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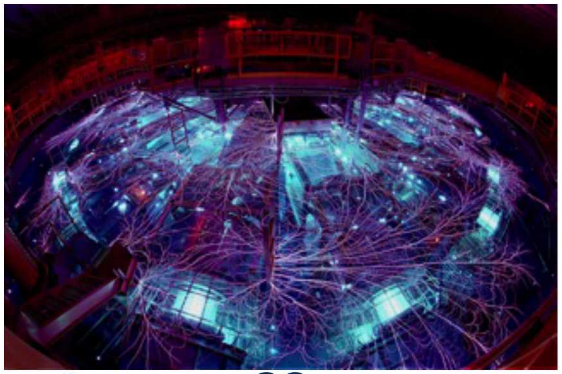

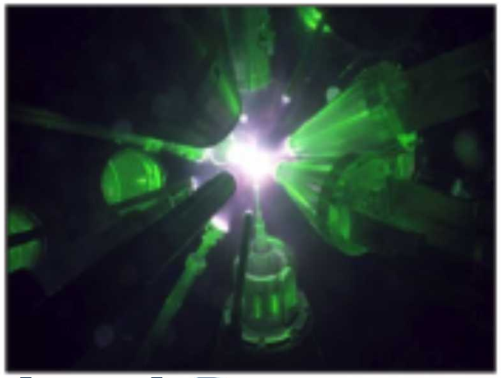

Radiation Effects, Pulsed Power, and Future HED Capabilities

Daniel Sinars, Sandia National Laboratories

Workshop on National Security & High Energy Density Science: Technical, Policy, and International Perspectives & Implications

August 8-9, 2019 UC San Diego

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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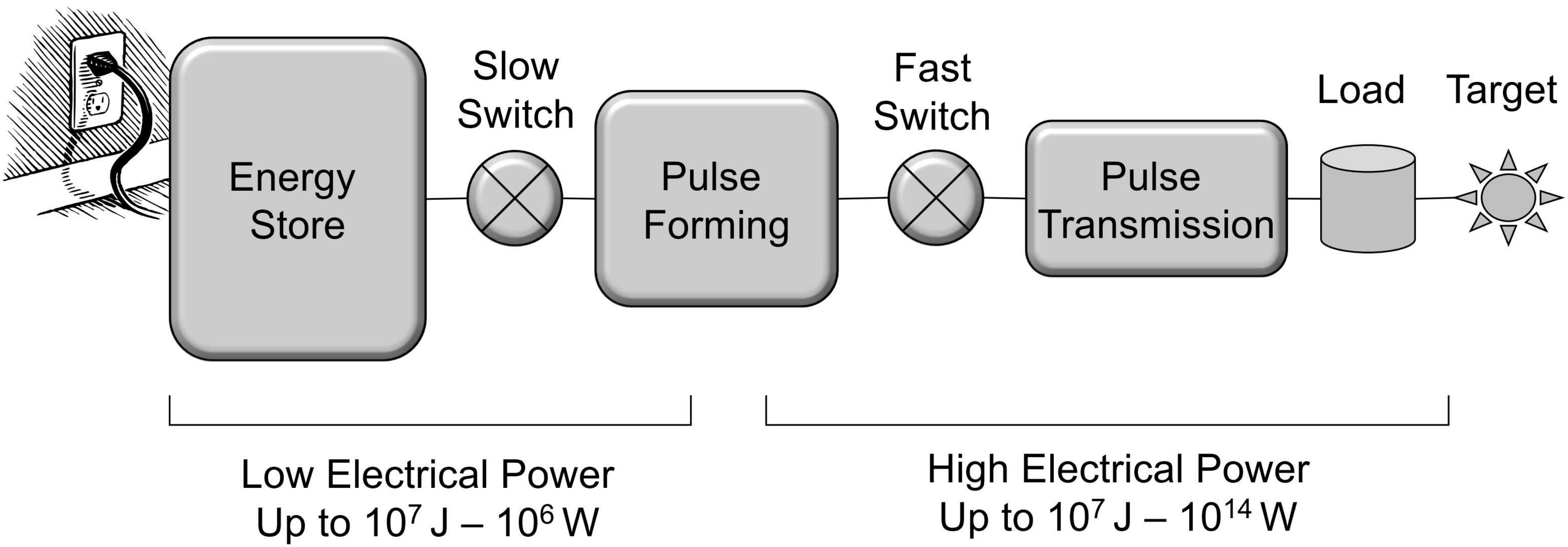
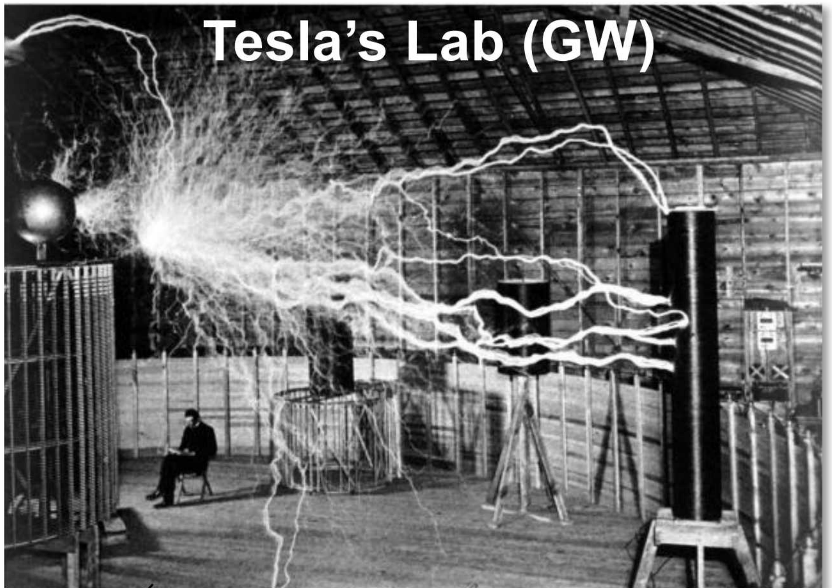
Pulsed power: The temporal compression of electrical energy to produce short bursts of high power

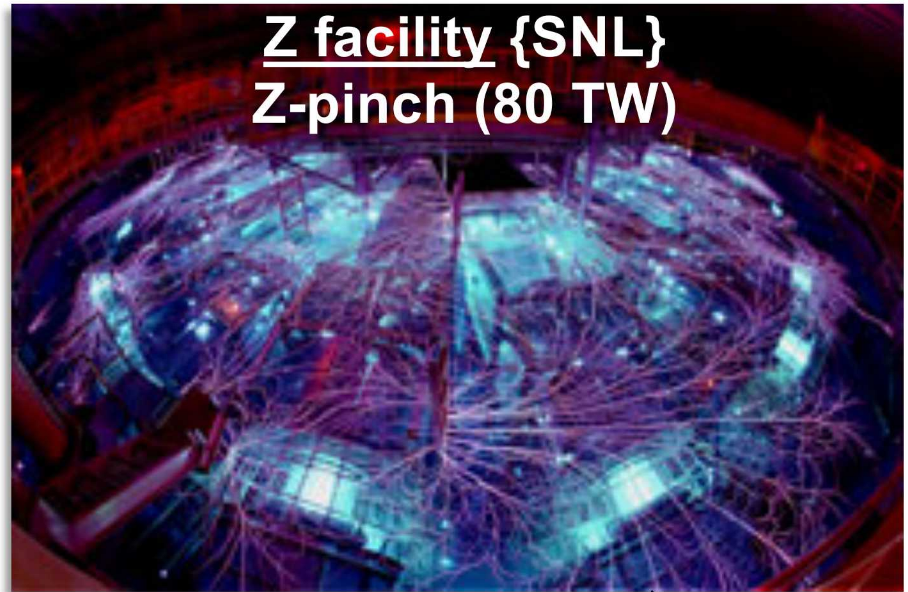


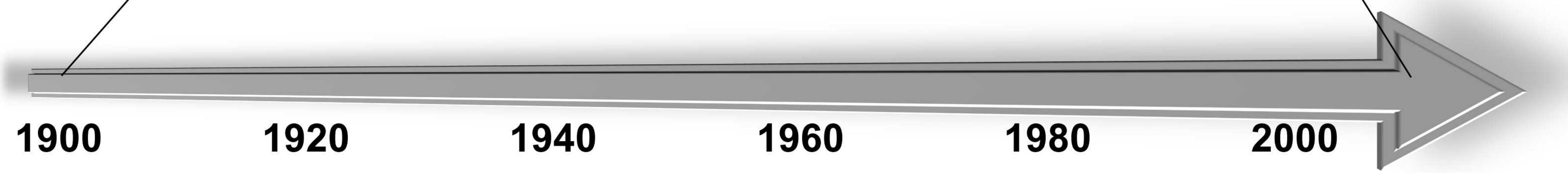
Take the equivalent electrical energy consumption in one evening's operation of a TV set (a few MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~15 TW).

…S T Pai & Qi Zhang, "Introduction to High Power Pulse Technology," World Scientific Publishing Co., Singapore, 1995.

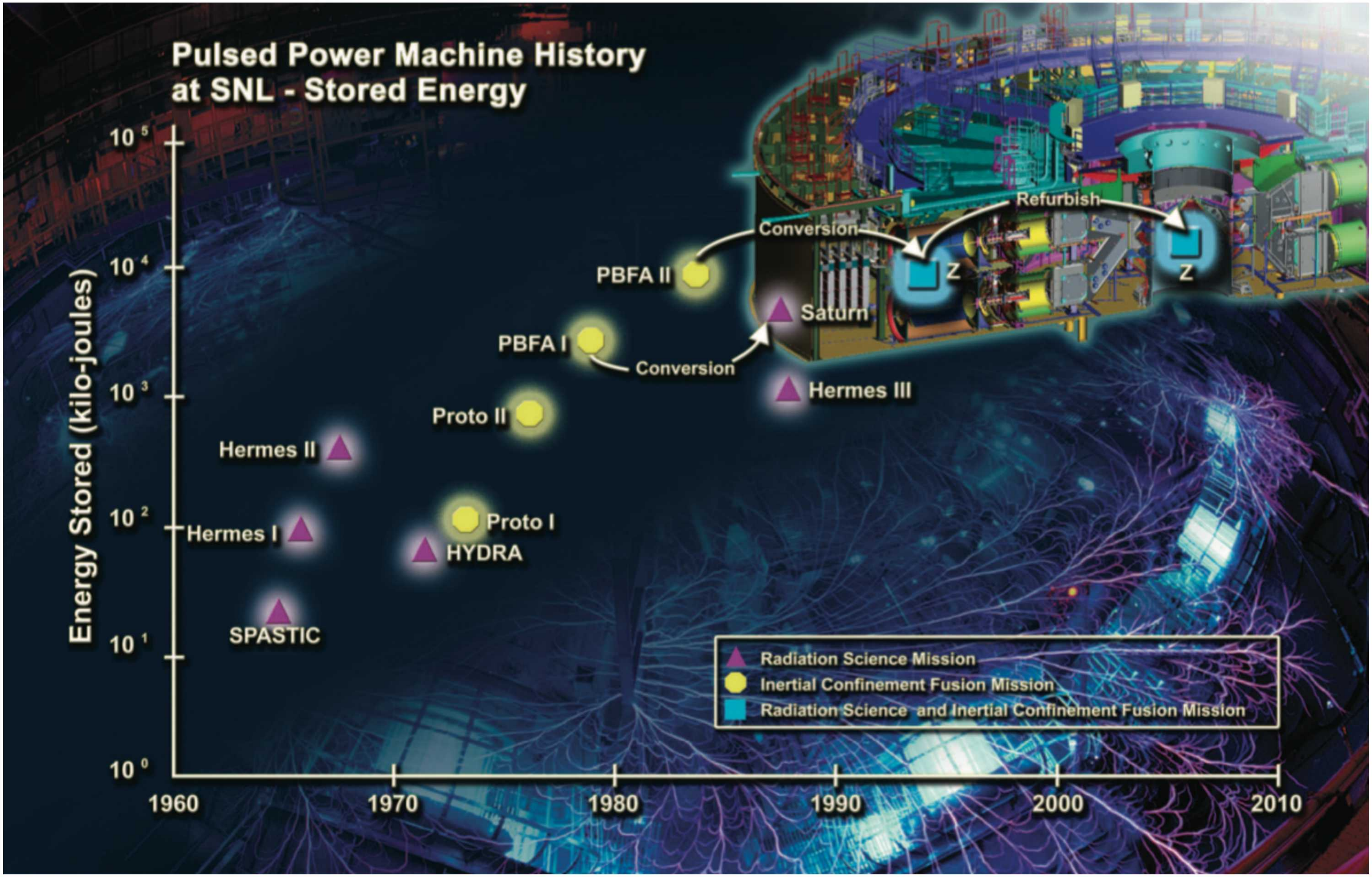
Pulsed power has been evolving for over a century!



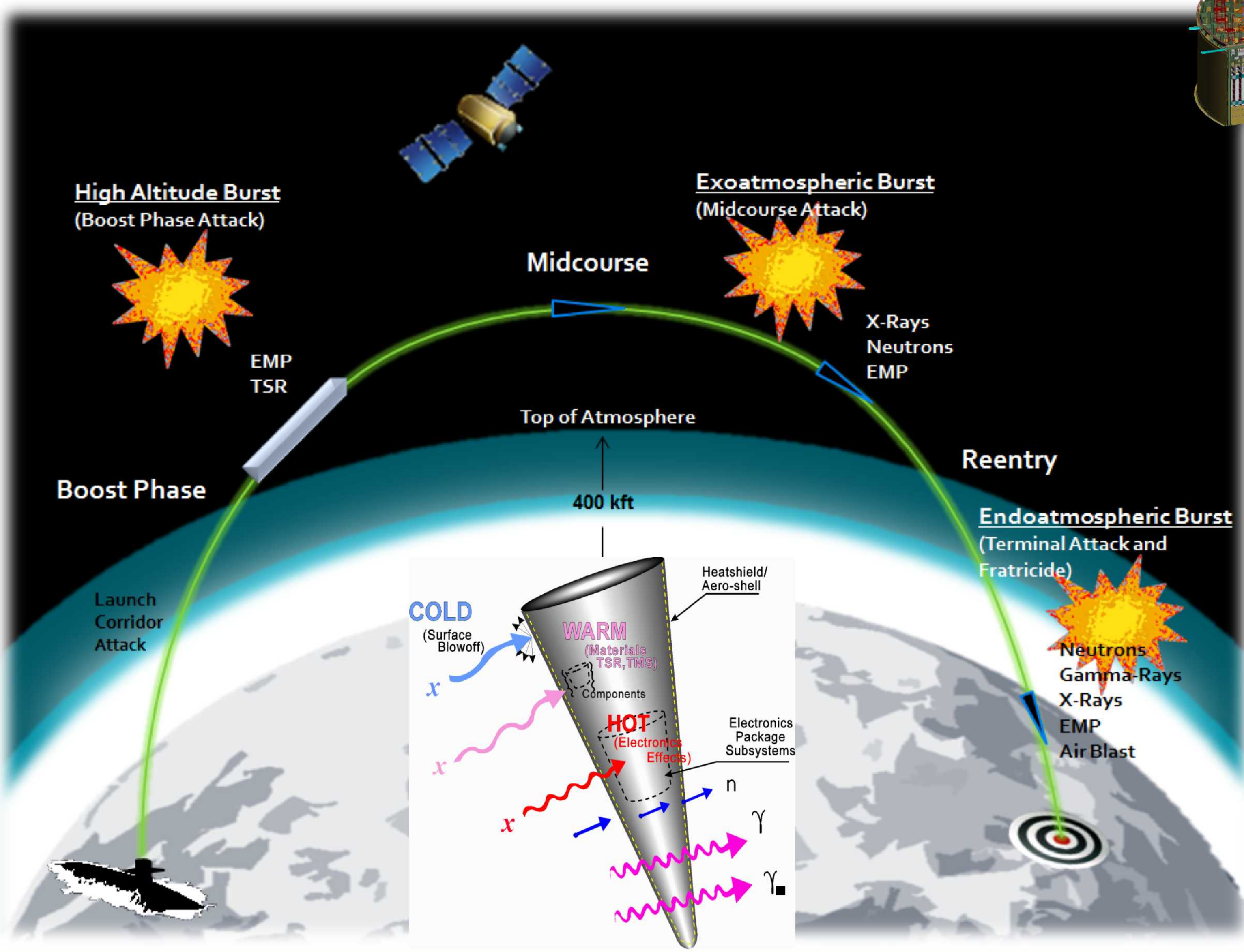


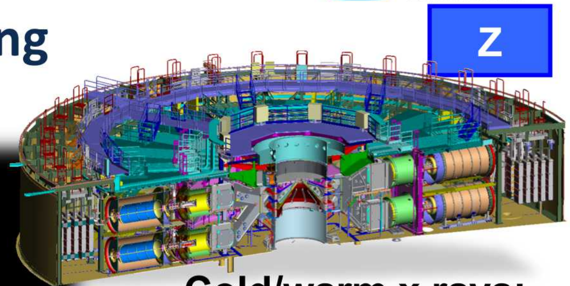


Sandia National Laboratories began developing pulsed power in the 1960s for weapon effects testing, despite ongoing and frequent underground nuclear testing

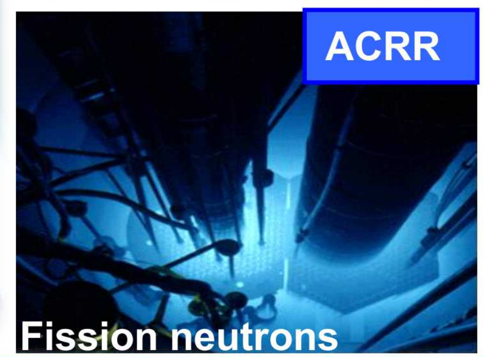


Today, Sandia maintains a suite of three pulsed power facilities and one nuclear reactor in order to support radiation effects testing





Cold/warm x rays; fast fusion neutrons



Pulsed Power Research at Sandia is in the Radiation Effects & High Energy Density Science Research Foundation

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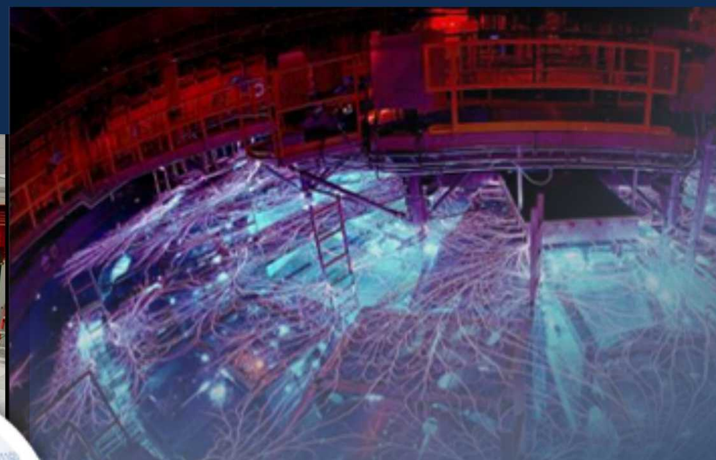
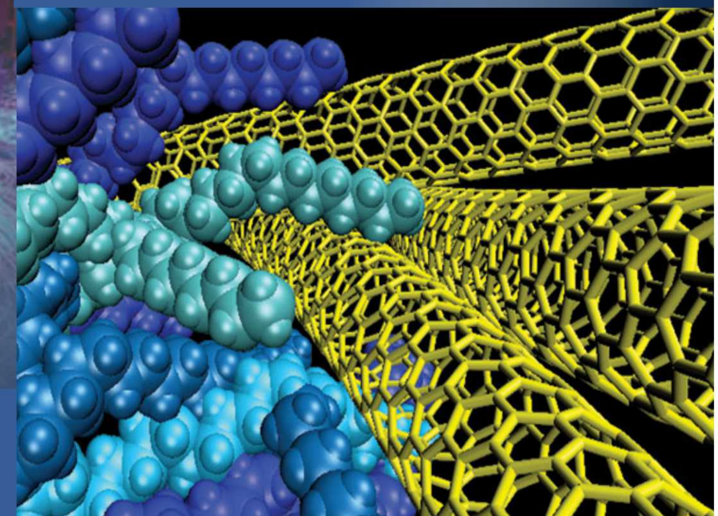
Computing & Information Sciences

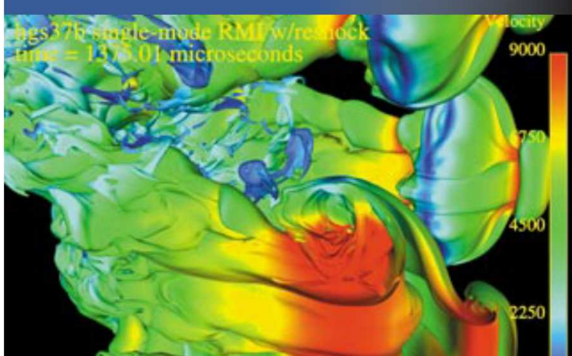


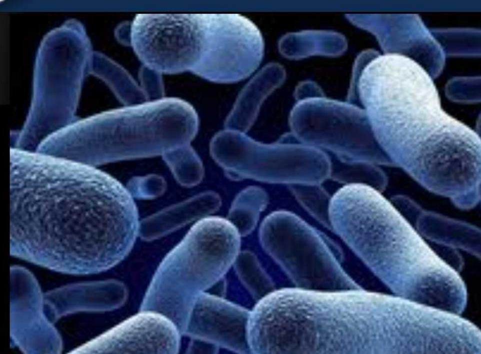
Radiation Effects & High Energy Density Science

Materials Science



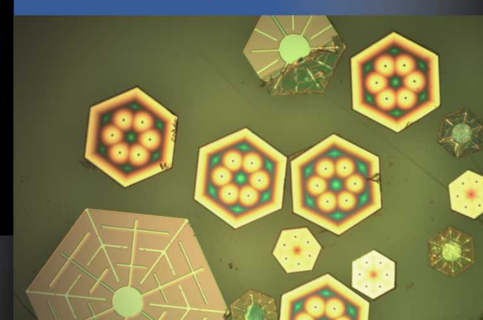
Engineering Sciences

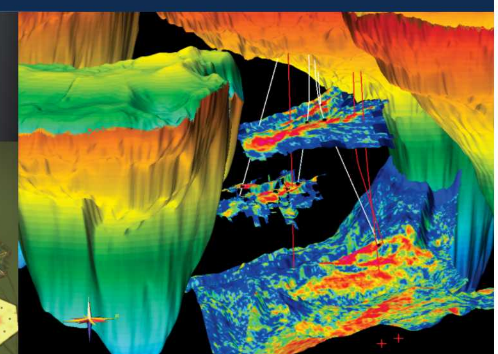




Bioscience

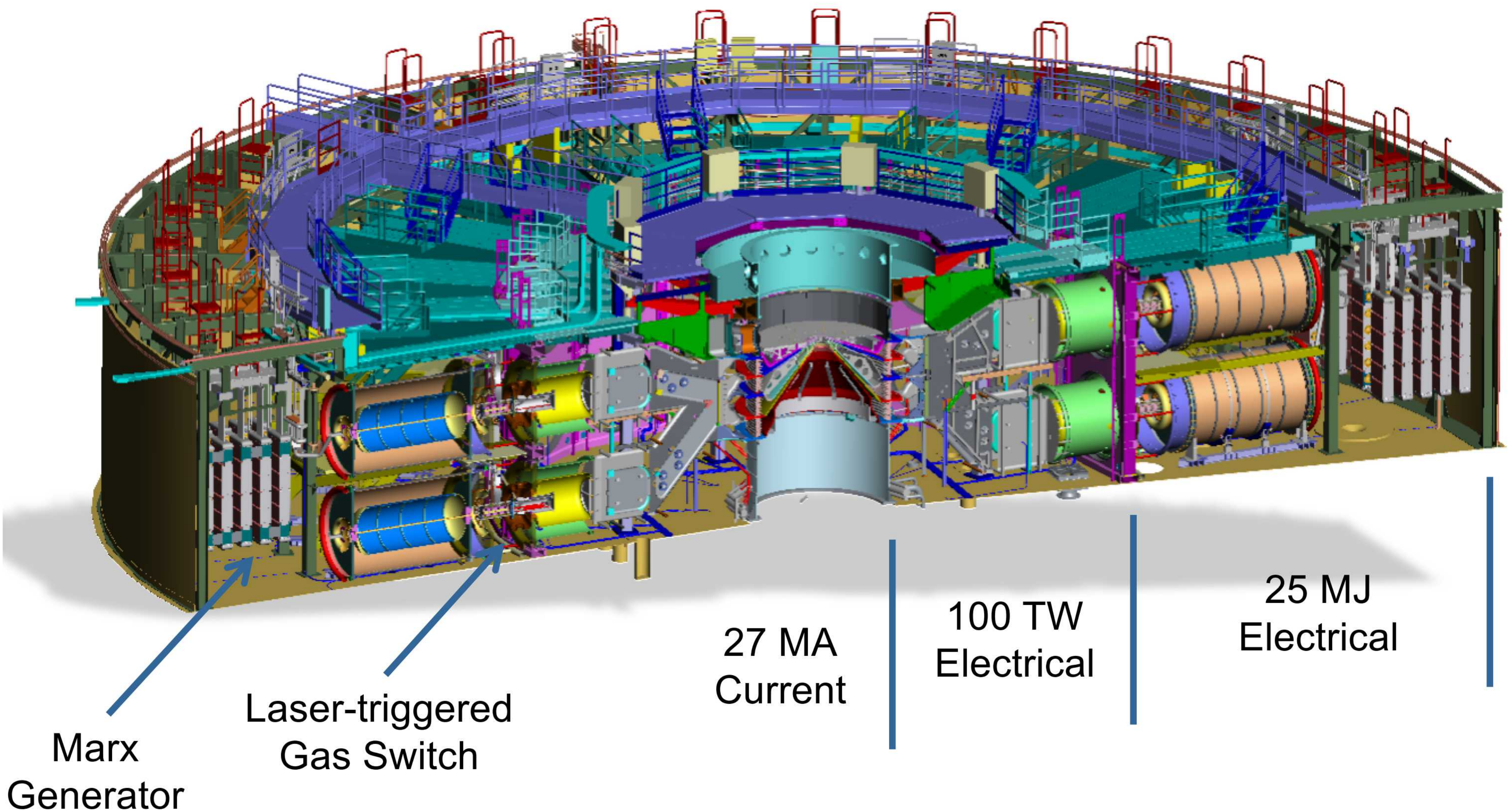
Nanodevices & Microsystems





Geoscience

The Z facility at Sandia National Laboratories is the most powerful pulsed power machine in the world



Energy is compressed in both space and time

The 80-TW Z machine is a superpower accelerator!

We define a *superpower* machine to be one that generates ≥ 10 TW of peak electrical power.

The total electrical-power-generating capacity installed worldwide is 4.7 TW:

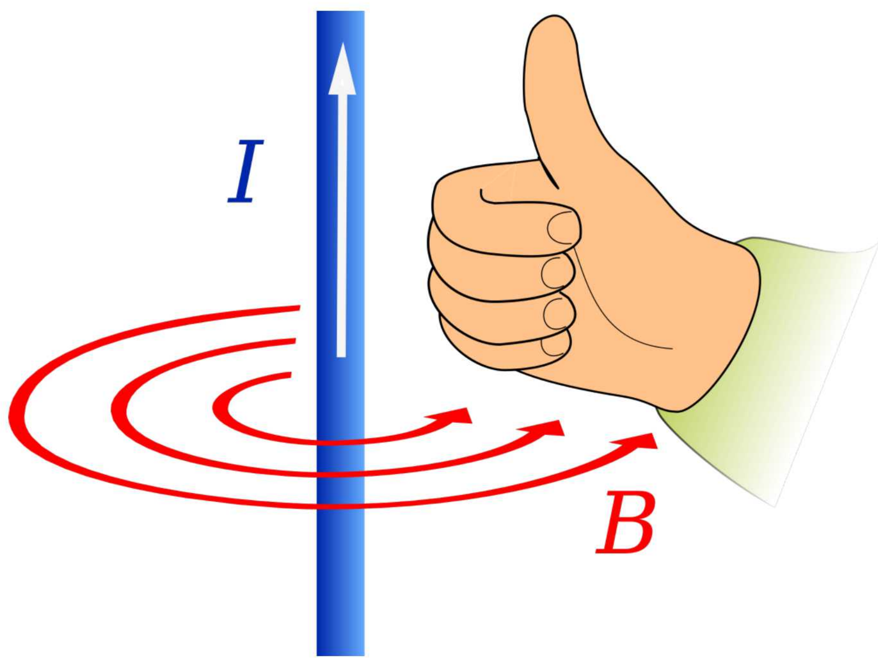
Conventional thermal	3.2 TW
Hydroelectric	0.9 TW
Nuclear	0.5 TW
Geothermal, solar, wind, and wood	0.1 TW
Total	4.7 TW

(International Energy Annual Report, DOE)

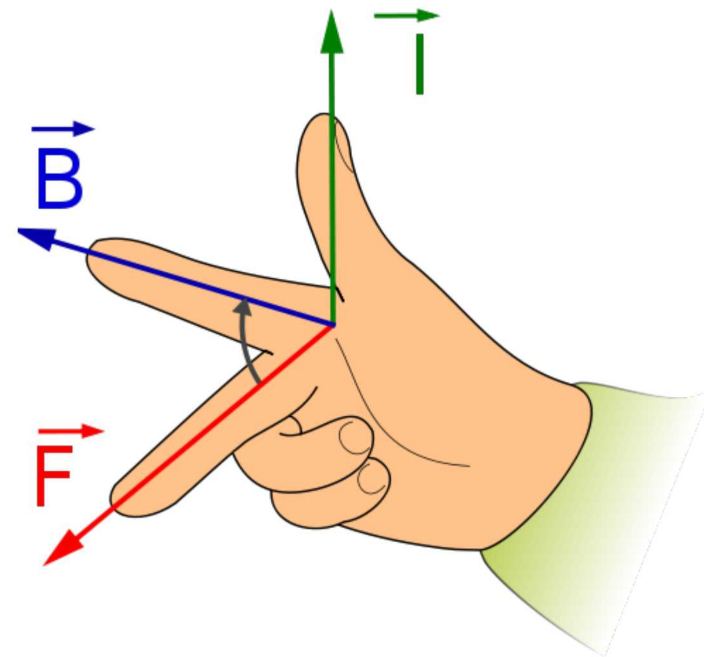
For 10s of nanoseconds, a superpower accelerator generates more electrical power than all the world's power plants, combined.

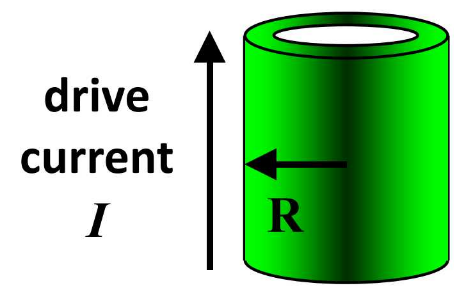
Large currents create strong azimuthal magnetic fields, which results in a radially inward "JxB" force

Current (I)



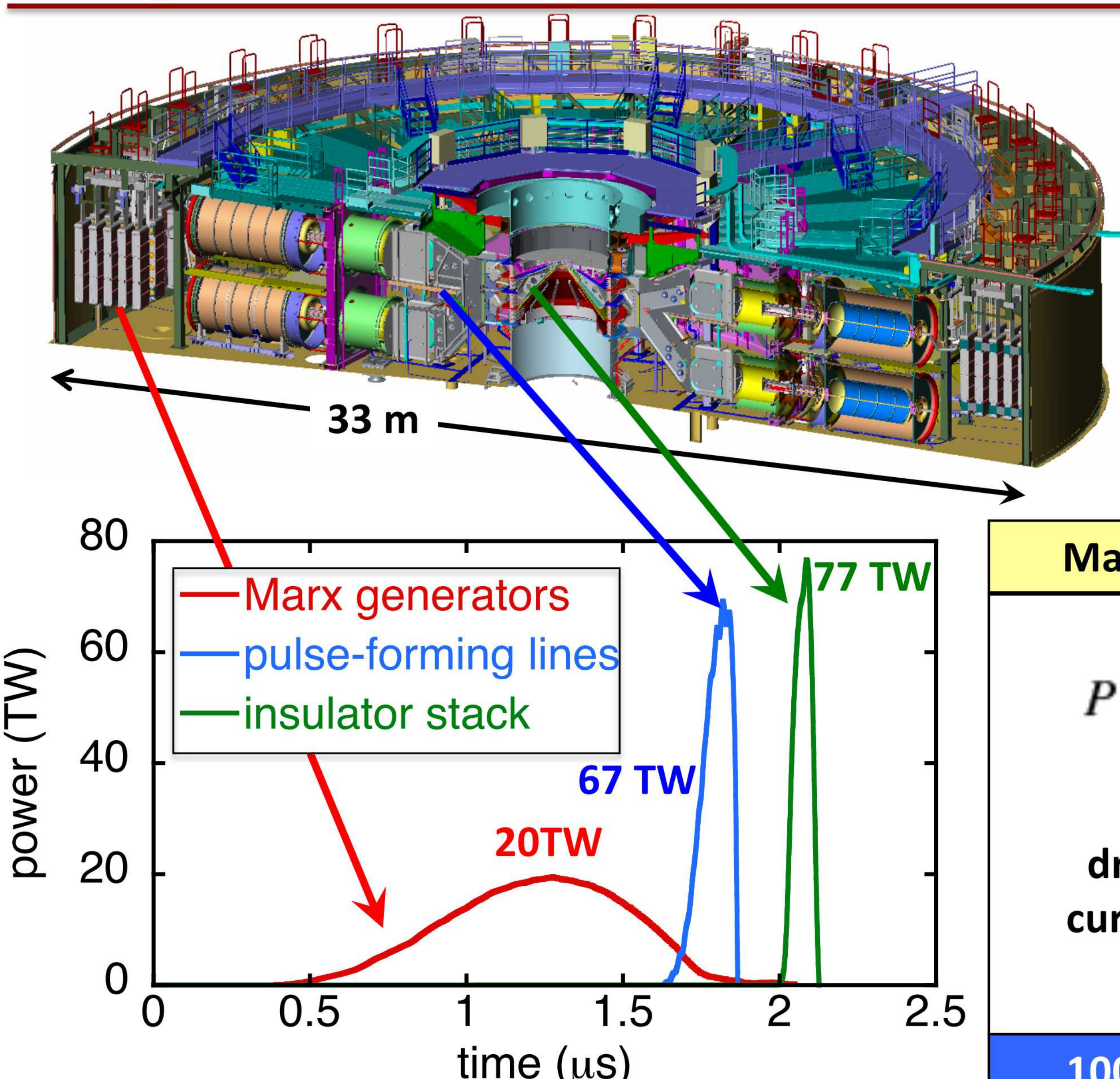
Magnetic Field (B)





A "Z-pinch"

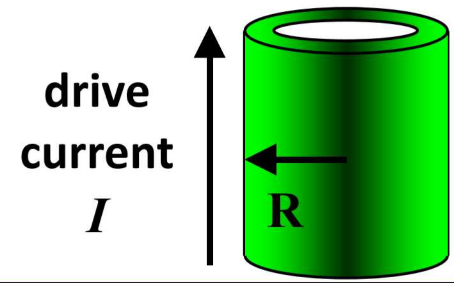
Very high pressures can be obtained using the large currents on Z



Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).

Magnetically Driven Implosion

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

Pulsed power can be used to obtain even higher pressures such as those in inertial fusion

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- Pressure equivalent to Energy Density (J/m^3)
- 1 Mbar = 10^6 atm = 10^{11} J/m^3

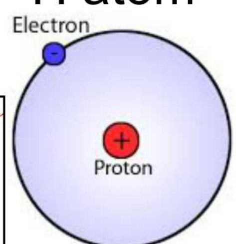
Z Storage capacitor

2e-6 Mbar

TNT

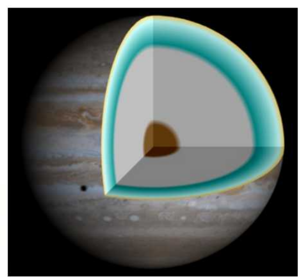
0.07 Mbar

Internal Energy of H atom



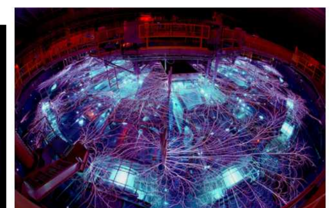
1 Mbar

Metallic H in Jupiter's core



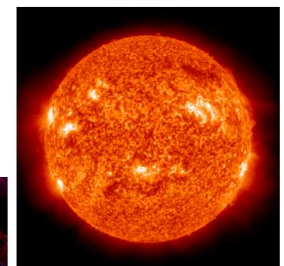
30 Mbar

Z Magnetic Drive Pressure



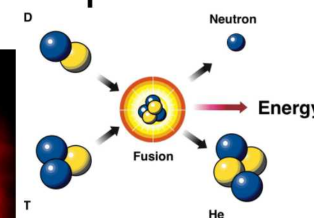
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma

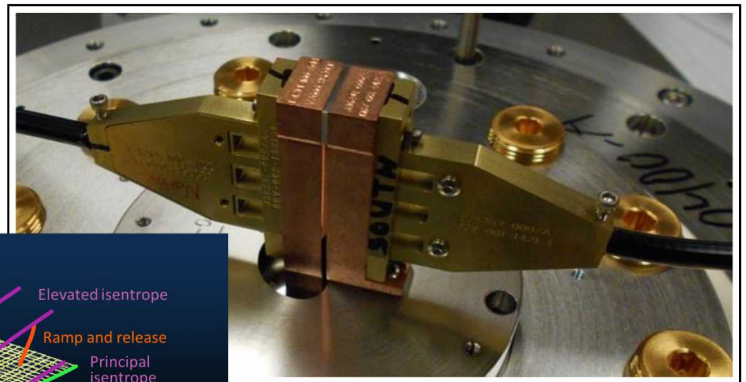


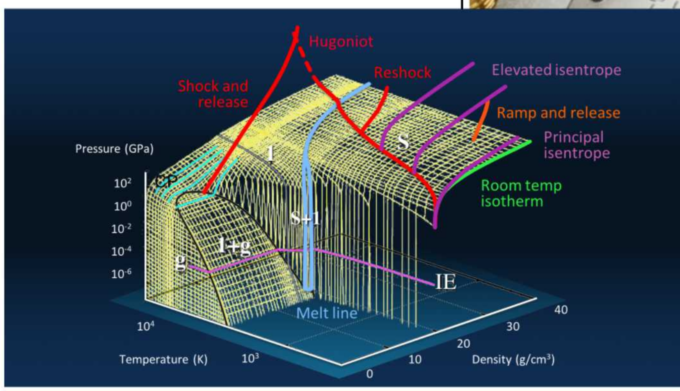
800,000 Mbar

Push on samples ← → **Throw fuel at high velocity**

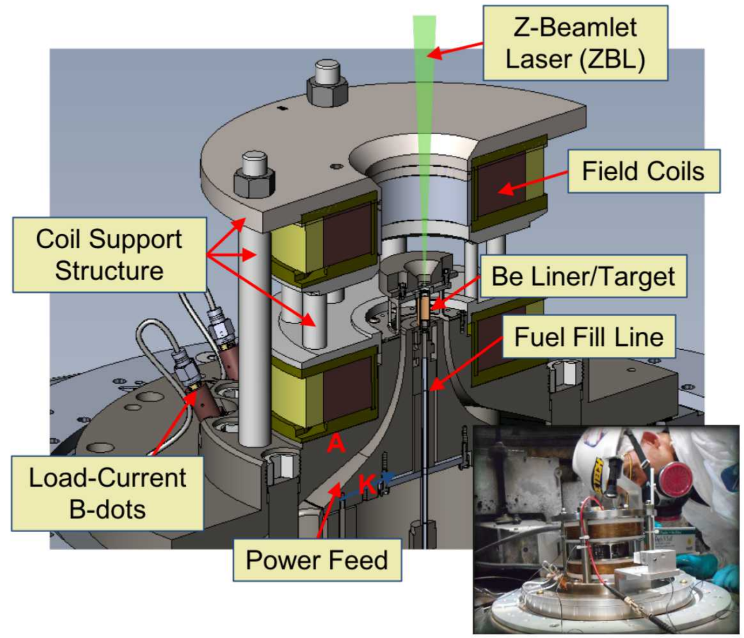
We use Z to create high energy density matter and/or extreme x-ray environments for different applications

Dynamic Material Properties



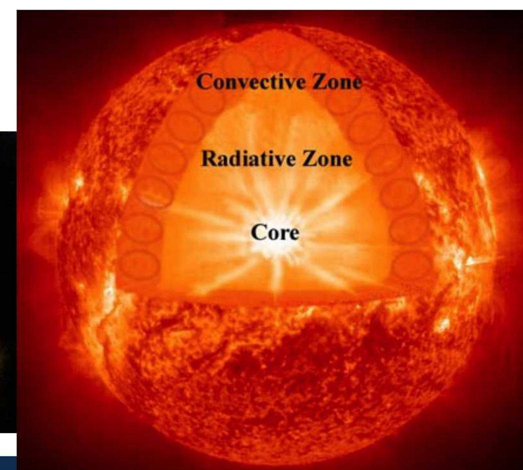


Inertial Confinement Fusion



Radiation-driven Science

Z Fundamental Science Program



A challenge for making measurements on Z is that experiments release the energy of a few sticks of dynamite

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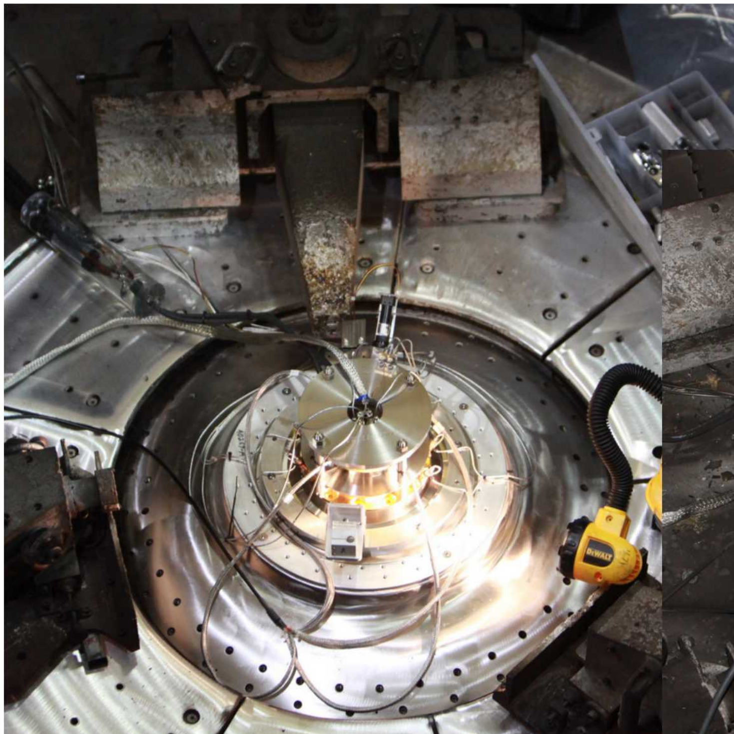

Pre-shot photo of coils and target hardware

Post-shot photo

Explosive containment system for special nuclear materials

Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

The majority of the yield of our nuclear weapons occurs from matter in the High Energy Density state

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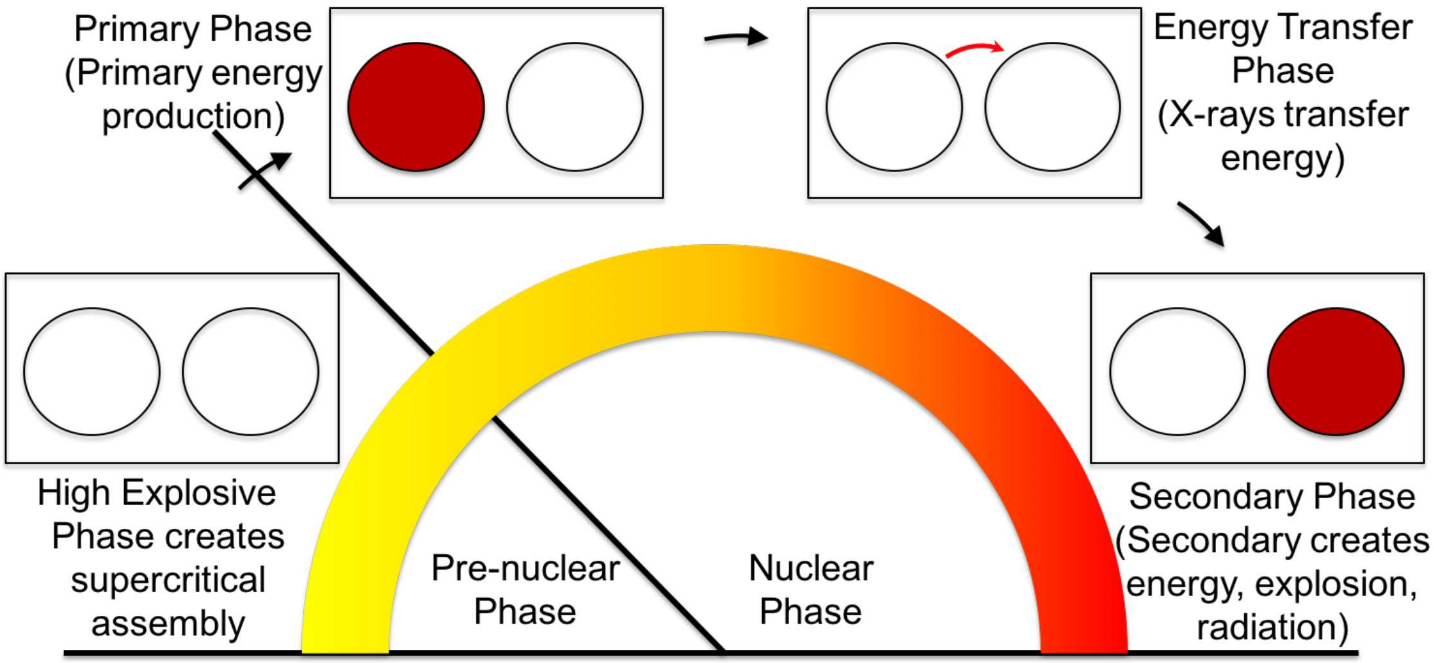

The Nuclear Phase can be studied using underground tests, large lasers, or large pulsed power facilities.

The ICF program stewards three major facilities capable of directly creating high energy density conditions and of producing large amounts of x-rays and/or neutrons

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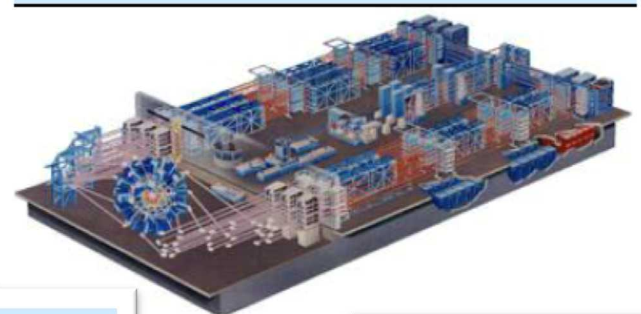
Omega



NIF

Z

The Nuclear Phase can be studied using underground tests, large lasers, or large pulsed power facilities.

Today the U.S. enjoys some of the most advanced capabilities in high energy density physics

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Omega

- High shot-rate academic facility
- Platform and diagnostic development
- 20 TW / .03 MJ

NIF

- Hottest temperatures and highest pressures on Earth
- **Largest Laser on Earth**
- **400 TW / 1.8 MJ (Max Power & Energy)**

Z

- Larger samples & time scales than NIF
- **Largest Pulsed Power Facility on Earth**
- **80 TW / 3 MJ (Max Power & Energy)**

The Nuclear Phase can be studied using underground tests, large lasers, or large pulsed power facilities.

Pulsed power HED plays a unique role as a capability that can fill in gaps in stockpile stewardship

Examples

- X rays for hostile environment survivability research
- Platforms for high pressure dynamic materials testing
- New platforms for primary and secondary assessments
- Neutrons for transient electronics studies
- Grand challenge problems that attract future stewards
- Hardened diagnostics
- Avoid technological surprise

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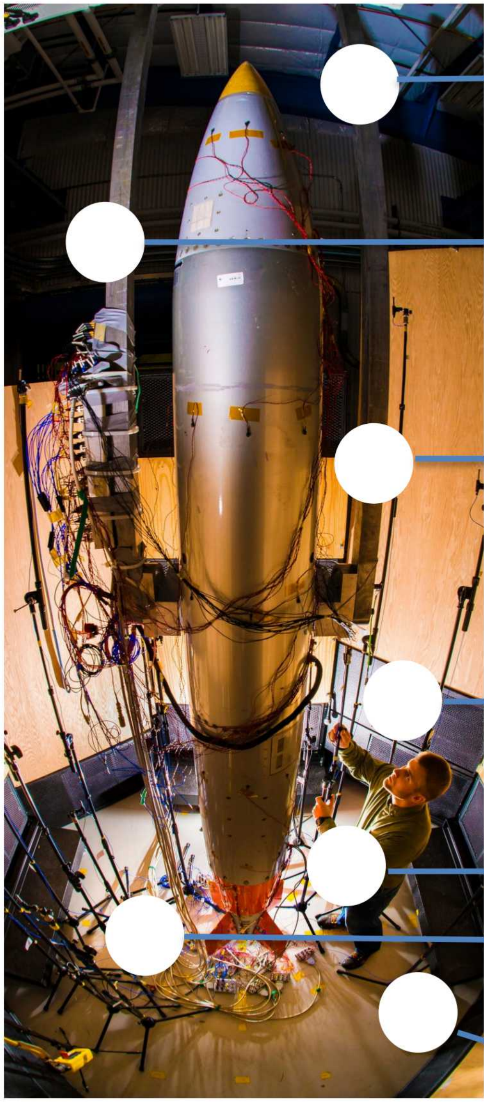
Examples



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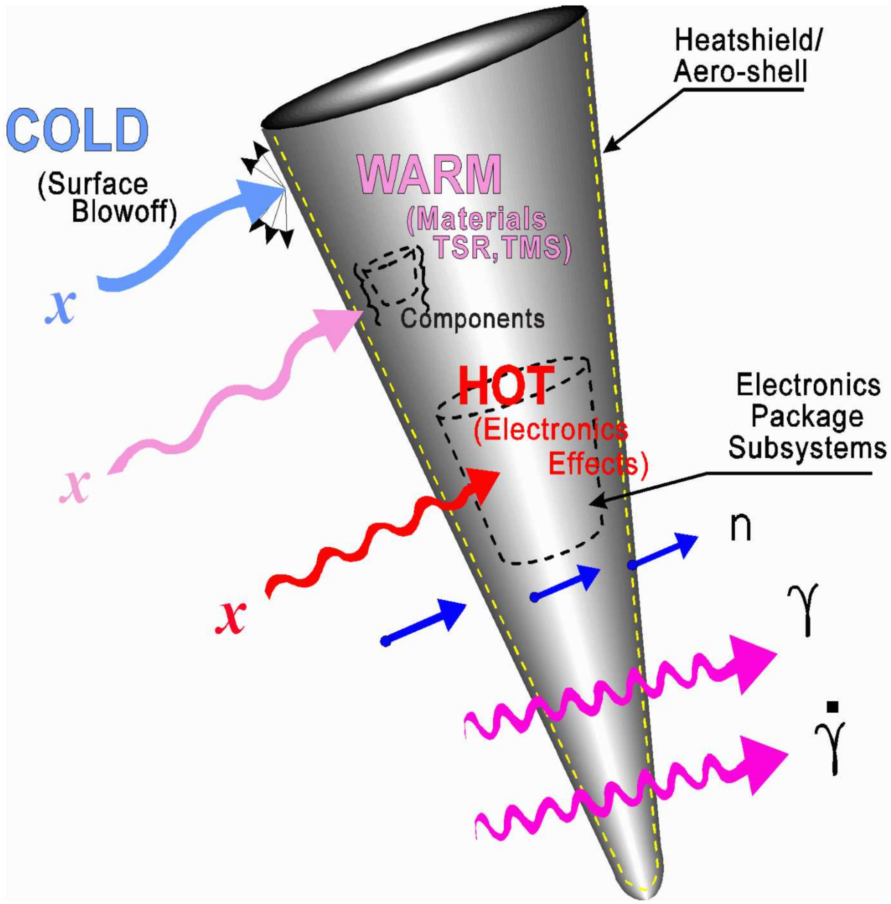
Hostile Environment Survivability Research: Nuclear Weapon Nominal Radiative Outputs*

- Most radiation emitted in <1 microsecond
- Thermal Radiation ~70-80%
  - Mostly x rays
  - Form blast wave in atmosphere
  - Exo-atmospheric concern
- γ-rays ~0.6%
  - Both Exo- and Endo-atmospheric
- neutrons ~2%
  - Exo- and Endo-atmospheric
  - Atmospheric scattering
- Remainder kinetic energy of bomb debris or residual radiation
- Electro-magnetic pulses (EMP) can also be generated from complex interaction of prompt gamma rays with atmosphere

* For further details on weapon outputs, see "The Effects of Nuclear Weapons" book by Glasstone and Dolan, 1977

Weapon outputs can produce transient-radiation effects on electronics (TREE) affecting components, circuits made from the components, and circuits combined to form systems*

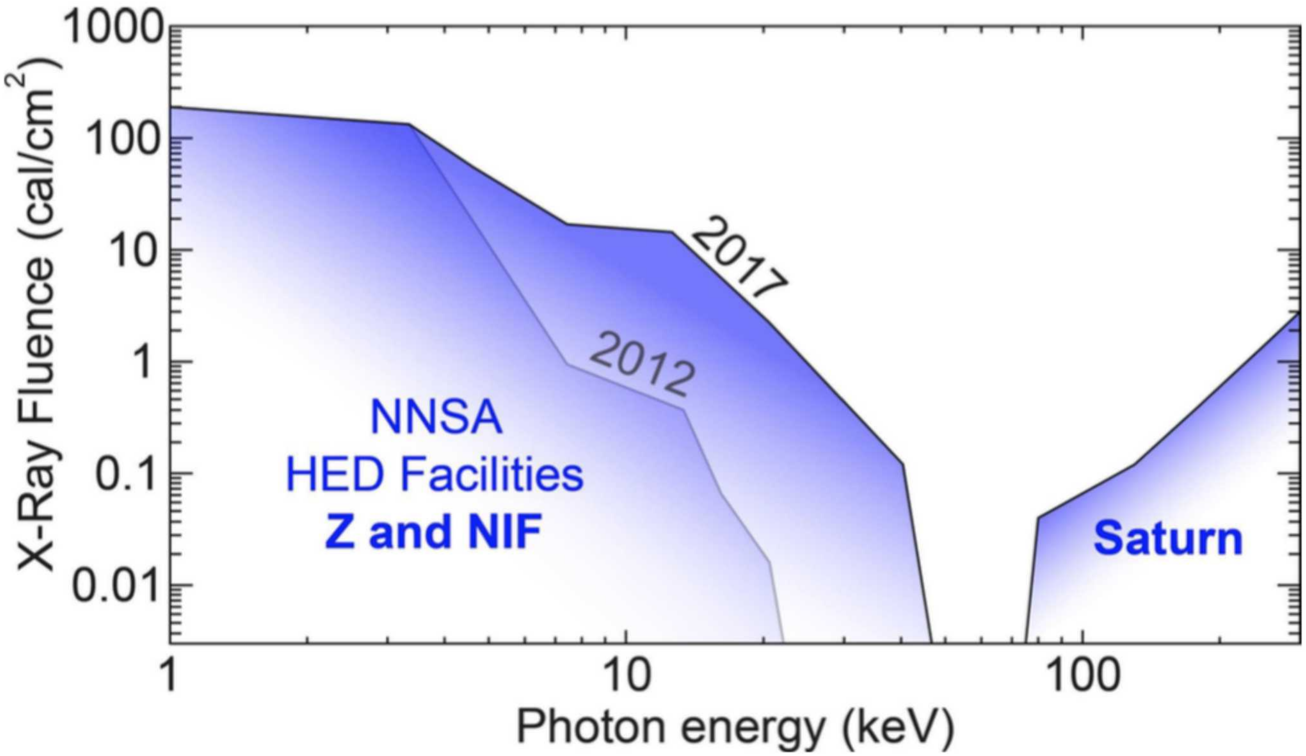
- Weapons can produce Transient-Radiation Effects on Electronics (TREE) affecting components, circuits made from component parts, and circuits combined to form systems
- TREEs in components and circuits are generally the result of:
  - Ionization (x-ray or gamma-ray) that adds electrons to electronics
  - Atomic displacements in lattice structures (neutrons)
- <u>There are many additional phenomena</u> that vary in complex ways with the incident photon or neutron energies, durations, weapon materials, & weapon configurations



* For further details on weapon effects, see "The Effects of Nuclear Weapons" book by Glasstone and Dolan, 1977

Today's ICF facilities continue to push the frontiers of what is possible, partly filling in some of these gaps

X rays for hostile environment survivability research



Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV capabilities

Other elements of NNSA's Research, Development, Testing, and Evaluation division use our HED platforms

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X rays for hostile environment survivability research

Scientists funded by NNSA field Z experiments to improve their models for System Generated Electro-Magnetic Pulses

The ICF program enables teams of scientists and engineers across the lab to do our annual assessments

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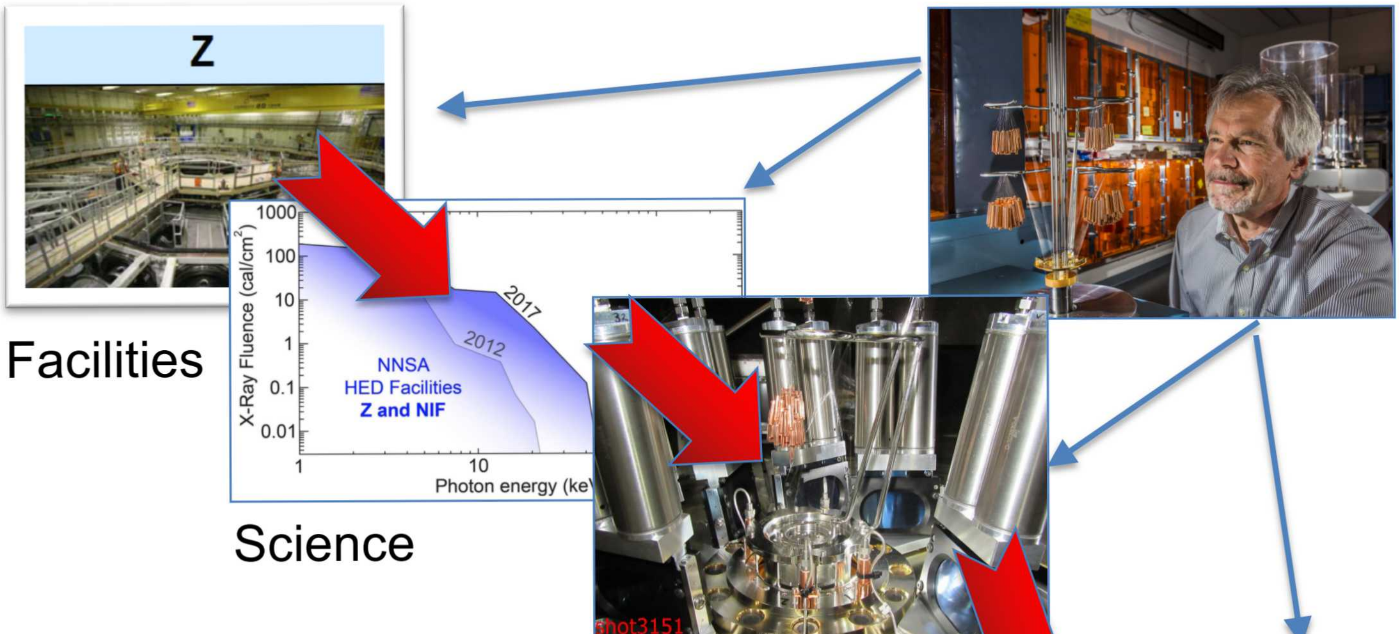
X rays for hostile environment survivability research

People



Facilities

Science

Model Validation

Model Applications

Significant Finding Investigations
Annual Assessments
Life Extension Programs

Pulsed power HED plays a unique role as a capability that can fill in gaps in stockpile stewardship

Examples

- X rays for hostile environment survivability research
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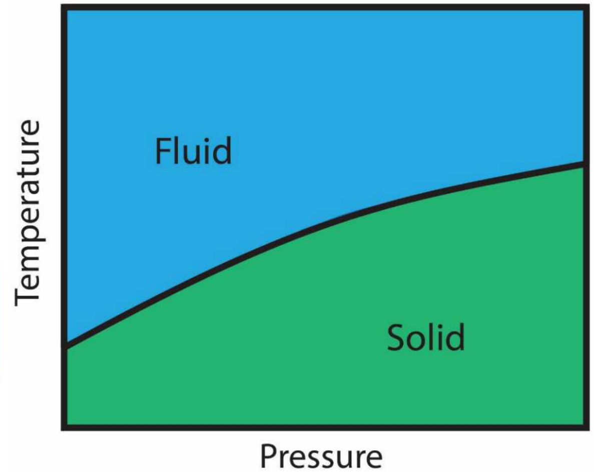
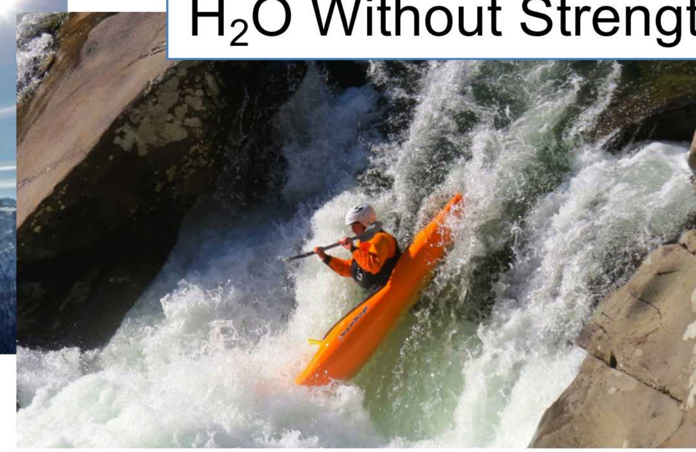
- Avoid technological surprise

Our existing ICF facilities allow us to study material properties at uniquely high pressures

Platforms for high pressure dynamic materials testing



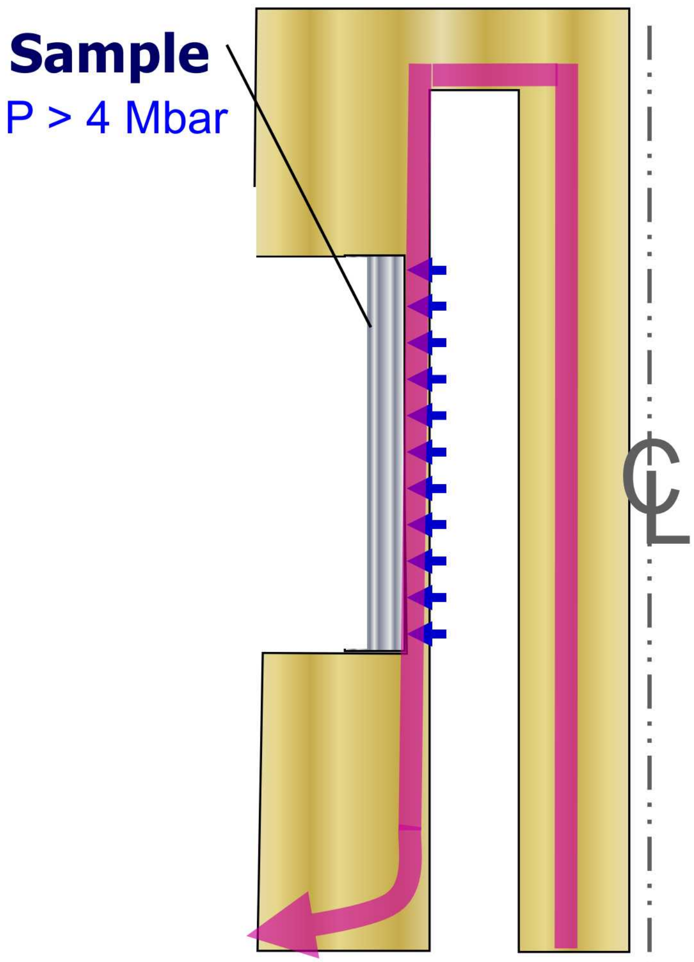
H_2O With Strength

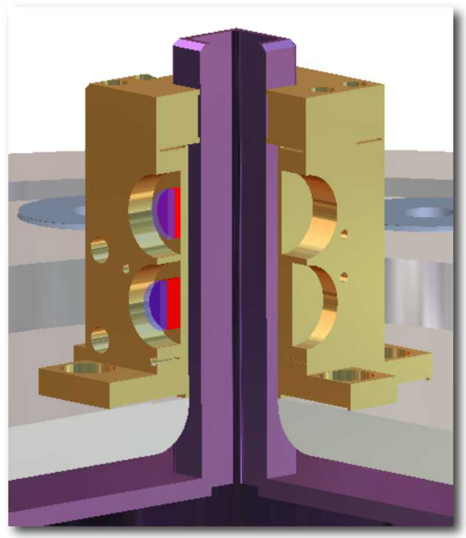


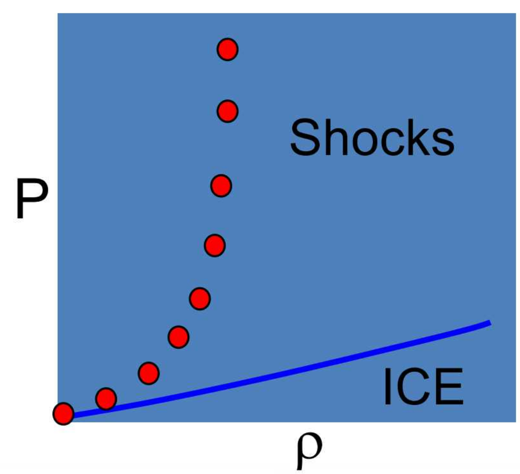
H_2O Without Strength

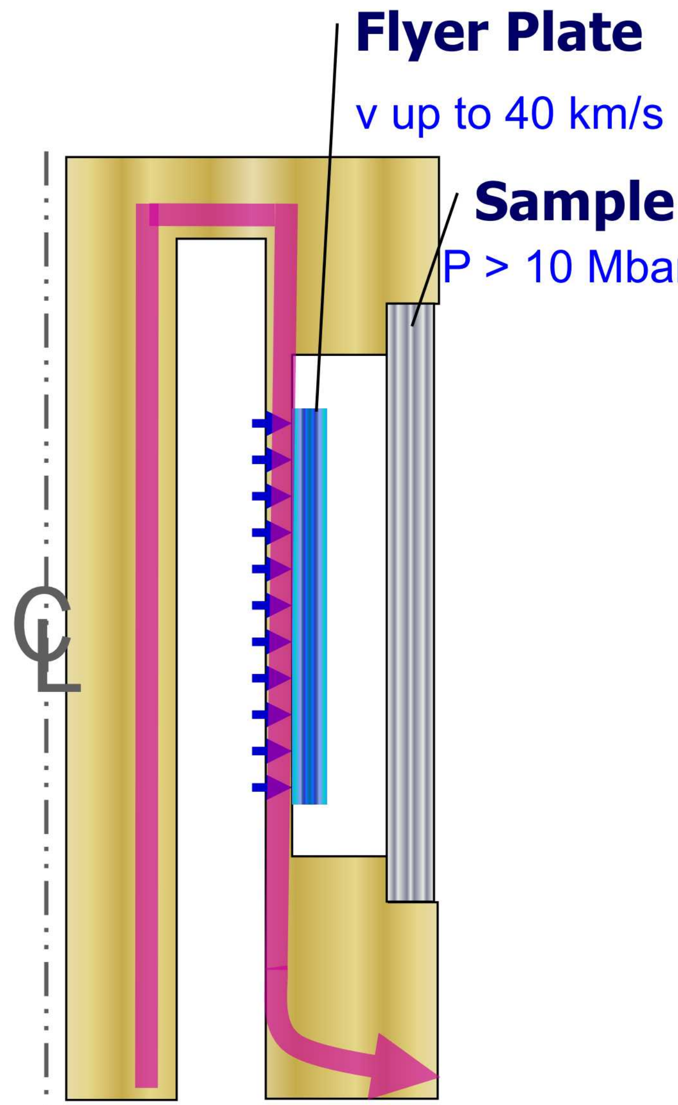
Solids can have different strengths depending upon their pressure and temperature!

Z can perform both shockless compression and shock wave experiments









<u>Shockless Compression Experiments:</u>
gradual pressure rise in sample

<u>Shock Hugoniot Experiments:</u>
shock wave in sample on impact

Plutonium experiments on Z are collecting data that is being used to answer questions about pit aging

Platforms for high pressure dynamic materials testing

The US stockpile is aging and understanding the properties of aged plutonium is important.

Recent experiments on Z have provided comparative data on new and old Pu.

The data is being used by LANL in developing new Pu models.

Pulsed power HED plays a unique role as a capability that can fill in gaps in stockpile stewardship

Examples

- X rays for hostile environment survivability research
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The purpose of facilities like Z is to provide the capability to answer questions that are not always possible to anticipate in advance

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- Z has evolved dramatically since 1996
  - >90% of shots on Z in 2019 use experimental platforms that were not clearly envisioned in 1996
  - As new platforms are developed, we are able to address new missions
    - e.g., capability to study dynamic materials + capability to use explosive containment vessels → Study of plutonium aging

- As technology and threats evolve, we adapt and provide data
  - e.g., micro-electronics have come a long way since 1996—no underground test (UGT) data exists for modern circuit elements
  - e.g., additively manufactured materials didn't exist in 1996. If we want to insert into the stockpile, we need to understand their behavior in HED regimes and hostile environments
  - e.g., as intelligence on potential adversaries comes in, we help assess the threats and proposed solutions

The Z Fundamental Science Program supported major discoveries in Astrophysics and Planetary Science in partnership with academic users

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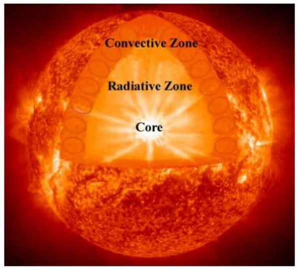
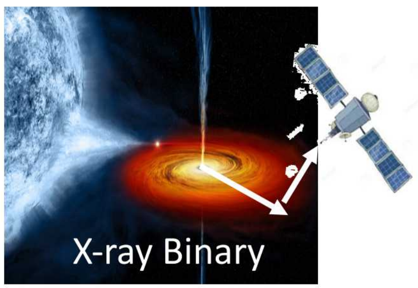
Solar Model



Black hole accretion



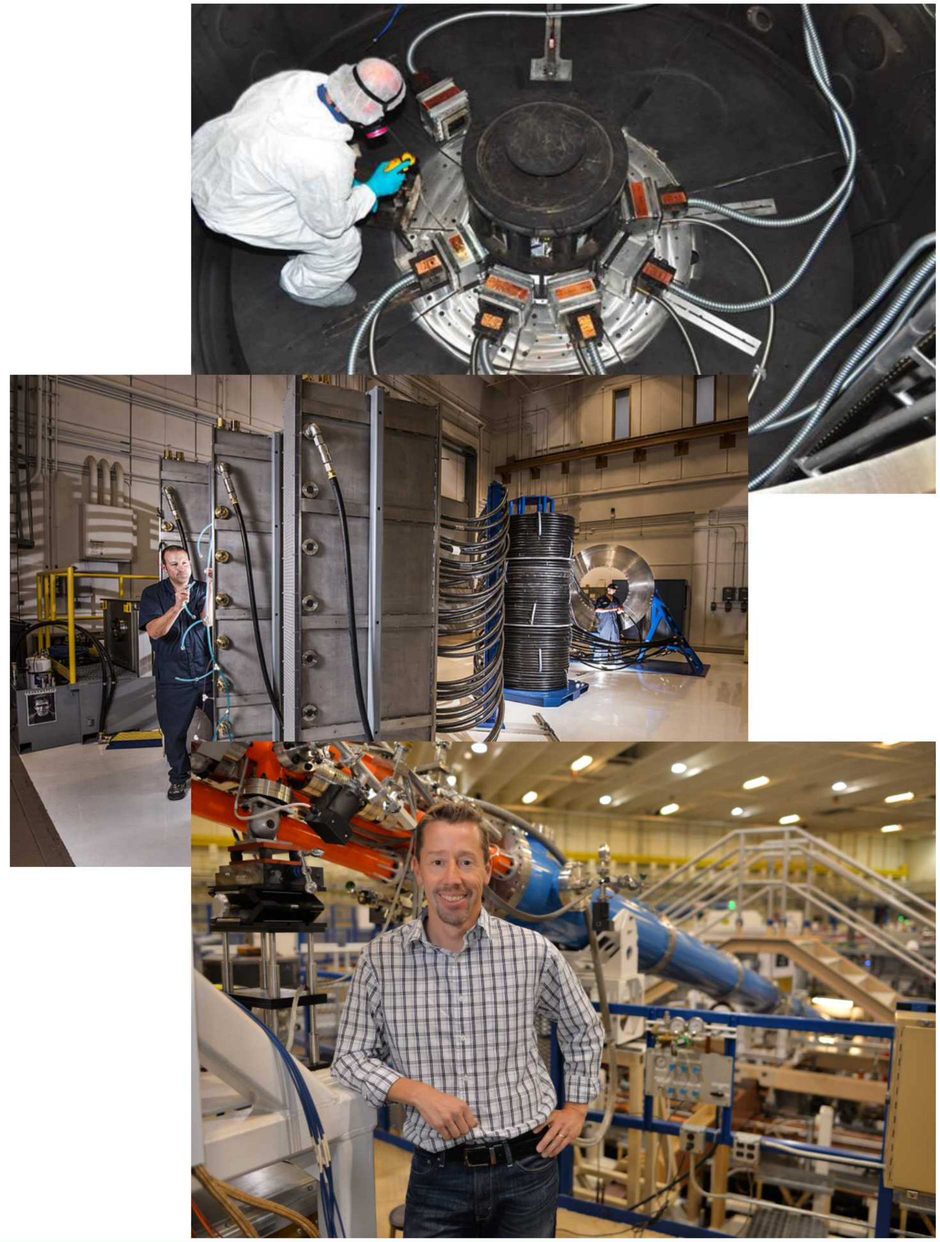
White dwarf photosphere

Planetary physics

1 µg of stellar interior at R ~ 0.7Rsol	*A higher-than-predicted measurement of iron opacity at solar interior temperatures* Jim Bailey *et. al*., Nature (2015)
10^{-3} liters of accretion disk at R~100-1000 km from black hole	*Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources* G. P. Loisel *et al*., Physical Review Letters (2017)
~0.1 liters of white dwarf photosphere	*Laboratory Measurements of White Dwarf Photospheric Lines: HB* Ross Falcon *et. al*., The Astrophysical Journal (2015)
1.3 mg (0.8 µL) of metallic hydrogen	*Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium* Marcus D. Knudson *et. al*., Science (2015).
20 mg (2.5 µL) shocked iron	*Impact vaporization of planetesimal cores in the late stages of planet formation* Richard D. Kraus *et. al*., Nature Geoscience (2015)

The Z Facility today plays a significant role in nuclear deterrence

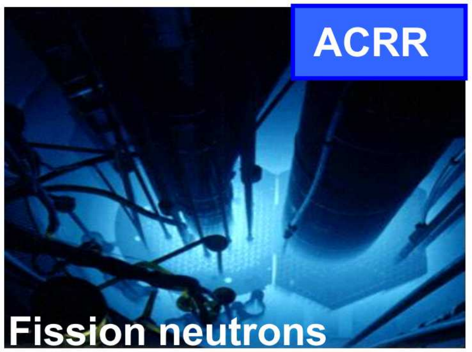
- World's most powerful warm x-ray source for hostile nuclear survivability research
- Used by all three NNSA laboratories for the study of high energy density physics relevant to the nuclear explosive package
- Attracts and tests stewards of pulsed power and weapons research
- Strengthens nuclear deterrence and global peace by publicly demonstrating U.S. scientific preeminence
- Provides a venue for scientific and technical innovation for national security

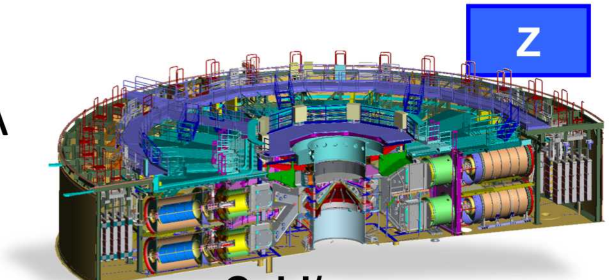


Sandia submitted several effects-related proposals to the NNSA as part of its Capital Acquisition planning process for major capabilities needed through 2040

- Sandia's submission to NNSA included three Radiation Effects and High Energy Density Science (REHEDS) facility investment priorities:
  - Refurbish/Recapitalize SATURN accelerator
  - Combined Radiation Environments for Survivability Testing (CREST)
  - Next Generation Pulsed Power Facility (NGPPF)

- Saturn refurbishment is being treated as a non-line item (funded through ongoing programs)
- CREST is proceeding toward CD-0 in FY19
- NGPPF was assigned to be worked by NA-113 (NNSA Office of Experimental Sciences; ICF/Science Programs) as a "Future HED Capability"





Cold/warm x rays;
fast fusion neutrons

A Next-generation pulsed power facility (aka "Z-Next") is an explicit part of a tri-laboratory vision for the next 20 years of stockpile stewardship

- NNSA Administrator, Ms. Gordon-Hagerty, was briefed on a variety of projects at Sandia including the Z-Next proposal while visiting in January.
- Asked Steve Younger to bring her a unified tri-laboratory vision for the future
- The three lab directors worked on a unified vision for "Stockpile Stewardship 2.0", and briefed her in mid-April
  - Emphasized People, Capabilities, and Processes
  - "Stockpile Stewardship 1.0 was designed to maintain the existing stockpile"
  - "Stockpile Stewardship 2.0 transitions from maintaining the existing stockpile to a responsive, agile, cost-effective design and production capability"
  - Both a NIF upgrade and a "Z-Next" are explicitly proposed
  - Calls for reinvigorating Discovery Science: "In seeking to 'reduce risk' in research, we run a greater risk of technology surprise"

High energy density science and inertial confinement fusion have been linked together for many years—high yield fusion is an enabling capability for stockpile stewardship

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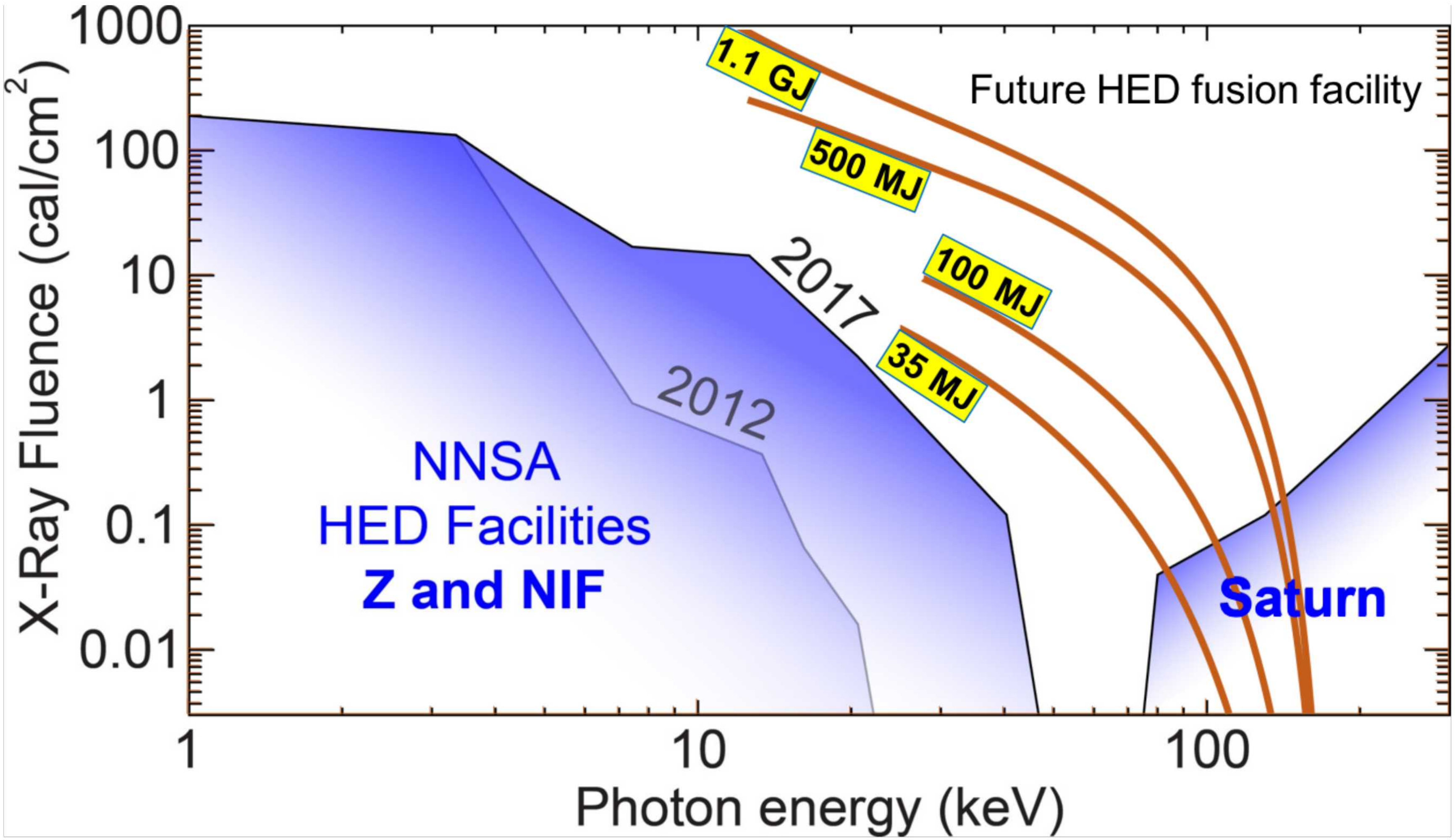
Yield	High Energy Density Science Applications
~0.01 MJ	• Interplay of thermonuclear fusion burn and mix • Nuclear physics data (reaction-in-flight, fission, and radiochemistry)
>0.1 MJ	• Transport of charged particles in plasmas • Threshold for fusion-fission physics
~few MJ	• Threshold for enabling complex mix physics studies. • Robust radiation and charged particle transport • Robust fusion-fission experiments
20-30 MJ	• Higher fidelity versions of the above experiments are possible • Neutron sources for outputs and environmental studies
>500 MJ	• Use of fusion targets to drive complex experiments • Use of fusion targets for material properties (EOS, opacity) research • Combined neutron and x-ray environments for outputs and effects studies

Table taken from NNSA 2018 ICF Framework document

Z and NIF have demonstrated 0.01-0.05 MJ yields to date

Future high yield facilities could provide even more powerful sources of 10-100 keV x rays, with multiple benefits for stewardship



Large fusion yields as a path to 10-100 keV x rays has been discussed since late 1980s
On a big enough pulsed power driver, x-ray only sources can also partly fill in the gap

Building the NGPPF may take the US over a decade to complete!

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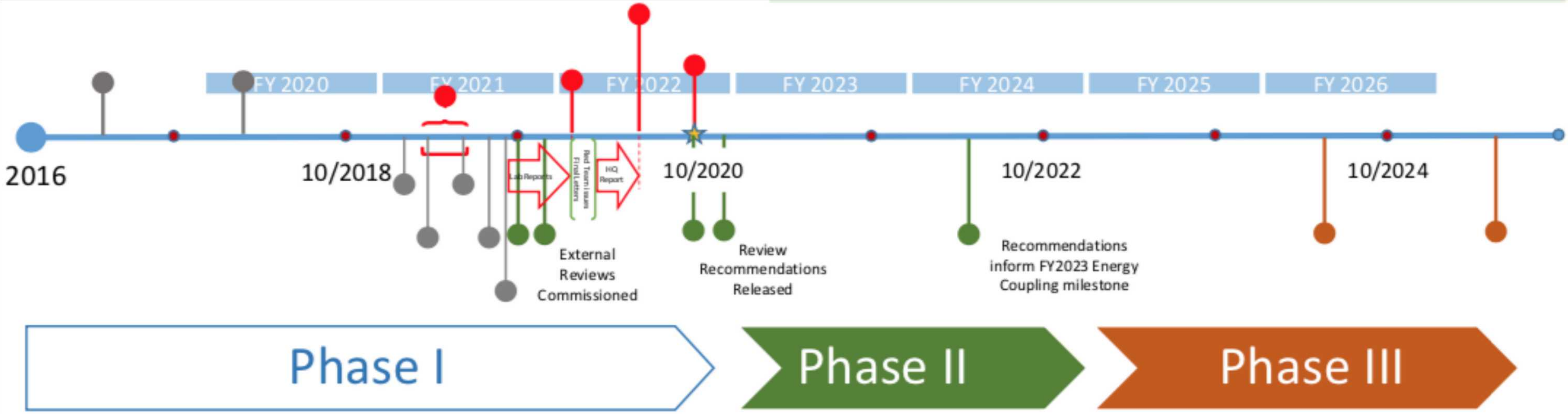


Phase I

- Records FY2020 state of scientific understanding of ignition scaling
- Prioritizes needs/activities to drive down uncertainties and reduce barriers
- Baselines FY2020 capabilities
- Informs program planning within budget constraints

Phase II

- Provides independent assessment of program capabilities & scientific understanding of scaling
- Reviews merits of experimental plans
- Examines the value in pursuing ignition

Phase III

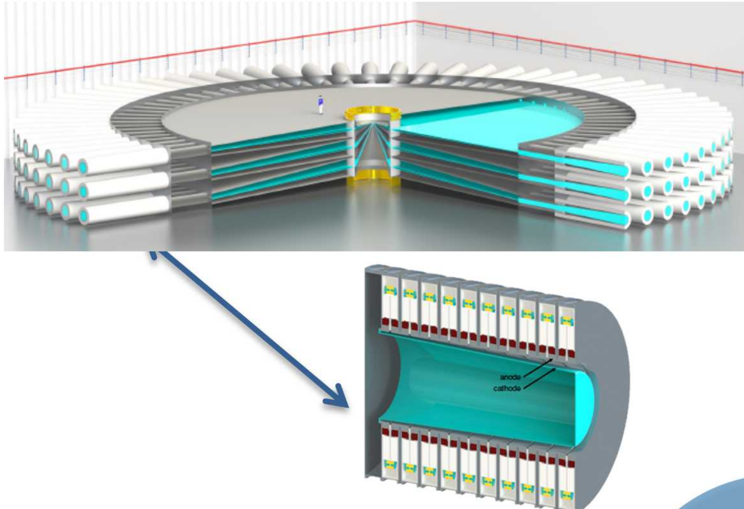
- Proposes programmatic path forward informed by internal (Red Team) and external (i.e. JASON, DPAC) reviews, as well as NNSA resources & direction

Budget Development

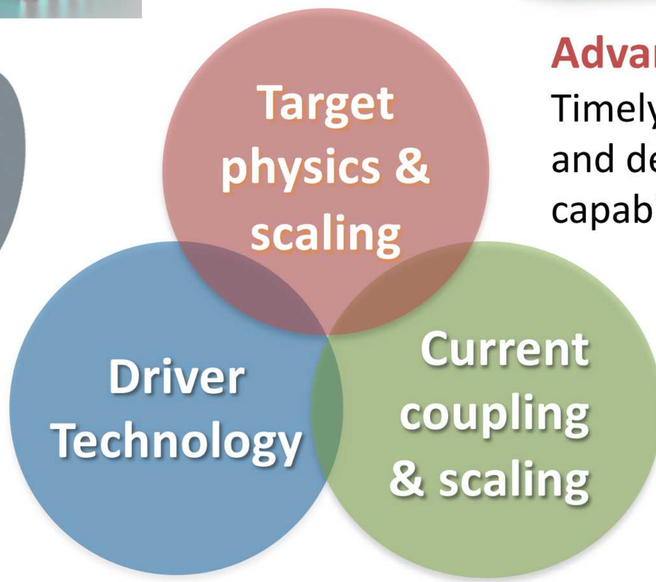
"The 2020 Report will be central to the development of out-year Program Plans and reviews addressing future facility investments, program priorities, and the best low-risk, physics approach to pursuing laboratory ignition."

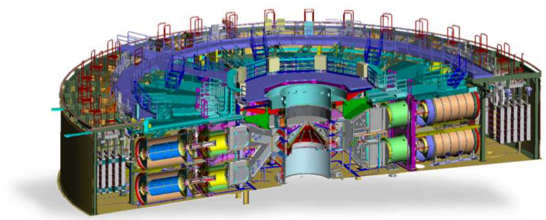
- Optimistically, CD-0 (Mission Need) could be established at outset of Phase 3 in 2022
- A 3-year Analysis of Alternatives process could be reasonable (ECSE took just under 4 years)
- Suggests Critical Decision Review (CDR) could occur in 2025, with CD-1 in 2026.
- If the real project dollars start flowing in 2026, then the first operations begin ~2032 (CD-4)

We see several major investments as valuable to reduce the risks for a Z-Next



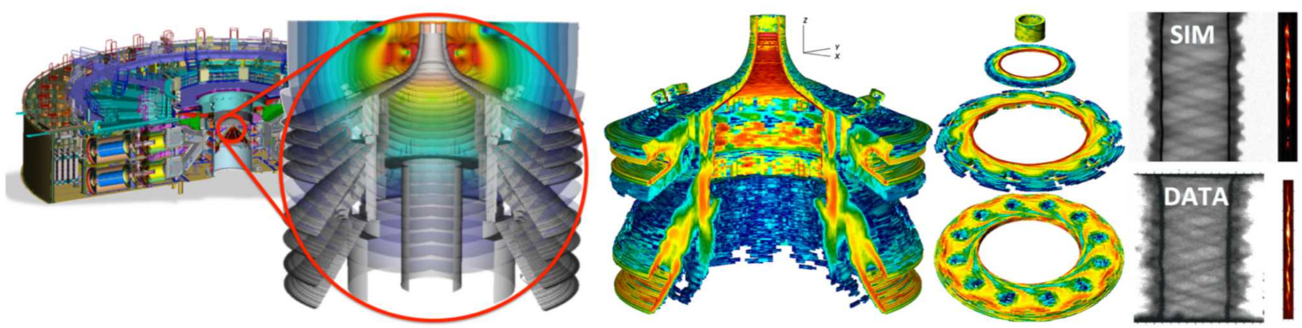
Build a Z-Next Module
Demonstrate technology & develop supply chain



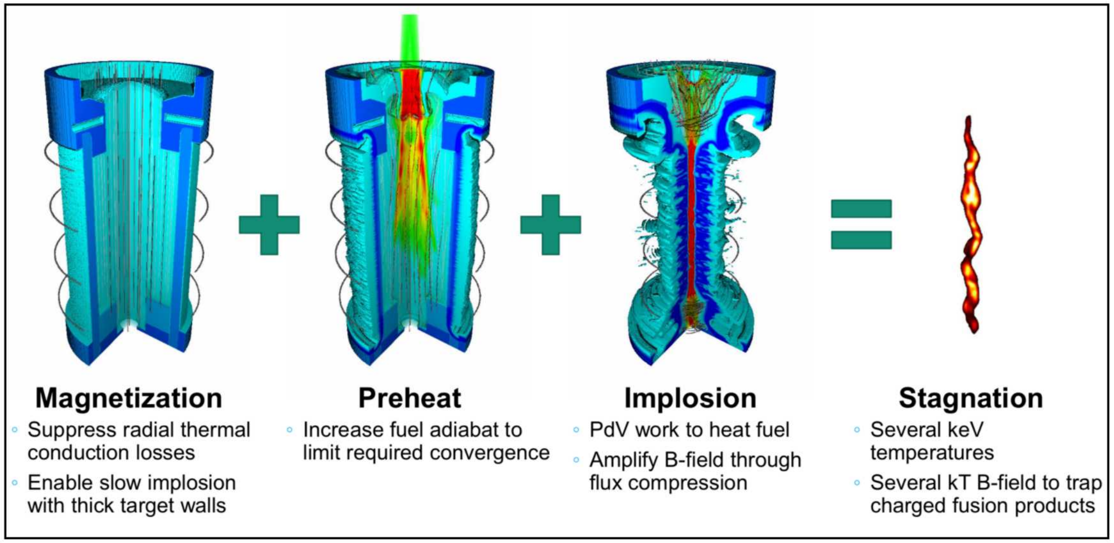


Advanced diagnostics and experiments
Timely evaluation of new magnetic drive targets and develop advanced diagnostics & new capabilities while supporting today's stockpile

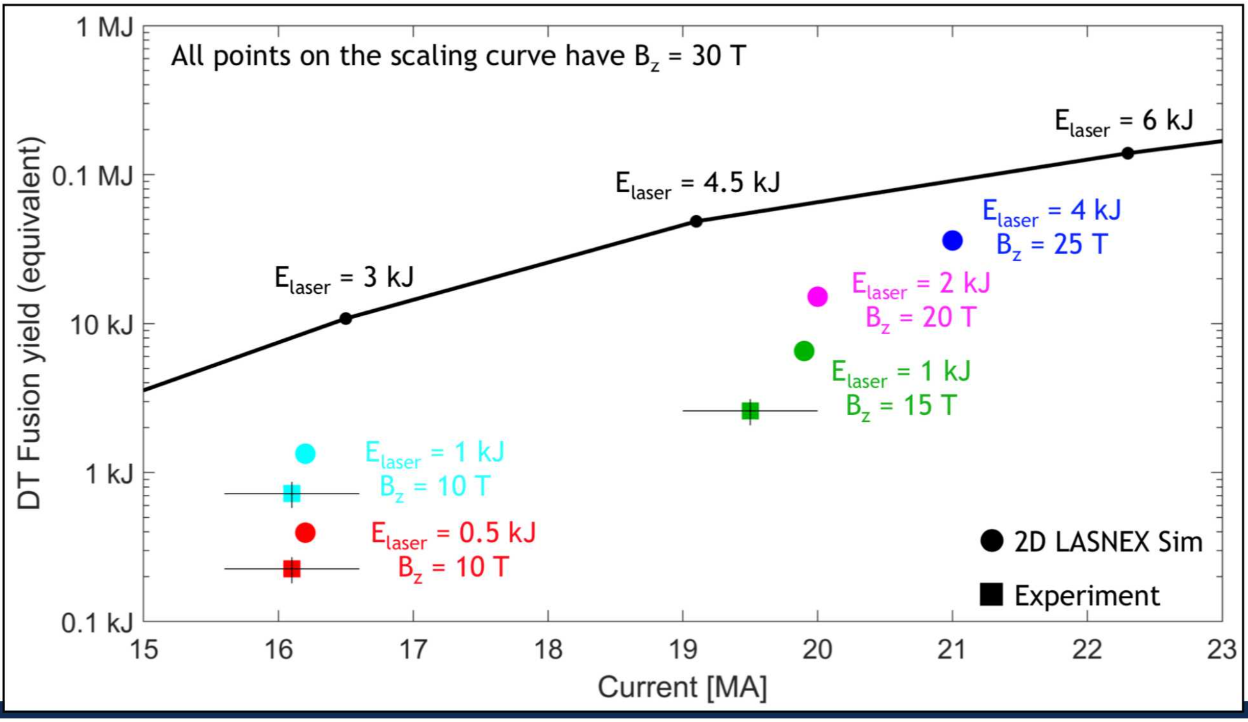
Develop next-generation plasma science & engineering code
Reduce risks & increase predictive capability tools for scaling to a Z-Next



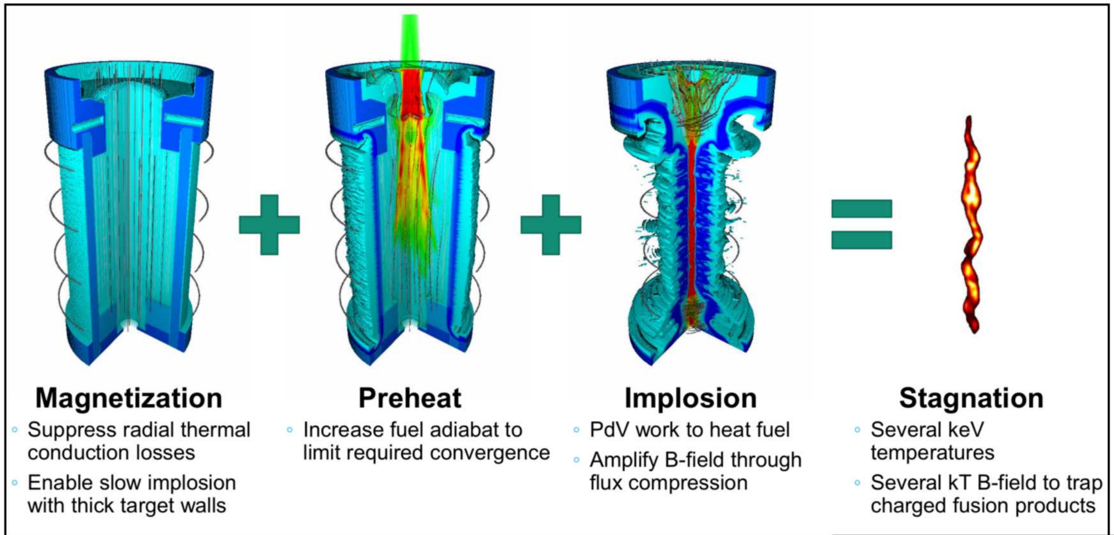
In collaboration with LLNL and LANL, Sandia scientists are continuing to push forward the extrapolation of ICF targets on Z over the next few years



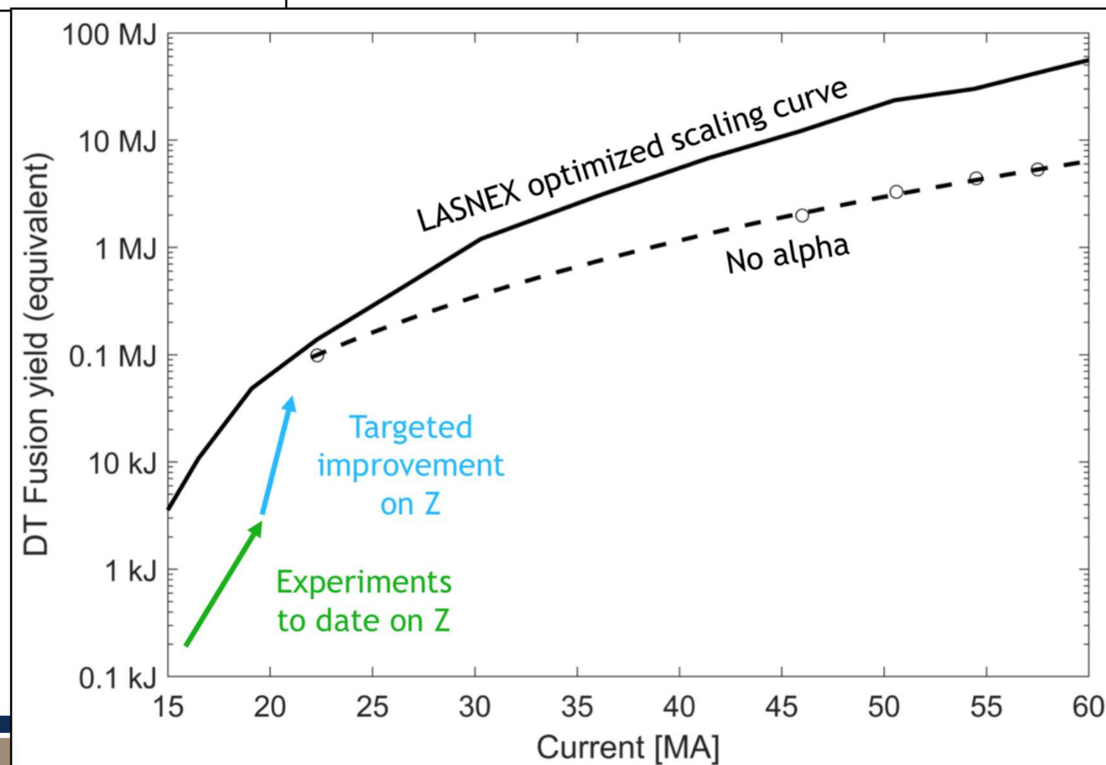
It should be possible to demonstrate >20 kJ yield from MagLIF targets in 2021



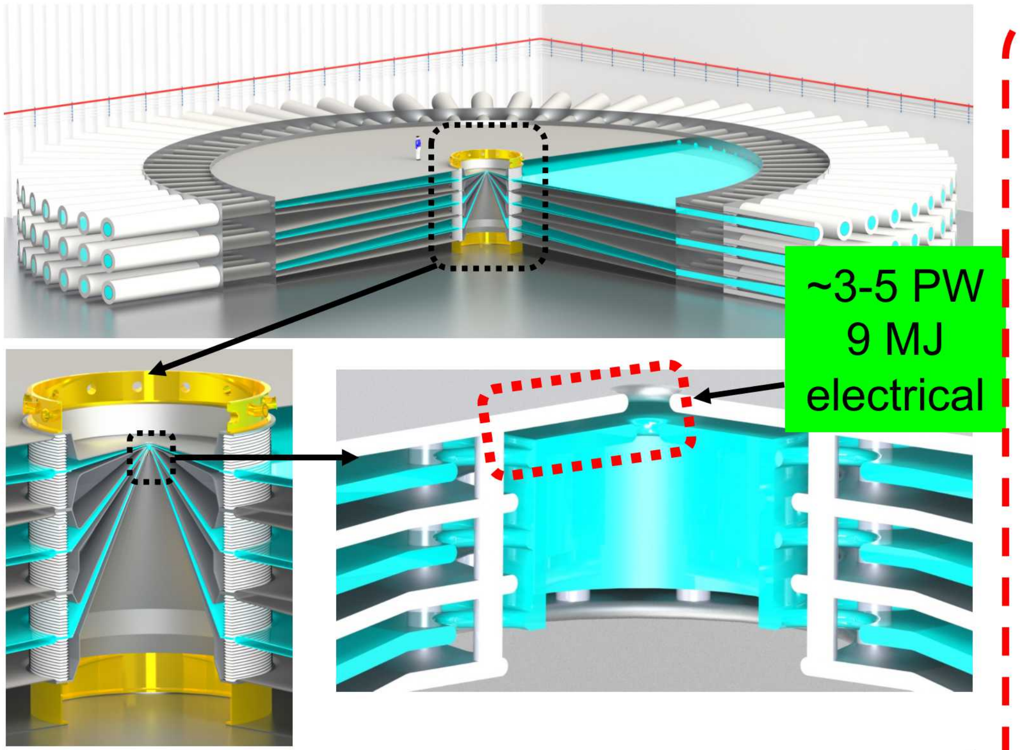
In collaboration with LLNL and LANL, Sandia scientists are continuing to push forward the extrapolation of ICF targets on Z over the next few years



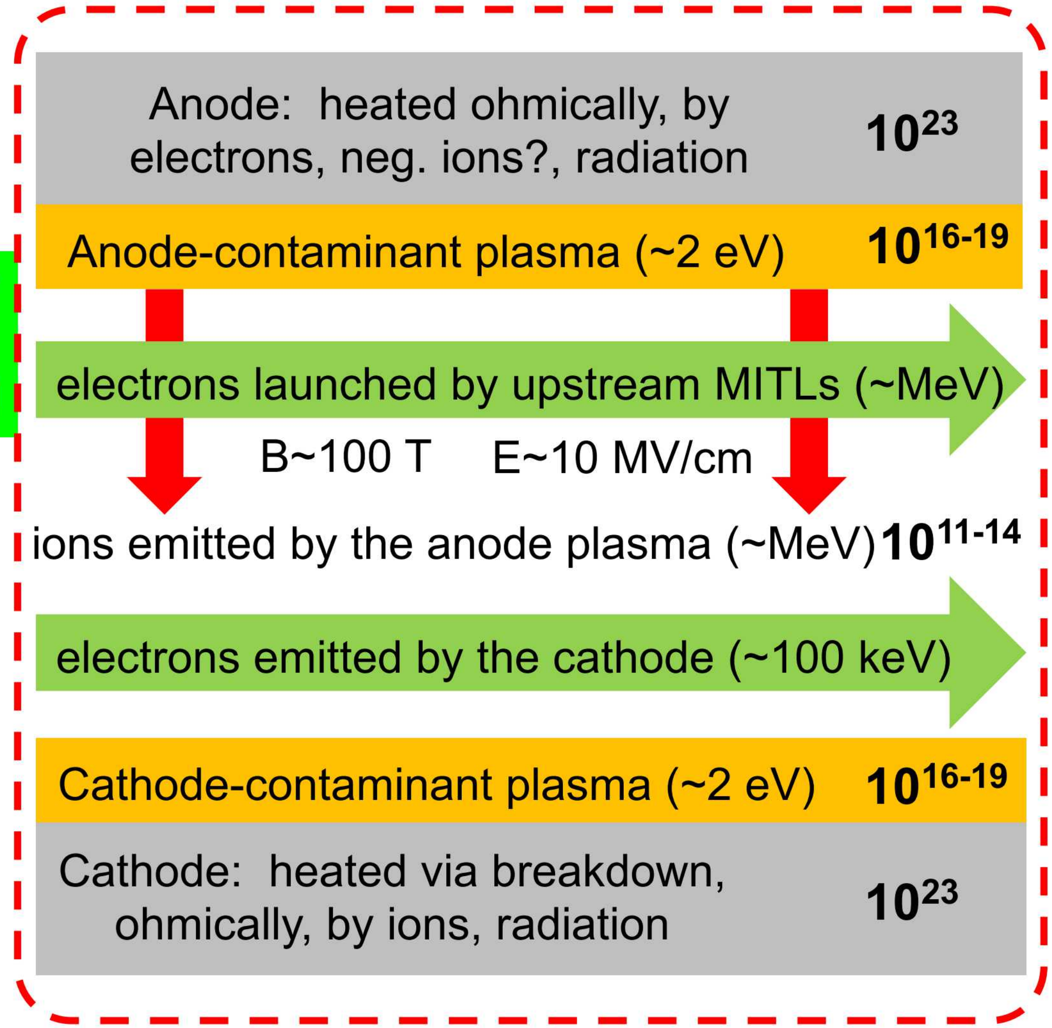
Targeted improvements in performance on Z extrapolate to 10s of MJ yields at high current (volume ignition) and possibly 100s (ice burning)



We are investing in driver-target coupling physics, which is an uncertainty in going to larger machines capable of ignition



section of a “vacuum” transmission line



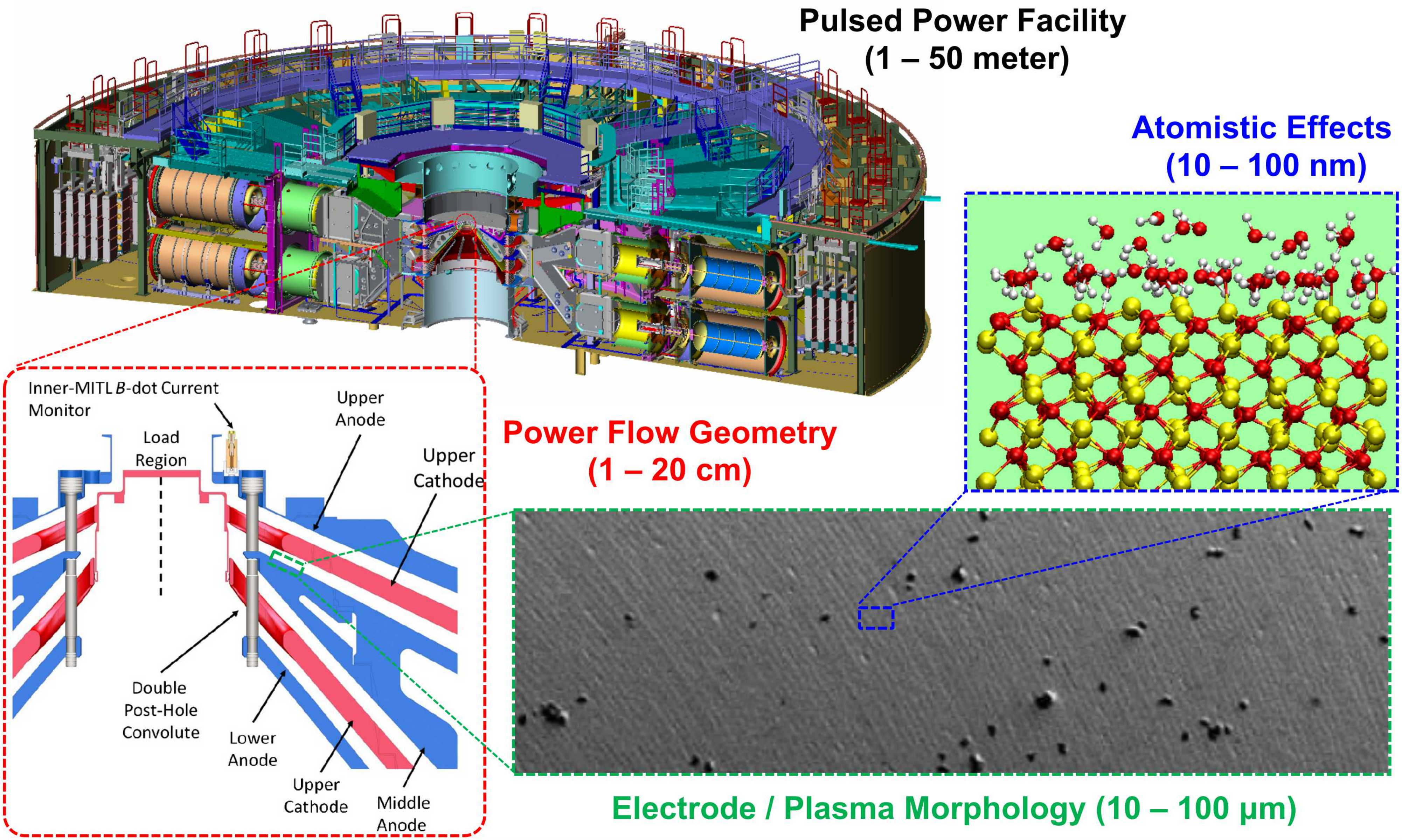
<u>Example driver uncertainties</u>

Electrode plasma formation/expansion

Current loss

Multi-scale and non-neutral plasmas crossing PIC and Continuum regimes

The PLASMA Grand Challenge LDRD is developing new code capabilities and exploring new physics models at multiple scales



Sandia is also making experimental investments in plasma physics relevant to power flow in order to validate these computations

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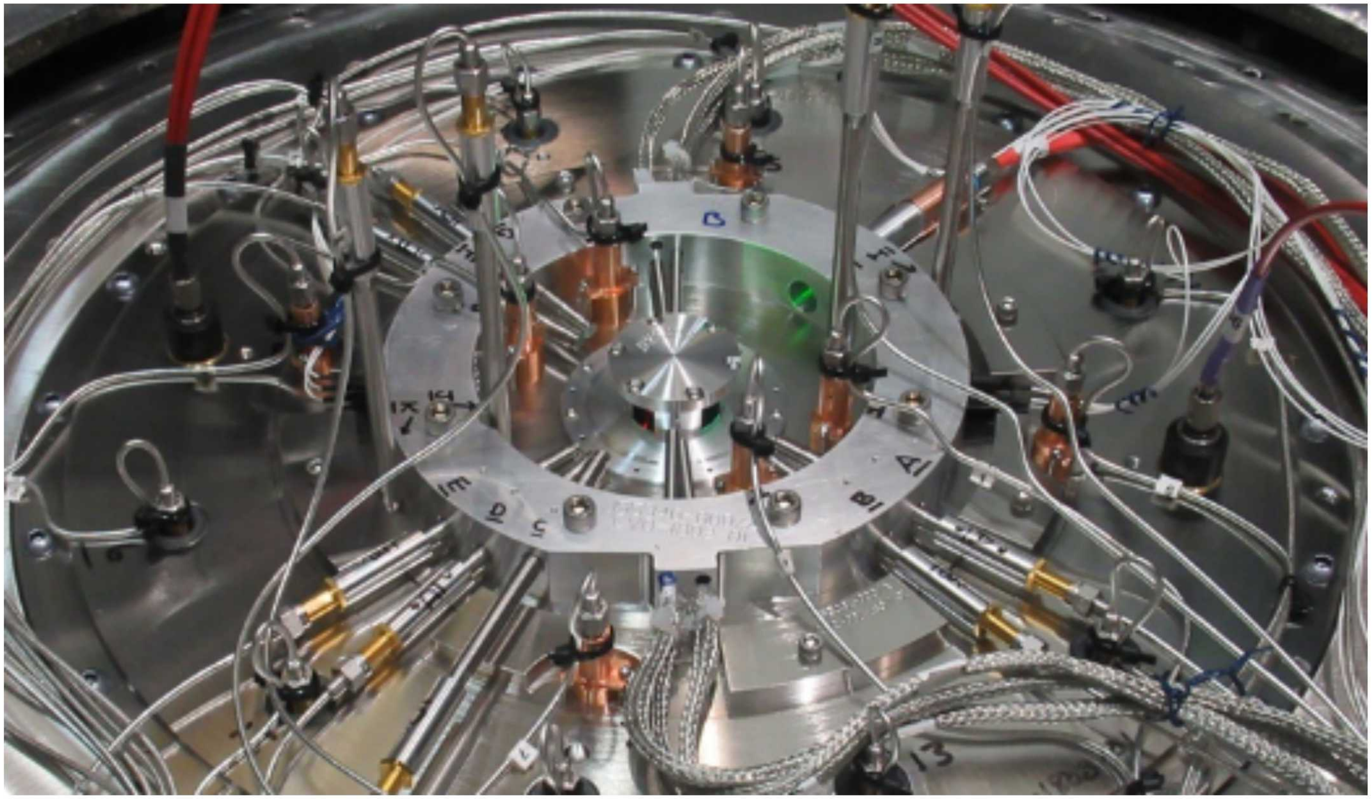
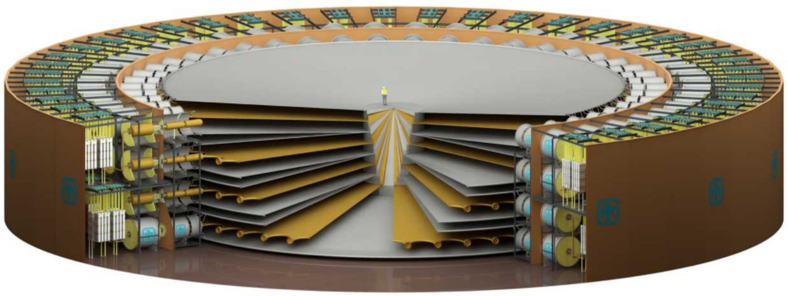
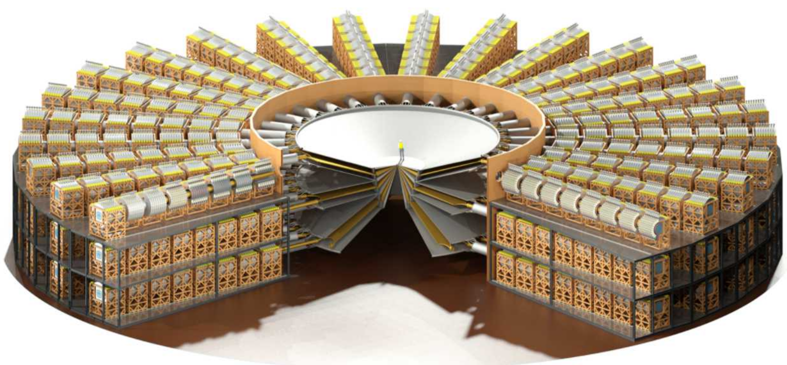
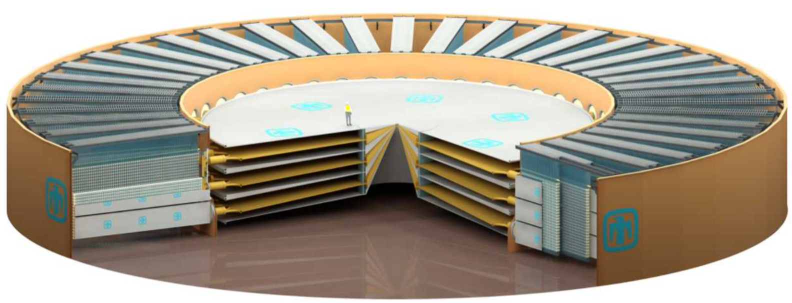


5-10 Z experiments/year devoted to power-flow measurements in 2018 and 2019;
>12 new diagnostics developed and fielded specifically for power flow physics;
Plan to continue developing platforms and advanced diagnostics going forward

Sandia is evaluating pulsed power driver architectures and technology alternatives for NGPPF designs







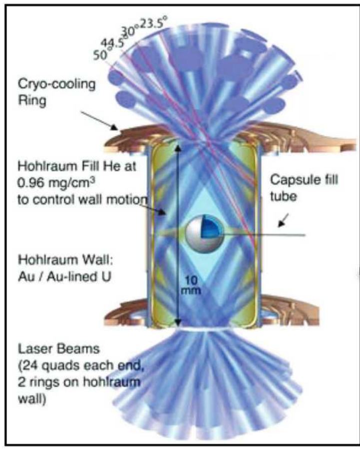
NGPPF is envisioned as a substantial increase in size and complexity relative to Z today

- About 3x larger diameter
- About 9x the energy coupled to targets
- If it must be capable of >10 MJ yields, it will require different ways of operating than Z today

Notional numbers for baseline targets are ~10 MJ coupled and ~60 MA peak current

We are trying to evaluate different pulsed power technology and architecture options for such a facility

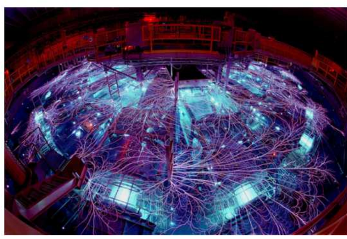
Increasing fusion yield in the laboratory to 10-30 MJ, and ultimately >500 MJ, would create a challenging environment!



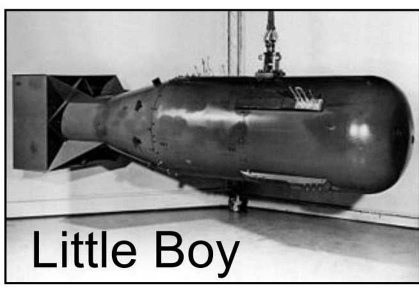
NIF capsule today


Firecracker


Dynamite


Z Stored Energy

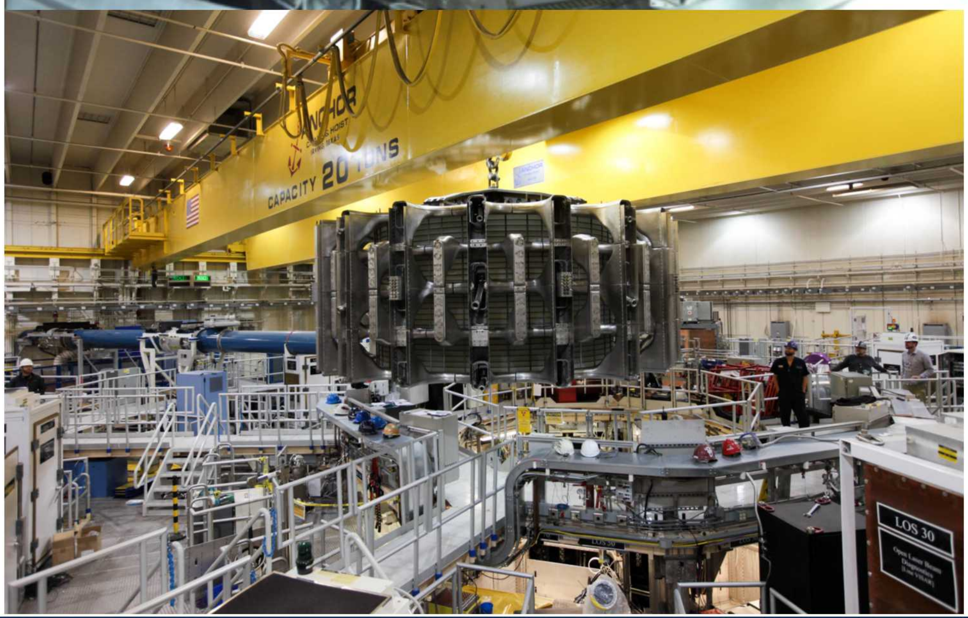
Energy in Barrel of Oil


Little Boy

- 30 J
- 20 kJ
- 2 MJ
- 20 MJ
- 1 GJ (0.24 tons)
- 6.1 GJ (1.5 tons)
- 63,000 GJ (15 kt)

1 GJ = 1,000,000,000 Joules = 0.24 tons TNT

In addition to target physics, driver technology, and driver-target coupling physics, Sandia is also thinking about operational challenges for Z-next



Other nations seek to have comparable or superior capabilities as our ICF/HED program provides, which would increase the risk of technological surprise

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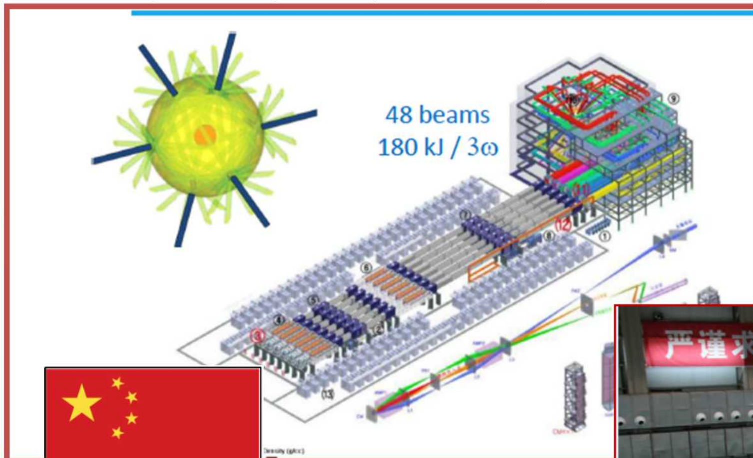
Shenguang III (180 kJ) Laser



UFL-2M Laser

Primary Test Stand (PTS)

Avoid technological surprise

China has a number of institutions applying pulsed power technology for either high energy density science research or defense applications

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- Chinese Academy of Engineering Physics
  - Mianyang (near Chengdu)
  - Note: 180 kJ SG-III laser here
- Northwest Institute of Nuclear Technology (Xi'an)
- Xi'an Jiaotong University (Xi'an)
- Institute of Applied Physics and Computational Mathematics (Beijing)
- Tsinghua University (Beijing)
- National University of Defense Technology of China (Changsha)
- Huazhong University of Science and Technology (Wuhan)
- Harbin Institute of Technology (Harbin)

China's pulsed power research efforts have dramatically increased over the last decade, and they now have the largest program in the world

- Chinese Academy of Engineering Physics
  - Mianyang (near Chengdu)
  - Note: 180 kJ SG-III laser here
- Northwest Institute of Nuclear Technology (Xi'an)
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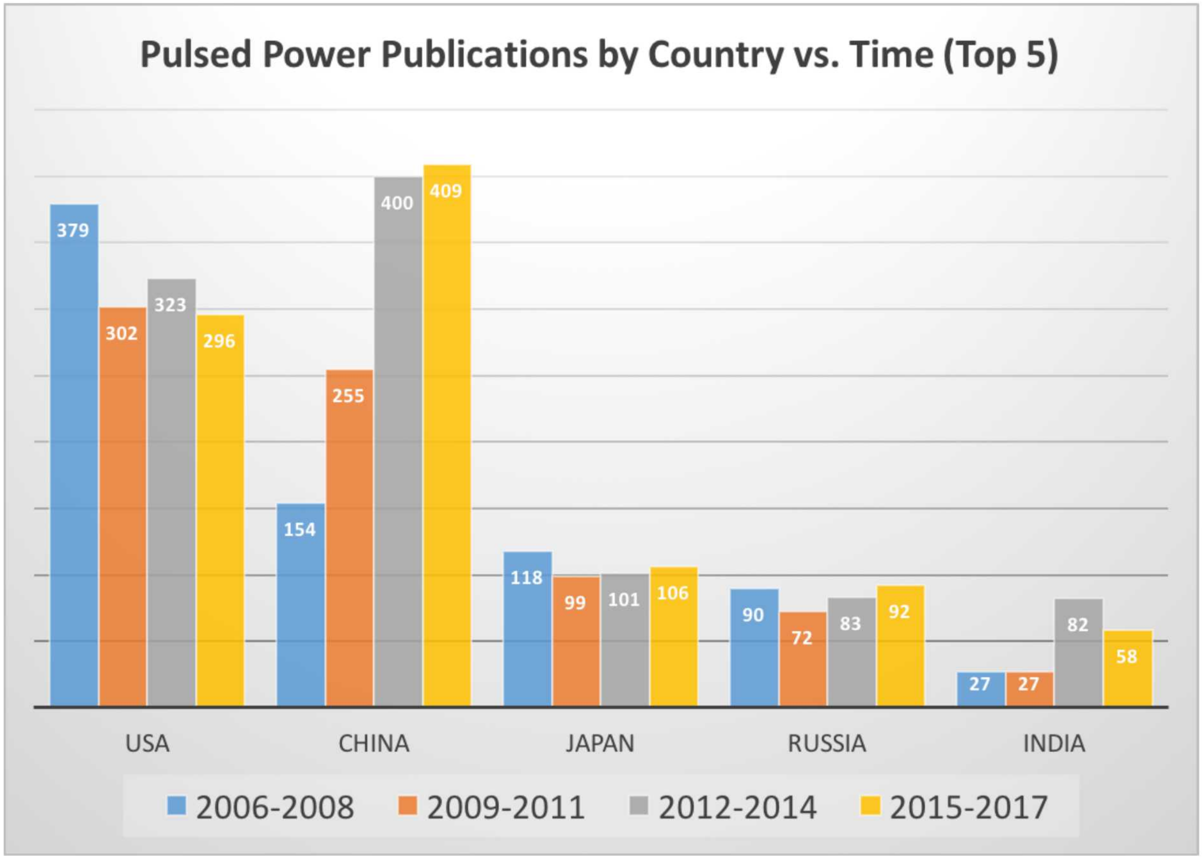
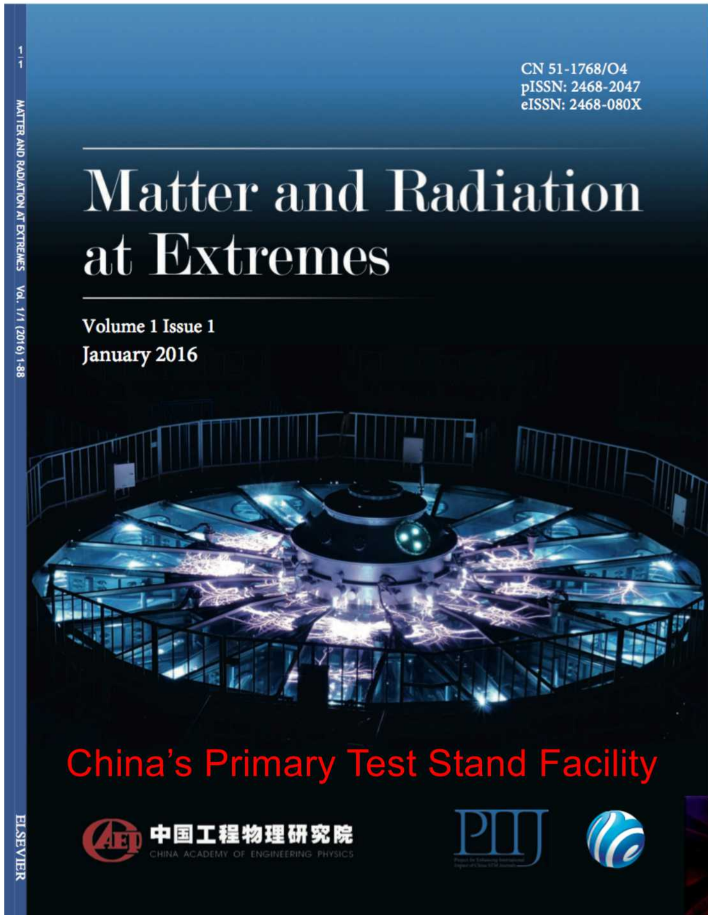


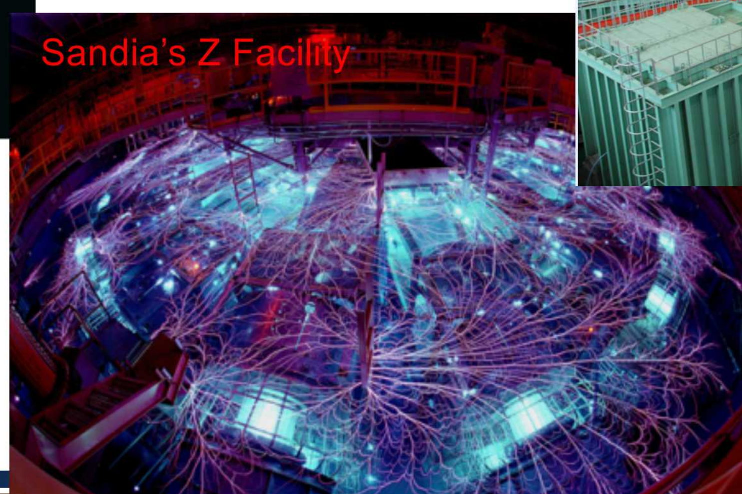
Based on Web of Science data, English-abstract journals only
Key search term: Pulsed Power

The CAEP has successfully built and operated the world’s second largest pulsed power facility and is positioning itself to be a world leader



Sandia Z facility:
26 MA, 110 ns rise time, 36 modules
Z conversion 1996, Z refurbished 2007

CAEP Primary Test Stand facility:
10 MA, 90 ns rise time, 24 modules
China’s first multi-module PP facility
Project started in 2002, 1st shot in 2013



China acknowledges Z as the premier pulsed power facility; it is now apparent that they have been staffing up and demonstrating to their government that they can emulate our HED research on Z

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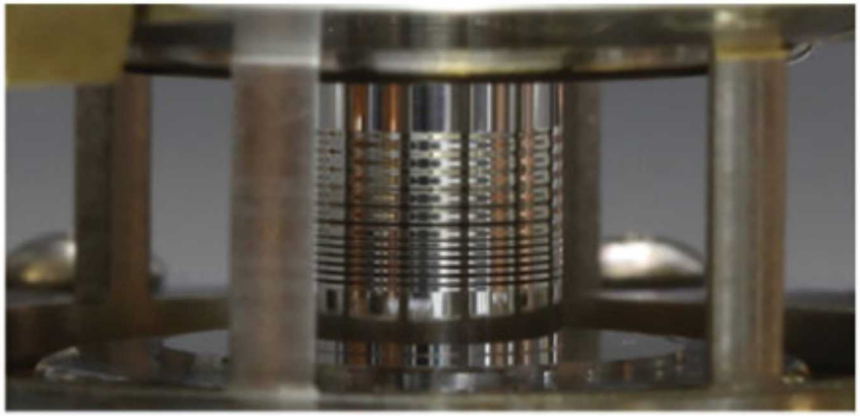
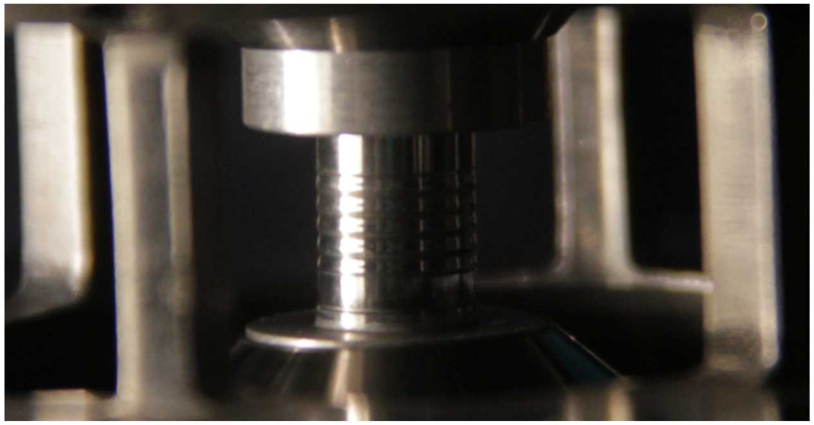
Liner target on Z



Copycat target on Julong-1



Z experiment diagnosed with
1.865 & 6.151 keV Spherical Crystal Imager
D.B. Sinars *et al.*, Rev. Sci. Instrum. (2004).

Diagnostic requires our Z-Beamlet laser:
1-2 kJ, 1-TW Nd:glass laser

Julong-1 experiment diagnosed with a copied
1.865 keV Spherical crystal imager
Q. Yang *et al.*, Rev. Sci. Instrum. (2016).

To do this, they built a near-copy of Z-Beamlet, a 1 kJ, 1-TW Nd:glass laser

China sees an opportunity to be the first to ignition and high yield

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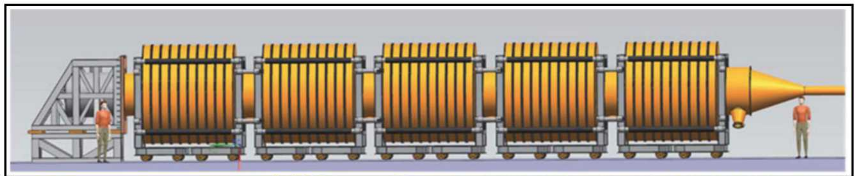
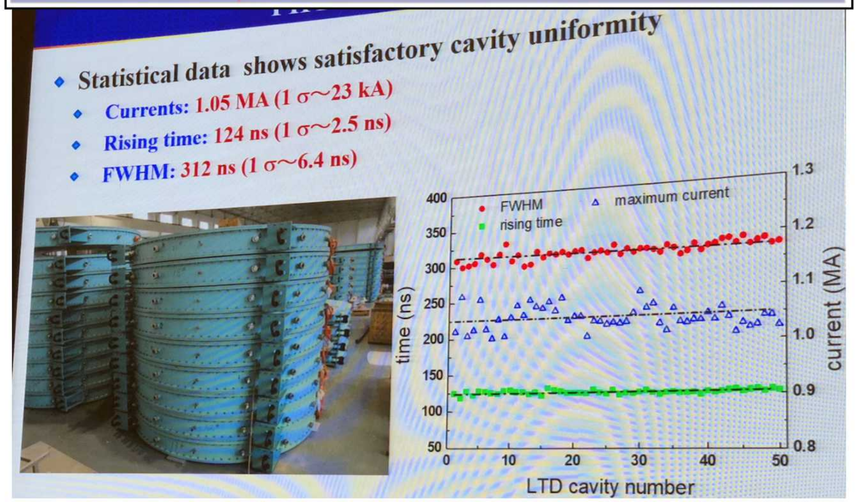
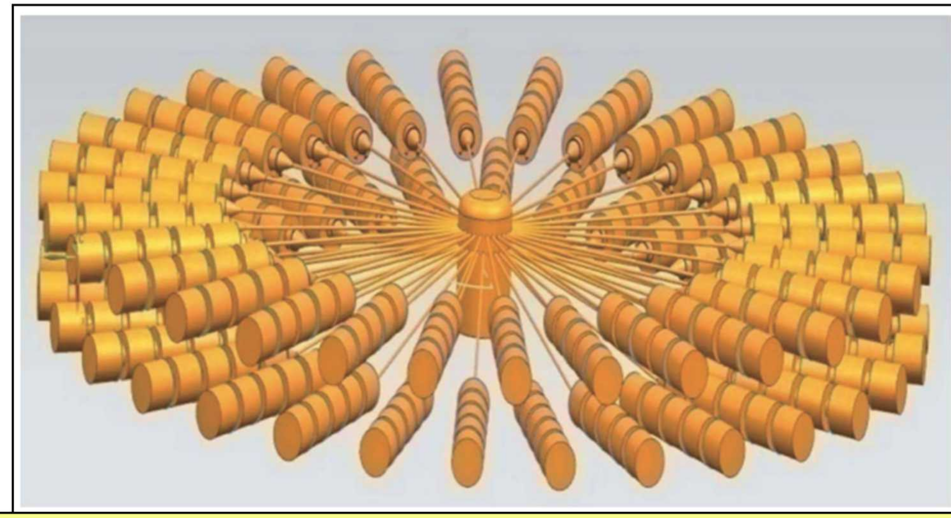
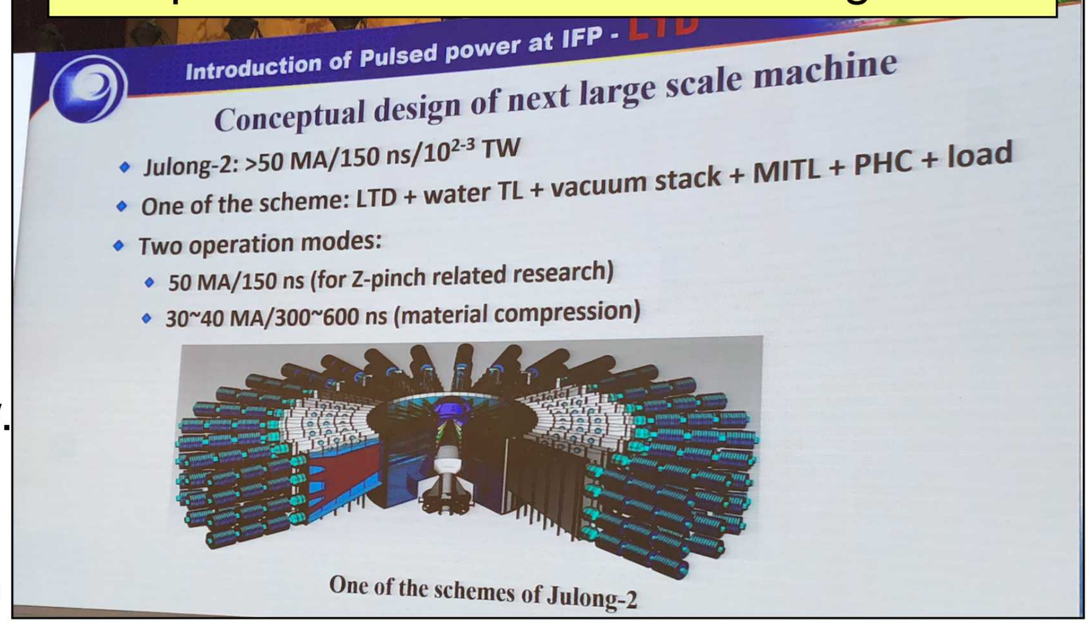
China will have a 50-cavity LTD module on the floor in 2019







China is openly exploring multiple pulsed power architectures for “Julong-2”



South China Morning Post article in December claimed they would build a >50 MA facility to challenge Z. They mocked US government for being slow.

Multiple sources appear to confirm China’s intent to build a >50 MA facility

Pulsed power in China is an interesting mix of high ambition, aggressive technology investment, and (to date) relatively basic science

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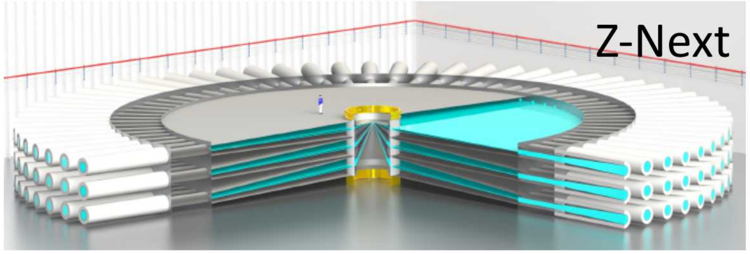
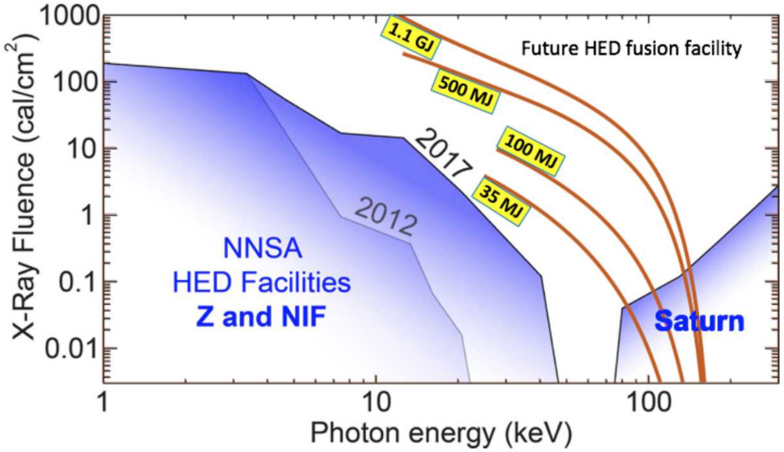
- Since the completion of the 8-10 MA Primary Test Stand at the China Academy of Engineering Physics in 2013, their ambitions have expanded
  - Clear goal of demonstrating that they can duplicate prior pulsed power accomplishments in the United States (Z, Saturn)
  - Aggressive development of advanced pulsed power technology and significant investments in building prototypes that goes beyond comparable US investment
  - Significant hiring boom
- To date, their scientific progress in HED research remains behind the US
  - Biggest gap is in advanced computational models and theory.
  - Diagnostics and facilities are much closer to US state of the art.
  - Have successfully reproduced key elements of fusion and dynamic materials research in US
- They appear willing to make major investments and accept relatively large risks for the chance of getting ahead of the US.
- It is credible that they could build larger pulsed power facilities than Z at Sandia. It is reasonable to think their scientific prowess will follow.

We are exploring the idea of a Z-Next as a multi-mission pulsed power facility to address scientific opportunities and threats to our nuclear stockpile



- **Opportunities: A Z-Next facility capable of ~30 MJ yield could address key physics gaps**
  - Provide combined neutron and x-ray hostile environments
  - Achieve higher-pressure capabilities for actinide dynamic material properties
  - Address critical nuclear weapon primary and secondary physics issues
- **Threats: New technology developments are driving a reassessment of threats; U.S. preeminence in pulsed power could be lost in coming years**
  - Changing threat landscape in nuclear survivability
  - Both China and Russia have active plans to build larger pulsed power (and laser) facilities than the U.S.
  - China has a larger pulsed power program than the U.S. and is catching up technically
  - Z has been an “engine of discovery”; do we want to risk technological surprise?



China’s 10 MA Primary Test Stand

We believe the impact of pulsed power for national security will continue to evolve! Questions?

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