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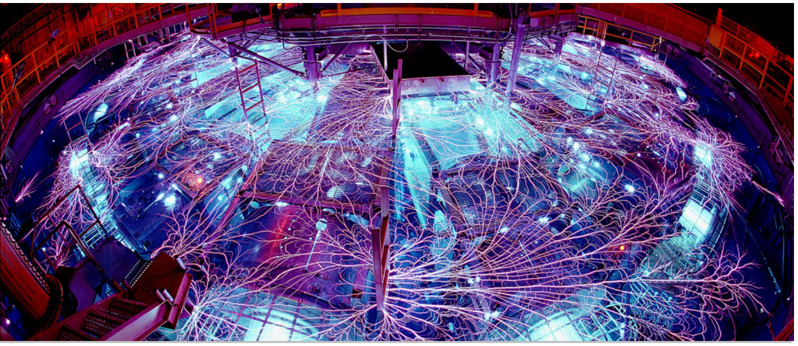

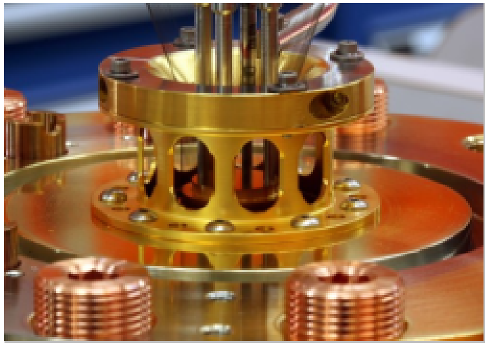

Overview of Pulsed Power Science & Technology for High Energy Density Physics Applications

George R. Laity (grlaity@sandia.gov)

R&D Manager, Advanced Capabilities for Pulsed Power

Sandia National Laboratories, Albuquerque, NM

High Energy Density Science Summer School, August 6th, La Jolla, CA, USA

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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Pulsed Power involves lots of great people!

C. R. Aragon[1], T. J. Awe[1], K. Beckwith[1], K. S. Bell[1], N. L. Bennett[1], M. T. Bettencourt[1], D. E. Bliss[1], K. Chandler[1], K. Cochrane[1], M. E. Cuneo[1] , D. H. Dolan[1], J. D. Douglass[1], A. S. Fierro[2], M. R. Gomez[1], M. H. Hess[1], B. T. Hutsel[1], C. A. Jennings[1], M. D. Johnston[1], M. C. Jones[1], J. Koski[1], M. R. Kossow[1], D. C. Lamppa[1], J. M. Lane[1], K. LeChien[3], J. Leckbee[1], K. Leung[1], Y. Maron[4], R. D. McBride[5], C. E. Myers[1], S. Patel[1], K. J. Peterson[1], A. J. Porwitzky[1], A.C. Robinson[1], D. V. Rose[6], M. E. Savage[1], S. C. Simpson[1], D. B. Sinars[1], A. M. Steiner[1], B. Stoltzfus[1], W. Stygar[3], A. P. Thompson[1], J. P. VanDevender[1], E. M. Waisman[1], T. J. Webb[1], D. R. Welch[6], D. A. Yager-Elorriaga[1], ***and many more…***

[1]Sandia National Laboratories, Albuquerque, NM

[2]University of New Mexico, Albuquerque, NM

[3]Lawerence Livermore National Laboratory, Livermore, CA

[4]Weizmann Institute of Science, Rehovot, Israel

[5]University of Michigan, Ann Arbor, MI

[6]Voss Scientific LLC, Albuquerque, NM

Presentation Outline

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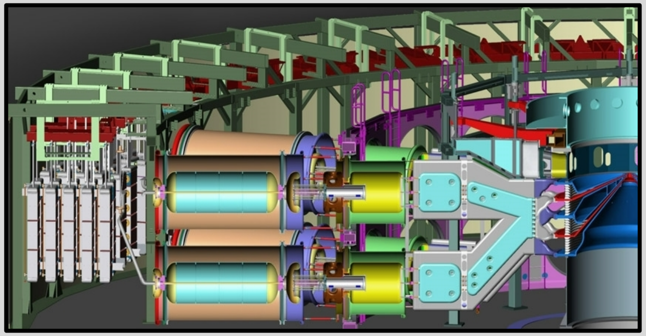
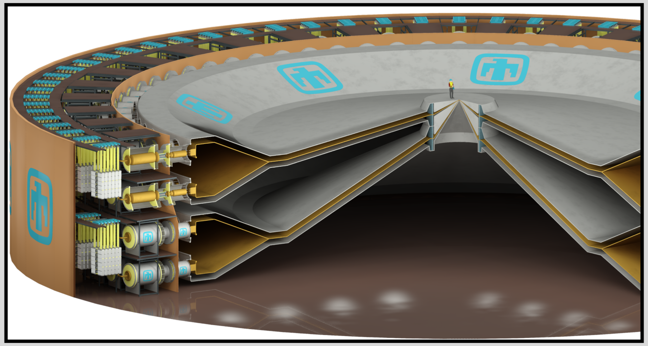
Background

- ✓ *What is pulsed power?*
- ✓ *Z Architecture*
- ✓ *Pulsed Power Facilities*



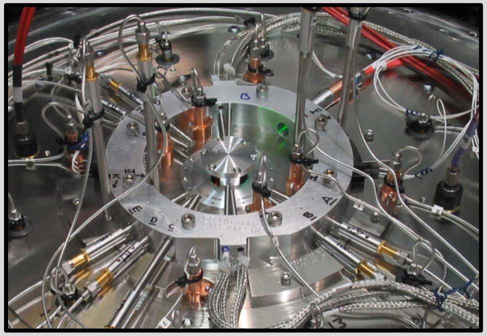
Accelerator Technologies

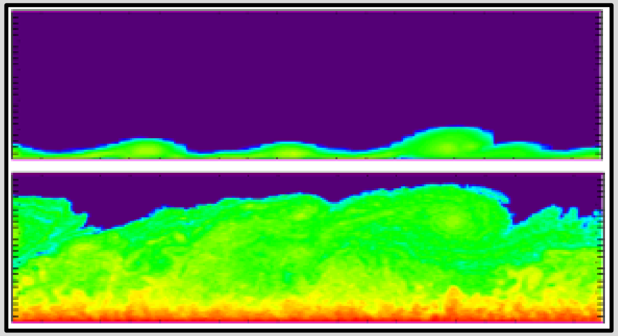
- ✓ *Next-Generation Pulsed Power*
- ✓ *New Technologies: LTD / IMG*
- ✓ *Multi-Pulse Accelerator Technology*



Pulsed Power Science

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





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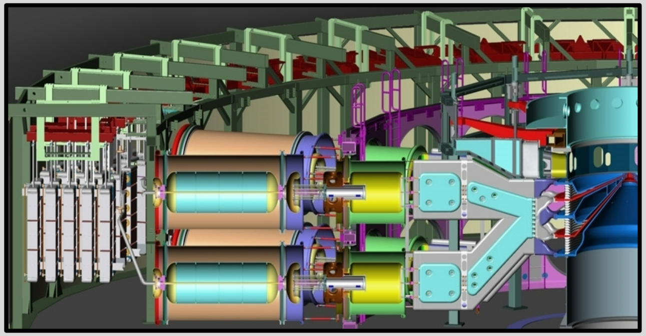

Accelerator Technologies
- ✓ *Next-Generation Pulsed Power*
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Pulsed Power Science
- ✓ *Power Flow / Current Loss*
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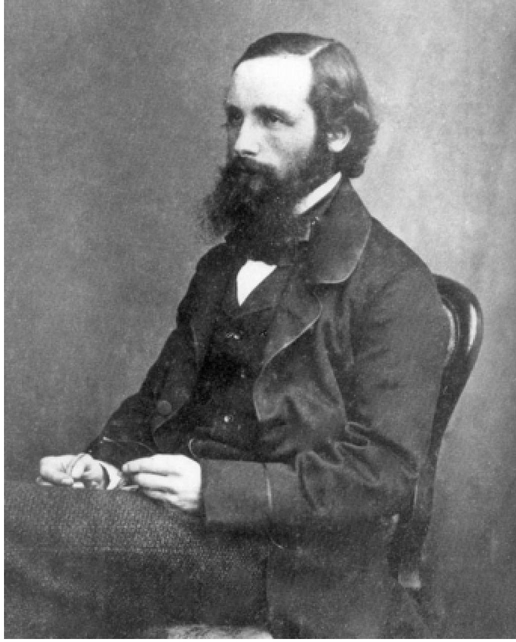
- ✓ *Electrode Models*

Pulsed power is an amazing technology

Pulsed power accelerators can routinely today:

- ✓ Serve as precision scientific instruments
- ✓ Deliver mega-joules of energy to milli-grams of matter on a time-scale of nano-seconds
- ✓ Achieve extreme states of matter over macroscopic volumes of interest
- ✓ Drive a wide variety of high-energy-density science experiments in support of the U.S. national security mission

Michael Faraday

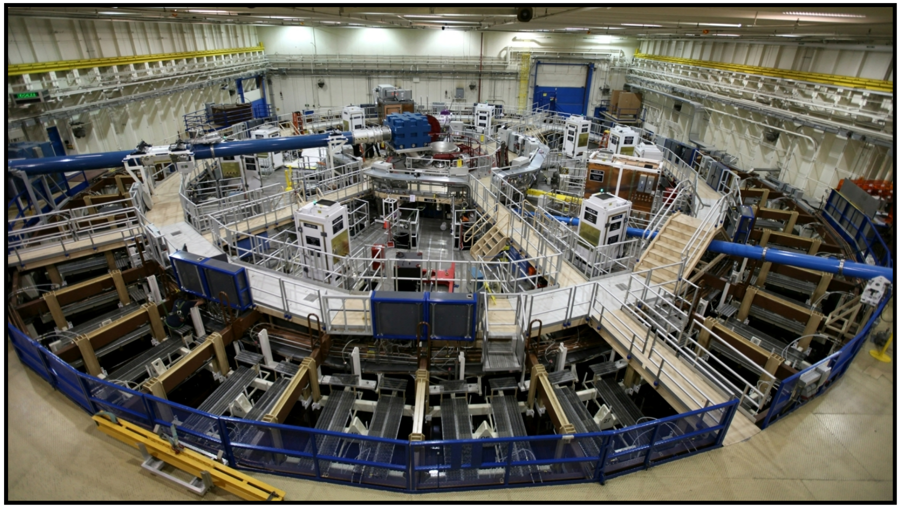


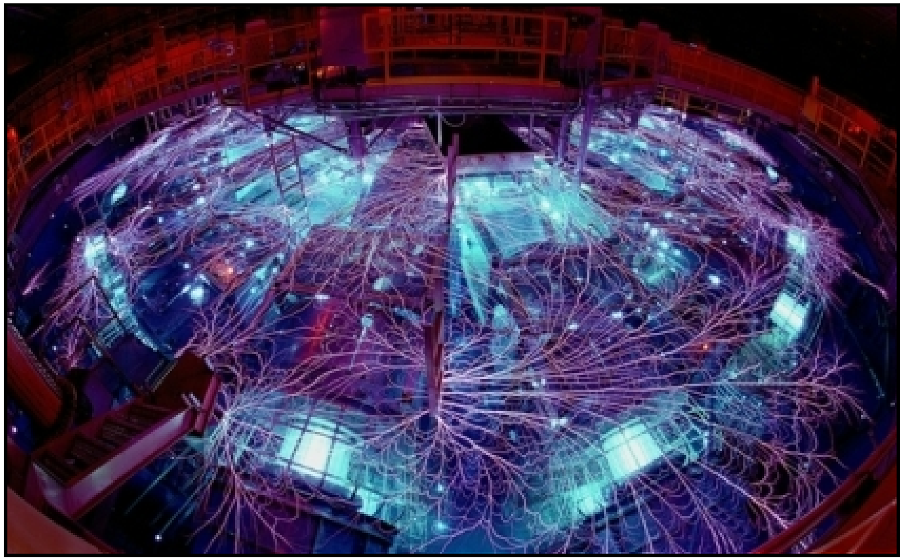
James Clerk Maxwell

Erwin Otto Marx

J. C. “Charlie” Martin

We use pulsed power technology to create high energy density (HED) conditions in experiments





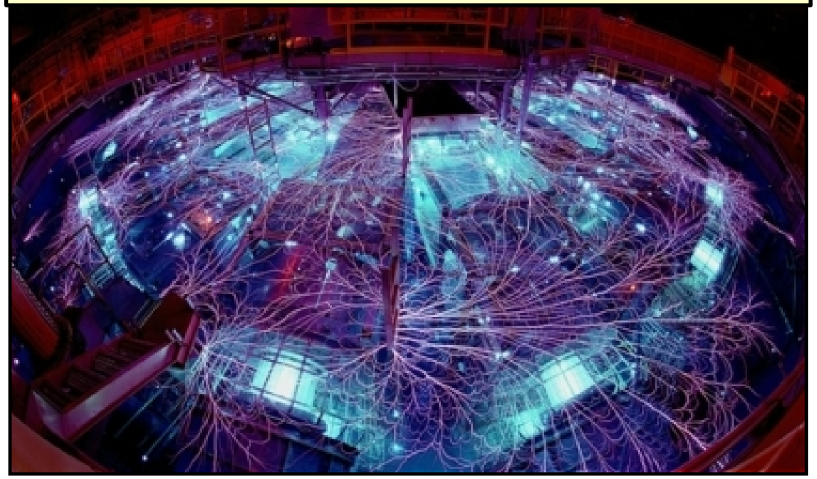
- What is pulsed power?
  - Store energy over a relatively long period of time (seconds to minutes)
  - Discharge over a relatively short period of time (ns to μs)
  - Compression in time of $>10^8$
- Z builds up >20 MJ of energy over about 2-3 minutes
  - Average power ~ 100 kW
- Z delivers 2-3 MJ of electrical energy to an HED science experiment in as fast as 100 ns
  - **Z peak power = ~80 TW!**
  - Worldwide Generation = ~5 TW

Why is this difficult?

- **Doing something faster is generally more challenging!**
- For example, if you needed to travel 1000 ft –
  - ✓ If a few minutes is acceptable, you could just walk
  - ✓ If one minute is acceptable, you could ride a bicycle
  - ✓ 10’s of seconds requires a typical car
  - ✓ 4 seconds requires a *nitro-fueled dragster*

20 MJ electrical energy released over hours…

The Z Machine is the top-fueled dragster of electrical systems!



Credit to Mark Savage for the useful analogy!

Sandia operates several pulsed power accelerators for radiation physics and HED science applications

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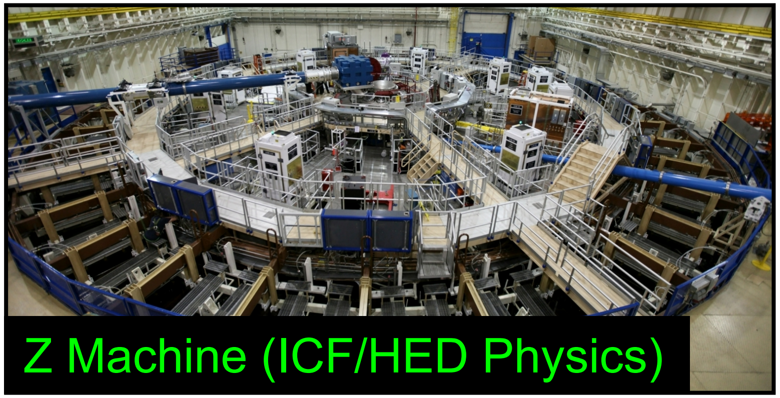
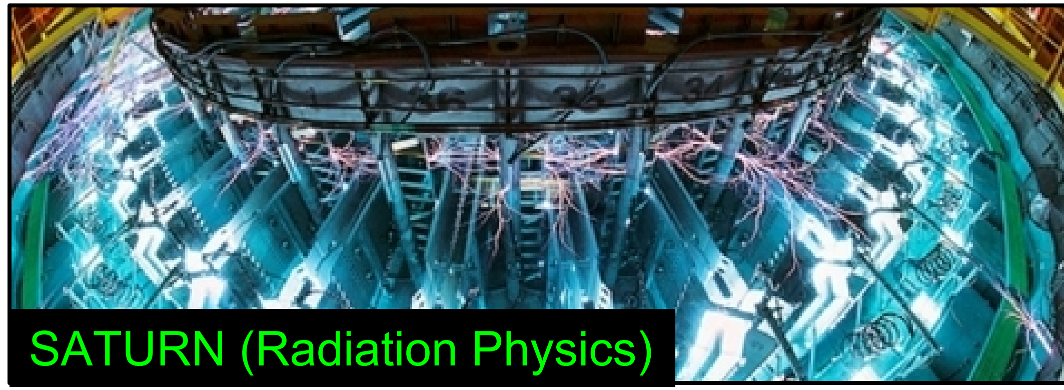
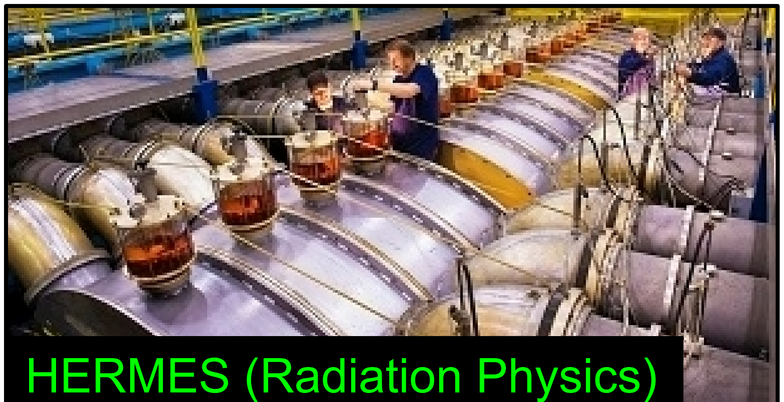


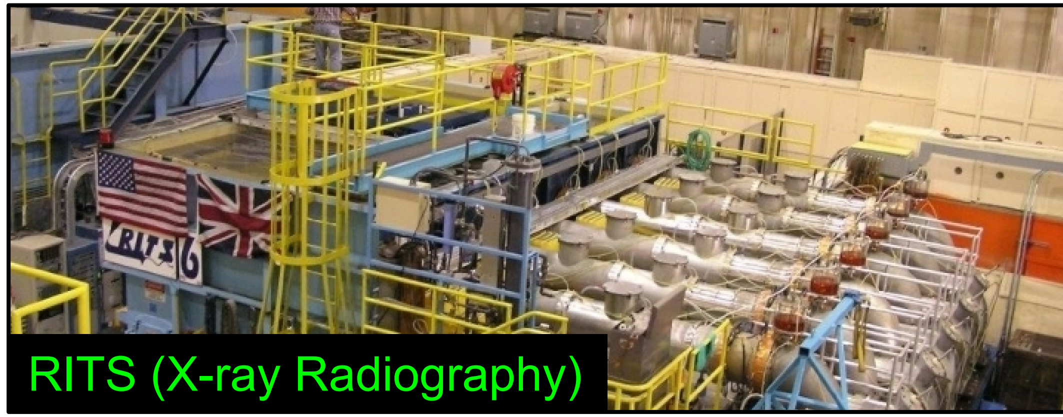
Z Machine (ICF/HED Physics)



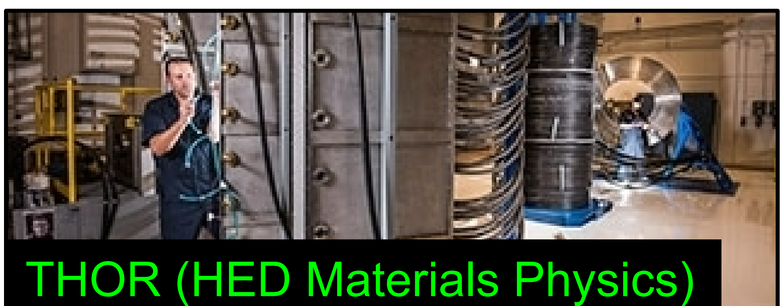
SATURN (Radiation Physics)



HERMES (Radiation Physics)



RITS (X-ray Radiography)



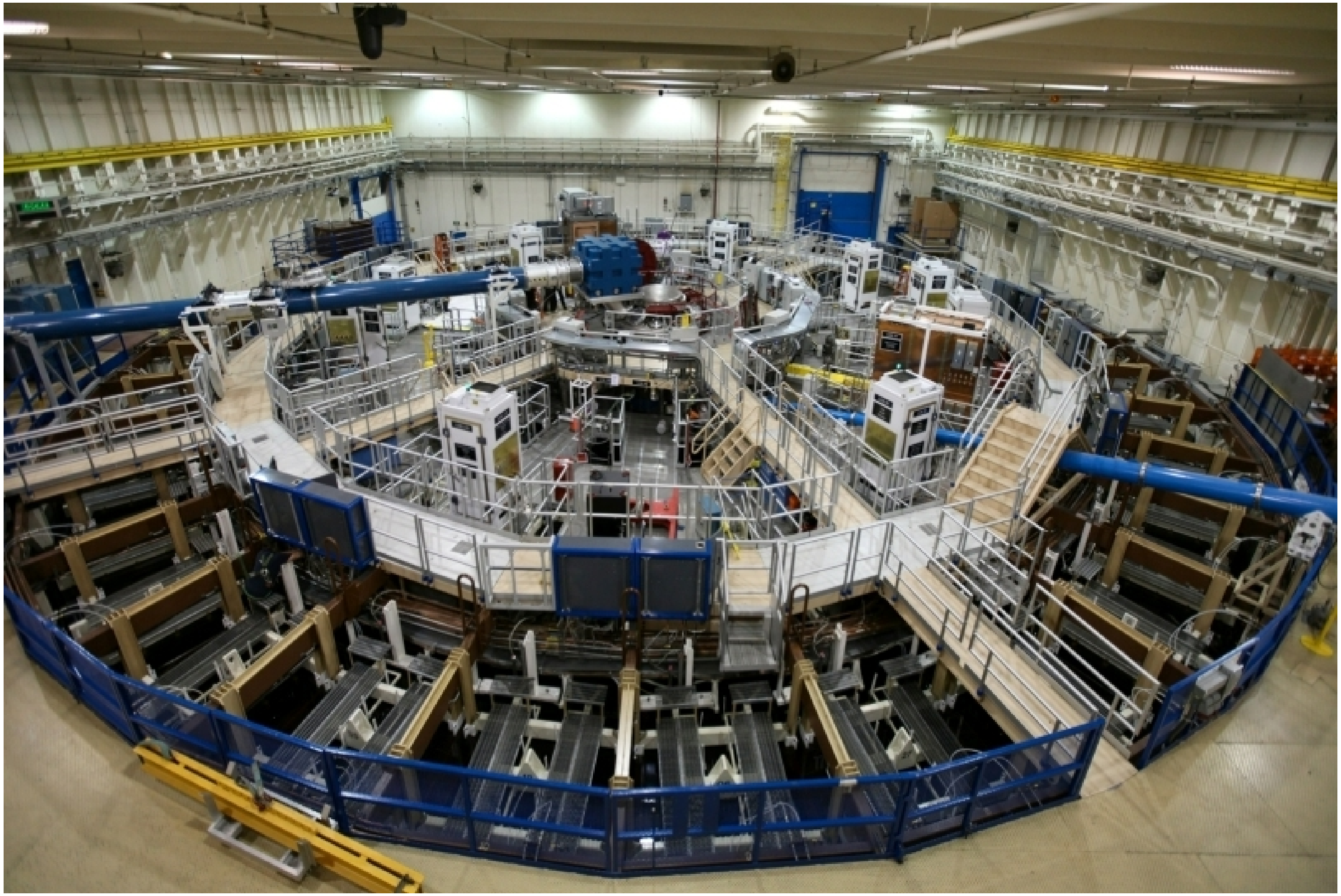
THOR (HED Materials Physics)

MYKONOS (Technology Development)

Sandia's Z accelerator is *presently* the world's largest and most powerful pulsed power machine

E_{stored} = 20 MJ	V_{stack} = 4 MV	I_{load} = 26 MA	$E_{radiated}$ = 2.2 MJ
$P_{electrical}$ = 80 TW	L_{vacuum} = 12 nH	$\tau_{implosion}$ = 130 ns	diameter = 33 m

- Since 1997 we have conducted an average of 160 experiments each year
- To date, 3500 Z experiments have been conducted

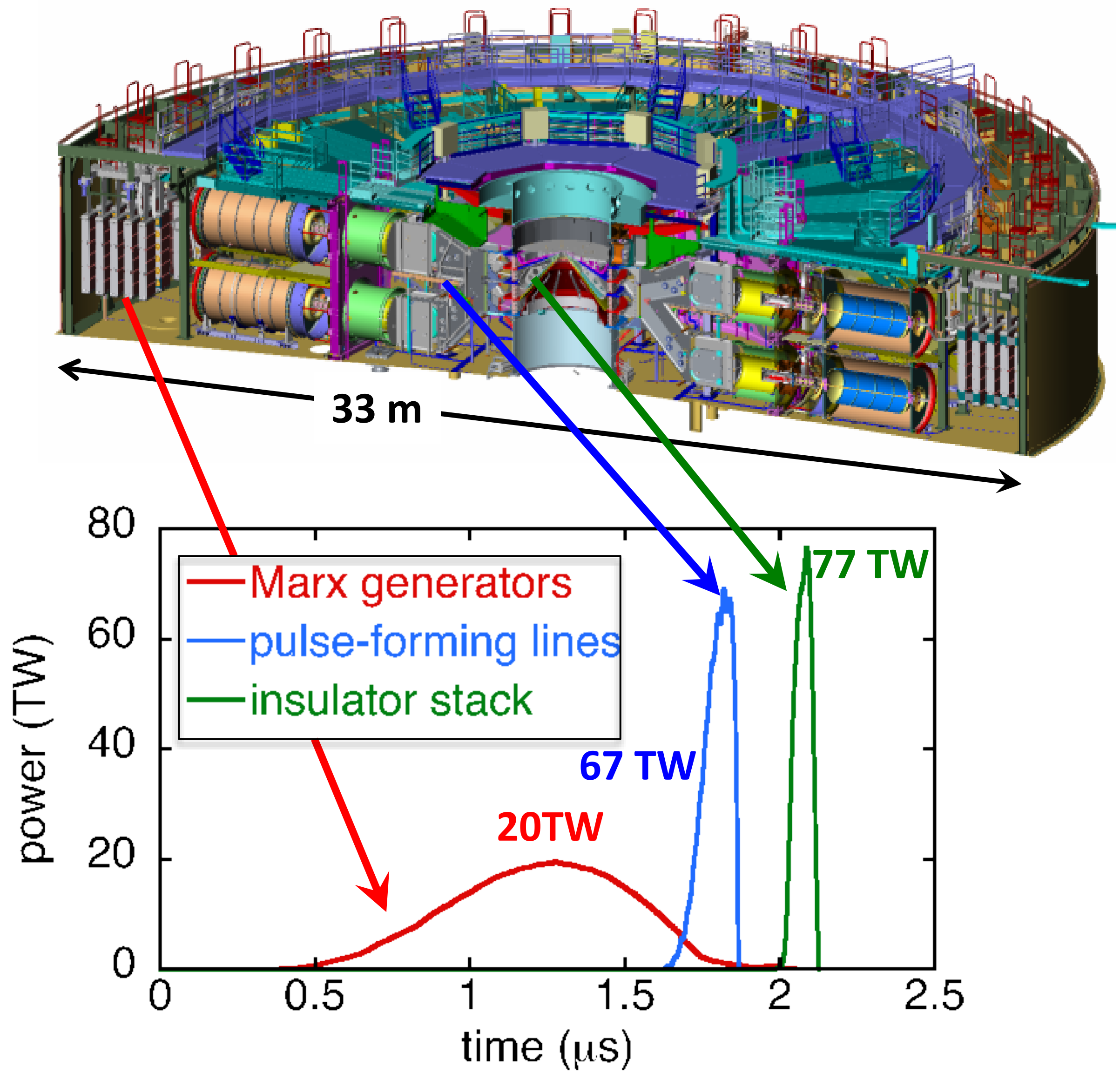


All of this electrical energy in a small volume can have destructive consequences!

Before

After

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!

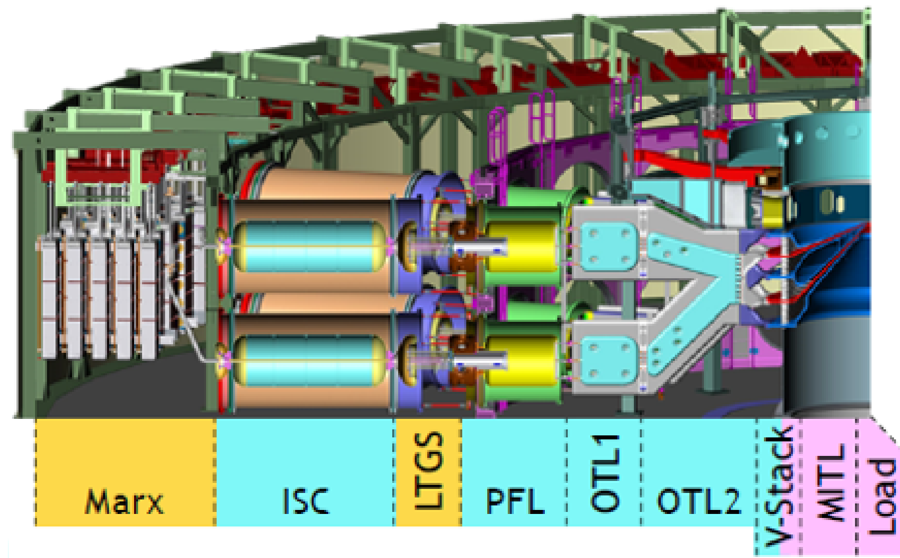
We are still advancing this technology today, with a focus on several aspects:

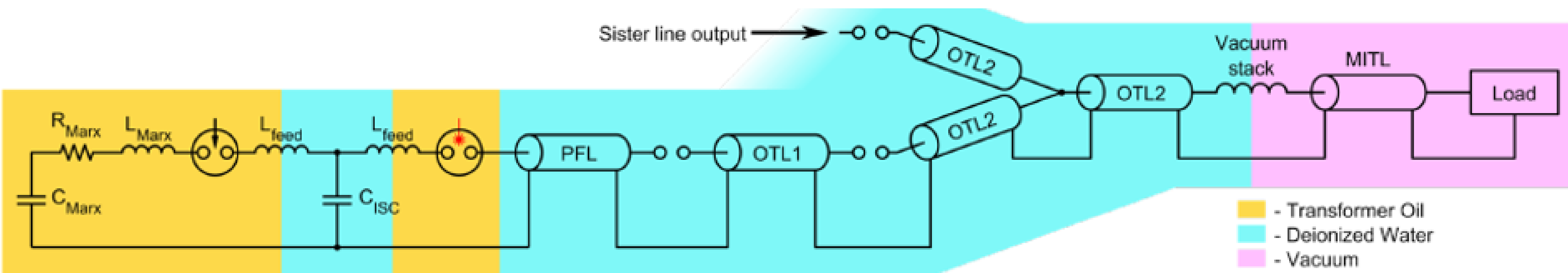
- ✓ Desire to move to **simpler components**, for improved modularity and easier maintenance
- ✓ Desire to increase the variety of **pulse shaping configurations** available

Stygar et al., *Phys. Rev. ST Accel. Beams* 12, 120401, (2009).

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

- **Why are the Z Marx generators in oil?**
  - *Oil allows us to charge in minutes; air can't hold the voltage required and water would be too lossy at that timescale*
- **Why are the intermediate store capacitors water-filled?**
  - *For pulses, water allows much more energy storage in a given volume*
- **Why are the laser-triggered gas switches in oil?**
  - *Oil more closely matches the plastic housing and SF_6 inside, reducing the electric field and improving switch reliability*
- **Why are the pulse-forming lines in water?**
  - *Water allows more current for a given voltage; a purely oil-based Z system would be much larger*



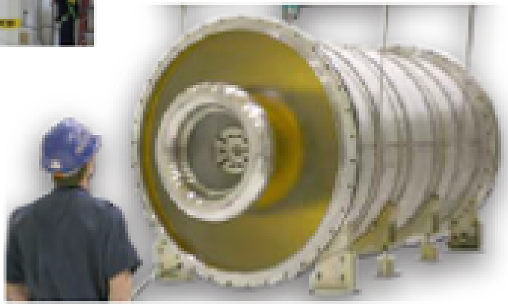


Several key pulsed power technologies have been continuously developed for decades

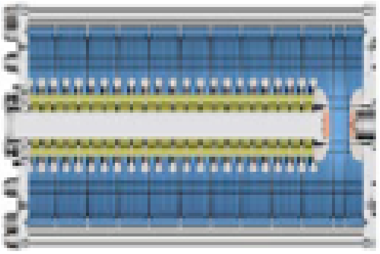
- **Fundamental requirements are simple:**
  - ✓ Accumulate energy slowly and then release it
  - ✓ Medium (or reservoir) to store energy
  - ✓ Method to initiate (trigger) energy release
- **Examples of key technologies in use at Z include:**
  - ✓ Marx capacitor banks (1924-)
  - ✓ Intermediate storage capacitor (1970-1985)
  - ✓ Laser triggered gas switches (1969-1985)
  - ✓ Magnetically insulated transmission lines (1975-1996)
  - ✓ Large area, multi-level insulator stack (1977-1996)
  - ✓ Current addition via post-hole convolute (1980-1996)

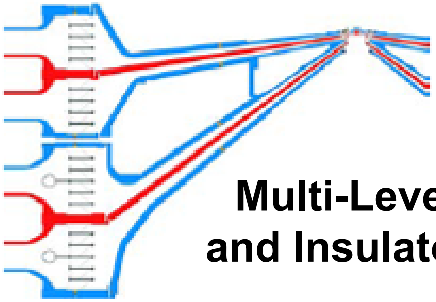
Marx Generator

Intermediate Storage Capacitor

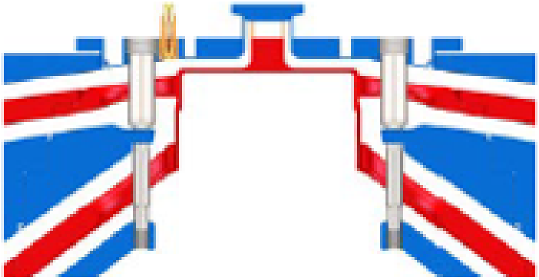


Laser Triggered Gas Switch





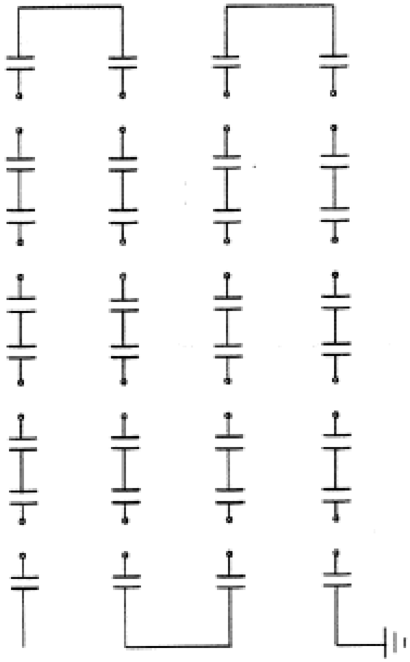
Multi-Level MITL and Insulator Stack

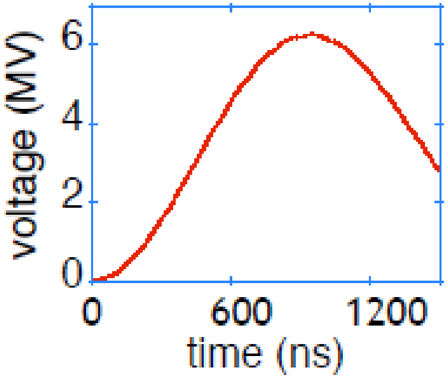


Post-Hole Convolute

Marx generators have been the primary pulse compression system for most pulsed power devices since the 1960's

- Marx generators rely on the principle that capacitors are charged in parallel and discharged in series → **voltage multiplication**
  - ✓ The entire Z Machine comprises 2,160 capacitors, each is 2.6μF @ 100kV
  - ✓ Each of the 36 Marx generators on Z has 60 capacitors, 30 switches, 116 resistors, and weighs ~10 tons
  - ✓ The 36 Marx generators are charged from a common power supply (2A @ 200kV)
  - ✓ The Marx Switch pre-fire probability is less than 10^{-6}
  - ✓ 500,000 Marx shots have been executed with this design since ~1980, on multiple accelerators, with continuous improvements

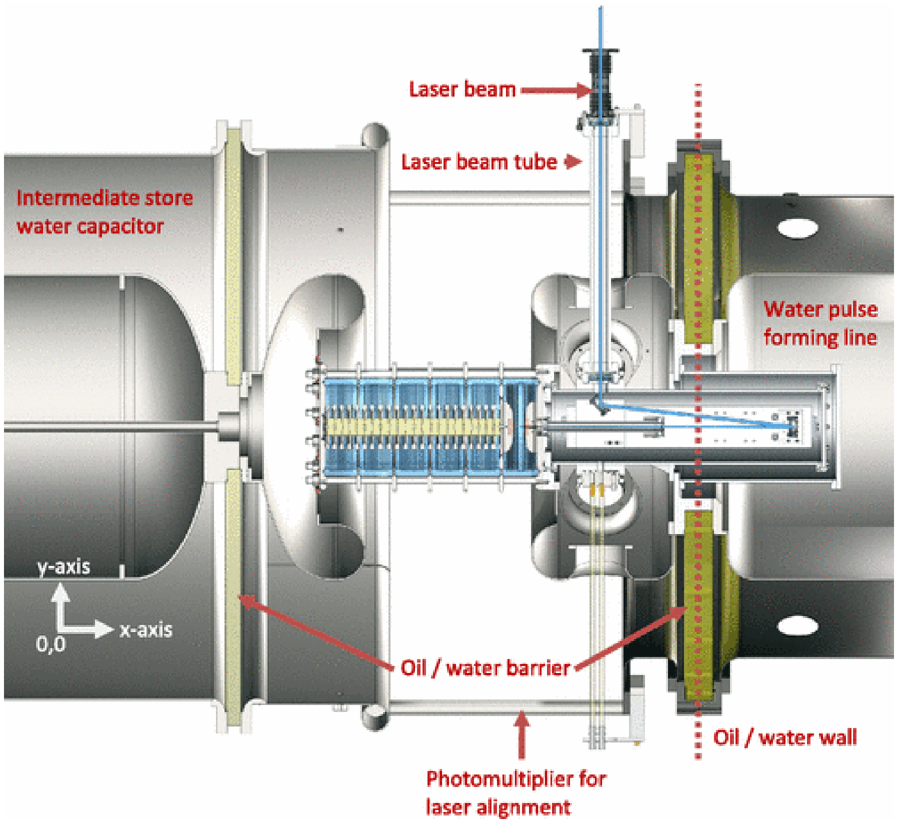


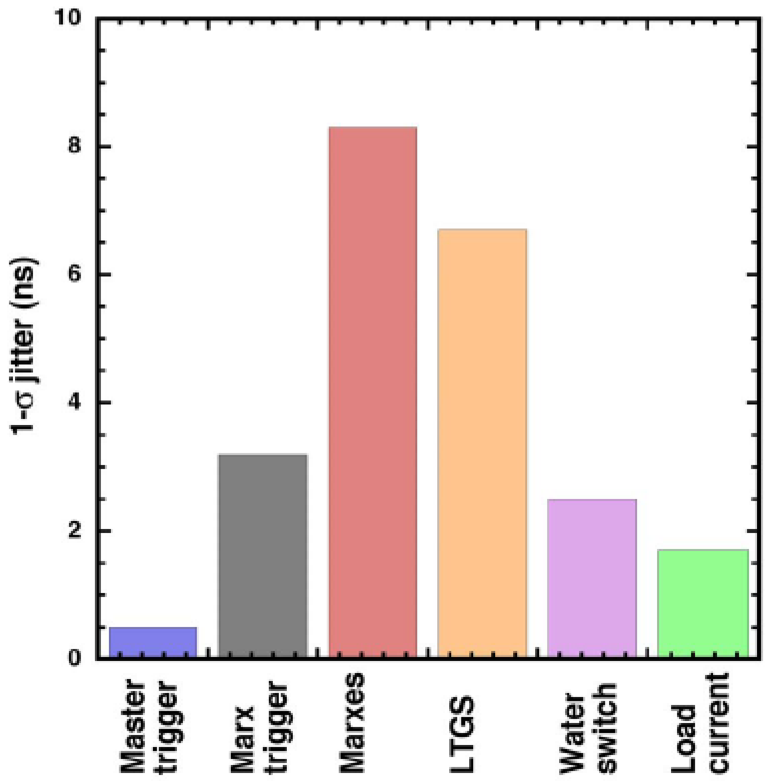


$$\frac{t_{in}}{t_{out}} \sim \frac{1.5min}{1\mu s} \sim 10^8$$

Multi-module pulsed power accelerators rely on high performance electrical and laser triggered gas switches

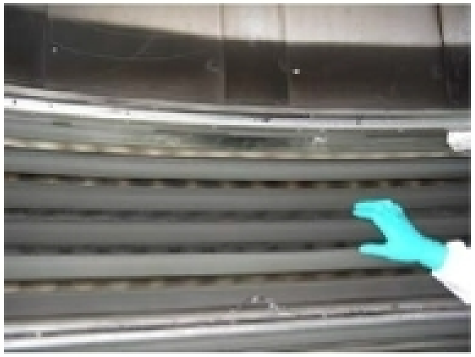
- Z can trigger modules individually via a 6.1MV, laser-triggered gas switch
- No part of the machine has a 1-sigma jitter greater than 10 ns
- The system is operated at low pre-fire probability → reliability has been a major focus!



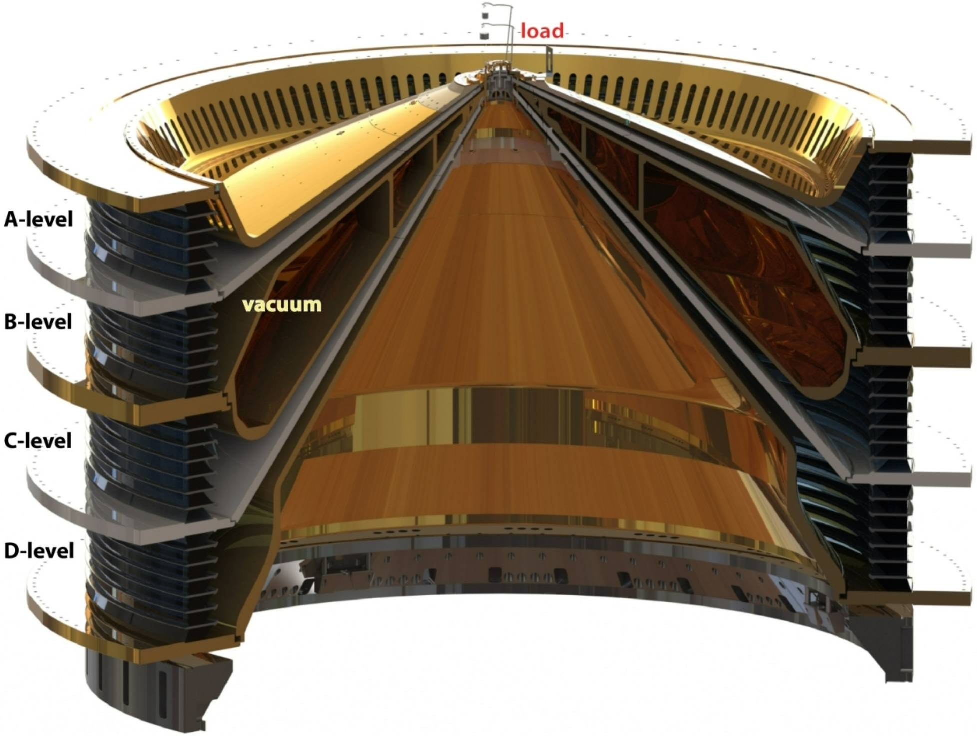


The water-vacuum interface has four levels operating at ~5MV driving four magnetically insulated transmission lines

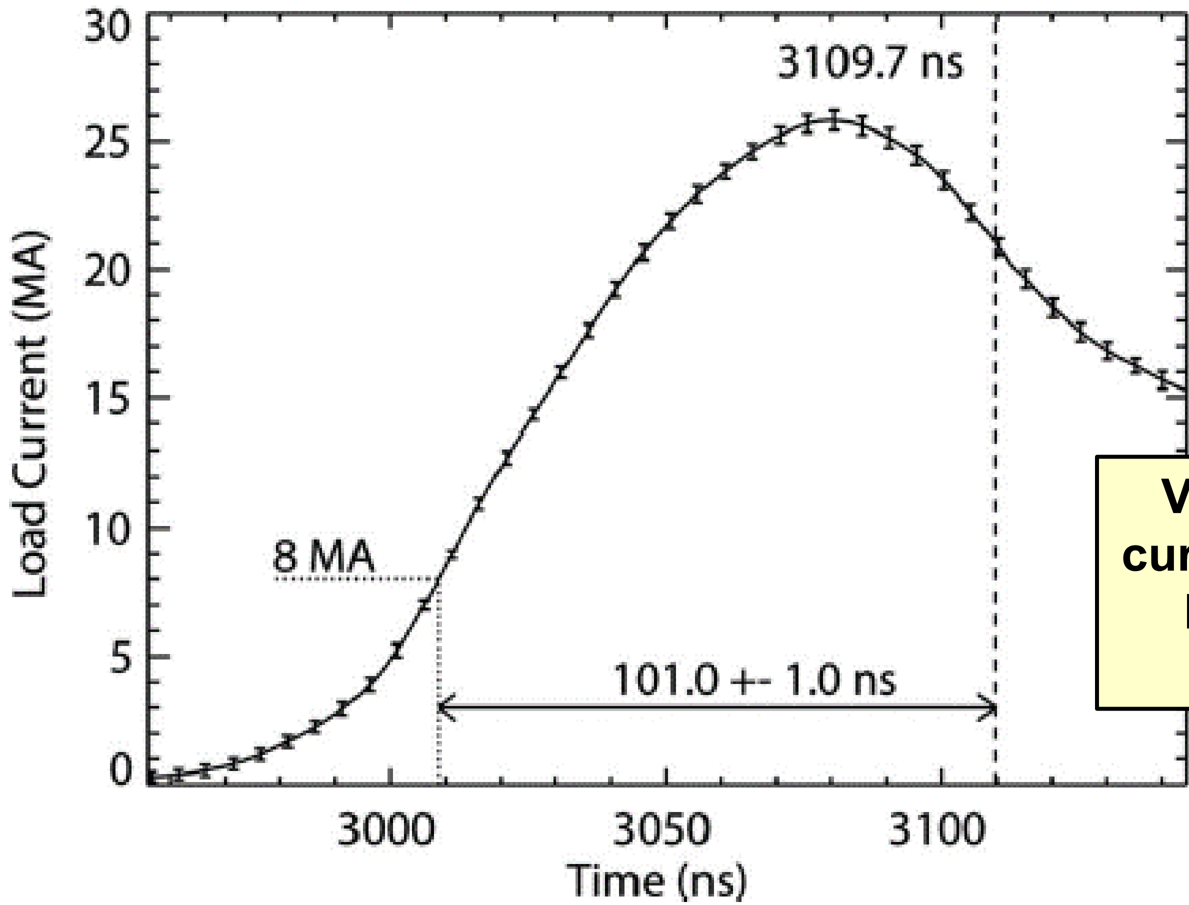
- **This water/vacuum/insulator interface ("stack") is maintained every day:**
  - ✓ The total size is approximately 3 meters in diameter and 2 meters tall
  - ✓ The total insulator (plastic) surface area is 21 m^2
  - ✓ The average (designed) electric field at the interface is 15 MV/m = 150 kV/cm
  - ✓ Using four levels in parallel lowers the MITL output inductance to ~10nH

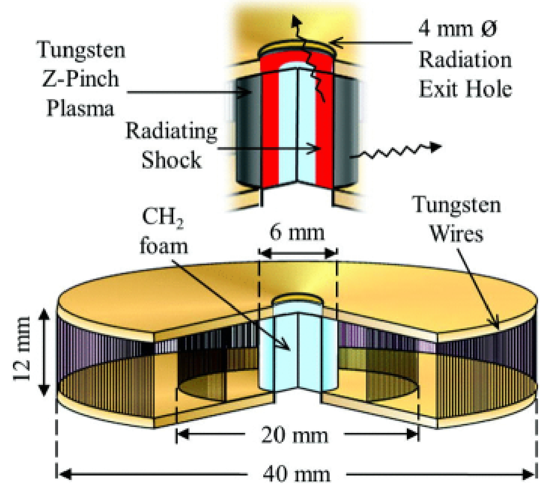


$$V = L\frac{dI}{dt} \qquad L \sim \frac{5MV}{25MA/100ns} \sim 20nH$$

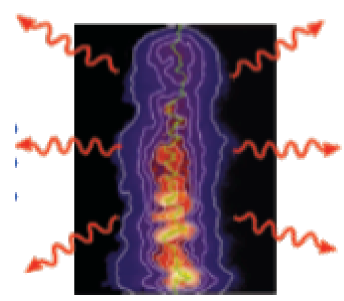


Large pulsed power machines like Z can be used as precision scientific instruments for HED science!





Very reproducible output current (±1%) into wire-array loads for astrophysical properties research!



Sandia has scaled up high current pulsed power drivers for beams, z-pinches, radiation effects, and HEDS for decades

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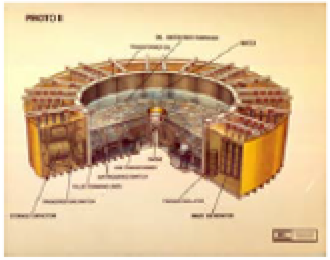
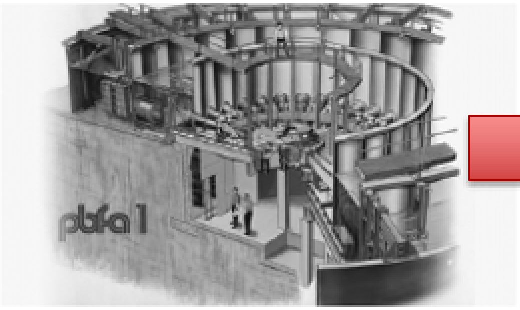
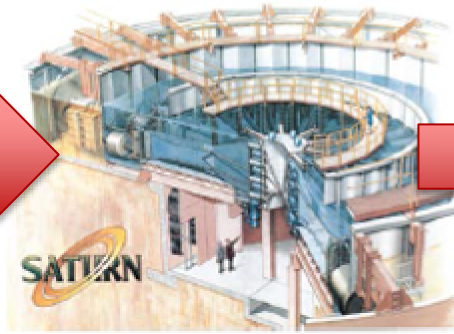
Proto I, 1974
1 Marx, 25'
60 kJ, 0.5 MA



Proto II, 1977
8 Marxes, 44'
1 MJ, 4 MA

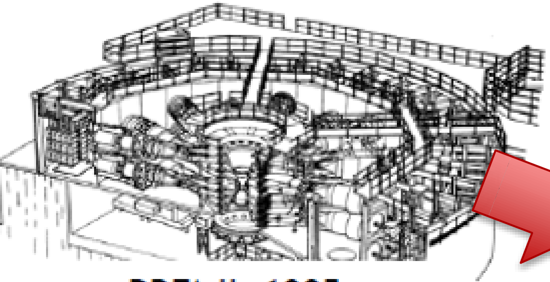


PBFA I, 1980
36 Marxes, 101'
3.3 MJ

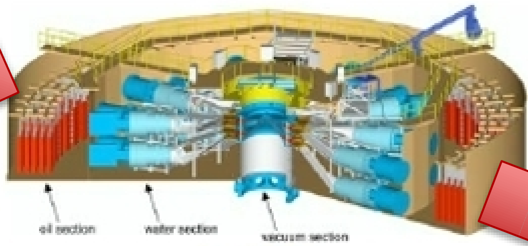


Saturn, 1987
36 Marxes, 101'
4.8 MJ, 7 MA

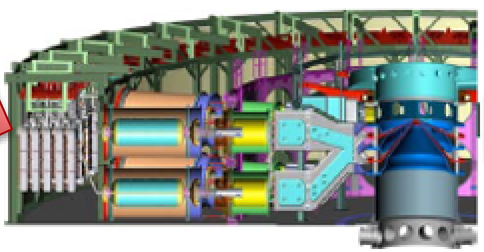
SATURN Recapitalization FY21-25



PBFA II, 1985
36 Marxes, 108'
11.4 MJ



Z, 1996
36 Marxes, 108'
11.4 MJ, 22 MA



ZR, 2007
36 Marxes, 108'
22 MJ, 31 MA

What's next?

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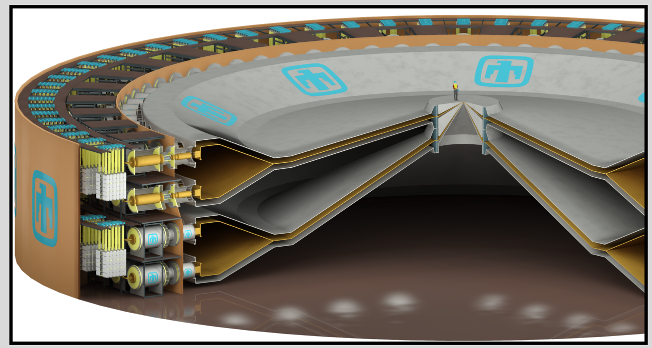
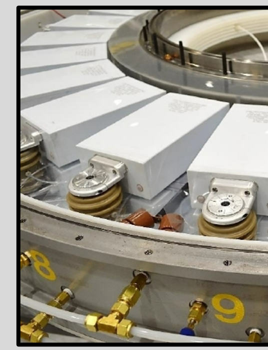




Pulsed Power Science

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

We are evaluating driver options and developing designs to advance magnetically driven HED science to 40-60 MA levels

Z will celebrate ~35 years of z-pinch physics in 2030, with some parts of infrastructure ~45 years old.

By 2030 we will achieve the limits of performance with Z, for all programs, and point of diminishing returns

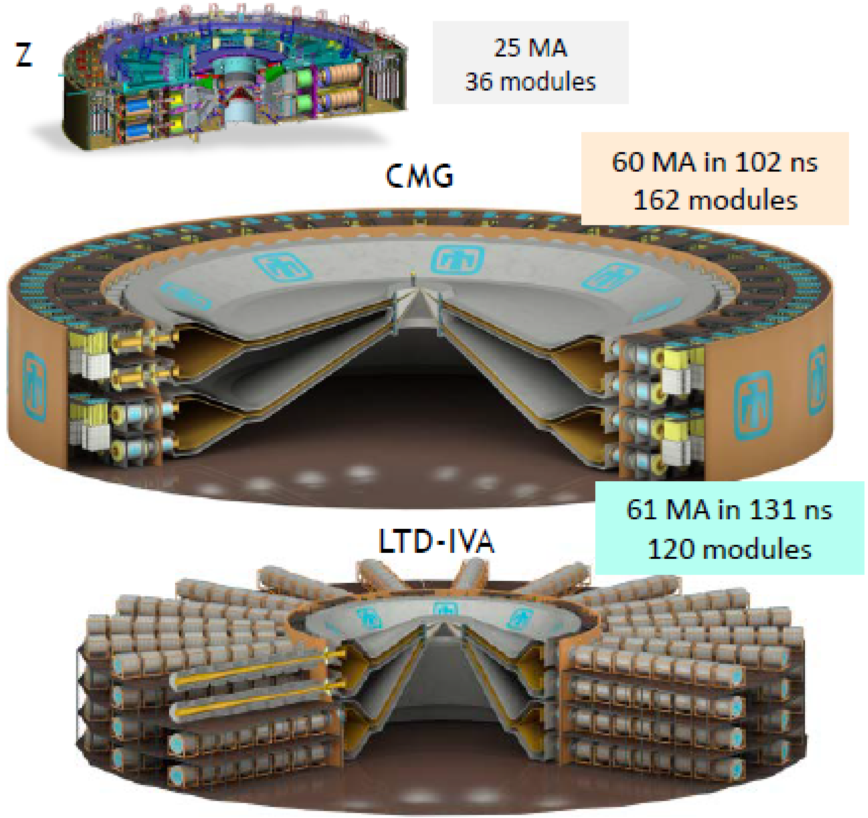
World's most powerful warm x-ray and fast fusion neutron source (hostile survivability, fundamental science)

Enabling capability for high energy density physics (nuclear explosive package certification, fundamental science)

It would attract and test tomorrow's stewards of pulsed power research

It would provide a venue for scientific and technical innovation for national security

An unprecedented engine of discovery for coming generations of scientists across the NSE



These designs can deliver >5→10 MJ to HED/ICF targets

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

Current Adder

THOR → 4 MA (2017)

- ✓ Dynamic Materials
- ✓ Arbitrary MA waveform generator

Current / Voltage Adder

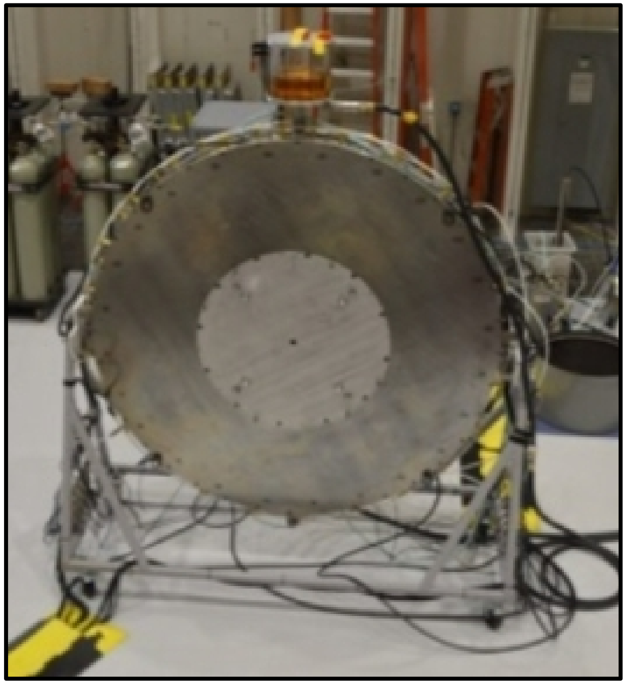
6^{th} Gen LTD → 1 MA, 100GW cavity (2017)

- ✓ ICF, Radiation Physics, Shock Materials
- ✓ Fast (100ns) pulse

Multi-Pulse Voltage Adder

CENTIPEDE → 4x pulse, 250kV, 1GW (2017)

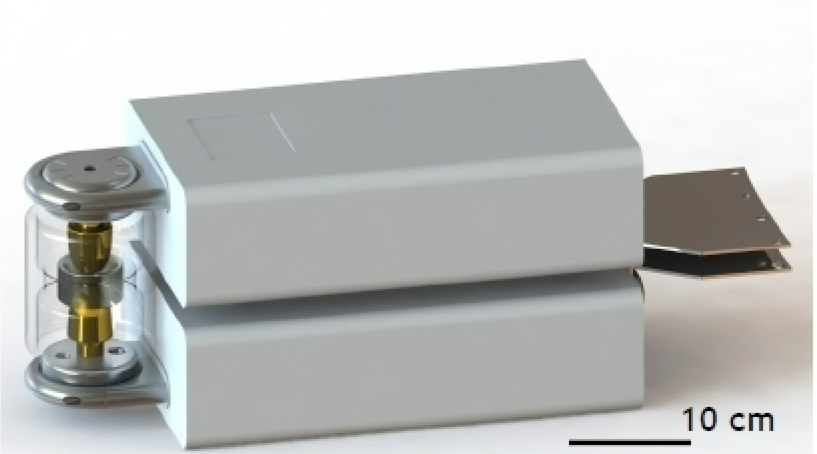
- ✓ Advanced radiographic (x-ray) applications
- ✓ Multi-pulse capability



We have developed a 100 ns “brick” that generates 5 GW of electrical power → possible “quantum” of future systems

- **This fourth generation “brick” has good performance characteristics:**
  - Peak electrical power = 5.4 GW
  - Output power variation = 2%
  - Timing jitter = 2 ns
  - Switch pre-fire rate = 0.02%
  - Lifetime = >10,000 shots

Palo Verde nuclear power plant: 3.3 GW



LTD brick: 5 GW

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

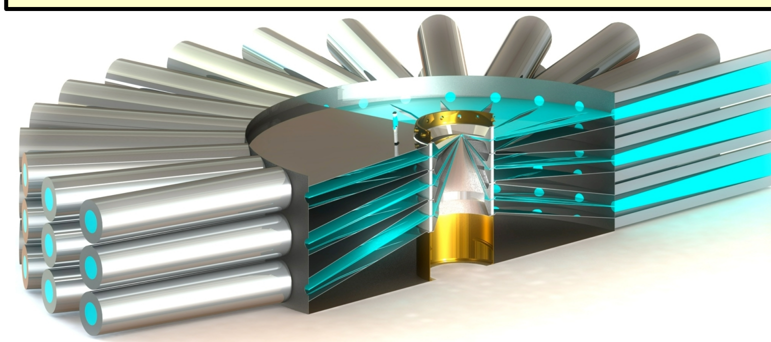
Sandia National Laboratories

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!

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

We have been advancing LTD technology for 15 years

Sandia National Laboratories

2017

6th Generation 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.

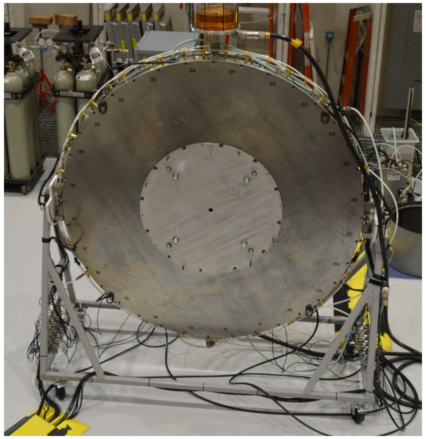
2008

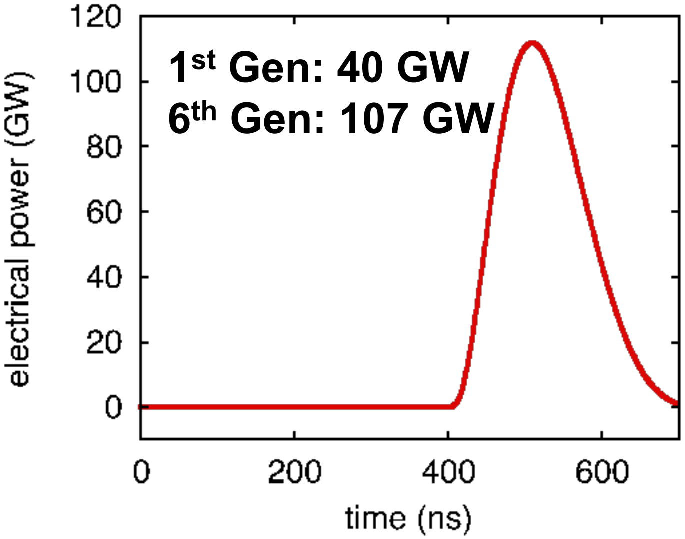
MYKONOS LTD
- ✓ 3 meter, 100 ns, 1000kA, 80 GW / cavity, 40 bricks
- ✓ Demonstrated multi-cavity, high current / voltage module

2004

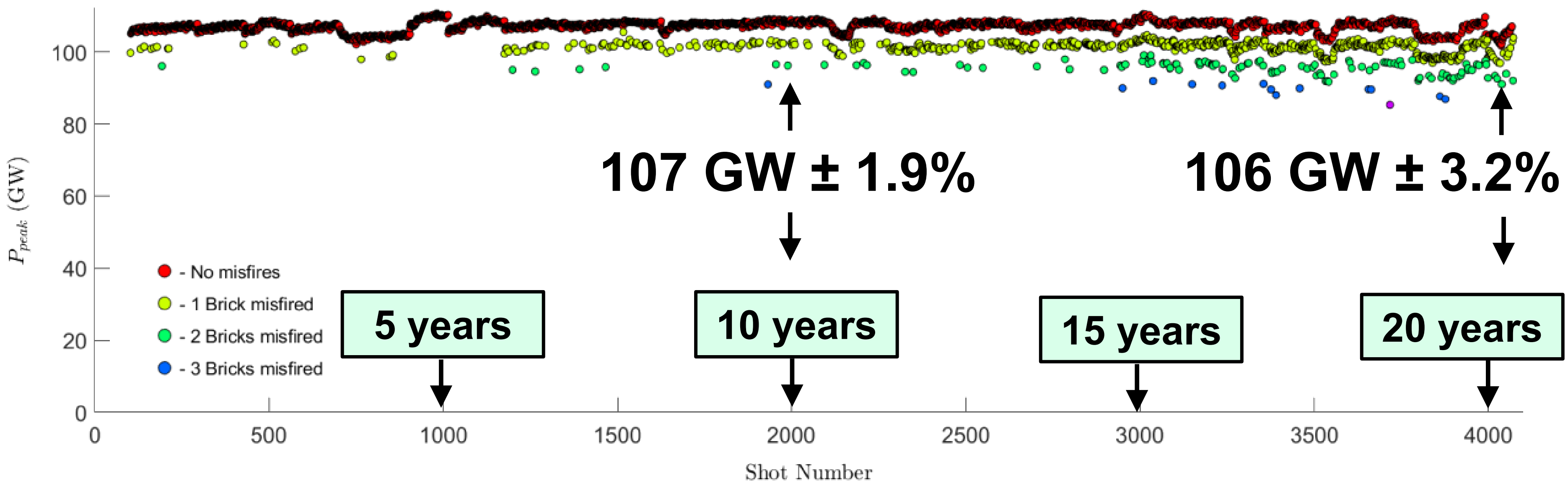
LTD-I
- ✓ 2 meter, 75 ns, 450kA, 40 GW, 20 bricks
- ✓ Intended for ZX-IFE Program

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

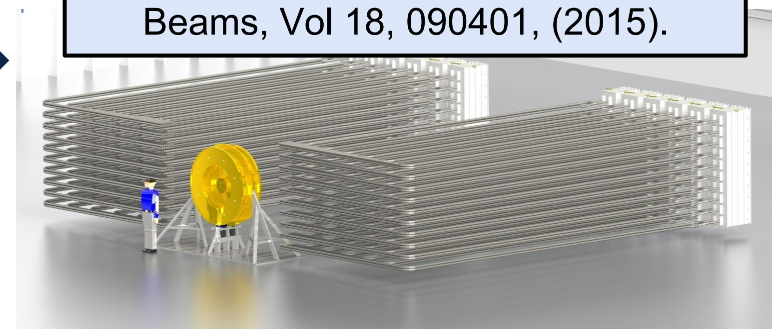
THOR-72

4 MA / 200 ns / 0.5 Mbar

THOR-240

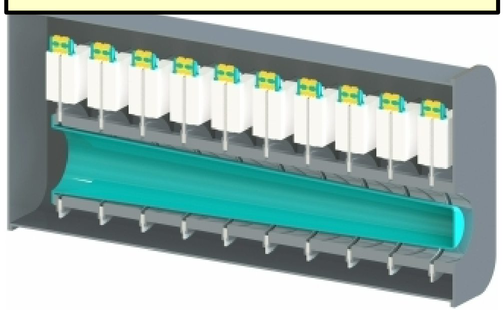
1.2 TW / 7 MA / 200 ns / 2 Mbar

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



Impedance Matched Marx Generator (IMG)

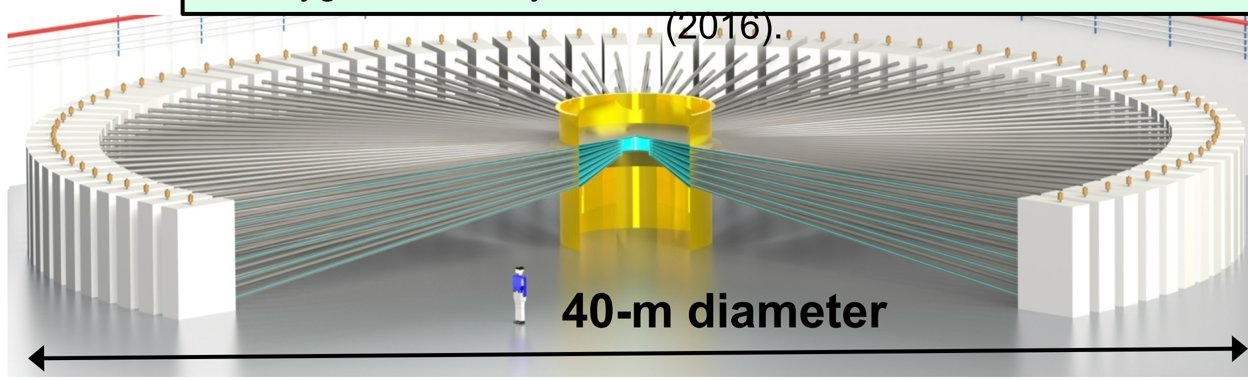
Stygar et al., Phys. Rev. Accel. Beams, Vol 20, 040402, (2017).



NEPTUNE

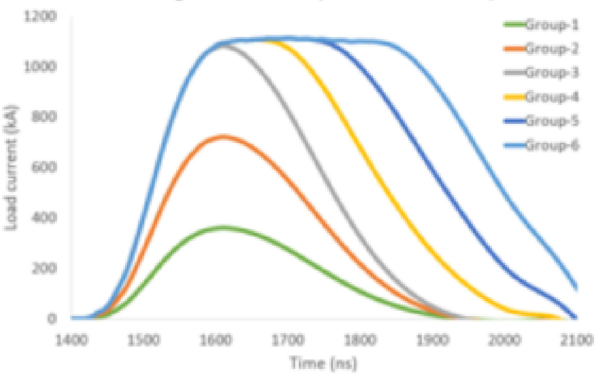
50 TW / 23 MA / 750 ns / 20 Mbar / 4,800 IMGs

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

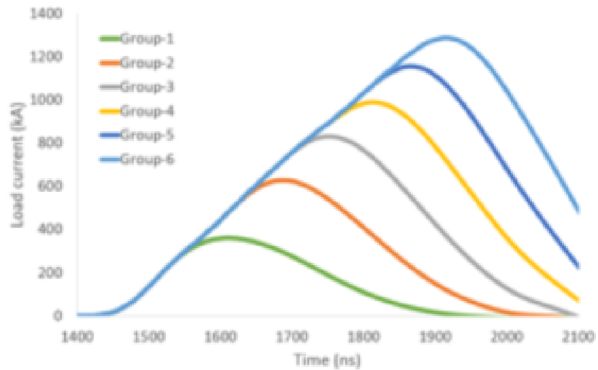


THOR is essentially a multi-MA arbitrary waveform generator, allowing greater flexibility in accessing materials properties

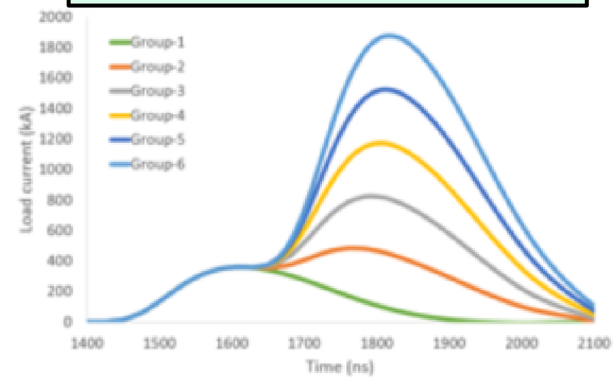
Ramp-Hold-Release



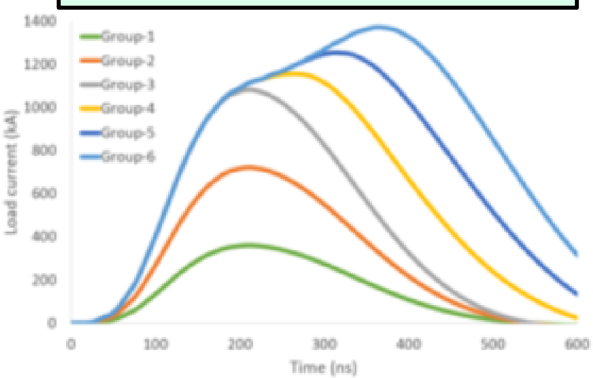
Ramp



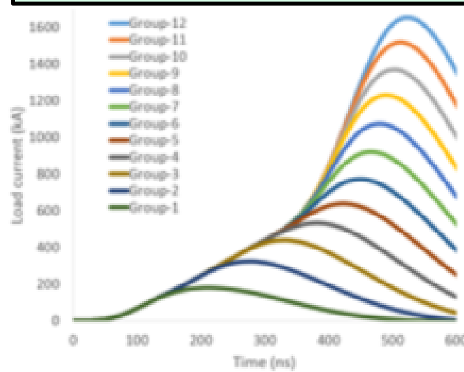
Ramp-Hold-Ramp



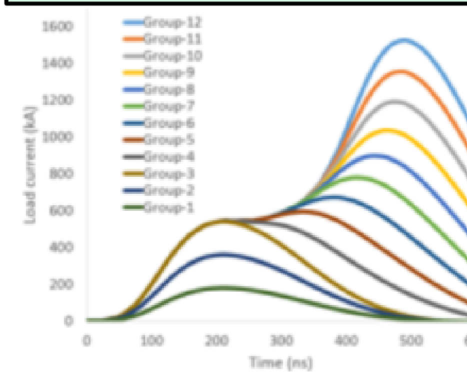
Shock-Ramp



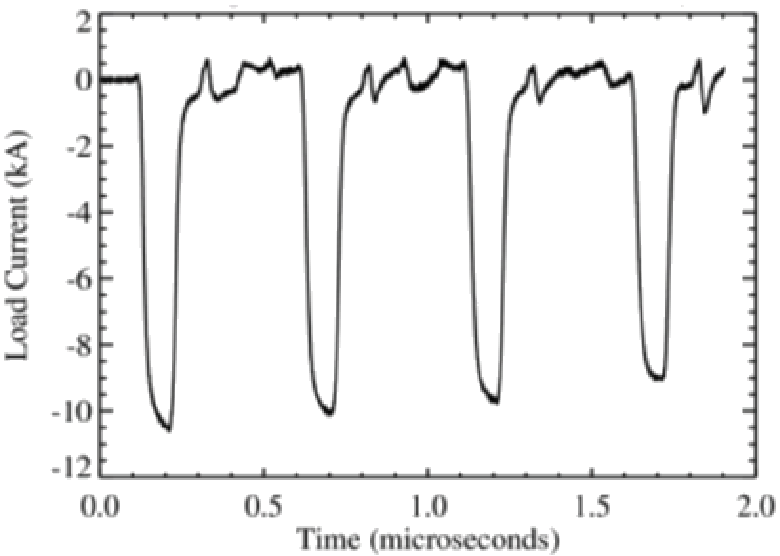
Shockless Ramp



Ramp-Hold-Ramp



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

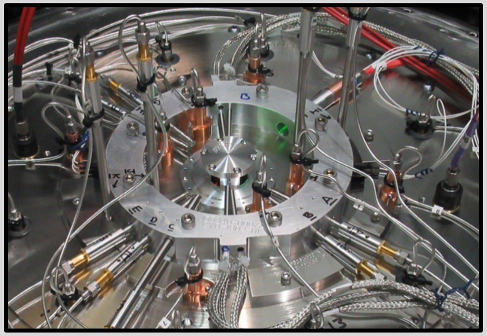
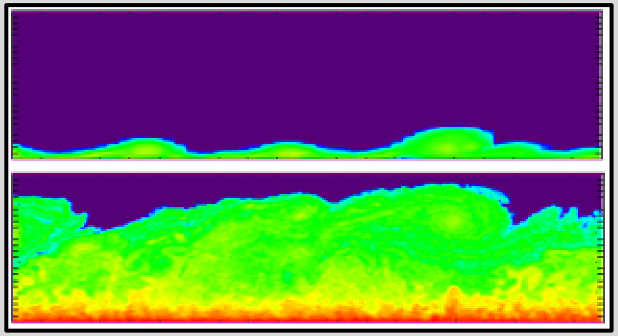
- ✓ 4x arbitrary timed pulses are generated using series connected pulse forming lines (PFLs)
- ✓ Voltage from PFLs combined using an inductive voltage adder (IVA)
- ✓ Architecture is similar to what could be used to build the SCORPIUS injector
- ✓ Sandia's pulsed power team (scientists, engineers, technologists) 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

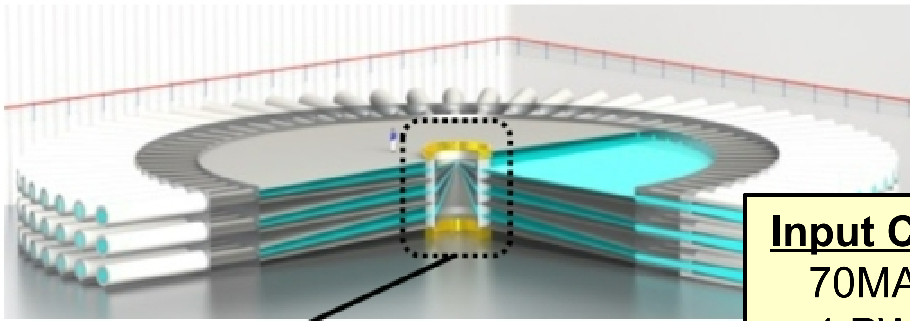
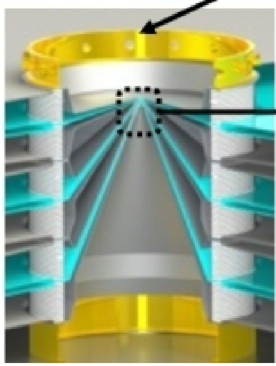
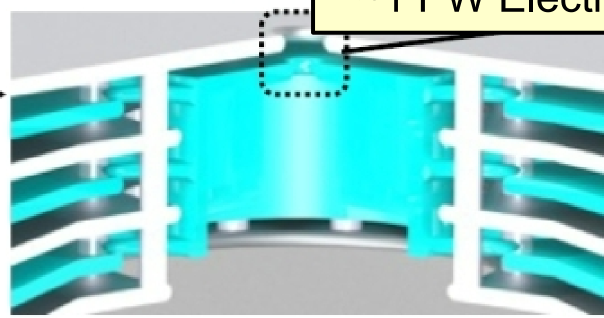
Background
- ✓ *What is pulsed power?*
- ✓ *Z Architecture*
- ✓ *Pulsed Power Facilities*

Accelerator Technologies
- ✓ *Next-Generation Pulsed Power*
- ✓ *New Technologies: LTD / IMG*
- ✓ *Multi-Pulse Accelerator Technology*

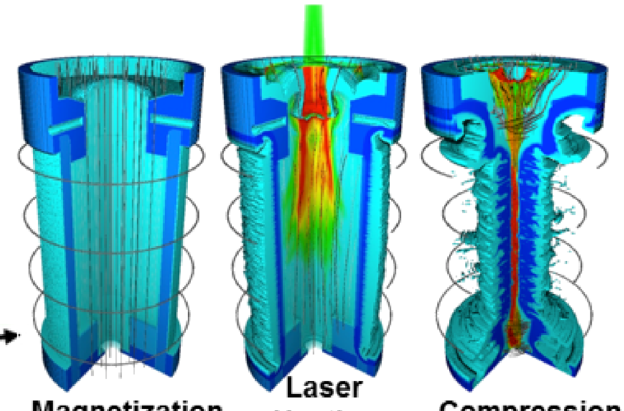
Pulsed Power Science
- ✓ *Power Flow / Current Loss*
- ✓ *PIC / Circuit Models*
- ✓ *Electrode Models*

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



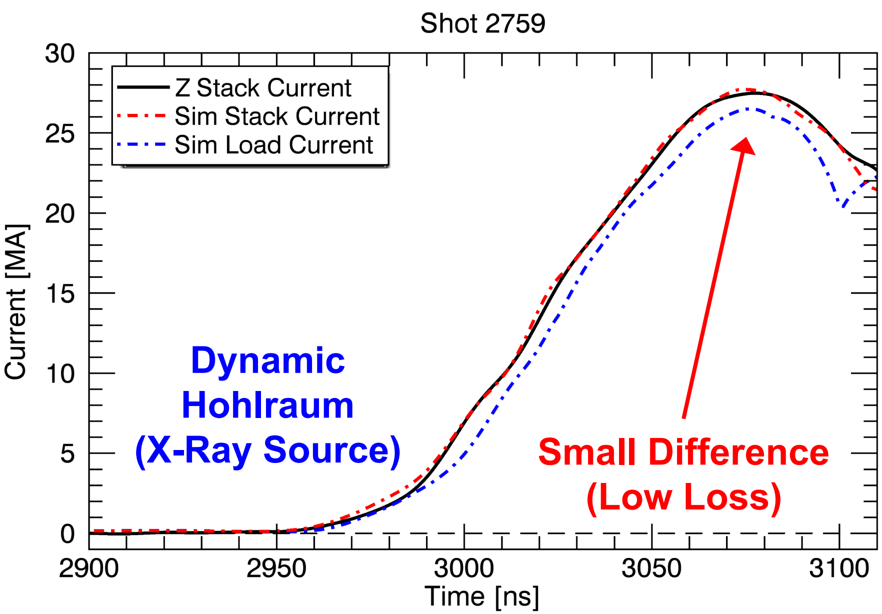
Output Conditions
30 PW D-T Neutrons
400 PW X-Rays

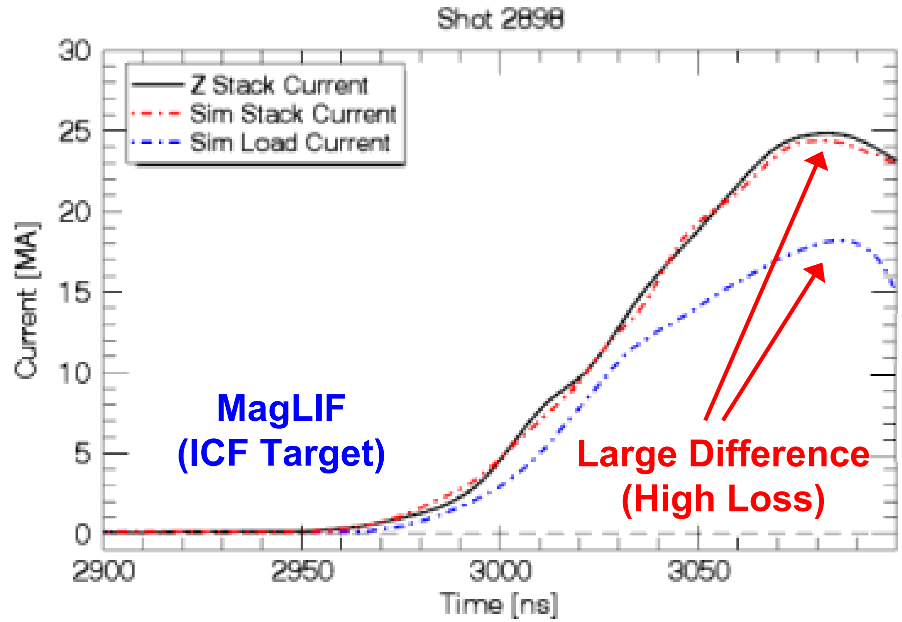
Driver / Source Design Principles
- ✓ Electromagnetics, Pulsed Power
- ✓ Mechanical / Electrical / Civil Engineering

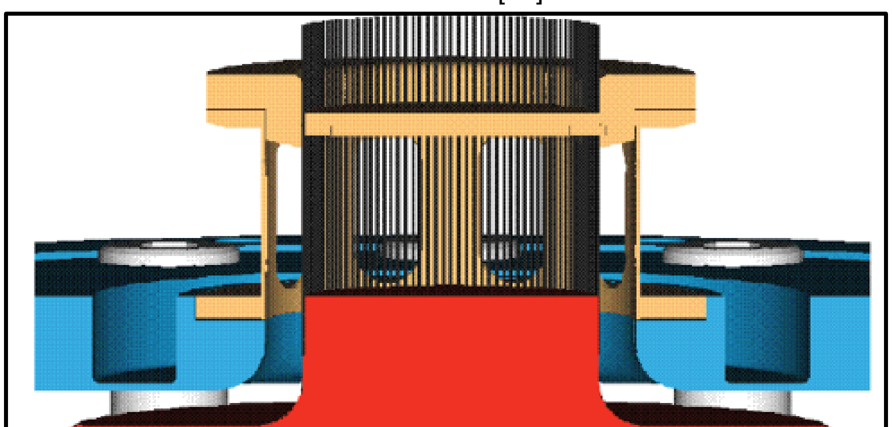
Example Driver Uncertainties
- ✓ Electrode Plasma Formation / Expansion
- ✓ Current Loss

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

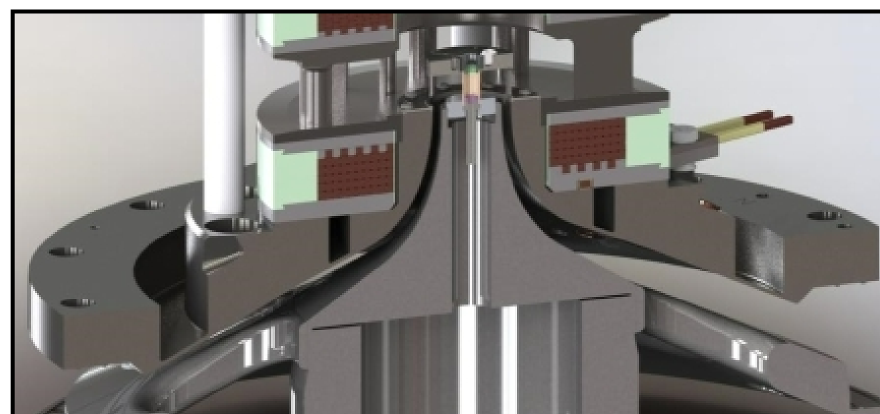
Plasmas that form in the vacuum transmission lines can reduce the efficiency of current coupled to the load







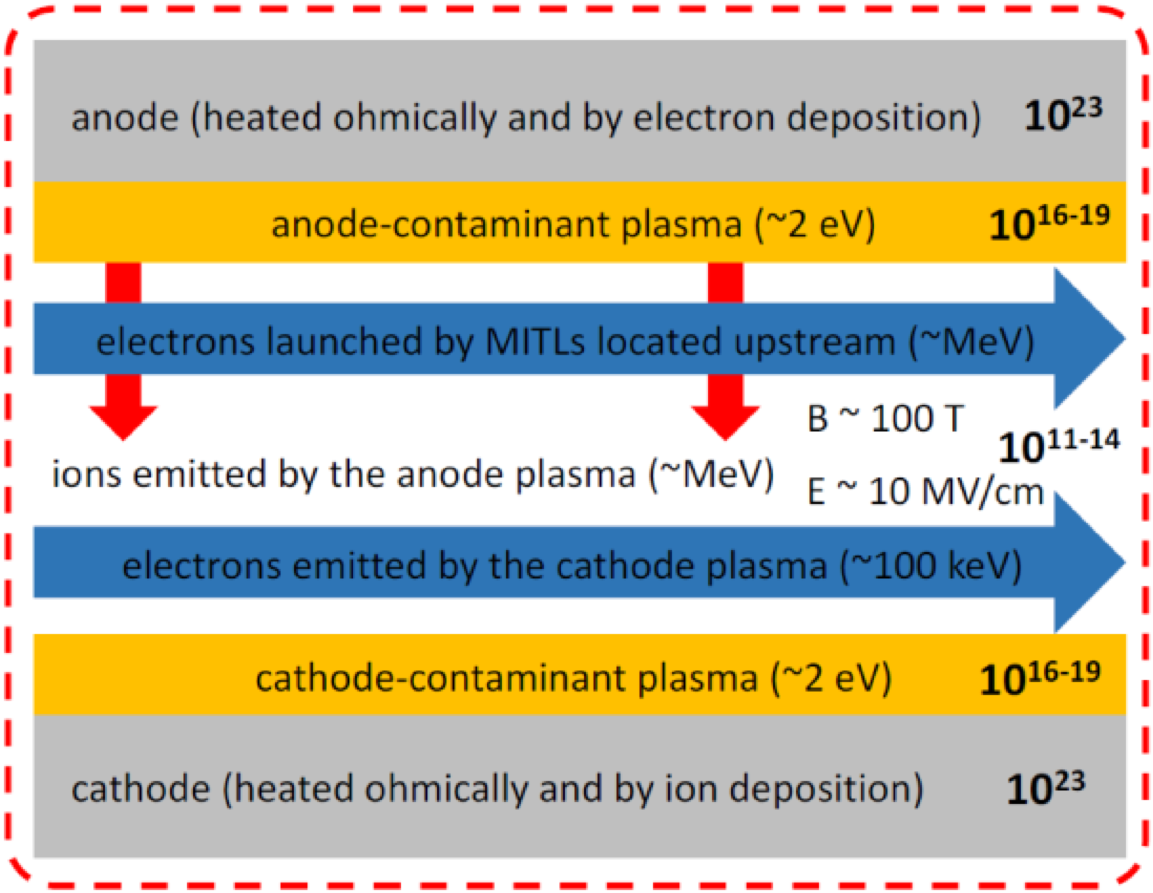
Dynamic Hohlraum = Low Inductance (<3.0 nH)



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:

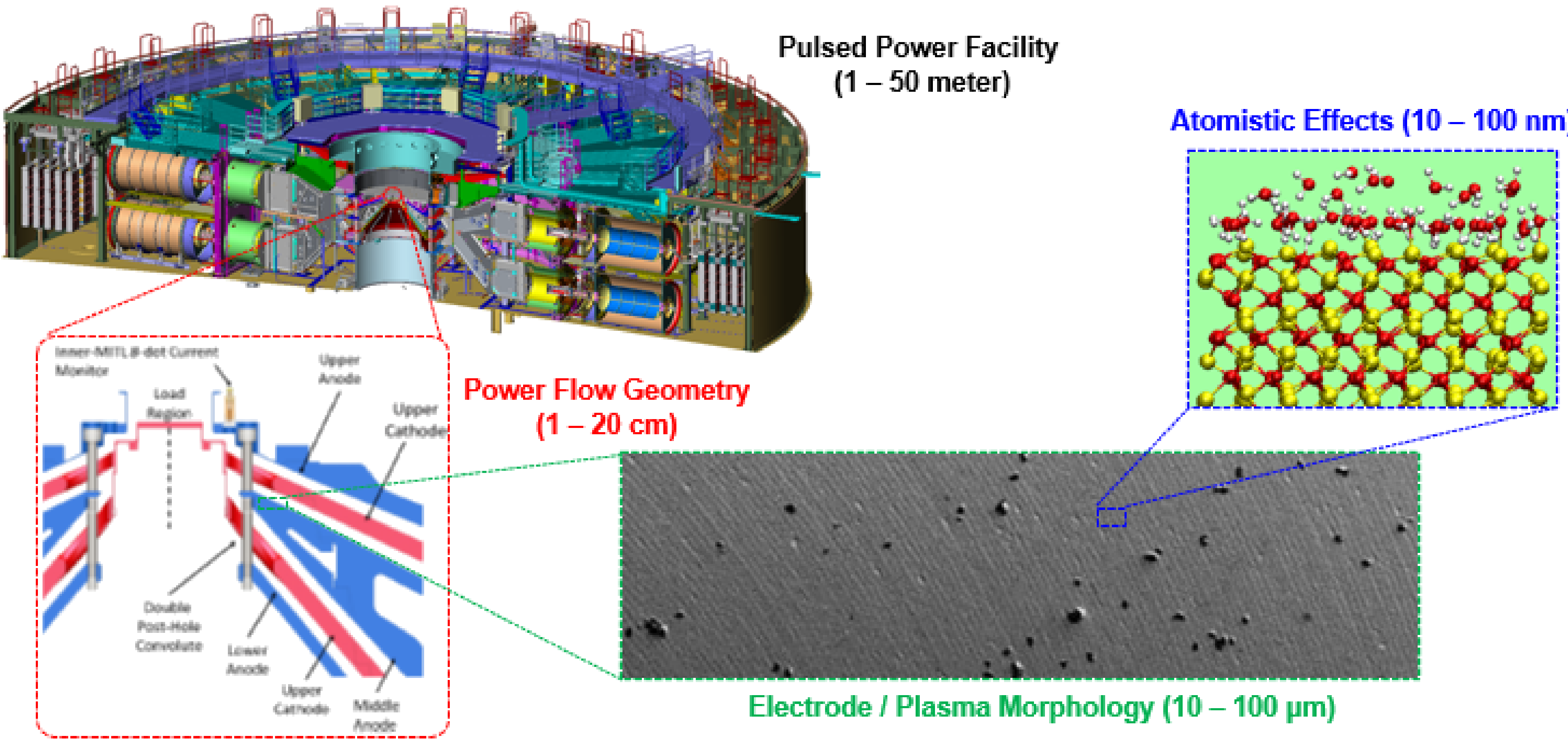
- Energy deposition into electrodes
- Neutral desorption and ionization
- Magnetization of the particles and plasmas
- Electron flow fraction and loss
- Kinetic, MHD, XMHD, Collisions
- Electromagnetic waves

Experiments could measure:

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

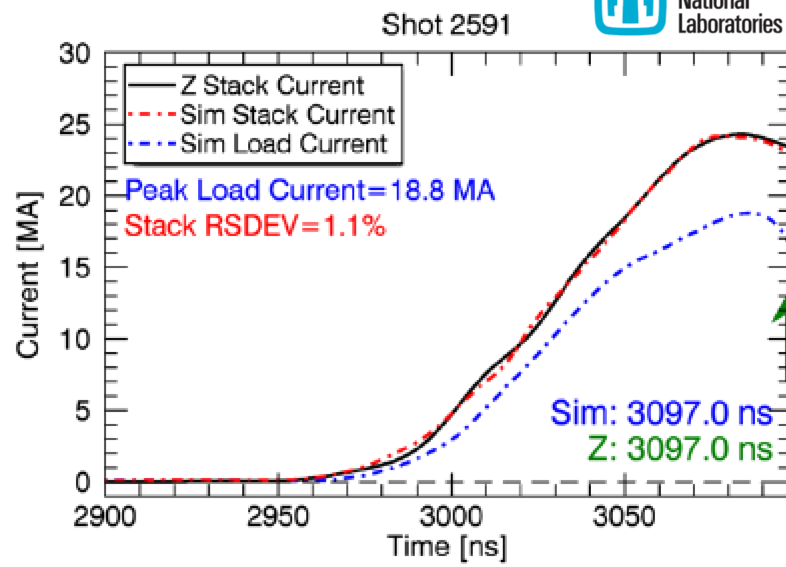
Stygar et al., *Phys. Rev. ST Accel. Beams*, Vol. 9, 090401, (2006).

We are exploring the phenomena responsible for electrode plasma formation at multiple scales

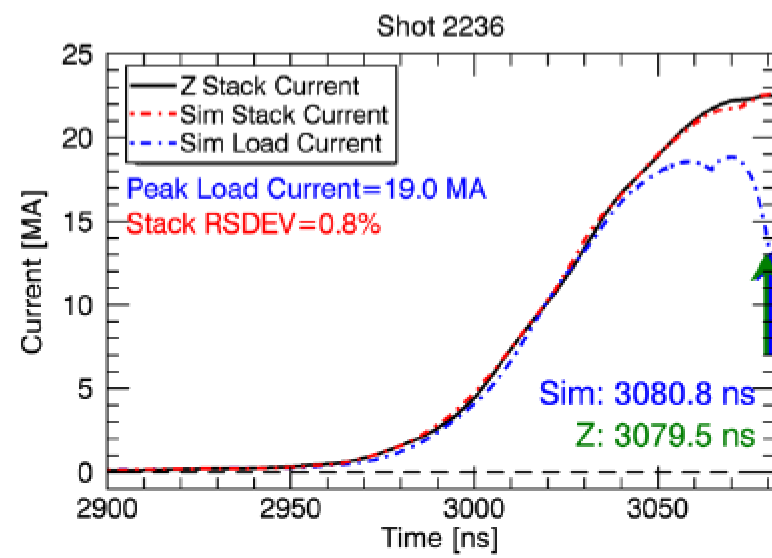


We have developed a predictive physics-based circuit model (BERTHA) that agrees with Z Facility current measurements within 2%

- 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



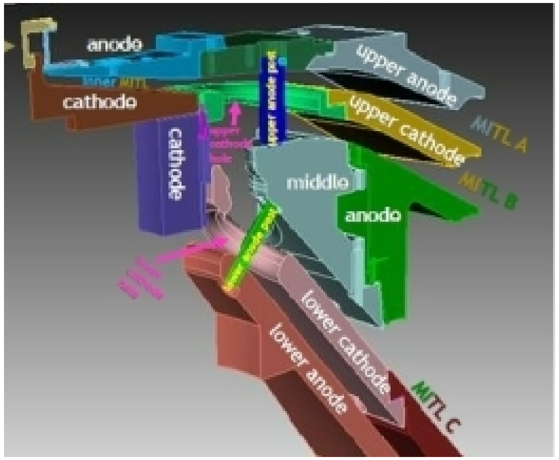
Standard MagLIF, 7.5 mm target



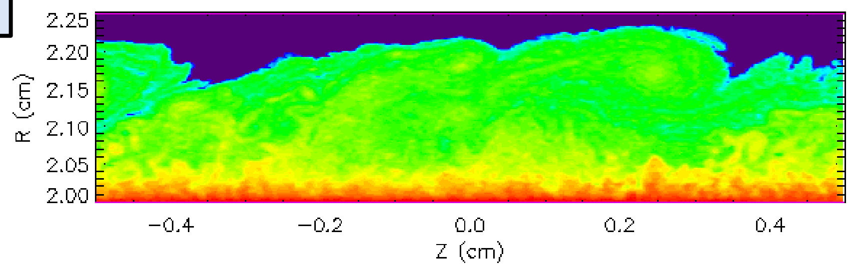
Nested stainless steel wire array

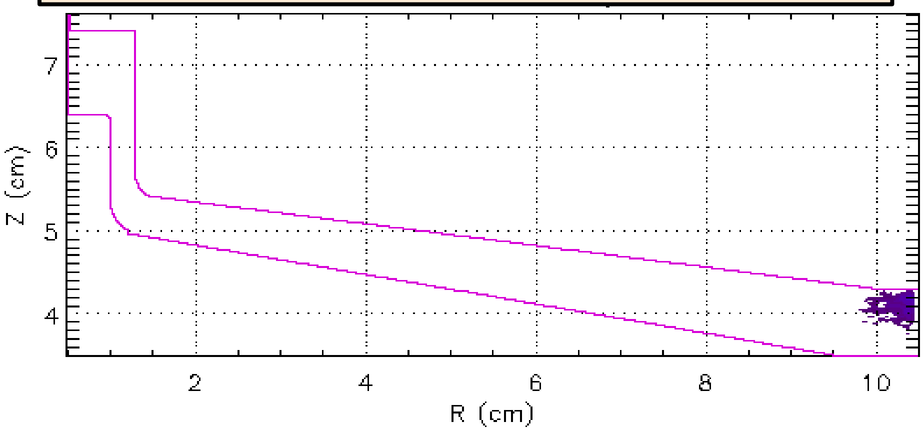
We are developing advanced kinetic PIC models to explore electrode plasma formation on accelerators

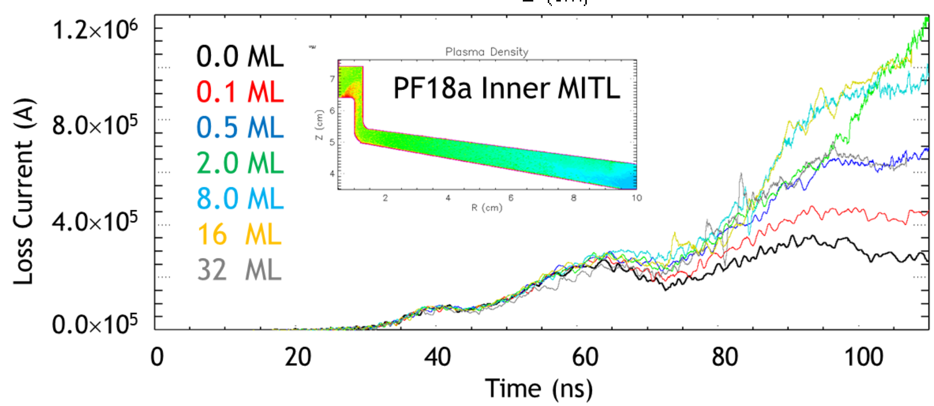
- Multiple tools are being developed with different algorithms to provide detailed code comparisons and to reduce risk in model extrapolation (LSP/CHICAGO, EMPIRE/EMPHASIS)
- Large effort to develop hybrid kinetic/fluid modeling tools to seamlessly incorporate multi-physics phenomena (power flow, target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



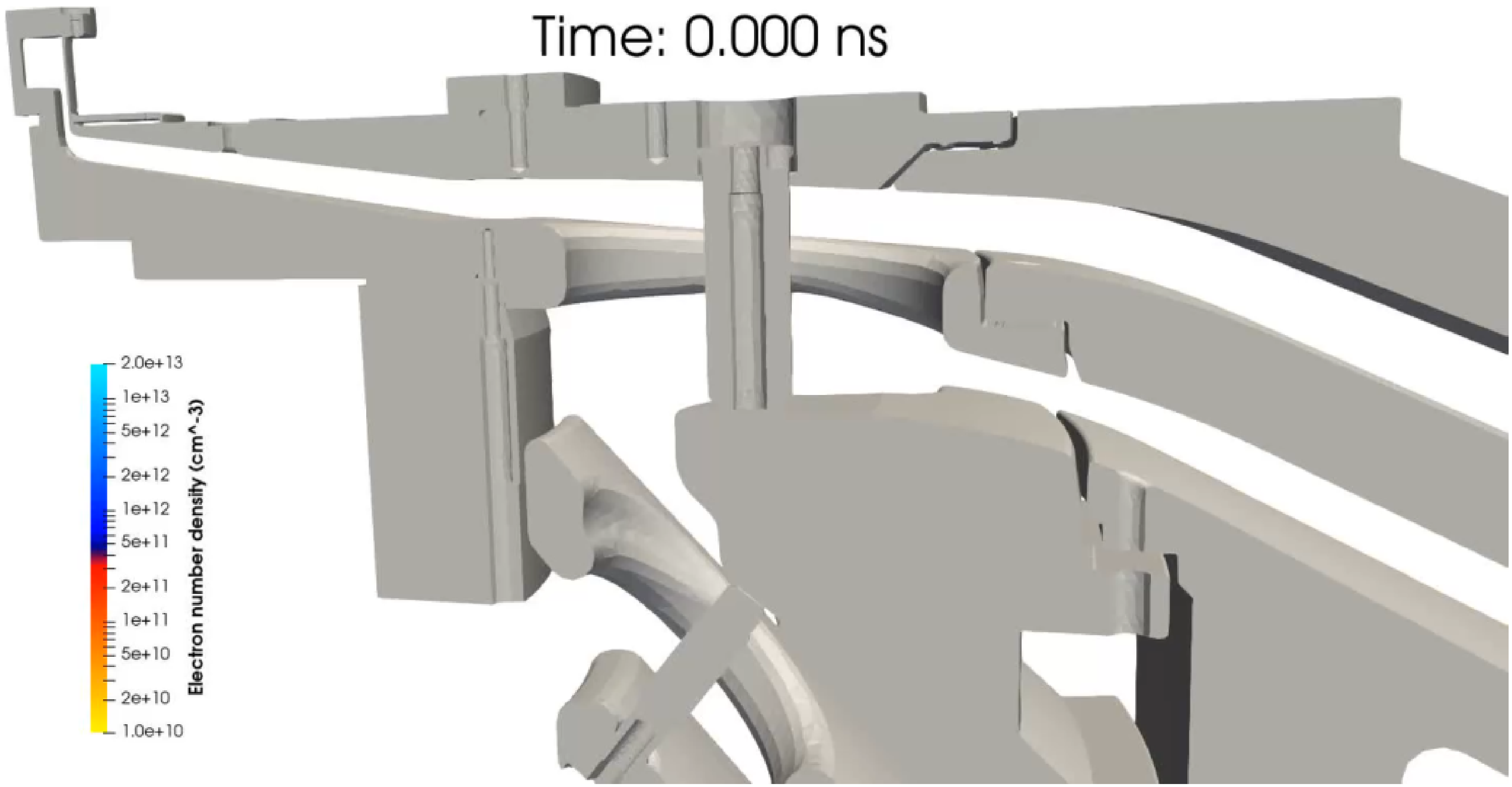
Inner MITL plasma simulation of Power Flow 18a experiment using CHICAGO/PIC







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



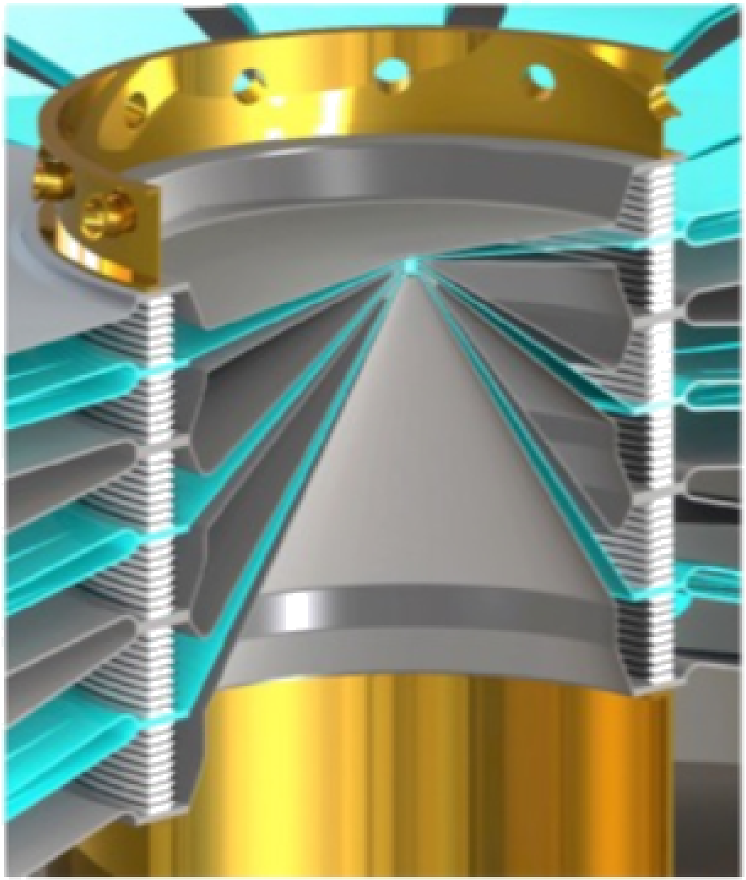
Circuit and PIC models demonstrate that current loss in the Z vacuum section is significant when certain conditions are met

<u>Important MITL Conditions:</u>

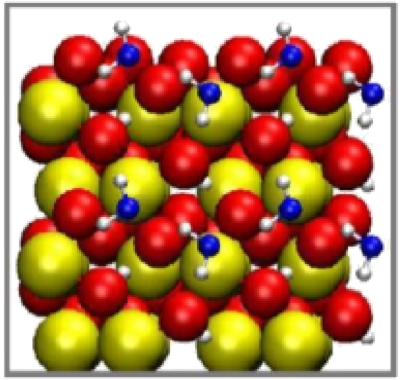
- ✓ Electrons are emitted in the outer MITLs and ExB drift towards the convolute and inner MITL
- ✓ Anode surfaces at the convolute / inner MITL become space charge limited (SCL) ion sources
- ✓ Anode-Cathode gaps of the convolute / inner MITL close significantly during the power pulse
- ✓ Characteristic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

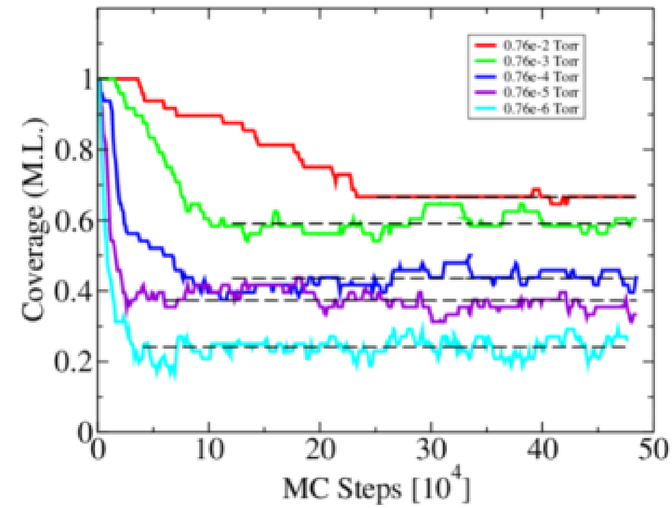


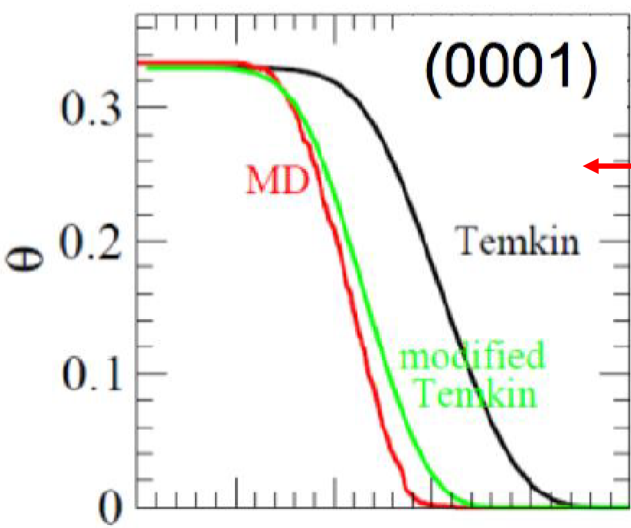
Density Functional Theory

✓ 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

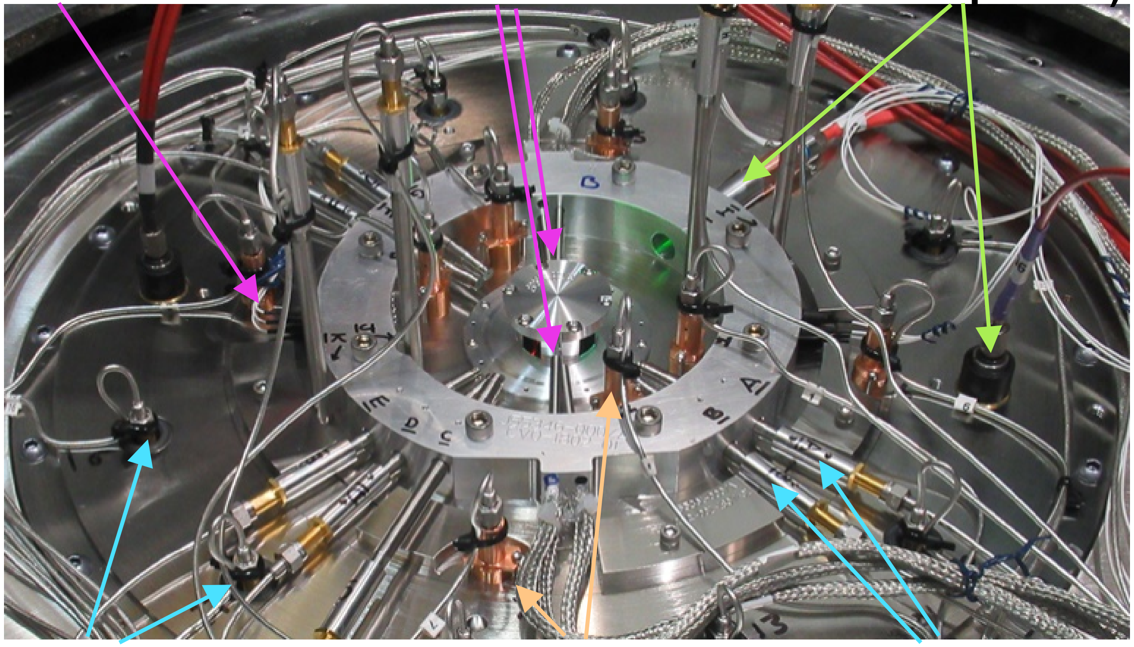
✓ Simulate the desorption of contaminants as a function of rapid current-induced surface heating (2×10^9 C/s)

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!

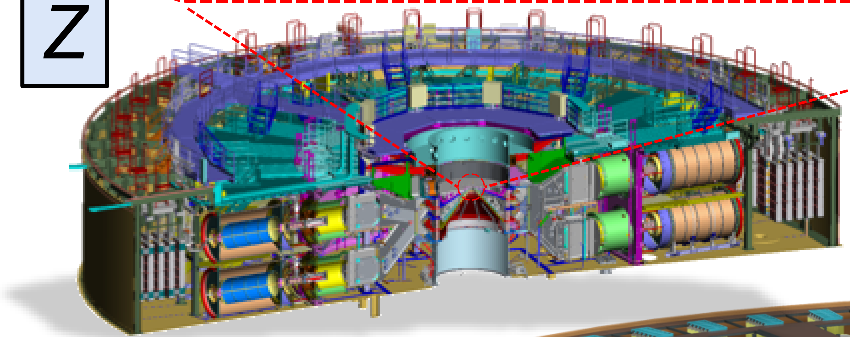
These efforts will **deliver the plasma physics S&T foundation** to realize a next-generation HED facility for discovery science!

Sandia National Laboratories

Discovery Science:

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

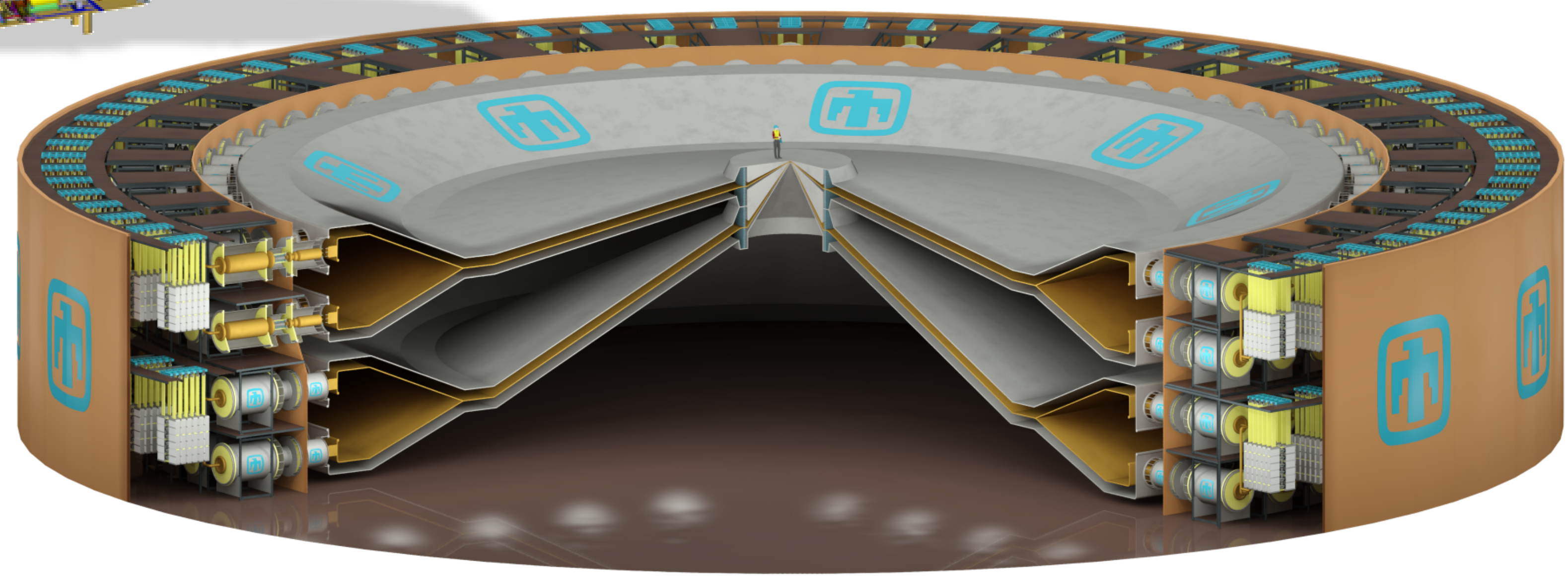
Z



We are investing in Foundational S&T for:

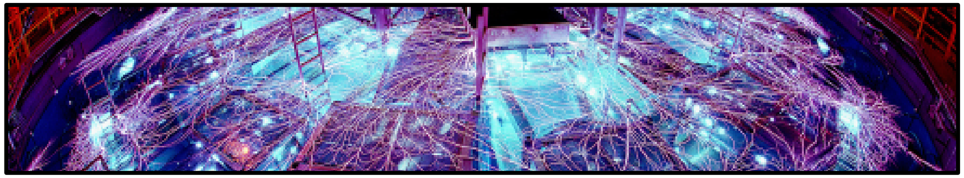
- ✓ *Computational Plasma Physics Models*
- ✓ *Improvements in Algorithm Efficiency / Speed*
- ✓ *Models of Real Electrode Surfaces in the Lab*

NGPP



Summary

- The Z machine creates large currents, allowing us to study fundamental physics in HED science, dynamic materials, and inertial confinement fusion
- Pulsed power can inexpensively, efficiently, and flexibly drive many different kinds of applications at large currents and high voltages (beyond the traditional "z-pinch")
- 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 various 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 kinetic/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…



Comprehensive References for Interested Readers

- Textbooks on relevant pulsed power technologies:
  - Bluhm, *Pulsed Power Systems: Principles and Applications*, (2006)
  - Lehr, *Foundations of Pulsed Power Technology*, (2017)
  - Martin, *J.C. Martin on Pulsed Power*, (1996)
  - Mesyats, *Pulsed Power*, (2005)
  - Smith, *Transient Electronics: Pulsed Circuit Technology*, (2002)
- Review publications on relevant pulsed power technologies:
  - ✓ Cuneo et al., *IEEE Trans. Diel. Elec. Insul.* 6, 469, (1999).
  - ✓ Kim et al., *IEEE Trans. Plasma Sci.* 48, 749, (2019).
  - ✓ McBride et al., *IEEE Trans. Plasma Sci.* 46, 3928, (2018).
  - ✓ Schamiloglu et al., *Proc. IEEE* 92, 1014, (2004).
  - ✓ Sinars et al., *Phys. Plasmas* 27, 070501, (2020).
  - ✓ Smith et al., *Phys. Rev. ST Accel. Beams* 7, 064801, (2004).