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Sandia National Laboratories

22 September 2016

Current-adder pulsed power generators for high-pressure dynamic material studies

D.B. Reisman, E. M. Waisman, B.S. Stoltzfus, K.N. Austin, W.A. Stygar, T. Ao, D.V. Morgan (NSTec), M.E. Cuneo, L. Collier, T.A. Haill, R.J. Hickman, J.-P. Davis, J.L. Brown, C.T. Seagle, T. Mulville, E. W. Breden, P.D. Gard, and R.B. Spielman (ISU)

Presented at
Megagauss 2016

Sandia National Laboratories

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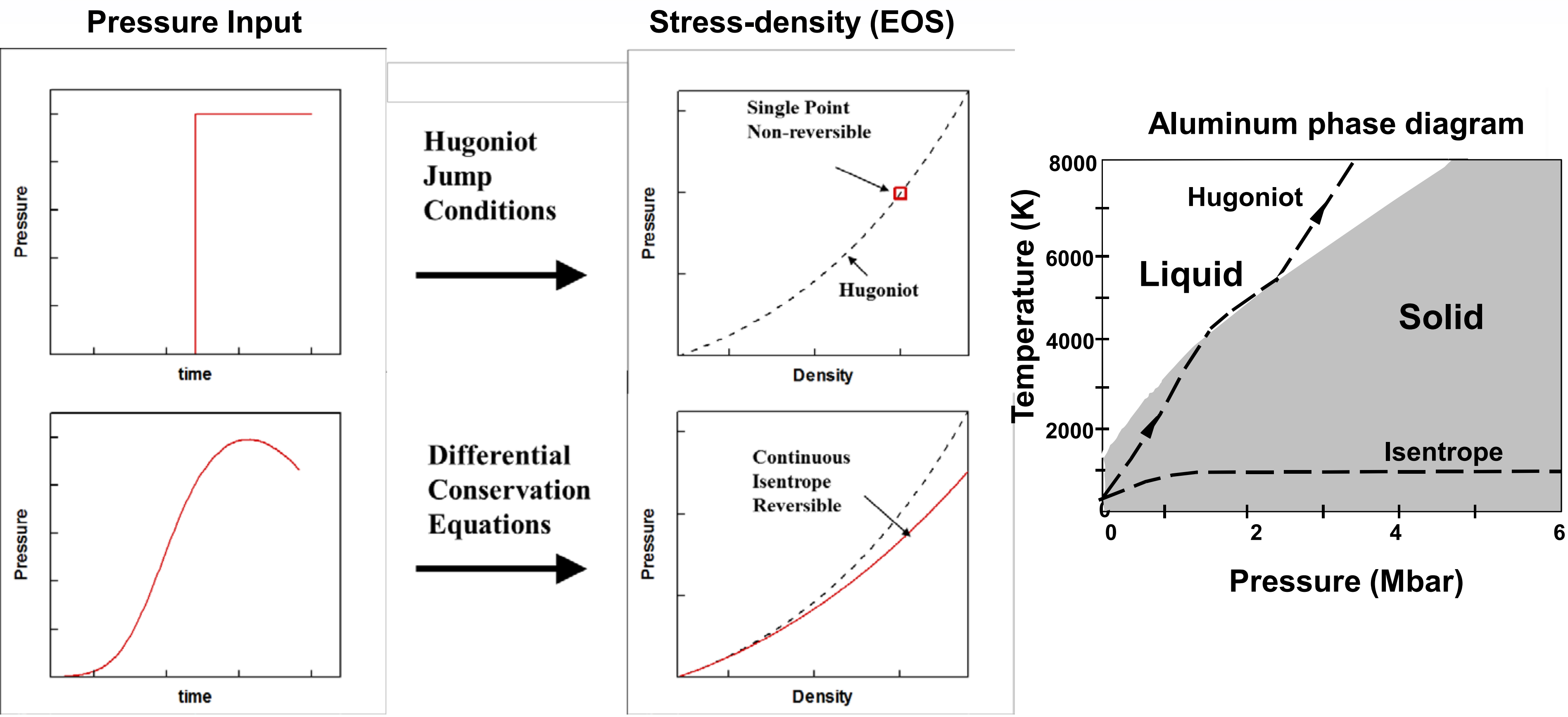
Shock and isentropic compression experiments access different material regimes



- Shock compression: higher-temperature, high-pressure
- Isentropic compression: low-temperature, high-pressure
- Valuable for Equation of State (EOS) studies

Z and other pulsed-power machines are used to drive material-physics experiments.

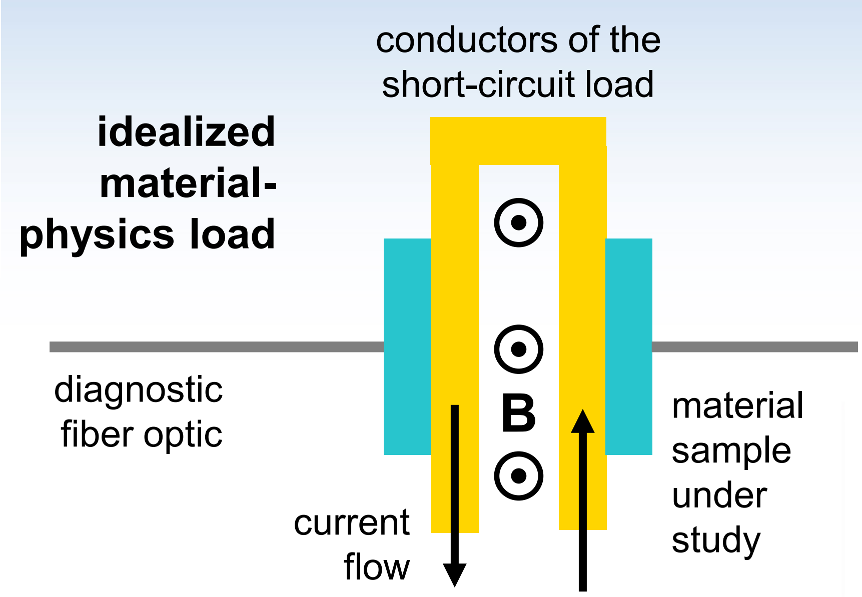
- The magnetic pressure generated within a short-circuit load drives the experiment.
- A smooth pressure profile can be guaranteed by the circuit
- Velocity measurements are used to determine the isentrope

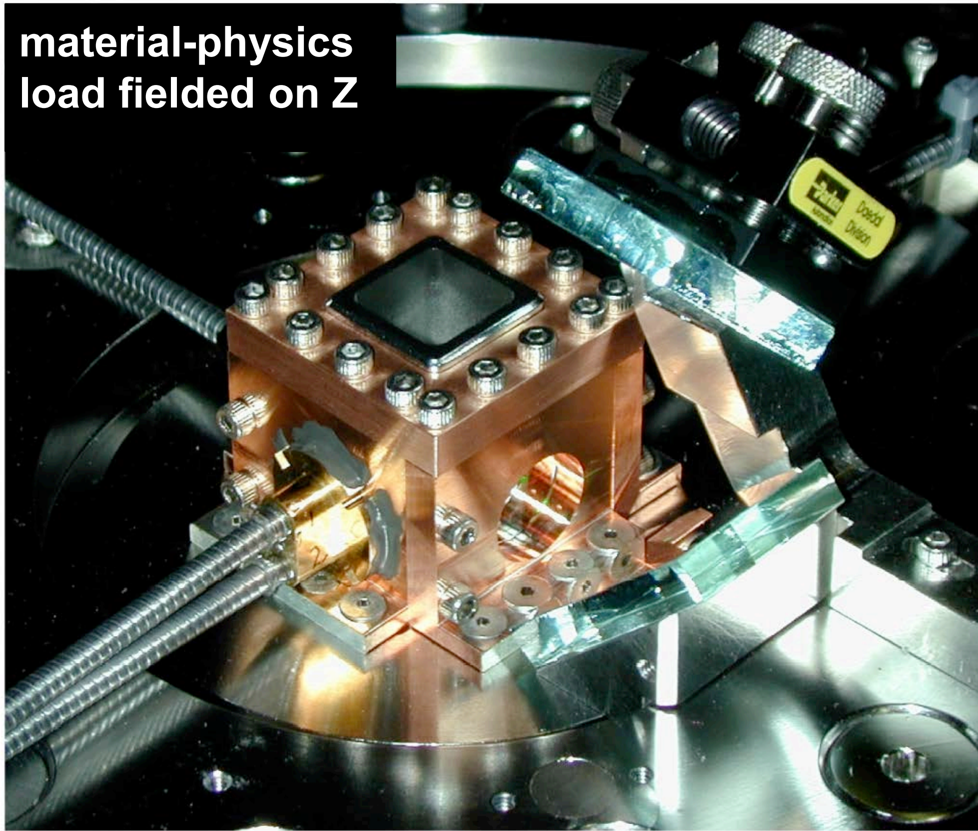
$$P_{magnetic} = \frac{\mu_0 I^2}{2 w^2}$$

I = current

w = width of the conductor

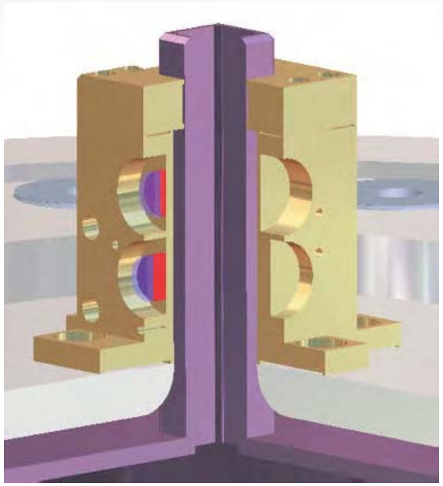
D.B. Reisman , *et al.*, J. Appl. Phys. (2001)
C.A. Hall, *et al.*, Rev. Sci. Instrum. (2001)



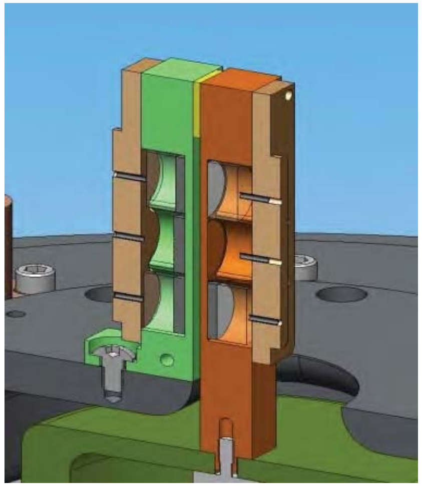


ICE on ZR have been performed on a variety of materials

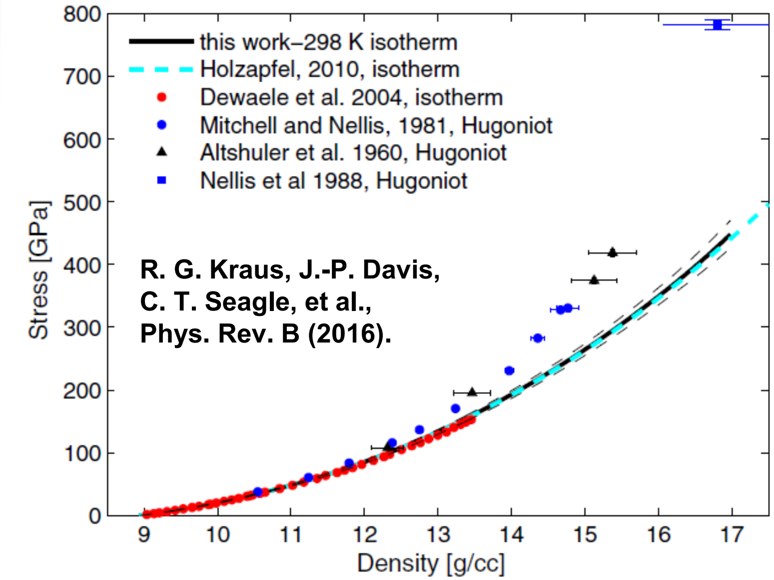
Square Short



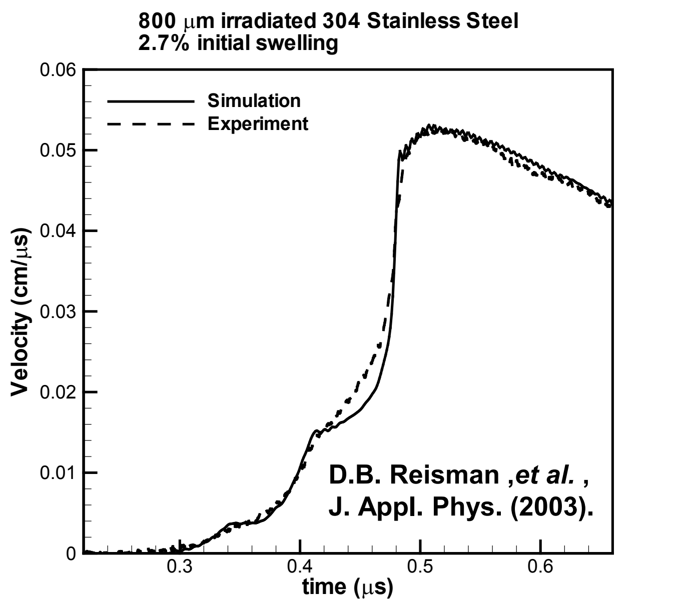
Stripline



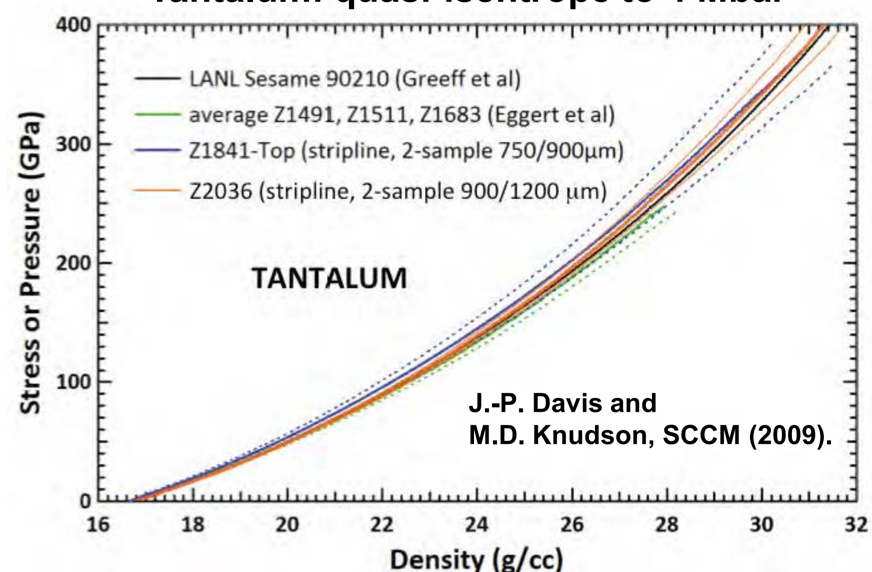
Copper: 5 Mbar reduced isotherm



Validated Void-Collapse Model

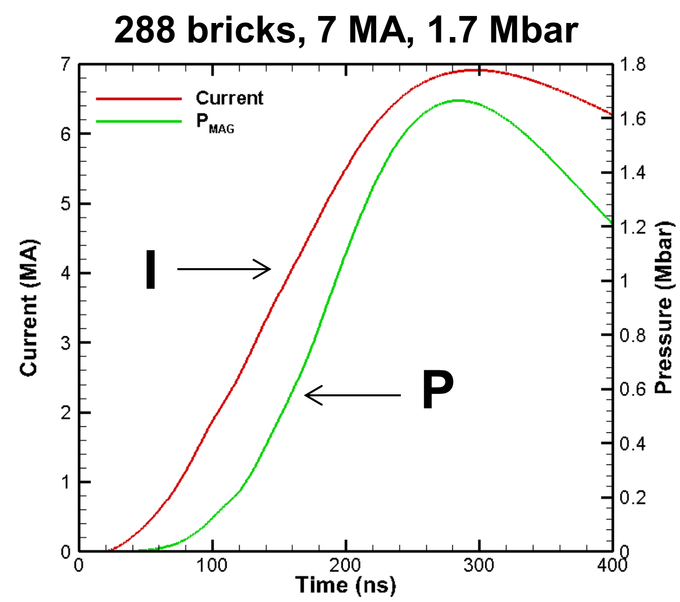


Tantalum: quasi-isentrope to 4 Mbar

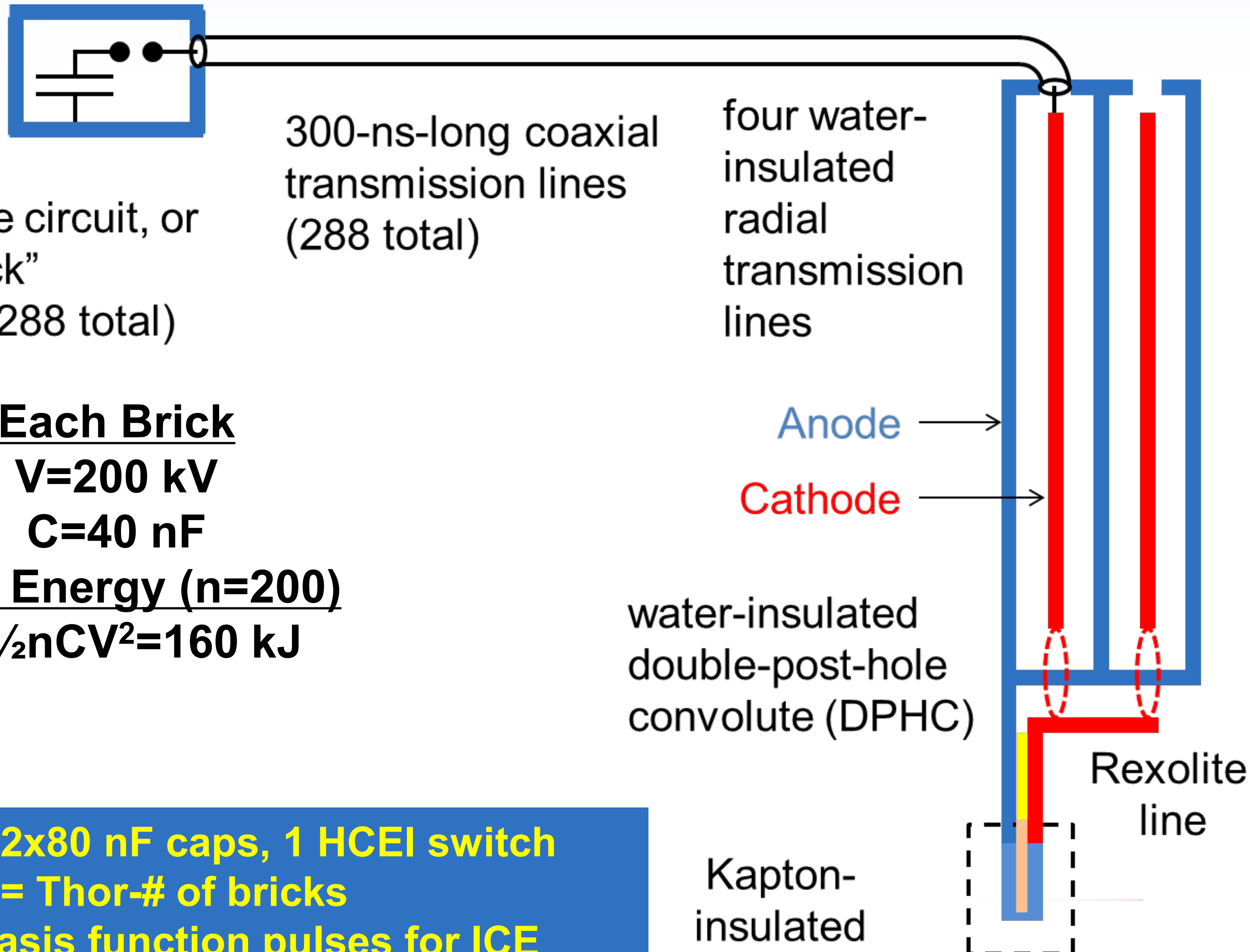


Thor Specifications for a Megabar-class pulsed power accelerator

- Peak current: 7 MA
- Current rise time: 200-500 ns
- Pulse shaping through independent, de-coupled switches
- Megabar+ (100 GPa) peak magnetic pressures
- Enables a variety of experiments:
  - Soft Materials: Cerium, Lithium
  - Flat Top Pulse: Strength
  - Shock-Ramp: Iron
- High throughput – 2+ shots per day
- Cost-effective university-scale machine
- Conditions relevant to geophysics



The Thor concept meets the requirements for a compact, megabar-class ICE driver



<u>Each Brick</u>

V=200 kV

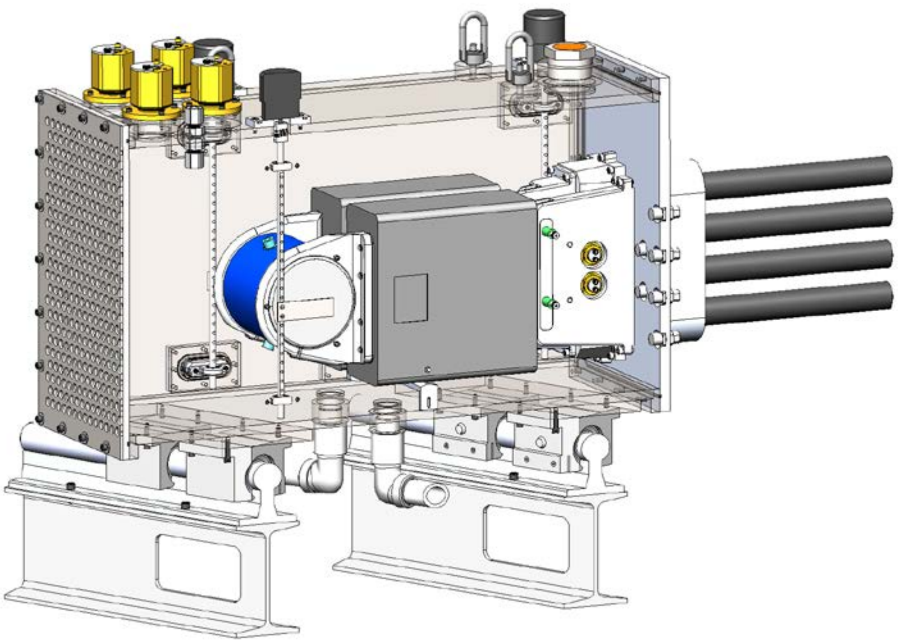
C=40 nF

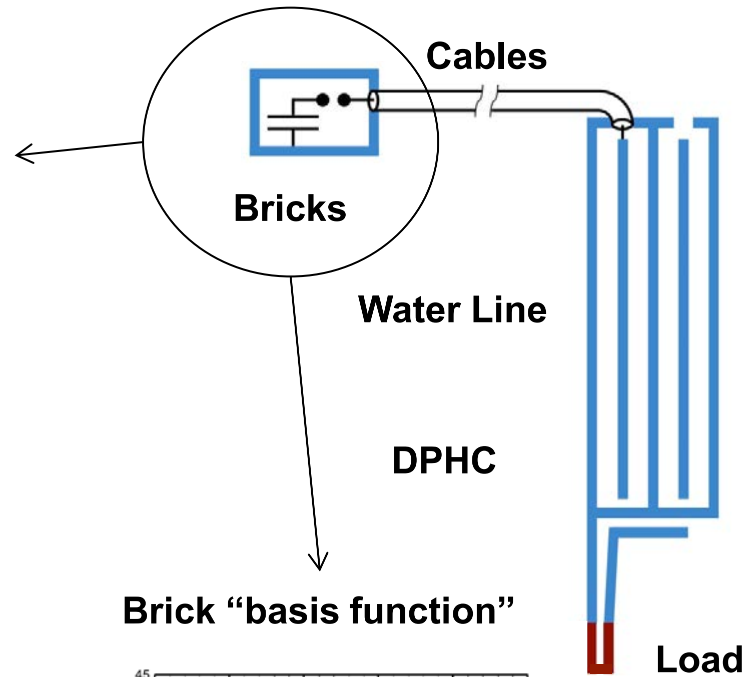
<u>Total Energy (n=200)</u>

$E=\frac{1}{2}nCV^2$=160 kJ

- **Bricks – 2x80 nF caps, 1 HCEI switch**
- **Thor-XX = Thor-# of bricks**
- **100-ns basis function pulses for ICE**
- **Veloce-type stripline loads**

Each Thor brick consists of two capacitors and a switch

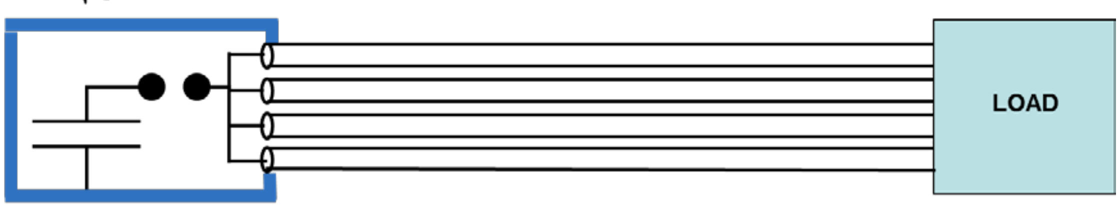




Cables are impedance-matched to bricks

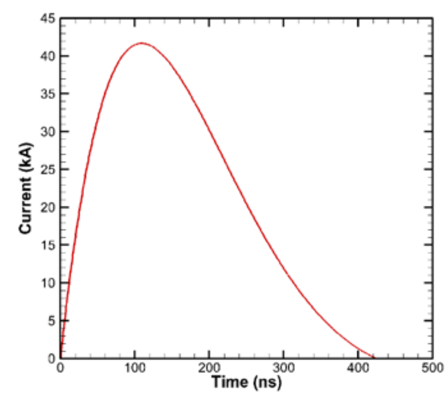
C=40 nF, L=240 nH, R=0.37 Ω

$$Z = 1.1\sqrt{\frac{L}{C}} + 0.8R = 3.00\Omega$$

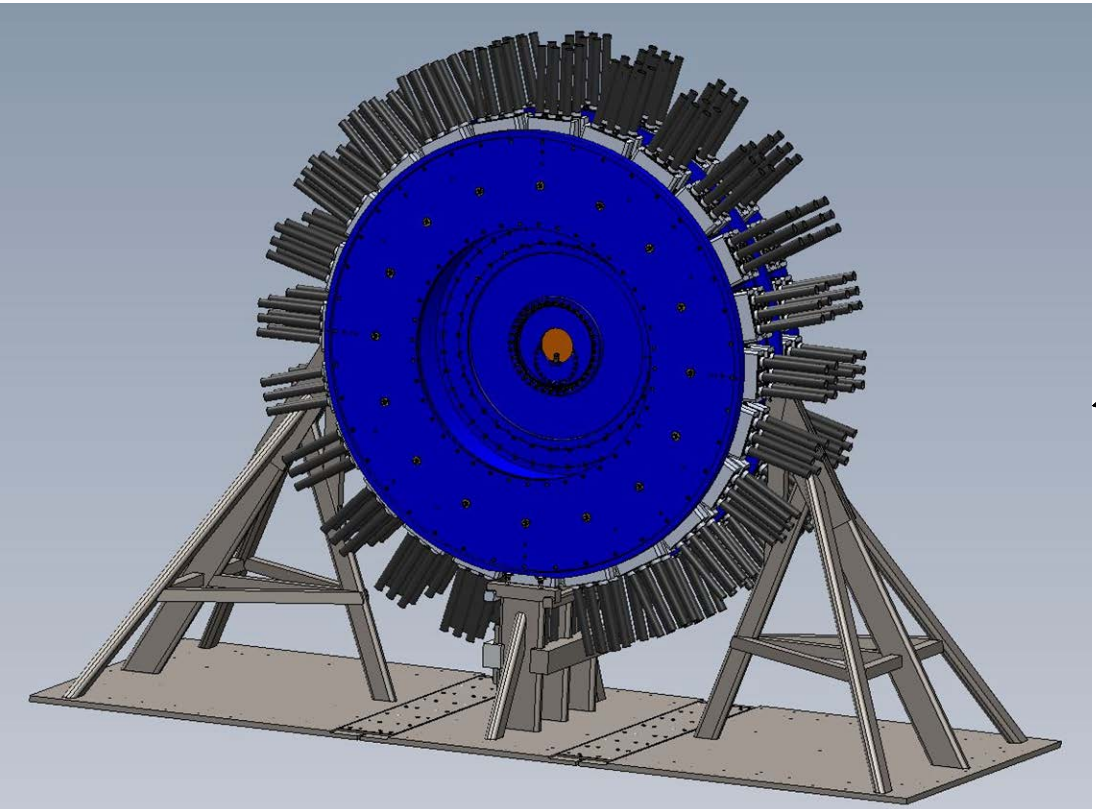


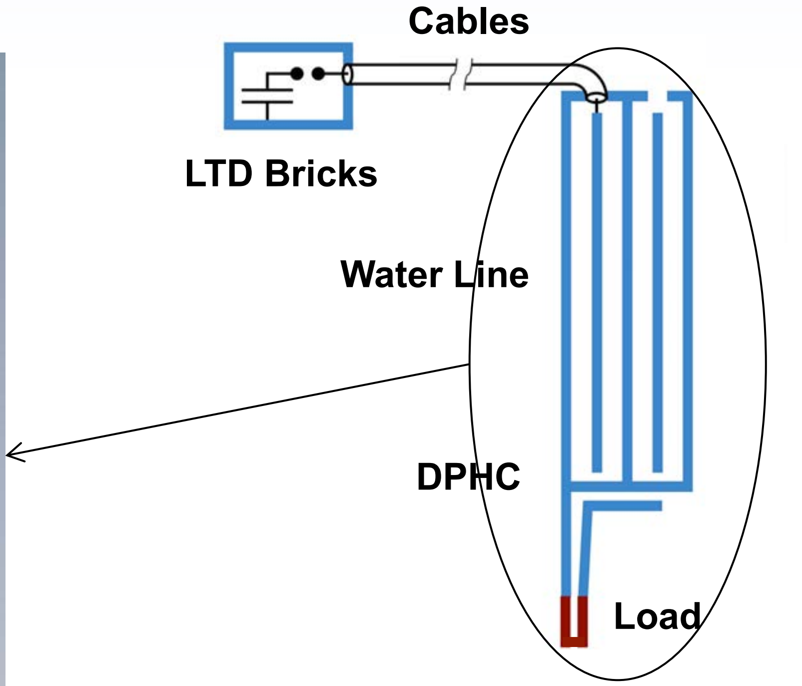
4 x 200 ft. 11.2 Ω Cables
DS-X 1.25 in diameter
Z=2.8 Ω

Brick "basis function"

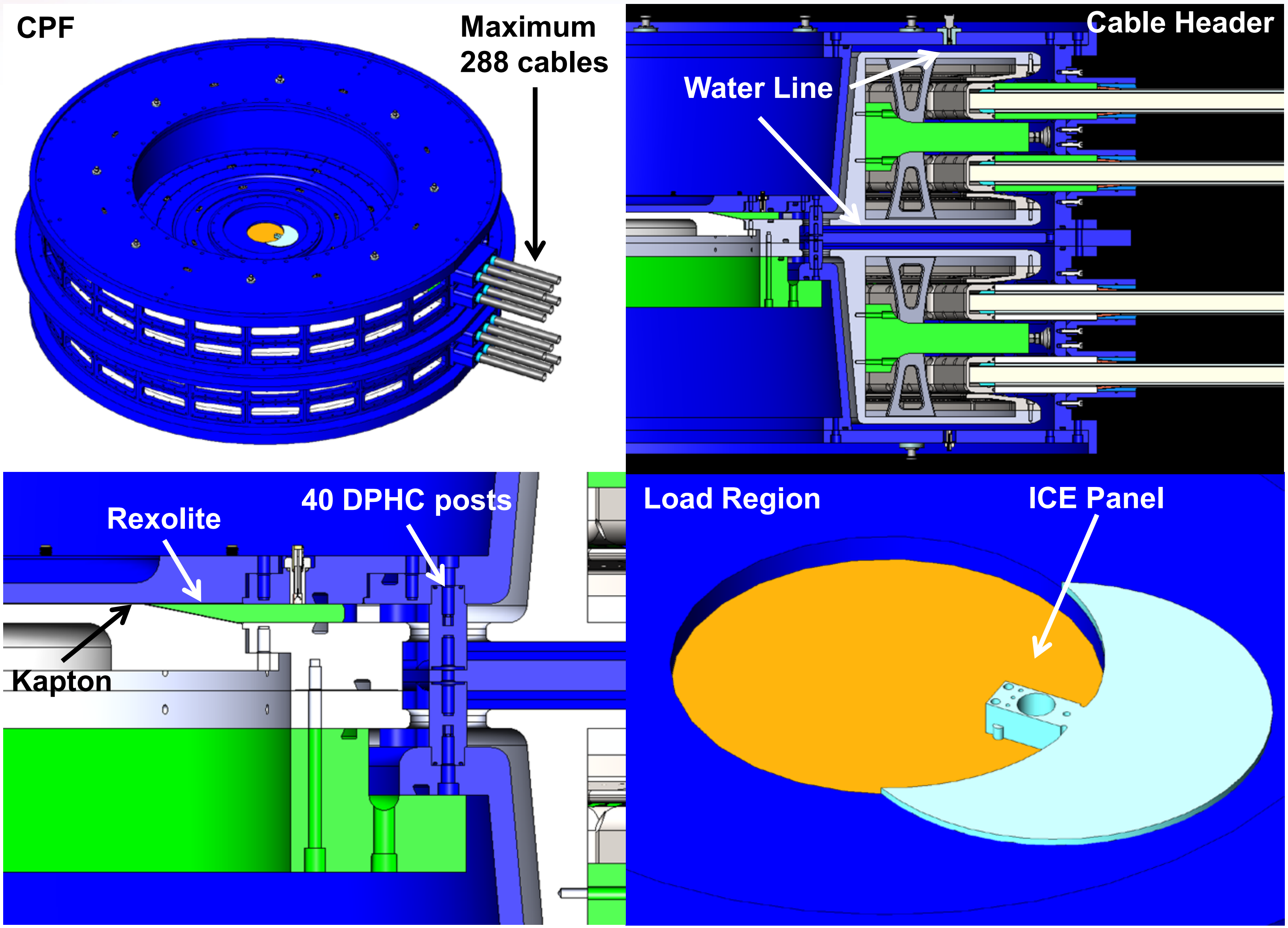


The central power flow (CPF) section is 2 meters in diameter



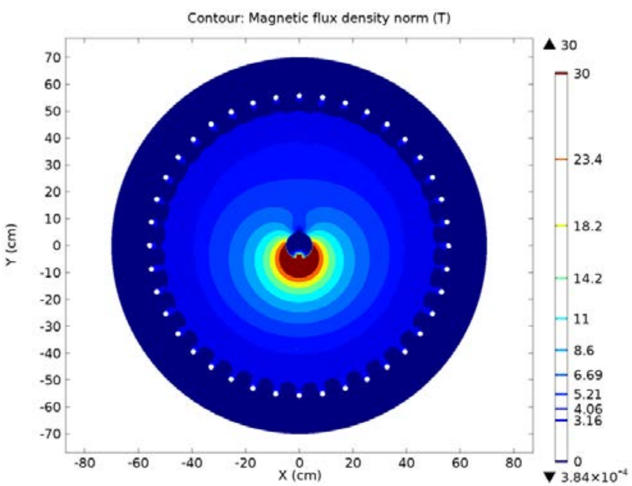


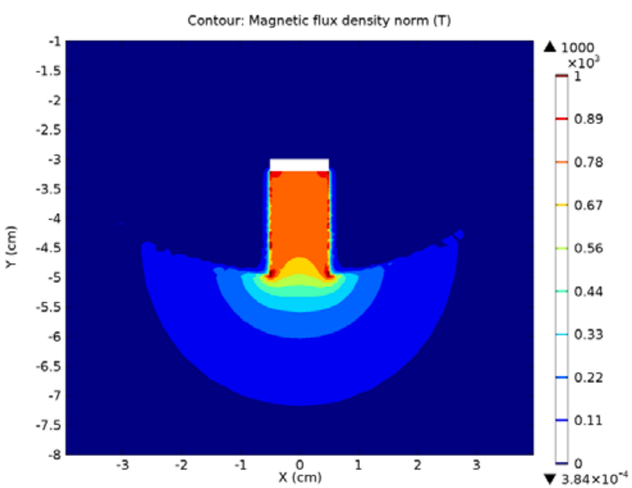
The central power flow (CPF) combines current from the cables into transmission lines



Current is delivered to a strip-line ICE load to maximize magnetic pressure for ICE

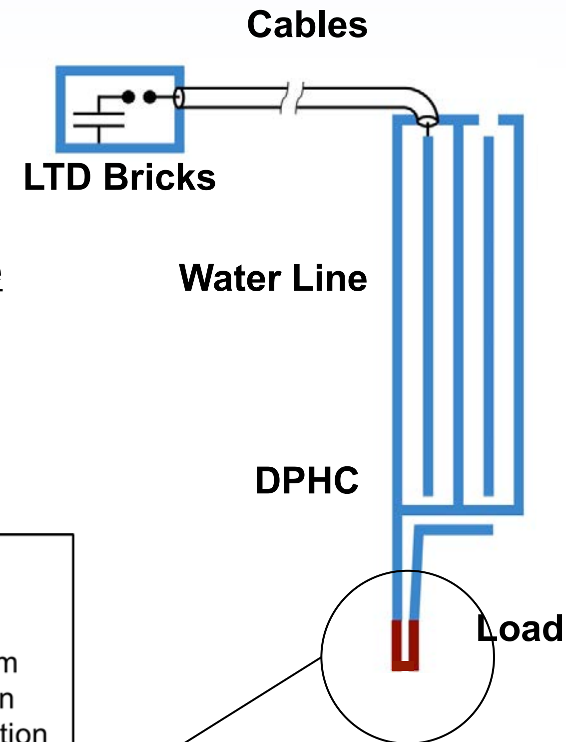
Panel on plate

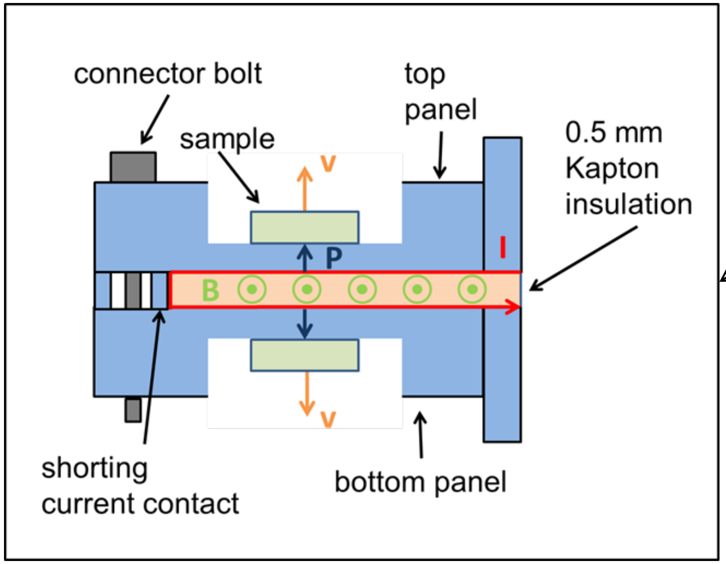




B concentrated into stripline

$$P \sim \left(\frac{I}{w}\right)^2$$



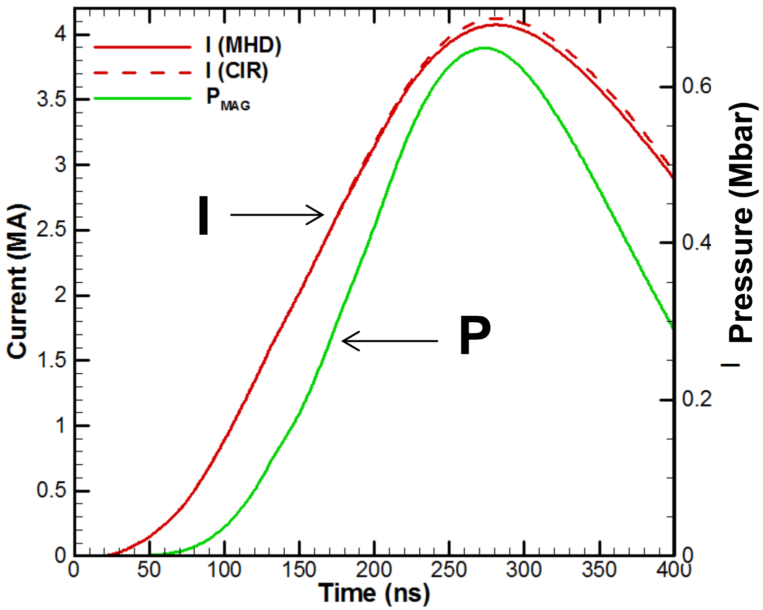


Thor can produce pressures of well over a Mbar

Brick #	Cables per brick	Etot (KJ)	Peak I (MA)	Peak P (Mbar)	Eload (kJ)	Eff. (%)
96	3	76.8	4.1	0.65	27.0	35
144	2	115	5.4	1.1	56.1	49
288	1	230	6.9	1.7	111	48

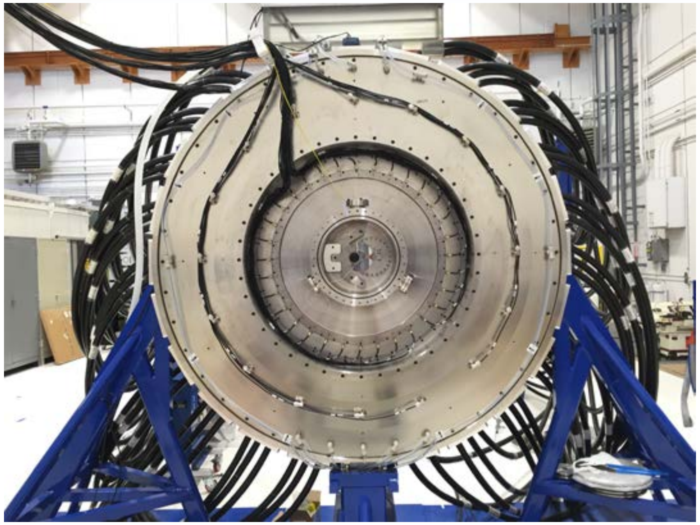
- **4 triggers spaced 50 ns apart**
- **Current rise time ~ 200 ns**
- **10 mm X 20 mm (WxL) Cu panels**

Thor-96
10 mm Cu panels

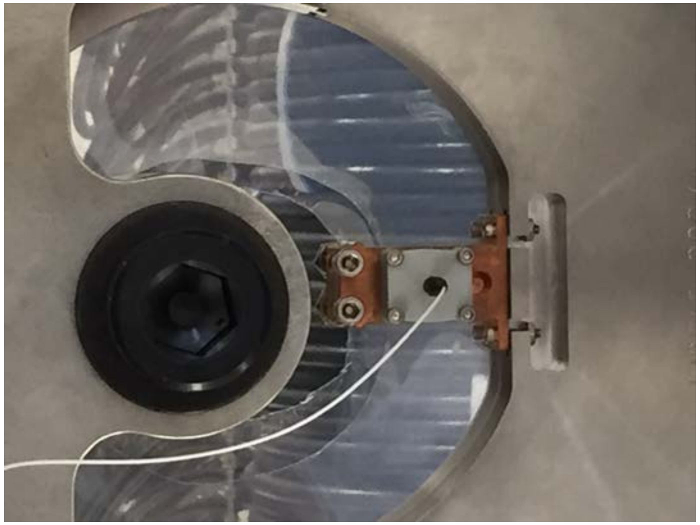


Thor-24 was commissioned in September

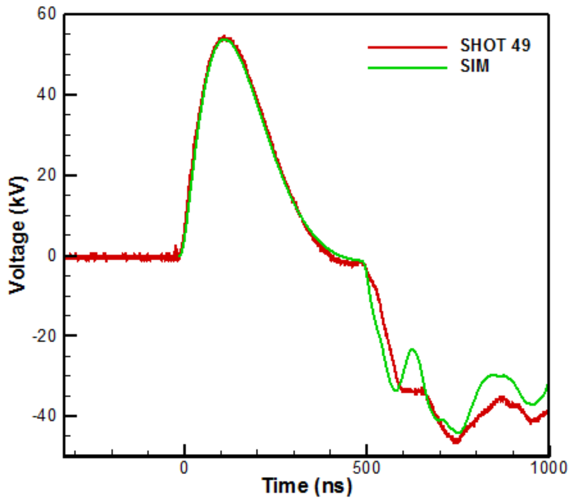
CPF



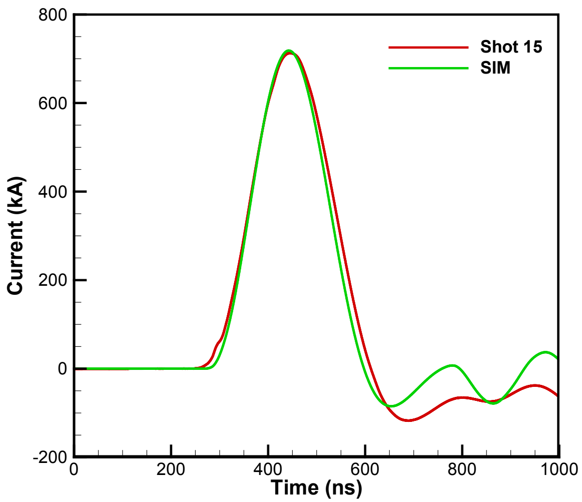
Load region



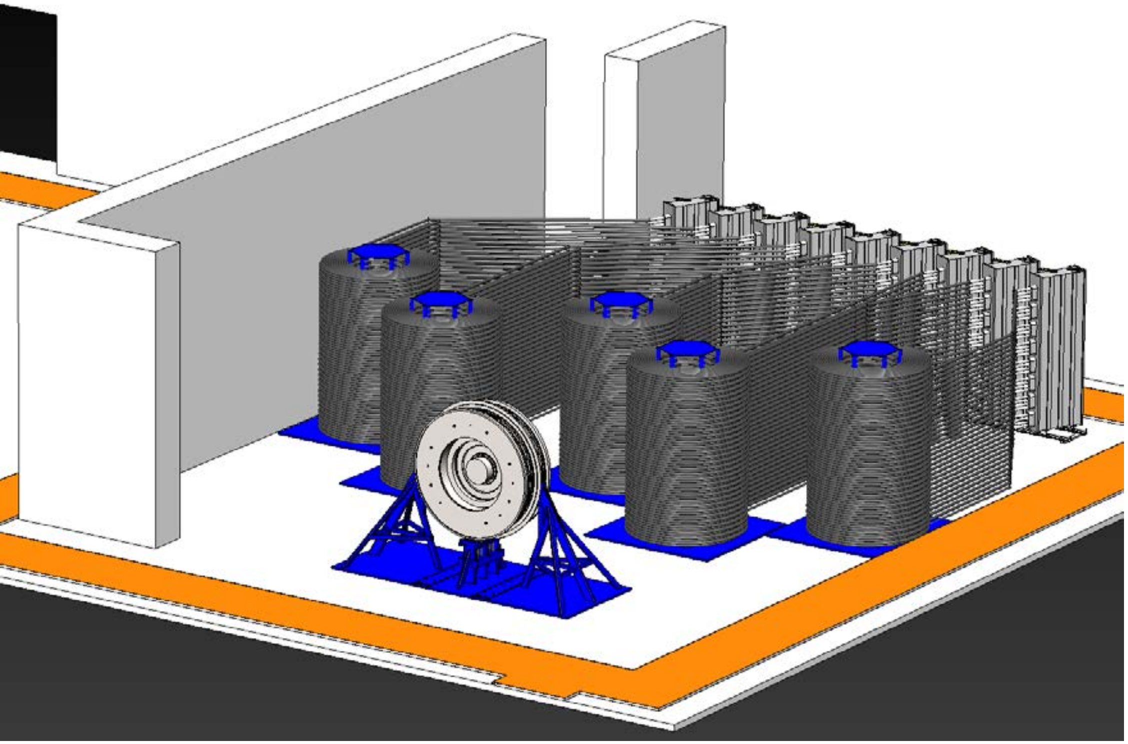
Brick Voltage (±50 kV Charge)

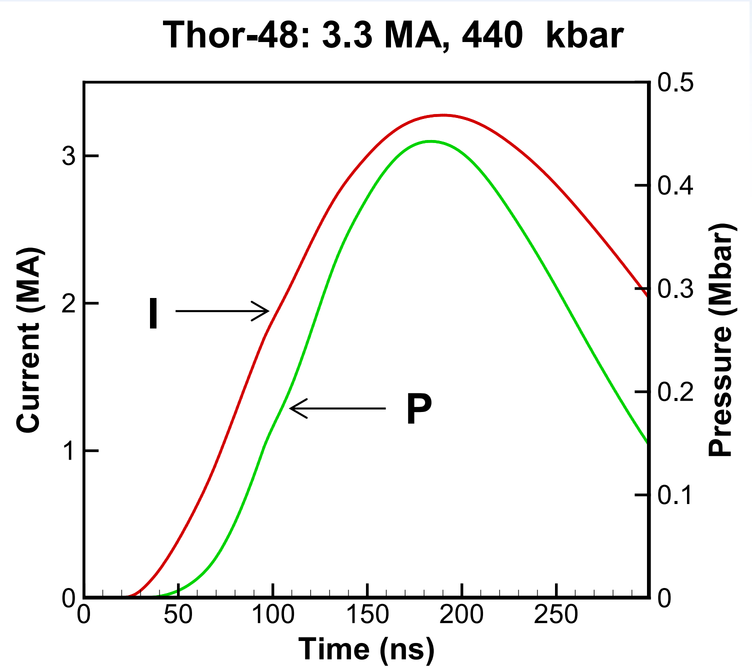


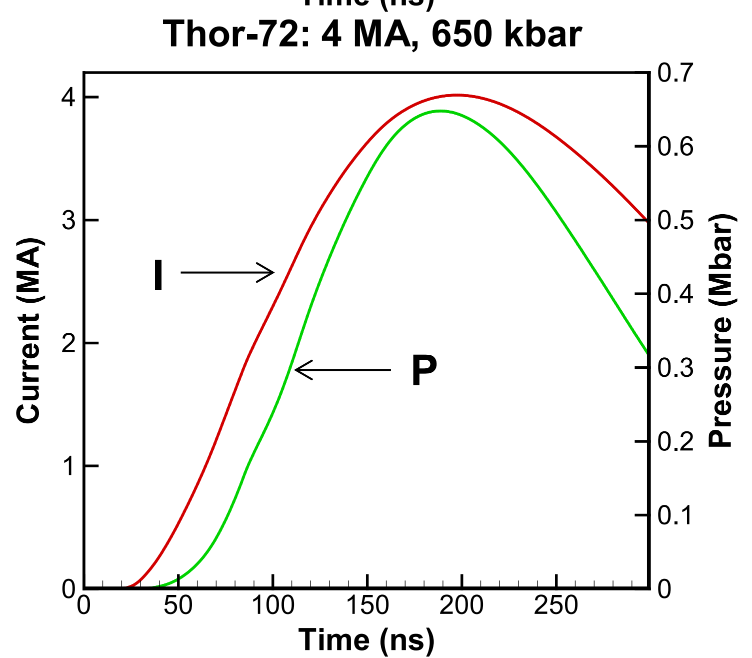
Load Current (±50 kV Charge)



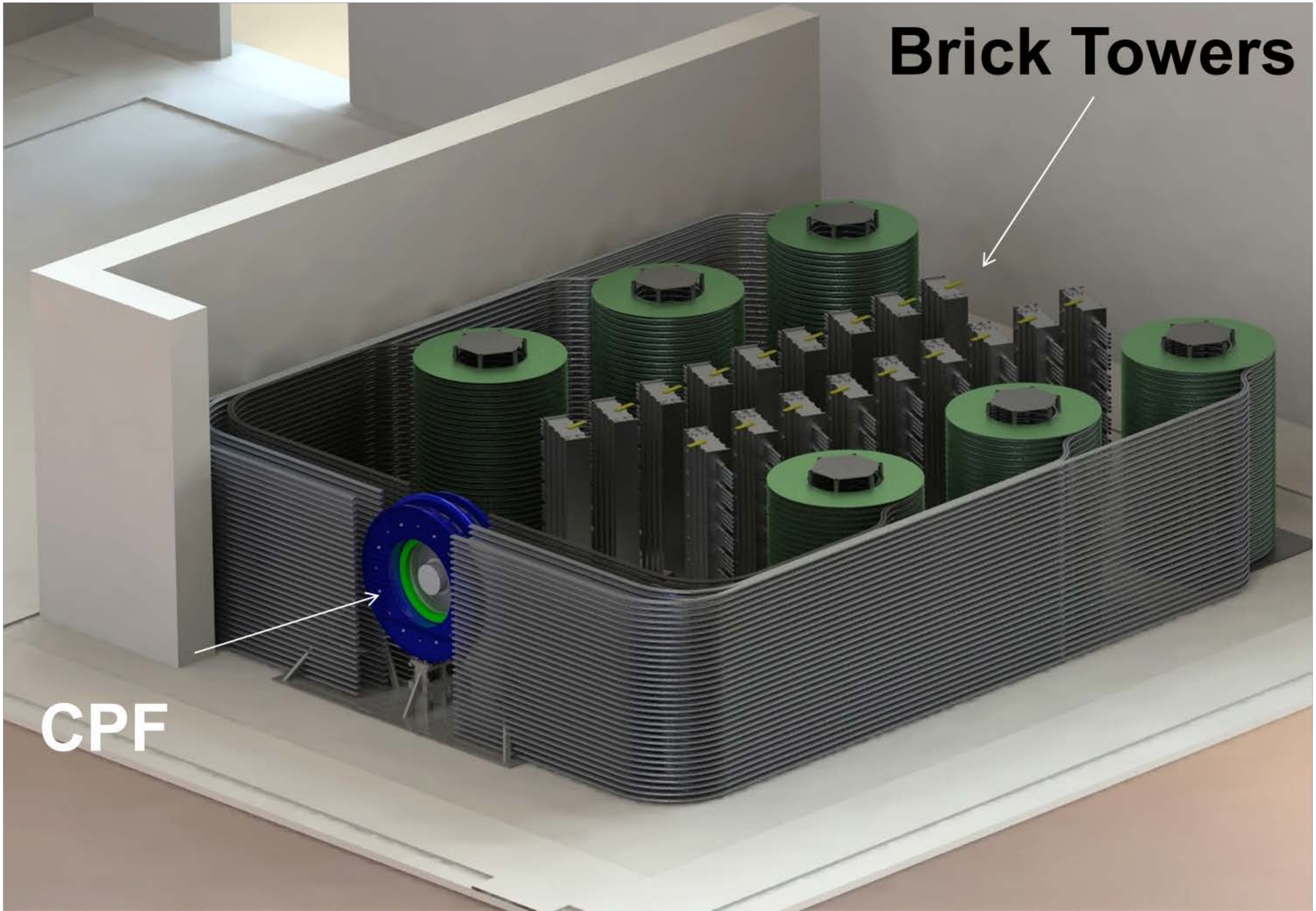
Thor-48 will be commissioned in FY17



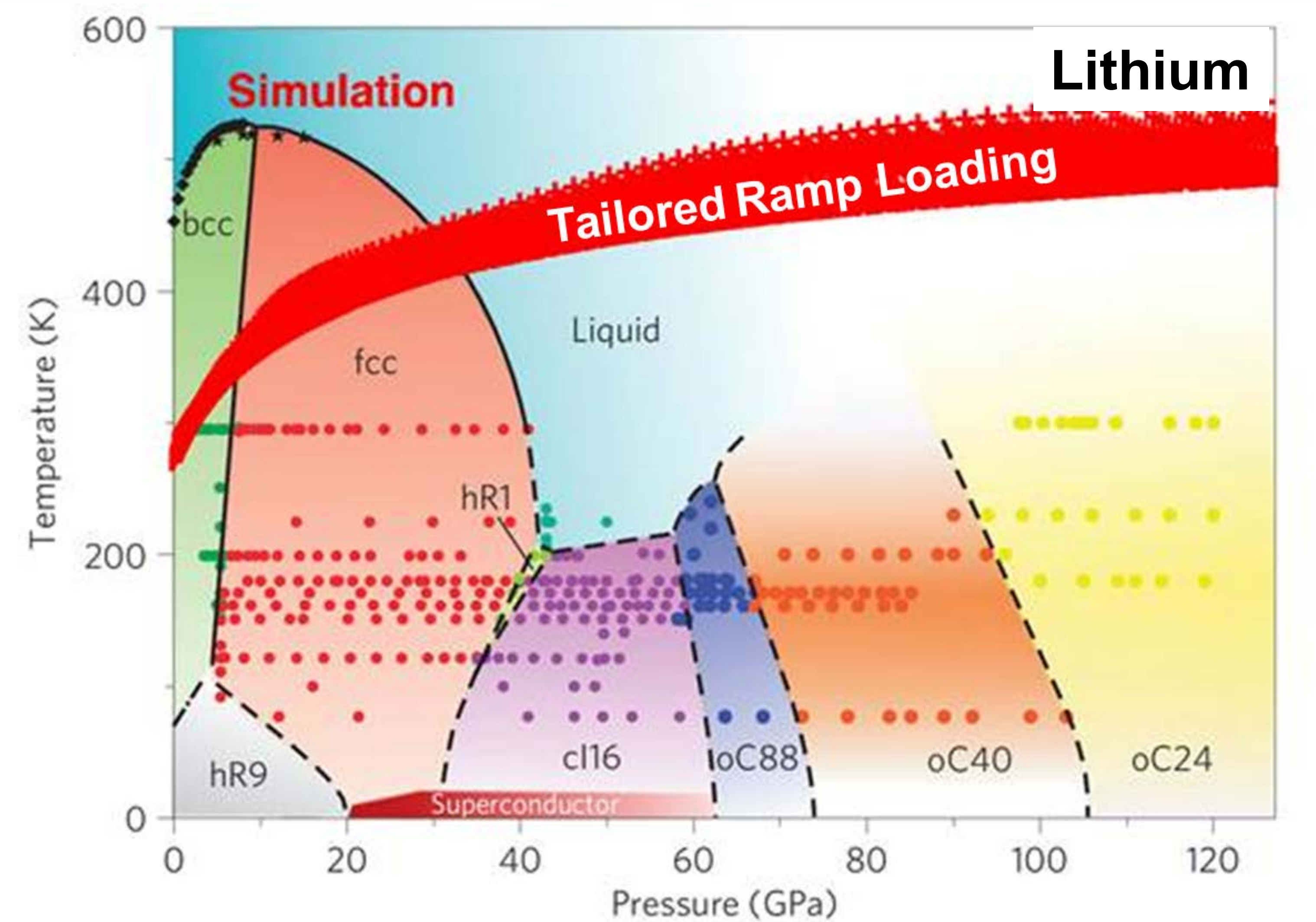




Thor-144 will fit comfortably within the building 961 high bay at Sandia

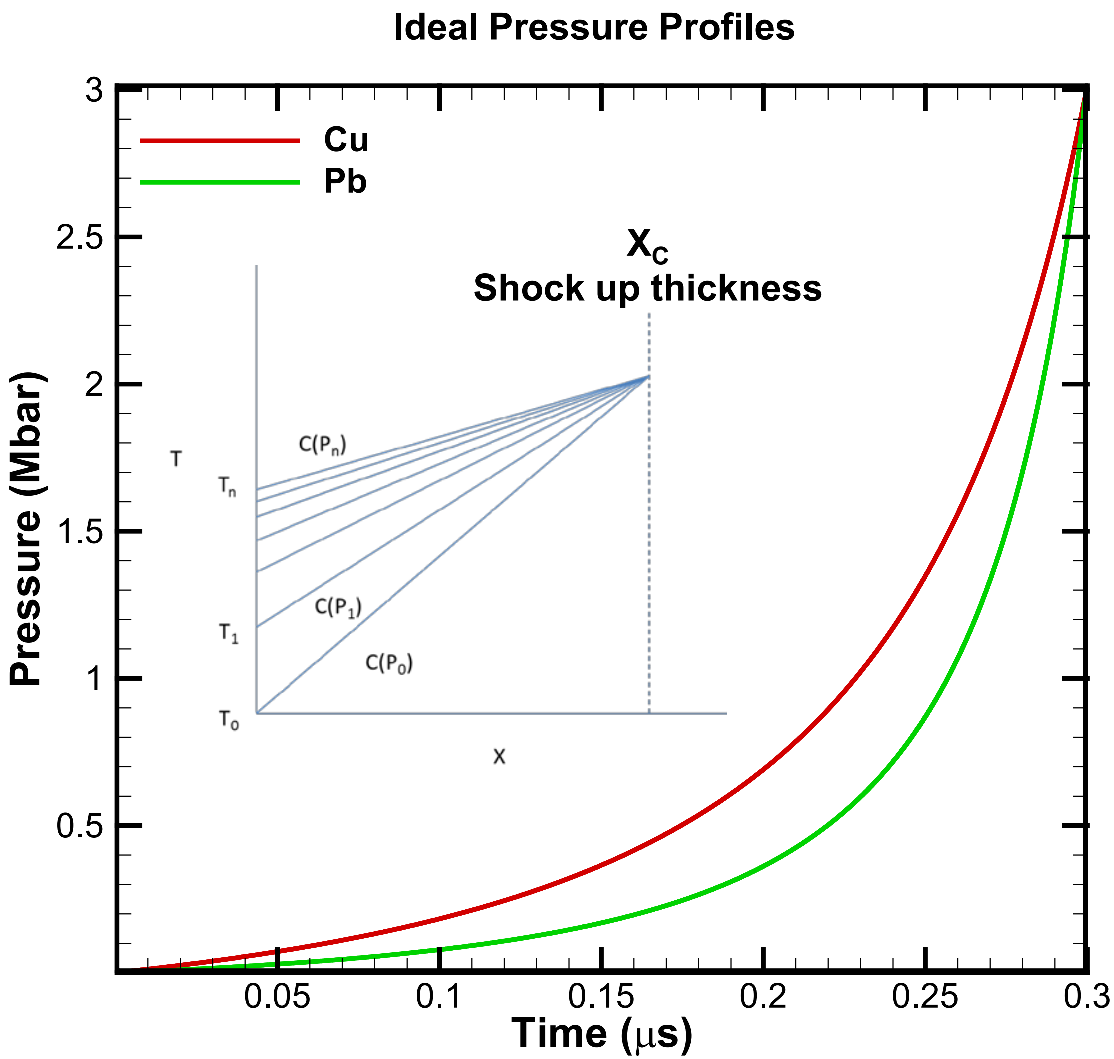


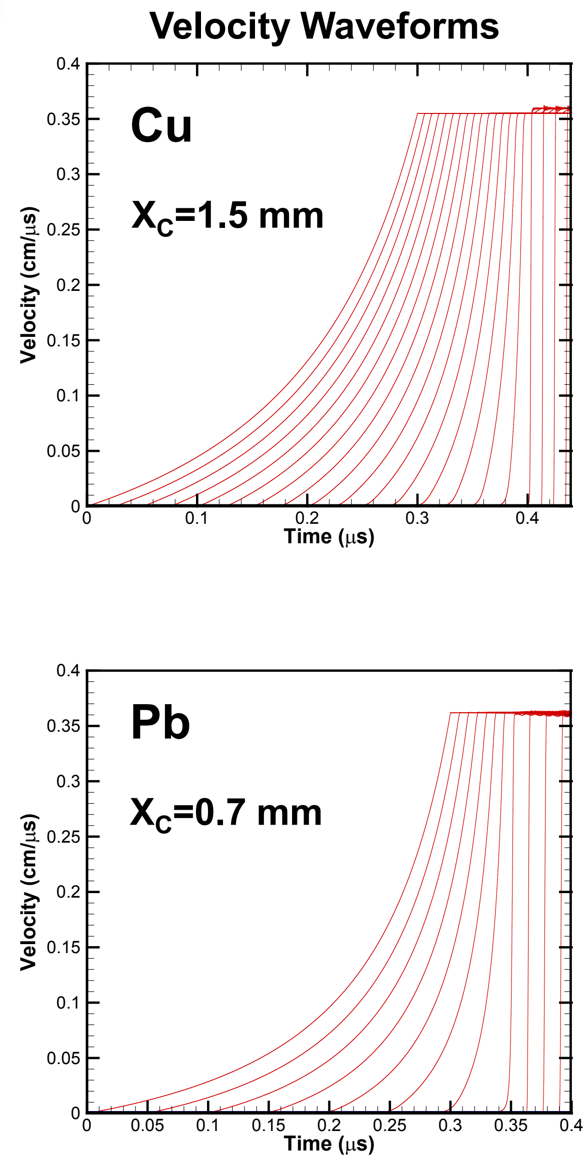
Pressure pulse tailoring enables study of many materials of interest in relevant regimes



C.L. Guillaume, *et al.*, Nature Physics 7, 211–214 (2011)

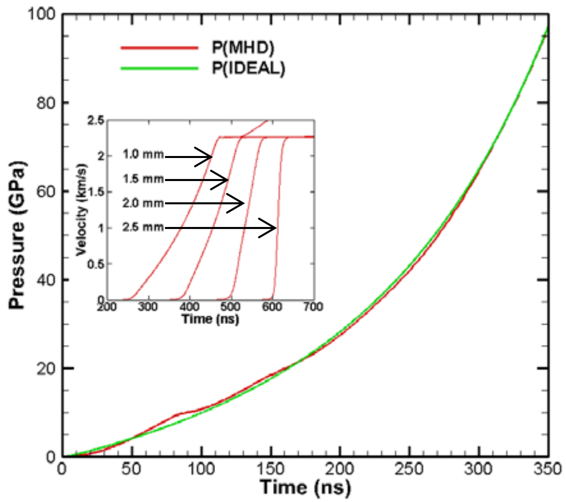
Pulse tailoring is required to maintain shockless loading

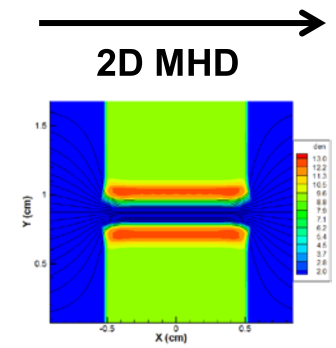




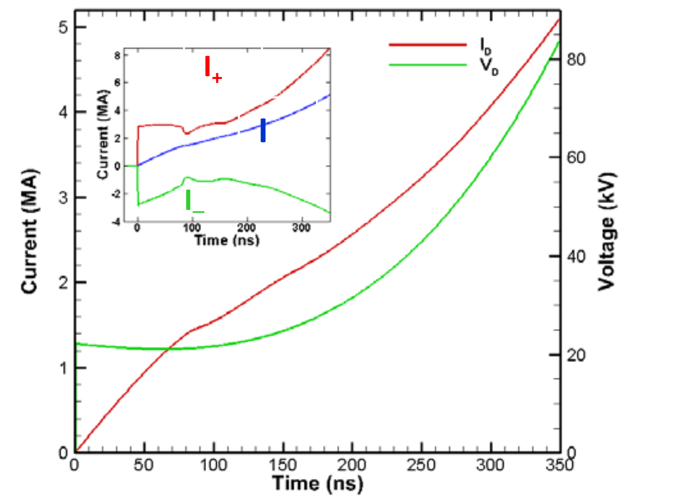
We have developed a circuit-free method to tailor the current pulse

Ideal pulse for Cu/LiF Window: Xc=2400 μm

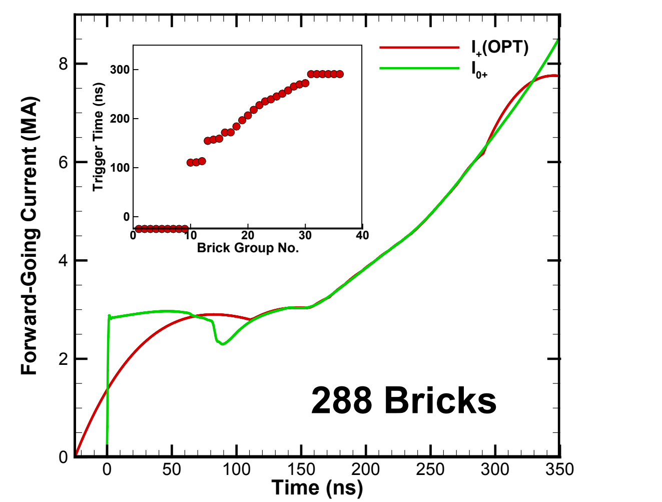




Find desired current and voltage



Find optimized forward-going current I_+



$$I_{0+} = \frac{1}{2}\left[\frac{V_D + L_C \dot{I}_D}{Z} + I_D\right]$$

Form forward-going current

$$I_{+} = \sum_{k=1}^{N} i_k\left(t - \tau_k\right)$$

Express current as brick sum*

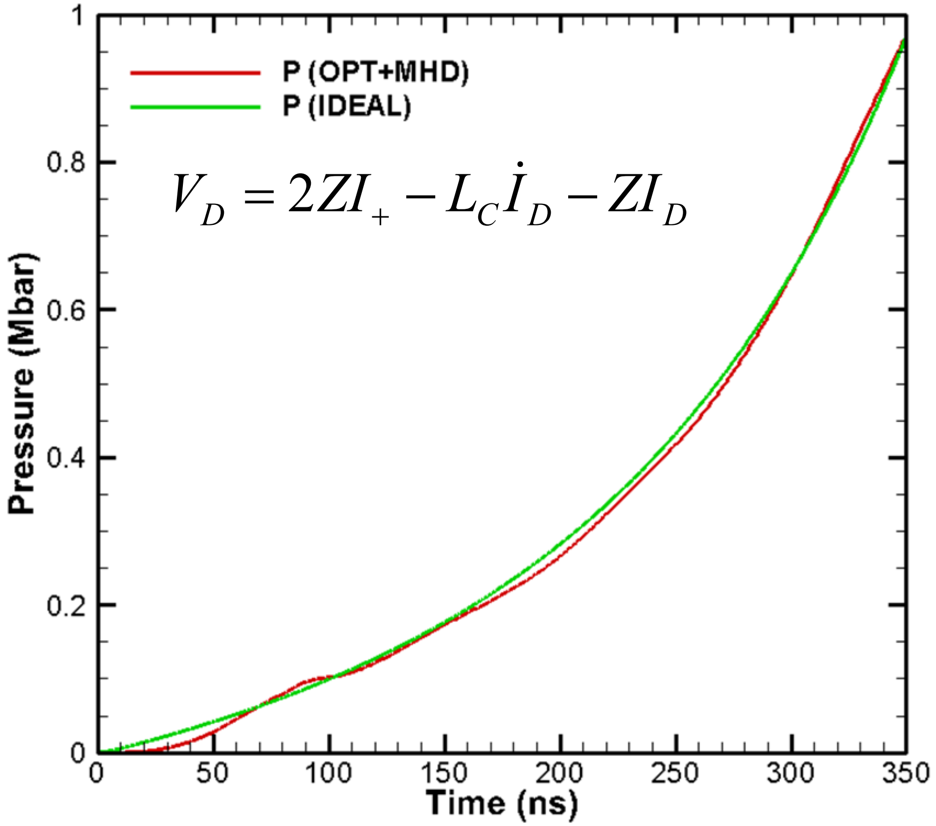
$$F(\vec{\tau}) = \int_0^T dt\left[I_+(t) - I_{0+}(t)\right]^2$$

Optimize to find trigger times:

$$\vec{\tau} = \left(\tau_1, \ldots, \tau_n\right)$$

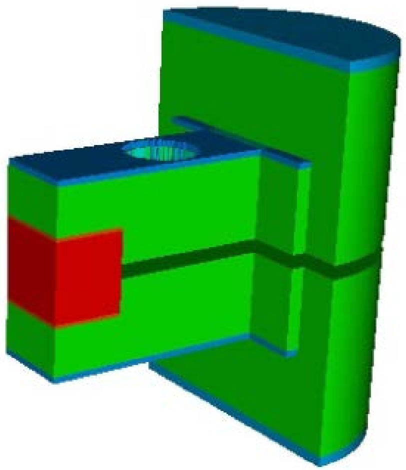
***Result of transit-time isolated transmission lines**

Optimization results are verified with the MHD code



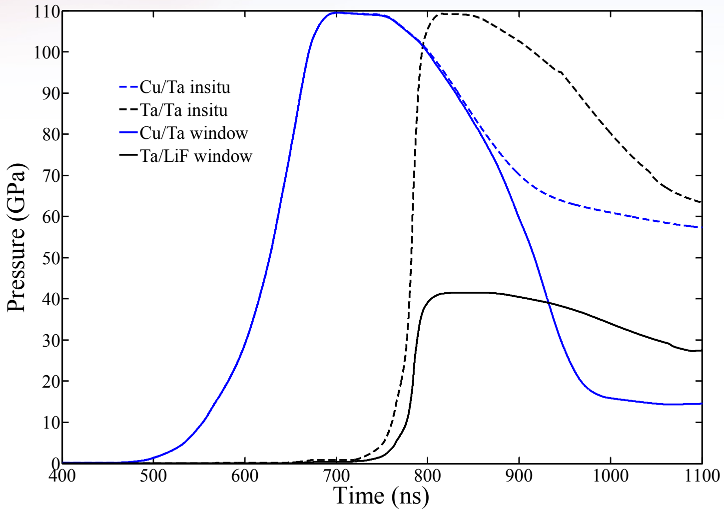
D.B. Reisman, *et al.*, PRSTAB 18, 090401 (2015)

- Use open circuit voltage to drive load:
  - $V_{OC}=2ZI_+$
- Circuit model can be expressed as LR series circuit
- We are now using this approach in ALEGRA 3D MHD modeling

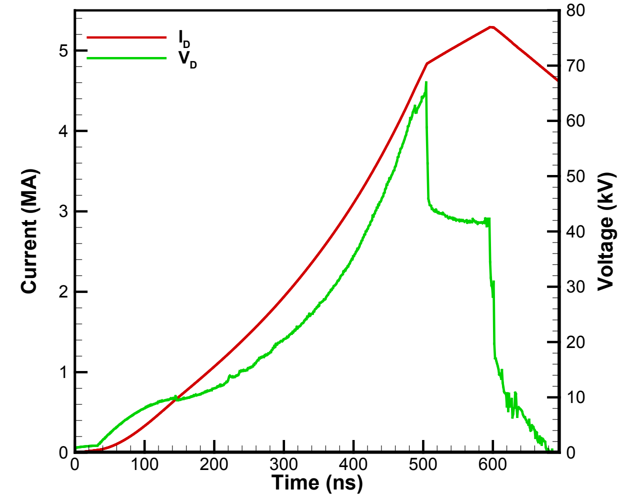


Optimization procedure is used to design 1.1 Mbar Cu/Ta strength experiments

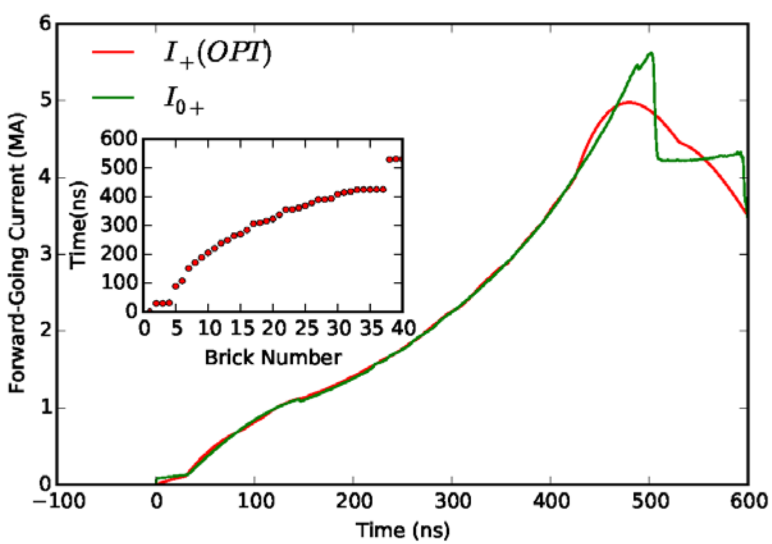
1.5 mm Cu, 0.8 mm Ta , 4 mm LiF



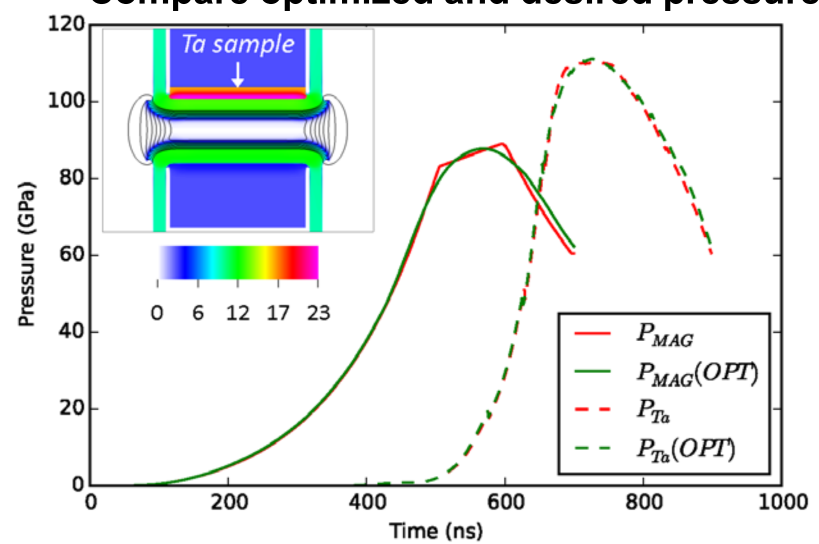
Desired voltage and current



Optimization to determine triggering

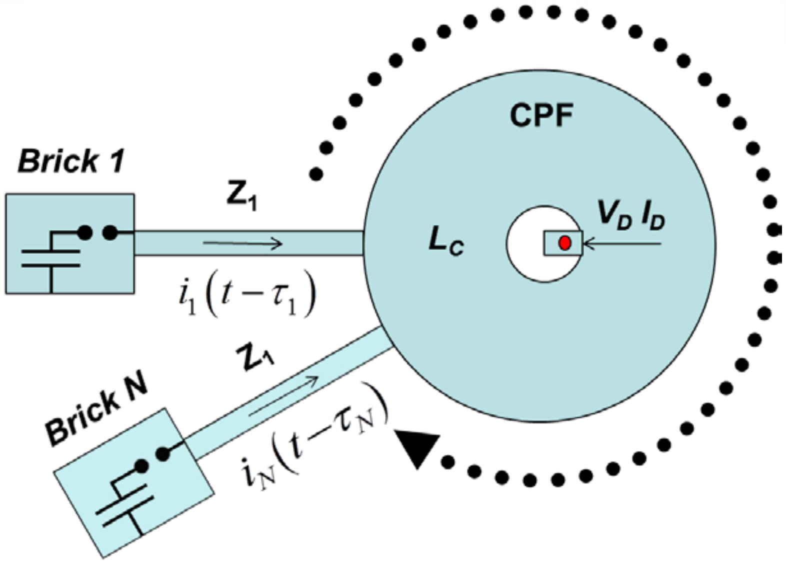


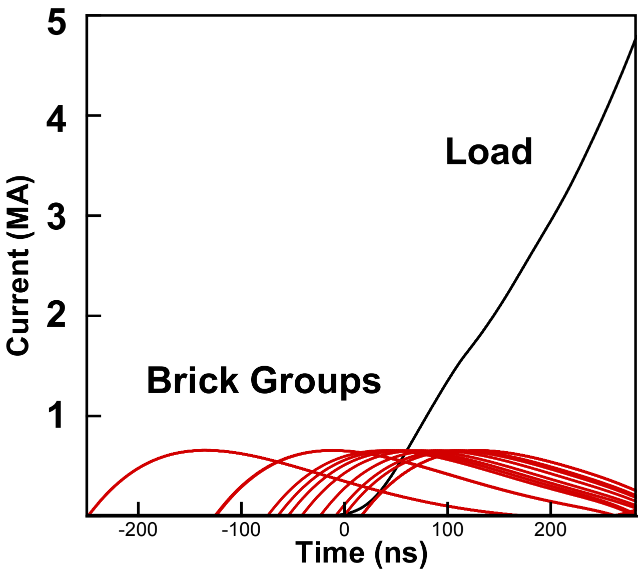
Compare optimized and desired pressures

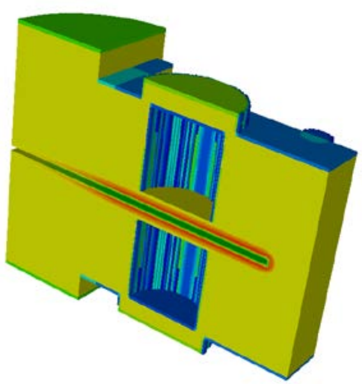


E.M. Waisman, D.B Reisman, *et al.,* Rev. Sci. Instrum. 87, 063906 (2016)

We are able to design Thor "virtual experiments" using the circuit/MHD capability of ALEGRA 3D







3D Stripline

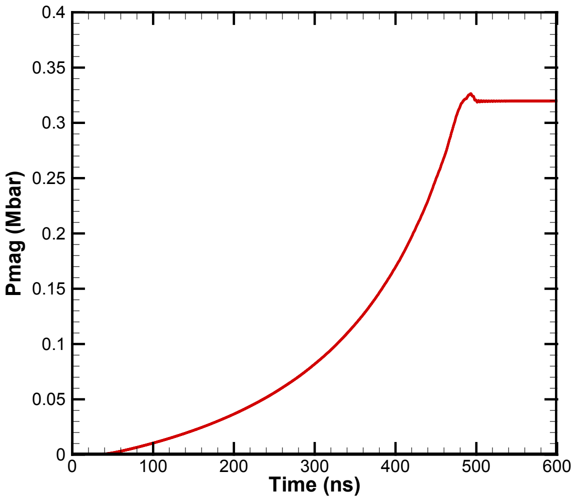
- All circuit elements are modeled, down to the brick level
- Circuit is self-consistently coupled to the 3D MHD simulation
- Simulation performed with brick timing

$$\vec{\tau} = (\tau_1, \ldots, \tau_n)$$

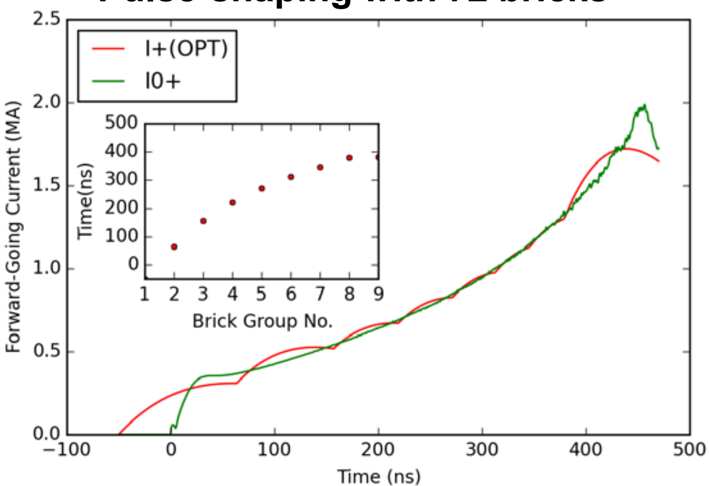
- Allows us to accurately predict ICE load performance with a single physics code

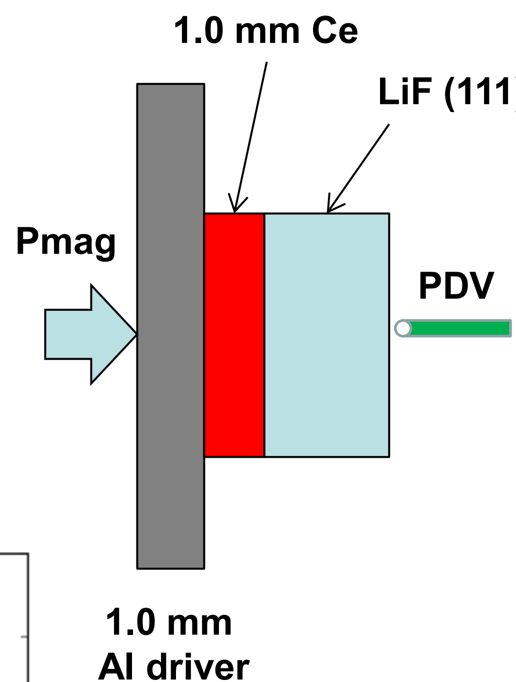
Thor-72 point design for Cerium: pulse tailoring

~300 kbar pressure pulse

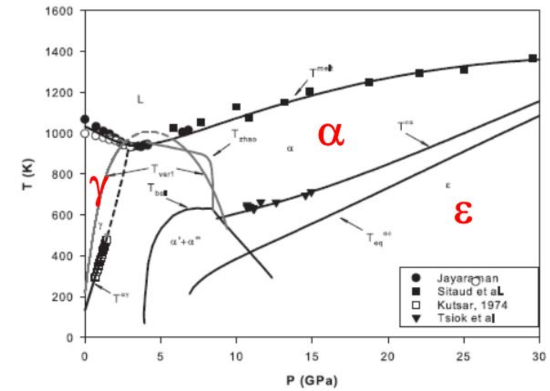


Pulse-shaping with 72 bricks

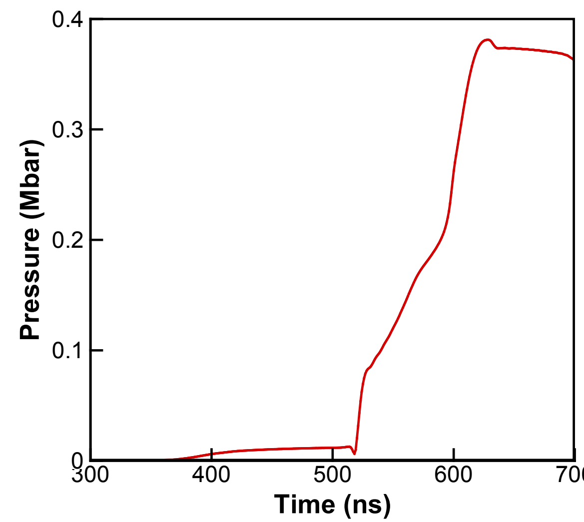




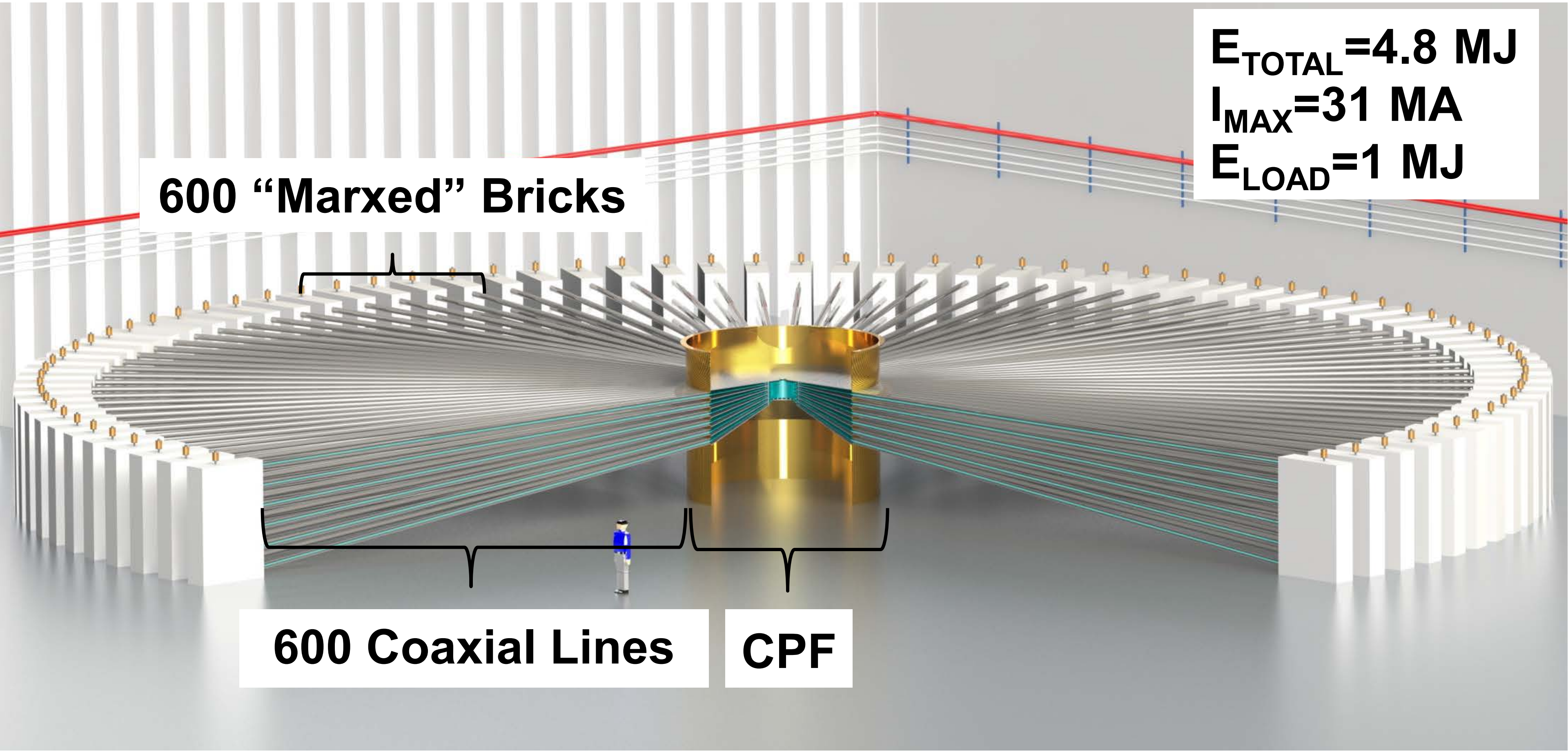
Phase diagram



Cerium pressure history



We have extend the current-adder architecture to the megajoule-class Neptune machine



W.A. Stygar, D. B. Reisman, B. S. Stoltzfus, K. N. Austin, *et al.,* PRAB 19, 070401 (2016)

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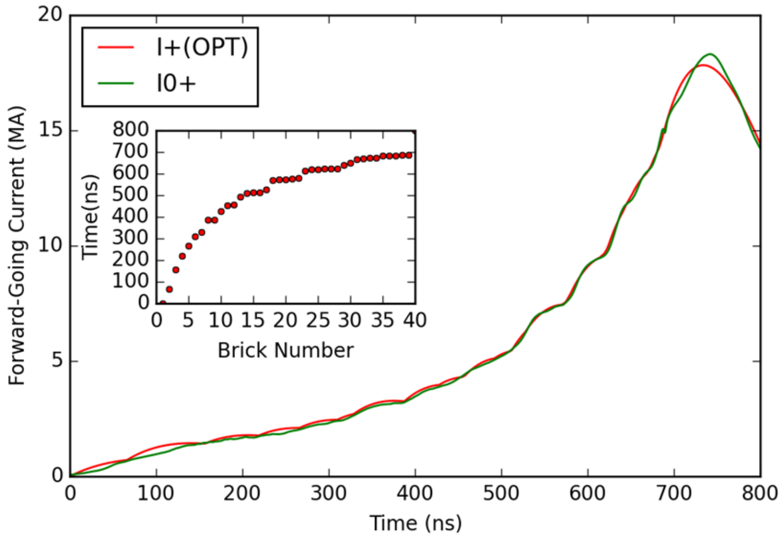
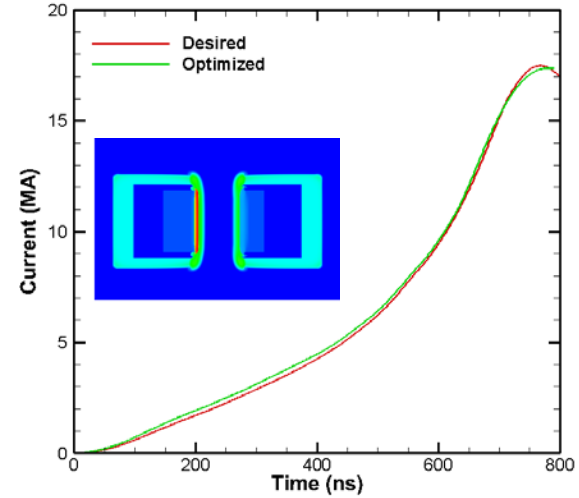
Neptune can reproduce ZR performance

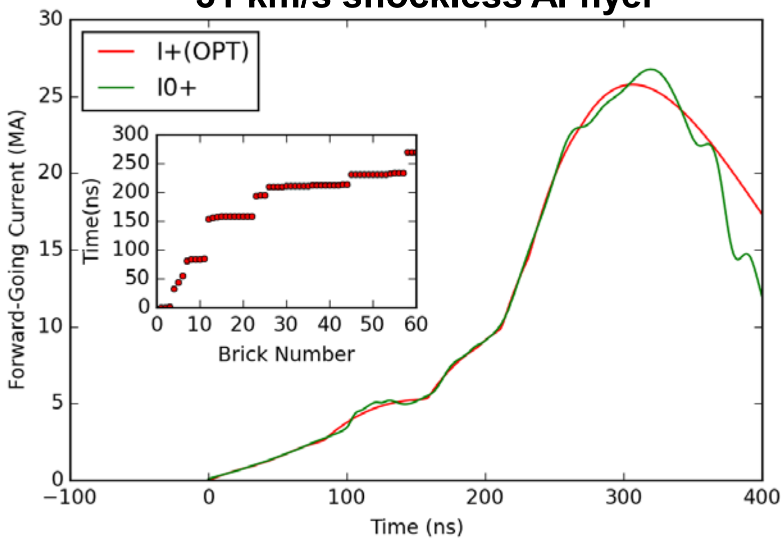
6 Mbar Ta ICE

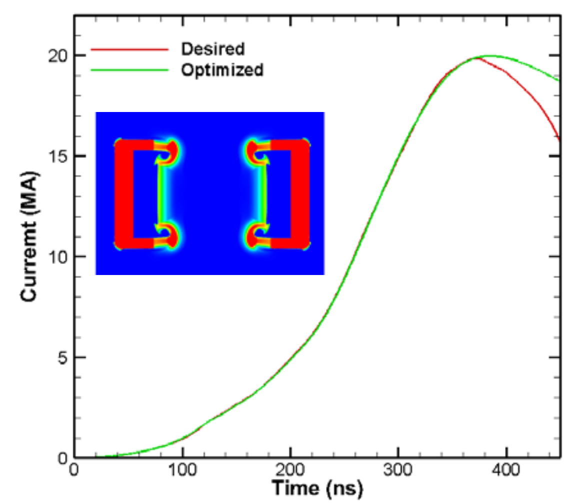


Optimized and desired current



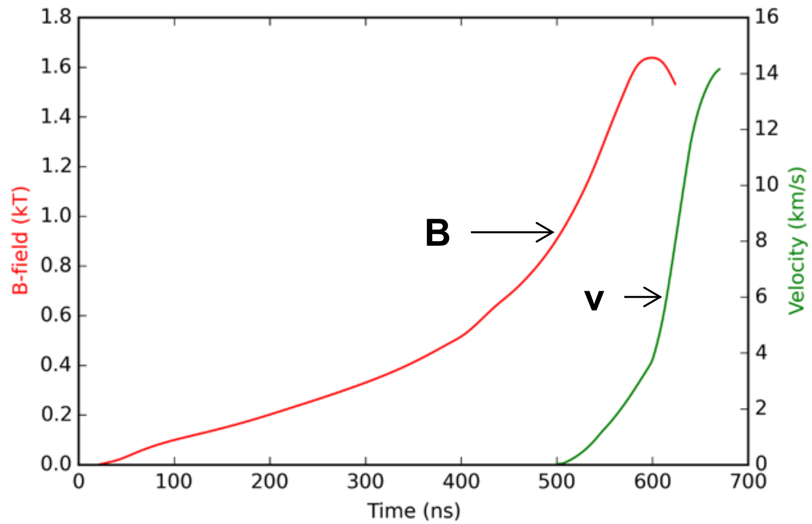
31 km/s shockless Al flyer



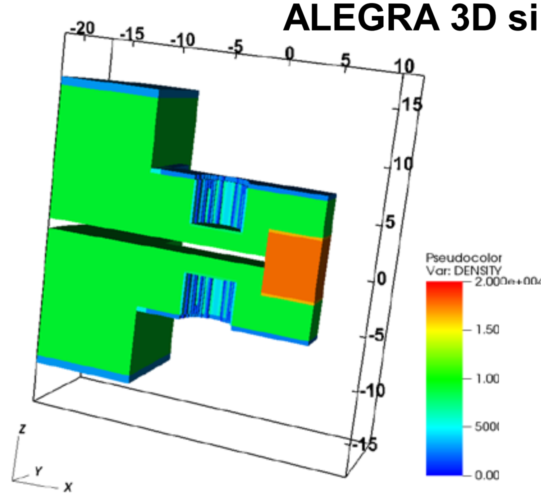


Neptune can reach 1 TPA (10 Mbar) for ICE

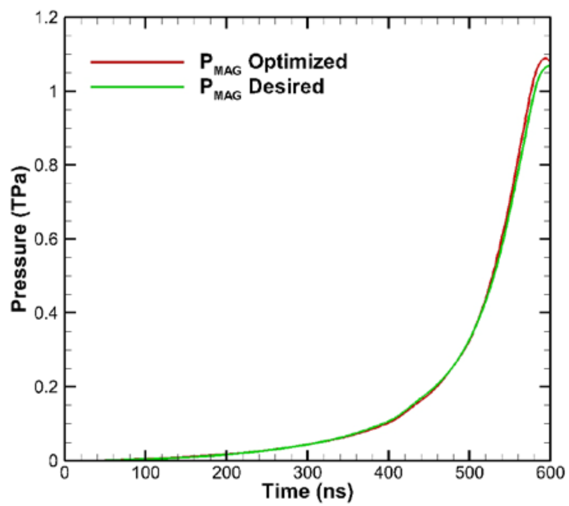
Magnetic Field and FS velocity for 1.8 mm Cu

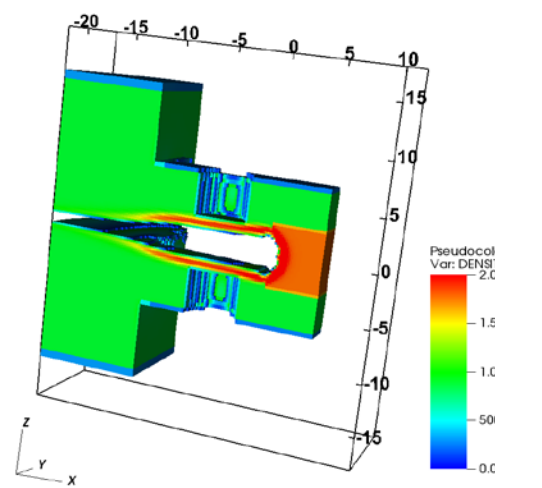


ALEGRA 3D simulation



Over 1 TPa (10 Mbar) pressure





D.B. Reisman, J.-P. Davis, et. al., Rev. Sci. Instrum. (in preparation).

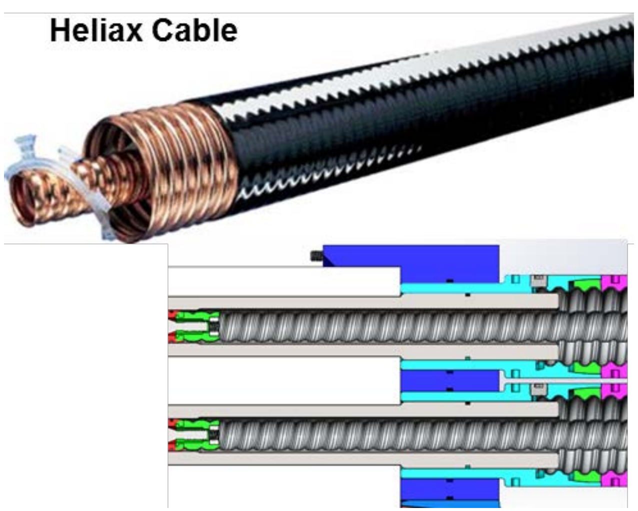
Conclusions

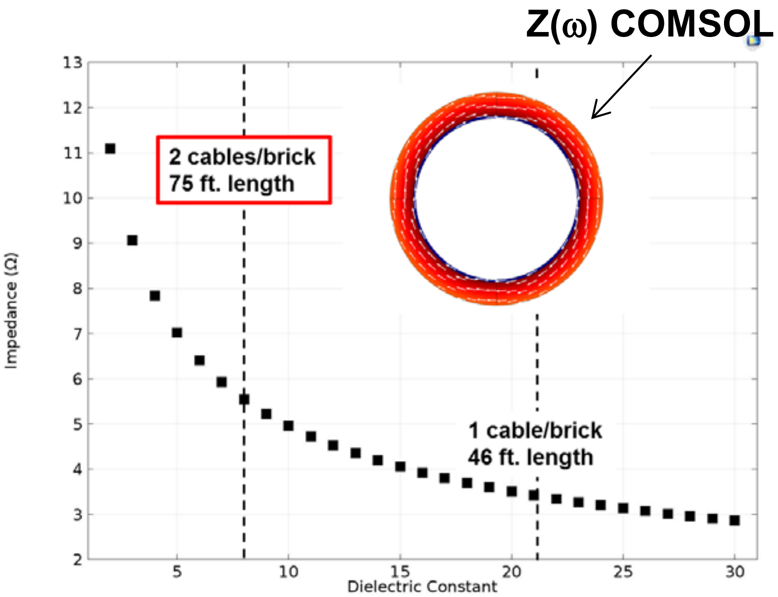
- We have developed a compact, low-cost platform for performing dynamic material experiments in the megabar (100 GPa) regime
  - Precise pulse tailoring with gradient-based optimization technique
  - Ability to explore shockless-loading regime for equation of state (EOS), dynamic strength, and phase transition studies
  - Capability for XRD being developed
- A physics campaign on Thor will be conducted in FY17. This will include:
  - Validation of ICE on Thor
  - Pulse tailoring
  - First pulsed power driven X-ray diffraction experiments
  - Flyer plate experiments
- We have developed the Neptune machine
  - 1 TPA (10 Mbar) ramp wave experiments possible in a variety of materials (Cu, Ta, Pb).

Bonus Slides

The ultimate performance of Thor depends on the number and type of coaxial cable

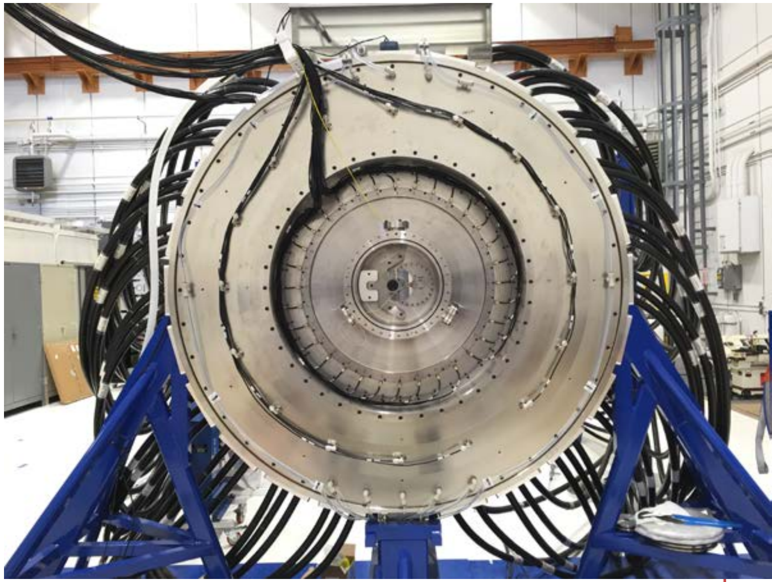
- The Thor CPF can accommodate 288 cables
- With the present cable (4 cables/brick), this limits the number of bricks to 72
- An effort is underway to reduce cable number and length
  - Increase dielectric constant ε_r →reduce Z and c → reduce no. of cables and length
  - Nano-ceramic-poly: 1 (2) cable/brick, 46 (75) foot length, 144 (288) brick system
  - Water (DI) cable: 2 cables/brick, 30 foot length, 144 brick system
- We will be manufacturing a high-epsilon cable next year





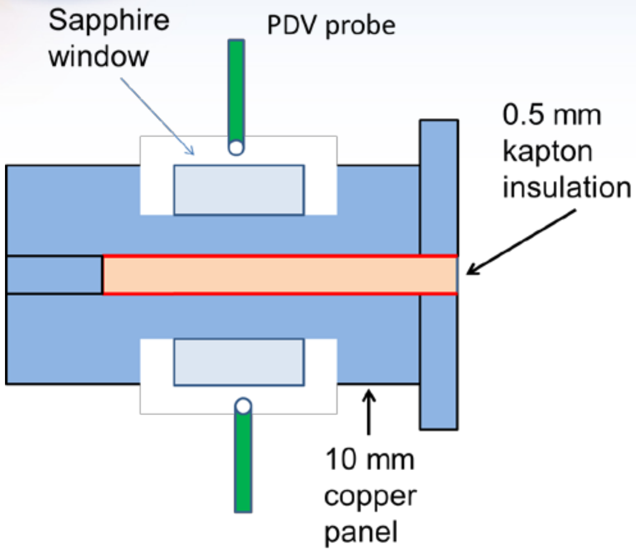
There are compelling reasons why Thor/ICE is important to the materials community

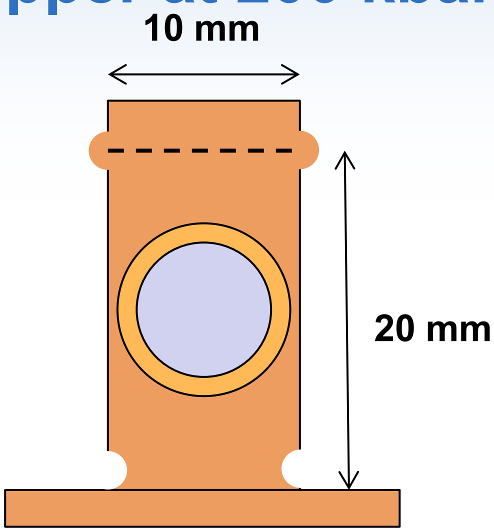
- **Sample size – cm scale width, mm scale in thickness, many grains across propagation direction**
- **Strain rate – 10^6 – 10^7**
- **Ability to tailor pulses – required to avoid shocks, tunable for different phase paths.**
- **A standard driver – A validated technique for high pressure measurement, valuable to the high-pressure community:**
  - "Dynamic compression of copper to over 450 GPa: A high-pressure standard", R. G. Kraus, J.-P. Davis, C. T. Seagle, *et al.,* Phys. Rev. B 93, 134105 (2016)
- **Capable of obtaining dynamic XRD data with a compact source:**
  - "Single-pulse x-ray diffraction using polycapillary optics for in situ dynamic diffraction", B.R. Maddox, et al., Rev. Sci. Instrum. 87 (2016)
- **Vertical orientation allows placement at a synchrotron facility.**

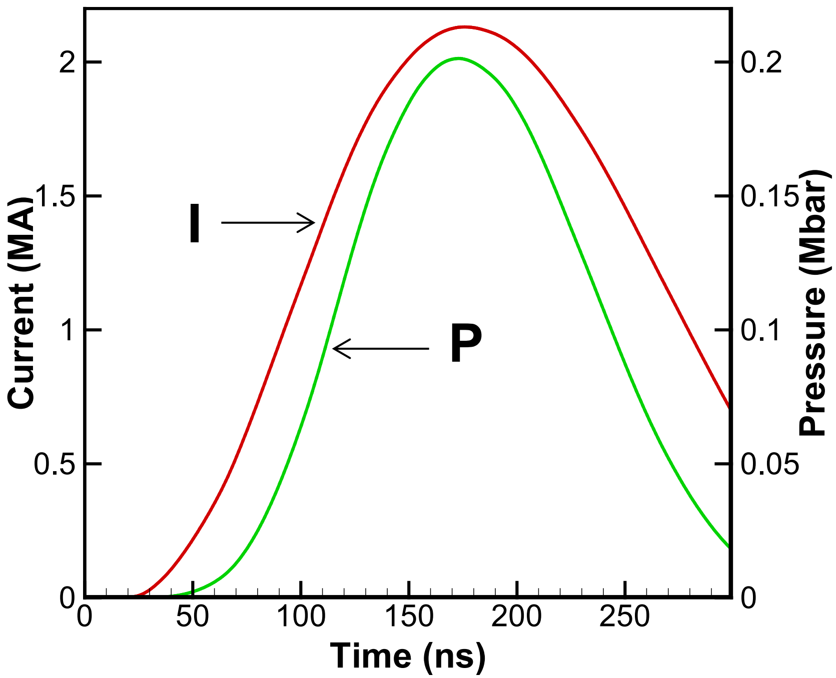


Sandia National Laboratories

Thor-24 shot series in September: copper at 200 kbar







Velocity profiles