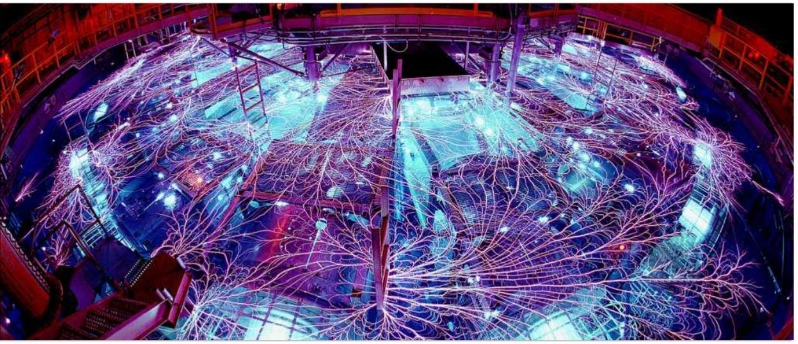
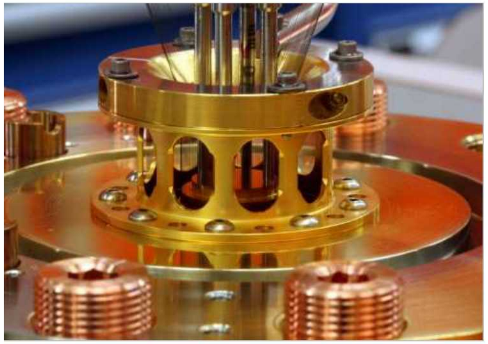
SAND2019-3686PE





Advances in Pulsed Power Science and Technology for High Energy Density Physics

George R. Laity (grlaity@sandia.gov)

R&D Manager, Advanced Pulsed Power Capabilities Group

Sandia National Laboratories, Albuquerque, NM

Texas Tech University – College of Engineering Seminar, March 29th, Lubbock, TX, USA

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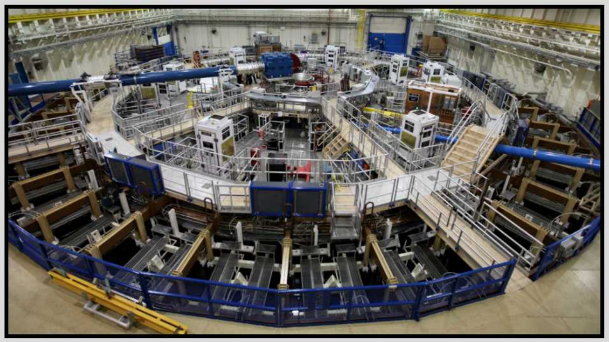
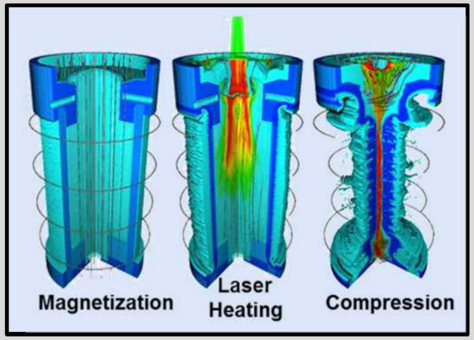
Presentation Outline

Background

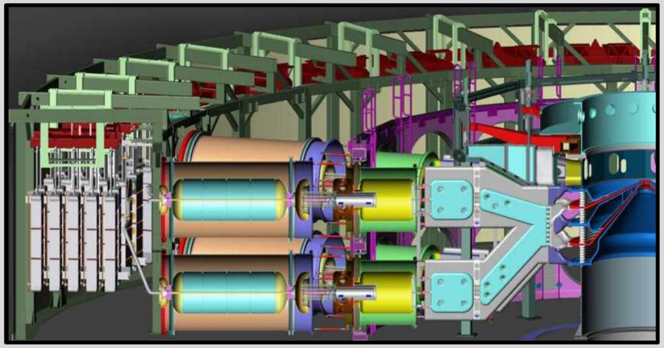
- ✓ *What / where is Sandia?*
- ✓ *Pulsed Power / HED Mission*
- ✓ *ICF / Science Experiments*





Accelerator Technology

- ✓ *Z Pulsed Power Facility*
- ✓ *Future Technologies: LTD / IMG*
- ✓ *Multi-Pulse Accelerator Technology*



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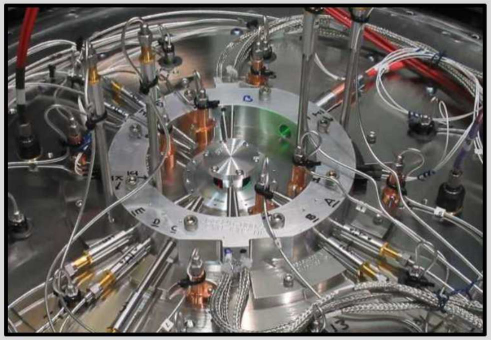
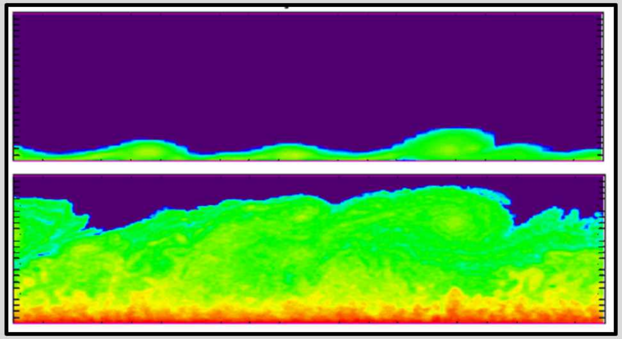
- ✓ *Power Flow / Current Loss*
- ✓ *PIC / Circuit Models*
- ✓ *Electrode Models*





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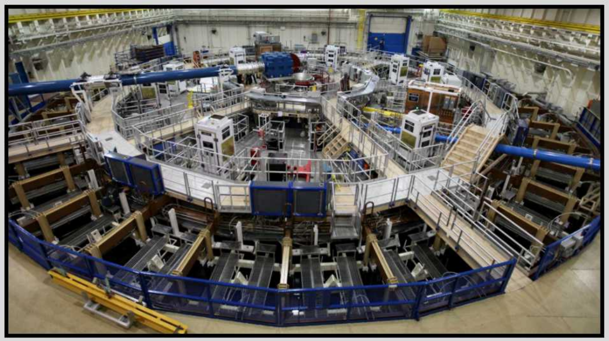

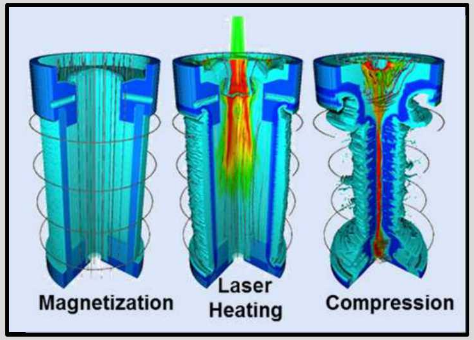

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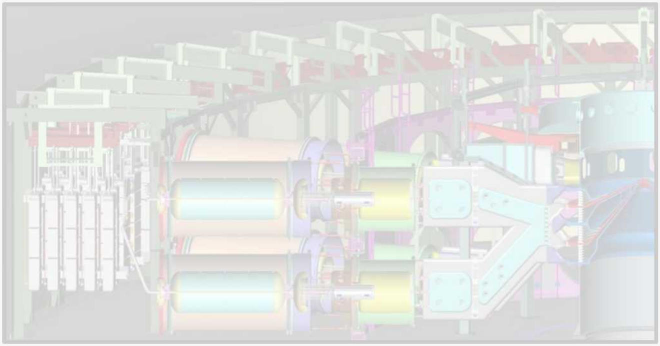

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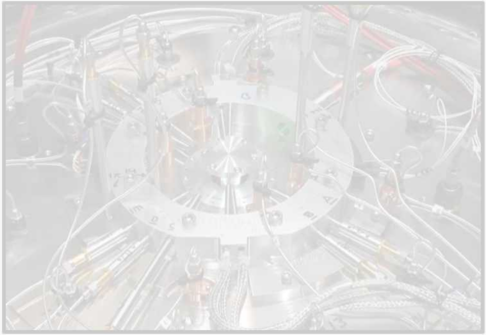
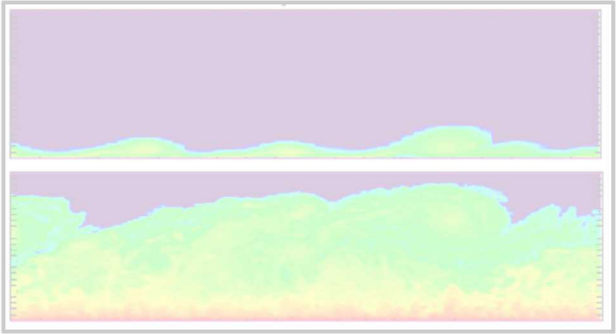
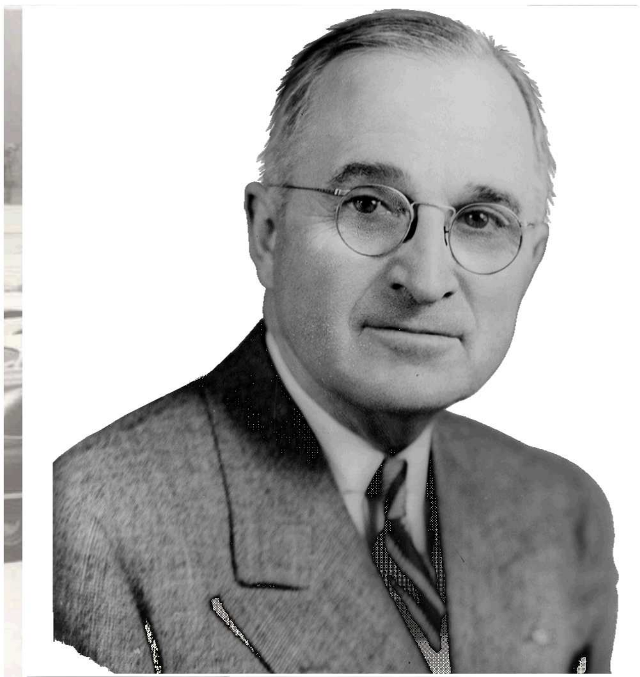
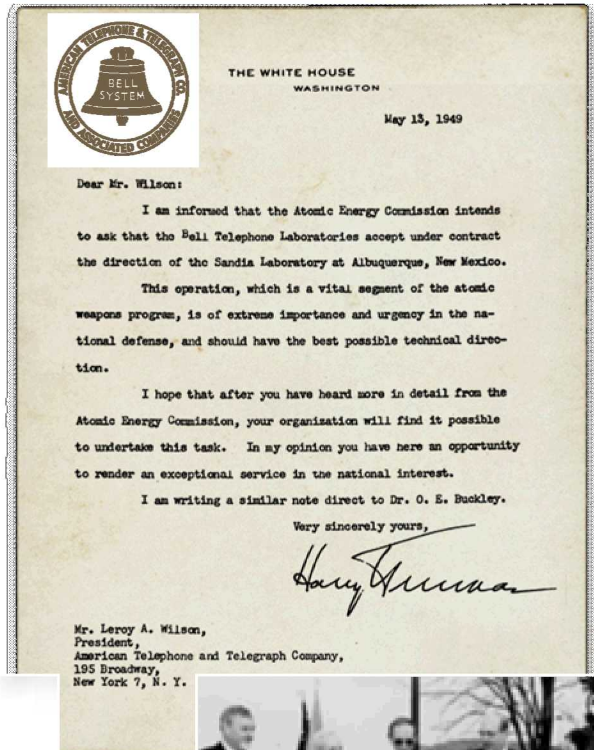




Sandia National Laboratories' history dates back to World War II

"Exceptional service in the national interest…"





BELL SYSTEM

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
- **November 1, 1949:** Sandia Laboratory established (today DOE national lab)
- **1949–1993:** AT&T
- **1995–2017:** Lockheed Martin Corporation
- **2017-Beyond:** Honeywell Corporation

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

Sandia National Laboratories

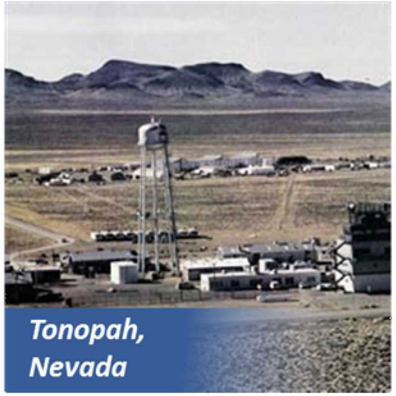

Albuquerque, New Mexico


Livermore, California

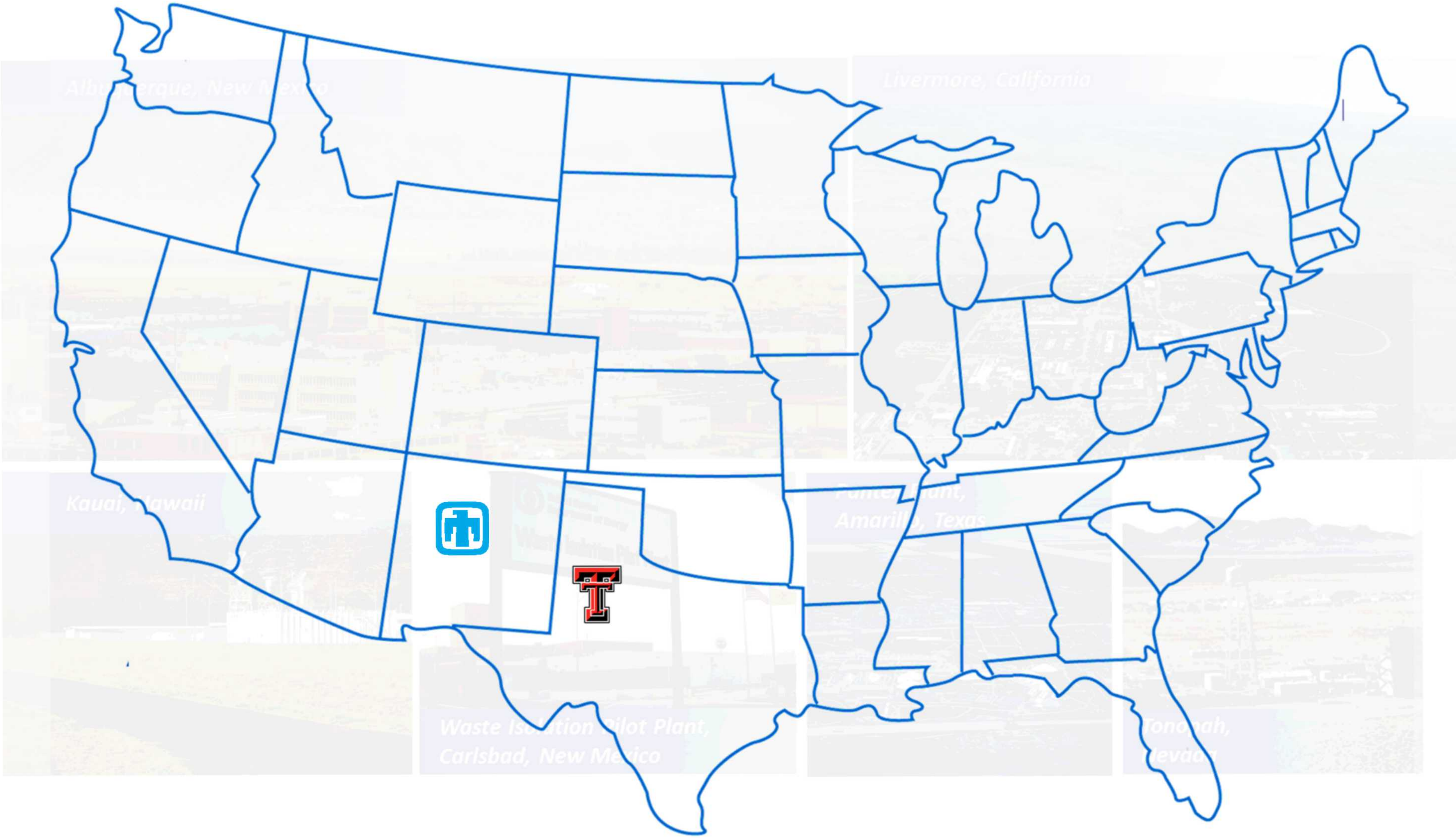

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico


Pantex Plant, Amarillo, Texas

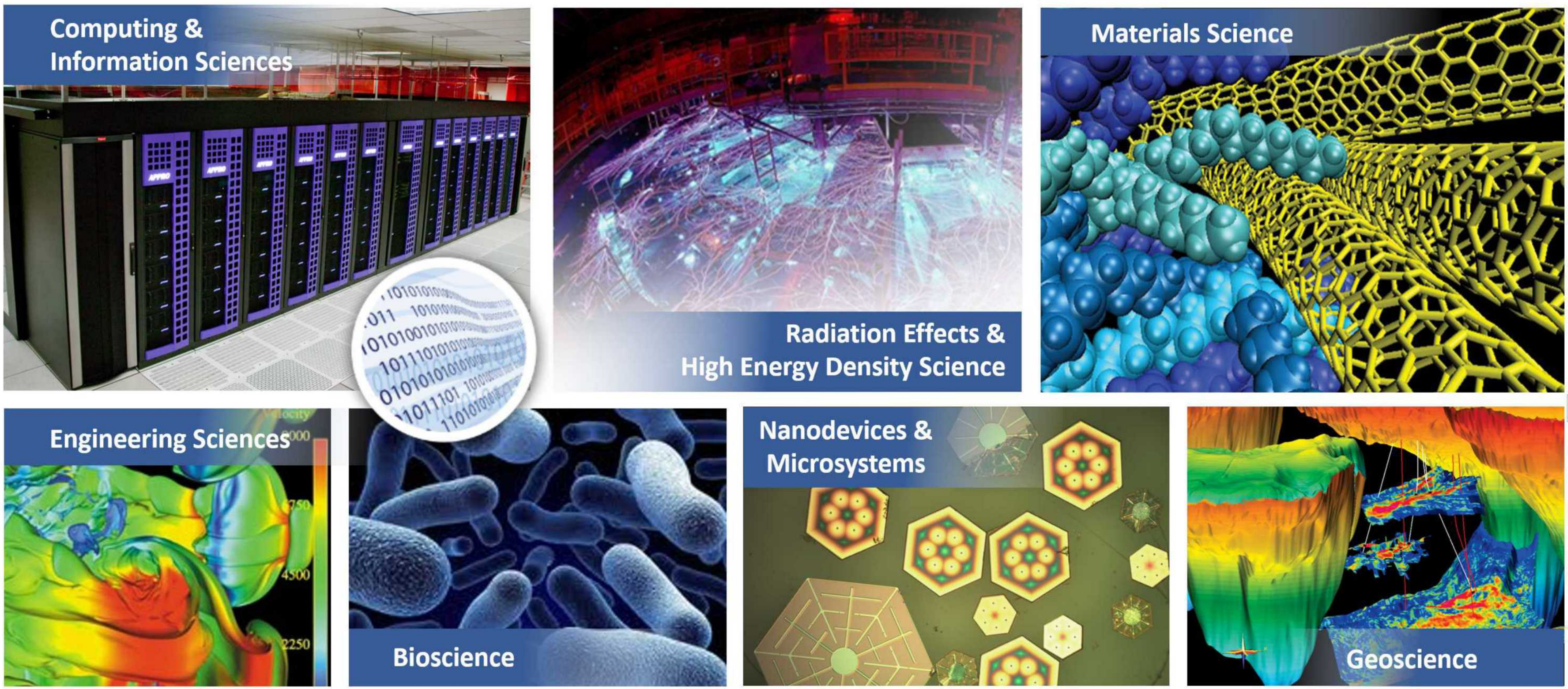

Tonopah, Nevada

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



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

Sandia National Laboratories



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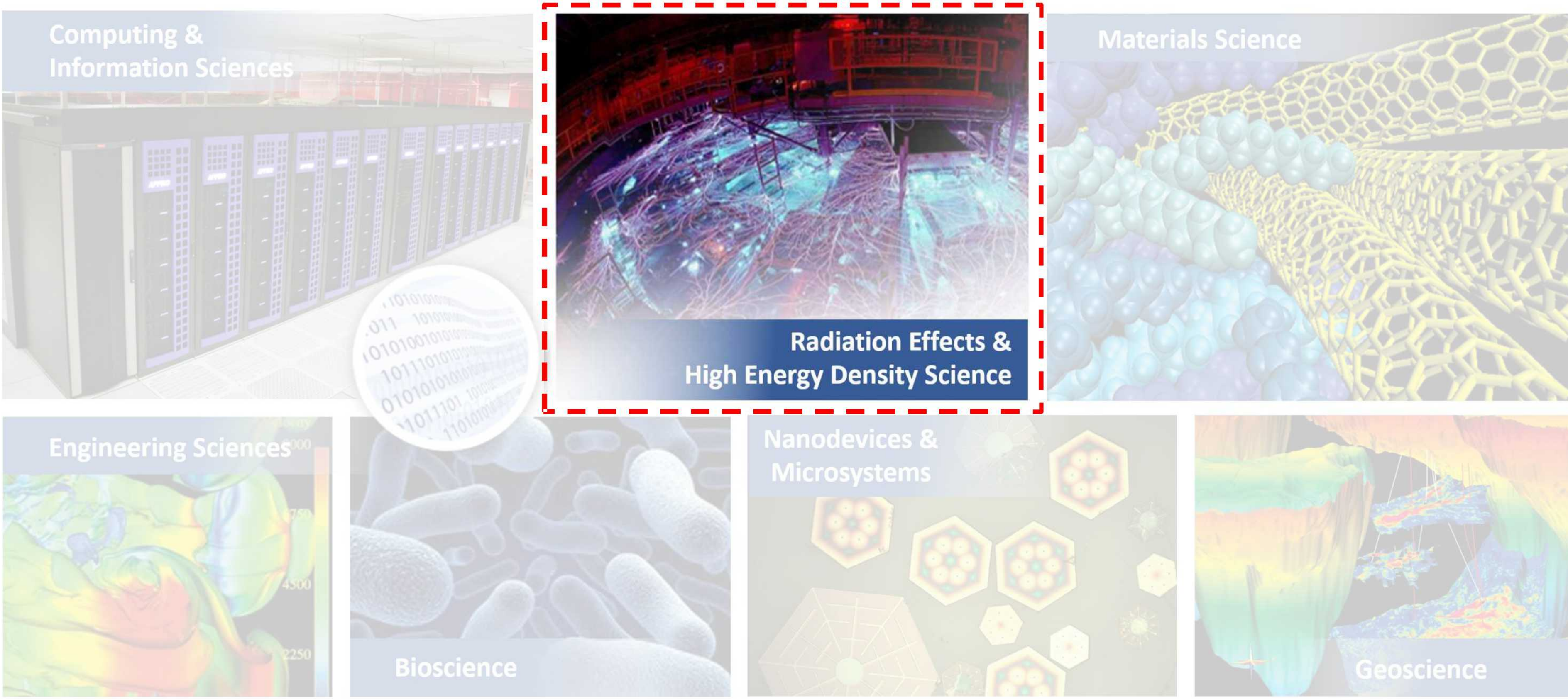
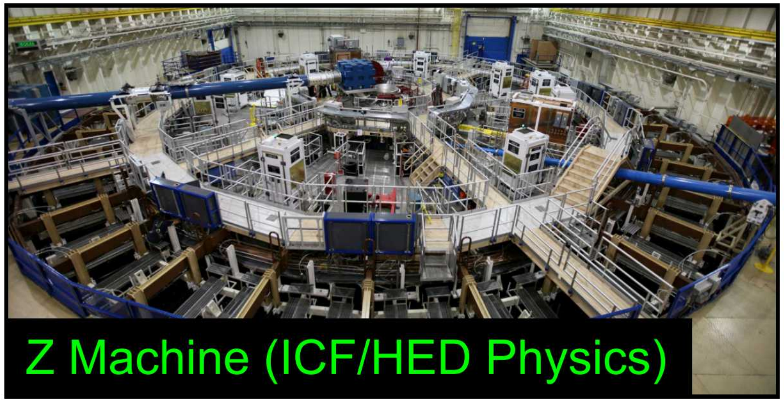
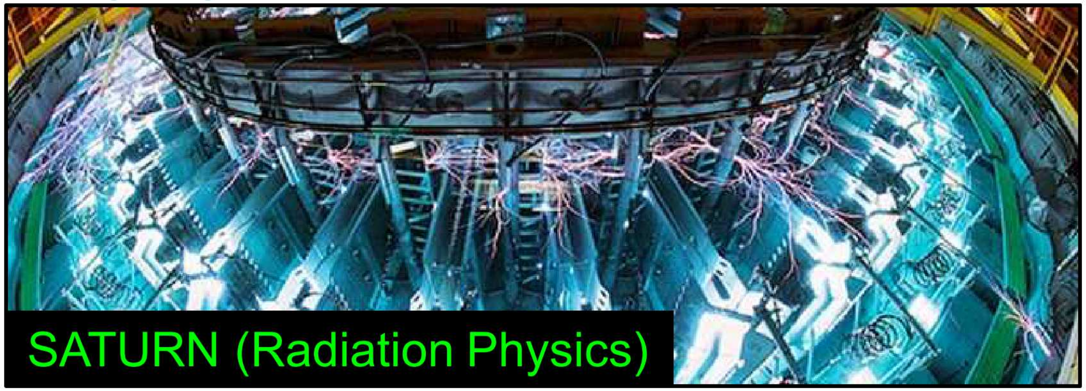


Sandia operates a variety of pulsed power accelerators for radiation physics and HED science

Sandia National Laboratories



Z Machine (ICF/HED Physics)



SATURN (Radiation Physics)

HERMES (Radiation Physics)

RITS (X-ray Radiography)

THOR (HED Materials Physics)

MYKONOS (Technology Development)

Matter in the HED state has an energy density equivalent to >1 Mbar = 100 kJ/cm^3

4600lbs + 70MPH ≈ 1MJ   V ≈ 10^{7}cm^3

Energy Density ≈ 0.1 J/cm^3

0.145kg + 100MPH ≈ 150J   V ≈ 200cm^3

Energy Density ≈ 1.0 J/cm^3

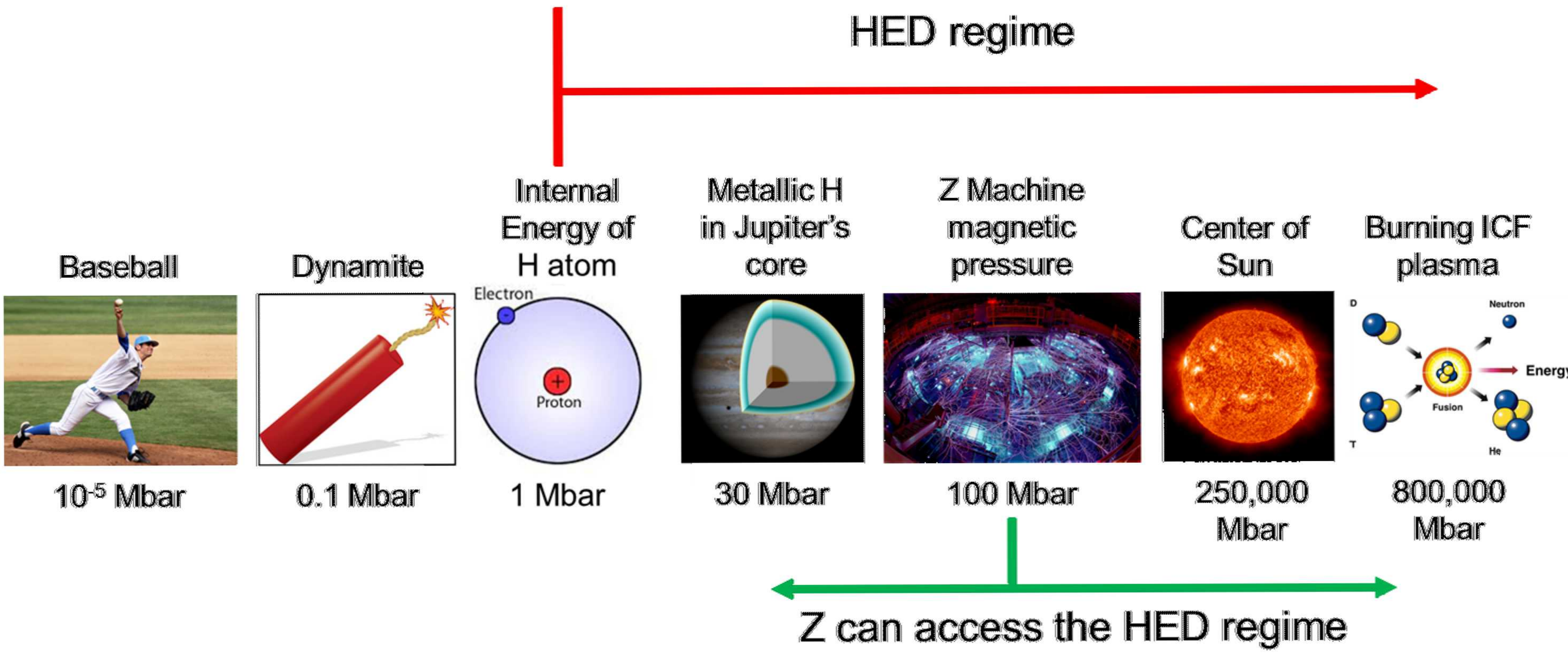
Released Energy ≈ 1kJ   V ≈ 0.33cm^3

Energy Density ≈ 3 kJ/cm^3

Released Energy ≈ 1MJ   V ≈ 160cm^3

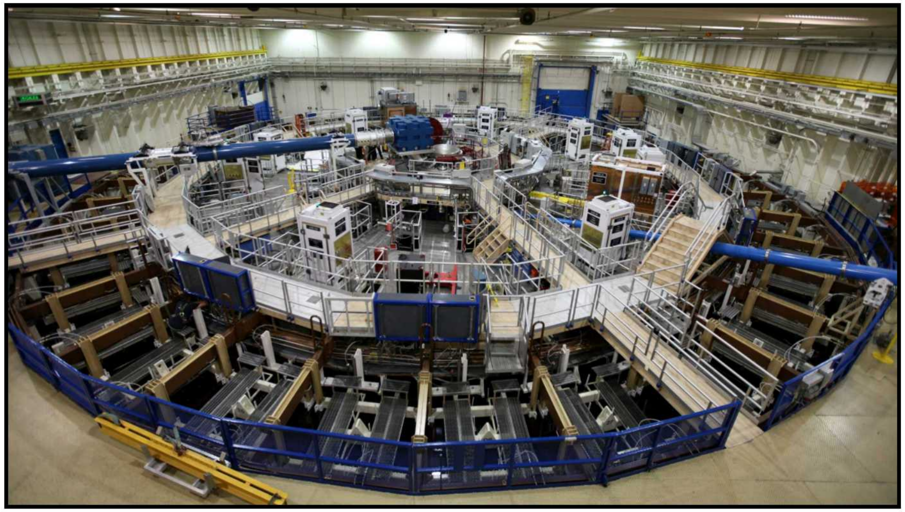
Energy Density ≈ 10 kJ/cm^3

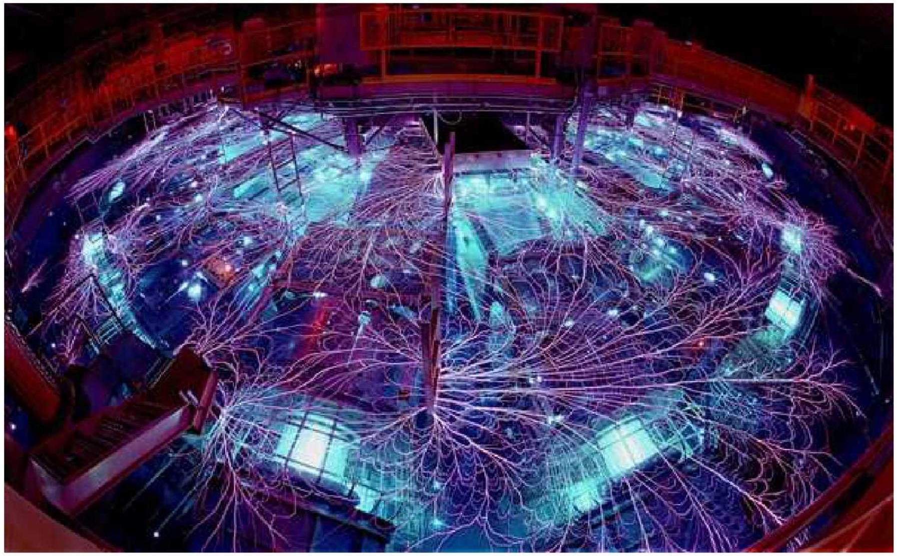
The HED regime is beyond what we normally experience, but common in the universe!



How do we access this HED regime in practice?

We use pulsed power technology to create high energy density (HED) matter

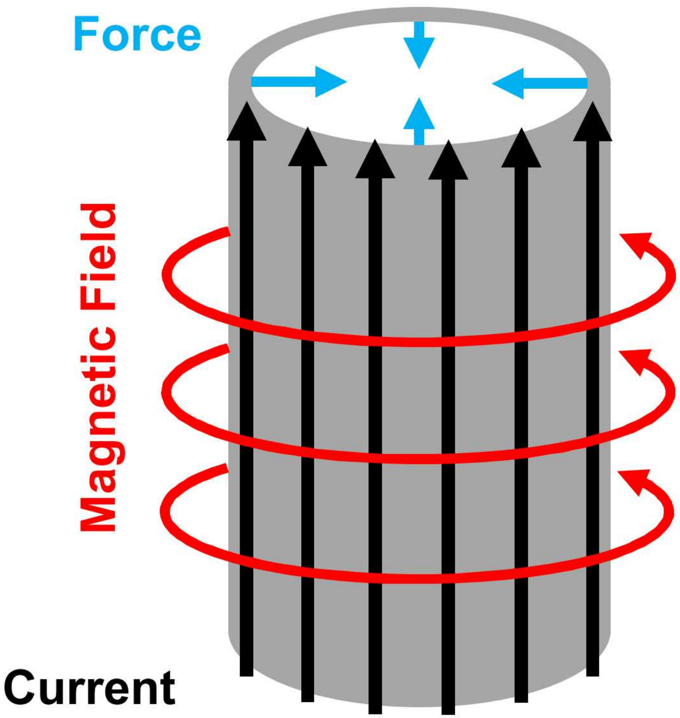


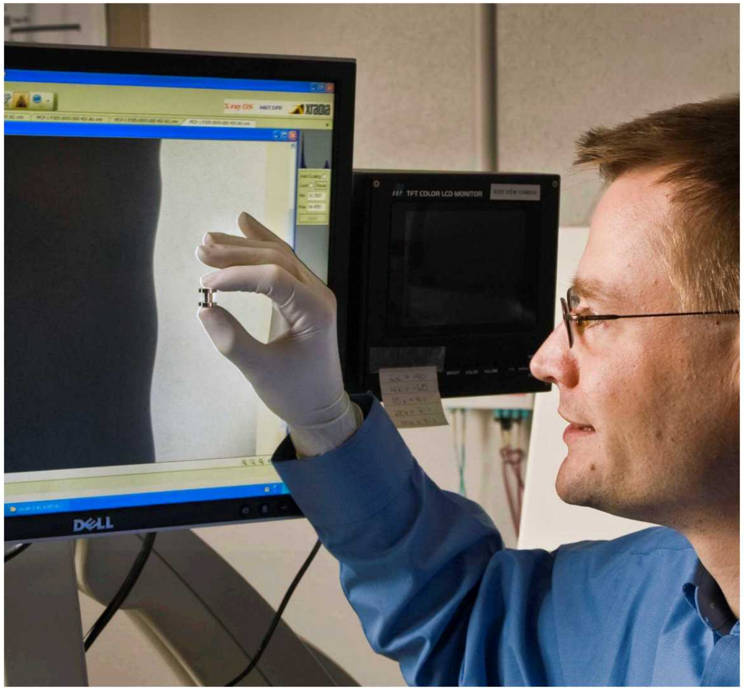


- What is pulsed power?
  - Store energy over relatively long period of time (seconds to minutes)
  - Discharging over a relatively short period of time (ns to µs)
  - Compression in time of ~10^9
- Z stores about 20 MJ of energy over about 3 minutes
  - Average power ~ 100 kW
- Z delivers around 3 MJ of energy in a 100 ns risetime pulse to the experiment
  - **Peak power ~80 TW!**
  - World Generation: ~3 TW

Enormous current (>25MA) is used to accelerate matter to extreme velocities

Cylindrical geometry
Radiation sources and ICF



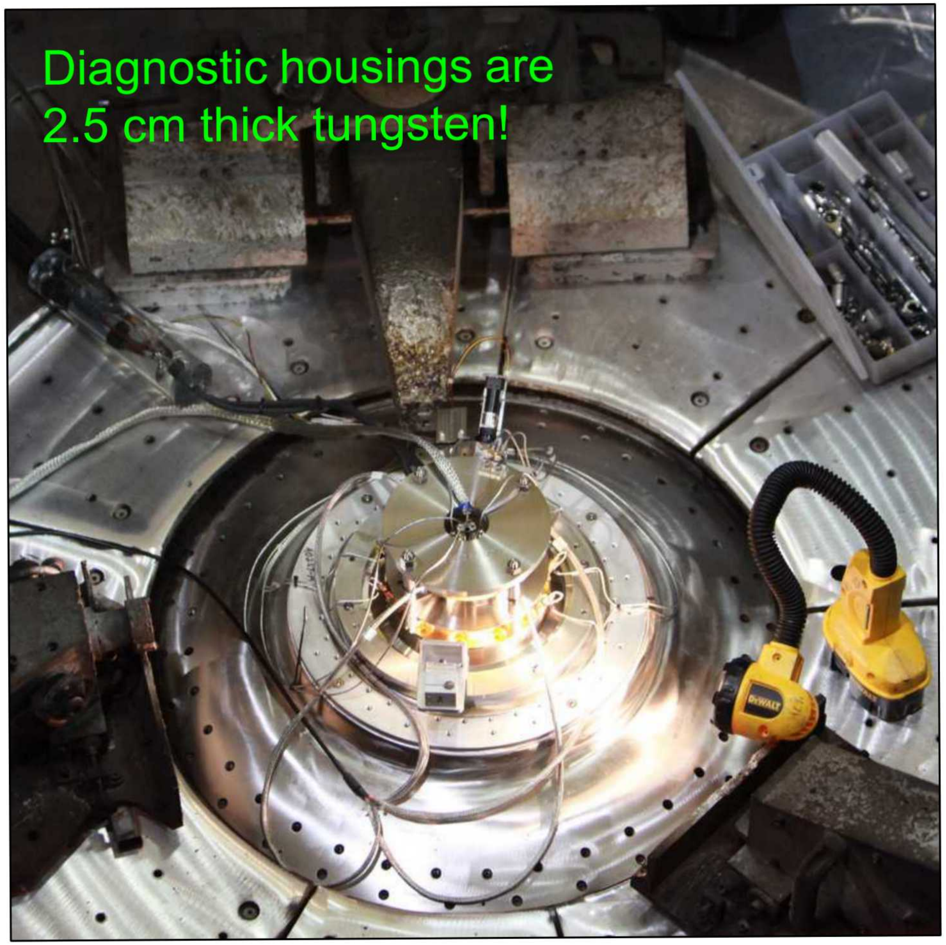


- Current flows through a conducting cylinder
- Produces a self-magnetic field
- Generates a radially-inward force ("z-pinch")

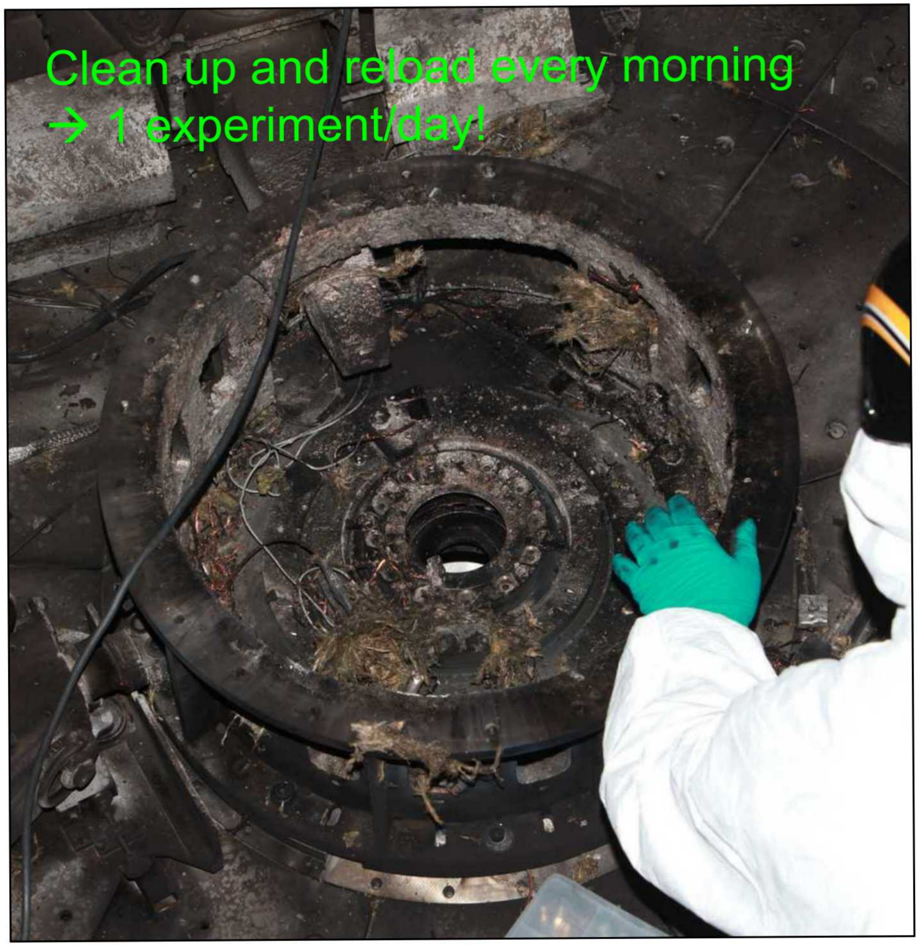
D. Ryutov et al., *Rev. Mod. Phys.*, Vol. 72, 167, (2000).

All of this energy completely destroys the nearby components!

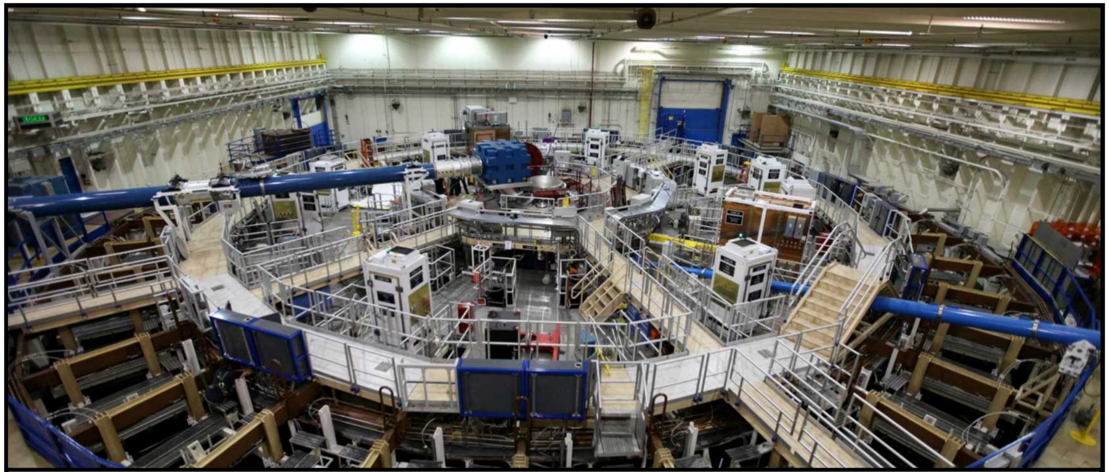
Before



After



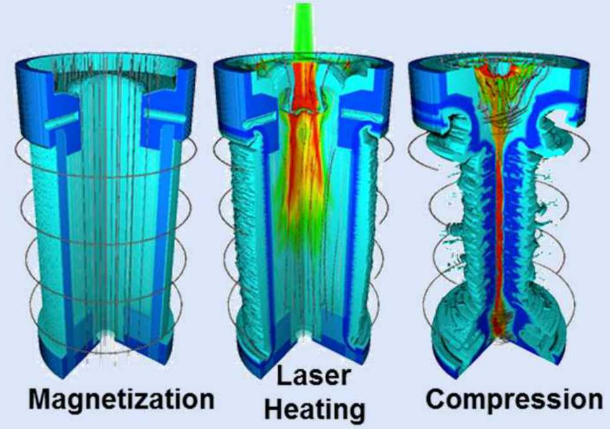
The Z Facility provides a national capability for high energy density (HED) physics experiments



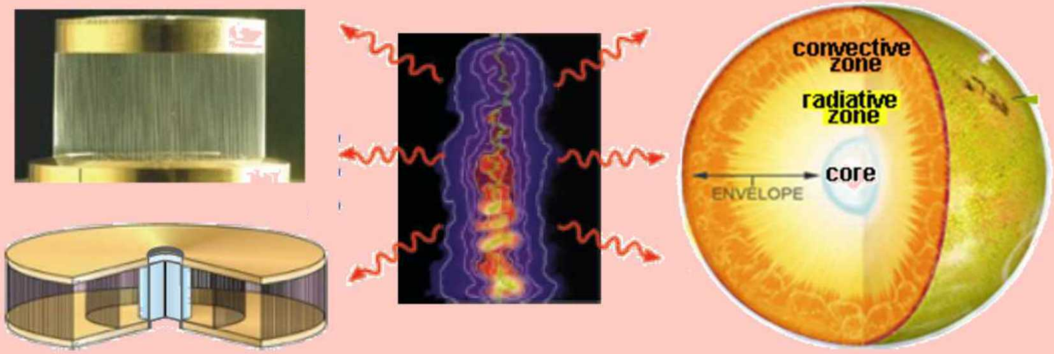
22 MJ stored→1-3 MJ delivered to load

27 MA / 100 ns pulse→ >100 Mbar pressures

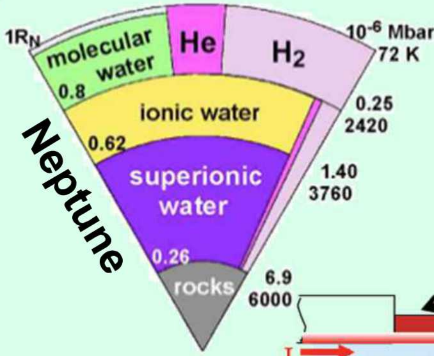
Inertial Confinement Fusion



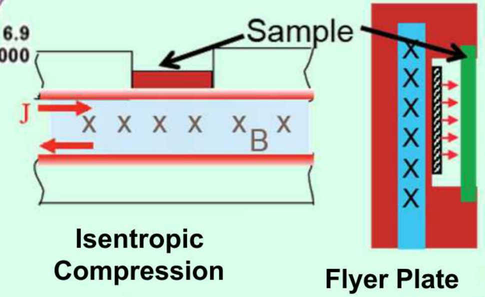
X-Ray Radiation Science & Astrophysics



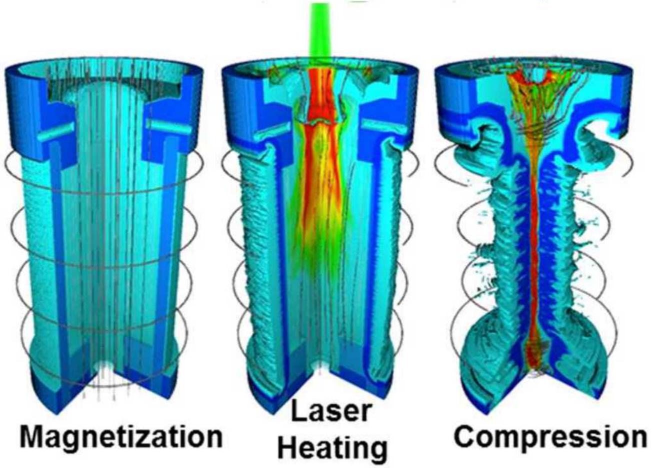
Dynamic Materials Properties



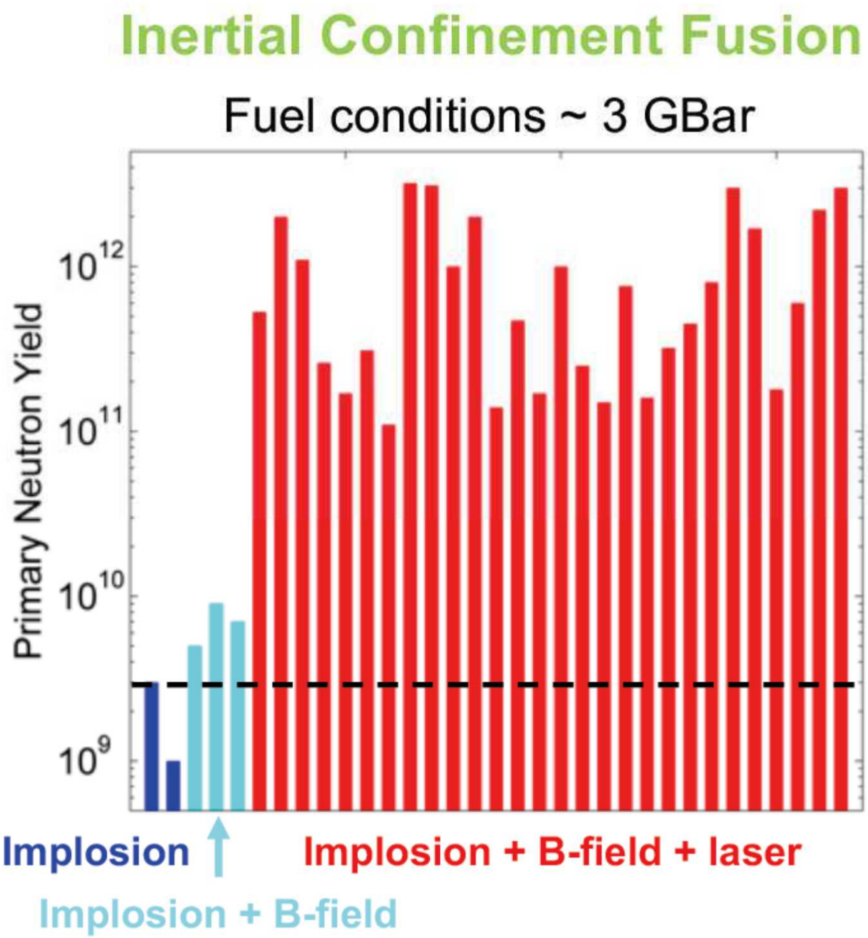
Planetary Science



We are developing a pulsed power enabled magneto-inertial fusion concept called MagLIF

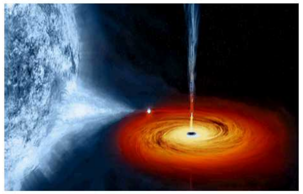
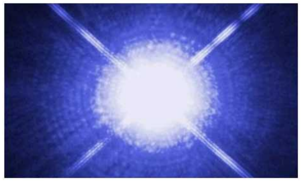
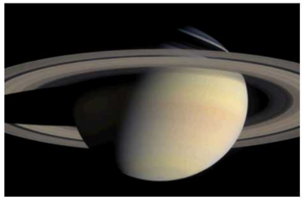


	No B-field	B-field
No Laser Heating	$3x10^9$	$1x10^{10}$
Laser Heating	$4x10^{10}$	$3x10^{12}$



We have demonstrated that good MagLIF performance requires all three components!

The Z Facility serves as a unique experimental platform for laboratory astrophysics and planetary science

Laboratory Astrophysics		1 µg of stellar interior at $R \sim 0.7\ R_{sol}$	*"A Higher-than-Predicted Measurement of Iron Opacity at Solar Interior Temperatures"* Bailey et al., Nature **517**, 14048, (2015).
		1 ml of accretion disk $R \sim 10^3$ km from black hole	*"Benchmark Experiment for Photo-ionized Plasma Emission from Accretion Powered X-Ray Sources"* Loisel et al., Phys. Rev. Lett. **119**, 075001, (2017).
		100 ml of white dwarf photo-sphere	*"Laboratory Measurements of White Dwarf Photo-spheric Lines"* Falcon et al., Astrophysical J. **806**, 214, (2015)
Planetary Science		1.3 mg (0.8 µL) of metallic hydrogen	*"Direct Observation of an Abrupt Insulator-to-Metal Transition in Dense Liquid Deuterium"* Knudson et al., Science **348**, 1455, (2015).
		20 mg (2.5 µL) of shocked iron material	*"Impact Vaporization of Planetesimal Cores in the Late Stages of Planet Formation"* Kraus et al., Nature Geoscience **8**, 269, (2015).

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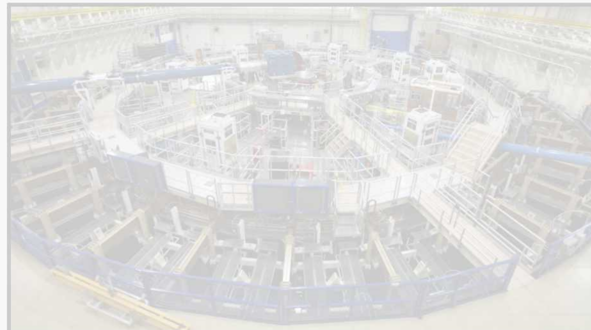

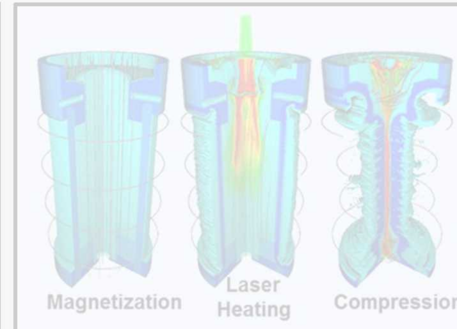

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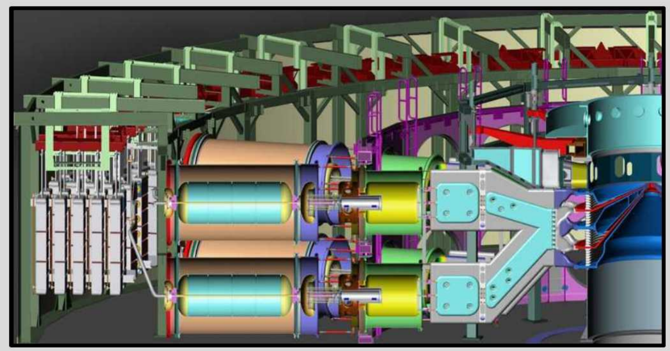

Pulsed Power Science

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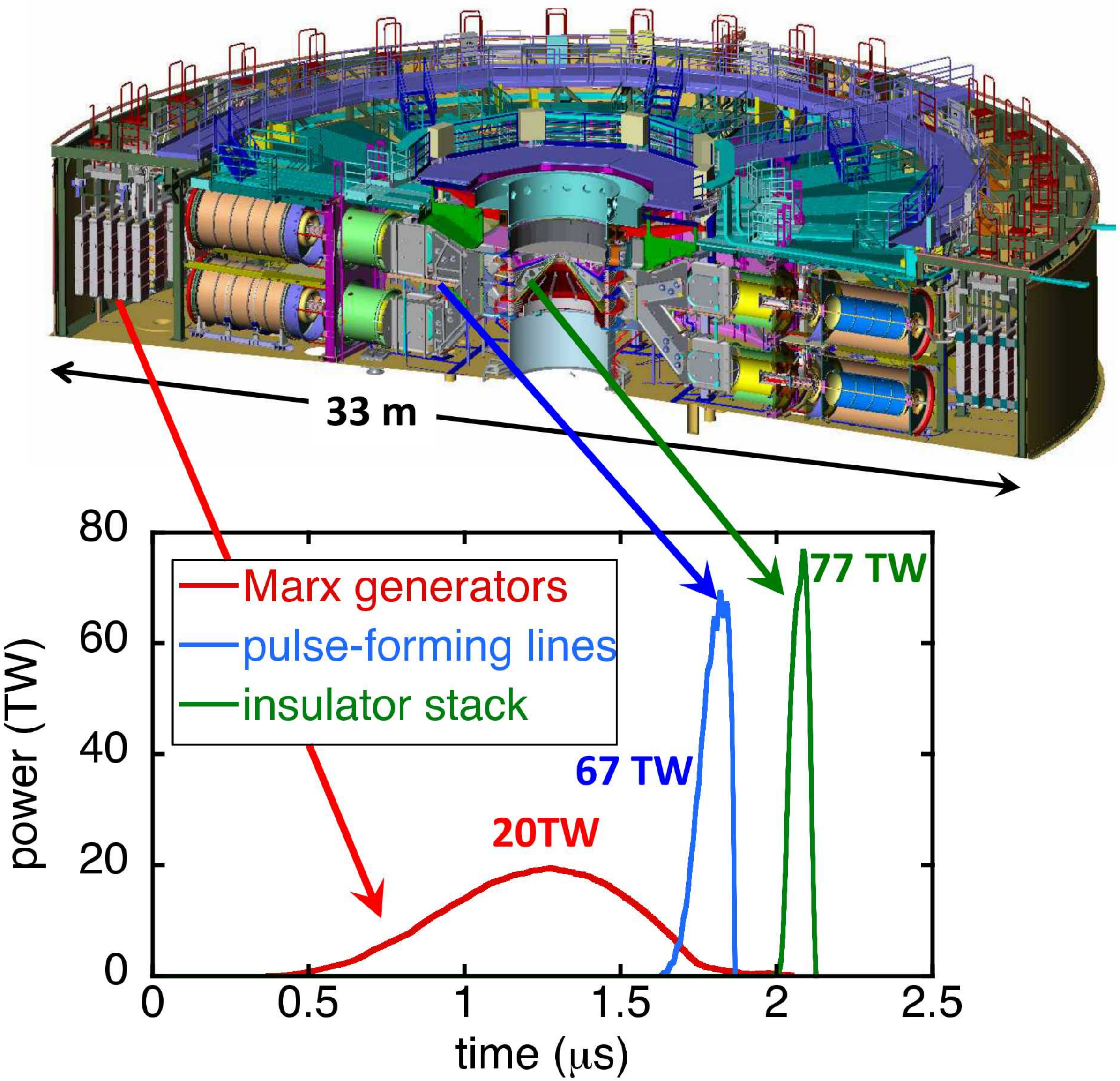
The Z Facility uses traditional pulse compression technology to deliver very large current to a load



Marx generator / water insulated transmission line technology has been successfully demonstrated on multiple pulsed power machines for decades!

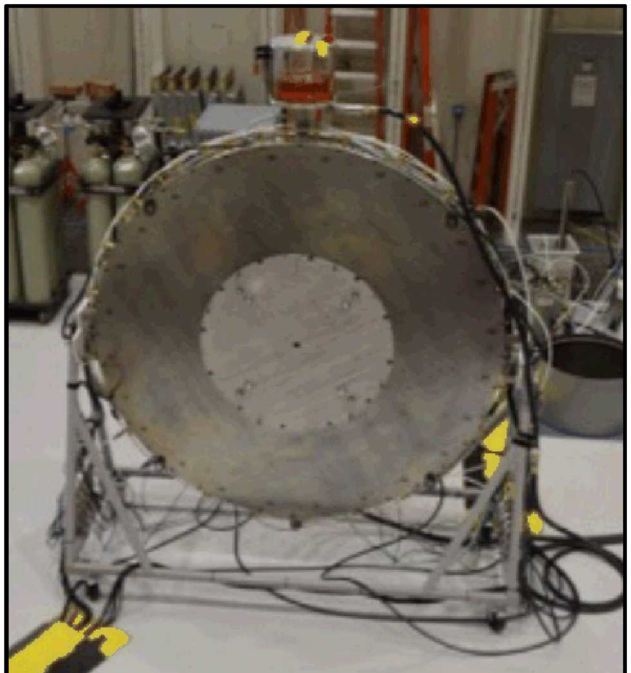
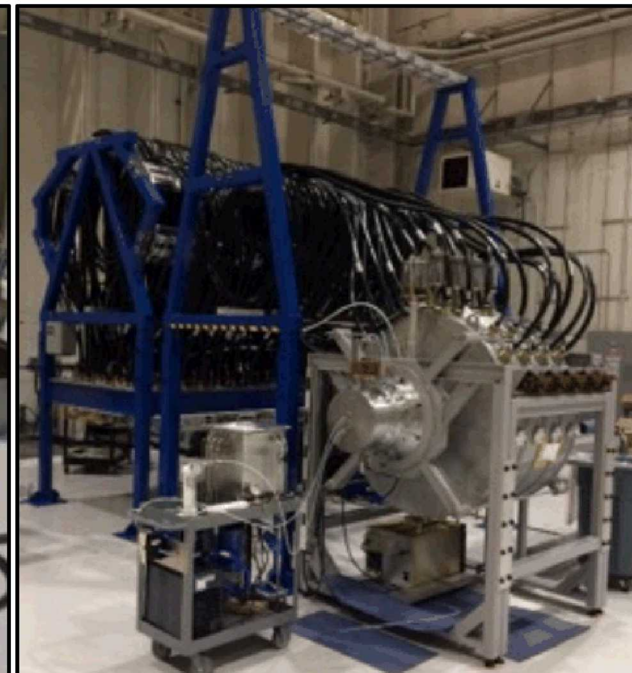
We are still advancing this technology today, but some aspects of the design are challenging:

- ✓ Desire to move to **smaller components**, for improved modularity and easier maintenance
- ✓ Desire to increase the variety of **pulse shaping configurations** available

W. Stygar et al., *Phys. Rev. ST Accel. Beams*, Vol. 10, 030401, (2007).

We are rapidly developing a new generation of pulsed power driver concepts for multiple future scientific missions

Current Adder	Current / Voltage Adder	Multi-Pulse Voltage Adder
THOR → 4 MA (2017)	**6th Gen LTD → 1 MA, 100GW cavity (2017)**	**CENTIPEDE → 4x pulse, 250kV, 1GW (2017)**
✓ Dynamic Materials ✓ Arbitrary MA waveform generatorC	✓ ICF, Radiation Physics, Shock Materials ✓ Fast (100ns) pulse	✓ Advanced radiographic (x-ray) applications ✓ Multi-pulse capability

We are exploring a modular architecture that can scale to 300–1000 TW and is 2x electrically efficient as the Z Facility

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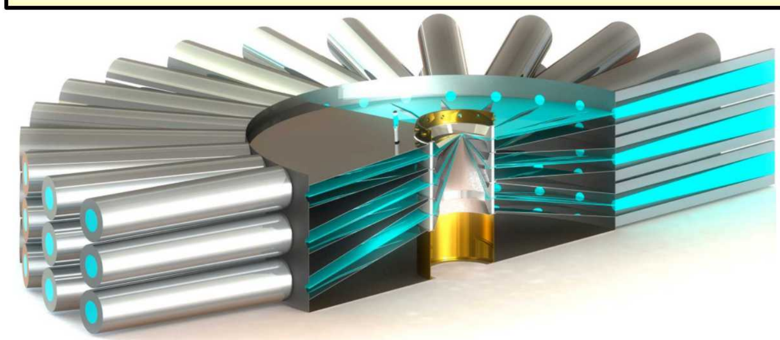
Brick
"Quantum" of next-generation systems, single step pulse compression to 100ns

Cavity
Connect multiple bricks in parallel, add current from each brick (50 kA/brick)

Linear Transformer Driver Module
Connect multiple cavities in series, add voltage from each cavity (100 kV/cavity)

LTD Accelerator
Connect modules in parallel, add multiple levels (5 TW / module)



Next generation accelerator: 20,000 – 200,000 bricks, 30 - 60 cavities/module, 70 – 800 modules!

W. Stygar et al., *Phys. Rev. ST Accel. Beams*, Vol. 18, 110401, (2015).

We have been advancing LTD technology for 15 years

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2017

Z-Next LTD Cavity
- ✓ 2.2 meter, 100 ns, 1050kA, 100GW, 20 bricks
- ✓ Demo for 9,000 cavity, 50MA ICF driver
- ✓ Component cost, inductance, reliability, etc.

2014

LTD-IV
- ✓ 2.2 meter, 100 ns, 1100kA, 24 bricks
- ✓ Demo for 50-stage PLUTO module
- ✓ Evaluation of capacitor vendors, switches, etc.

2010

LTD-III
- ✓ 2.1 meter, 75-100 ns, 810kA, 80 GW, 20 bricks
- ✓ Testbed for Metglas cores, new switches, etc.

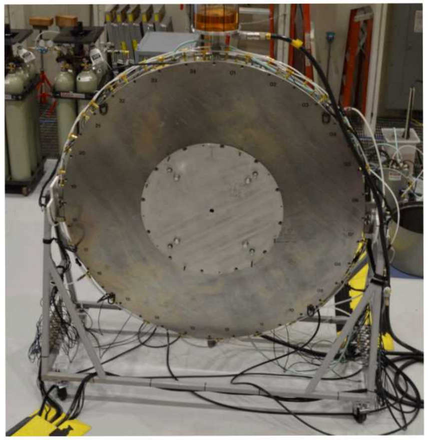
2008

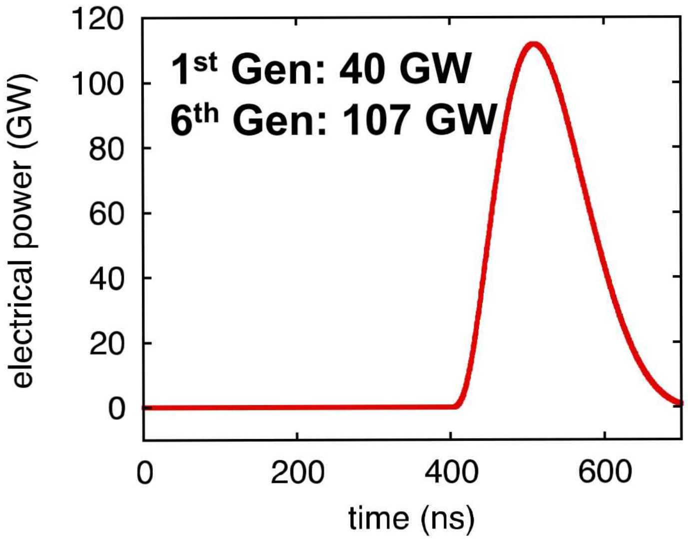
MYKONOS LTD
- ✓ 3 meter, 100 ns, 1000kA, 80 GW / cavity, 40 bricks
- ✓ Demonstrated multi-cavity, high current / voltage module

2004

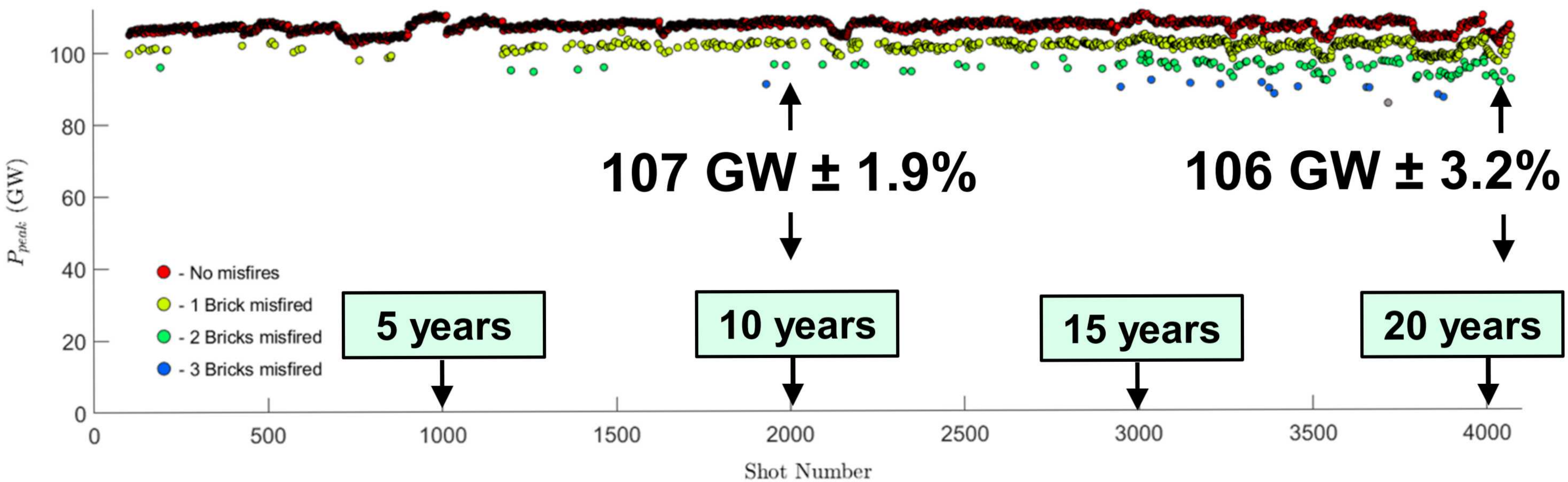
LTD-I
- ✓ 2 meter, 75 ns, 450kA, 40 GW, 20 bricks
- ✓ Intended for ZX-IFE Program

We have demonstrated 5000 shots over 6 months at full voltage with no major configuration change / component failure





Shots	Cavity Power (GW)	Module Variation (42 cavities)	Machine Variation (100 modules)
2000	107 ± 1.9%	±0.3%	±0.03%
3970	106 ± 3.2%	±0.5%	±0.05%



Leveraging advancements in “brick” technology will enable development of alternative pulsed power driver options

5 GW Brick

THOR-72

4 MA / 200 ns / 0.5 Mbar

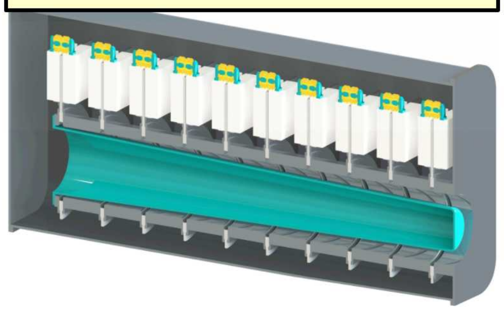
THOR-240

1.2 TW / 7 MA / 200 ns / 2 Mbar

Reisman et al., Phys. Rev. ST Accel. Beams, Vol 18, 090401, (2015).

Impedance Matched Marx Generator (IMG)

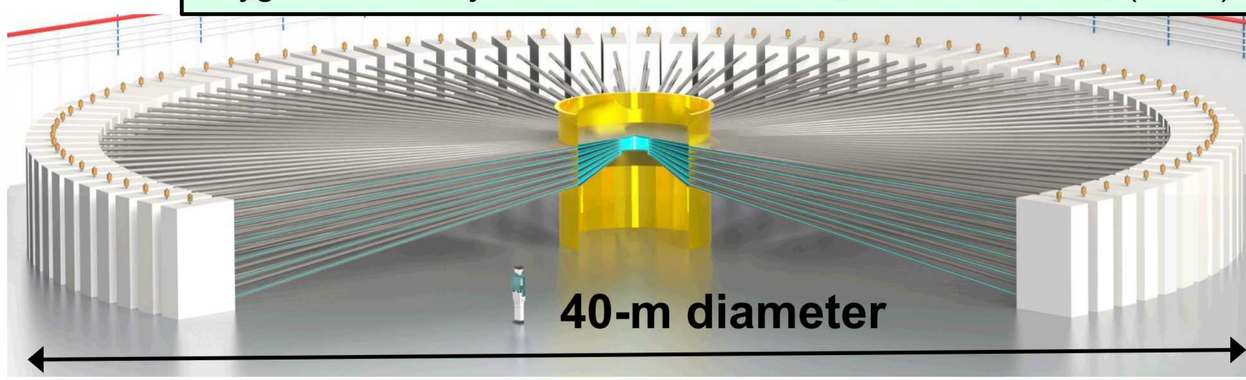
Stygar et al., Phys. Rev. Accel. Beams, Vol 20, 040402, (2017).



NEPTUNE

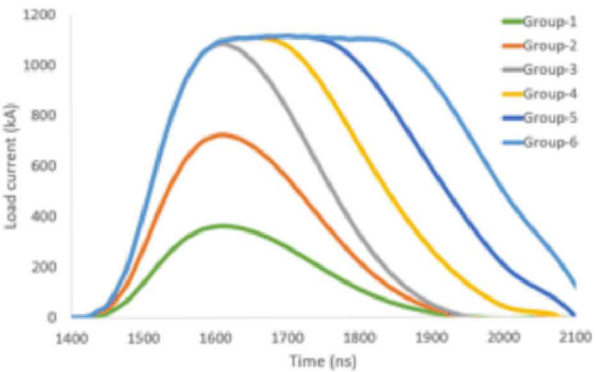
50 TW / 23 MA / 750 ns / 20 Mbar / 4,800 IMGs

Stygar et al., Phys. Rev. Accel. Beams, Vol 19, 070401, (2016).

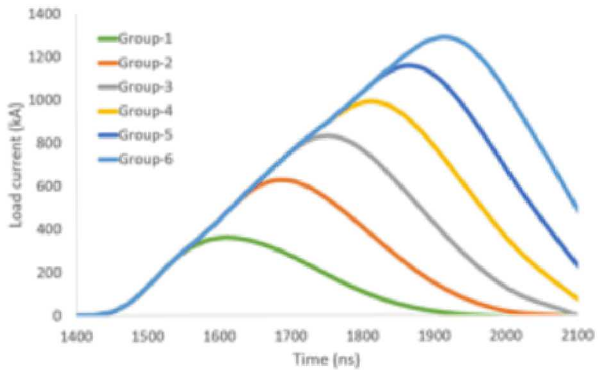


THOR is essentially a multi-MA arbitrary waveform generator, allowing greater flexibility in accessing materials properties

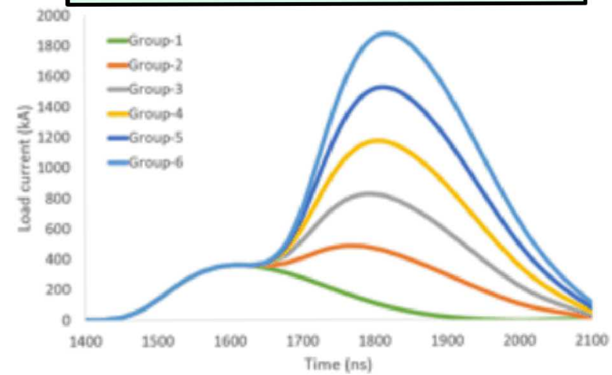
Ramp-Hold-Release



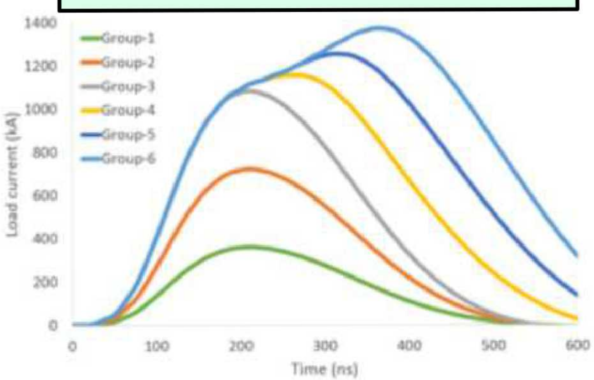
Ramp



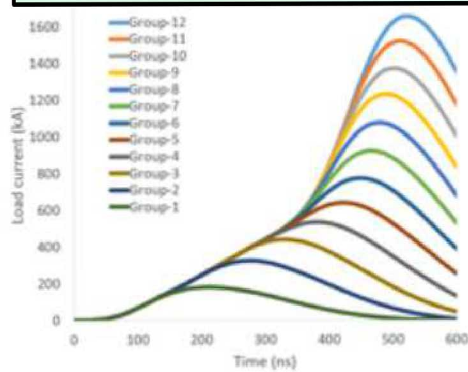
Ramp-Hold-Ramp



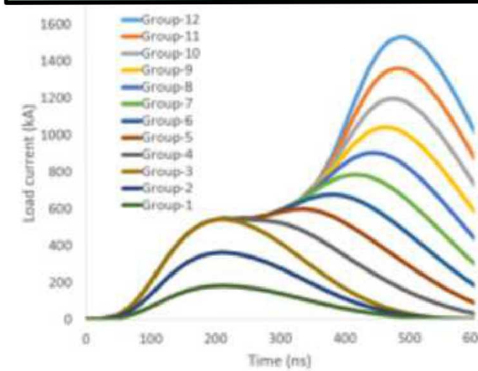
Shock-Ramp



Shockless Ramp

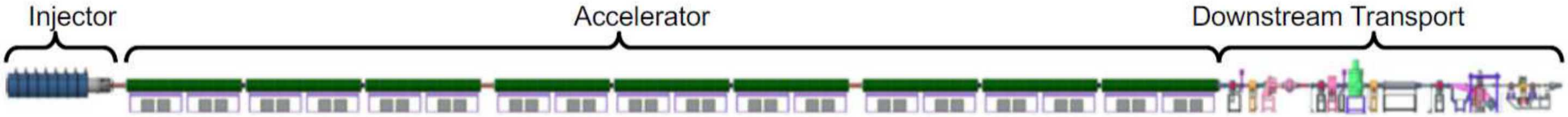


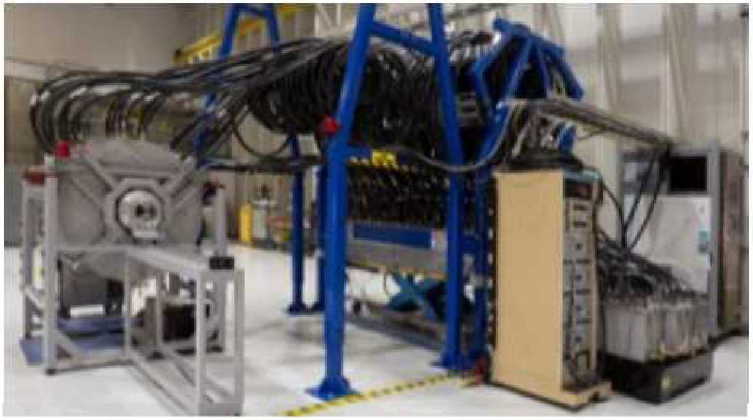
Ramp-Hold-Ramp

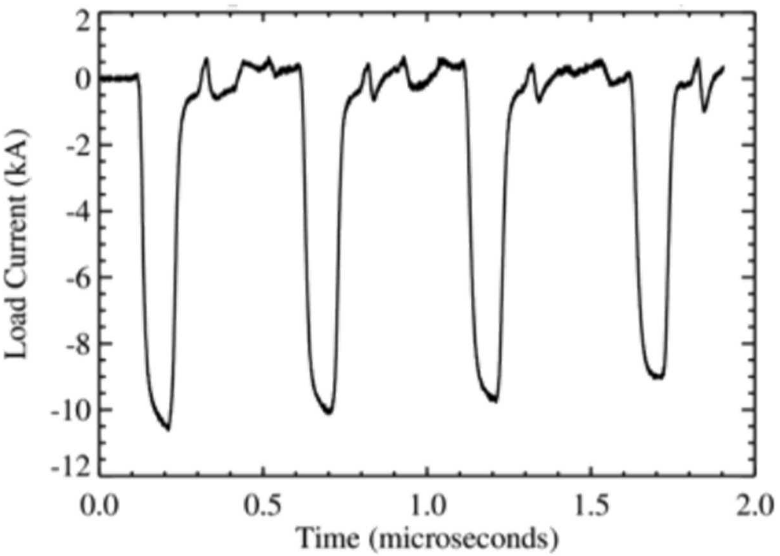


E. Waisman et al., *Rev. Sci. Instrum.*, Vol. 87, 063906, (2016).

CENTIPEDE is a multi-pulse technology demonstrator, as part of the SCORPIUS national radiographic accelerator project







SCORPIUS (LANL, LLNL, SNL, NNSS)
✓ 20 MeV, 2 kA, 4x pulse, 80 ns FWHM

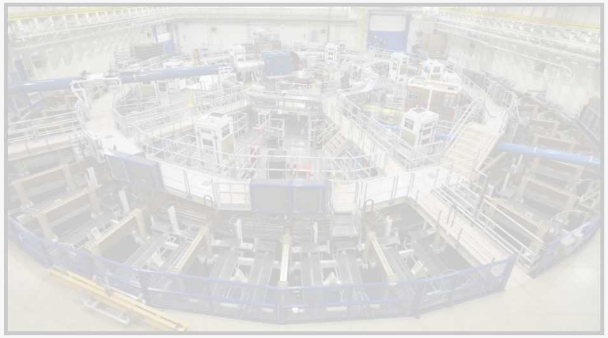
CENTIPEDE (2017)
✓ 250 kV, 22 Ω, 4x pulse, 100ns FWHM

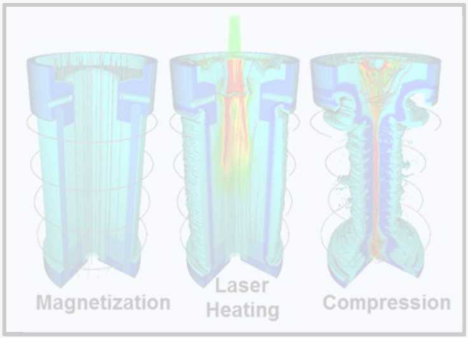
- ✓ 4x arbitrary timed pulses are generated using series connected pulse forming lines (PFLs)
- ✓ Voltage from PFLs combined using an inductive voltage adder (IVA)
- ✓ Architecture is similar to what could be used to build the SCORPIUS injector
- ✓ Sandia's pulsed power team (scientists, engineers, technologists) designed, built, and commissioned CENTIPEDE in less than one year
- ✓ Also being used as a test bed to study multi-pulse breakdown in vacuum, oil, solid dielectrics

Presentation Outline

Background

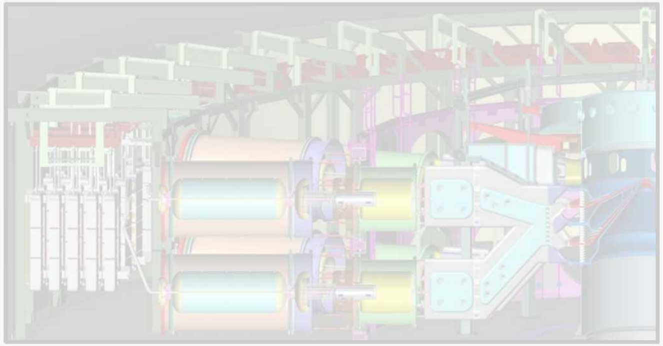
- ✓ *What / where is Sandia?*
- ✓ *Pulsed Power / HED Mission*
- ✓ *ICF / Science Experiments*





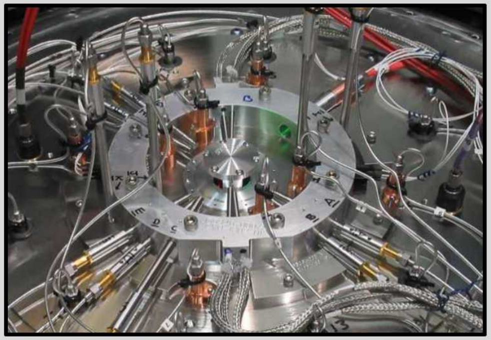
Accelerator Technology

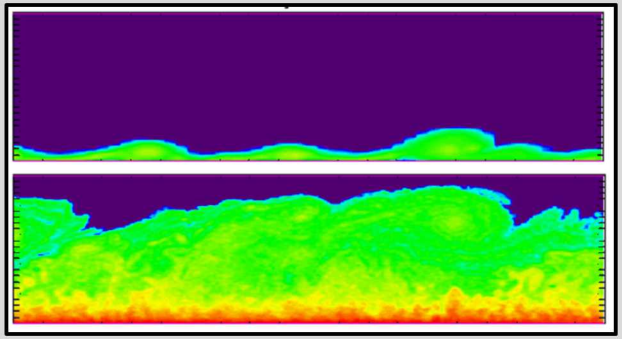
- ✓ *Z Pulsed Power Facility*
- ✓ *Future Technologies: LTD / IMG*
- ✓ *Multi-Pulse Accelerator Technology*



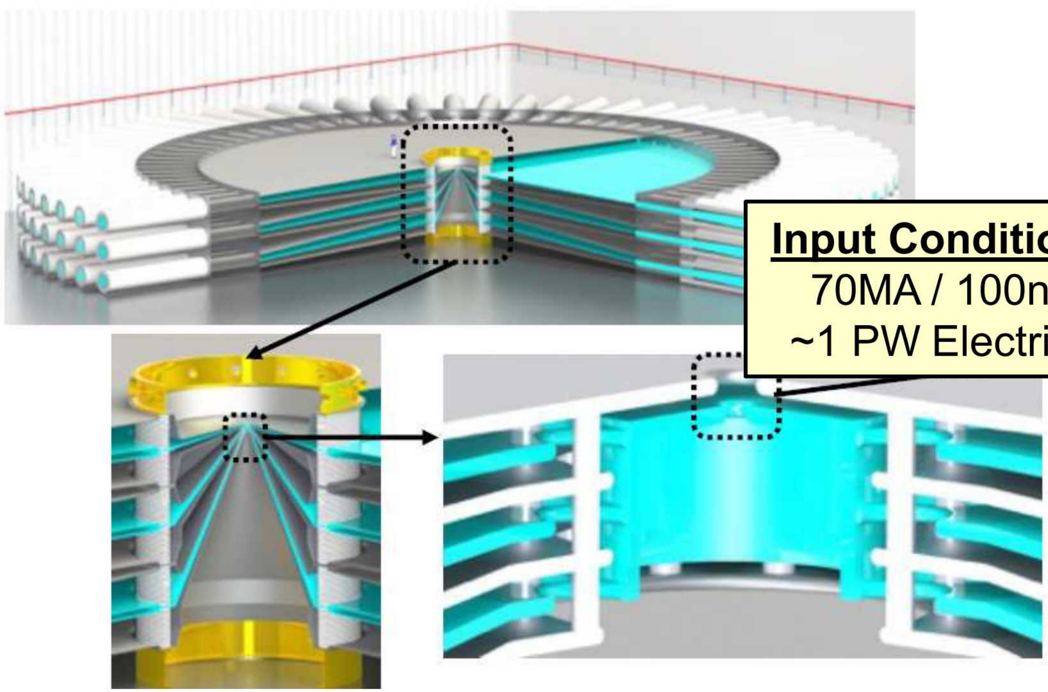
Pulsed Power Science

- ✓ *Power Flow / Current Loss*
- ✓ *PIC / Circuit Models*
- ✓ *Electrode Models*

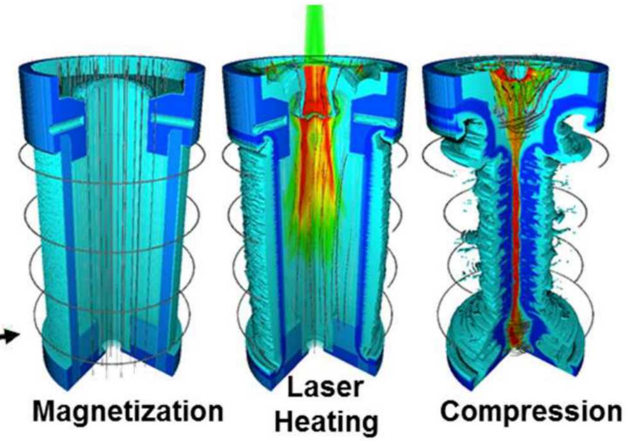




Our job as pulsed power scientists is to deliver the accelerator electrical power to a radius of 1 cm to enable discovery science



Input Conditions
70MA / 100ns
~1 PW Electrical



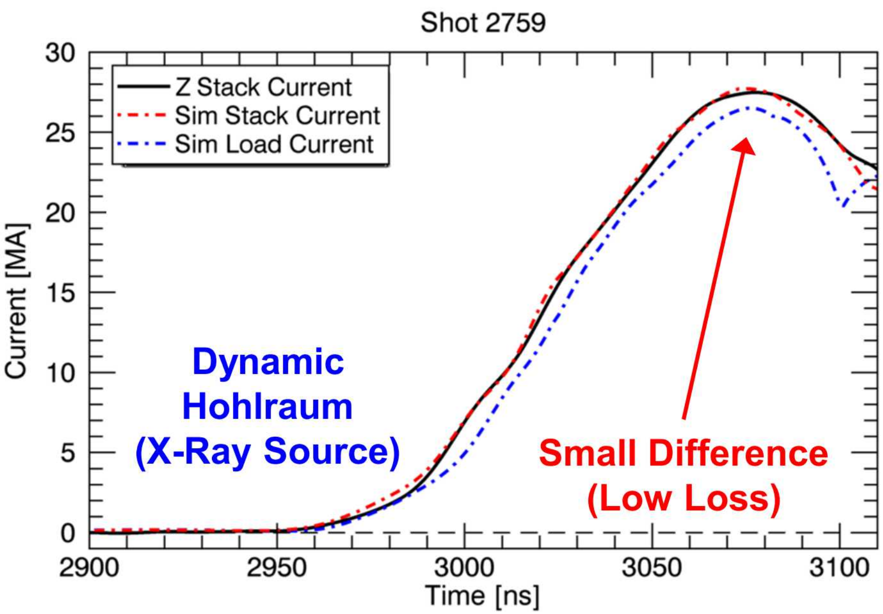
Output Conditions
30 PW D-T Neutrons
400 PW X-Rays

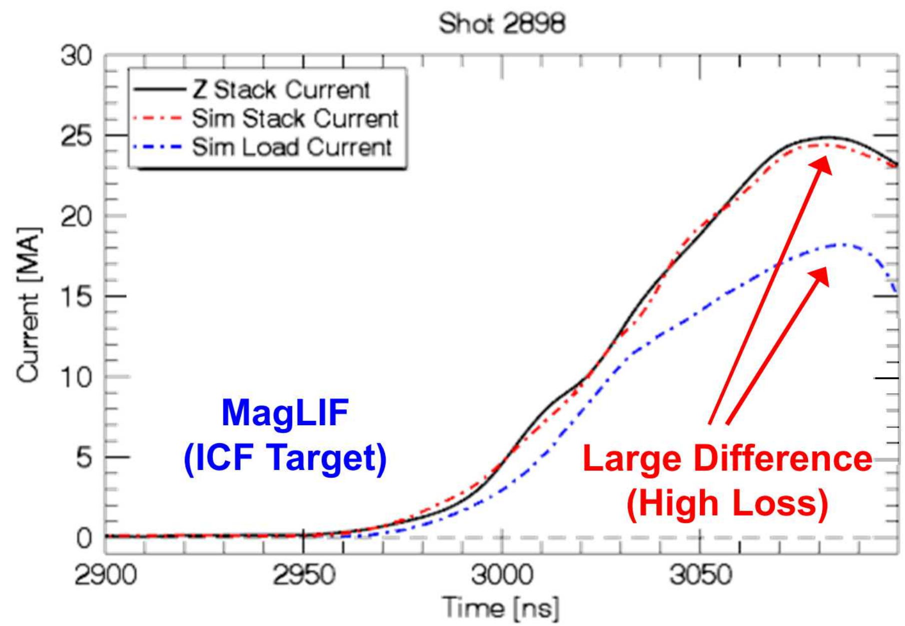
Driver / Source Design Principles
- ✓ Electromagnetics, Pulsed Power
- ✓ Mechanical / Electrical / Civil Engineering

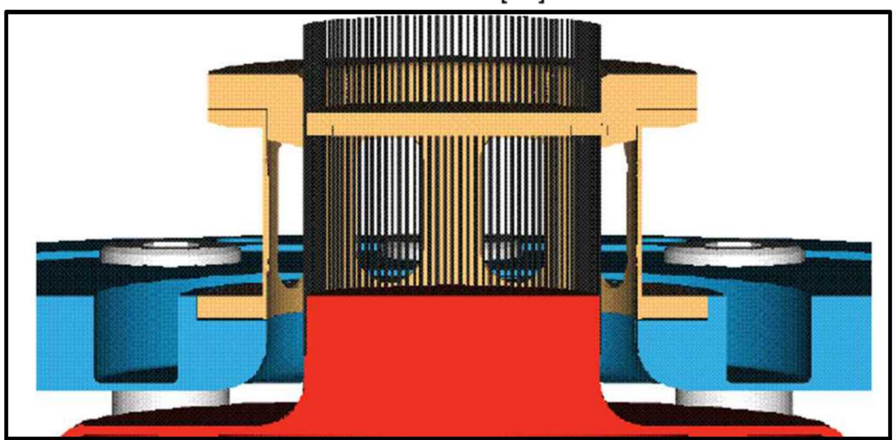
Example Driver Uncertainties
- ✓ Electrode Plasma Formation / Expansion
- ✓ Current Loss

Discovery Science Experiments
- ✓ Fusion Ignition
- ✓ Astrophysics / Planetary Science
- ✓ X-Ray / Radiation Physics
- ✓ Dynamic Materials Science
- ✓ National Security Applications

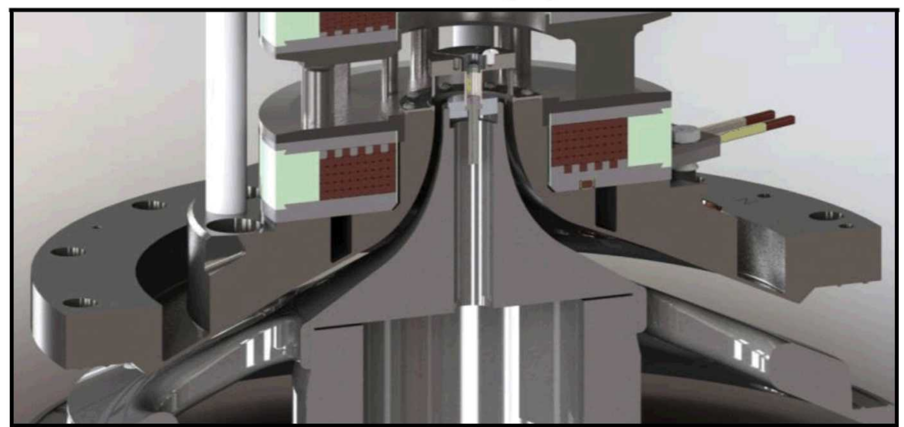
Plasmas that form in the vacuum transmission lines can reduce the efficiency of current coupled to the load







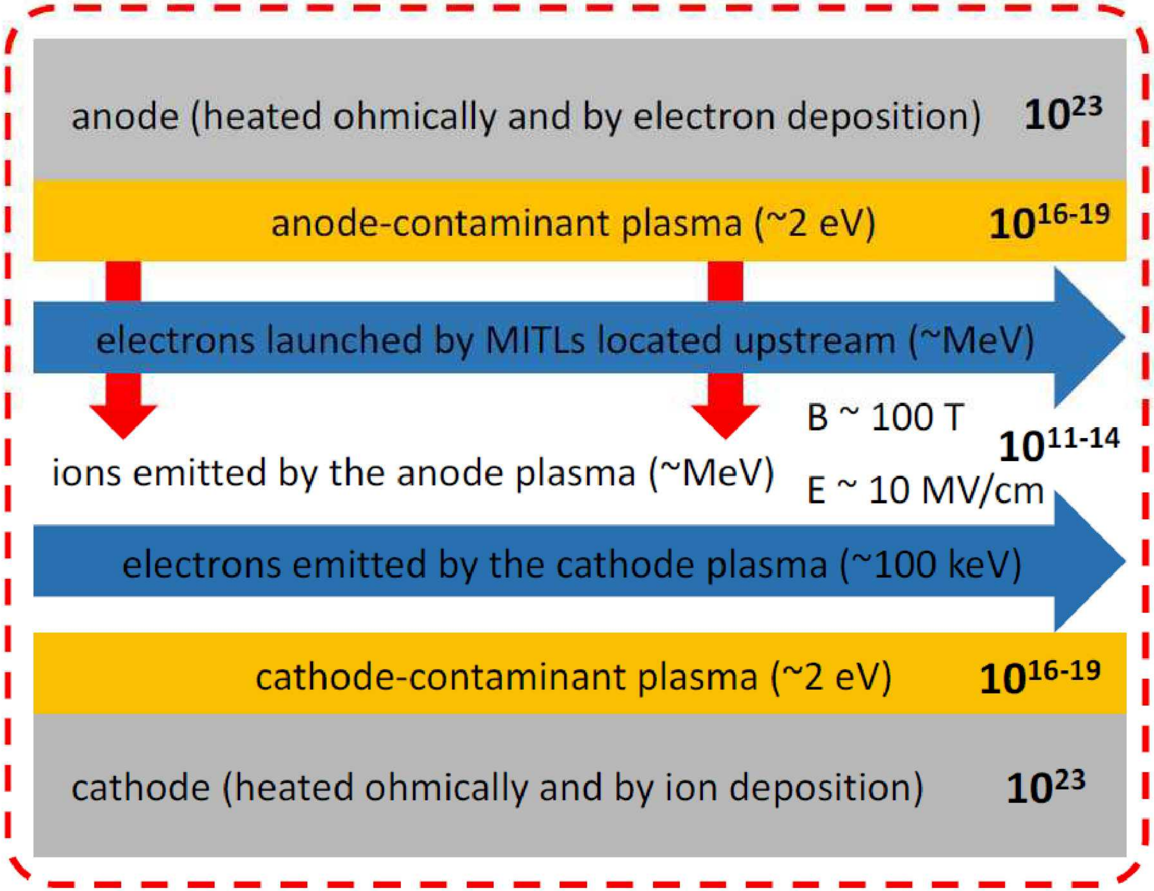
Dynamic Hohlraum = Low Inductance (<3.0 nH)



MagLIF = High Inductance (>6.0 nH)

A terawatt-class power pulse generates plasmas within a vacuum transmission line

section of a "vacuum" transmission line at small radius



Multi-scale plasmas crossing PIC and Continuum regimes

Such plasmas are:

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

Simulations should account for:

- Energy deposition into electrodes
- Neutral desorption and ionization
- Magnetization of the particles and plasmas
- Electron flow fraction and loss
- Kinetic, MHD, XMHD, Collisions
- Electromagnetic waves

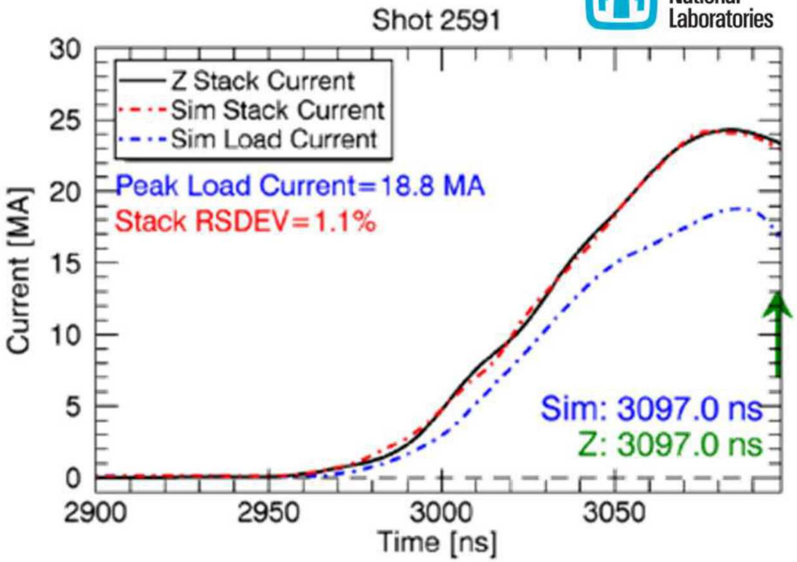
Experiments could measure:

- Coupled or transmitted current
- Electrode heating
- Plasma onset and properties
- Electron flow fraction and loss
- Ion current
- Electric and magnetic fields

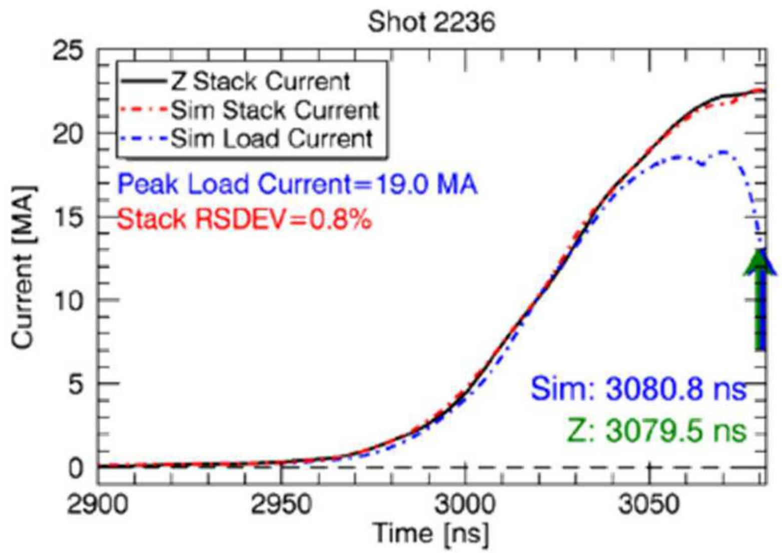
W. Stygar et al., *Phys. Rev. ST Accel. Beams*, Vol. 9, 090401, (2006).

We have developed a predictive physics-based circuit model (BERTHA) that agrees with Z Facility current measurements within 2%

- Physics based parameters include:
  - ✓ Electron emission threshold
  - ✓ Magnetically insulated electron losses
  - ✓ Ohmic heating / energy loss
  - ✓ Anode / Cathode plasma expansion velocity
  - ✓ Anode plasma formation threshold
  - ✓ Ion emission from anode plasmas
  - ✓ Space charged limited ion enhancement
  - ✓ Electron flow physics
  - ✓ Magnetically un-insulated ion thresholds
- Swarm analysis techniques led to one set of physics parameters → fits 52 shots on 8 platforms
- Model is actively exercised to guide designs for Z driver-target coupling experiments
- Various physics parameters are being investigated / validated via experimental programs



Standard MagLIF, 7.5 mm target

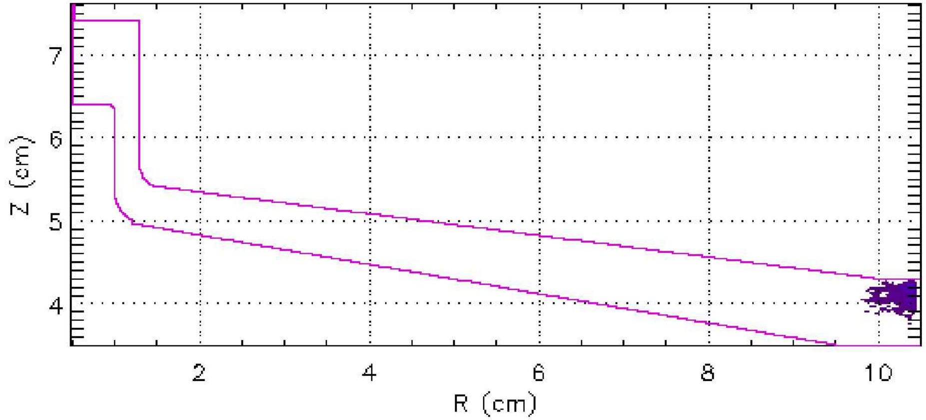


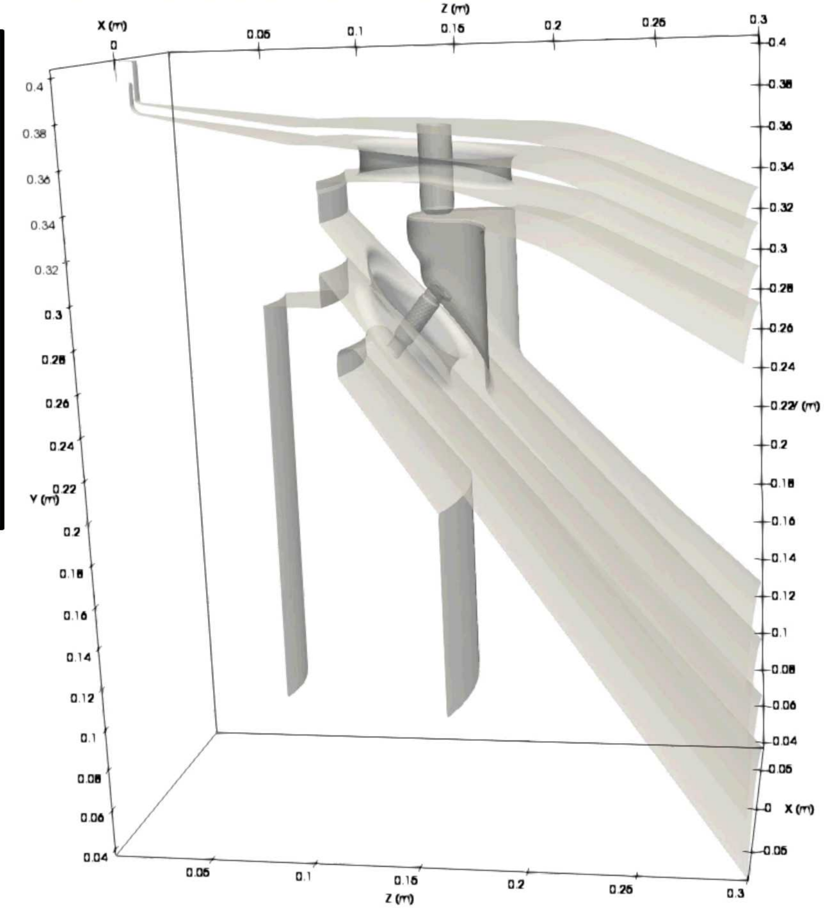
Nested stainless steel wire array

We are developing advanced kinetic PIC models to explore electrode plasma formation on accelerators

- Multiple tools are being developed with different algorithms to provide detailed code comparisons and to reduce risk in model extrapolation (LSP/CHICAGO, EMPIRE/EMPHASIS)
- Large effort to develop hybrid kinetic/fluid modeling tools to seamlessly incorporate multi-physics phenomena (power flow, target physics)
- Testing code scaling on large computing platforms

Inner MITL plasma simulation of Power Flow 18a experiment using CHICAGO/PIC





Electron physics simulation of the Power Flow 18a experiment using EMPHASIS/PIC

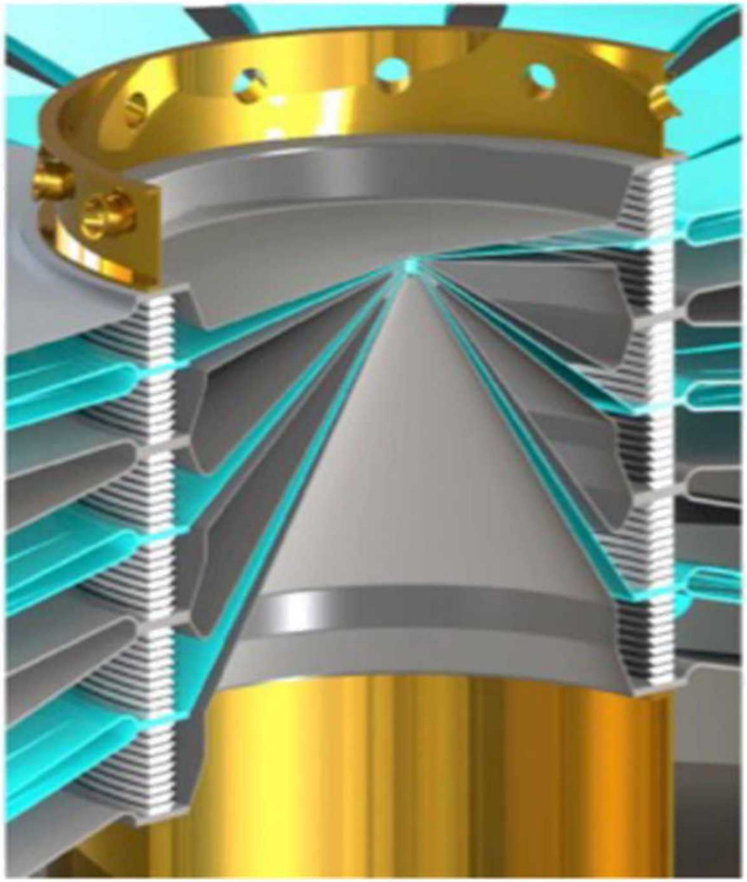
Circuit and PIC models demonstrate that current loss in the Z vacuum section is significant when certain conditions are met

Important MITL Conditions:

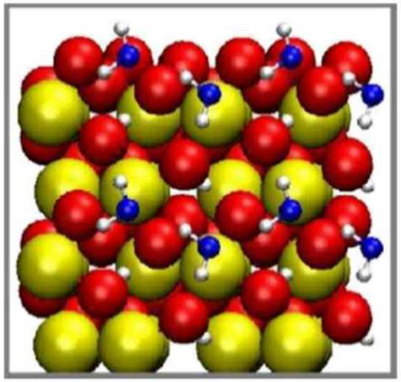
- ✓ Electrons are emitted in the outer MITLs and ExB drift towards the convolute and inner MITL
- ✓ Anode surfaces at the convolute / inner MITL become space charge limited (SCL) ion sources
- ✓ Anode-Cathode gaps of the convolute / inner MITL close significantly during the power pulse'
- ✓ Characteristic impedances of the inner MITL and load (target) are relatively high

Modeling suggest that when one (or more) of these conditions are not met → current loss on the Z accelerator is negligible

One of the goals of our power flow physics program is to confirm these hypotheses!



We are using multi-scale modeling approaches to understand the desorption of electrode contaminants

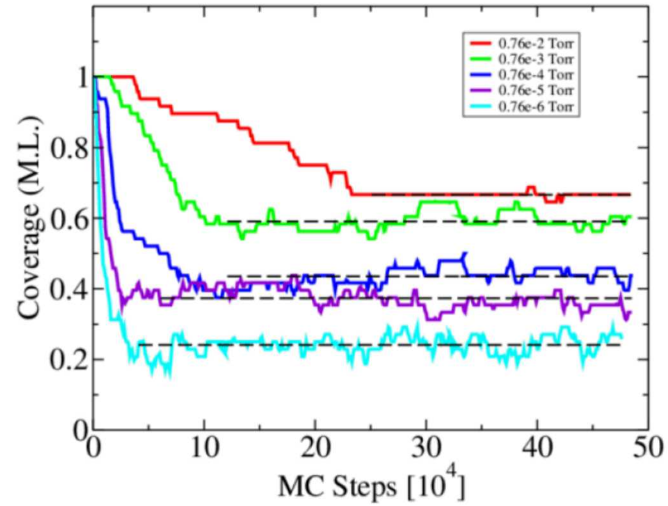


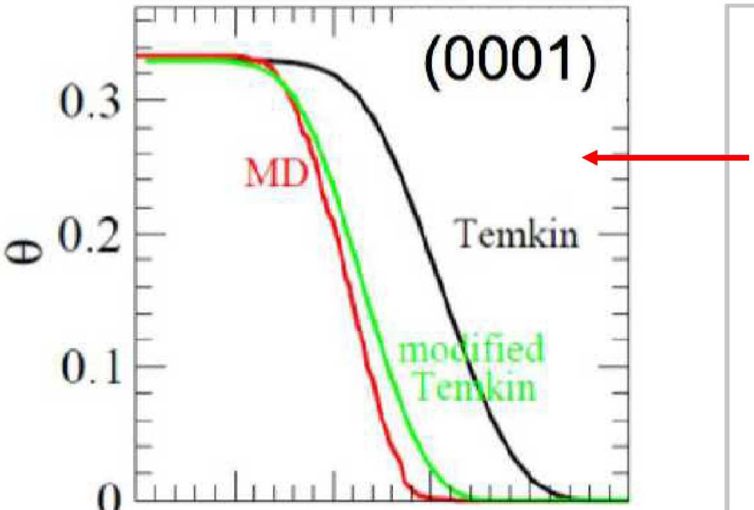
Density Functional Theory

- ✓ Calculate the adsorption / desorption energies of contaminants (H_2O, CO_2, etc.) to steel surfaces (Fe_2O3, Cr_2O_3, etc.)

Grand Canonical Monte Carlo

- ✓ Calculate the amount of contaminant adsorption ("mono-layers") as a function of background vacuum





Molecular Dynamics

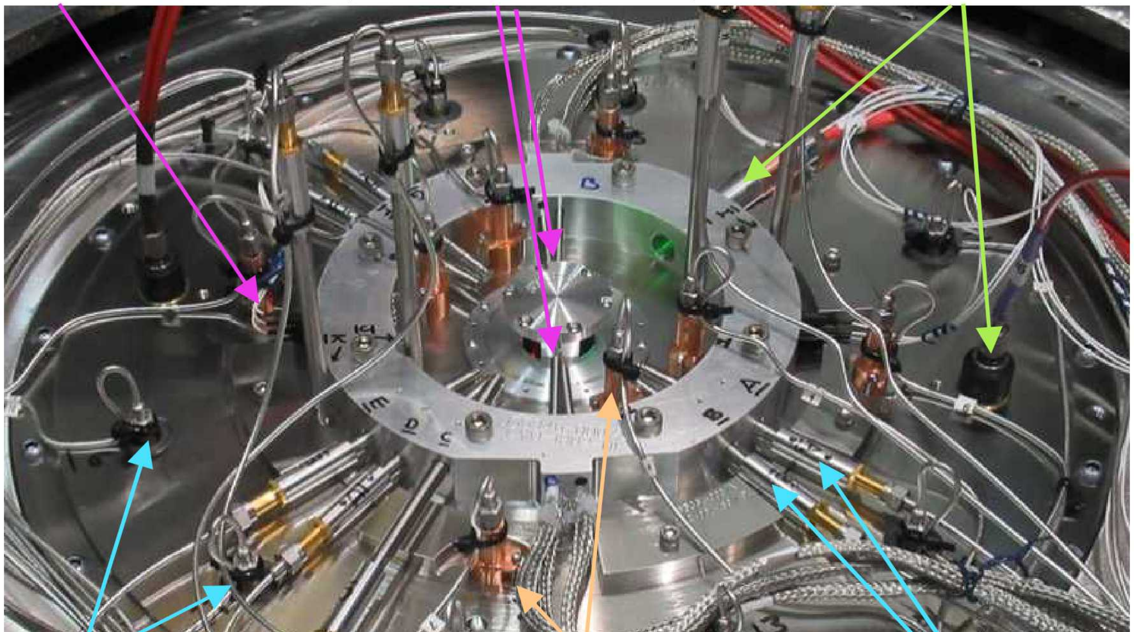
- ✓ Simulate the desorption of contaminants as a function of rapid current-induced surface heating ($2x10^9$ C/s)

We are developing integrated experimental platforms and diagnostics to explore power flow physics on Z

Chordal PDV Interferometer (Plasma Timing)

PDV/VISAR Velocimetry (Load Current)

UV/VIS Spectroscopy (Cathode Temperature, Plasma Properties)



Faraday Cup Anode Post (Particle Fluence)

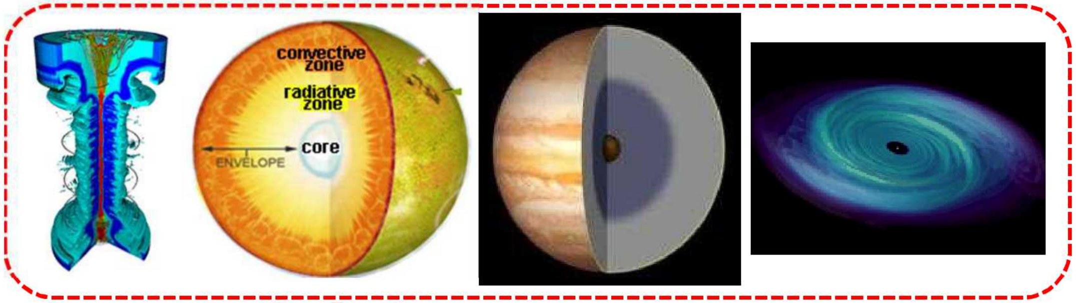
B-Dot (Load Current)

Mini-XRD (Cathode Temperature)

Each Z experiment included 30 electrical data channels, 55 optical data channels, and 10 film/sample recoveries supporting convolute/inner MITL power flow!

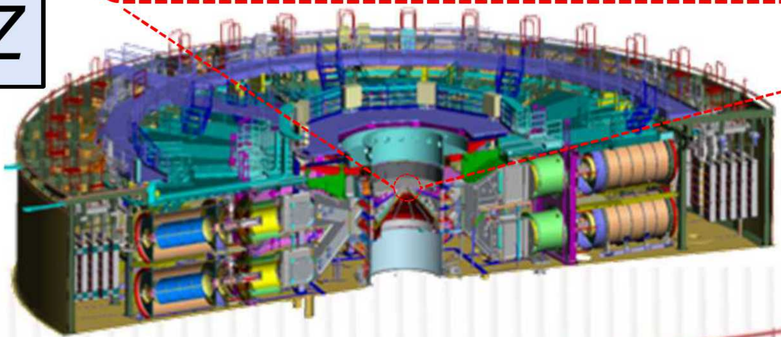
These efforts will **deliver the plasma physics S&T foundation** to realize a next-generation HED facility for discovery science!

Sandia National Laboratories



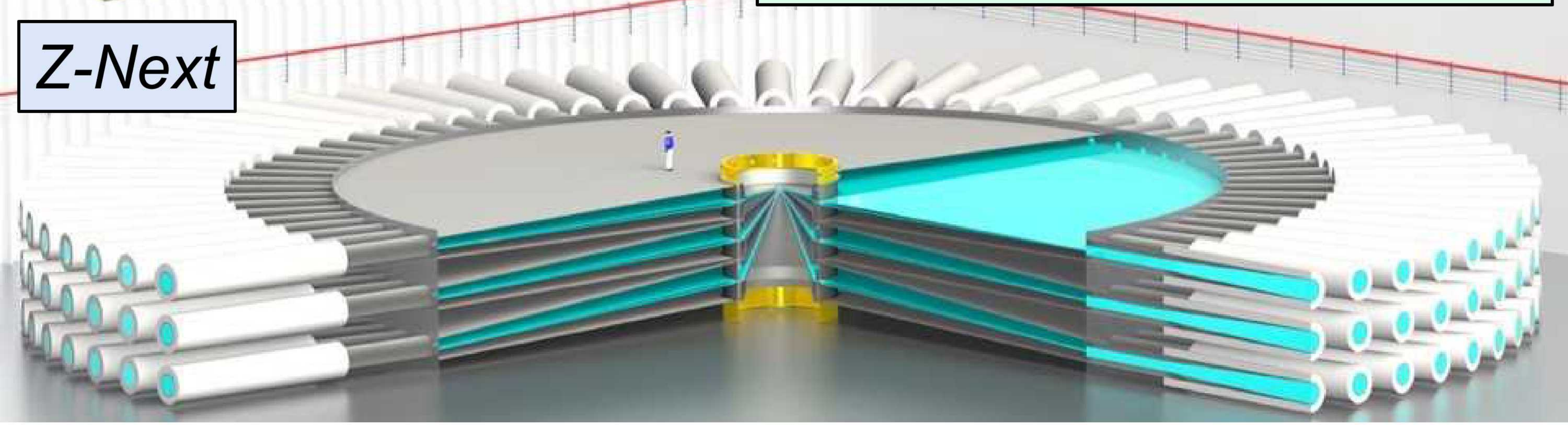
Discovery Science:
- ✓ *Fusion Ignition*
- ✓ *Astrophysics*
- ✓ *Planetary Science*
- ✓ *National Security Applications*

Z



We are investing in Foundational S&T for:
- ✓ *Computational Plasma Physics Models*
- ✓ *3D Hybrid Kinetic-Fluid Simulation Methods*
- ✓ *Improvements in Algorithm Efficiency / Speed*
- ✓ *Models of Real Electrode Surfaces in the Lab*

Z-Next



Summary

- Sandia stewards the U.S. capabilities in fast high-current pulsed power, and we are rapidly developing the next generation of pulsed power driver technologies
- We have an extensive R&D program spanning engineering design, applied physics, and technology demonstration with a lot of work to accomplish over the next 5-10 years:
  - ✓ Demonstrate multi-pulse technology for a national radiography accelerator project
  - ✓ Upgrade several accelerator facilities currently in wide-spread use at Sandia to support multiple scientific missions (THOR, SATURN, etc.)
  - ✓ Steward and improve the achievable performance of the Z Facility
  - ✓ Develop the technology foundation for a next-generation ICF/HED accelerator
  - ✓ Develop and demonstrate advanced pulsed power modeling capabilities including circuit codes, hybrid PIC/fluid codes, and electrode modeling codes
  - ✓ Conduct significant S&T evaluations of insulator flashover / breakdown, multi-pulse e-beam cathode performance, laser triggered switches, mechanical/thermal/vacuum analysis, engineered reliability/operability of high-shot rate accelerators, and more…
- We would like to double the science/engineering staff in our pulsed power S&T organization over the next few years to address these R&D challenges!