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Sandia National Laboratories

Exceptional service in the national interest

From 25 years at Z onward to the Next Generation of Pulsed Power

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SAND2022-5048 C

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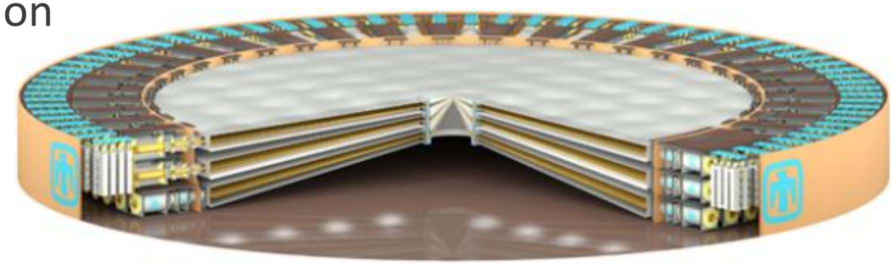
These are exciting times to be working with pulsed power!

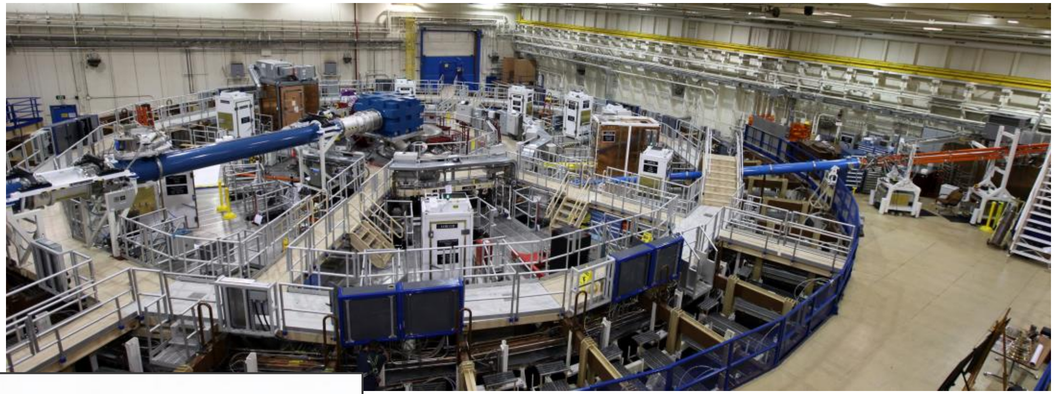
Sandia develops and applies pulsed-power technology to expand the frontiers of high energy density science, fusion, and extreme radiation environments with the primary goals to

- Provide essential data for the Nation’s nuclear stockpile
- Be an engine of discovery for national security

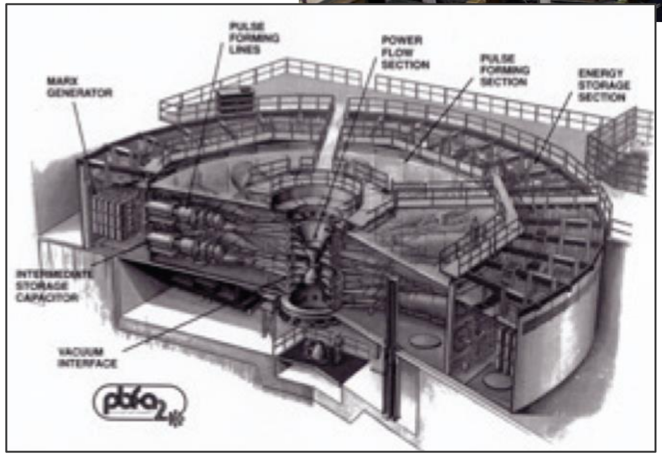
Today’s talk will give an overview of our journey from Z towards a Next Generation Pulsed Power (NGPP) machine

Next-Generation Pulsed Power (2030s)





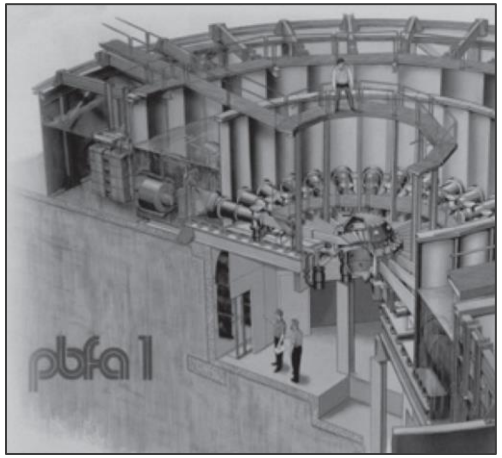
Z Machine Today

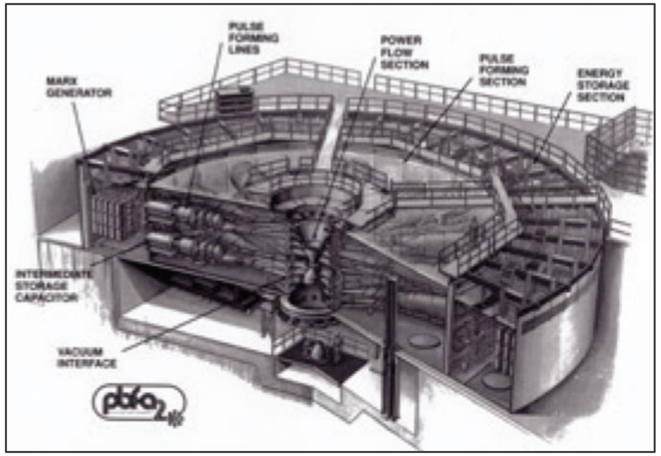


Particle Beam Fusion Accelerator 2 (1985)

Sandia is the home of three of the world’s biggest pulsed power machines built in the 1980s for survivability and fusion research

Particle Beam Fusion Accelerator 1 (1980): Built to study light ion beams for fusion target research

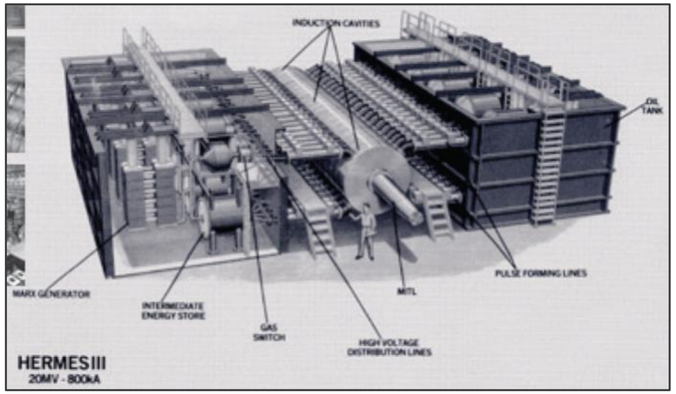




★ Focus of today’s talk

PBFA-2 (1985): Largest pulsed power machine in the world, converted to “Z machine” in 1996

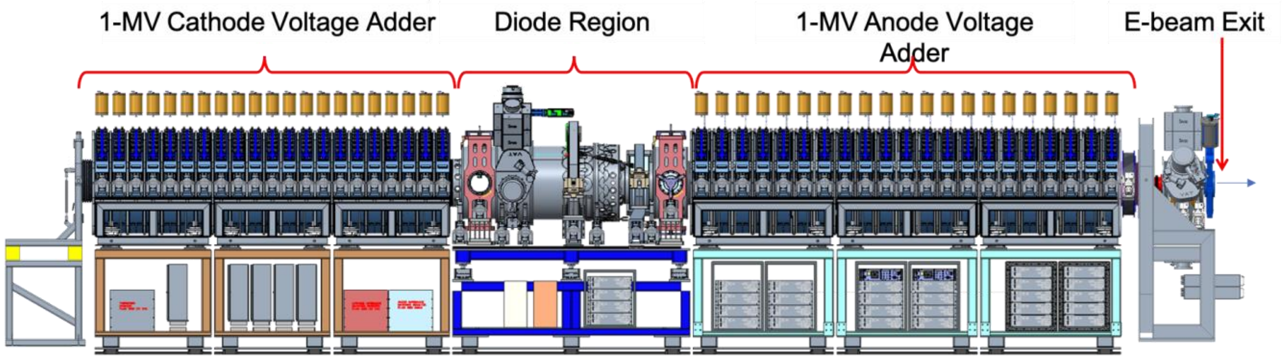
PBFA-1 converted into Saturn (1987): The world’s largest, large-area hot x-ray simulator

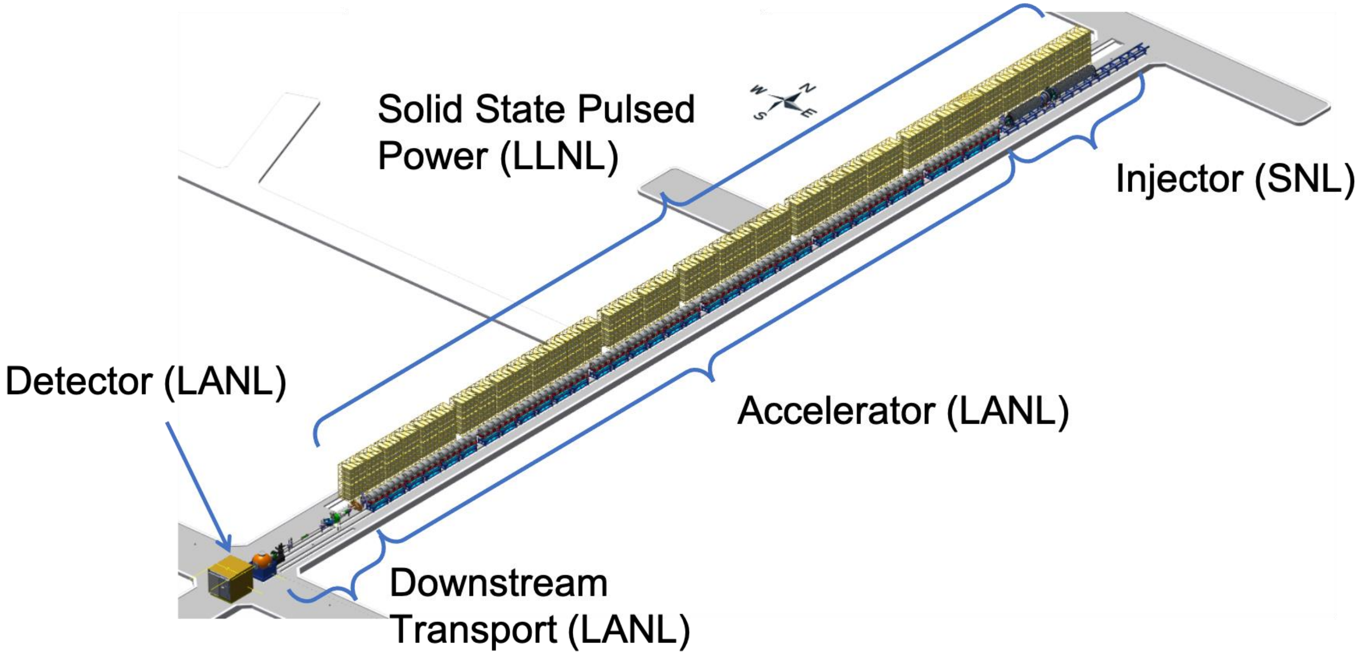


Hermes-III (1988): The world’s most powerful gamma-ray accelerator

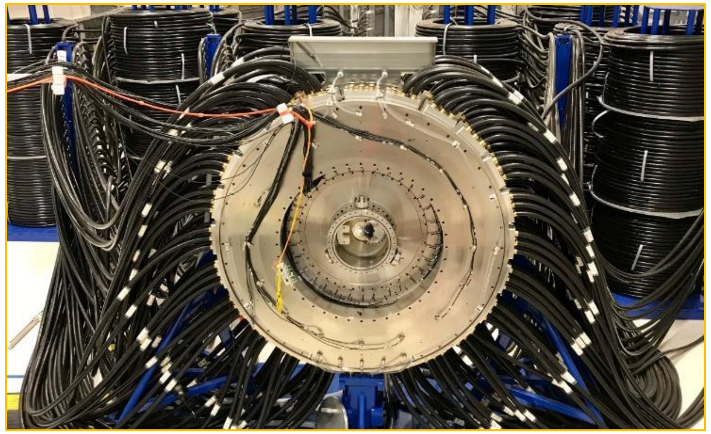
In addition to its three main facilities, Sandia has been engaged in many additional pulsed power projects

Scorpius injector work at Sandia





Thor cable pulser



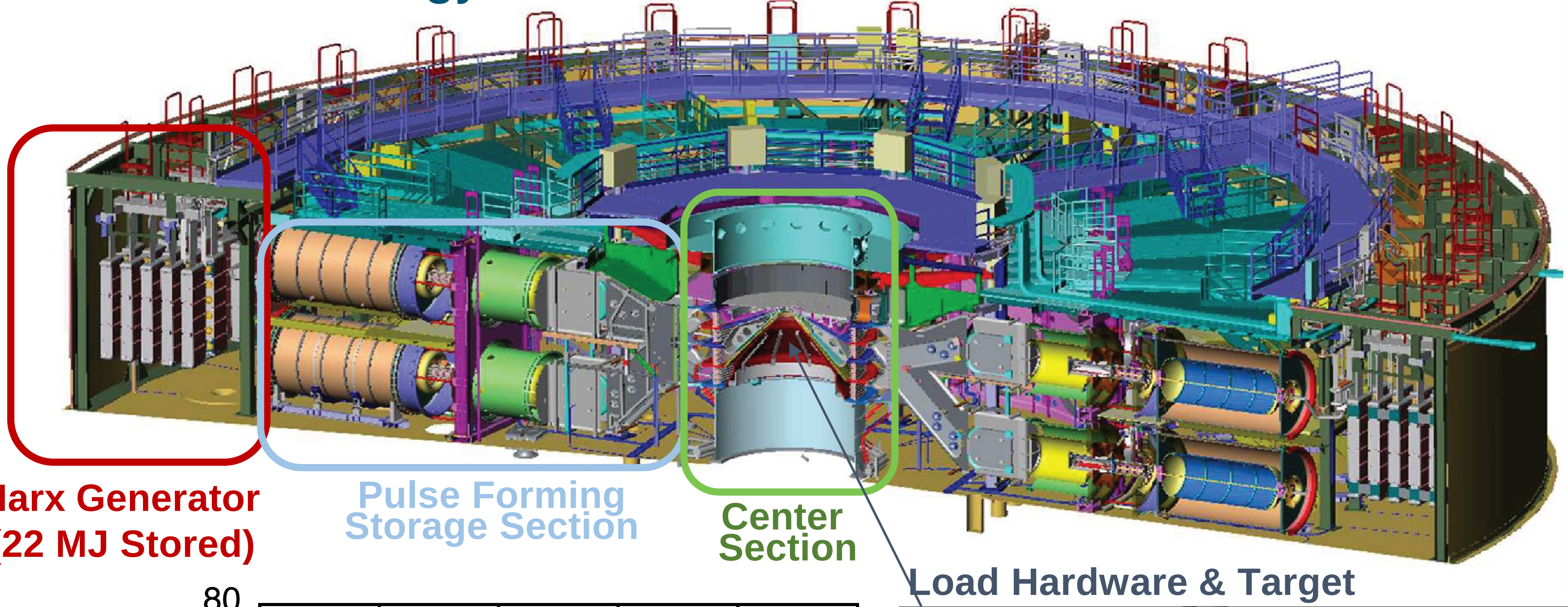
Linear Transformer Drivers (LTD)

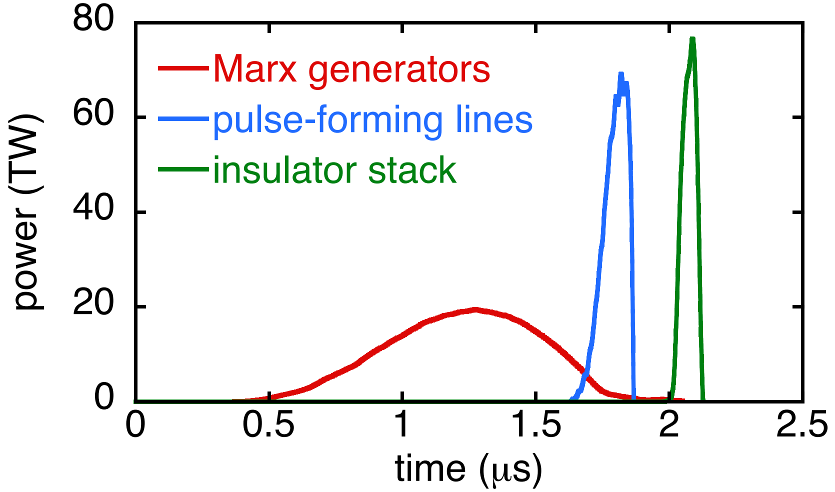
Mykonos (1st gen)

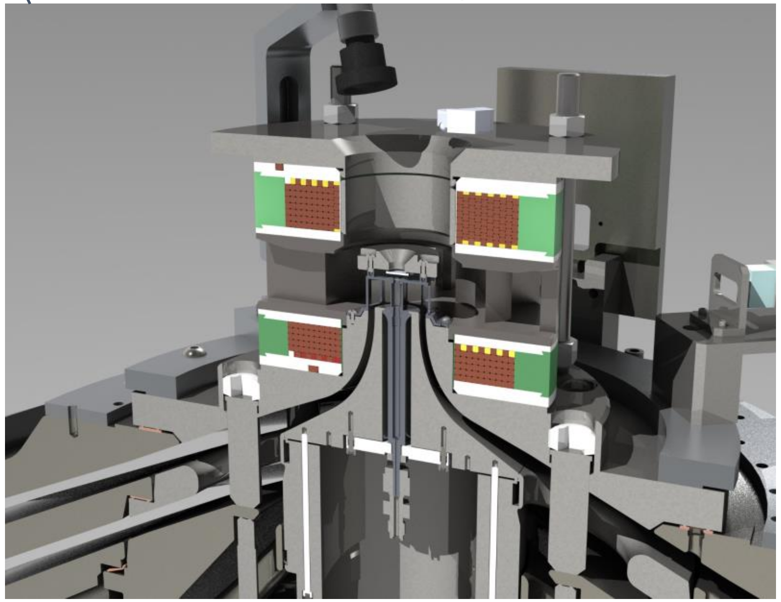
7th gen cavity

TA-IV at Sandia is a hub of pulsed power and related capabilities

Z, the world's largest pulsed power machine, delivers 80 TW and 6 MJ of electrical energy to its center section

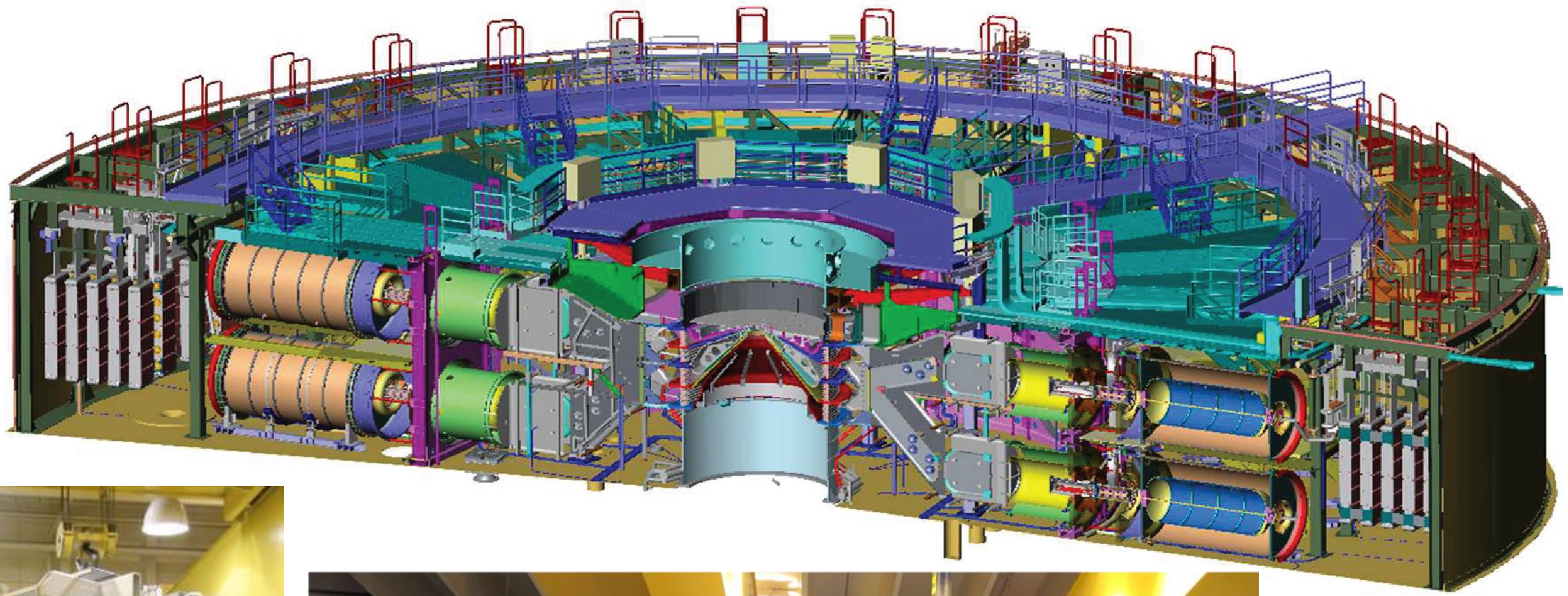




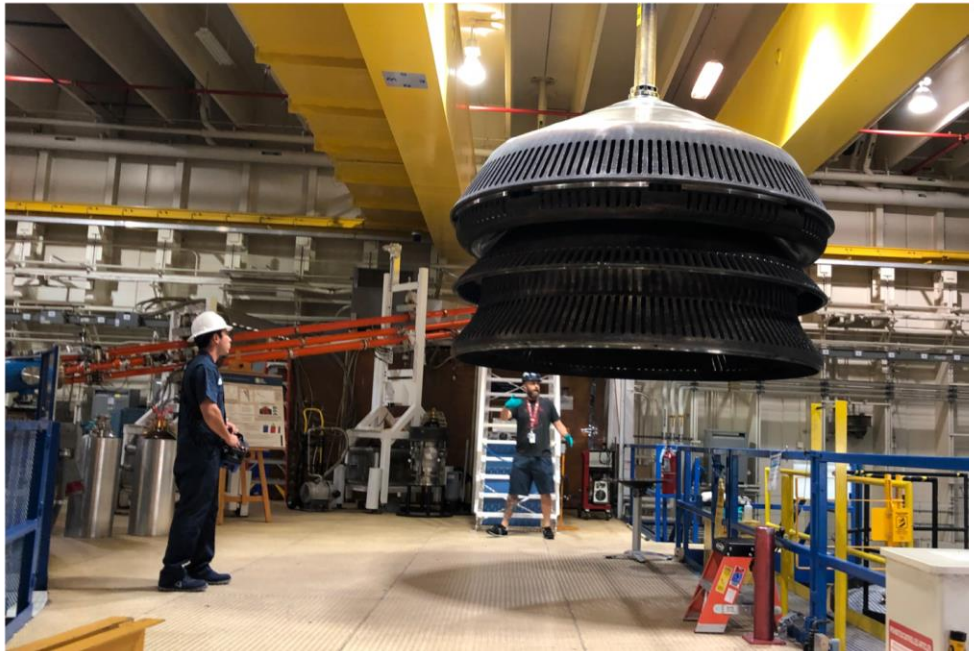


Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

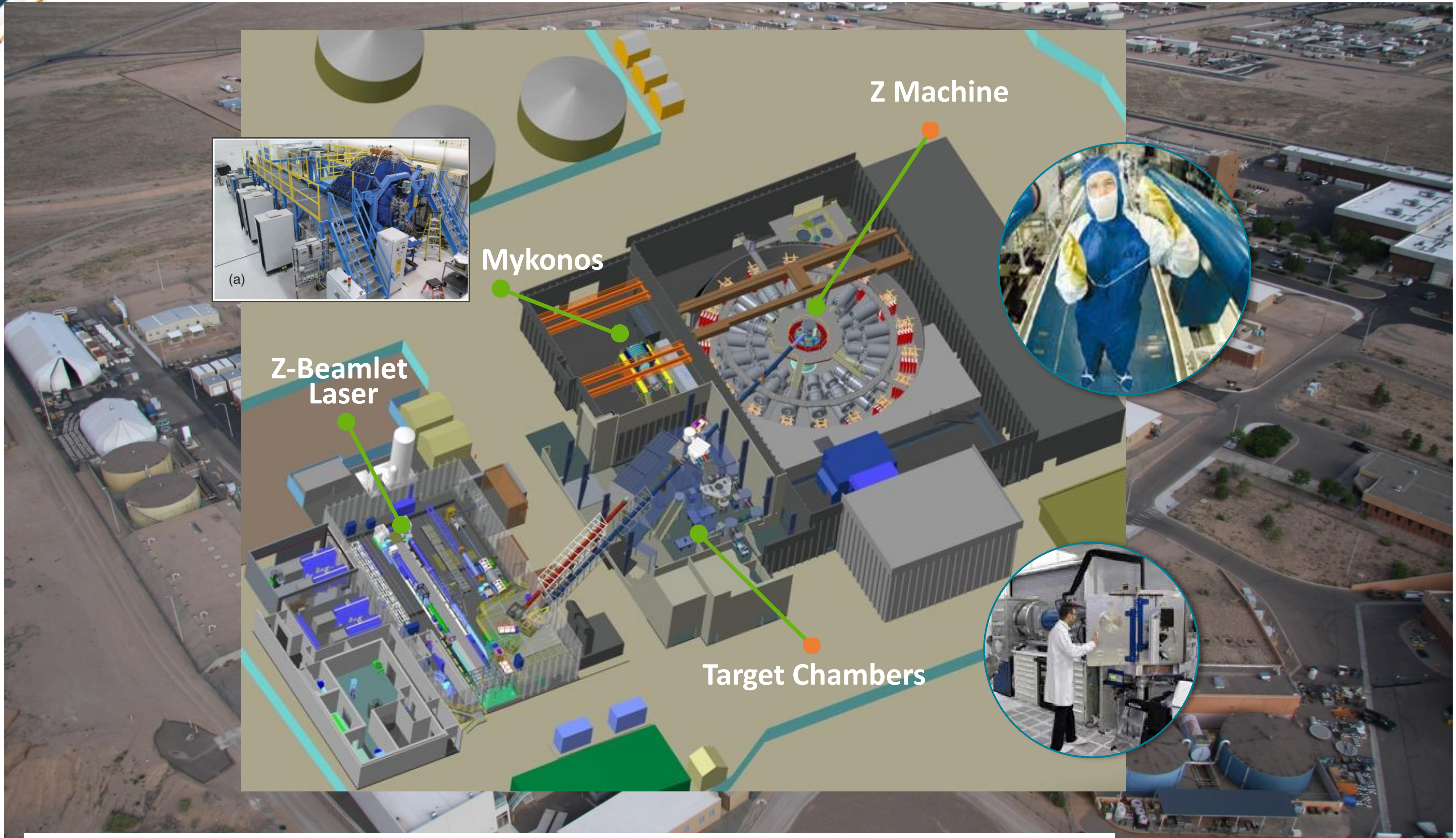
Z is "big science" and executes ~150 experiments per year



Post-shot



The Z facility includes the multi-kJ, 2-TW Z-Beamlet laser

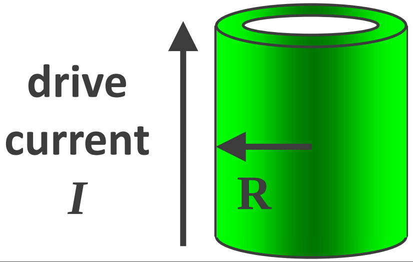


P.K. Rambo *et al.*, Applied Optics 44 (2005); P. Rambo *et al.*, Proc. SPIE 10014 (2016).

Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in fusion

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

100 GPa = 1 Mbar ≈ 10^6 atmospheres

Pressure equivalent to Energy Density (J/m³)

1 Mbar = 10^{11} J/m³, threshold of High Energy Density regime

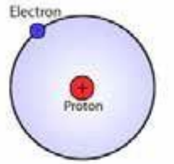
Z Storage capacitor

2e-6 Mbar

TNT

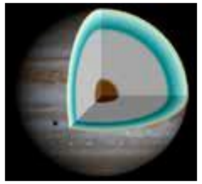
0.07 Mbar

Internal Energy of H atom



1 Mbar

Metallic H in Jupiter's core

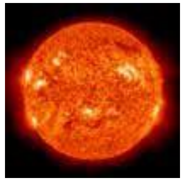


30 Mbar

Z Magnetic Drive Pressure

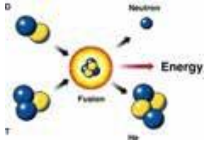
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



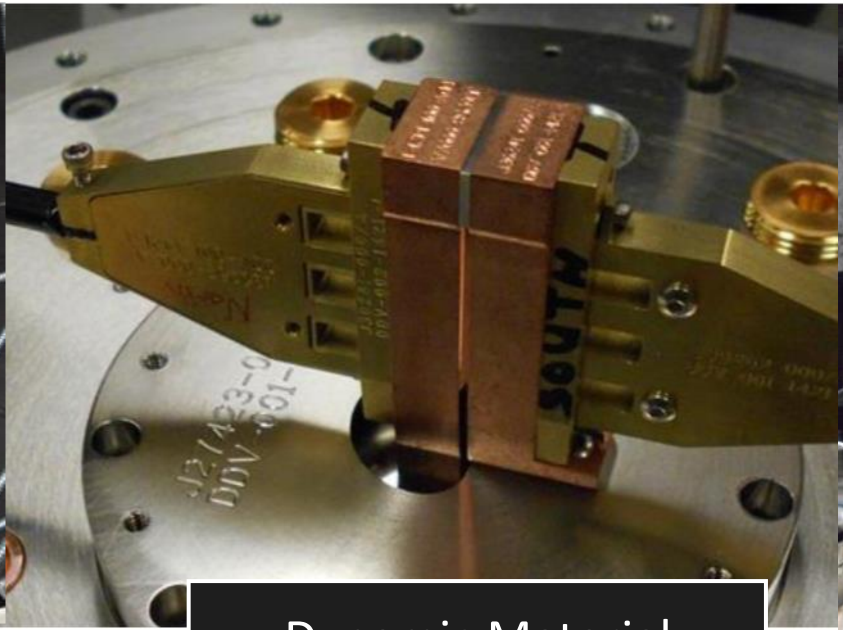
800,000 Mbar

Push on samples

Compress fuel at high velocity

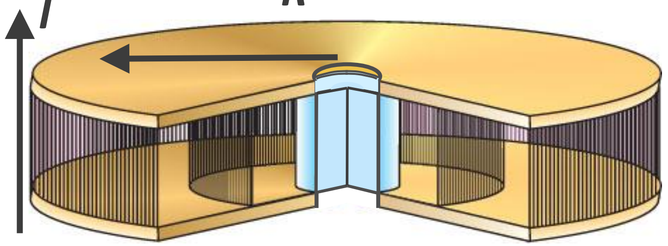
Z is a precision tool for high energy density science

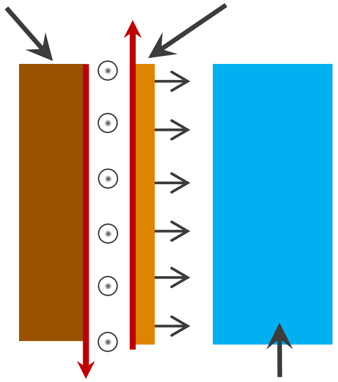
Radiation Science

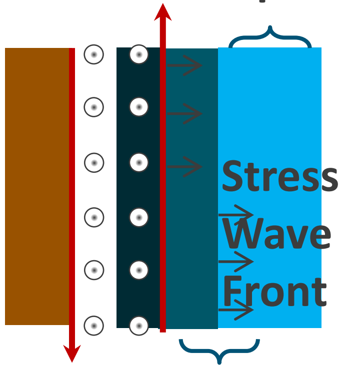


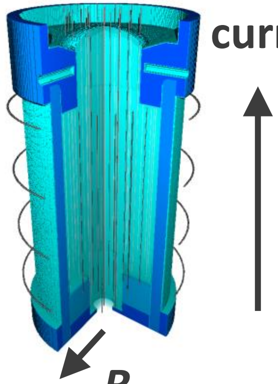
Dynamic Material Properties

Inertial Confinement Fusion

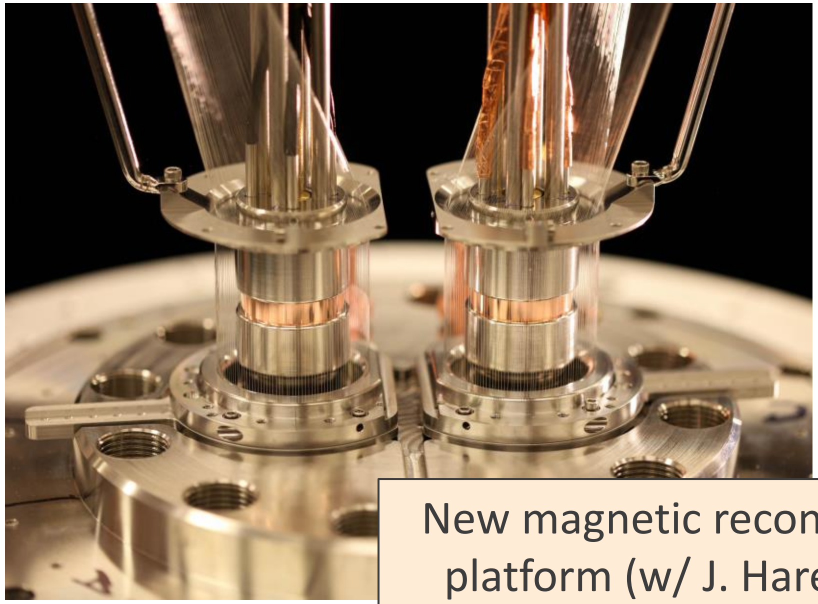




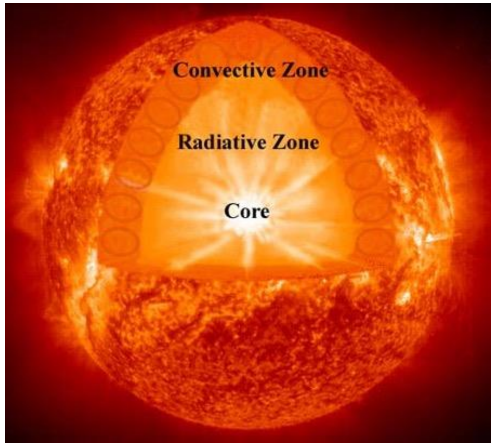


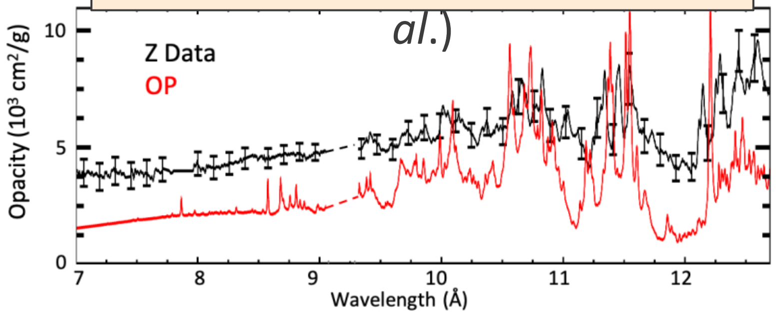


Examples from the last two years illustrate we are doing frontier radiation, materials, and fusion science on Z

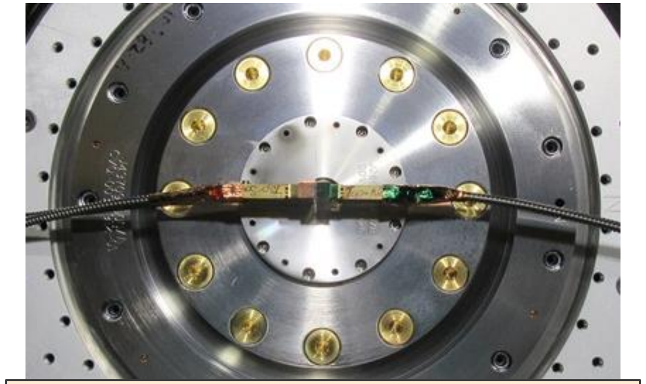


New magnetic reconnection platform (w/ J. Hare, MIT)

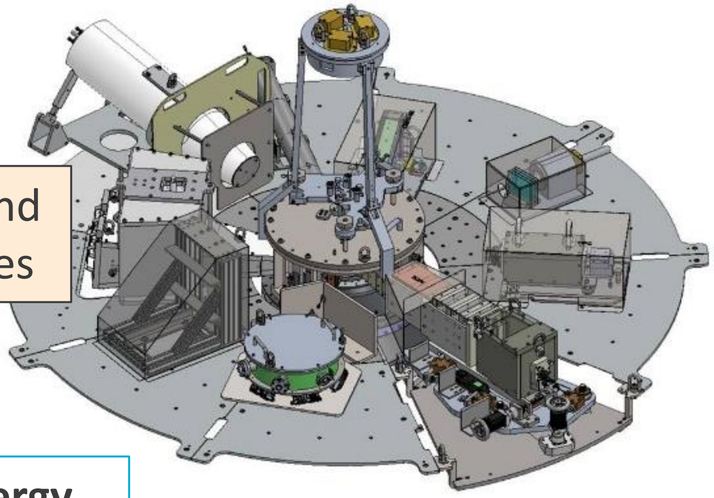




New time-resolved x-ray opacity science platforms (w/ LANL, UT-Austin, UNR *et al.*)



New tiny stripline platform reaches record ~8 Mbar in Pt



Advanced ICF diagnostics and cryogenic tritium capabilities

See "Review of pulsed-power-driven high energy density physics research on Z at Sandia," published July 2020 in Physics of Plasmas for other examples

We have a capability development road map for Z for the next decade that will enable more frontier HED science

Mission Priority	Objective
Thermo-nuclear Burn	Realize and apply magnetic-direct-drive fusion platforms for stockpile applications
Material Properties	Be a world leader in multi-Mbar material and opacity science for the stockpile
Survivability	Realize the world's brightest x-ray and fast neutron environments for weapon survivability
Pulsed-Power	Be the world leader in pulsed-power science and technologies for key national security applications.

2022
- *Plutonium Production Science*
- *Plasma Transport Requirements*
- *Vulcan Operational*
- *Engineering Materials Assessment*

2023
- *Assess 25 MA power-flow*
- *Z-NIF Opacity Comparison*
- *3D MIF Modeling*

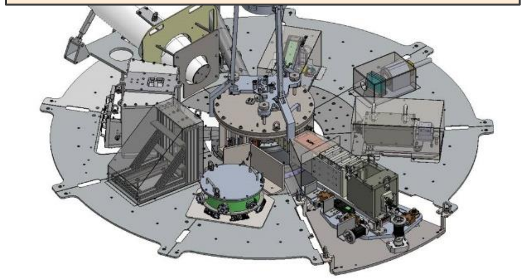
2024
- *High-pressure SNM (tiny stripline)*
- *Advanced Insulator Technology*
- *Multi-physics xMHD models*
- *Warm x-ray scaling*

2025
- *Fusion-Fission on Z*
- *Refined High-Yield Requirements*
- *Assess 60 MA power-flow*

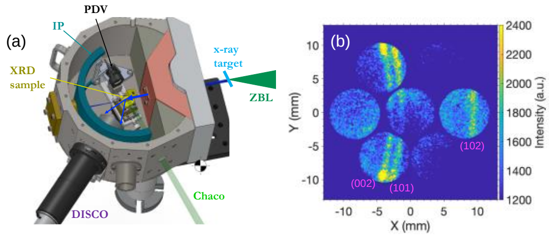
2026
- *Pre-heated SNM*
- *Fast-neutron Effects*
- *Fluid-kinetic MDD target models*
- *NGPP Module*

2027-30
- *Outputs opacity*
- *Innovative MDD assessment*
- *Enhanced Integrated Testing*
- *SNM Diffraction*
- *NGPP Tech Mat*

Advanced fusion platforms & diagnostics



X-ray diffraction, pre-heating, etc.



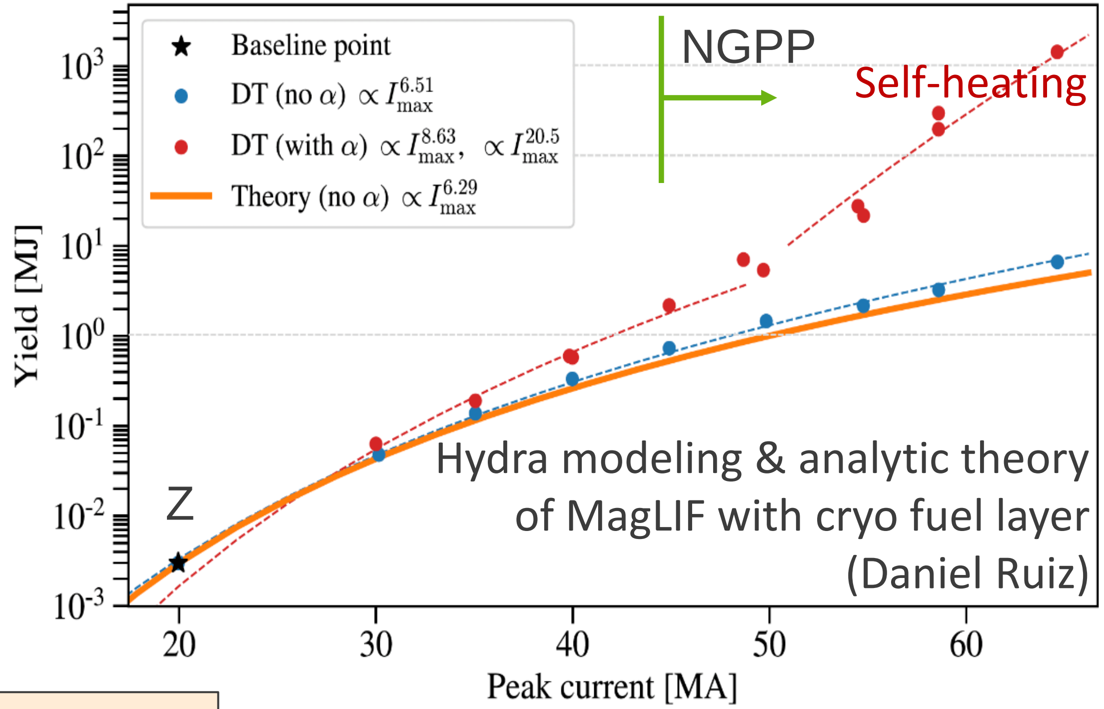
Advanced radiation science platforms

Building on the success of Z, we are working on the path to high-yield on future facilities with magnetic direct drive fusion targets*

The U.S. Magnetic Direct Drive effort has enhanced its focus on paths to high yield (>200 MJ)

- Prioritized platforms with high yield path
- Focused data science and diagnostic developments on high-yield platforms
- Continue to innovate!

MagLIF can reach 100 MJ yields at reasonable facility scales

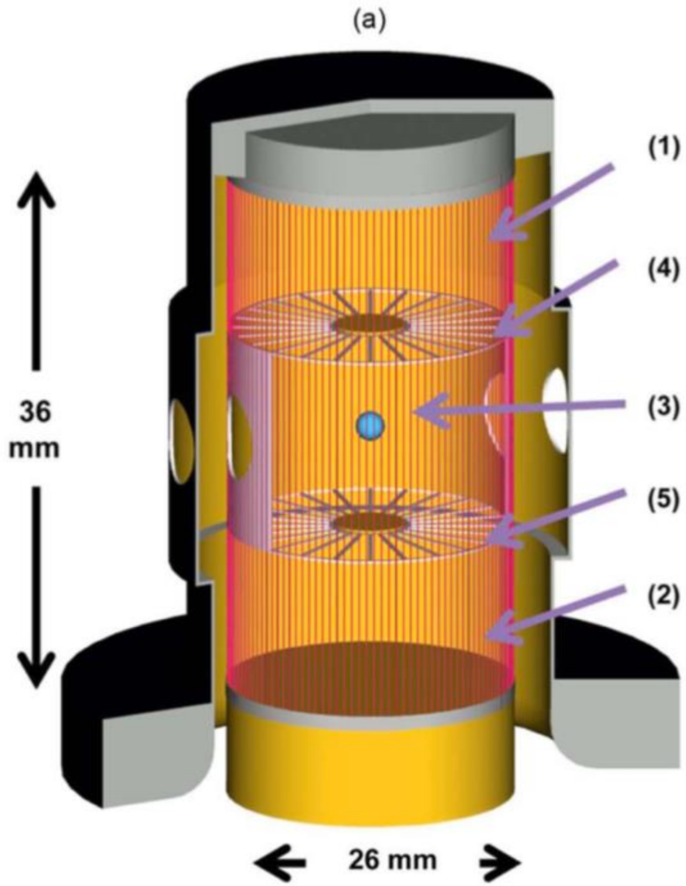


"*A conservative approach to scaling magneto-inertial fusion concepts to larger pulsed-power drivers*," P.F. Schmit and D.E. Ruiz, Phys. Plasmas (2020).
"*An overview of magneto-inertial fusion on the Z machine at Sandia National Laboratories*," D.A. Yager-Elorriaga *et al*., Nuclear Fusion (2022).
"*Dense hydrogen layers for high performance MagLIF*," S.A. Slutz, T.J. Awe, and J.A. Crabtree, Phys. Plasmas (2022).

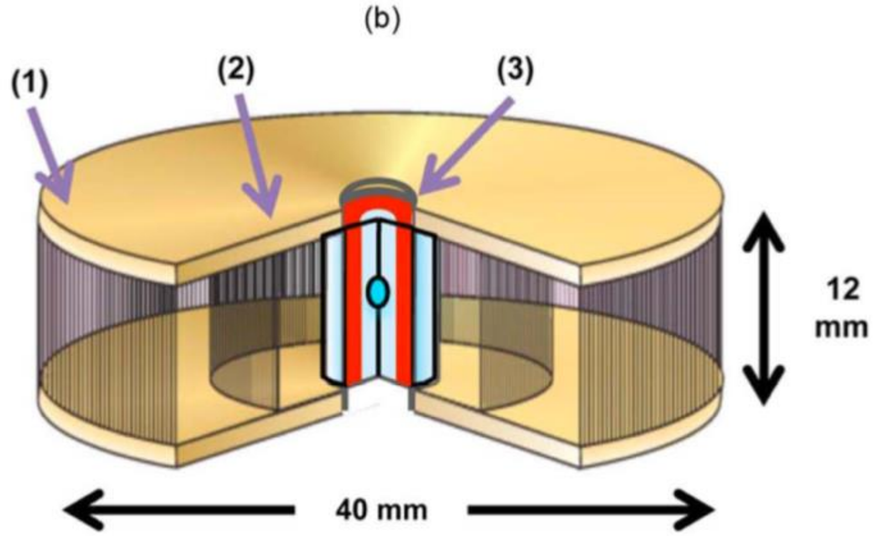
See MO 4.3-1 talk by D. Ruiz for scaling

More details on MagLIF
PO 4.01 Gomez
PO 4.03 Lewis

Magnetic indirect drive (radiation-driven) fusion also remains an option for a future high-current facility to build on the success of NIF

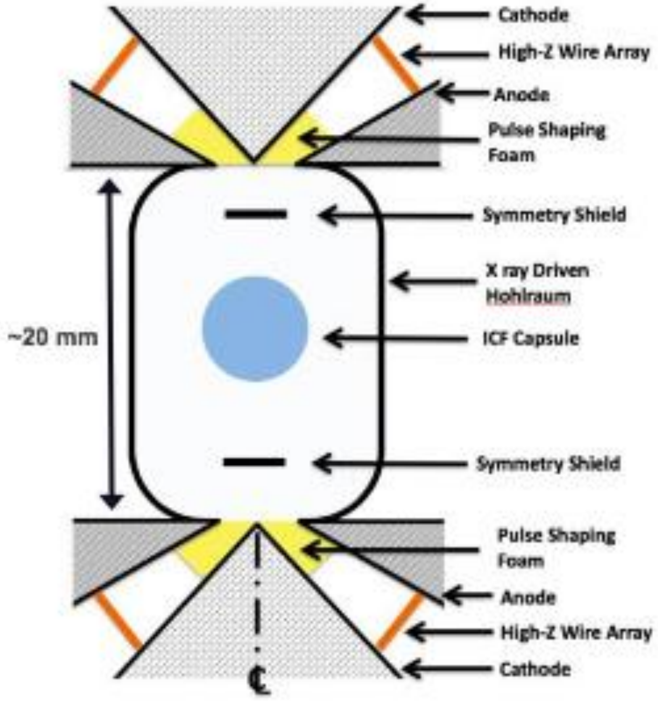


Double-ended Hohlraum



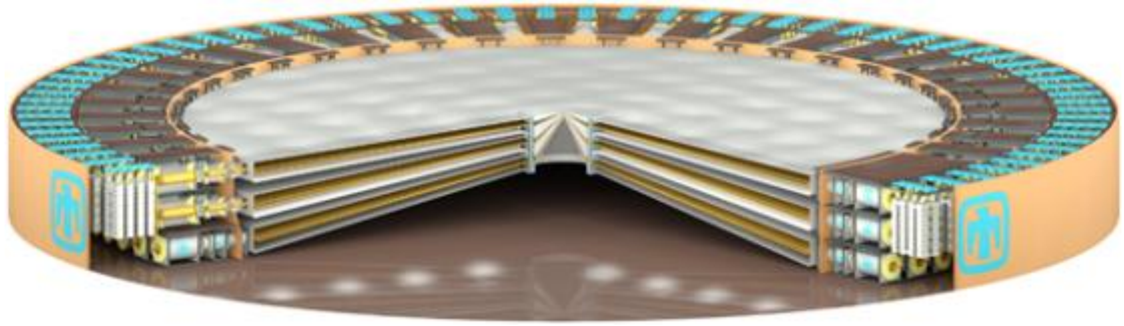
Z-pinch Dynamic Hohlraum

M.E. Cuneo *et al.*, IEEE Trans. Plasma Sci. (2012).



R.E. Olson *et al.*,
High Energy Density Physics (2020).

The NNSA is presently refining the requirements for a Next Generation Pulsed Power (NGPP) machine



Mission need and requirements finalized in 2022

Main project funding beginning in ~2025

Project completion in the 2030s

<u>NGPP will:</u>

Be the world's most powerful warm x-ray source

Support fusion yields up to ~100 MJ

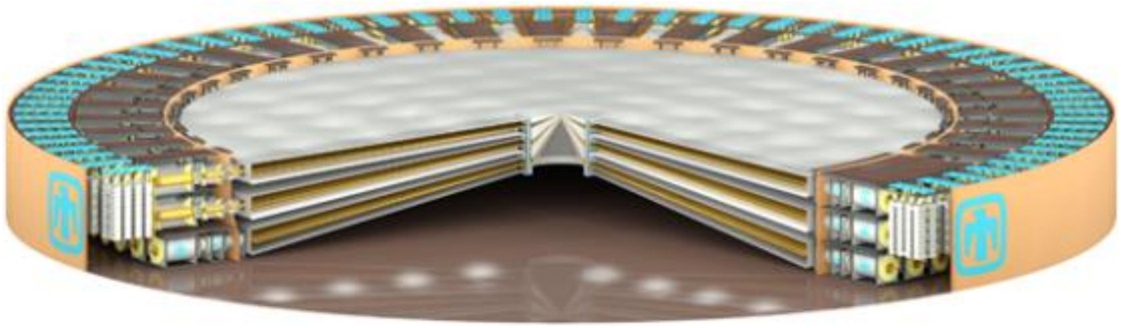
Provide advanced capability for high energy density physics (e.g., dynamic materials)

Advance the state-of-the-art for fast pulsed power technology

Provide a venue for scientific and technical innovation for national security

We have computationally evaluated >10,000 designs for NGPP as we continue to work with the NNSA on mission need and requirements

J.D. Douglass, Algorithmic machine design approaches



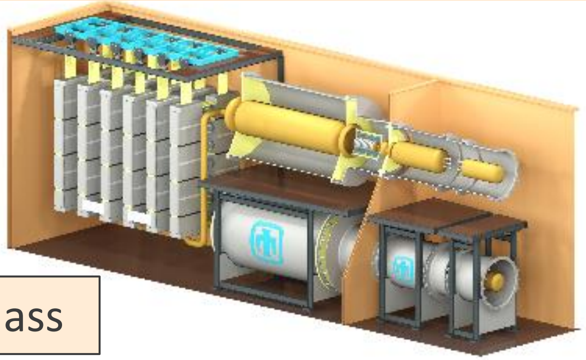
Advanced marx generator approach provides 50-70 MA with low technical risk

Parameter	Example NGPP Option	Z
Diameter	300’	108’
Marxes	75 @ 2400 kJ (180 MJ)	36 @ 600 kJ (22 MJ)
Capacitors	13,500 @ 2.95 µF	2,160 @ 2.65 µF
Power at Stack	602 TW	85 TW
Forward Energy at Stack	54 MJ (short pulse)	6 MJ (short pulse)

We are engaging on partnerships for pulsed-power technology development

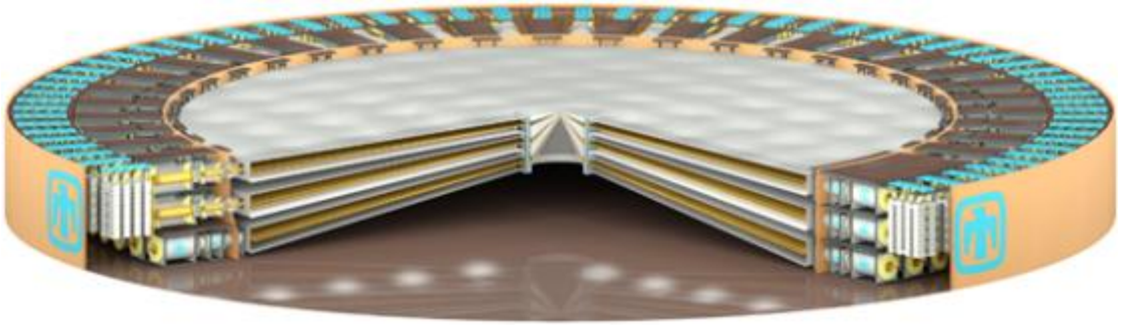
We are developing and maturing technology options needed for NGPP

Advanced Marx Generator (AMG) prototype module



J.D. Douglass

NGPP integrated designs



AMG approach has low technical risk but a large facility size

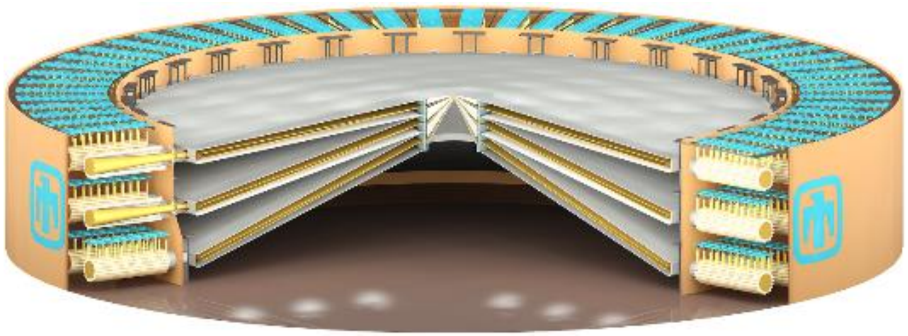
Fast Marx prototype and flashover test bed

Stoltzfus, Owens

Linear Transformer Drivers (LTDs)

Douglass, Hutsel

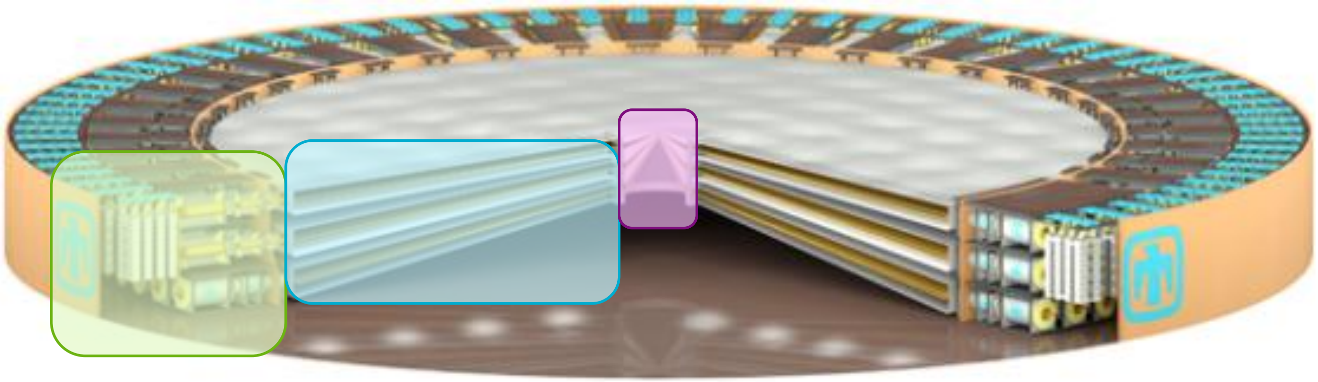
LLNL Impedance-matched Marx Generator



Fast-Marx, LTDs, Impedance-matched Marx Generator designs offer compelling potential advantages but should be demonstrated at higher TRL

We are engaging on partnerships for pulsed-power technology development

Pulsed power designs will benefit from research this decade



Primary energy storage and pulsed compression	Water-insulated power transmission	Central vacuum section

Advanced pulsed power drivers

- Advanced marx generator
- Fast marx generator
- Impedance-matched marx generator
- Linear Transformer Drivers

Elimination of SF6 gas
Improved capacitor energy density

Minimize mass of transmission lines

Increased electric field breakdown strength in water?

Better understanding of power flow in high energy density regions with melting conductors

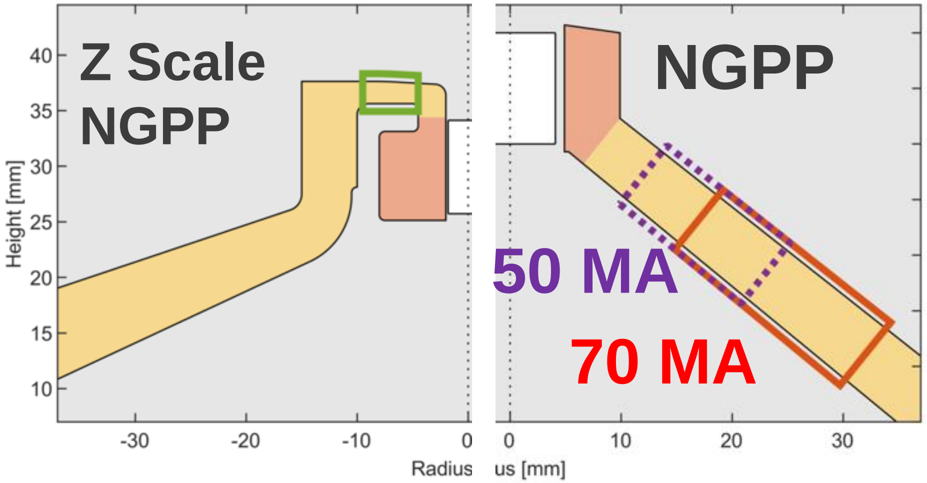
Debris mitigation

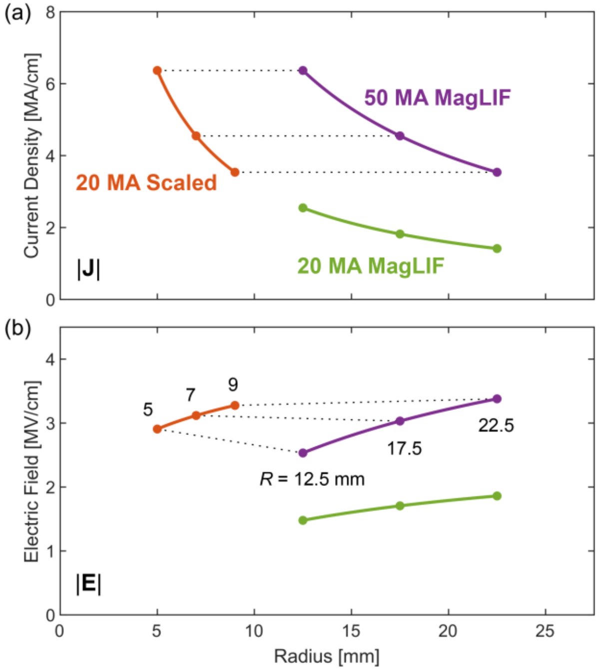
Validated multi-scale simulation tools for self-consistent coupling

We are engaging on partnerships for pulsed-power technology development

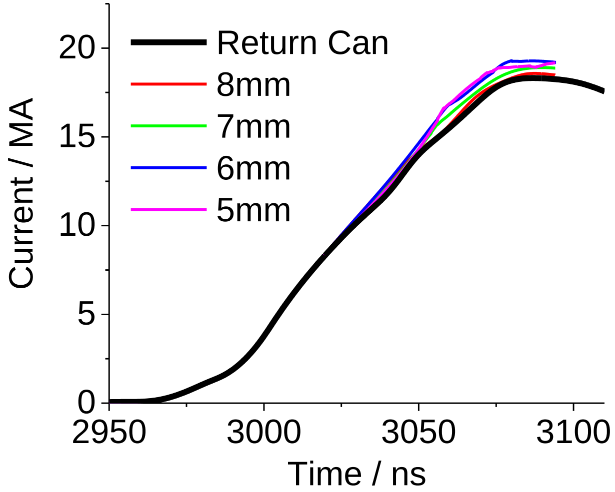
We have been executing scaled experiments on Z that replicate conditions representative of those found on NGPP to test the power flow

C. Myers *et al.*,
NGPP Scale Power Flow



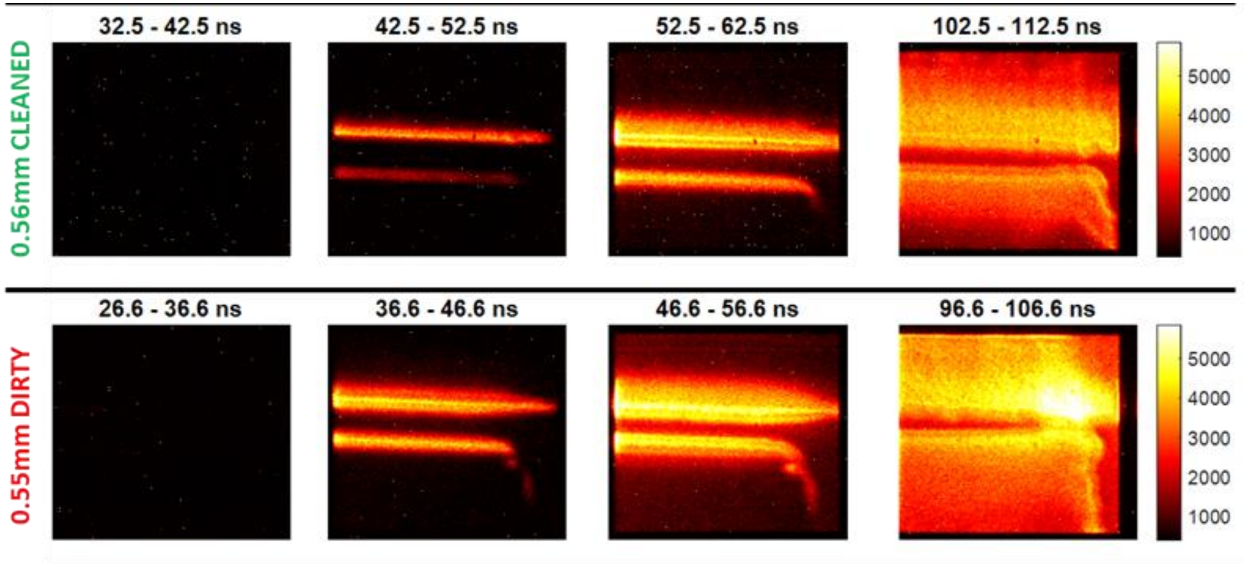


Conditions match nominal current density and electric fields



It may be possible to mitigate or delay the formation of plasma on an NGPP through several different methods

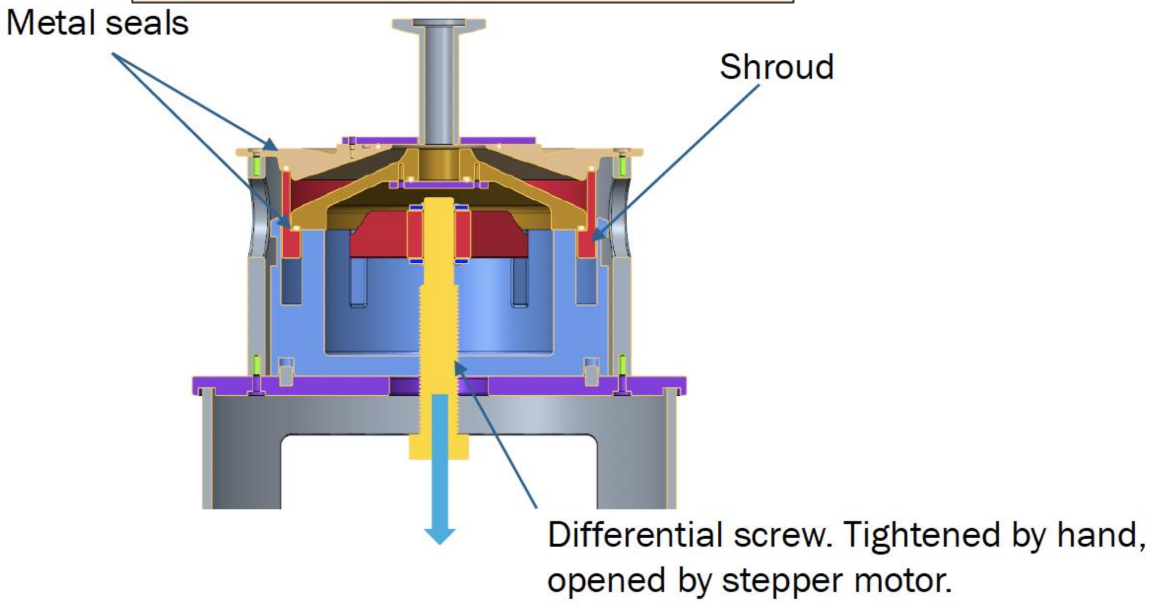
D. Lamppa *et al.*,
In-situ plasma discharges



Delay in plasma expansion and shorting
(Testing on Mykonos)

See MO 1.6-05 by Lamppa for details!

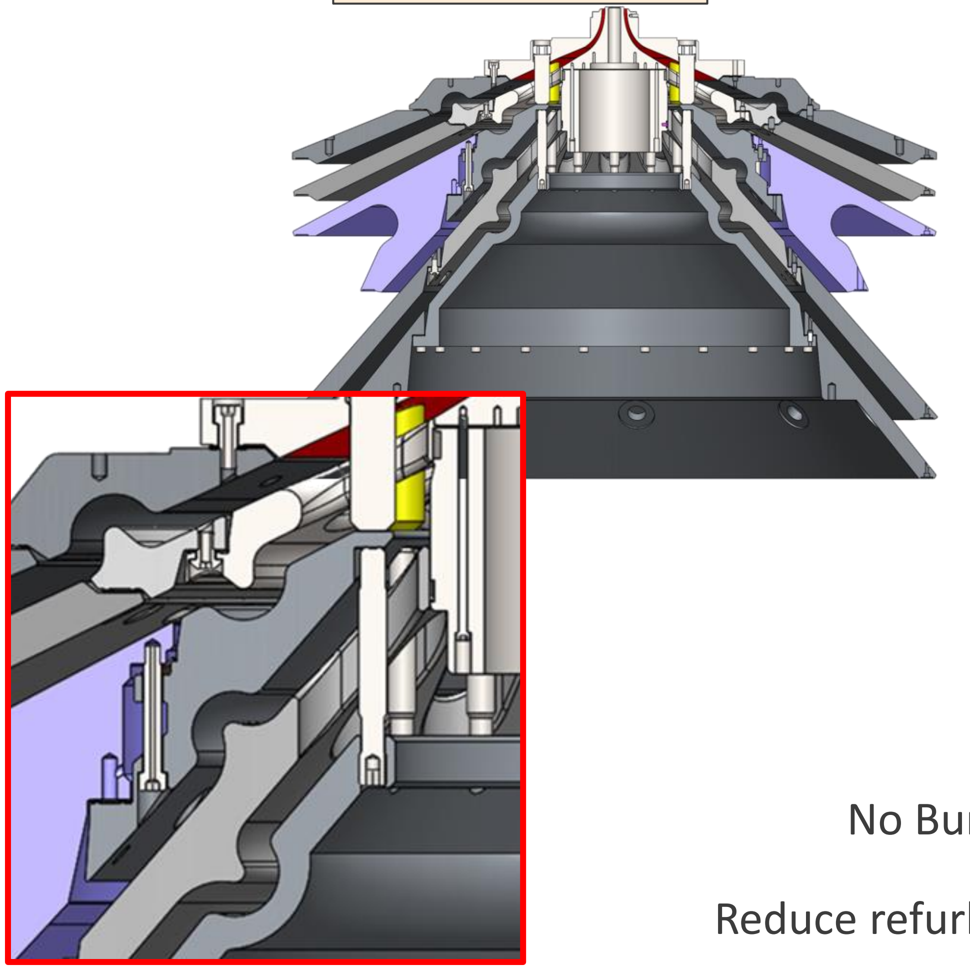
K.R. LeChien et al.,
Vacuum cassette for control of
inner MITL contamination



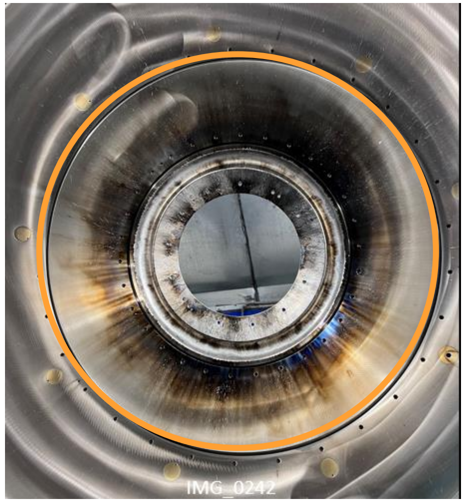
Test fit planned for Z this year

We are testing novel debris characterization and mitigation techniques on Z that may scale well to a NGPP machine

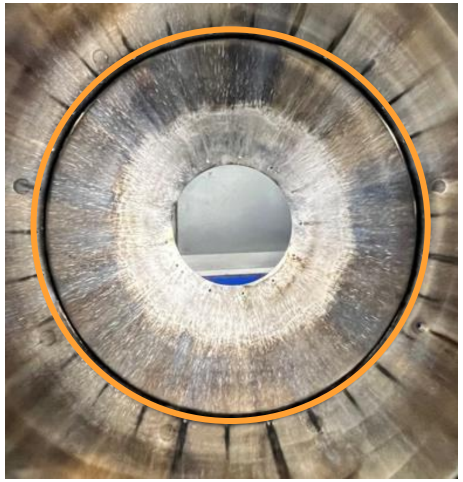
K. Chandler *et al.*
Speed Bumps



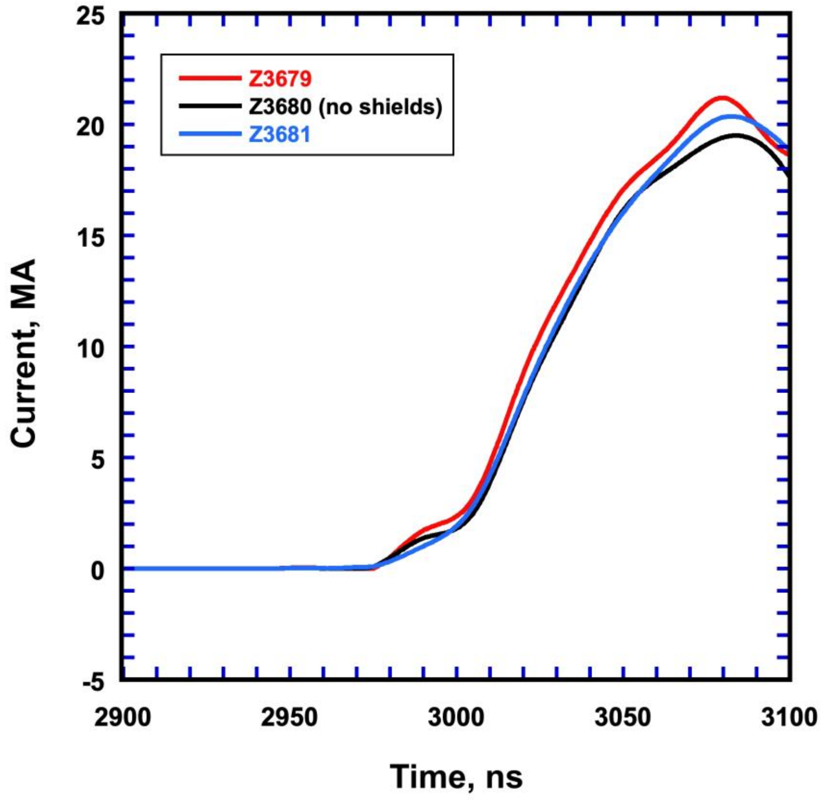
Bumps



No Bumps

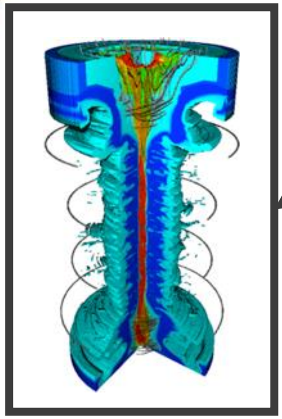


No current loss

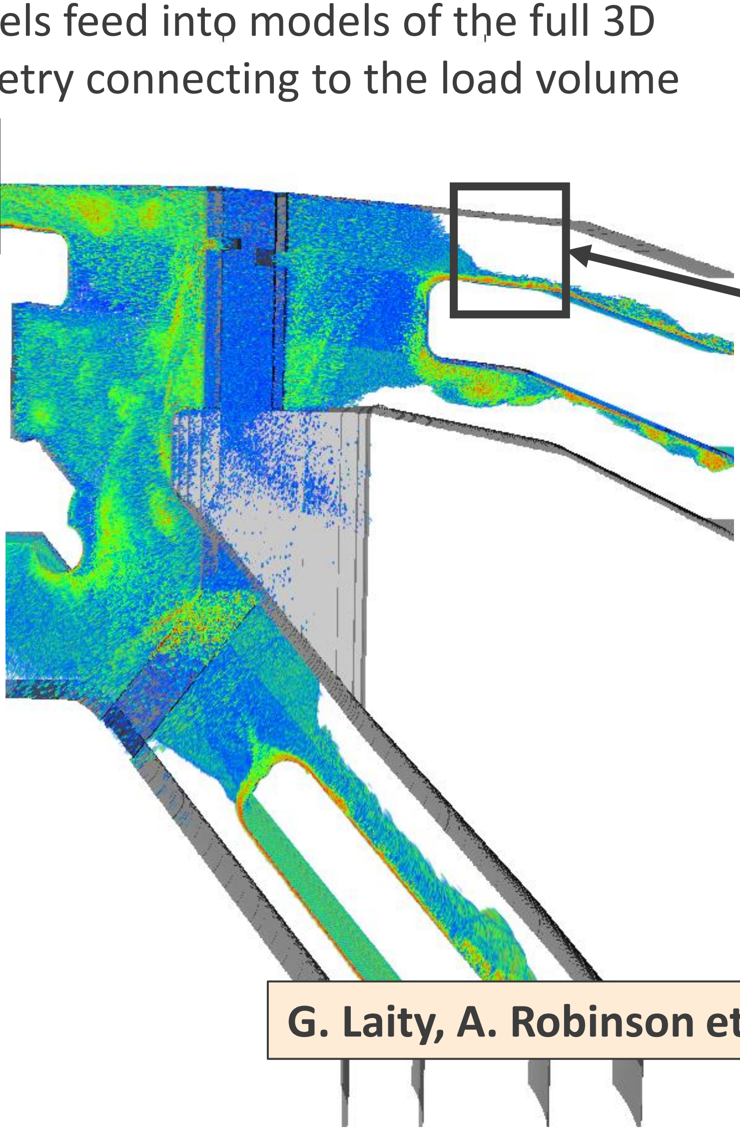


Reduce refurbishment time, protect the insulator stack

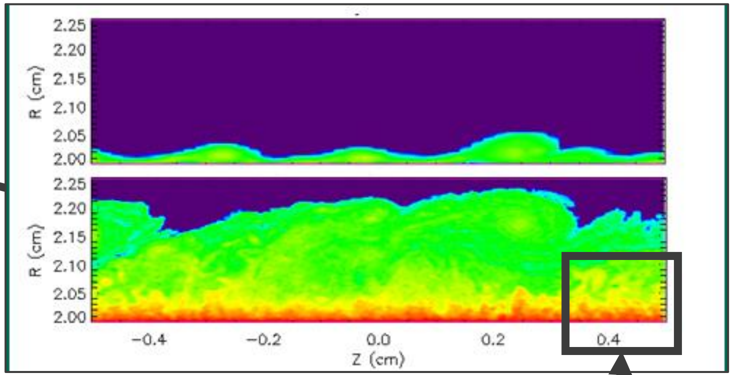
Advances in PIC/FLUID hybrid modeling / surface science for full system multi-scale modeling capability are now used for predictive power flow design



Electrode models feed into models of the full 3D electrode geometry connecting to the load volume

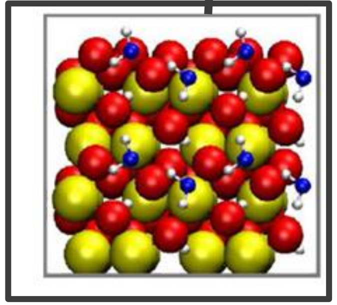


Plasma formation, heating, expansion

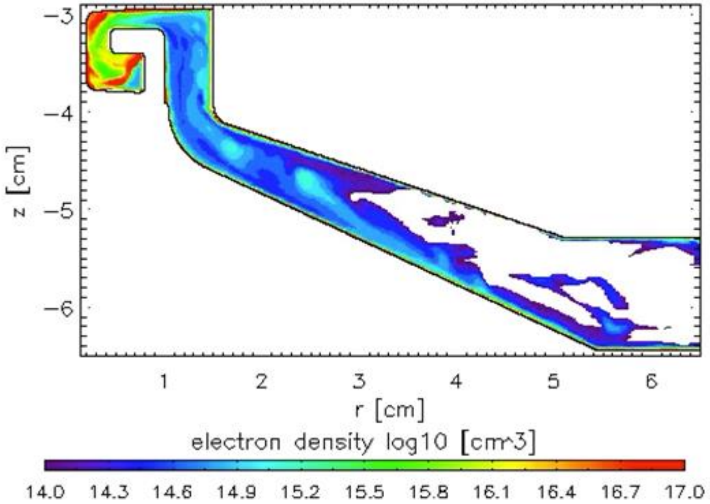


Predictive surface models incorporated into PIC and PIC/Fluid hybrid models

DFT calculations of H2O binding energy

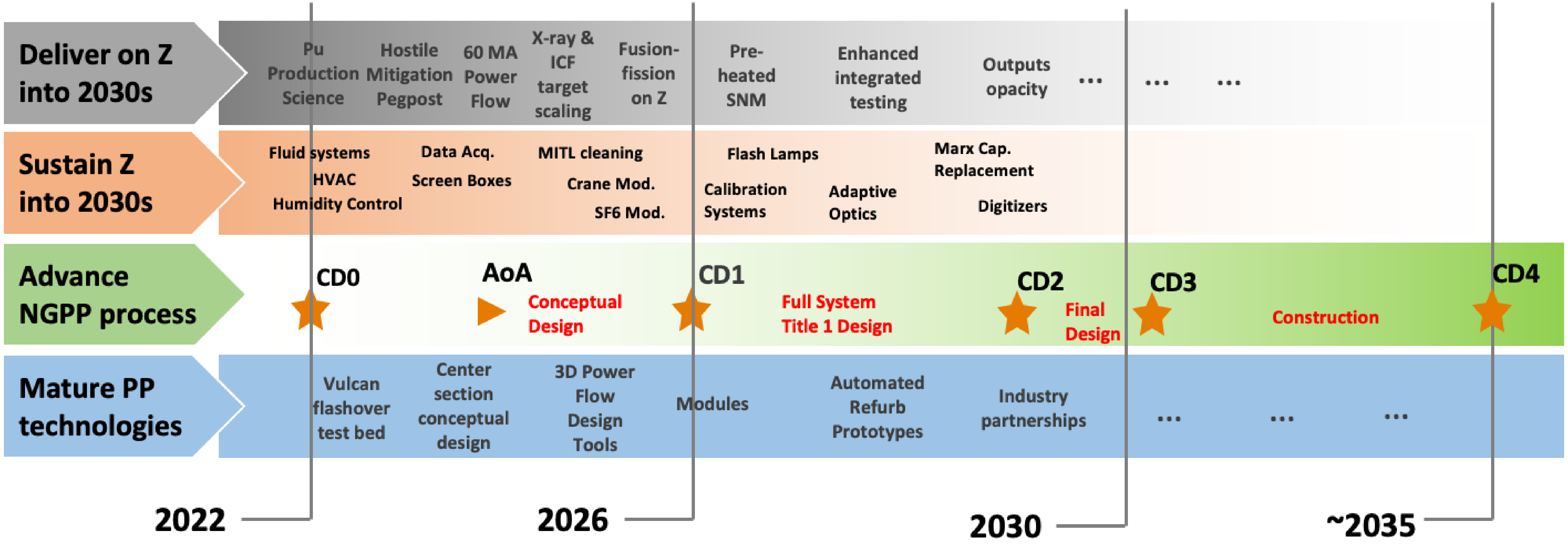


N. Bennett *et al.* Predictions of Power Flow Scaling



G. Laity, A. Robinson et al, LDRD 2018-2020

Our planning supports seamless stockpile stewardship delivery and a smooth transition from Z to NGPP



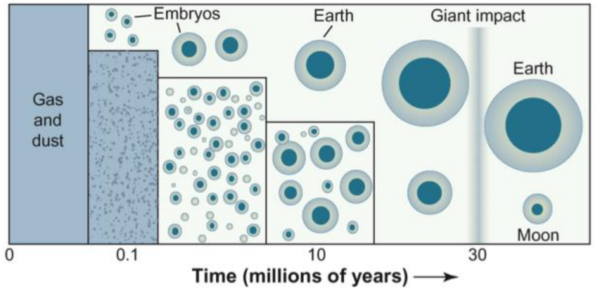
We are actively working on the first stages of the NGPP project with the NNSA and with colleagues from our sister laboratories

Z will operate as close to the completion of NGPP as possible—avoid a capability gap!

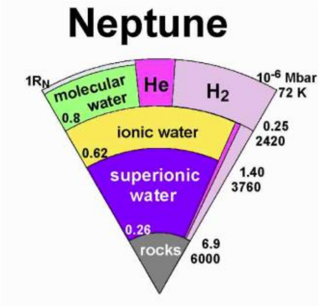
Eventually would like an intermediate-scale (8-10 MA) user facility somewhere!

Sandia is actively engaging in transformative pulsed power activities and is looking for additional lab, academic, & industry partnerships going forward

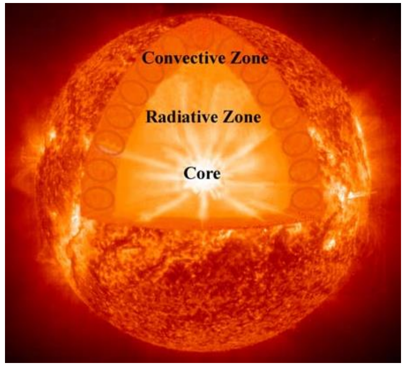
Z Fundamental Science Program



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

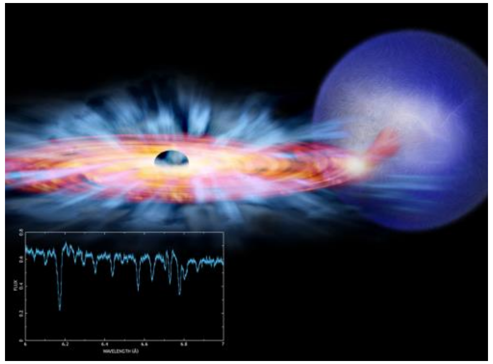


Photo-ionized plasmas
Range of ionization param. ξ

NNSA Laboratory Residency Graduate Fellowship

Students can complete residency projects with us

Laboratory Research and Development Funding

Radiation, Electrical, and High Energy Density Science Research Foundation ($9.5M annually)

Assured Survivability and Agility with Pulsed Power (ASAP) Mission Campaign ($40M FY20-26)

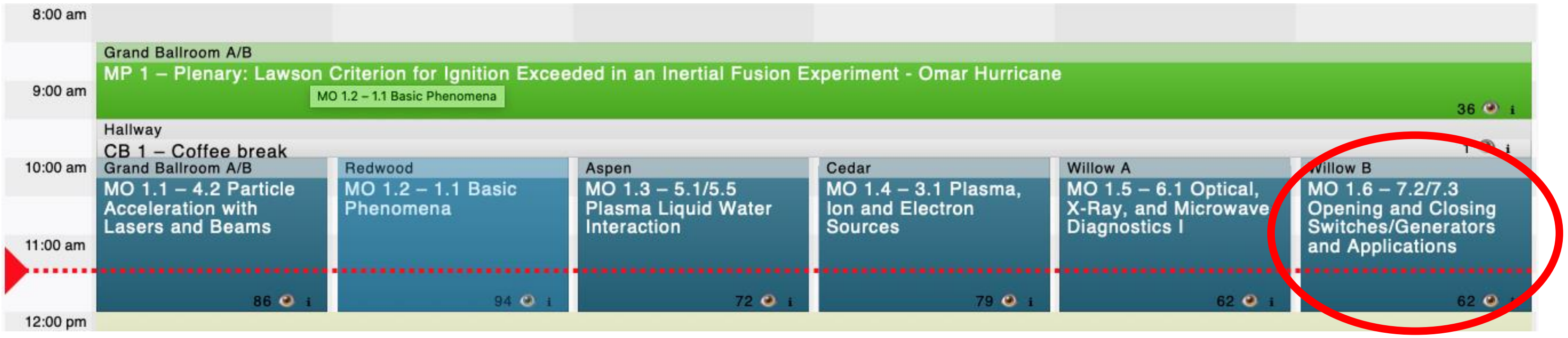
New Maxwell Fellowship opportunity (2 awarded in 2022)

Questions?

dbsinar@sandia.gov

Additional slides

Conference Abstract (Truncated version of TOFE abstract)



The Sandia Z facility has the world's largest pulsed power machine and includes the multi-kJ Z-Beamlet laser. Z has been used for inertial confinement fusion research for over 25 years, in addition to supporting other high energy density science [1]. Until 2006, wire array z-pinches were used to produce the highest soft x-ray power and total x-ray energy of any laboratory facility at the time using two different indirect-drive fusion concepts. These remain of future interest, but the largest uncertainty in scaling is the capsule physics that is best addressed using the National Ignition Facility. Today, research on Z is studying the use of magnetic pressure to directly compress solid liners containing fusion fuel [2], such as the Magnetized Liner Inertial Fusion (MagLIF) concept that demonstrated the fundamental principles of magneto-inertial fusion in the laboratory [3].

This talk will review the past and future of the pulsed power program at Sandia. The NNSA has begun working toward a Next Generation Pulsed Power facility, which will be completed in the 2030s, which is expected to be capable of up to 100 MJ of fusion yield.

Acknowledgement

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References

[1] "Review of pulsed power driven high energy density physics research on Z at Sandia," D.B. Sinars, M.A. Sweeney, C.S. Alexander *et al*., Physics of Plasmas 27, 070501 (2020).
[2] "Magnetically driven implosions for inertial confinement fusion at Sandia National Laboratories," M.E. Cuneo, M.C. Herrmann, D.B. Sinars *et al.*, IEEE Trans. Plasma Sci. 40, 3222-3245 (2012).
[3] "An overview of magneto-inertial fusion on the Z machine at Sandia National Laboratories," D.A. Yager-Elorriaga, M.R. Gomez, D.E. Ruiz et al., Nuclear Fusion 62, 042015 (2022).

The pursuit of high yield fusion for stockpile stewardship drives exciting fundamental and use-inspired science as well

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

Excerpt from NNSA 2018 ICF Framework Document

Sandia's demonstration of fundamental magneto-inertial fusion concepts helped motivate DOE ARPA-E investments into novel fusion research straddling inertial confinement fusion and magnetic confinement fusion

Future success in demonstrating high single-shot yields would strongly motivate inertial fusion energy investments by the DOE