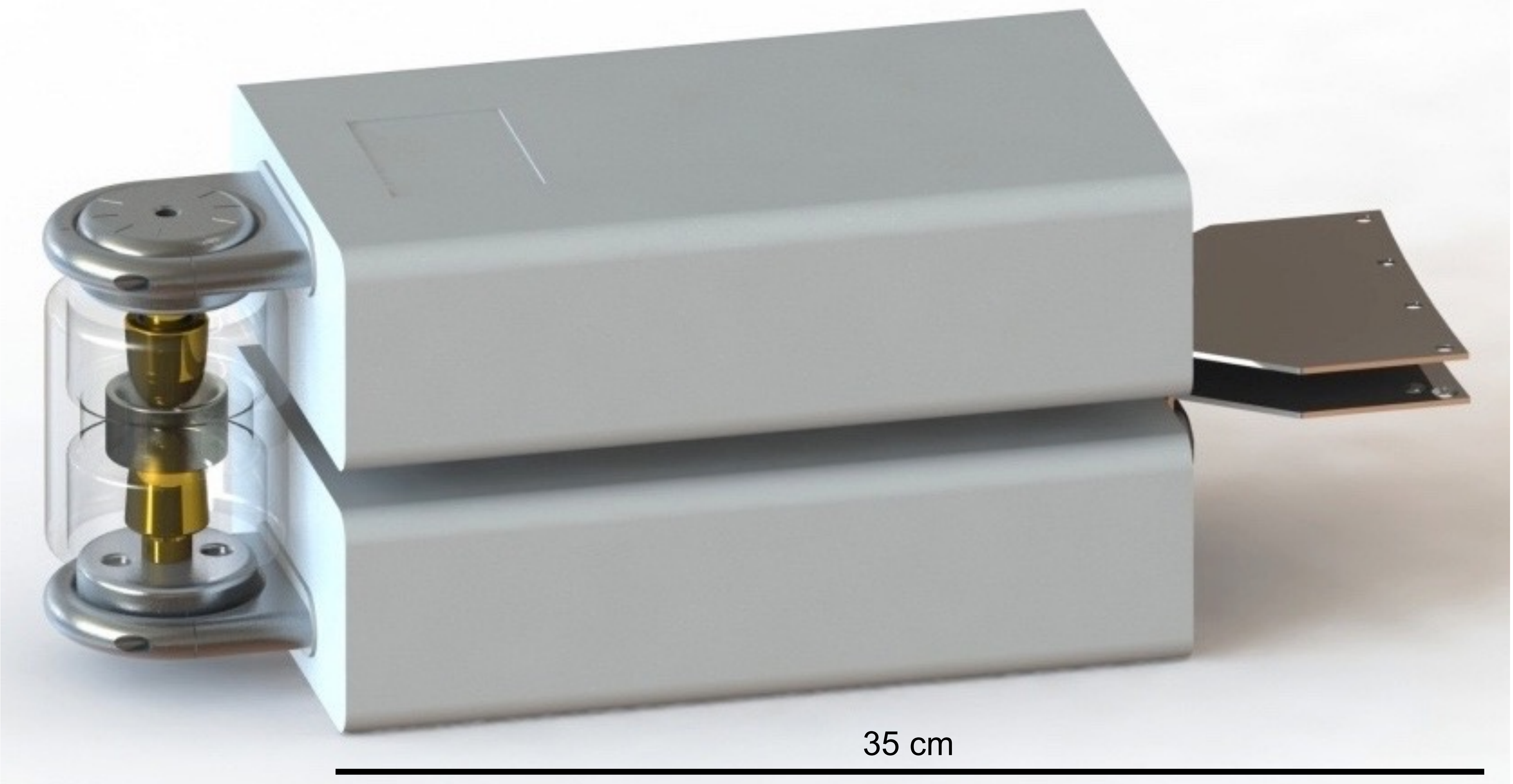
Thor - 0.2 TPa (2 Mbar)

- Is powered by 240 “bricks.”
- Stores 190 kJ of electrical energy.
- Generates a peak electrical power of 1.2 TW.
- Delivers an arbitrary pressure-loading time history to a physics load.



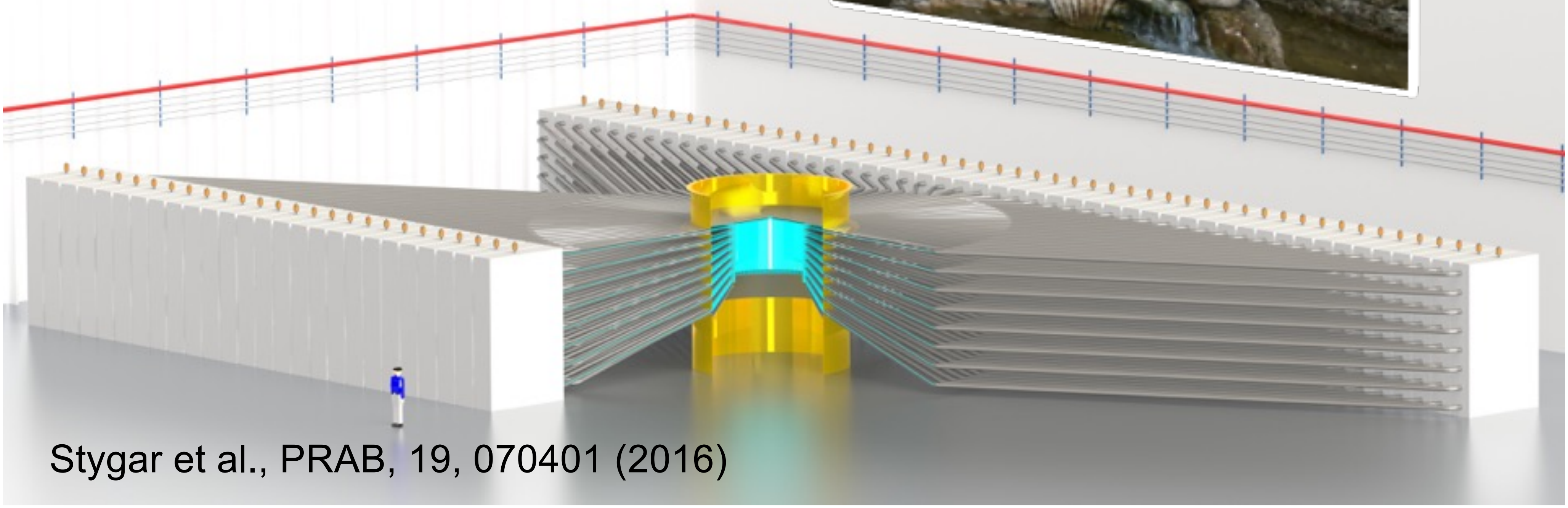
Thor is powered by 240 “bricks”

- Each brick consists of two capacitors connected in series with a single switch.
- A brick is a quantum of pulsed power.
- A brick is also the simplest possible impedance-matched Marx generator.
- The rest of Thor consists of oil, water, plastic, and stainless steel.



Neptune – 2 Tpa (20 MBar)

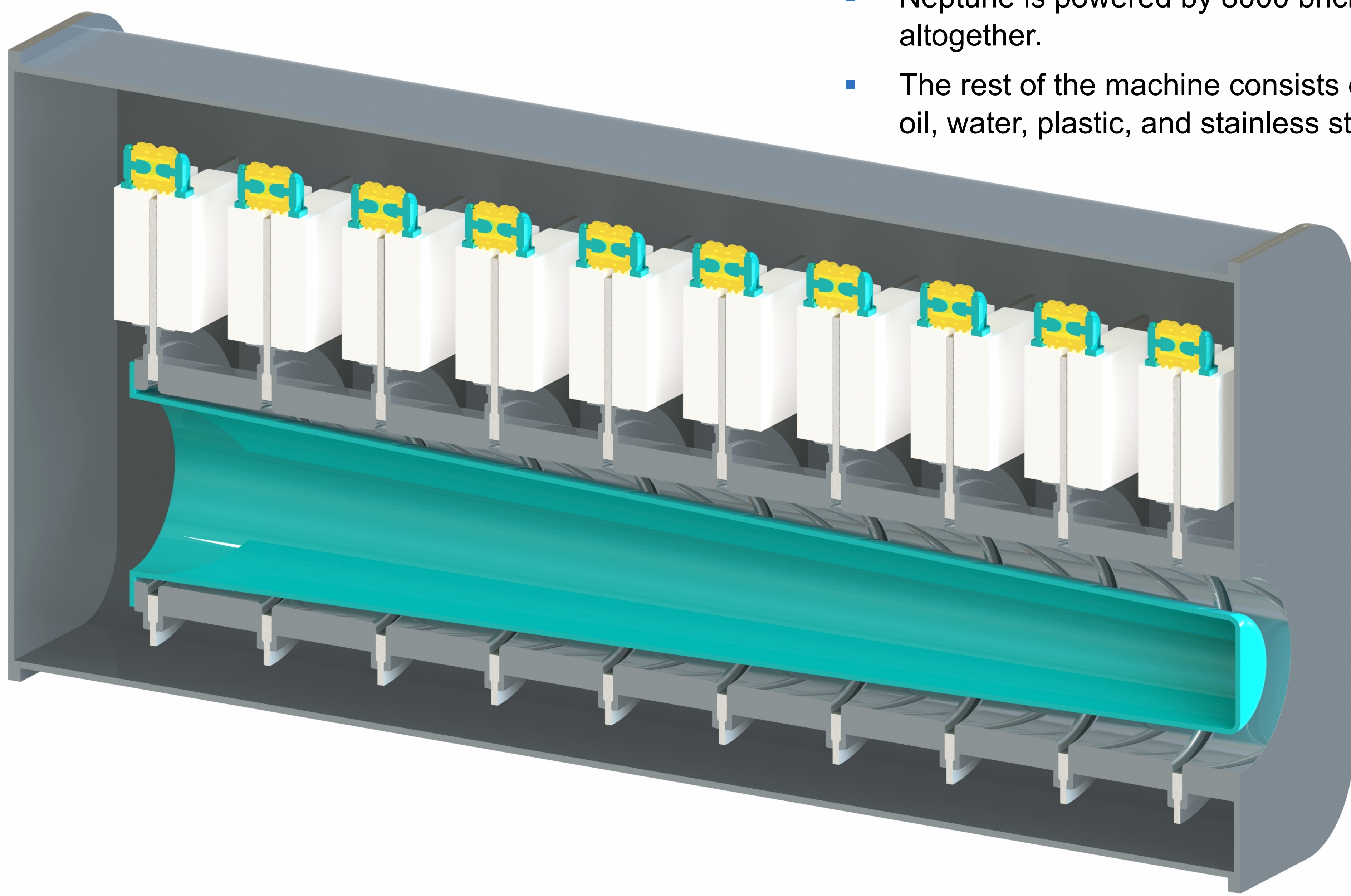
- Is powered by 800 impedance-matched Marx generators.
- Stores 11 MJ of electrical energy.
- Generates a peak electrical power of 50 TW.
- Delivers an arbitrary pressure-loading time history to a physics load.



Stygar et al., PRAB, 19, 070401 (2016)

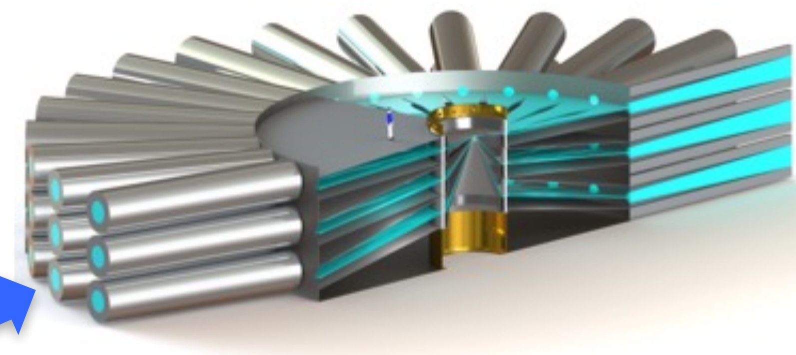
Neptune is powered by 800 impedance-matched Marx generators (IMGs)

- Each Neptune IMG has ten stages.
- Each stage is powered by a single brick.
- Neptune is powered by 8000 bricks altogether.
- The rest of the machine consists of oil, water, plastic, and stainless steel.



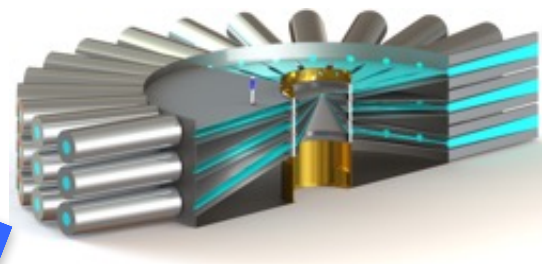
We are currently exploring ICF target designs and pulsed power architectures that may be on the path to >30 MJ fusion yields

Z-800 Goal
Yield = Emachine



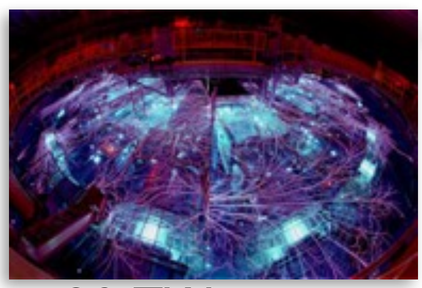
- 890 TW
- 52 m diameter
- 130 MJ stored energy
- 66 MA

Z-300 Goal
Yield = Etarget



- 320 TW
- 35 m diameter
- 47 MJ stored energy
- 49 MA

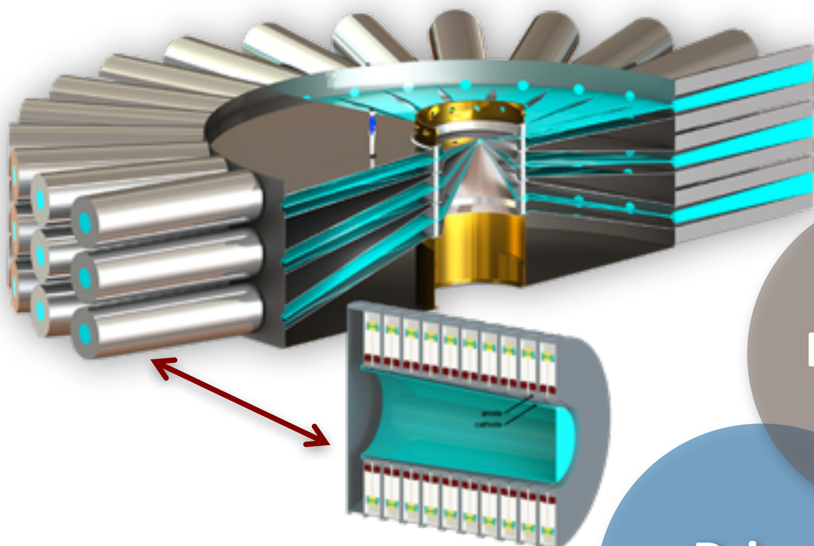
Z Goal
Yield = Efuel

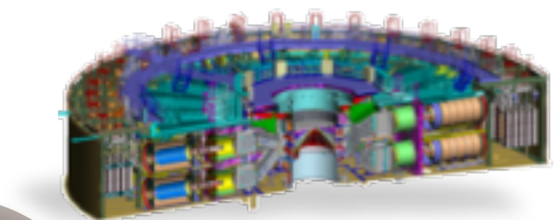


- 80 TW
- 33 m diameter
- 22 MJ stored energy
- 26 MA peak current

Stygar et al., PRSTAB, 10, 030401 (2007)
Stygar et al., PRSTAB, 18, 110401 (2015)

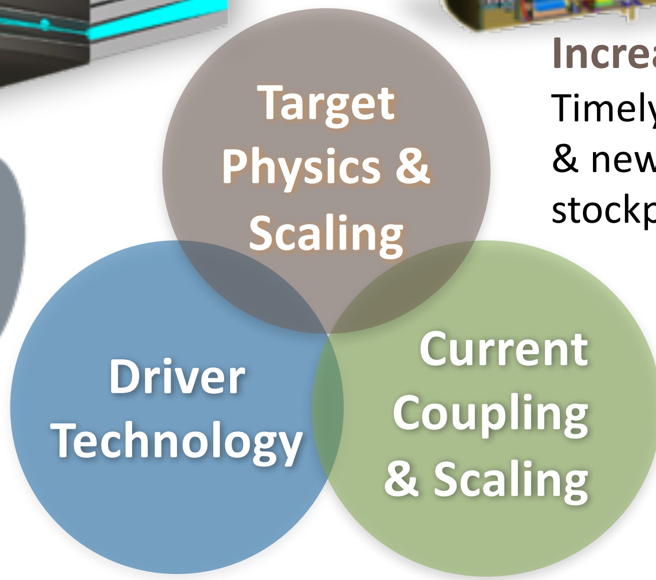
Multiple major investments are required to make a credible technical case for Z-Next





Increase the shot capacity of the Z facility

Timely evaluation of new magnetic drive targets & new capabilities while supporting today's stockpile

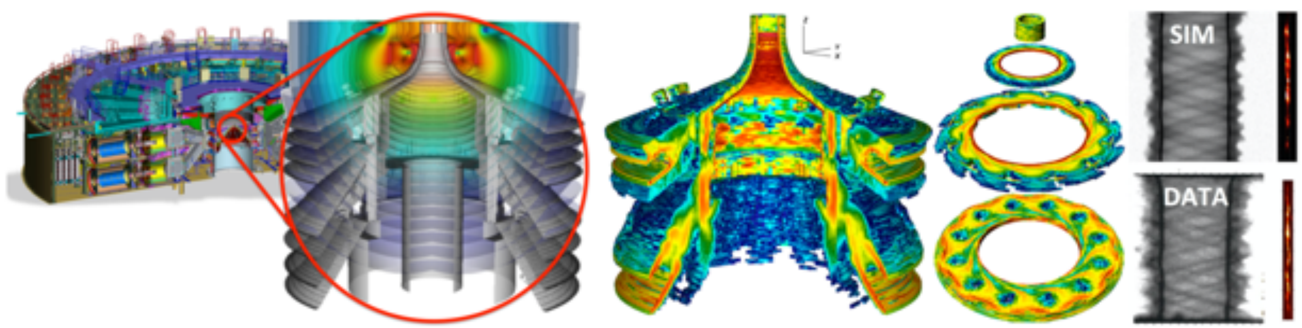


Build a Z-Next Module

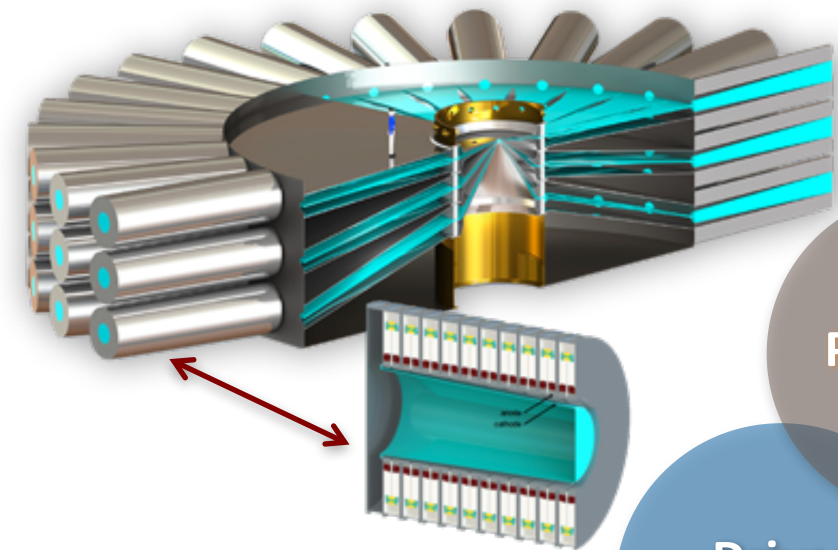
Demonstrate technology & develop supply chain

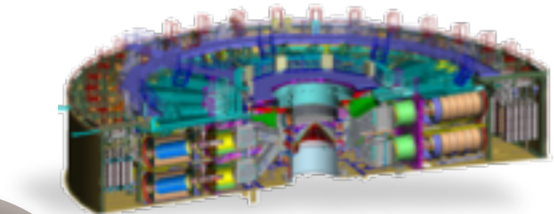
Develop next-generation plasma science & engineering code

Reduce risks & increase predictive capability tools for scaling to a Z-Next

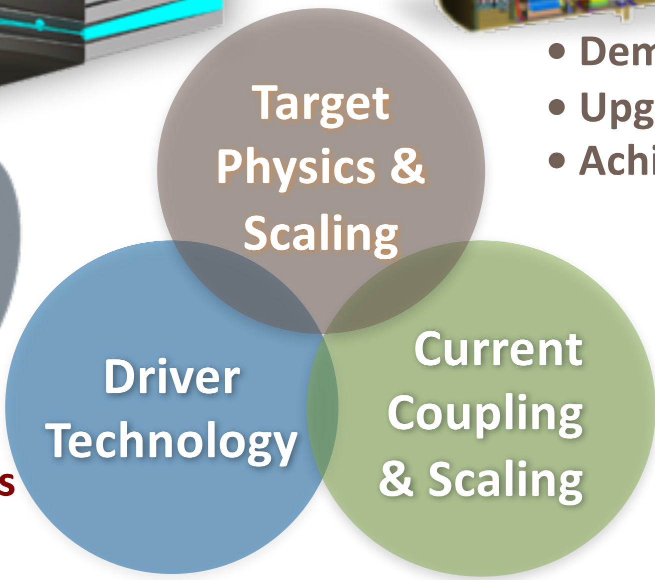


Multiple major investments are required to make a credible technical case for Z-Next



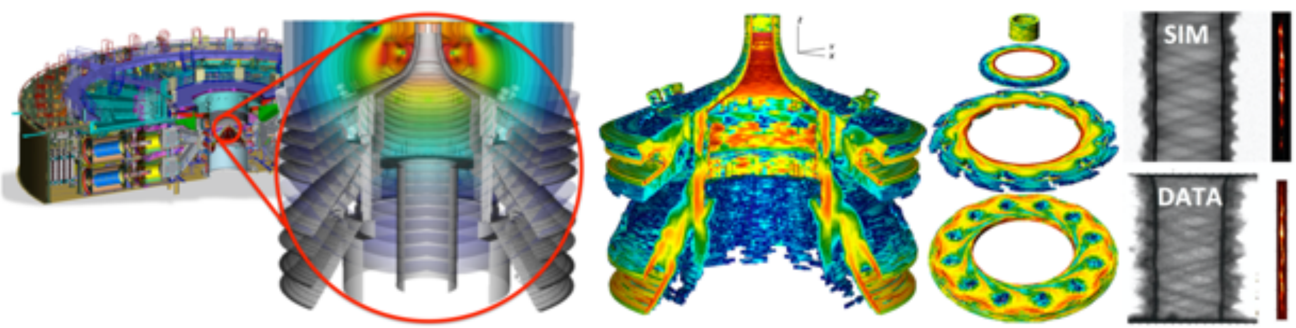


- Demo insulator stack on Z scales to Z Next
- Upgrade the facility to handle 50-50 DT
- Achieve 100 kJ DT fusion with MDD

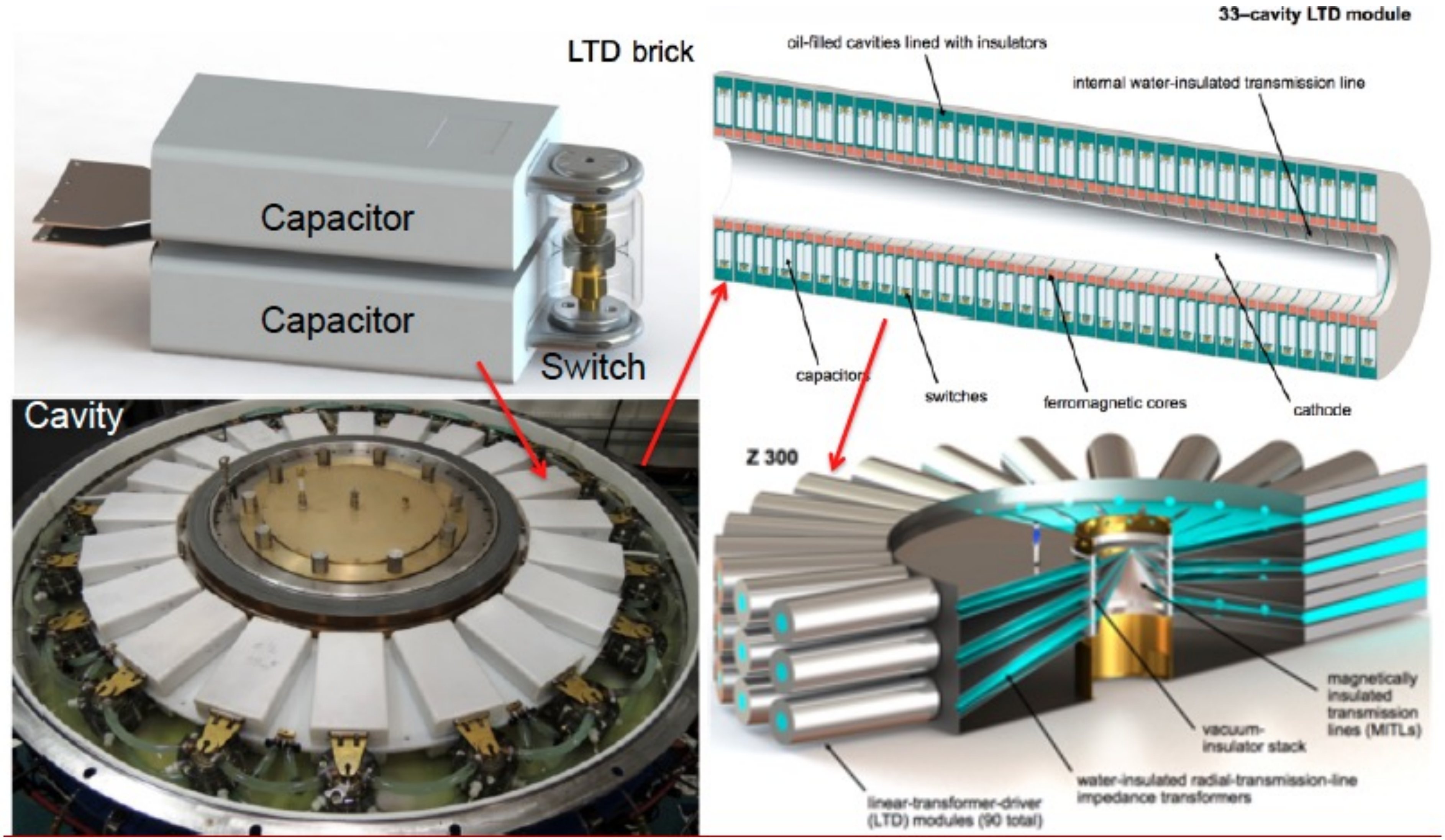


- Predictive plasma engineering code
- Demo coupling on Z scales to Z Next

- Downselect technology
- Triggering system 10^5 locations
- Build a ½ scale module
- Build a full scale module
- Demo reliability
- Develop supply chain and meet cost targets



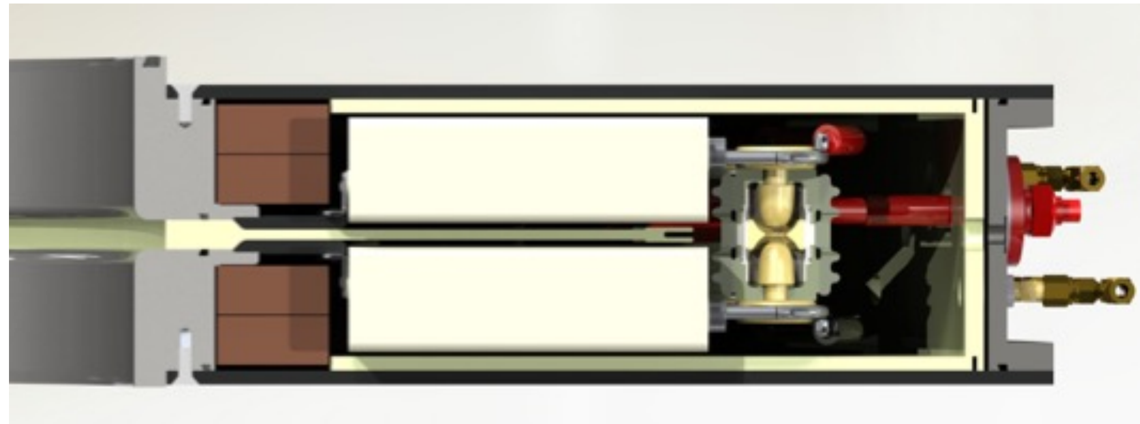
We have developed an architecture that can scale to 800-1000 TW and that is twice as efficient and twice as compact as Z



We have commissioned the world's most advanced LTD-Cavity-Test Facility

- The cavity's switch prefire and misfire rates are < 0.4% and < 4%, respectively.
- These meet the requirements we established for a Z Next-class accelerator.
- The cavity uses inherently safe capacitors, does not use SF_6 as an insulating gas (or any other greenhouse gas or asphyxiant), does not use lead (or any other neurotoxin) in the switch electrodes, and does not require hazardous lasers to trigger its 20 switches.
- The facility automatically conducts a cavity shot every 120 s.

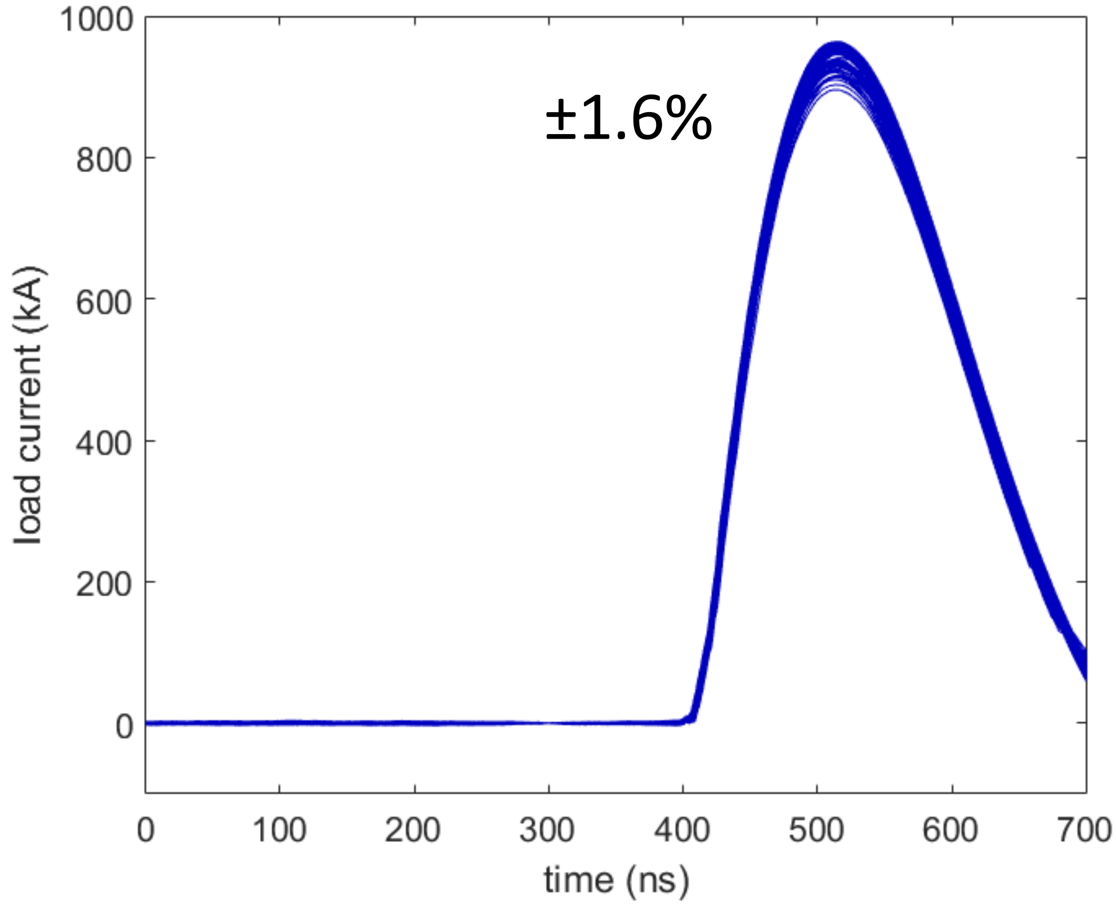
first U.S. megampere-class LTD cavity



We have conducted 100 shots with the first megampere-class LTD cavity designed by the U.S.

- The shots were conducted at a capacitor-charge voltage of 90 kV.
- At this voltage, the average value of the peak current generated by the cavity is 950 kA
- The cavity is powered by 20 bricks.
  - The world's first 20-brick cavity, which was designed by our Russian colleagues, generated a peak current of 440 kA.
- We are presently upgrading the cavity.
  - The performance of the upgraded cavity will be evaluated at 100 kV.

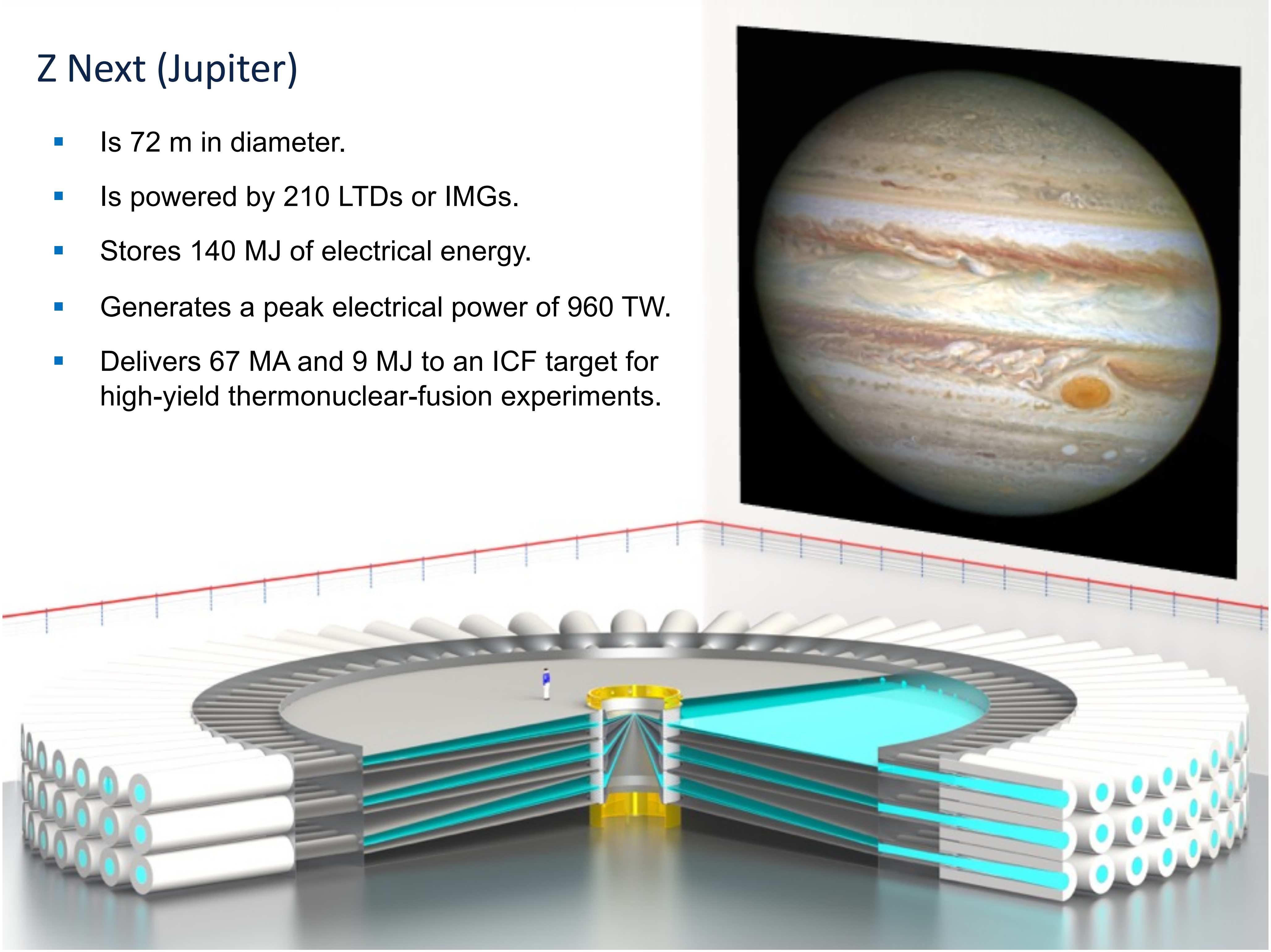
load-current time histories measured on 100 LTD-cavity shots



M. Wisher et al, (2017)

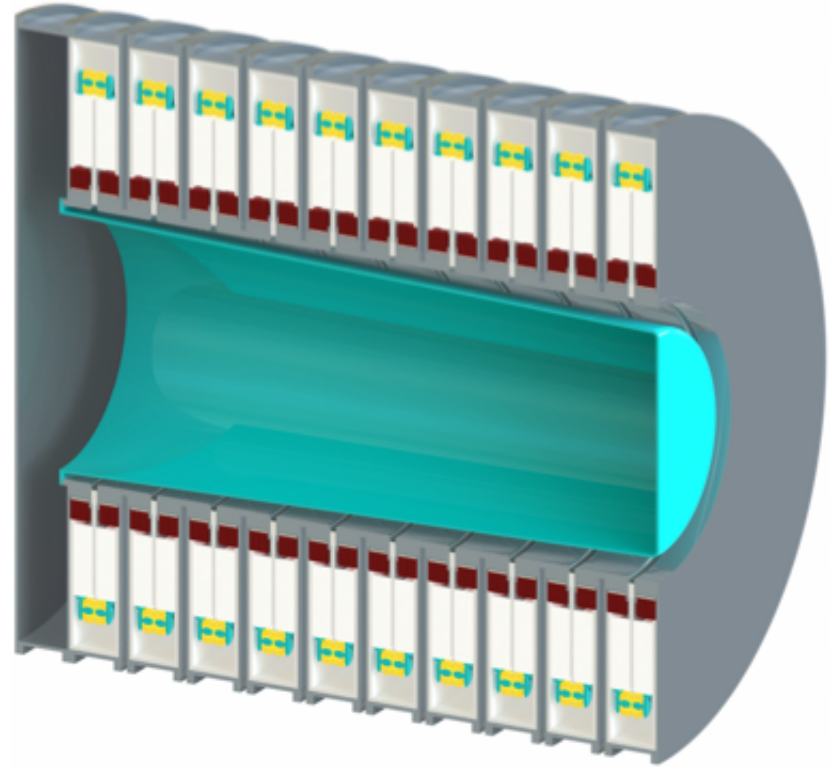
Z Next (Jupiter)

- Is 72 m in diameter.
- Is powered by 210 LTDs or IMGs.
- Stores 140 MJ of electrical energy.
- Generates a peak electrical power of 960 TW.
- Delivers 67 MA and 9 MJ to an ICF target for high-yield thermonuclear-fusion experiments.

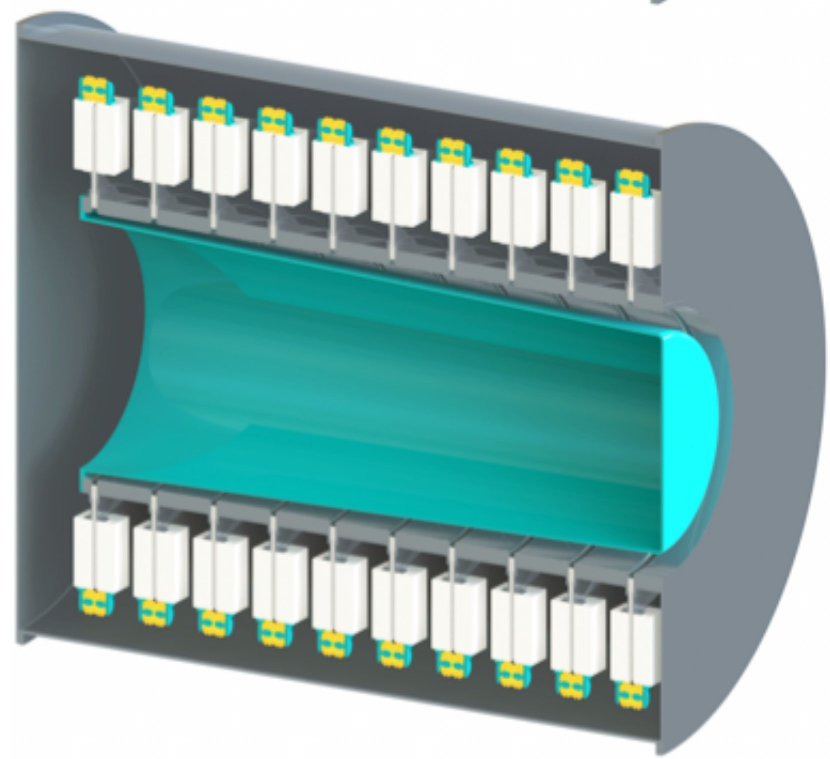


Jupiter will be powered either by linear transformer drivers (LTDs) or impedance-matched Marx generators (IMGs)

- Each LTD or IMG will comprise 42 stages connected electrically in series.
- Each stage will be powered by 20 bricks distributed azimuthally within the stage and connected electrically in parallel.
- We plan to build and evaluate a prototype LTD and an IMG in support of the Jupiter development effort.



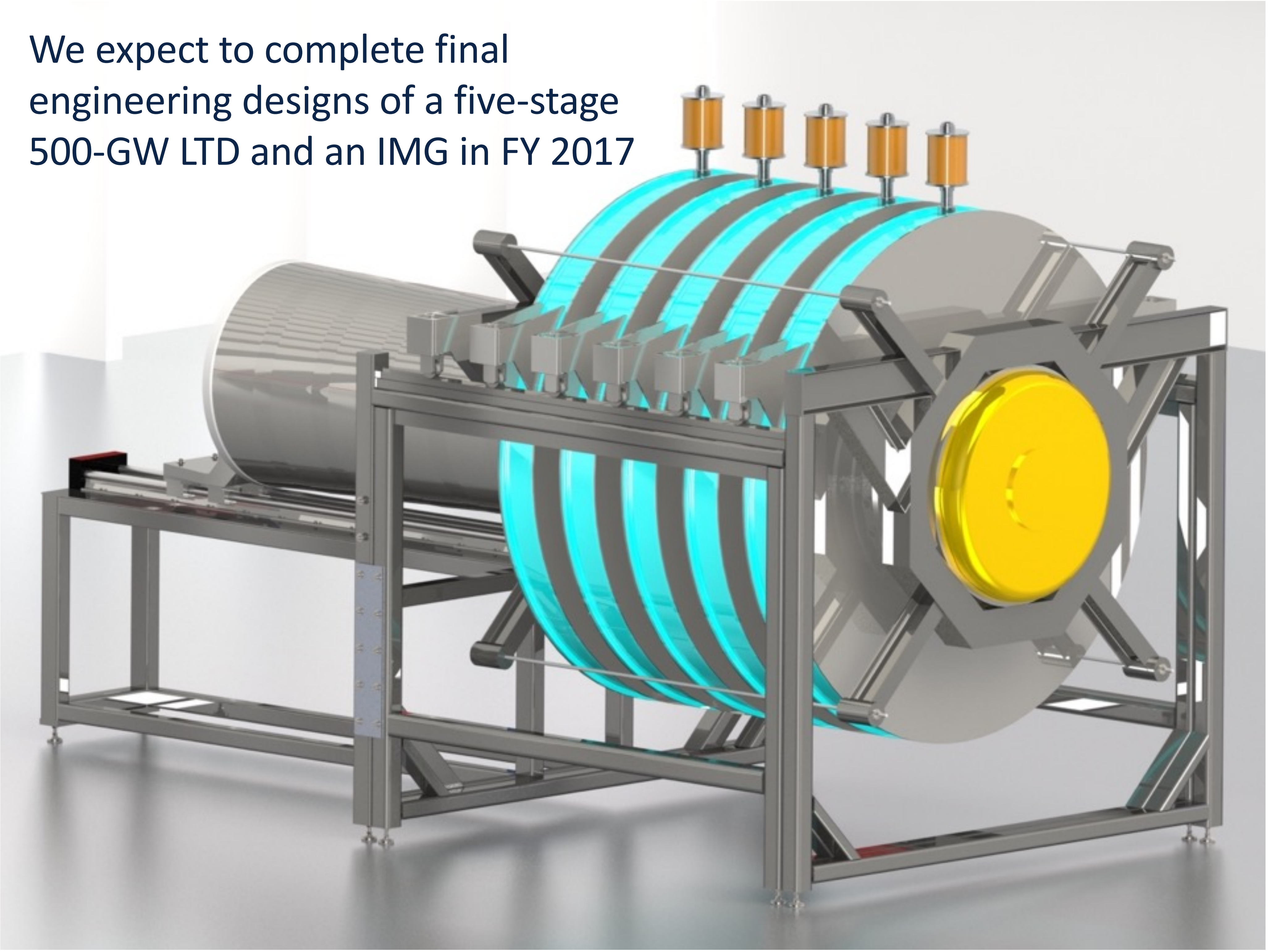
10-stage LTD module with 20 bricks per stage



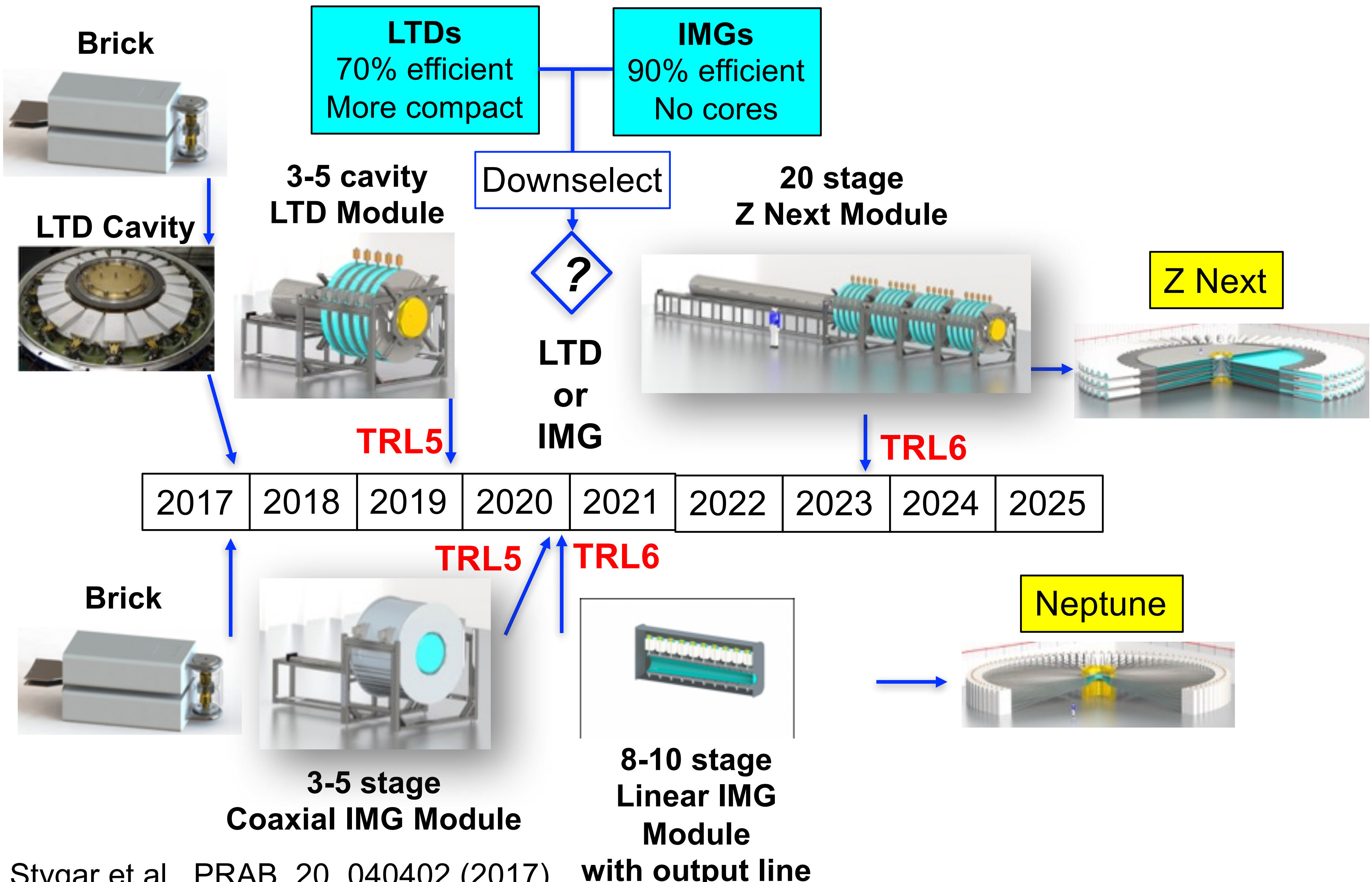
10-stage IMG module with 20 bricks per stage

Stygar, LeChien, Mazarakis et al., PRAB (2017).

We expect to complete final engineering designs of a five-stage 500-GW LTD and an IMG in FY 2017



We will develop Linear Transformer Drivers (LTDs) and Impedance matched Marx Generators (IMG) for future HEDP drivers



Stygar et al., PRAB, 20, 040402 (2017)

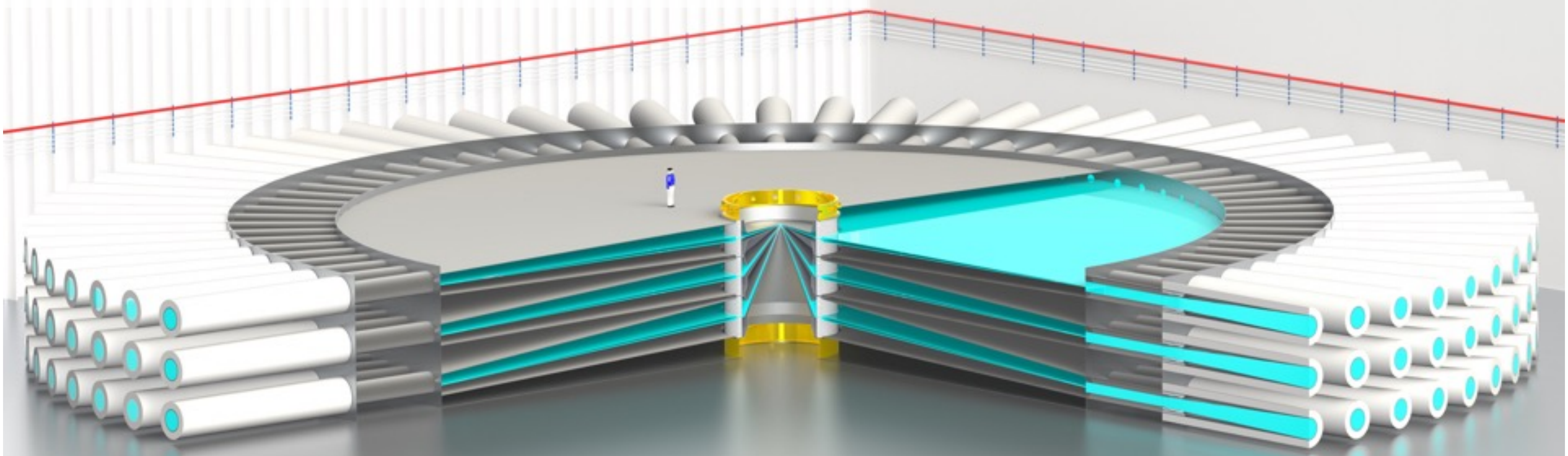
Z Next would store 140 MJ of electrical energy, and generates a peak electrical power of 960 TW

Peak current and energy delivered to the load: 67 MA and 9 MJ, respectively.

2D MHD simulations (Slutz and colleagues, POP, 2016) suggest Jupiter may achieve thermonuclear-fusion yields greater than 30 MJ in 1 ns burn widths.

1 PW electrical at stack
Up to 1-30 PW DT neutrons

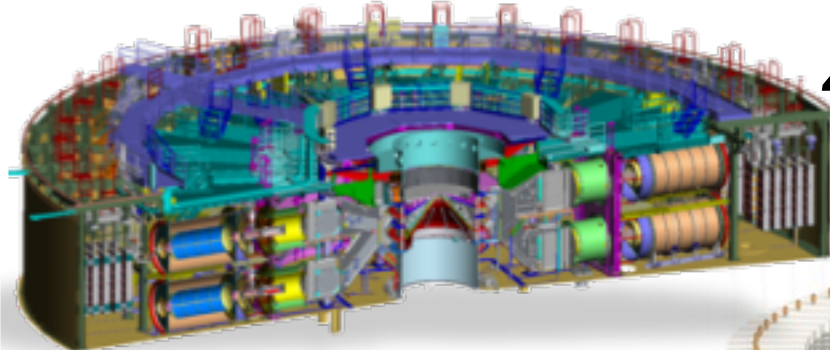
4-5 PW electrical at load
4-5 PW soft x-rays



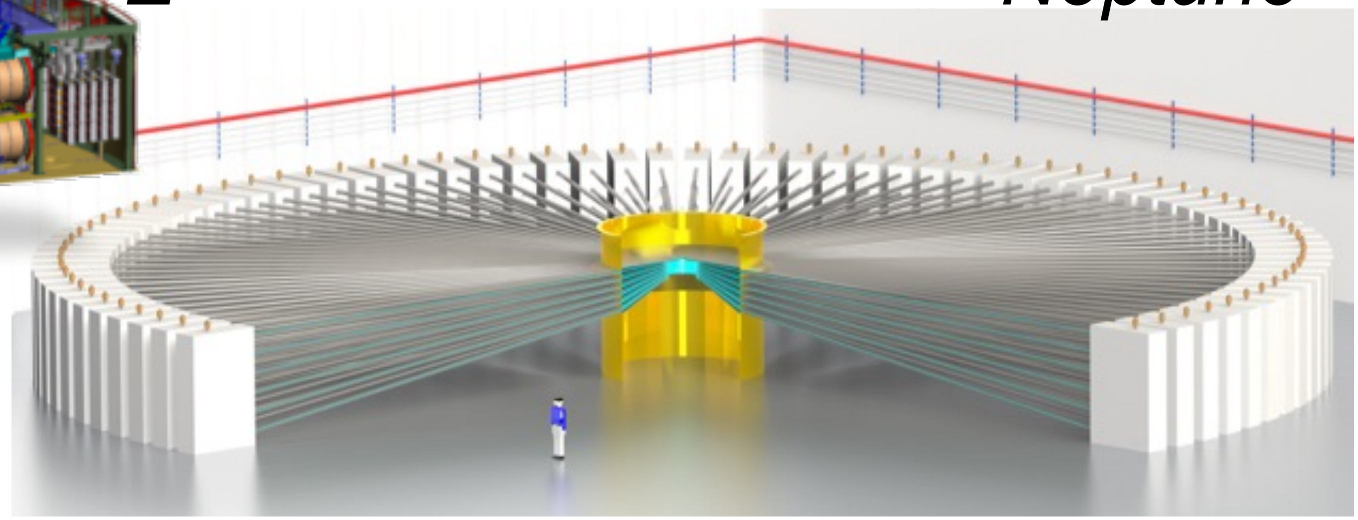
Stygar et al., International Conference on Fusion Science and Applications
St. Malo, France (2017)

Neptune & Z Next would be engines of discovery for HED and weapons science and achieve unprecedented conditions and outputs

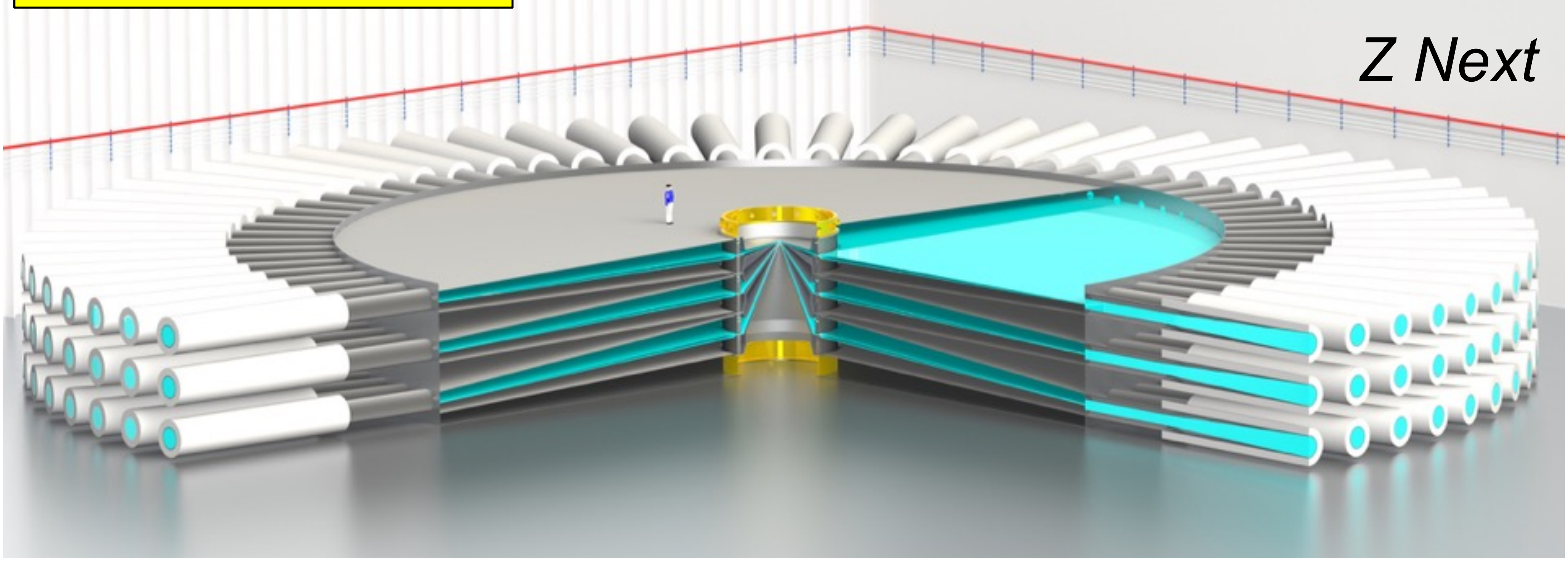
Z



Neptune

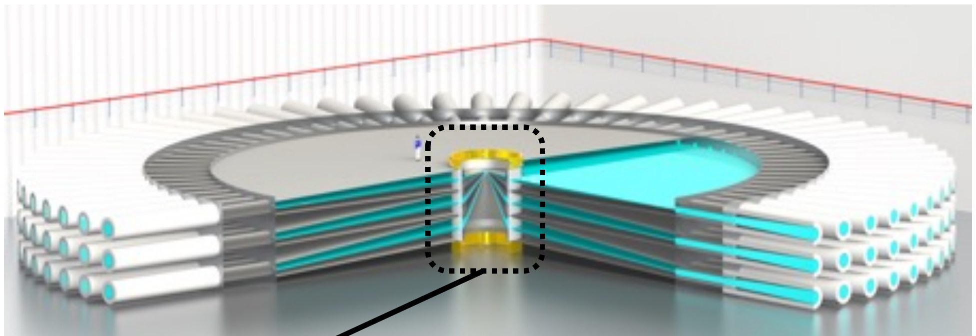


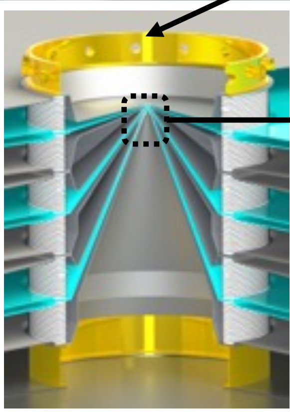
There is a significant amount of work to mature these pulsed power concepts and associated target designs

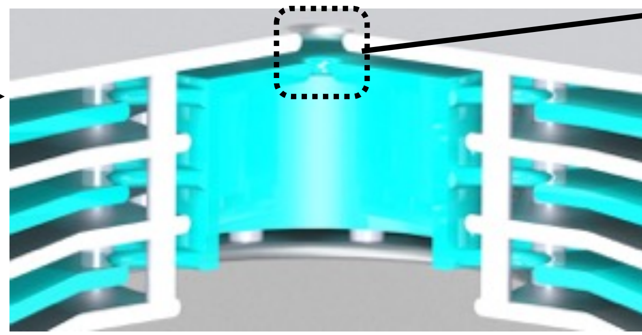


Our job as pulsed power scientists is to deliver the accelerator power to a radius of 1 cm to enable discovery science experiments

Z Next

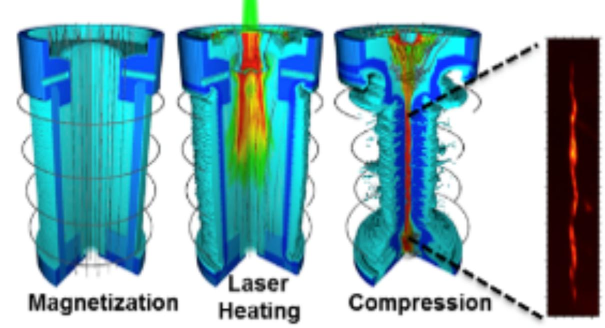






~1 PW electrical

Inertial Confinement Fusion Ignition
Hostile Environments



30 PW DT neutrons
400 PW x-rays

<u>Driver or source design</u>
electricity and magnetism, pulsed power, mechanical, electrical, and civil engineering

<u>Example driver uncertainties</u>
Electrode plasma formation/expansion
Current loss

Discovery Science Experiments

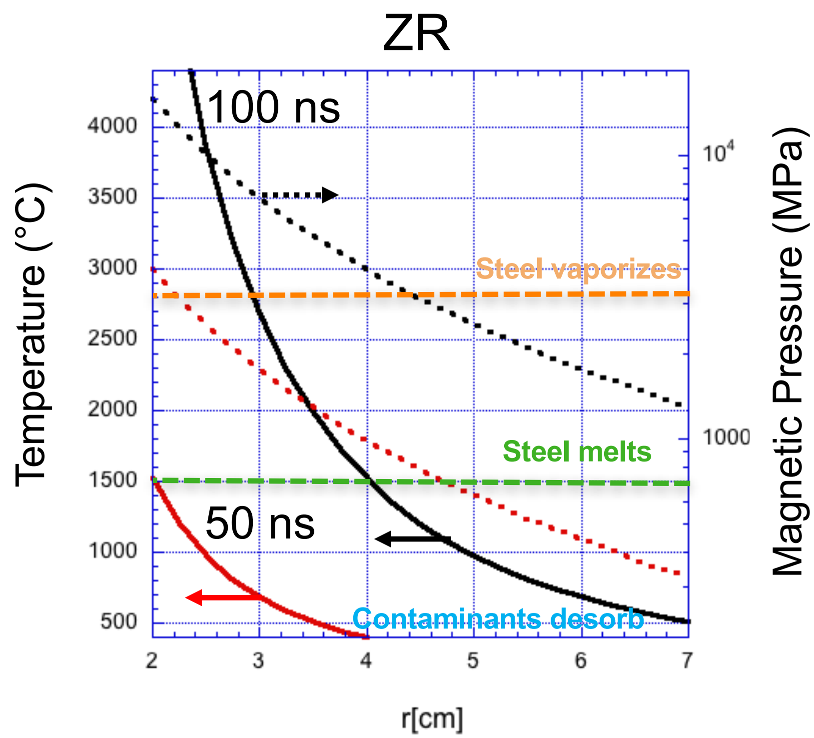
Plasma simulations often assume *"Ideal Electrodes"*

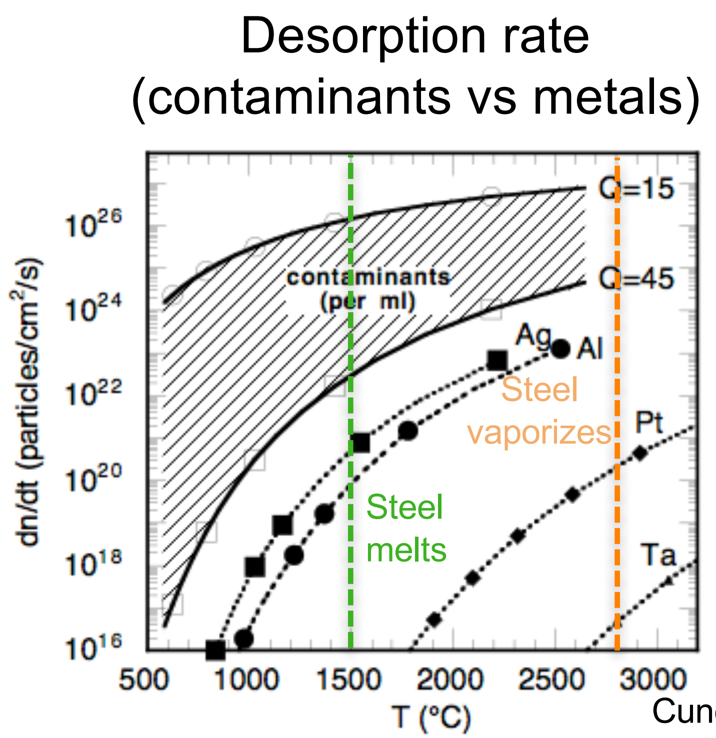
- Ideal electrodes have the following characteristics:
  - They are smooth
  - They are homogeneous and uniform
  - They often assume a single material (e.g aluminum, stainless, etc)
  - They are passive, e.g. immobile
    - Often electrodes are immovable, idealized boundary conditions or contact surfaces whose expansion and heating is not really resolved in the simulations
    - They may have ionization state and expansion given by thermodynamic state or an assumed state
  - They do not develop self-consistent electrode plasmas on the electrode surface

We need plasma modeling and simulations that employ validated models of *“Real Electrodes”*

- Real electrodes have the following characteristics:
  - They are rough
  - They are heterogeneous
    - surface and bulk contaminants
    - oxide layers with complex morphology and entrained contaminants
    - grain boundaries and inclusions
    - non-idealities from human contact: dust, fingerprints, sweat, skin cells, grease….
  - They are active, e.g. mobile
    - High magnetic pressures can move the electrodes
    - Also in high voltage pulsed devices, contaminants, oxides, and electrode materials are desorbed, melted, vaporized and become ionized, and they move
  - They are plasma forming, which can be partially or fully ionized
    - the plasmas can provide electrons, positive, and negative ions
    - charge-exchange neutrals

Estimates show that plasma will form on all electrodes on Z and Z-Next





$$\frac{dn}{dt} = \nu n \exp(-Q/RT)$$

$$\frac{dn}{dt} = \frac{3.5e22 P_{vap}}{\sqrt{MT}}$$

Cuneo, IEEE TDEIV, 6, 469 (1999)

- The area of the electrodes over which anode plasmas form is 5 to 10X larger on Z-Next compared to Z

TW to PW-class power pulses generate plasmas within a vacuum transmission line over multiple scales in space, density, particle energy, magnetic field, and electric field

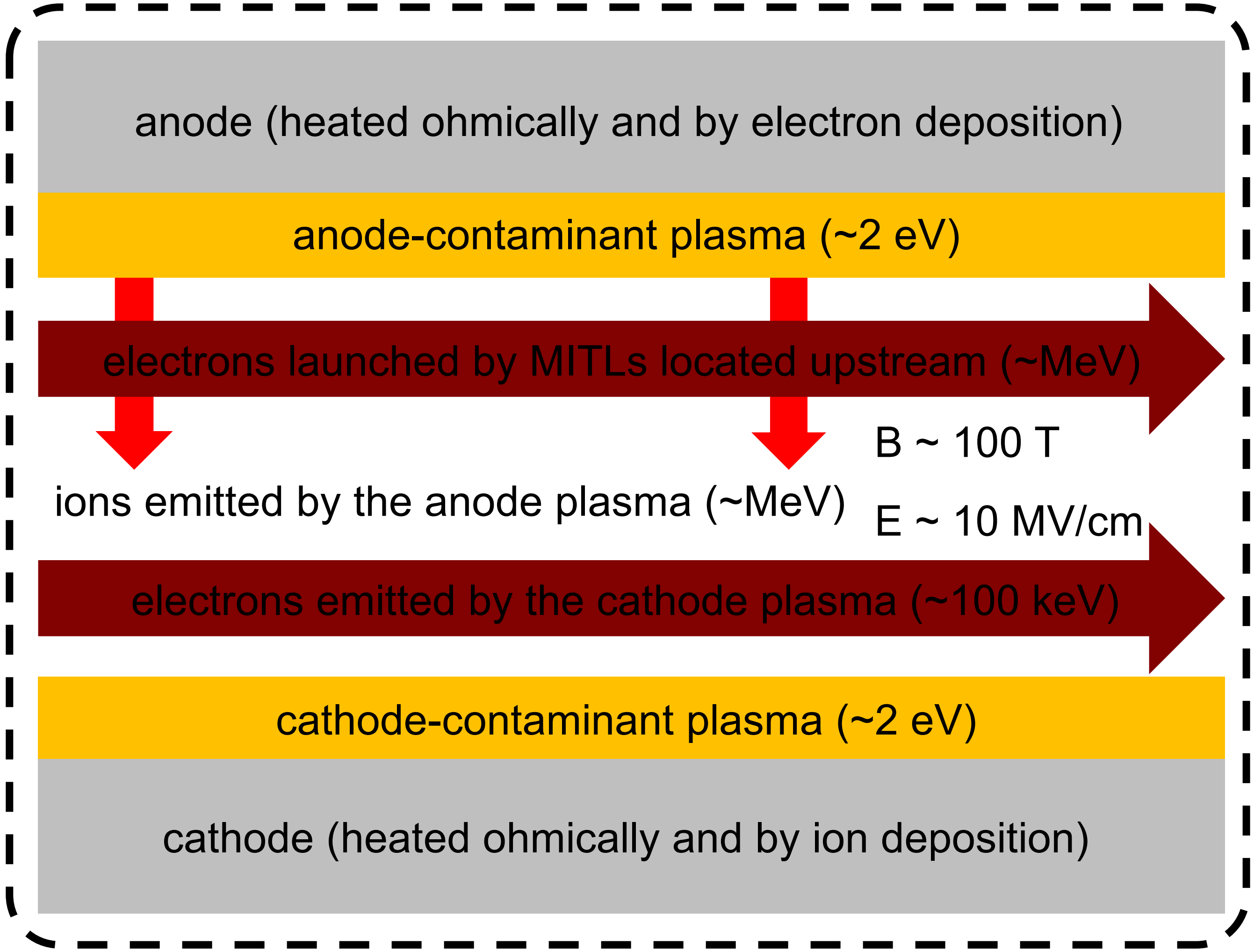
Such plasmas are

- Non-thermal
- Non-neutral
- Relativistic
- Electromagnetic
- Three-dimensional

A simulation of such plasmas must account for the following:

- Cyclotron motion
- Plasma oscillations
- Collisions
- Electromagnetic waves

section of a “vacuum” transmission line at small radius

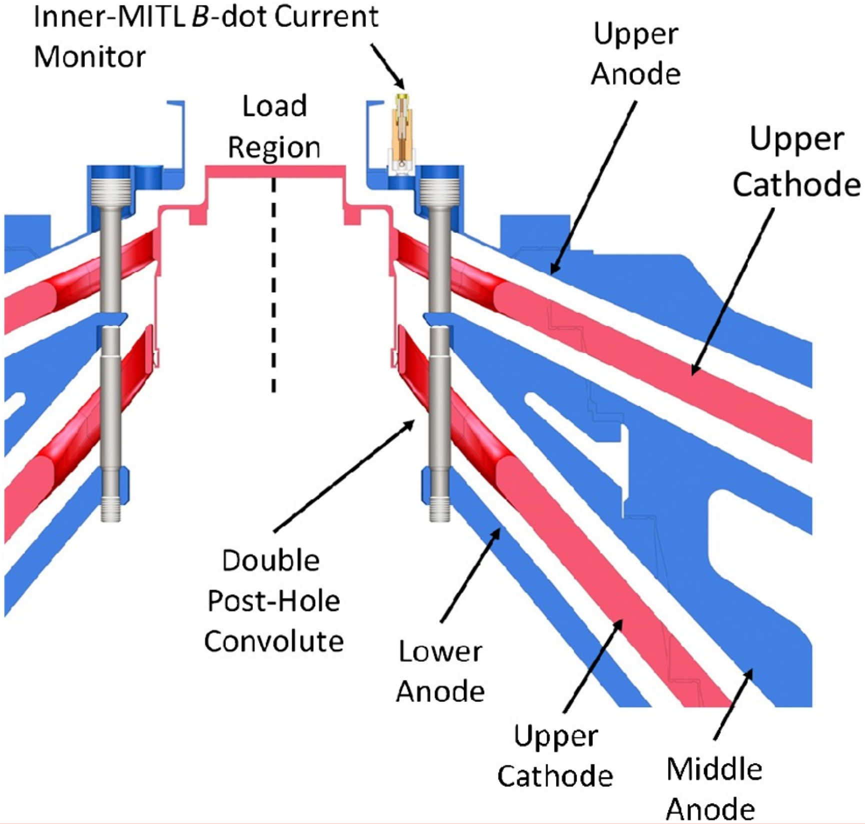


Our LDRD project “Plasma Science and Engineering” will advance algorithms and code capabilities, expand our community of practice, and develop real electrode models to enable extrapolation of these environments at the PW power level for next generation applications

Next-generation designs must be correct or we risk the performance of a >$1B-class Z-Next Facility

Z MITL-Convolute System

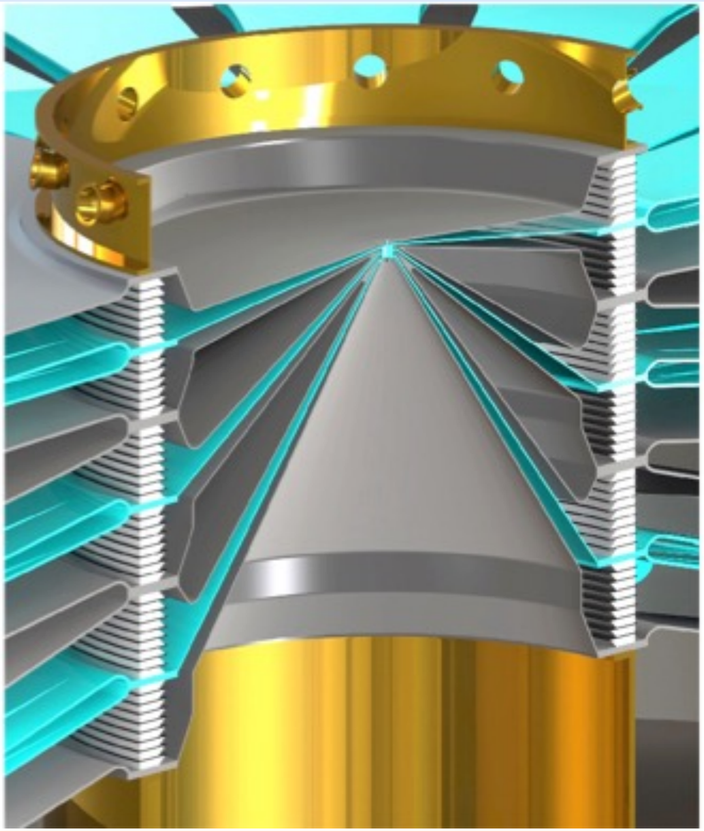
Double Post-hold convolute driven by 4 vacuum transmission lines (~2 meter diameter vacuum system)



We don't fully understand / model this system today!

Z-Next MITL-Convolute System

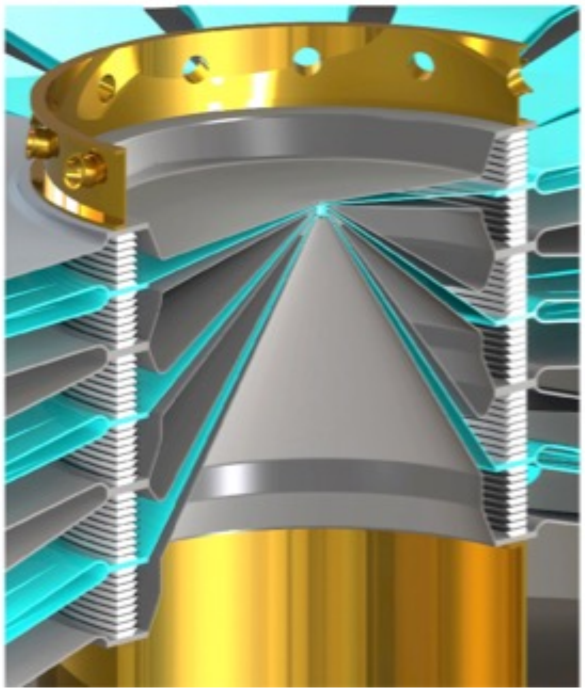
Triple Post-hold convolute driven by 6 vacuum transmission lines (~5 meter diameter vacuum system)



4-10x electrical power → can't predict this with "calibrated" codes!

Circuit and PIC models demonstrate that current loss in the Z vacuum section is significant when one or more of these conditions is met

1. Electrons are emitted in the Z outer MITLs and ExB drift toward the convolute and inner MITL
2. The anode surfaces of the convolute and inner MITL become space-charge-limited ion sources
3. The anode-cathode gaps of the convolute and inner MITL close significantly during the power pulse
4. The characteristic impedances of the inner MITL and load are relatively high.



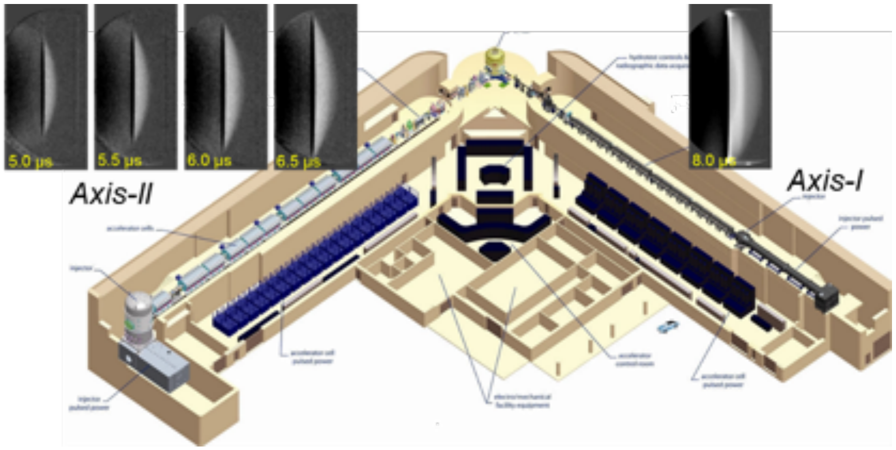
Modeling suggests that when one or more of these conditions are not met, current loss within the Z vacuum section is negligible.

One of the goals of ongoing power flow experiments is to confirm these hypotheses

We have a lot of work to do

- Reliability, maintainability, availability, operability of a high shot rate (400/yr), high neutron and x-ray yield facility
- Brick and module reliability meeting requirements
- Integrated triggering systems
- Supply chain and economies of scale meeting cost targets
- Safety engineering
- Improve insulator flashover performance by 20-30%
- Robotic handling and refurbishment
- High fidelity costing and project management
- Site, building, accelerator design
- Mechanical response
- Circuit models, plasma models, target physics, models showing extrapolated performance
- Validated power flow coupling
- Validated load performance

The US National Nuclear Security Agency (NNSA) needs to fill a gap in its ability to perform dynamic object radiography



U1a Facility at Nevada National Security Site

Cygnus Radiography

<u>Dual Axis Radiographic Hydrodynamic Test (DARHT)</u>
Multi-Pulse, Multi-Axis – Highly Penetrating Radiography
Limited Test Material Options

<u>Cygnus/U1a</u>
Multi-Axis – Modestly Penetrating Radiography
Broad Test Material Options

DARHT-Class Multi-Pulse Radiography

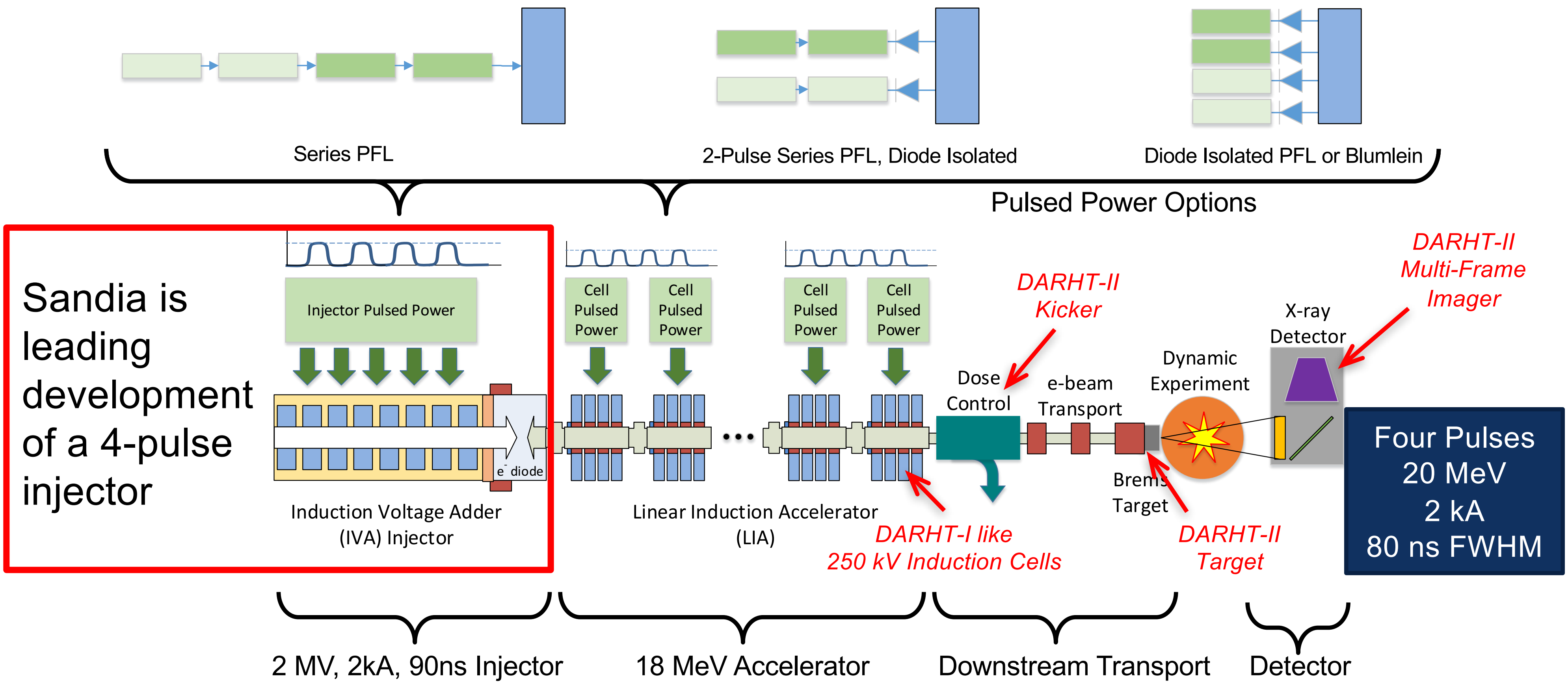
U1a Facility Test Material Options

Team

Los Alamos National Laboratory · Lawrence Livermore National Laboratory · Sandia National Laboratories · NSTec

NNSA

Scorpius is based on DARHT-1, with modifications to address the multi-pulse operation requirements



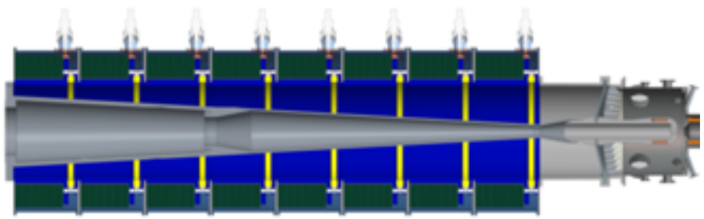
Conceptual Design Activities for Scorpius are underway

Injector

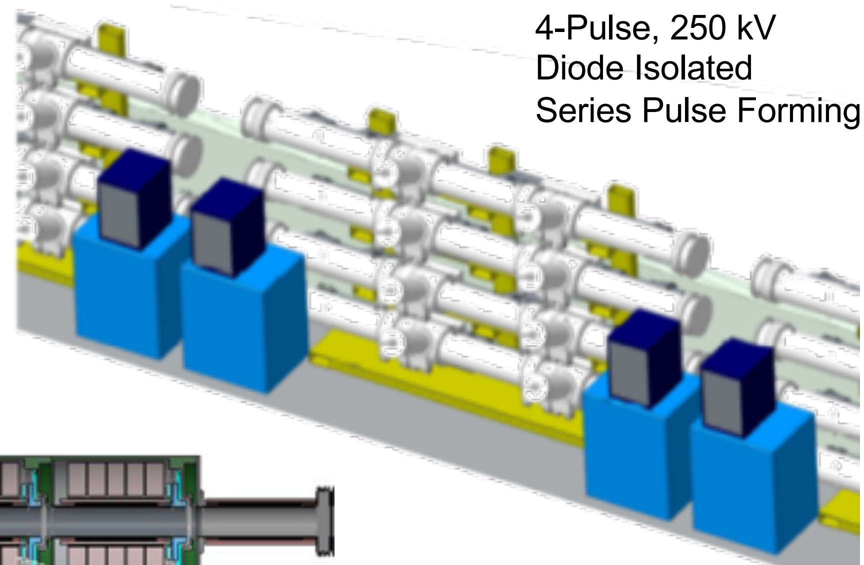
Accelerator

Downstream Transport

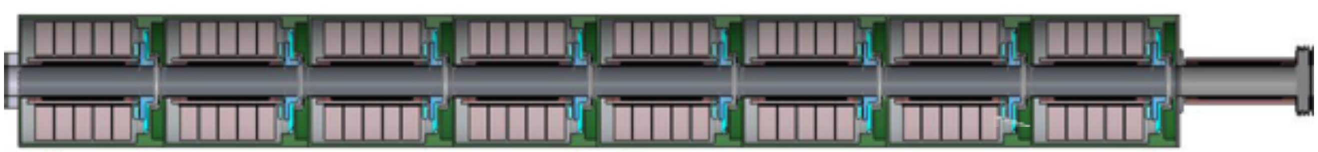
Injector:
8, 250 kV 4-pulse cavity IVA



Pulsed Power Module:
4-Pulse, 250 kV
Diode Isolated
Series Pulse Forming Line



Accelerator Module:
8, 250 kV 4-pulse cells with distributed vacuum pumping



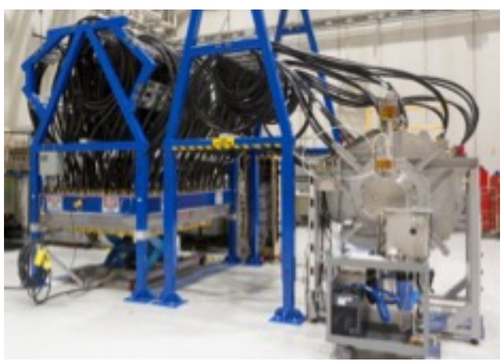
Sandia's pulsed power group is leading the development of the multi-pulse injector

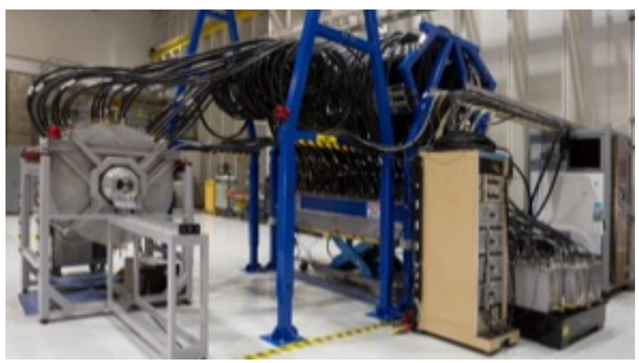
- Current and near term activities include:
  - Injector system design and prototyping
  - Multi-pulse Pulsed power circuit design
  - Simulation and analysis of complex systems
  - Experimental evaluation of multi-pulse vacuum insulator flashover
  - Experimental evaluation of multi-pulse e-beam cathode performance
  - Laser triggered switch development
  - Mechanical stress and thermal analysis and design
  - High vacuum system design and analysis
  - Design and evaluation of semiconductor diodes in series-parallel assemblies

Sandia's pulsed power team developed Centipede, the first four pulse capability to support the Scorpius project

- Centipede was designed, built and commissioned by Sandia's pulsed power team in a little over one year

- Team includes Pulsed Power Electrical Engineers, Mechanical Engineers, Drafters, Controls Engineers, and Pulsed Power Technologists

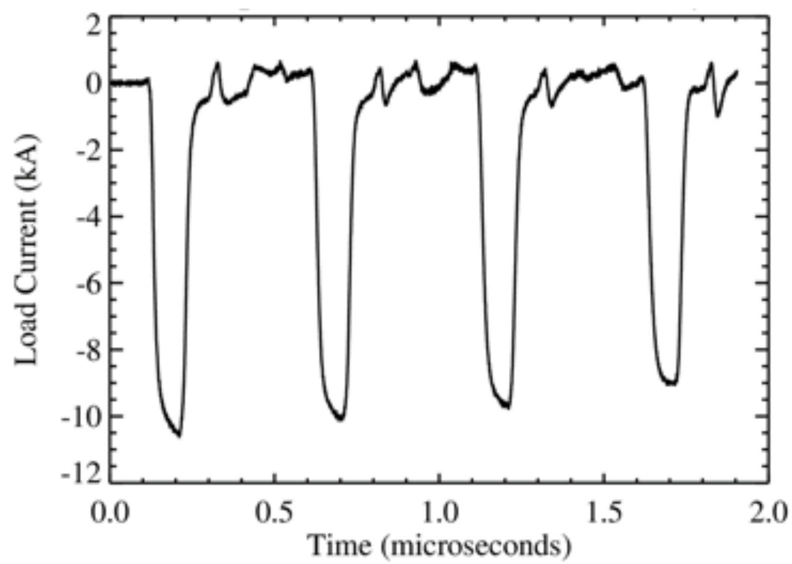




The Centipede pulser is being used to evaluate multipulse breakdown in vacuum, oil, and solid dielectrics

- Up to four arbitrarily timed pulses are generated by series pulse forming lines (PFL)
- Voltage from many individual PFLs is added in an inductive voltage adder (IVA)
- Architecture is similar to what could be used to build an injector

Centipede Specifications	
Load Voltage	250 kV
Pulse format	4 pulses x 100 ns FWHM
Load Impedance	22 Ω



Summary

- We steward the U.S. pulsed power capabilities
- We are developing the next generation of pulsed power capabilities
- We would like to double the staff of our pulsed power departments over the next 5 years (+7 Pulsed Power Scientists)
- Over the next 10 years we will
  - Develop multi-pulse pulsed power for a new radiographic capability
  - Develop next generation HED driver technology
  - Steward and upgrade the capabilities of the Z facility
  - Upgrade the Saturn facility
- Over the next 20 years, make the case for Z Next and achieve fusion ignition in the laboratory