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PHYSICS INFORMED OPTIMIZATION OF PULSED POWER INERTIAL CONFINEMENT FUSION

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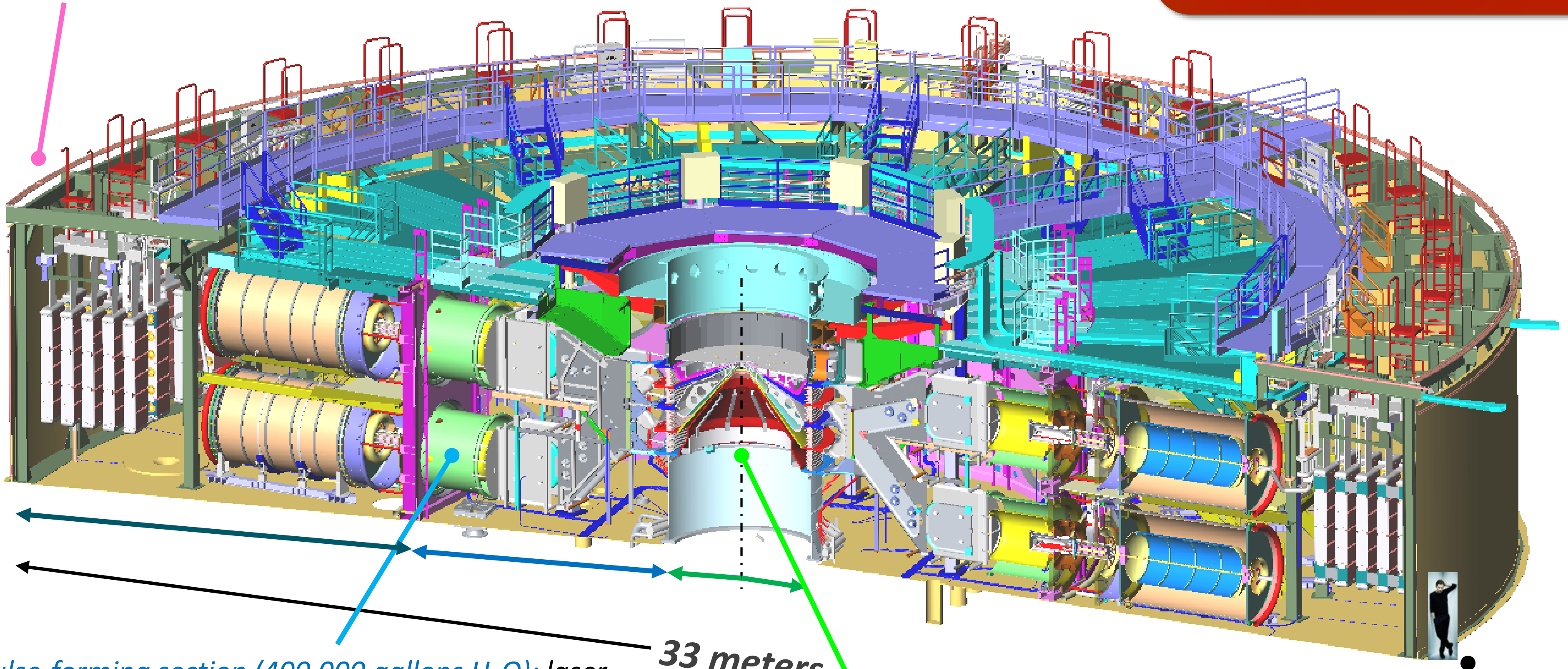
Z Machine at Sandia

To data, ICF program has only used a fraction of Z's design capability.

energy storage section (600,000 gallons oil): stores 23 MJ in 36 banks of 60 capacitors (each 2.3 µF), charged in parallel (90 kV), discharged in series (5.4 MV)

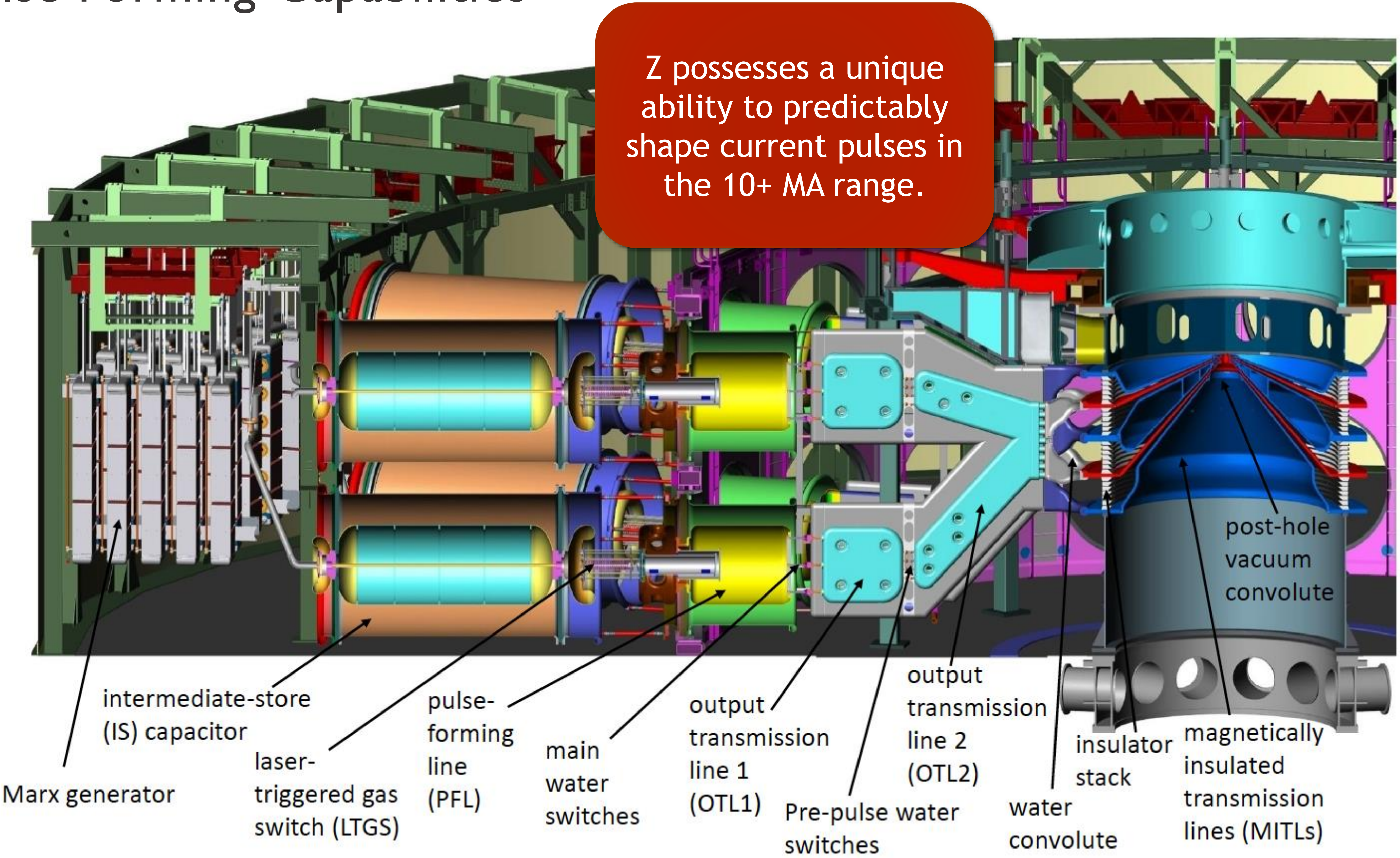


pulse-forming section (400,000 gallons H_2O): laser-triggered SF_6 gas switches & H_20 spark-gap switches compress pulse to 100-1500 ns rise time, tri-plates reduce 36 lines to 18, convolute reduces further to 4 radial feed gaps

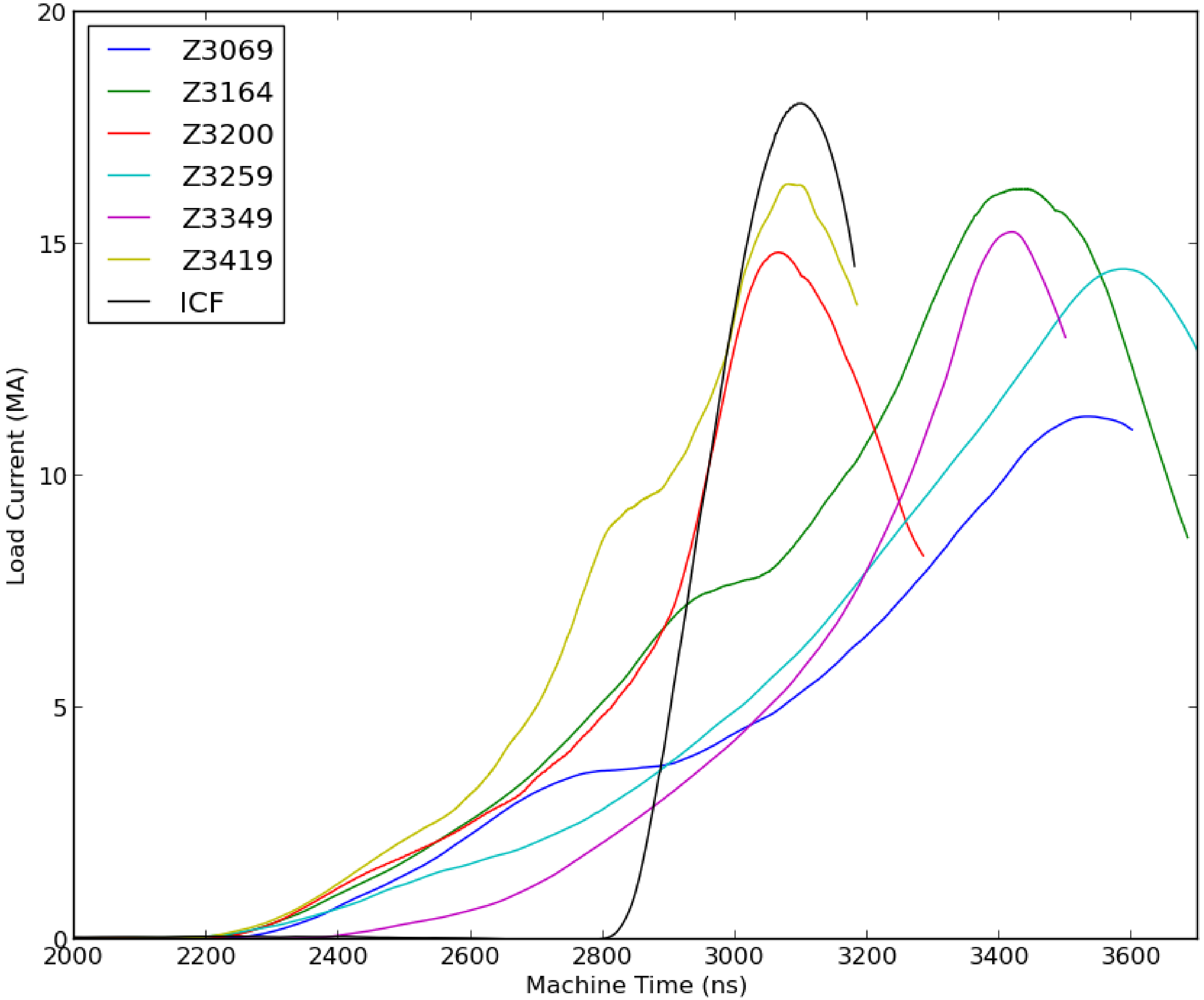
center section (10^{-5} torr vacuum): ***magnetically insulated transmission lines (MITLs) deliver up to 26 MA to the load; convolute reduces 4 feed gaps to 1***

Cumberbatch for scale

Pulse Forming Capabilities



Materials program had used pulse shaping to ramp compress samples to HED conditions for over a decade



A wide variety of custom designed pulse shapes are possible.

Identifying target pulse shapes for DMP is easy. What is the goal for ICF?

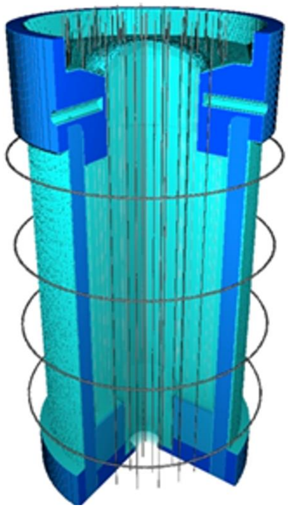
Large parameter space just from Z

Variable	Number on Z	Parameter Space
Basis time shift	36	-250 to 600 ns (5 ns increments)
Basis pulse shape	36	7 options
Marx charge	1	55-85 Volts, 5 Volt increments
Marx triggering delay	9	Boolean
Marx triggering delay time	1	0 to 500 ns (5 ns increments)

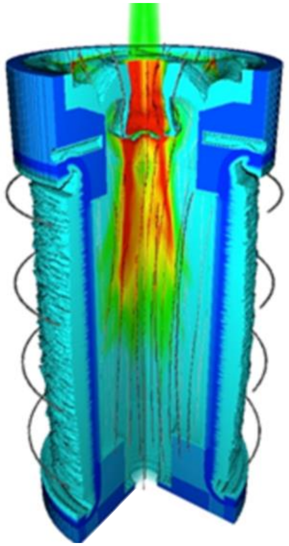
Parameter space consists of more than 80 discrete variables that are manually adjusted with expert insight.

What is the design goal?

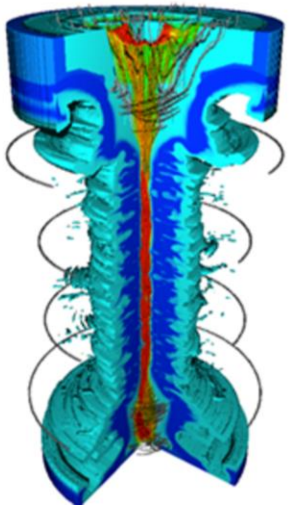
MagLIF (Magnitized Liner Inertial Fusion)[1]



- **Premagnetization[2]: 10-20 T quasi-static axial magnetic field, $B_{z,0}$, is applied to thermally insulate fuel**



- **Laser preheat[3]: The fuel is pre-heated using the Z-Beamlet Laser (4 kJ)**



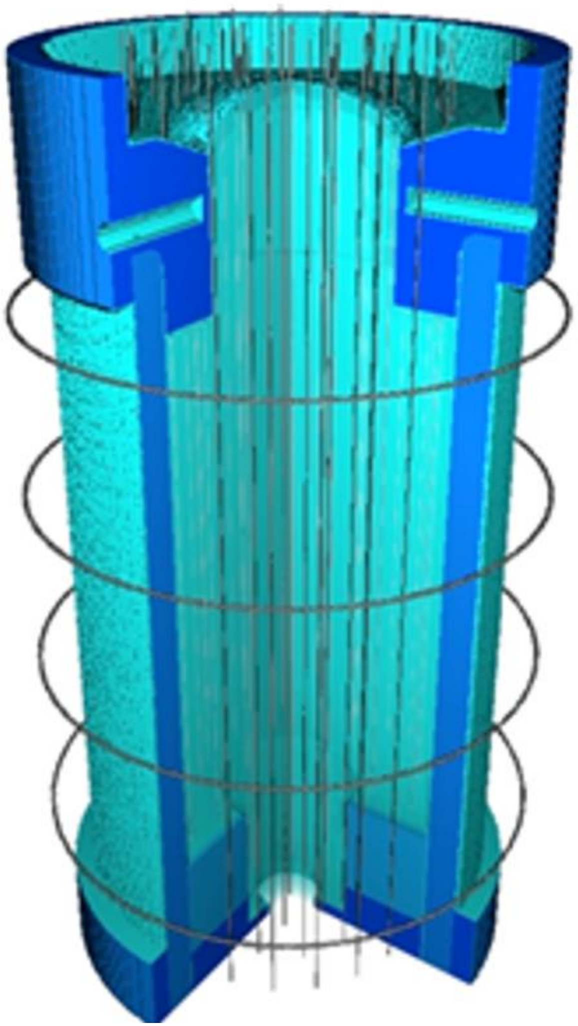
- **Compression: Z Machine drive current implodes liner, ~18 MA in ~100 ns**

[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010). [2] Rovang et al., Rev. Sci. Instrum. **85**, 124701 (2014). [3] Harvey-Thompson et al., Phys. Plasmas **26**, 032707 (2019).

Cylindrical target design constraints that can be optimized

- Liner inner radius
- Liner thickness
- Liner aspect radio (good metric of implosion stability)* = OR/thickness
- Laser preheat timing (MagLIF)
- Liner height (can affect preheat depth)
- Initial input field strength (MagLIF)
- Fuel density

Z can't compress any faster. Is there a benefit to slower liner compression?



*Shipley, *et al.* "Analysis of instability development in quasi-isentropically compressed cylindrical liner implosion simulations" later in this session.

Previous exploration of "shockless" liner compression for MagLIF

- McBride *et al.** outlined several advantages of shockless liner compression in 2013:
  - More hydrodynamically efficient (less wasted energy through shock heating of liner material)
  - Lower liner temperature (lower adiabat) could result in higher liner density
  - Delaying liner shock results in solid inner liner material later in time; possible MRT resistance
  - Lower liner temperature/electrical conductivity results in more efficient magnetic flux compression, functionally increasing compressed field at fixed input field
  - Solid inner liner can reduce liner-fuel mix
  - Longer pulse shapes lose less energy to pulse compression, potentially increasing the total energy coupled to the liner
  - Longer rise times are more favorable to future, larger pulsed power drivers
- A "shockless" current profile is easy to design, but all other target dimensions are chosen and locked in.
- Longer cylindrical implosion times are generally considered to be less stable, but that could be overcome with the above advantages

*R.D. McBride *et al.*, Beryllium liner implosion experiments on the Z accelerator in preparation for magnetized liner inertial fusion, Phys of Plasmas **20**, 056309 (2013)

Defining an experiment

NOW

- All existing MagLIF designs use 100 ns current rise times.
- Shockless liner current pulses have not been studied in-depth for some years, partly because the range of current pulse shapes is so immense and little target design criteria is specified.

Near Future

- Metric-defined intuitive target goals
- Pulse shapes are designed by optimization software to meet **metrics**, not to identify a narrowly defined class of current pulse (i.e. "shockless" implosion)
- Liner dimensions & laser preheat time can be optimized alongside pulse shape.

Code Workflow

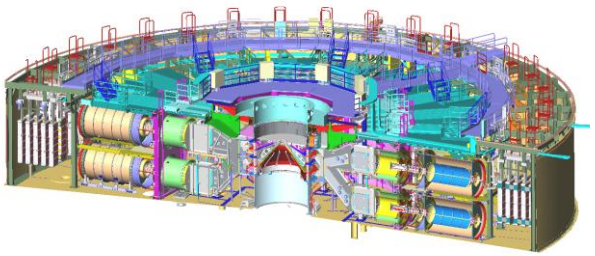
Dakota-MAD
- Calculate present response based on metric weights and aspirational targets
- Choose new input parameters or quit

Z Circuit Model
- Produce current vs time waveform

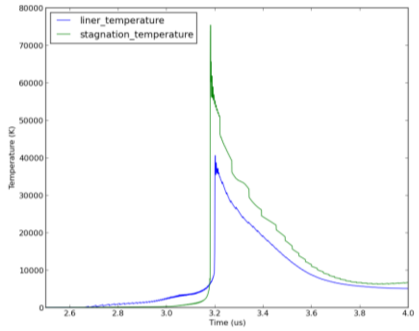
1D/1D+ MHD
- Drive liner/preheat configuration
- Generate metric-relevant data

Python Wrapper
- Calculate resulting metrics
- Feed data to Dakota-MAD

1: liner temperature
2: stagnation (fuel) temperature
3: current “smoothness”



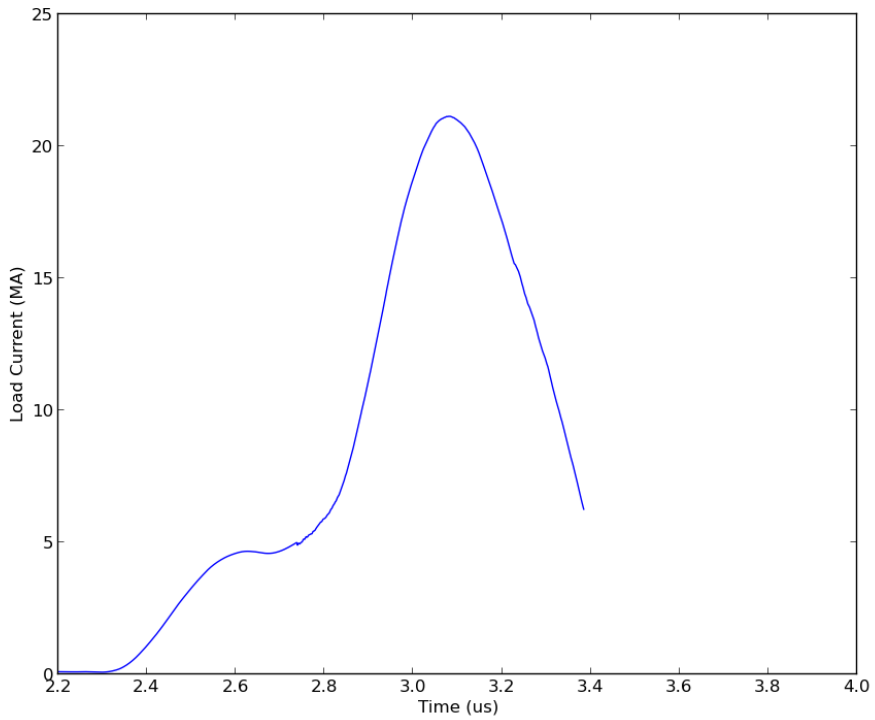
IR = 5.000 mm
thick = 0.700 mm (AR = 7.14)
D2 density = 1.0 g/cc
no preheat
no applied Bz



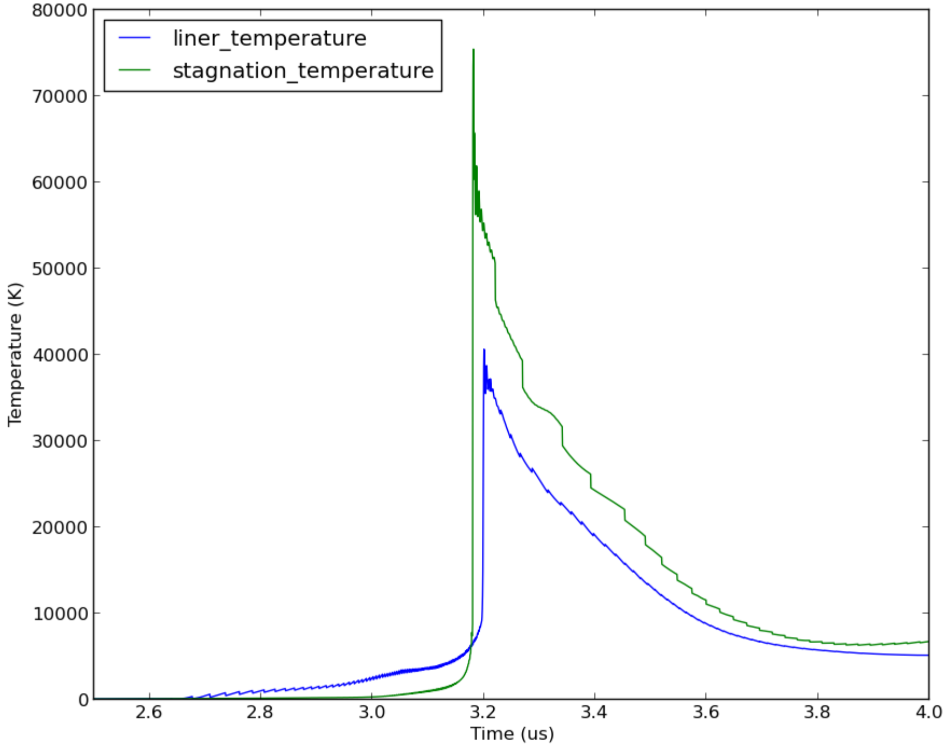
Sandia optimization code **Dakota** used with a mesh adaptive search algorithm to drive scripted workflow.
Rather than *one* bespoke design, *thousands* are generated and the “best” is identified automatically.

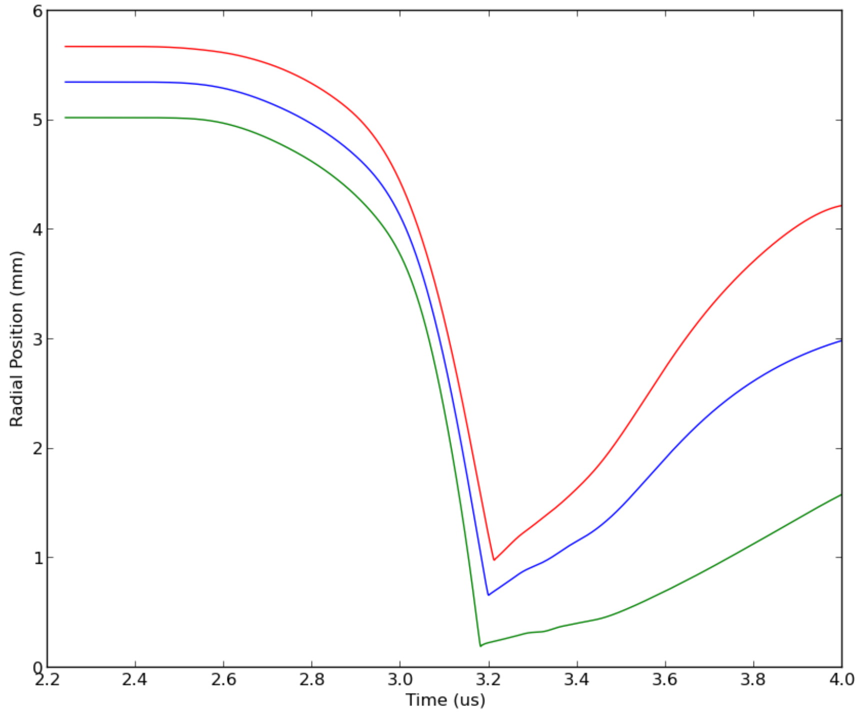
Initial test case

- Started with standard ICF pulse (100 ns rise)
- Develops a double-hump structure that delays liner shock to 3000 ns
- Outcome driven by current "smoothness", i.e. to stretch current pulse forward
- Demonstrates feasibility of concept



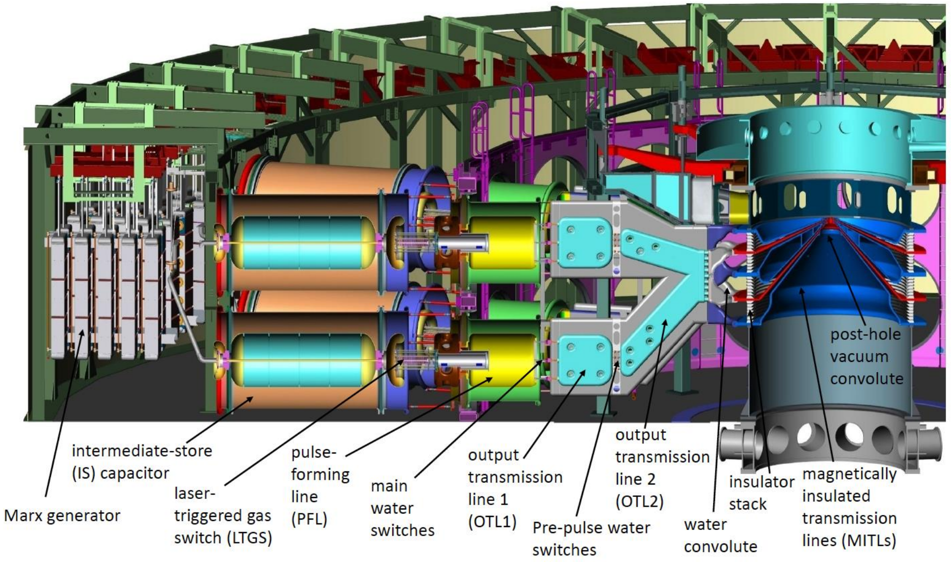
Higher dim. liner model that captures applied Bz and heat loss in development.

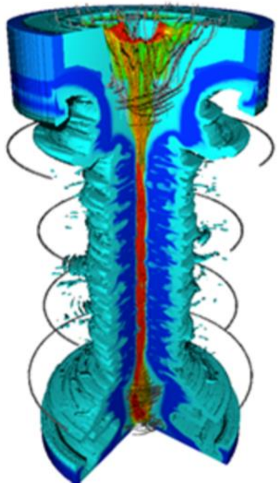




Conclusion and Future Work

- This framework represents an exciting new capability for expanding the possibilities for MagLIF into exciting new directions that may address present limitations.
- This method may be a way to increase implosion stability of high AR liners.
- Metric selection is the biggest challenge: what is realistic and what really matters?
- Increased dimensionality models will optimize with preheat and applied Bz.





Utilizing all the capabilities of Z

Abstract

Pulsed power driven inertial confinement fusion (ICF) targets in the 20 mega-ampere regime have almost exclusively been driven by pulse shapes with 100 ns rise times that incur significant current loss and shock the imploding cylindrical liner, melting the entirety of the liner material. The Z Machine at Sandia National Laboratories allows for modification of the current pulse to accurately distribute energy delivery over time, potentially decreasing current loss in the process. The major barrier preventing application of pulse shaping technology to pulsed power ICF has been identifying tractable metrics for the pulse shape. We present progress on an automated design framework that uses numerical optimization, as applied to the ICF MagLIF target, to modify pulse shape, liner thickness, liner aspect ratio, liner melt condition, initial magnetization, and laser preheat time to optimize metrics such as stagnation pressure/temperature, burn duration, etc. Results from the optimizer for different metric weights/goals as well as feasibility of target designs will be discussed.