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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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Director, Pulsed Power Sciences Center

Technology of Fusion Energy (TOFE)
2022 American Nuclear Society Annual Meeting

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SAND2022-6293 C

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U.S. DEPARTMENT OF ENERGY
NNSA

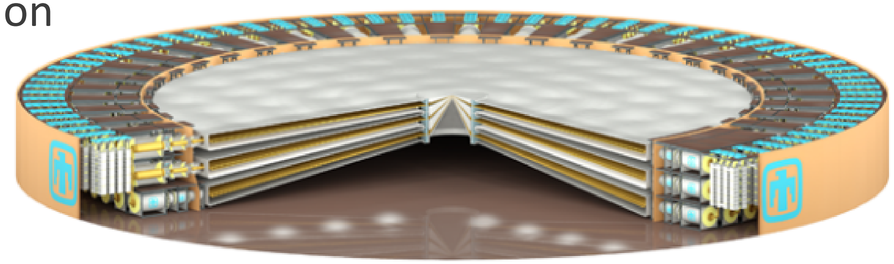
These are exciting times to be working with pulsed power!

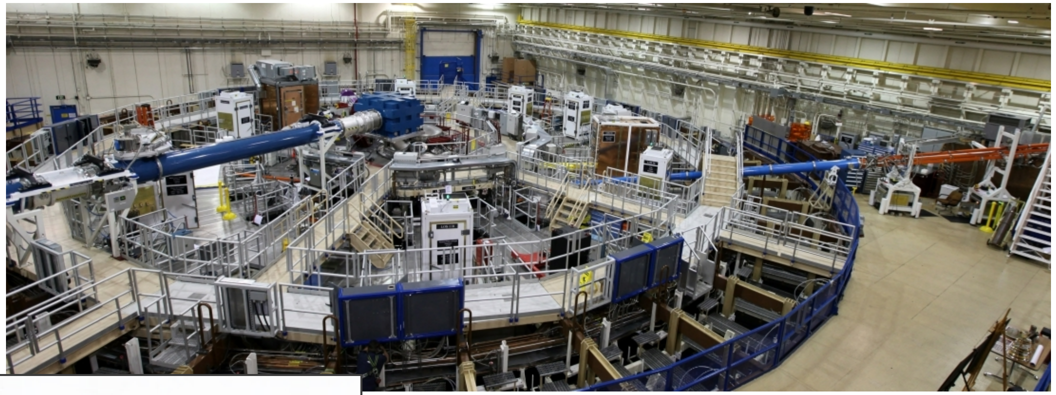
Sandia develops and applies fast pulsed-power technology to expand the frontiers of high energy density science, fusion, and extreme radiation environments

Magnetic direct drive fusion experiments on Z have broadened the credible landscape of inertial fusion to include magneto-inertial fusion concepts

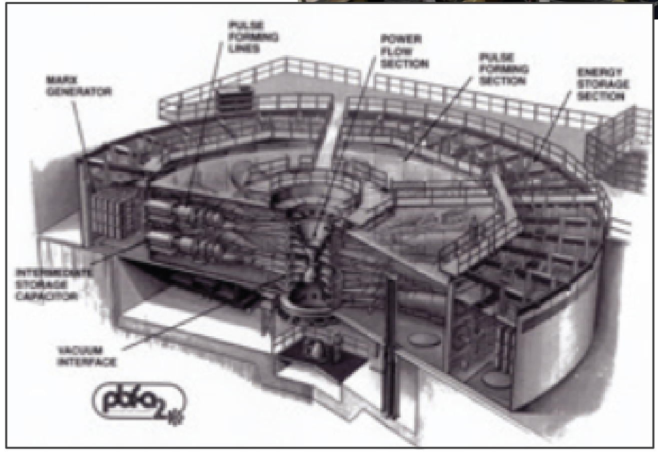
Today's talk will give an overview of our journey from Z towards a Next Generation Pulsed Power (NGPP) machine

Next-Generation Pulsed Power (2030s)





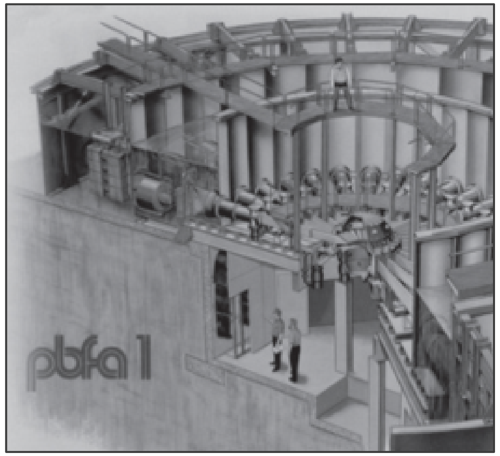
Z Machine Today

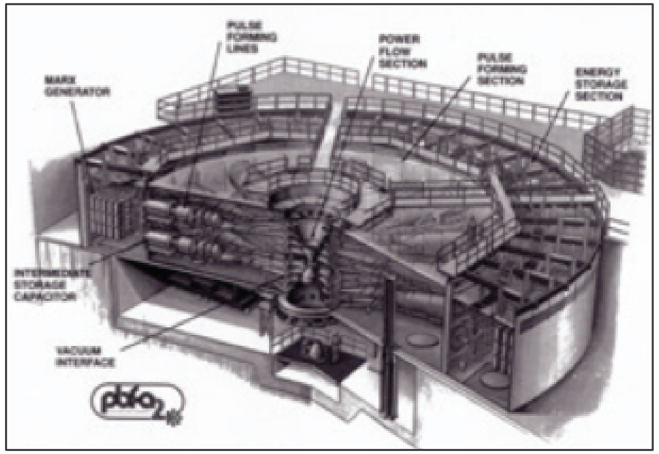


Particle Beam Fusion Accelerator 2 (1985)

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

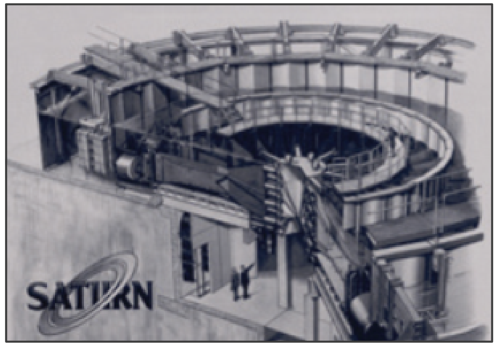


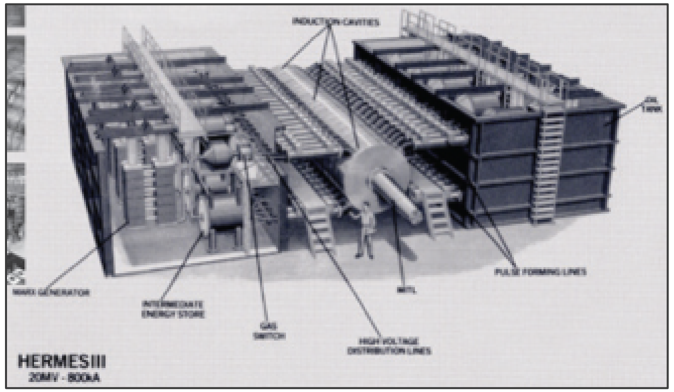


★ Focus of today's talk

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

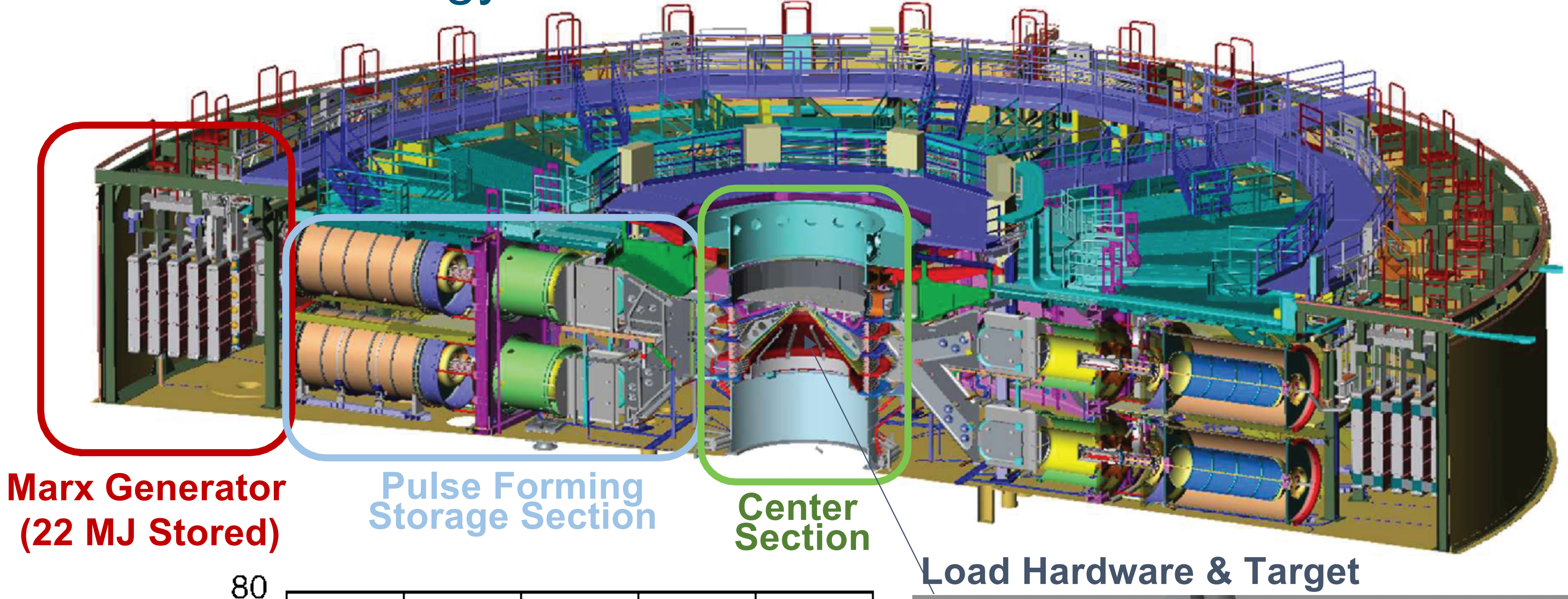
PBFA-1 converted into Saturn (1987): The world's largest, large-area hot x-ray simulator

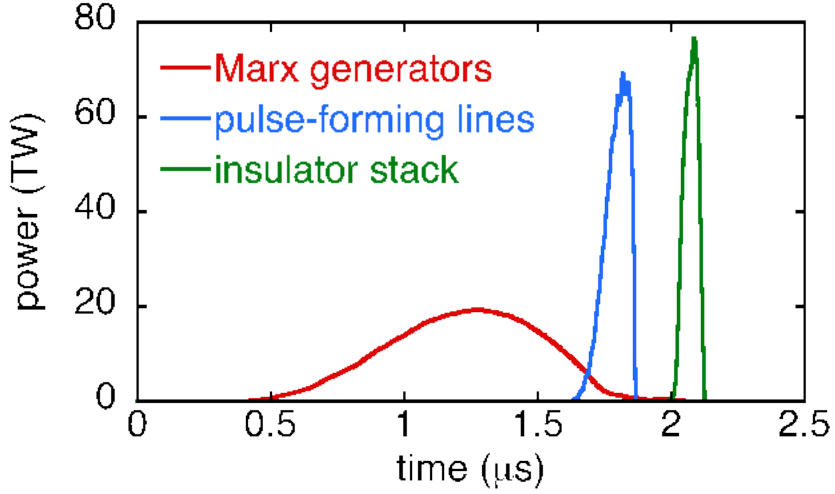


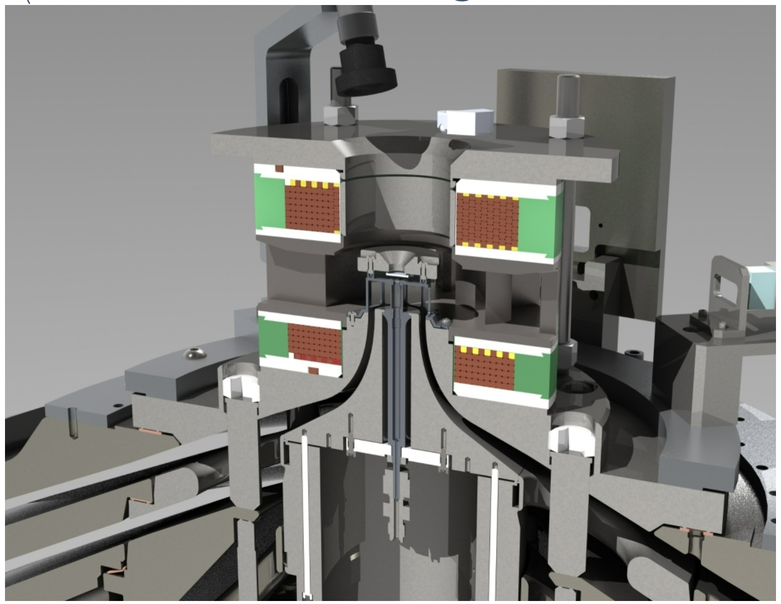


Hermes-III (1988): The world's most powerful gamma-ray accelerator

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

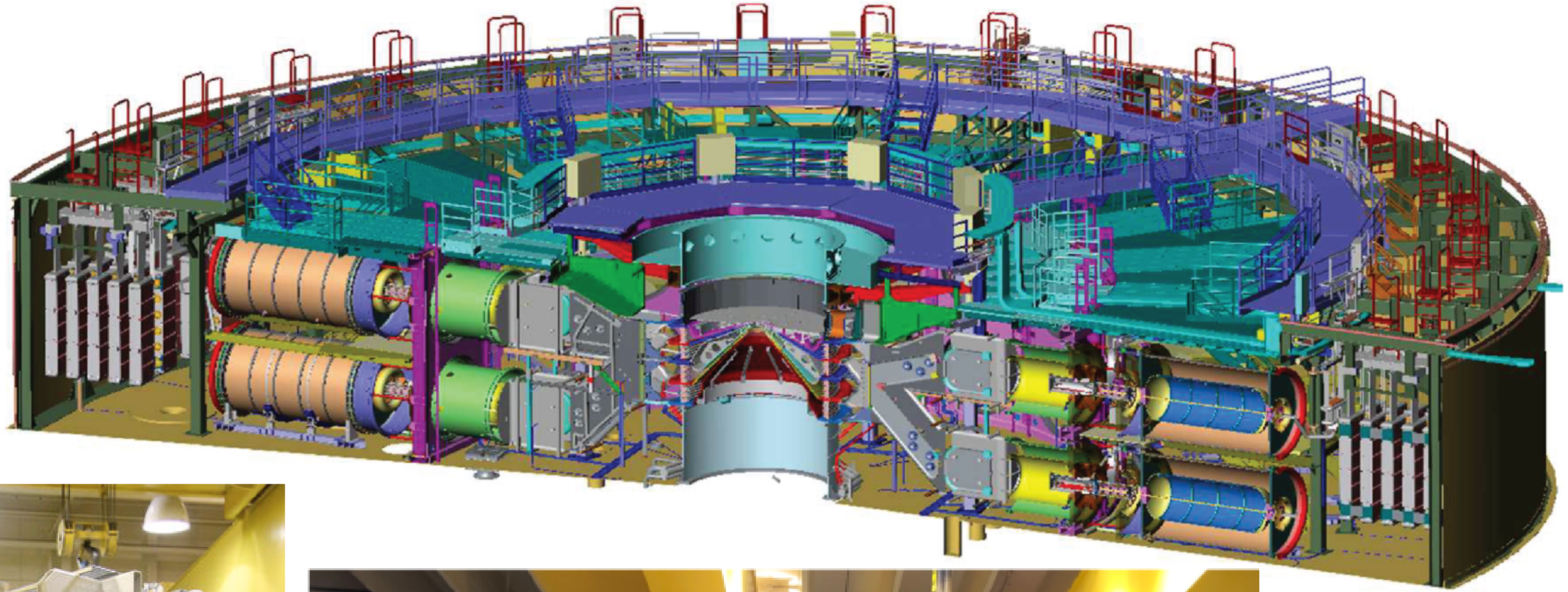






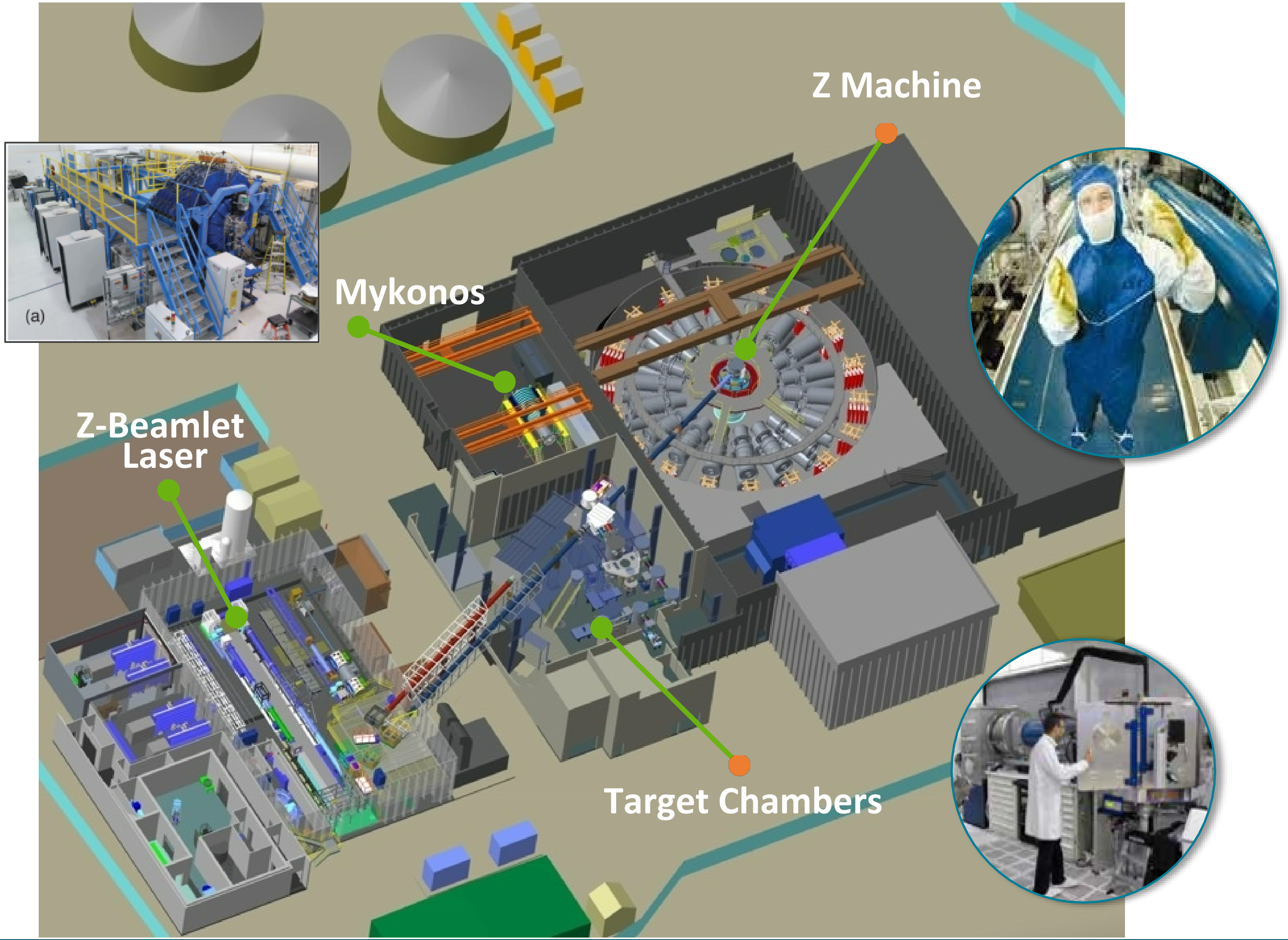
Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

Z is “big science” and executes ~150 experiments per year



Post-shot

The Z facility includes the multi-kJ, 2-TW Z-Beamlet laser [1,2]



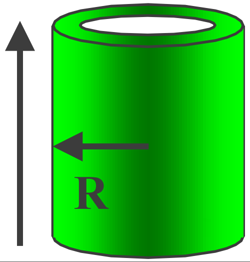
[1] P.K. Rambo *et al.*, Applied Optics 44 (2005).
[2] P. Rambo *et al.*, Proc. SPIE 10014 (2016).

Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in fusion [3]

Magnetically Driven Implosion

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

drive current I



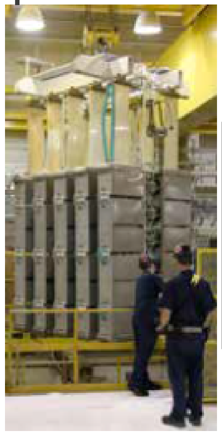
100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atmospheres

Pressure equivalent to Energy Density (J/m^3)

1 Mbar = 10^{11} J/m^3, threshold of High Energy Density regime

Z Storage capacitor

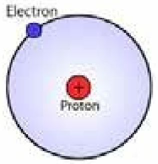


2e-6 Mbar

TNT

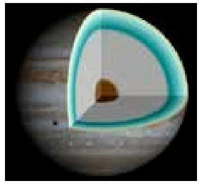
0.07 Mbar

Internal Energy of H atom



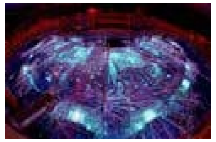
1 Mbar

Metallic H in Jupiter's core



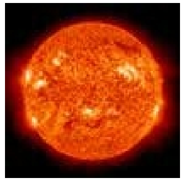
30 Mbar

Z Magnetic Drive Pressure



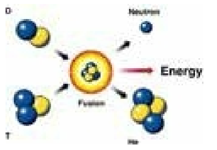
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



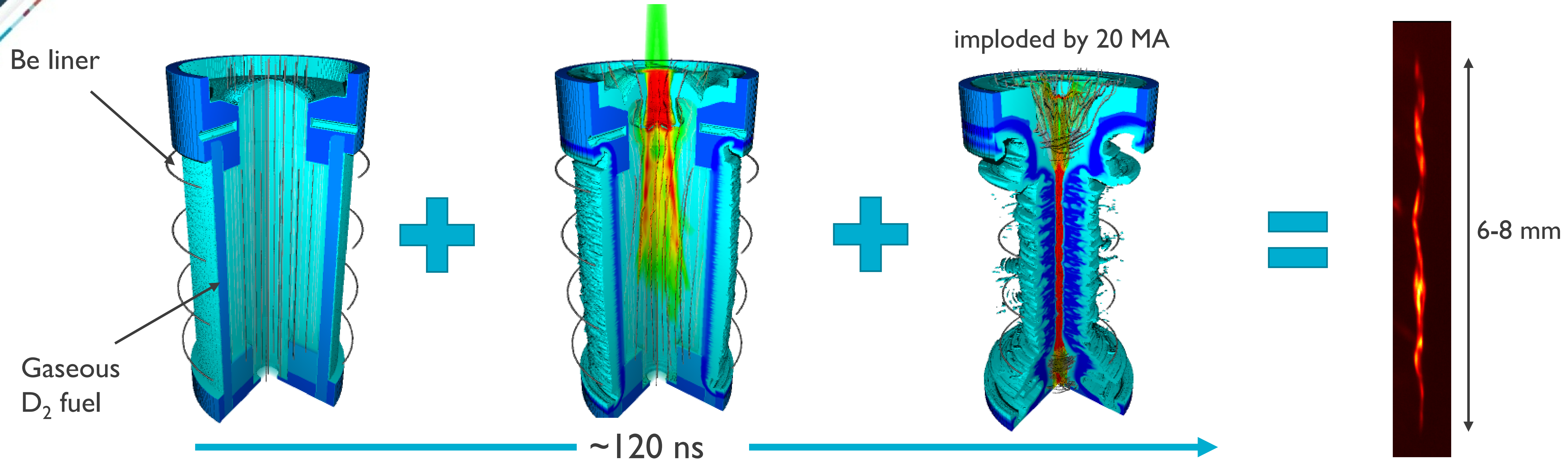
800,000 Mbar

Push on samples

Compress fuel at high velocity

[3] For examples of the full range of high energy density physics on Z, see "Review of pulsed-power-driven high energy density physics research on Z at Sandia," D.B. Sinars *et al.*, Phys. Plasmas (2020).

Magnetized Liner Inertial Fusion (MagLIF) is a magneto-inertial fusion concept combining external axial magnetic fields, laser preheat, and z-pinch implosions [4,5]



External B Field
- Suppress radial thermal conduction losses
- Trap α particles

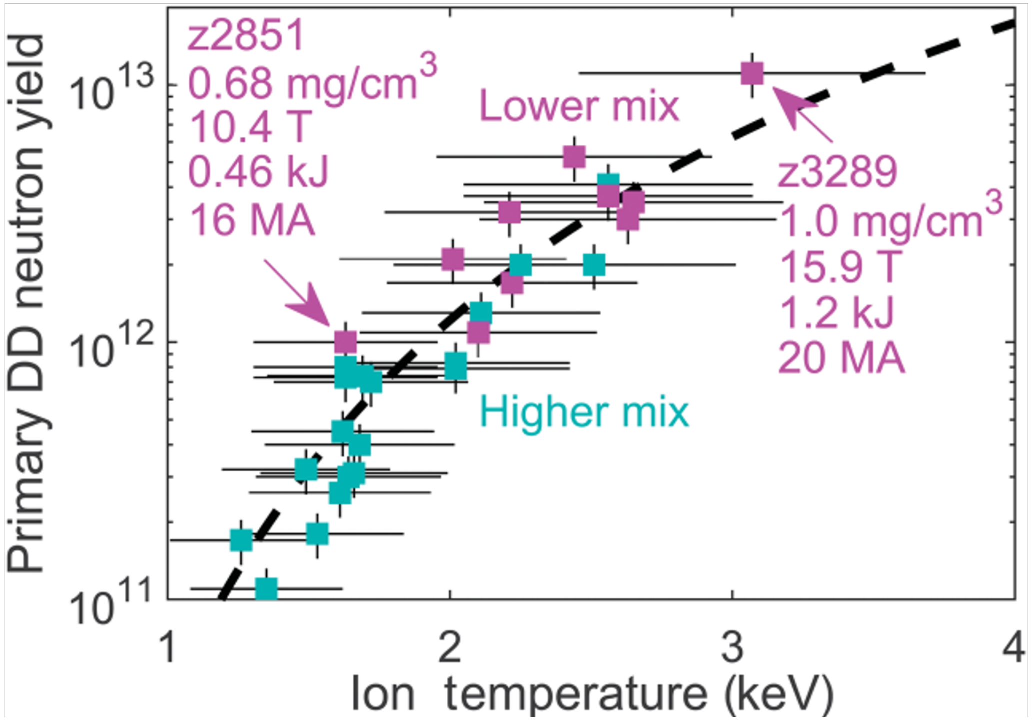
Preheat
- Increase fuel adiabat to limit required convergence ratio

Implosion
- PdV work to heat fuel
- Amplify B field through flux compression

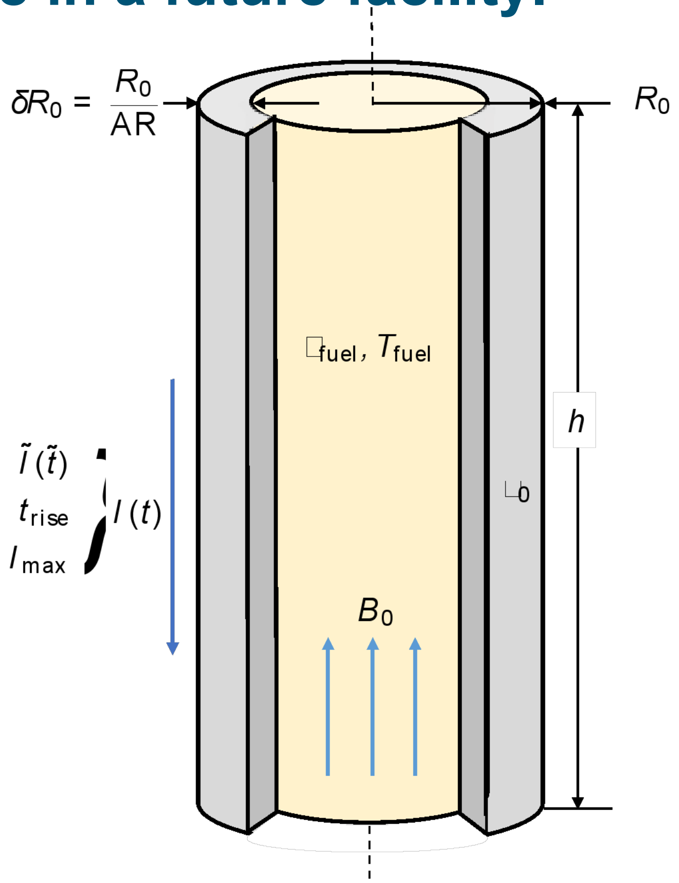
Stagnation
- Several keV temps
- Several Gbar pressures
- Several kT B-fields

[4] S. A. Slutz, M. C. Herrmann, R. A Vesey, *et al.*, Phys. Plasmas **17**, 056303 (2010).
[5] M. R. Gomez, S. A. Slutz, A. B. Sefkow, *et al.*, Phys. Rev. Lett. **113**, 155003 (2014).

Improvements to the initial conditions in MagLIF experiments have increased the yields on Z.[6] Higher yields are possible in a future facility.[7]



1. Peak current
2. Current rise time
3. Liner inner radius and outer radius
4. Liner material
5. Liner height
6. Preheat energy
7. Initial fuel density
8. Axial magnetic field



Experiments at Sandia have steadily improved performance of MagLIF.[3]

We are spending considerable effort to understand the scaling of MagLIF physics to higher current facilities

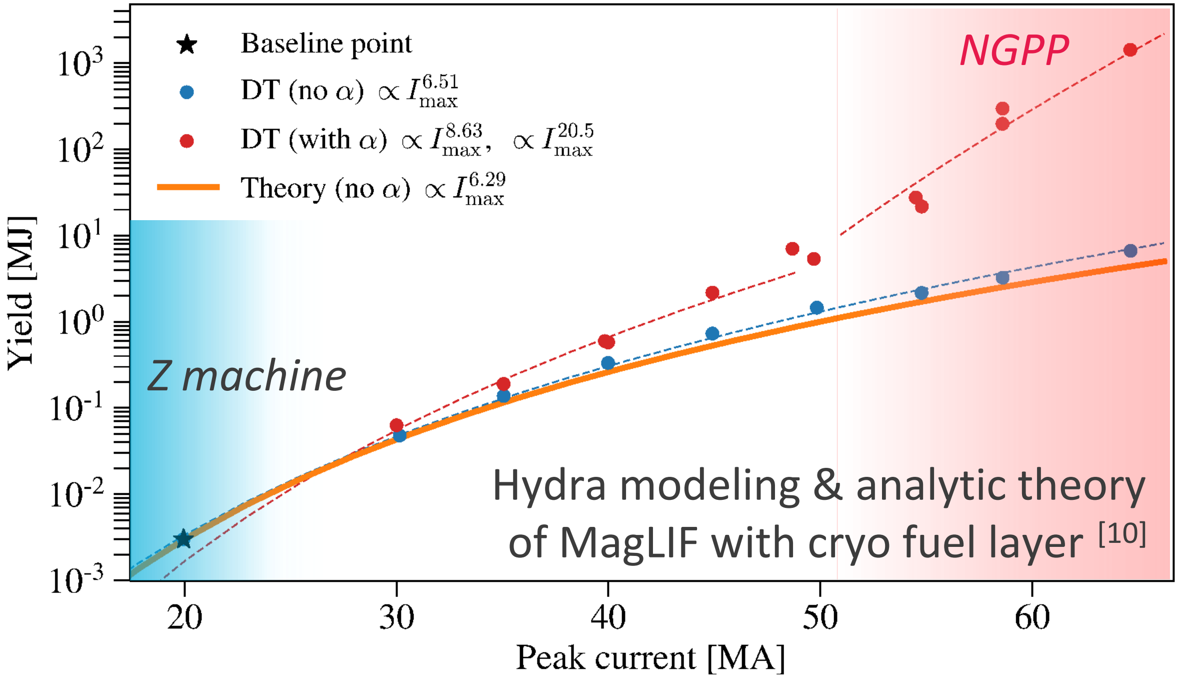
[6] M. R. Gomez, S. A. Slutz, C. A. Jennings, *et al.,* Phys. Rev. Lett. **125**, 155002 (2020).
[7] S. A. Slutz, W. A. Stygar, M. R. Gomez, *et al.*, Phys. Plasmas **23**, 022702 (2016).

Building on our Z database[8], we are working on the path to high yield [9,10] 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
- A next-step facility may have the capability to achieve single-shot facility gains ~0.5
- Cryogenic targets with ice fuel have the potential to get the largest yields through radial burn [11] Methods of Refs. [9]-[10] being adapted for ice layers.

MagLIF can reach 100 MJ yields at reasonable facility scales



[8] "*An overview of magneto-inertial fusion on the Z machine at Sandia*," D.A. Yager Elorriaga *et al.,* Nuclear Fusion (2022).
[9] "*A conservative approach to scaling magneto-inertial fusion concepts to larger pulsed power drivers*," P.F. Schmit & D.E. Ruiz, Phys. Plasmas (2020).
[10] D. E. Ruiz, *et al.*, "*Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling*", in preparation.
[11] "*Dense hydrogen layers for high performance MagLIF*," S. A. Slutz, T.J. Awe, and J.A. Crabtree, Phys. Plasmas (2022).

The MagLIF team is focusing efforts towards identifying and mitigating risks for scaling MagLIF to high yields.

1. Develop and experimental test new scaling framework

- Develop theoretical foundations for similarity scaling of MagLIF.
- Experimentally test the new framework on Z.
- Discover hidden variables and understand their scaling and associated risks.

2. Understand and mitigate MRT instabilities

- Advanced modeling of magneto-Rayleigh--Taylor instabilities in 2D and 3D.
- Test new methods to experimentally mitigate these instabilities.

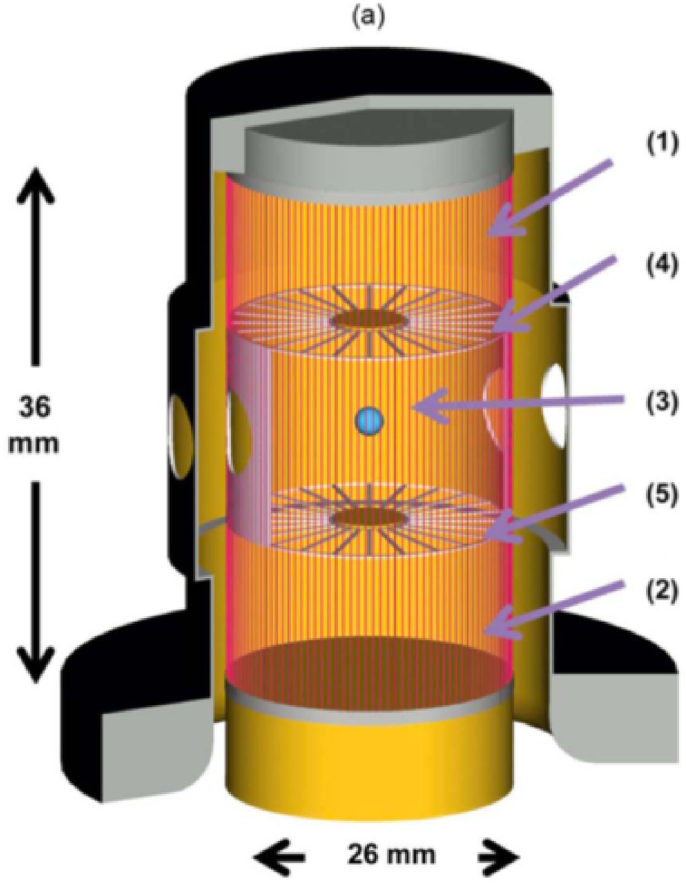
3. Assess preheat-energy delivery at NGPP scale

- Preheat only experiments to understand at-scale preheat and mix.
  - Preheat experiments on NIF to study at-scale preheat (E>20 kJ).
  - Experiments at Omega to study blast-wave induced mix.

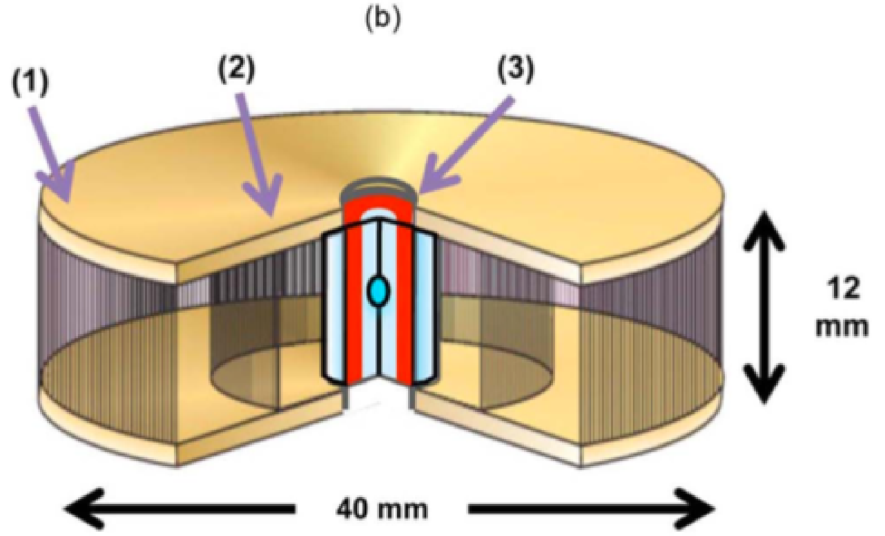
4. Field advance fuel configurations for MagLIF on Z

- Achieving high yields with MagLIF require ice layers.
- Demonstrate on Z a reliable fielding system for inner ice layers.
- Push simulation capabilities in the lower-magnetized fuel regimes required for high yields.

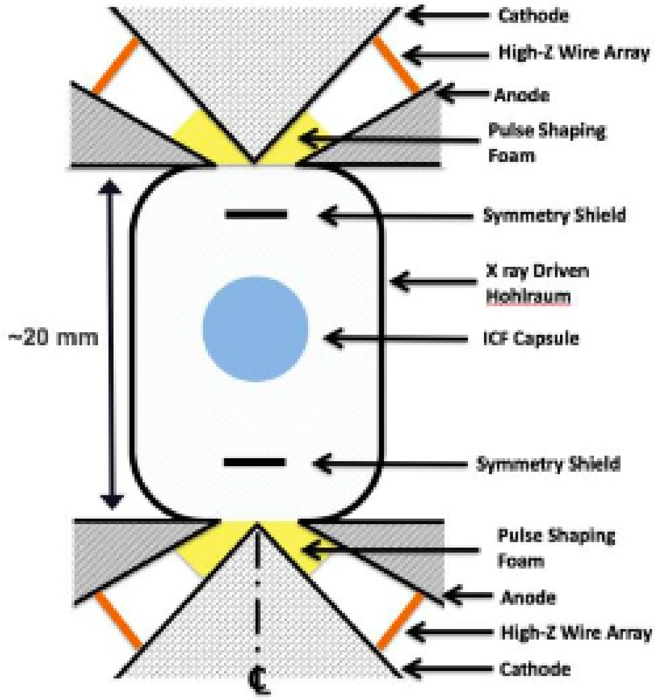
Magnetic indirect drive (radiation-driven) fusion also remains an option for a future high-current facility to build on the success of NIF [12,13]



Double-ended Hohlraum



Z-pinch Dynamic Hohlraum



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

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

We are working with the NNSA in CY22 to refine the requirements for a Next Generation Pulsed Power (NGPP) machine

<u>We expect that 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

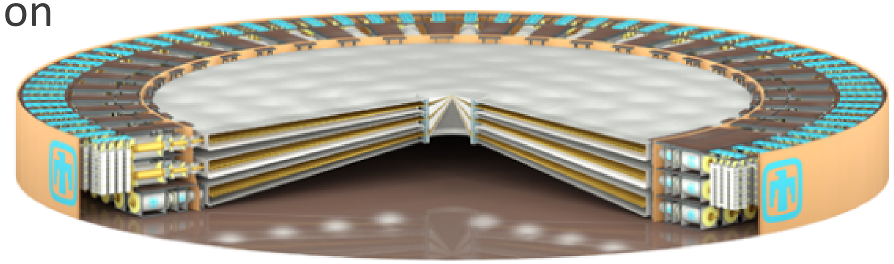
Provide a venue for scientific and technical innovation for national security

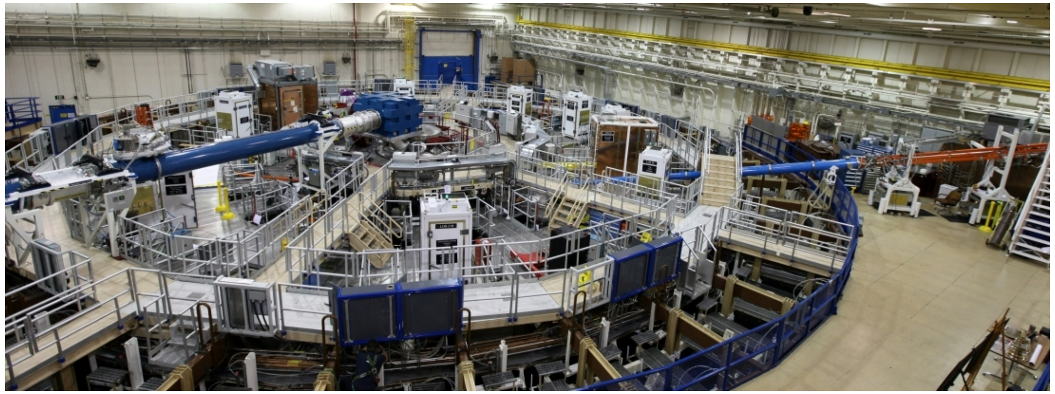
Mission need and requirements finalized in 2022

Main project funding beginning in ~2025

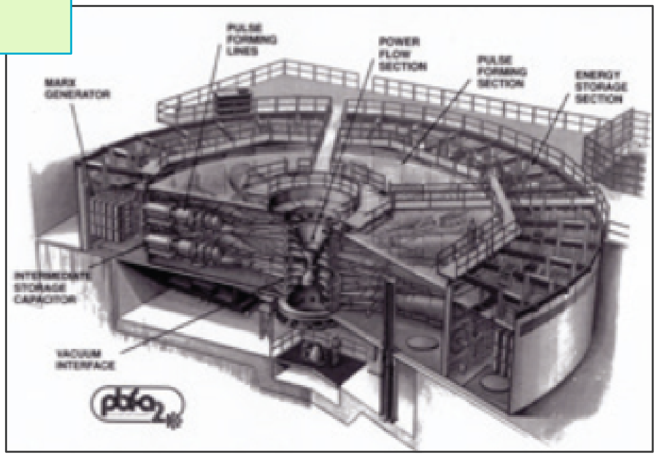
Project completion in the 2030s

Next-Generation Pulsed Power (2030s)





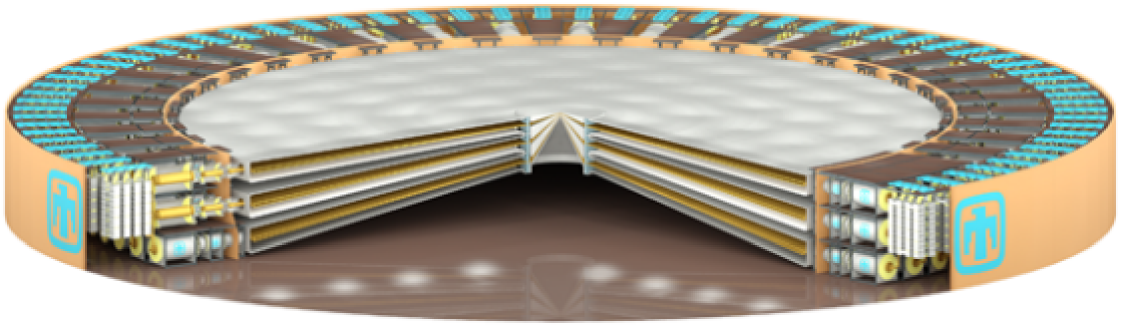
Z Machine Today



Particle Beam Fusion Accelerator 2 (1985)

We have computationally evaluated >30,000 designs for NGPP as we continue to work with the NNSA on mission need and requirements

J.D. Douglass, Algorithmic machine design approaches

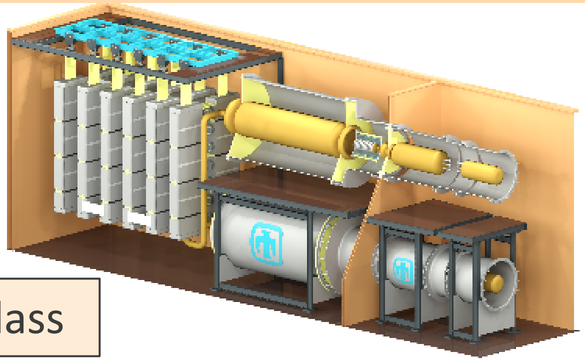


Advanced marx generator approach provides 50-70 MA with low technical risk

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)

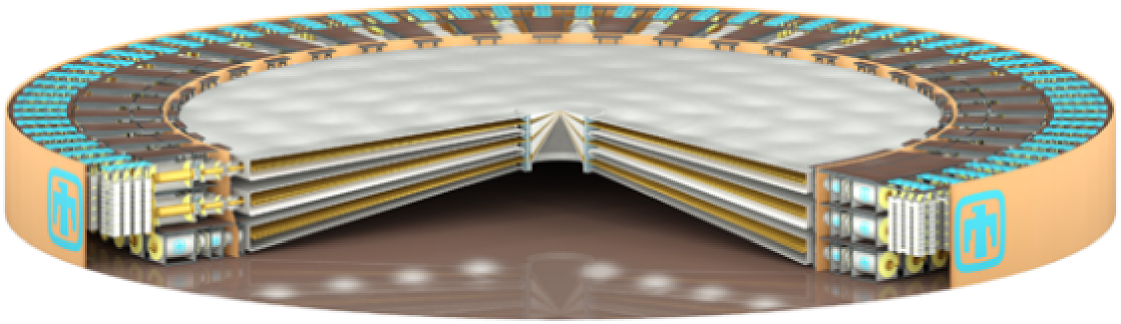
We are developing and maturing technology options needed for NGPP

Advanced Marx Generator (AMG) prototype module



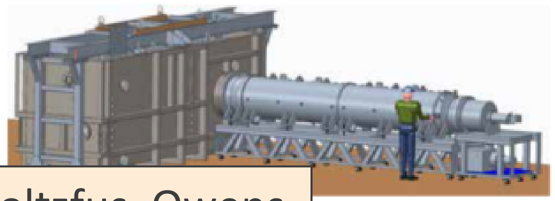
J.D. Douglass

NGPP integrated designs



AMG approach has low technical risk but a large facility size

Fast Marx prototype and flashover test bed

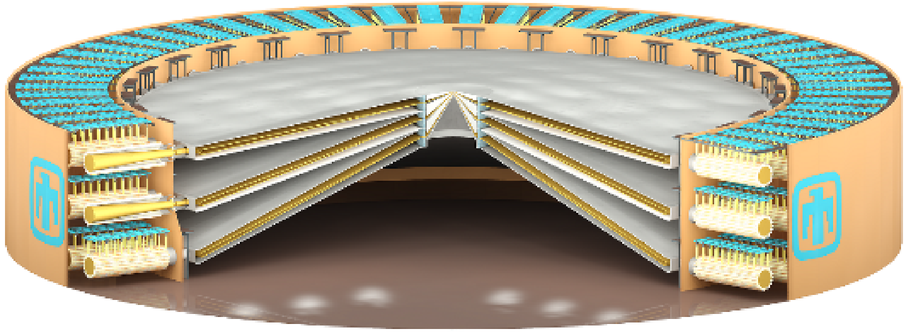


Stoltzfus, Owens

Linear Transformer Drivers (LTDs)

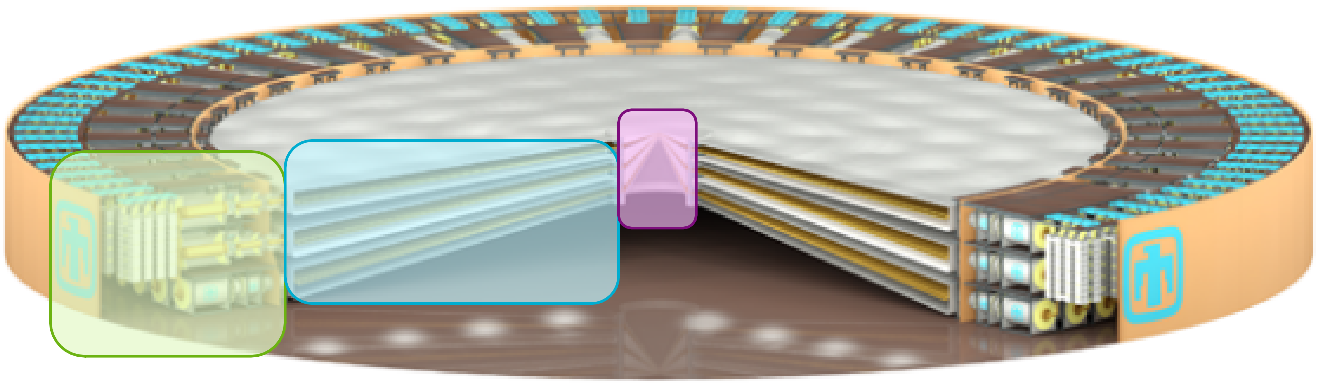
Douglass, Hutsel

LLNL Impedance-matched Marx Generator



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

Pulsed power designs will benefit from research this decade



Primary energy storage and pulsed compression

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

Water-insulated power transmission

Minimize mass of transmission lines

Increased electric field breakdown strength in water?

Central vacuum section

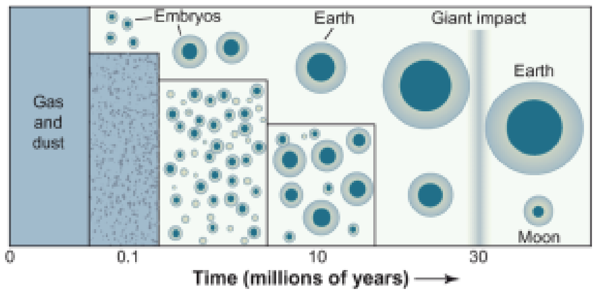
Better understanding of power flow in high energy density regions with melting conductors

Debris mitigation

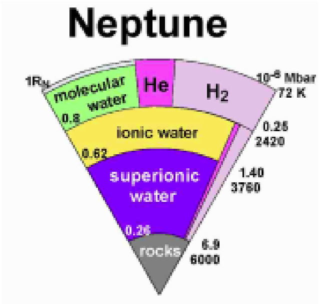
Validated multi-scale simulation tools for self-consistent coupling

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

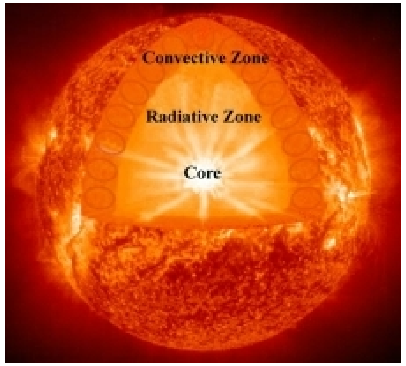
Z Fundamental Science Program



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

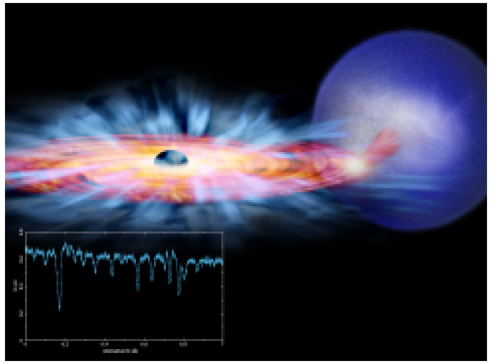


Photo-ionized plasmas
Range of ionization param. ξ

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)

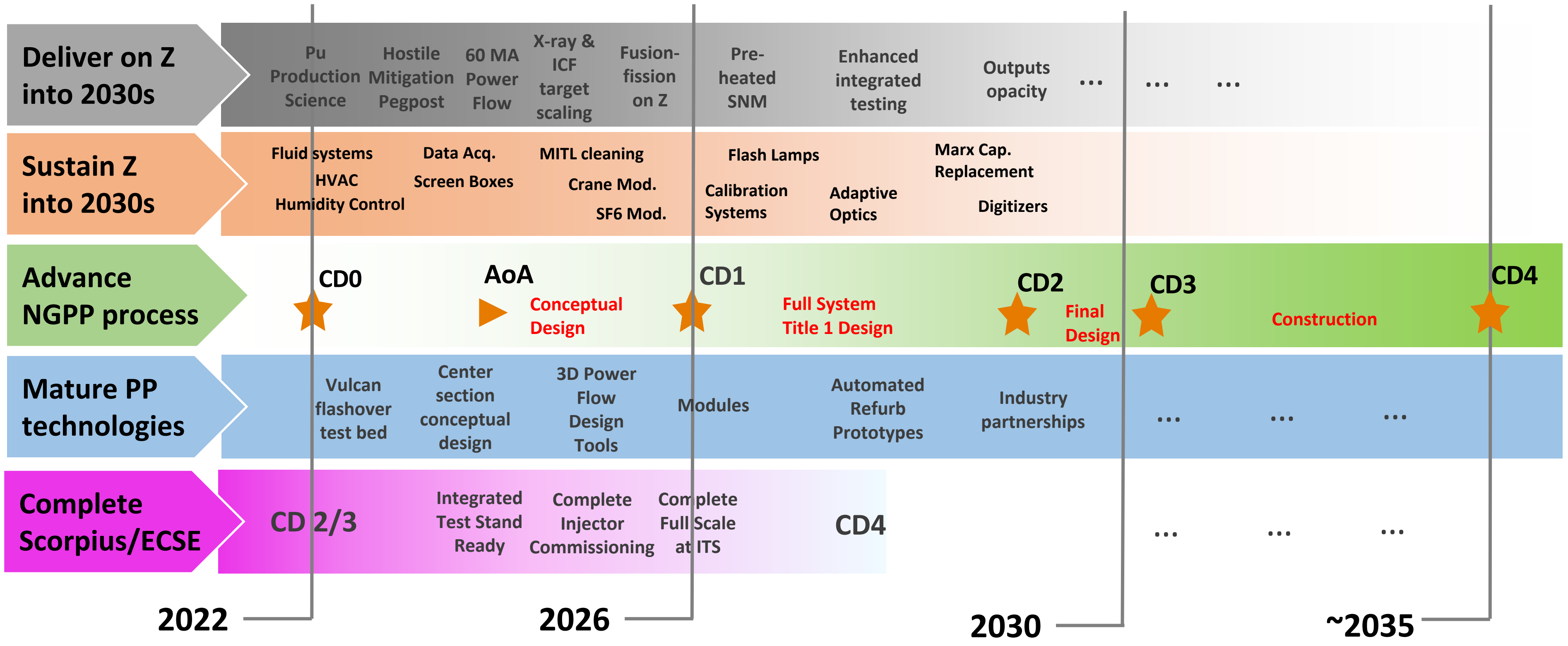
Assured Survivability and Agility with Pulsed Power (ASAP) Mission Campaign ($40M FY20-26)

New Maxwell Fellowship opportunity (2 awarded in 2022)

We are working on industry partnerships now

Capacitor production: General Atomics, etc.
Energy storage architectures: LLNL, etc.

Pulsed Power Sciences Center planning at Sandia sustains the science on Z into the 2030s while we advance towards NGPP

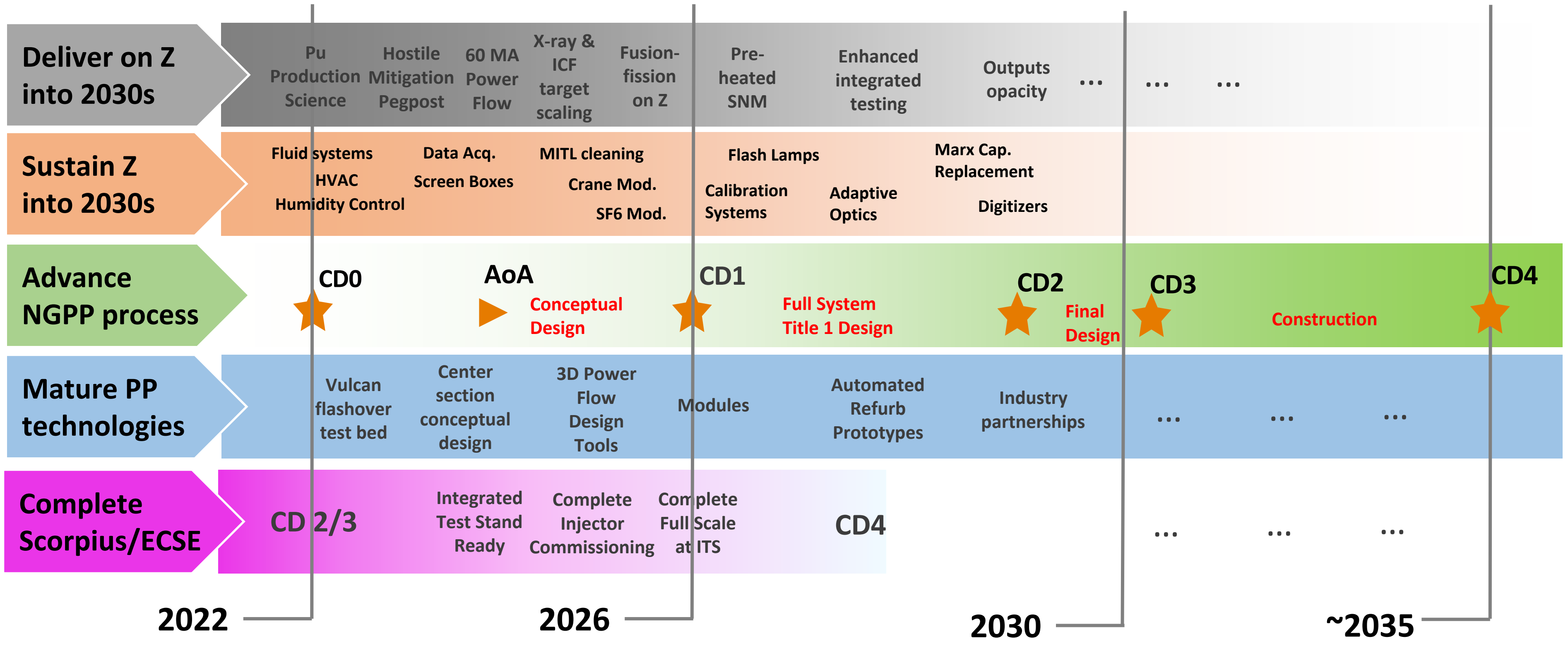


There are two major transitions that we are paying attention to

1) Transferring staff/expertise from the ECSE/Scorpius project to the NGPP project (and module development)

2) Transition from Z operations and staffing to NGPP operations—avoid a capability gap and maintain expertise

Our planning in the Pulsed Power Sciences Center sustains the science on Z into the 2030s while we advance towards NGPP

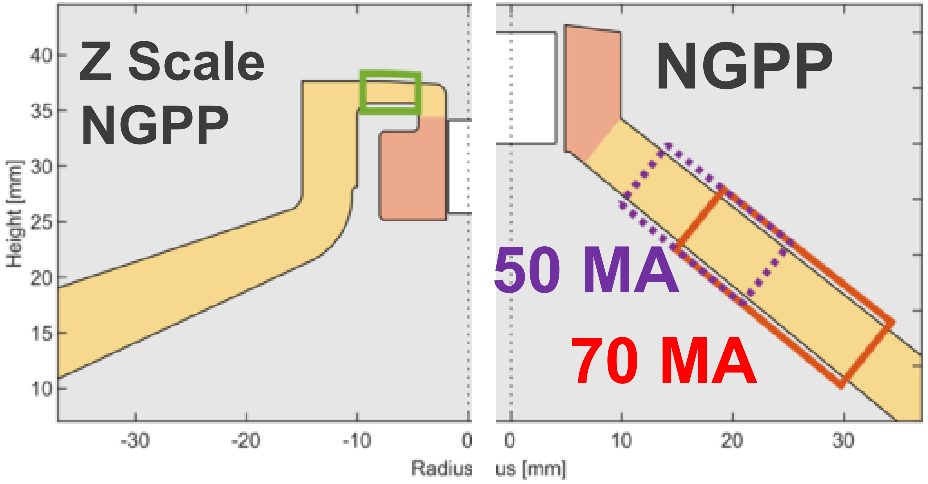


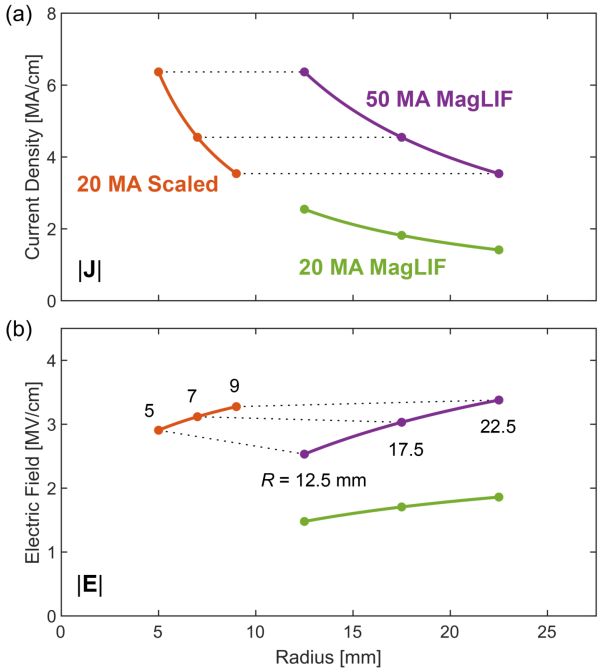
Questions?

dbsinar@sandia.gov

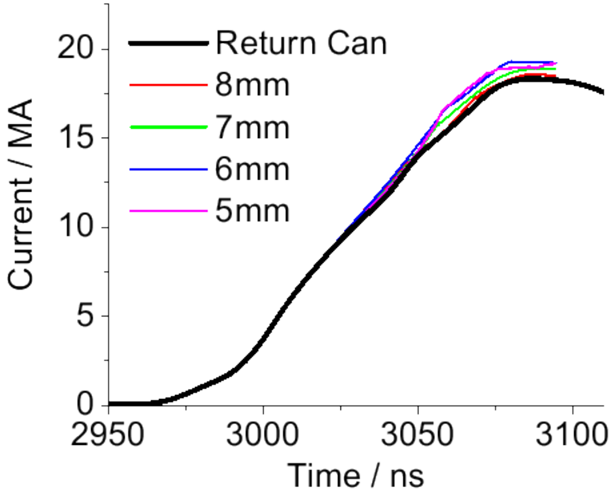
We have been executing scaled experiments on Z that replicate conditions representative of those found on NGPP to test the power flow

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

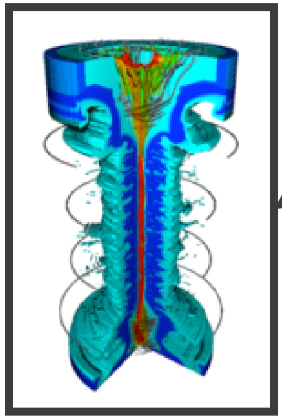


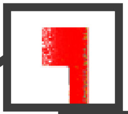


Conditions match nominal current density and electric fields

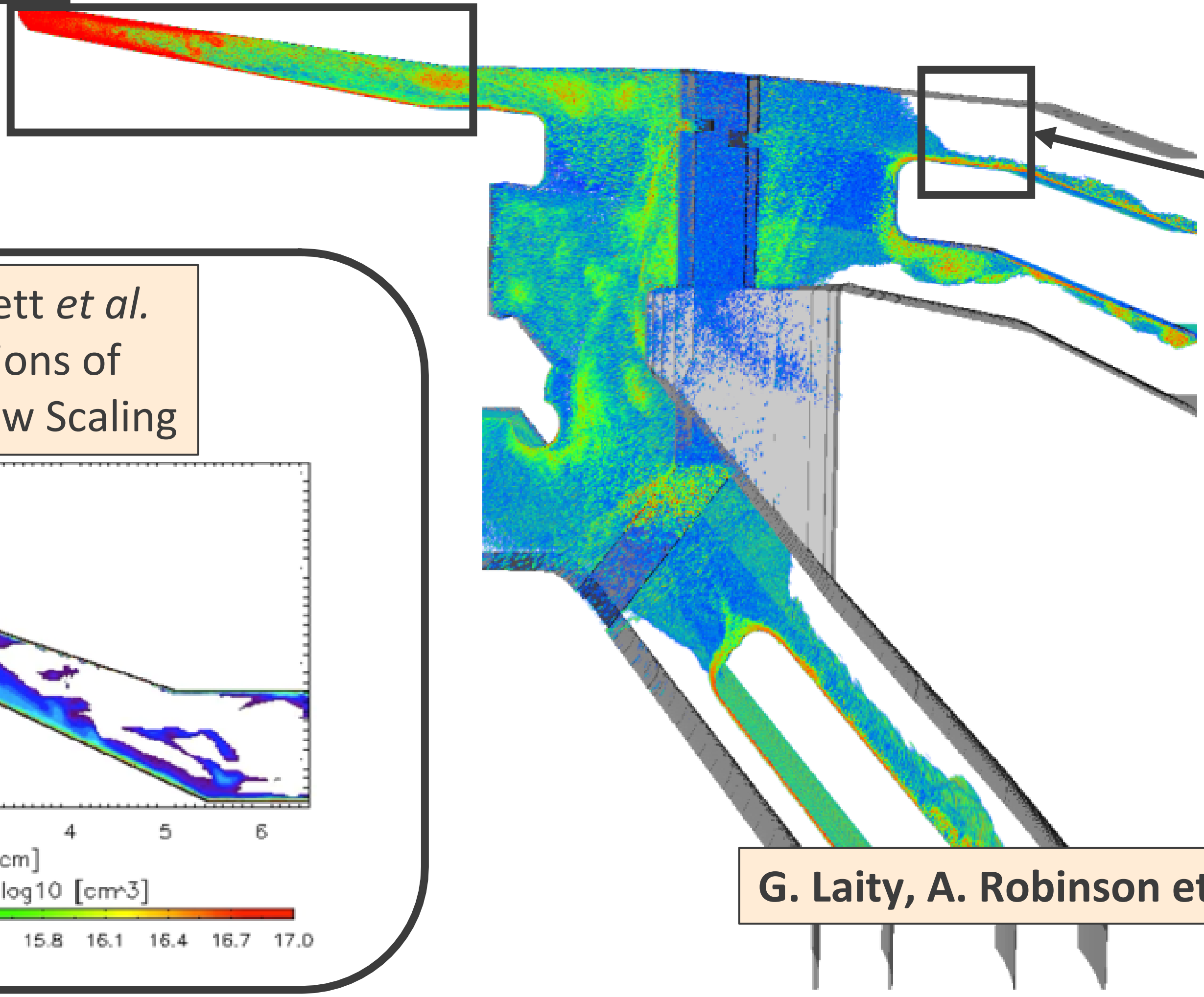


Advances in PIC/FLUID hybrid modeling / surface science for full system multi-scale modeling capability are now used for predictive power flow design



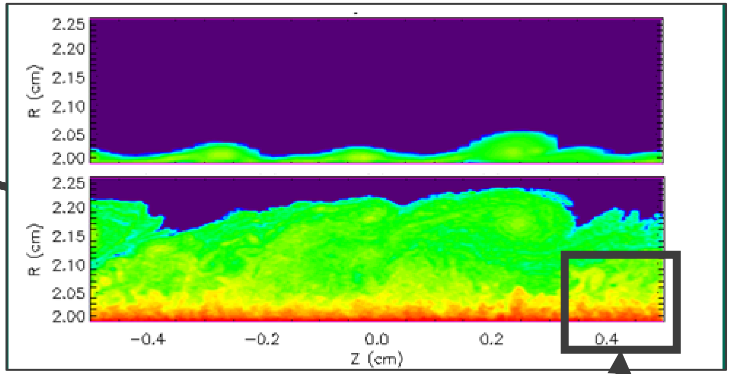


Electrode models feed into models of the full 3D electrode geometry connecting to the load volume



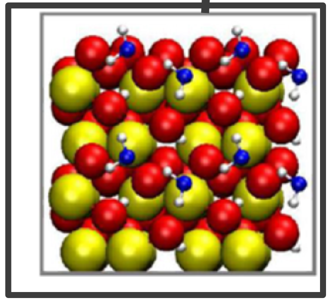
G. Laity, A. Robinson et al, LDRD 2018-2020

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