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Sandia National Laboratories

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Thor: a modern pulsed power accelerator for material science applications

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Presented at NNSA Seminar

Sandia National Laboratories

Abstract

The Thor pulsed power generator is being developed at Sandia National Laboratories. The design consists of up to 288 decoupled and transit time isolated capacitor-switch units, called "bricks", that can be individually triggered to achieve a high degree of pulse tailoring for magnetically-driven isentropic compression experiments (ICE) [D.B. Reisman, *et. al*, Phys. Rev. ST Accel. Beams 18, 090401 (2015).]. The connecting transmission lines are impedance matched to the bricks, allowing the capacitor energy to be efficiently delivered to an ICE strip-line load with peak pressures of over 100 GPa (1 Mbar). Thor will drive experiments to explore equation of state, material strength, and phase transition properties of a wide variety of materials. We will describe the design of Thor, which uses a novel "current-adder" architecture to achieve precisely tailored magnetic pressure pulses, a requirement for many material studies. We will show preliminary "first light" results from Thor which has been initially commissioned with 16 bricks. We will also present plans for upcoming materials physics experiments as Thor is extended to a 72 brick facility.

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Outline

- Introduction to Sandia pulsed power and liner transformer drivers (LTD)
- Introduction to magnetically driven quasi-isentropic compression (ICE)
- Introduction to Thor
- Dynamic material experiments on Thor
- Commissioning of Thor: first results, upcoming physics experiments
- Thor virtual experiments
- Neptune
- Conclusions

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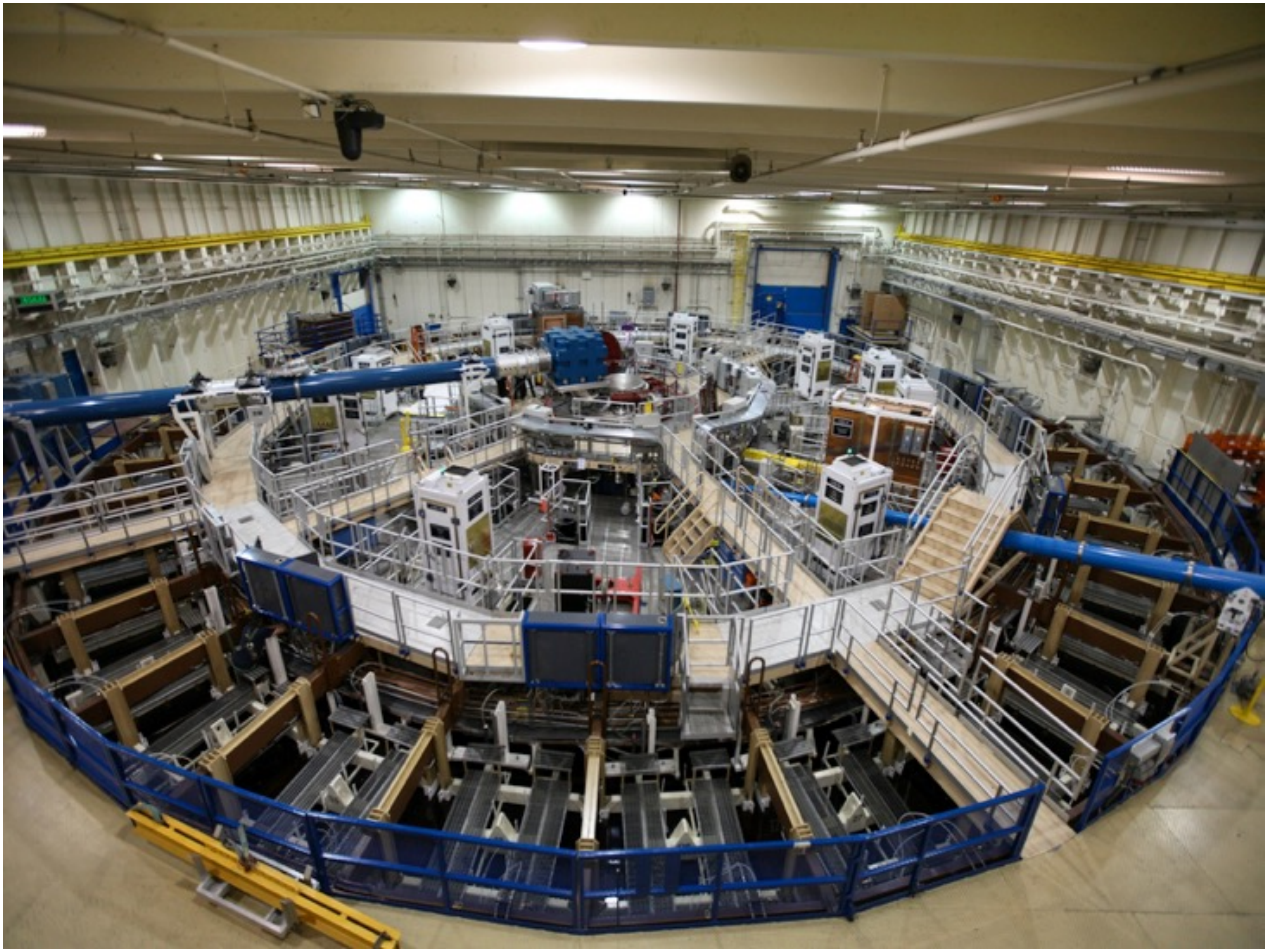
Sandia's Z accelerator is the largest, most powerful, and most successful pulsed-power machine in history.

E_{stored} = 20 MJ	V_{stack} = 4 MV	I_{load} = 26 MA	$E_{radiated}$ = 2.5 MJ
$P_{electrical}$ = 80 TW	L_{vacuum} = 12 nH	$\tau_{implosion}$ = 130 ns	diameter = 33 m

- Z delivers megajoules of energy to milligrams of matter.
- Since 1997, we have conducted, on average, 160 Z shots each year.
- To date, 2700 Z shots have been conducted altogether.

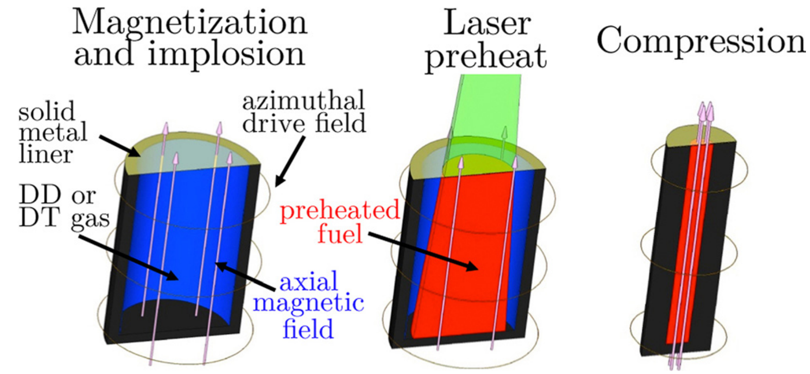


Z drives a wide variety of experiments in support of NNSA's national-security mission.

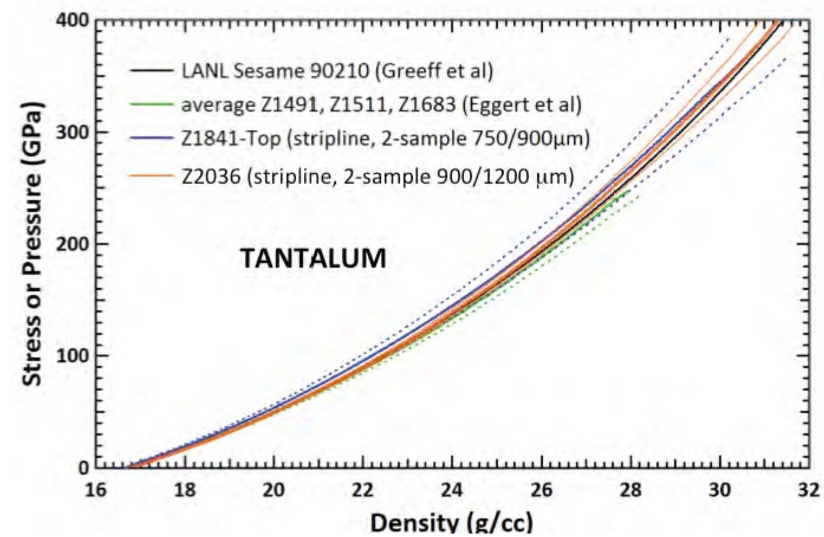
- Inertial confinement fusion
- Radiation physics
- Material physics
- Laboratory astrophysics

Results of experiments conducted on Z have been published in over 500 peer-reviewed journal articles.

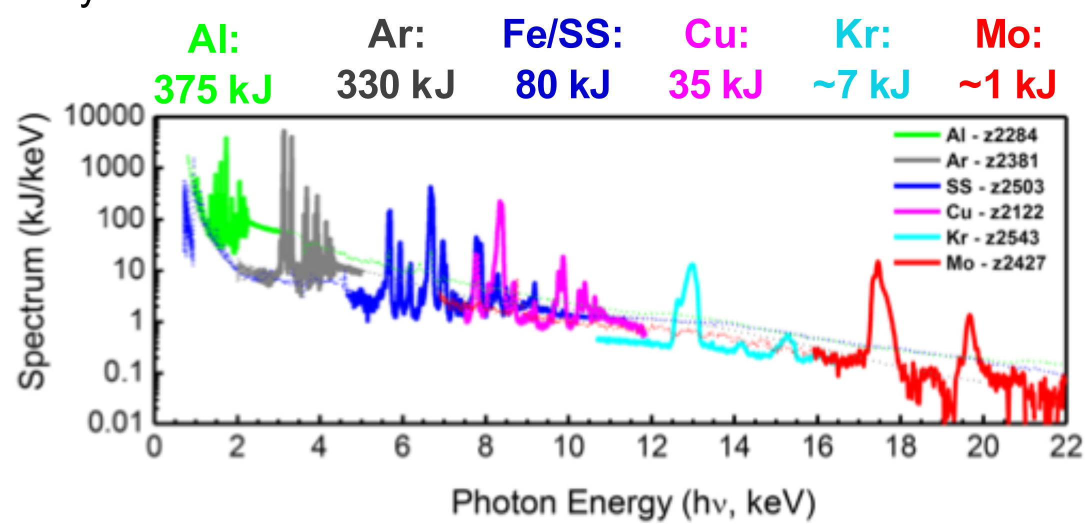
magnetized liner fusion (MagLIF) concept



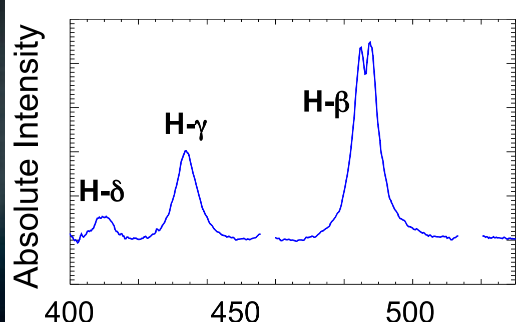
quasi-isentrope of tantalum to 4 Mbar



K-shell x-ray sources



white-dwarf line shapes

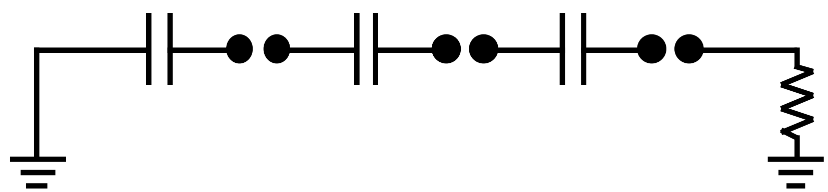


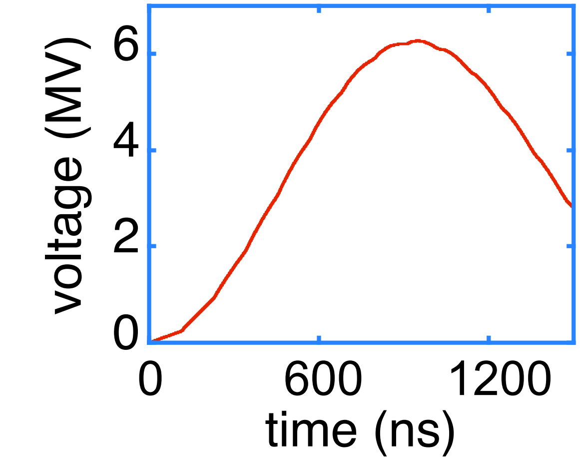
LTDs are the greatest advance in prime power generation since the invention of the Marx generator (1924).

A Marx generator and an LTD both charge capacitors in parallel and discharge them in series. A Marx does this as a large LC circuit:

Marx generator

$2\sqrt{LC} = 1000$ ns

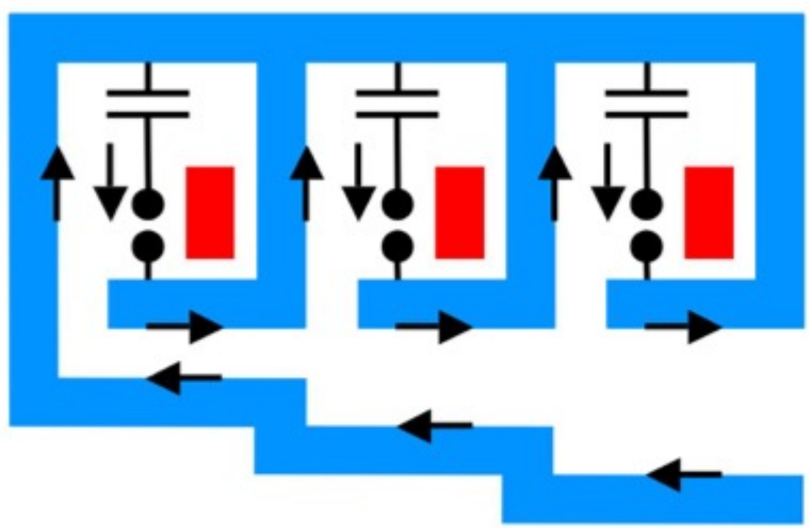


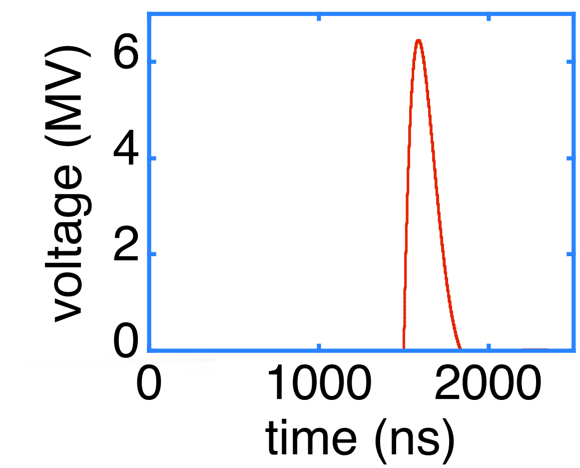


An LTD does this as an *induction voltage adder* (IVA), in which each of the adder's cavities is driven by LC circuits that are *contained within the cavity*:

3-cavity LTD module

$2\sqrt{LC} = 140$ ns



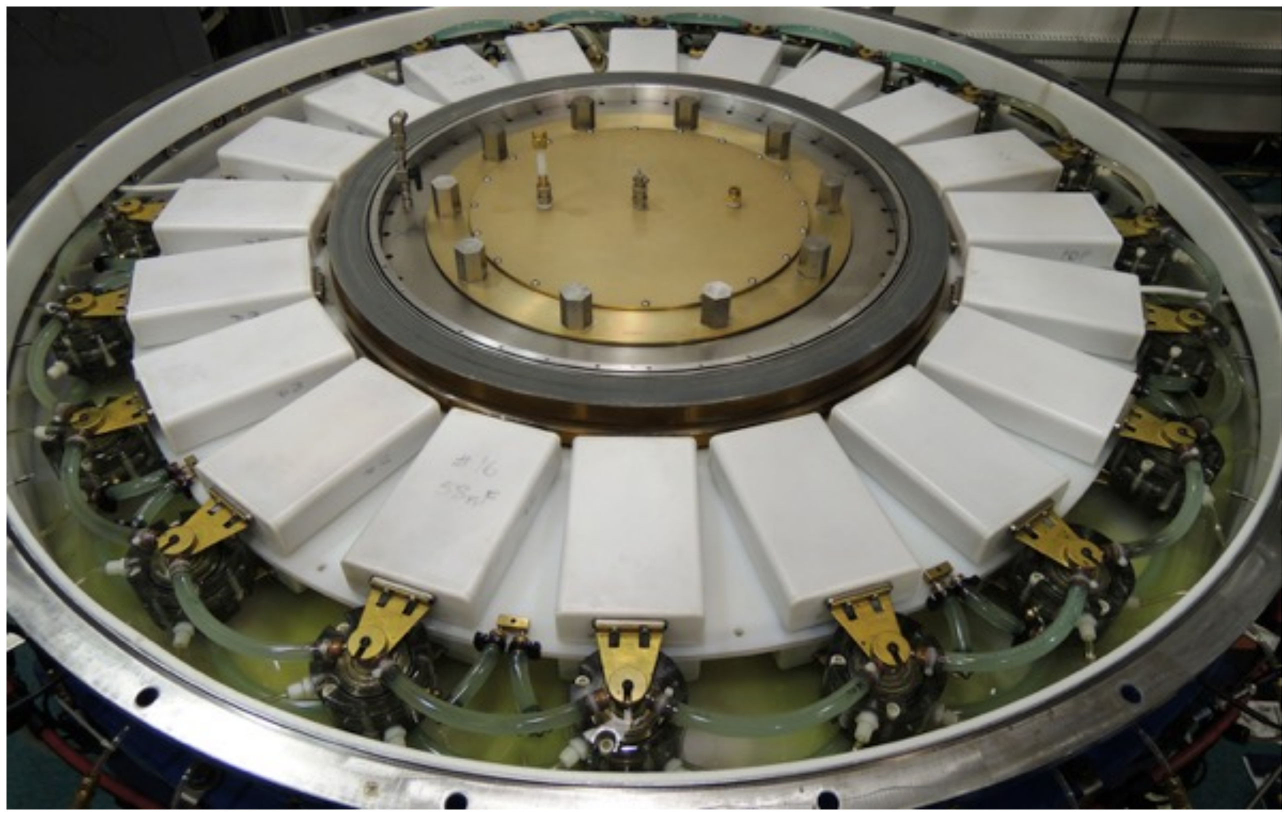


The quantum of an LTD is a "brick."

- An LTD brick consists of a single switch and two capacitors connected electrically in series.
- An LTD cavity consists of a number of bricks connected electrically in parallel.
- An LTD module consists of a number of LTD cavities connected in series

single 0.4-m-long LTD brick

20–brick 2-m-diameter LTD cavity



Z 800 will deliver 64 MA to a physics-package load, and be less than twice the diameter of Z.

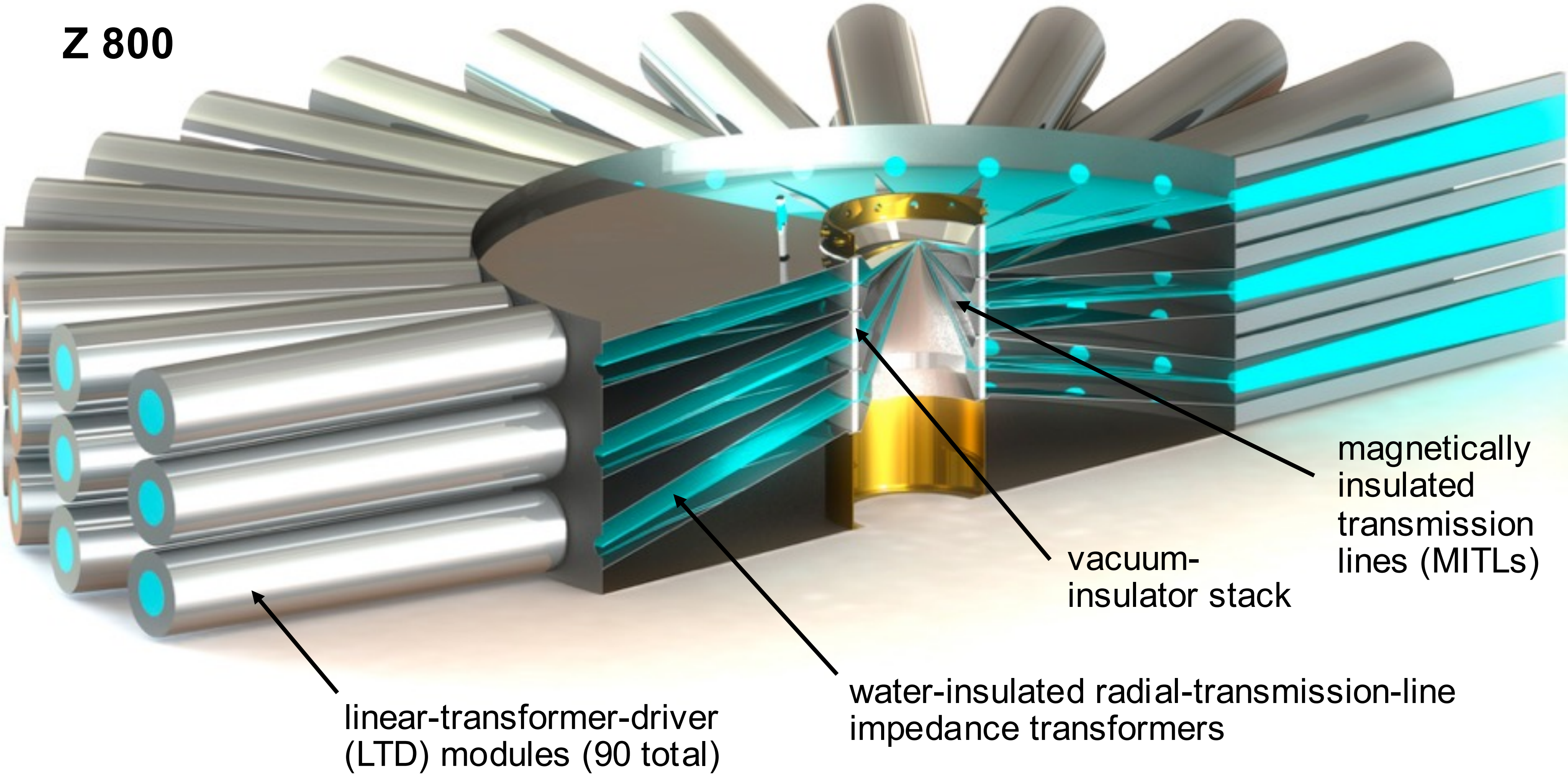
P_{LTDs} = 870 TW
E_{LTDs} = 130 MJ

V_{stack} = 16 MV
L_{vacuum} = 25 nH

I_{load} = 64 MA
$\tau_{implosion}$ = 120 ns

$E_{radiated}$ = 20 MJ
diameter = 55 m

η_{x-ray} = 15%



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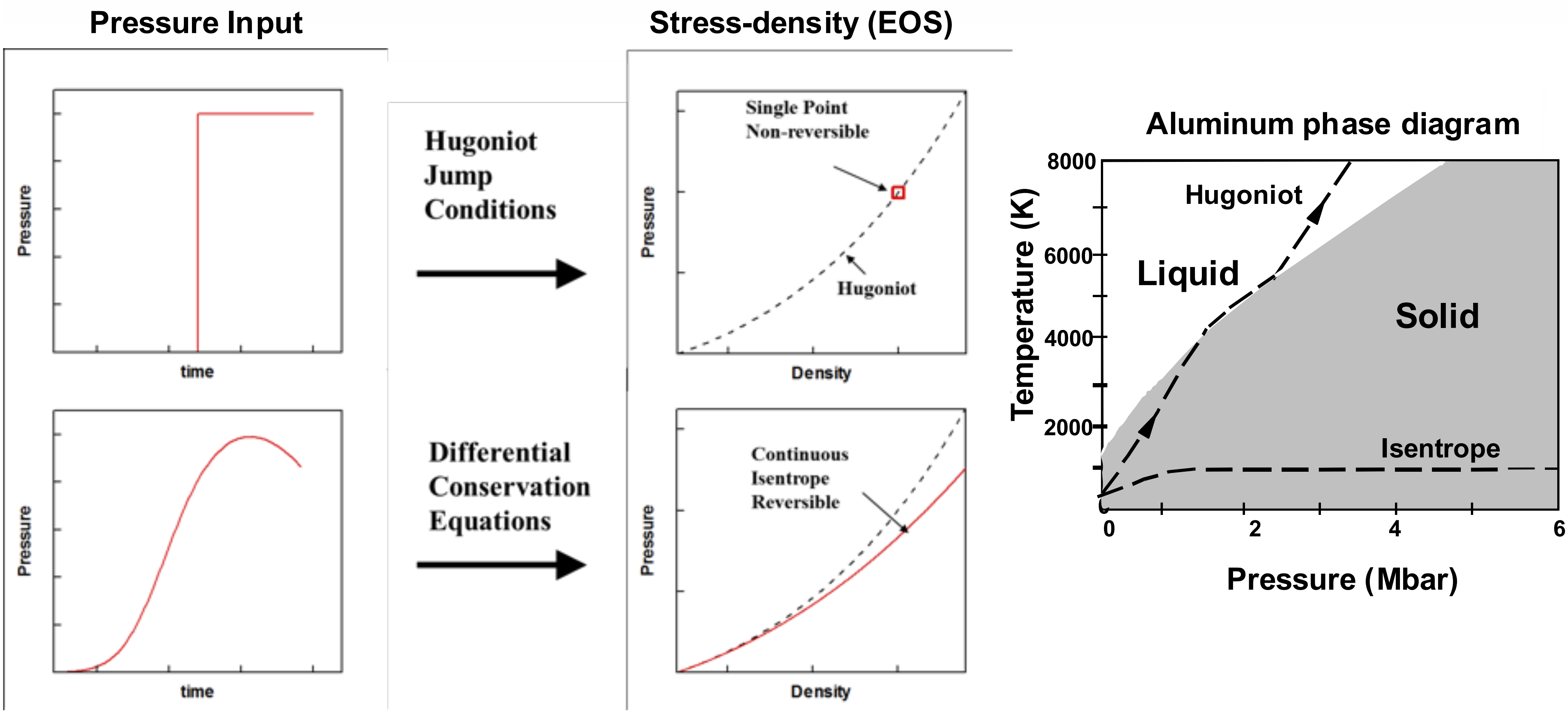
Shock and isentropic compression access different material regimes



- 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.

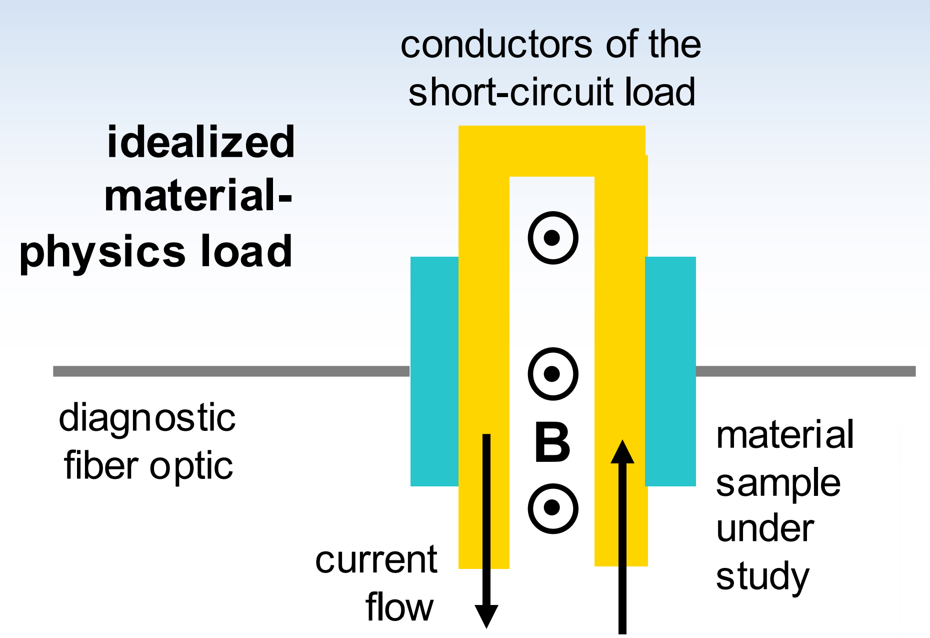
- The magnetic pressure generated within a short-circuit load drives the experiment.
- A smooth pressure profile can be guaranteed by the circuit
- Velocity measurements are used to determine the isentrope

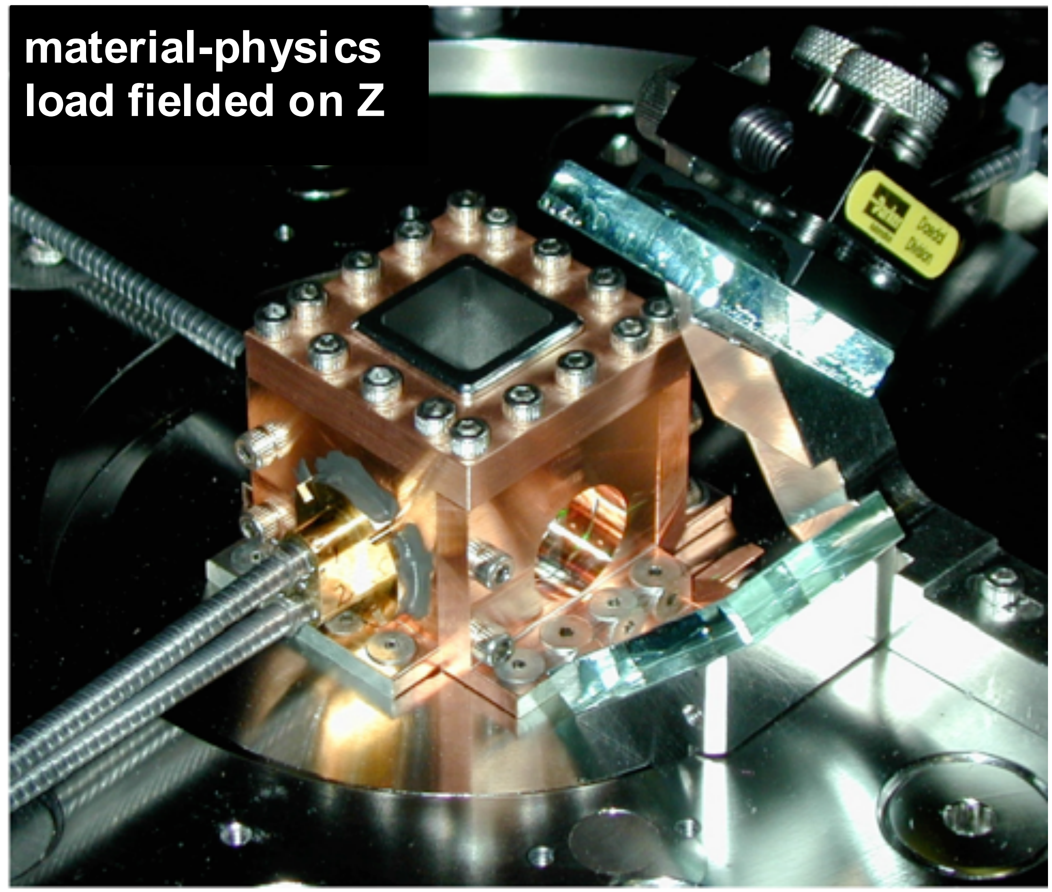
$$P_{magnetic} = \frac{\mu_0 I^2}{2 w^2}$$

I = current

w = width of the conductor

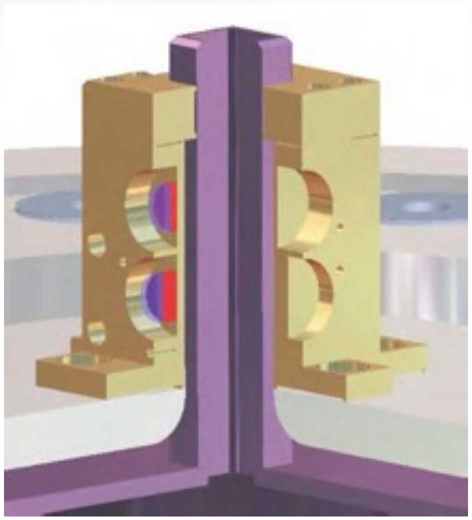
D.B. Reisman , *et al.*, J. Appl. Phys. (2001)
C.A. Hall, *et al.,* Rev. Sci. Instrum. (2001)



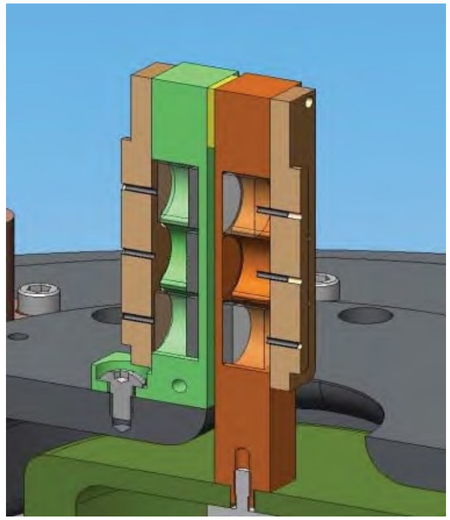


ICE on ZR have been performed on a variety of materials

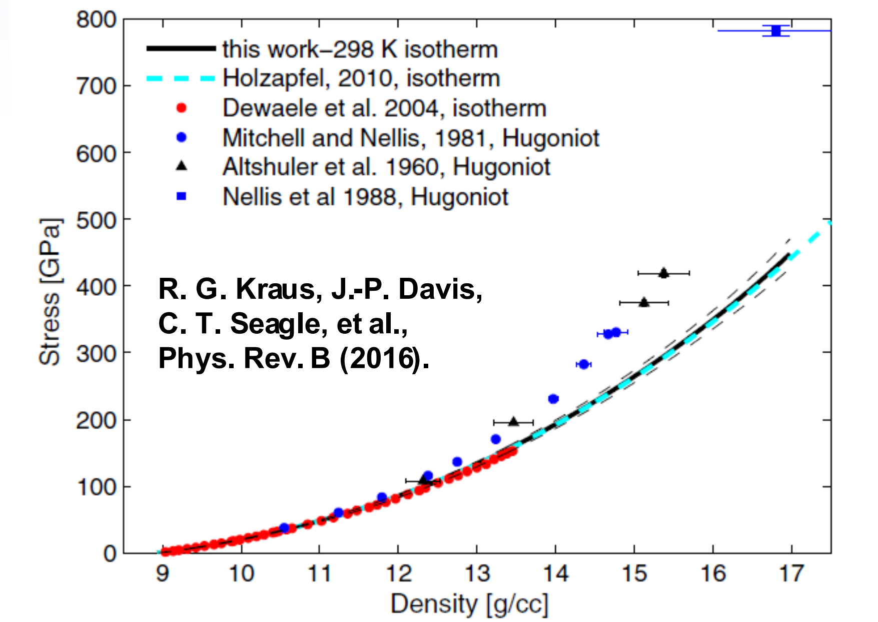
Square Short



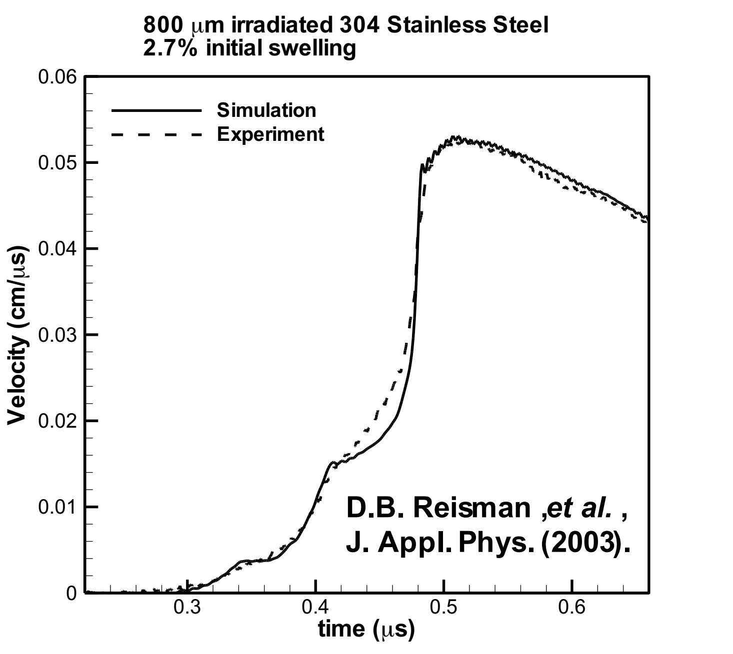
Stripline



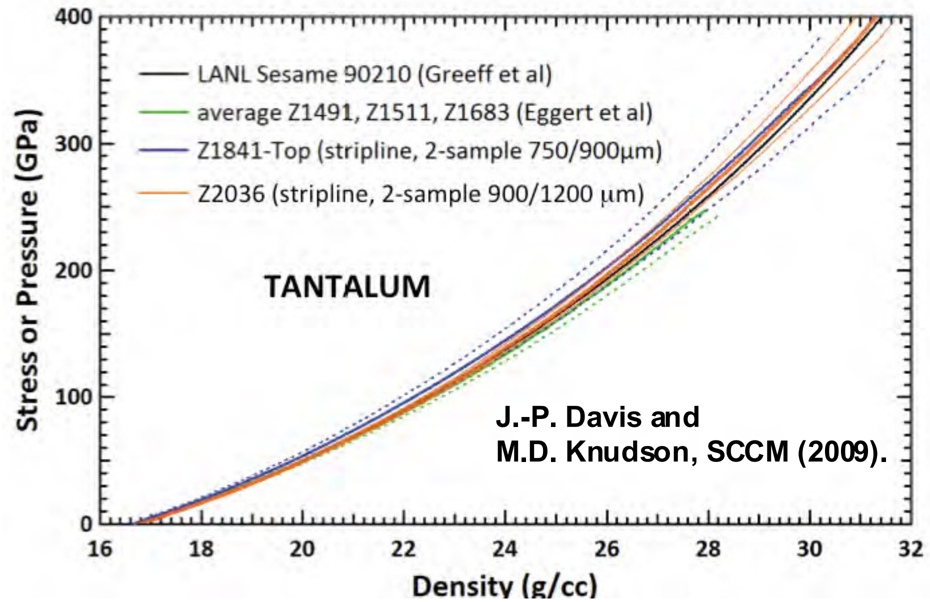
Copper: 5 Mbar reduced isotherm



Validated Void-Collapse Model



Tantalum: quasi-isentrope to 4 Mbar



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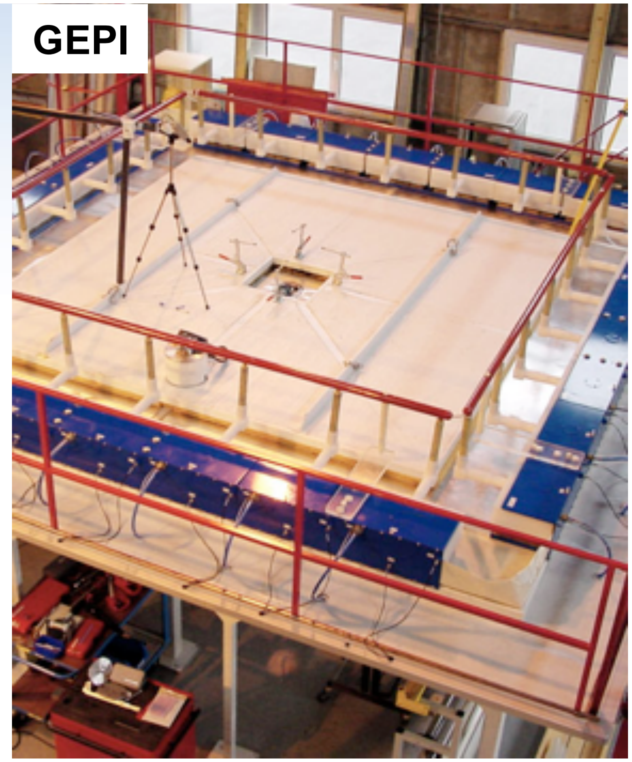
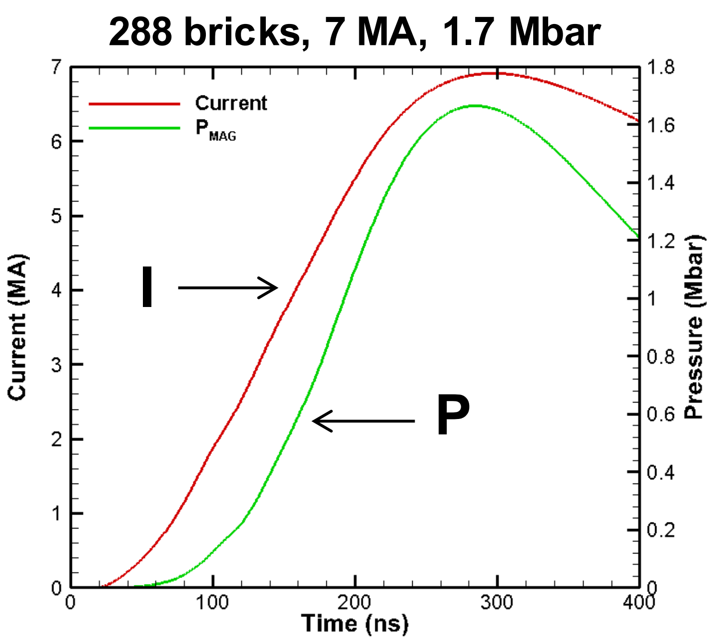
There is a need for a compact, economical machine to drive megabar-class material physics experiments.

- Small ICE machines have been built in the US (Veloce), France (GEPI), China (CQ-3), and the UK (MACH)
- These machines produce currents of 3-4 MA and magnetic pressure of under 0.5 Mbars over a near linear rise time of approximately 500 ns
- These machines suffer from two major limitations:
  - Pressure is sub-megabar. Near a megabar the Hugoniot and Isentrope for most materials diverge which is useful for equation of state studies.
  - They lack pulse tailoring capability which is required to maintain shockless loading of many materials
- We propose Thor to overcome these limitations and provide an important ICE driver for the physics community

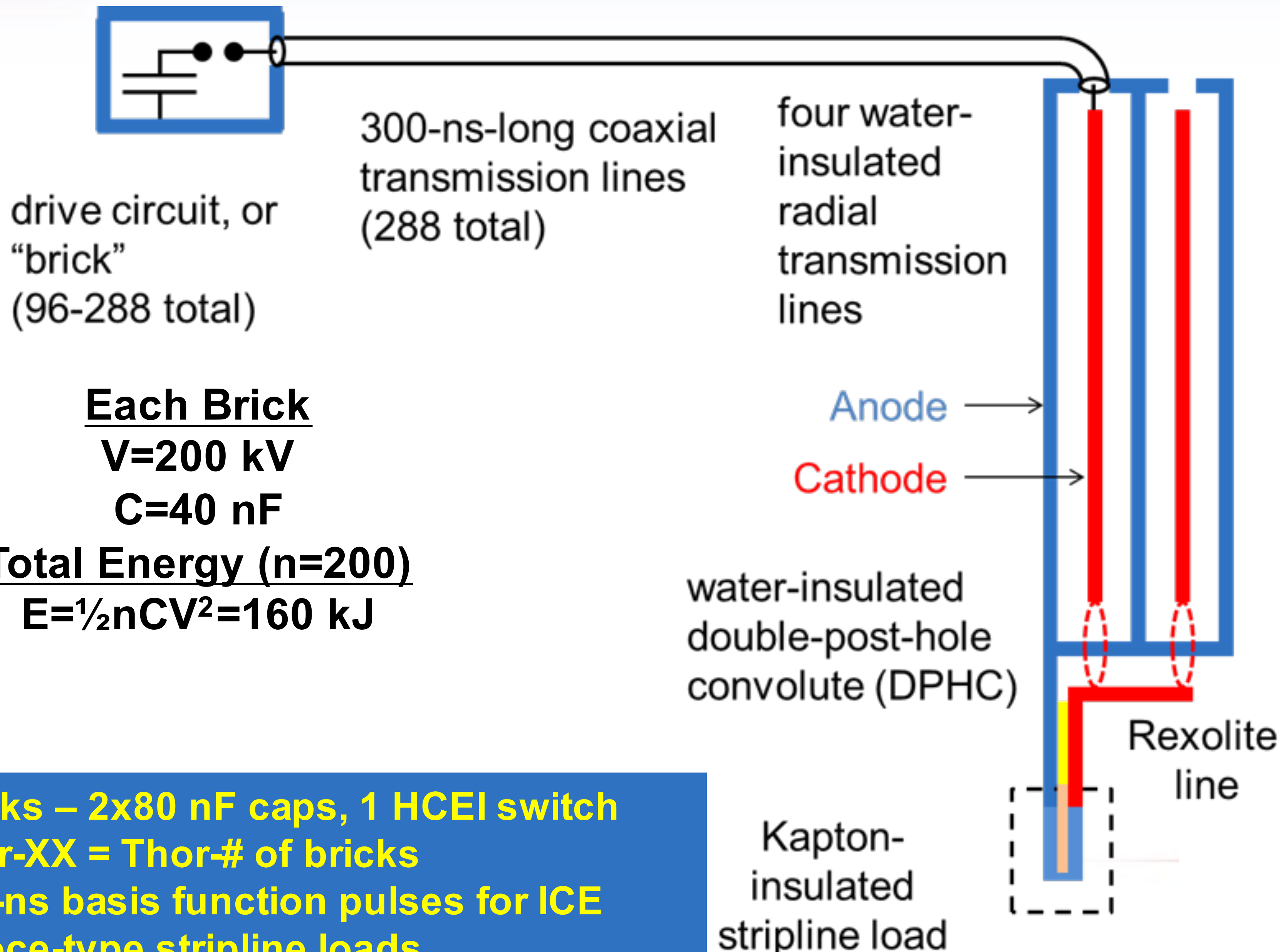


Thor Specifications for a Megabar-class pulsed power accelerator

- Peak current: 7 MA
- Current rise time: 200-500 ns
- Pulse shaping through independent, de-coupled switches
- Megabar+ peak magnetic pressures
- Enables a variety of experiments:
  - Soft Materials: Cerium, Lithium
  - Flat Top Pulse: Strength
  - Shock-Ramp: Iron
- Cost-effective university-scale machine
- Conditions relevant to geophysics
- Supports Scientific Based Stockpile Stewardship:
  - Investigate fundamental properties of materials
  - Compare simulation results to data
  - Supports ST&E facilities in the development of experiments and diagnostics



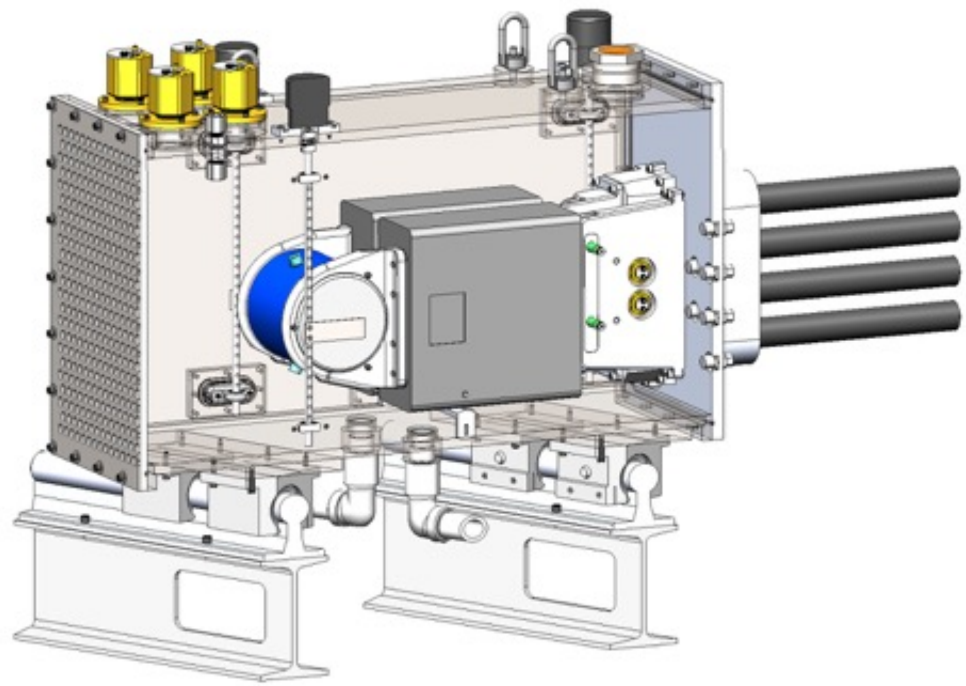
The Thor concept meets the requirements for a compact, megabar-class ICE driver

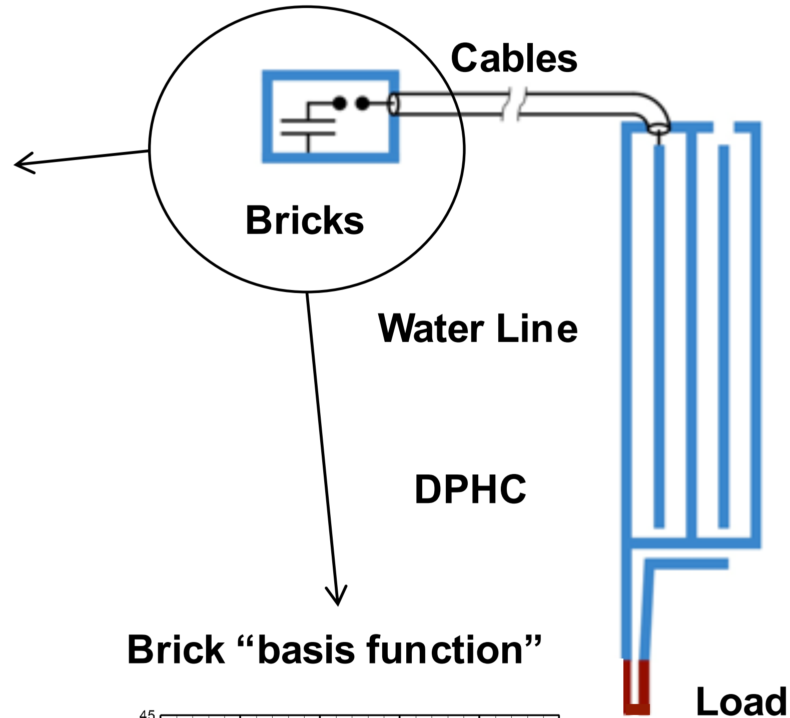


<u>Each Brick</u>
V=200 kV
C=40 nF
<u>Total Energy (n=200)</u>
$E=\frac{1}{2}nCV^2$=160 kJ

- **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

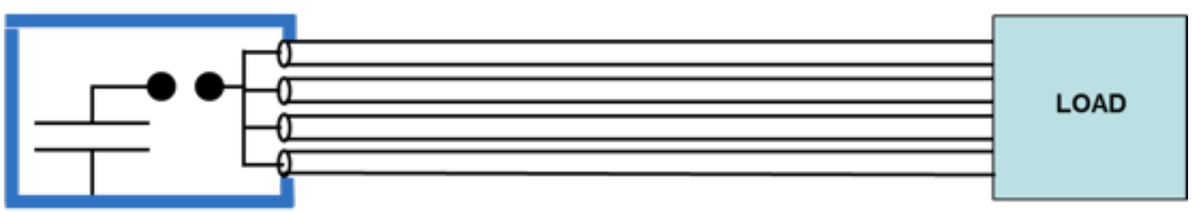




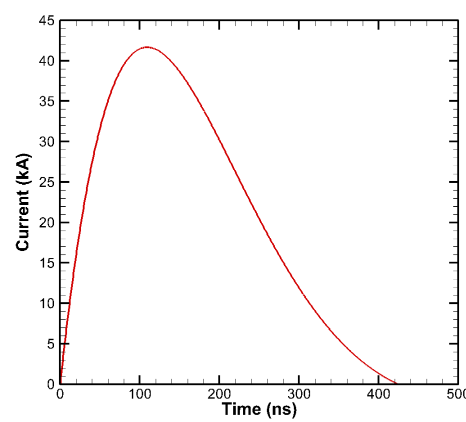
Cables are impedance-matched to bricks

C=40 nF, L=240 nH, R=0.37 Ω

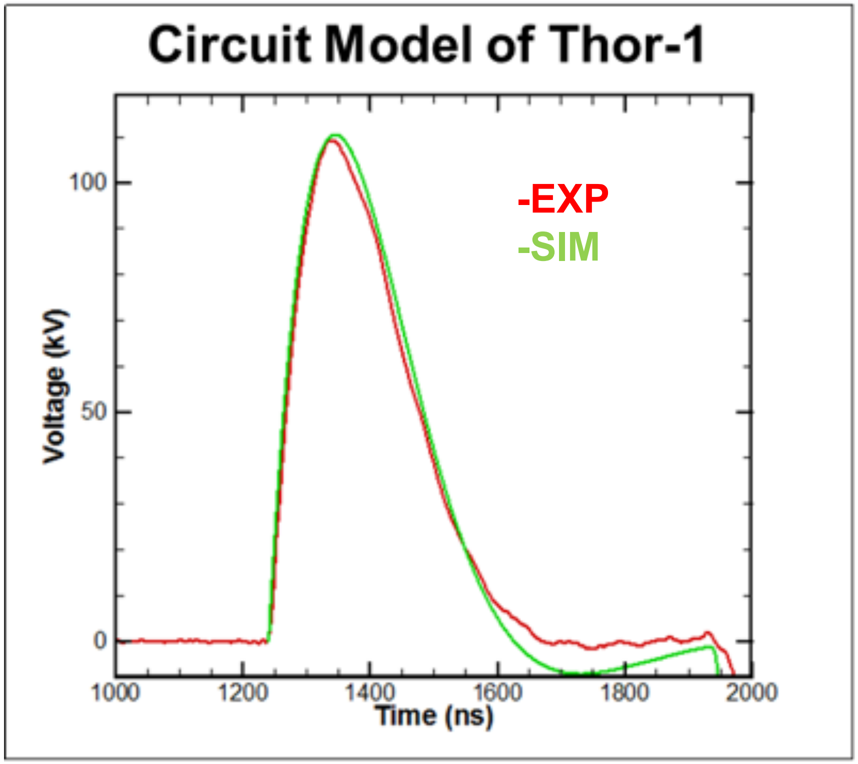
$$Z = 1.1\sqrt{\frac{L}{C}} + 0.8R = 3.00\Omega$$



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

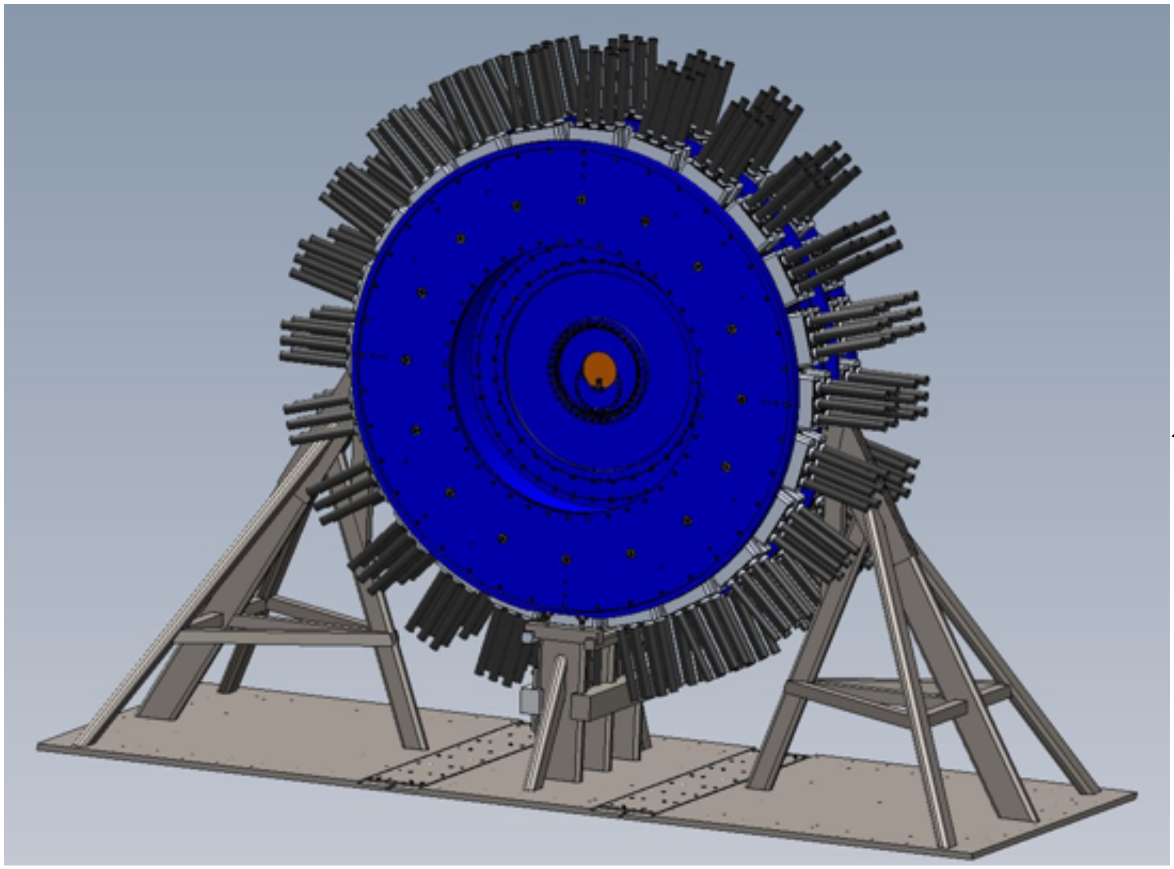


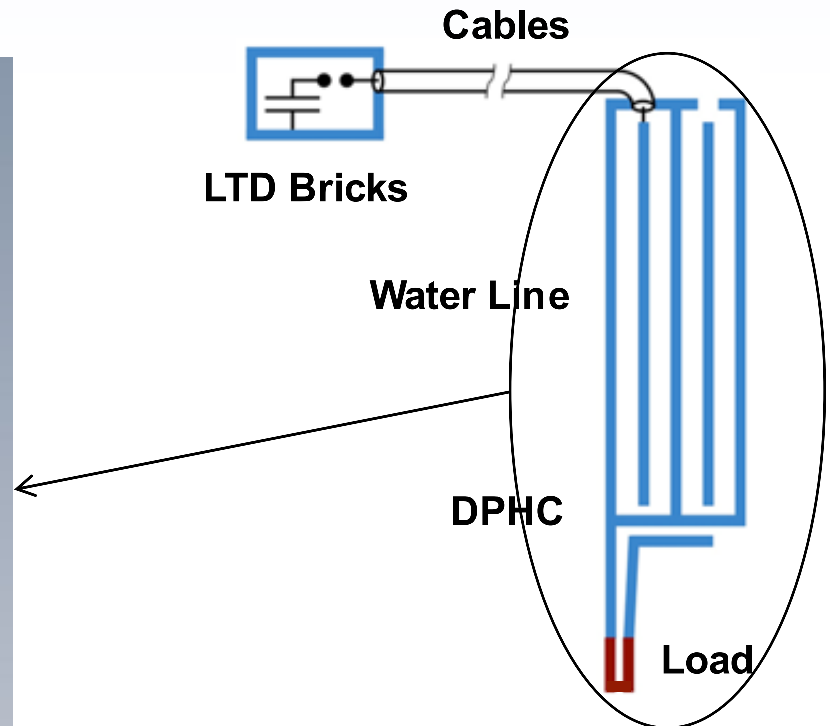
We are currently operating the Thor-1 single brick test stand



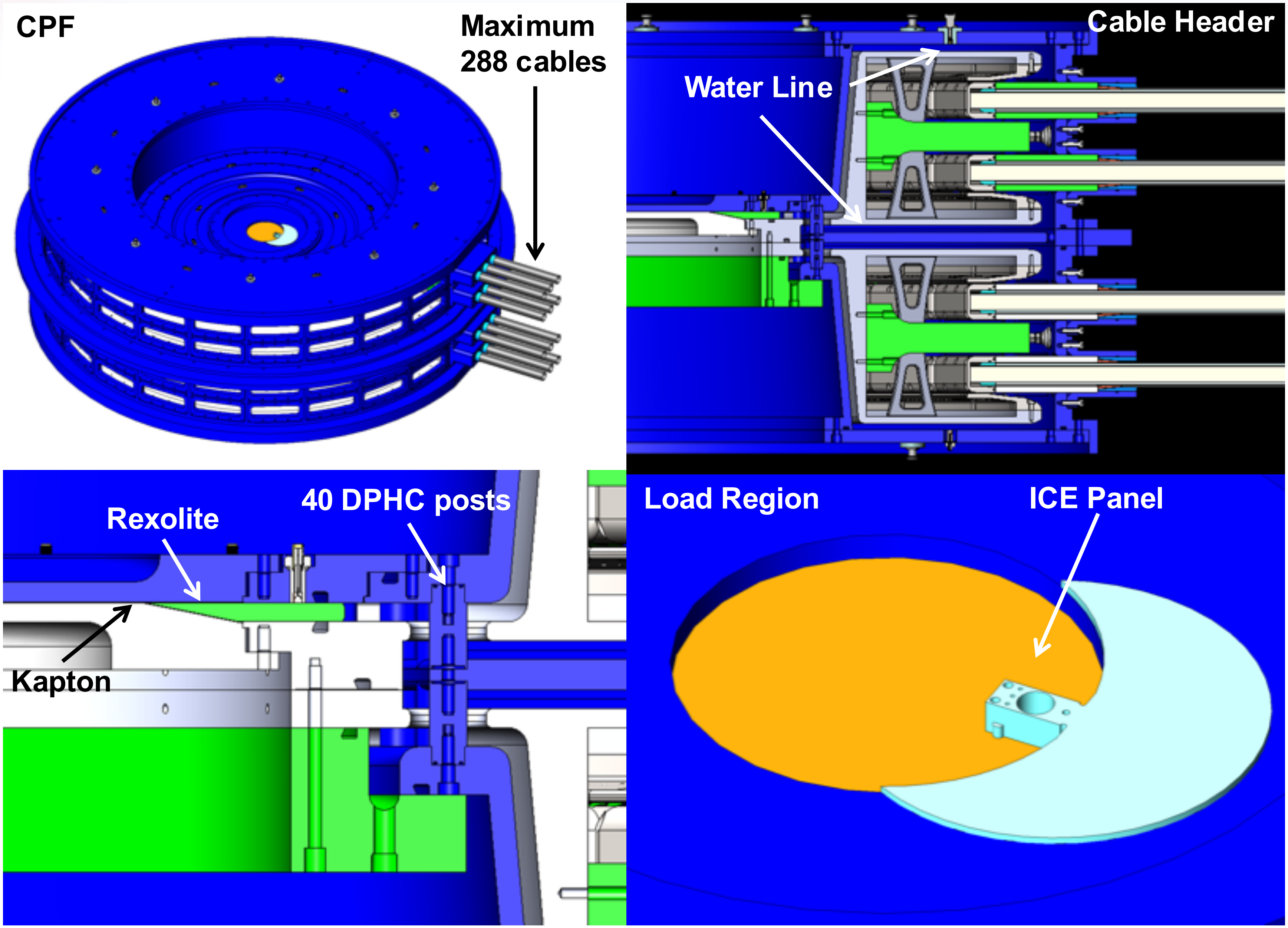
- 10,000 shots conducted
- +/- 100 kV
- 44 kA output
- Validated CSI/NWL capacitors, HCEI switches, DS Coaxial Cable
- Test bed for coaxial cables (poly, nano-poly, and water)

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



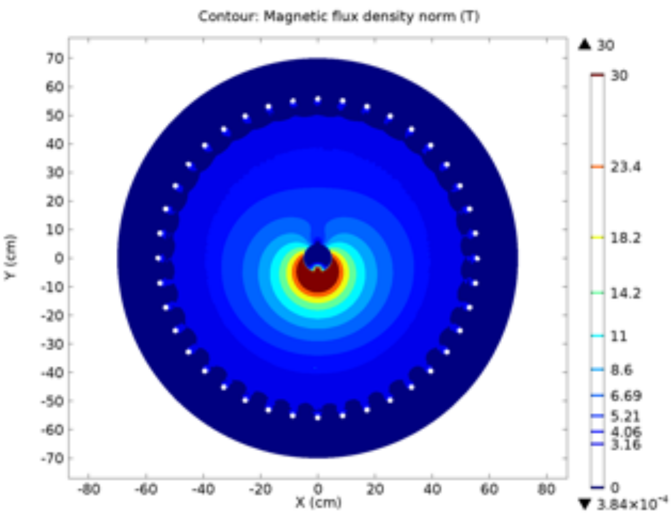


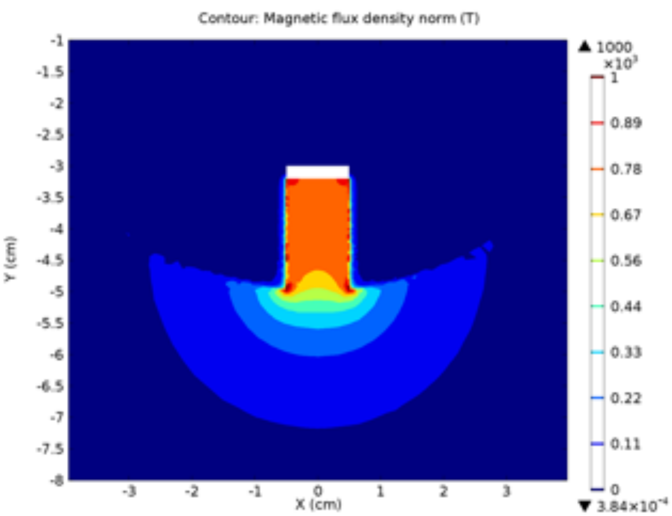
The central power flow (CPF) combines current from the cables into transmission lines



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

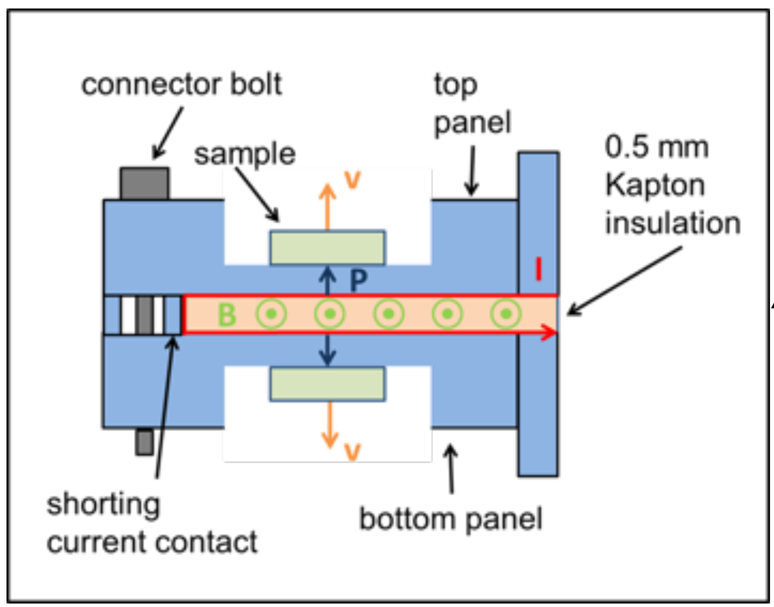
Panel on plate

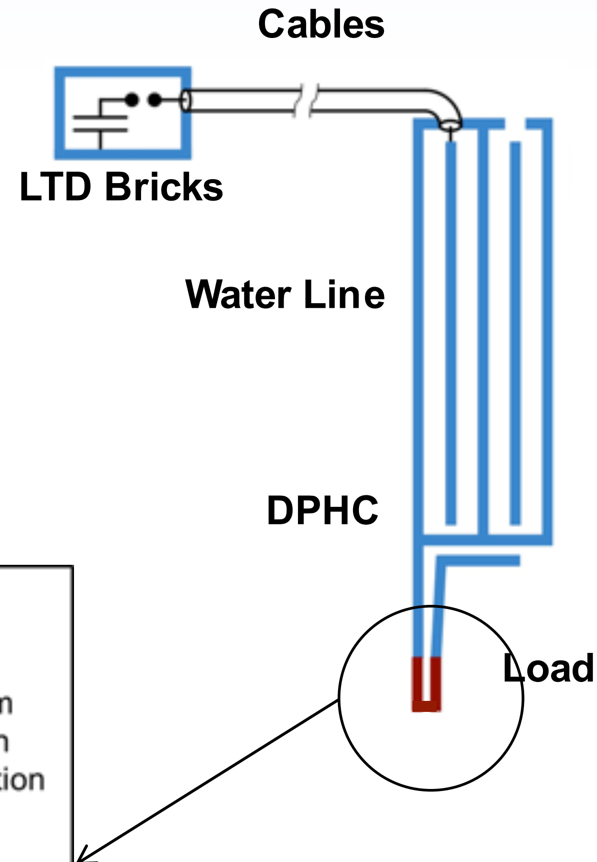




B concentrated into stripline

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

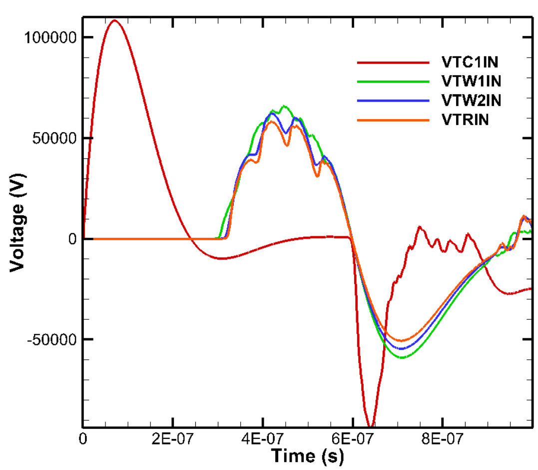




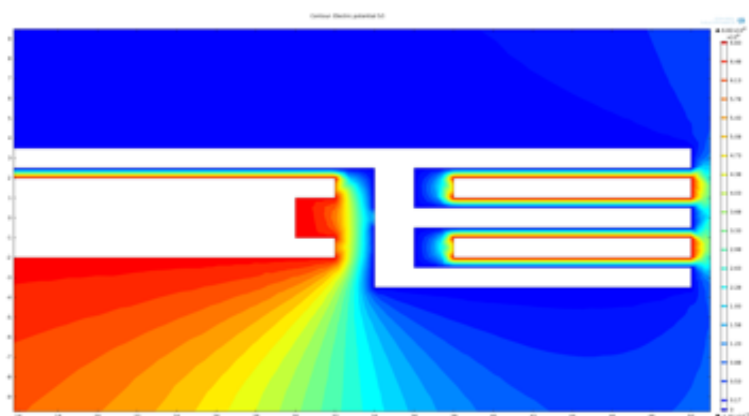
Simulation codes are used iteratively to determine design and performance

- **COMSOL** – Finite element code for E&M fields, calculate inductance and impedance
- **Screamer** – Circuit code to calculate element voltages, current, power
- **ALEGRA 2D/3D, Trac-II** –MHD codes to calculate pressure drive on ICE load, dynamic inductance.

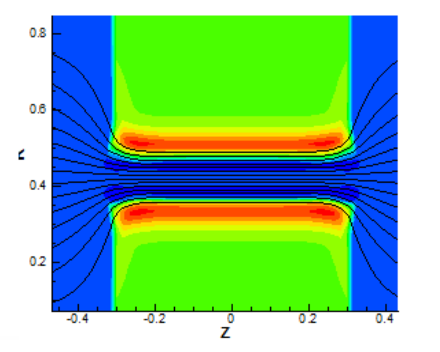
Voltages in SCREAMER



Electric Potential in COMSOL

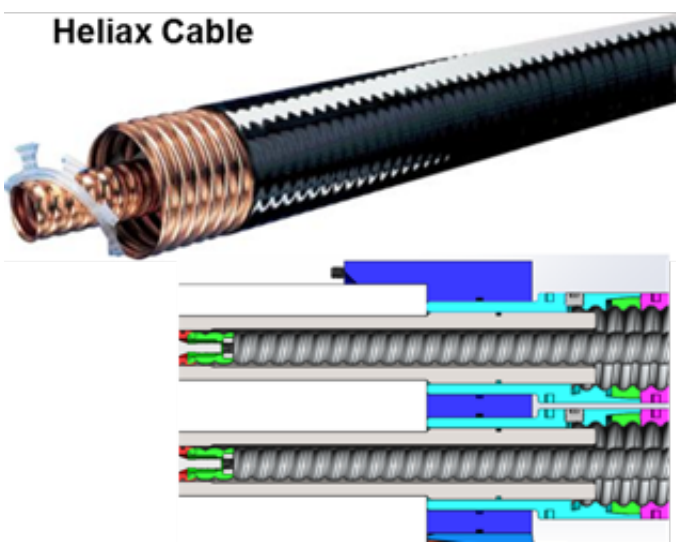


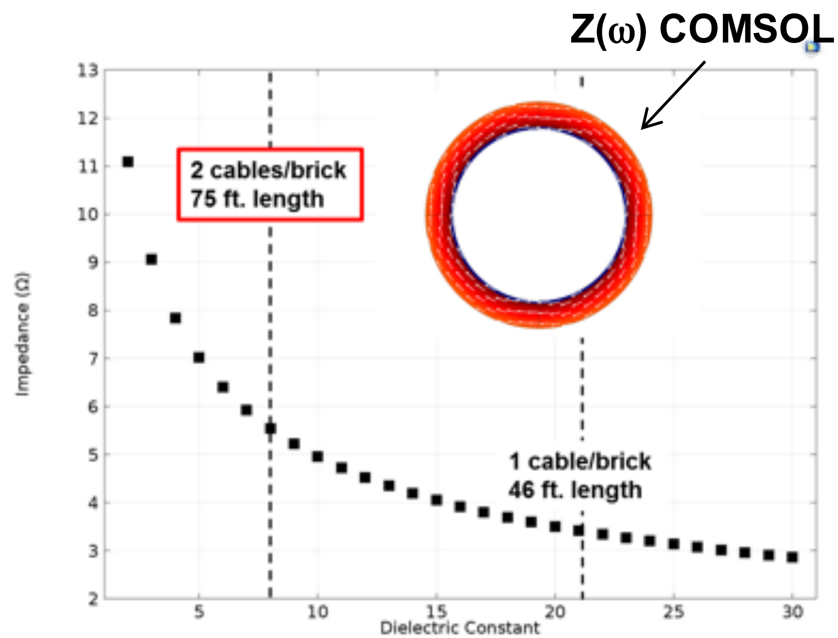
MHD in Trac-II



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

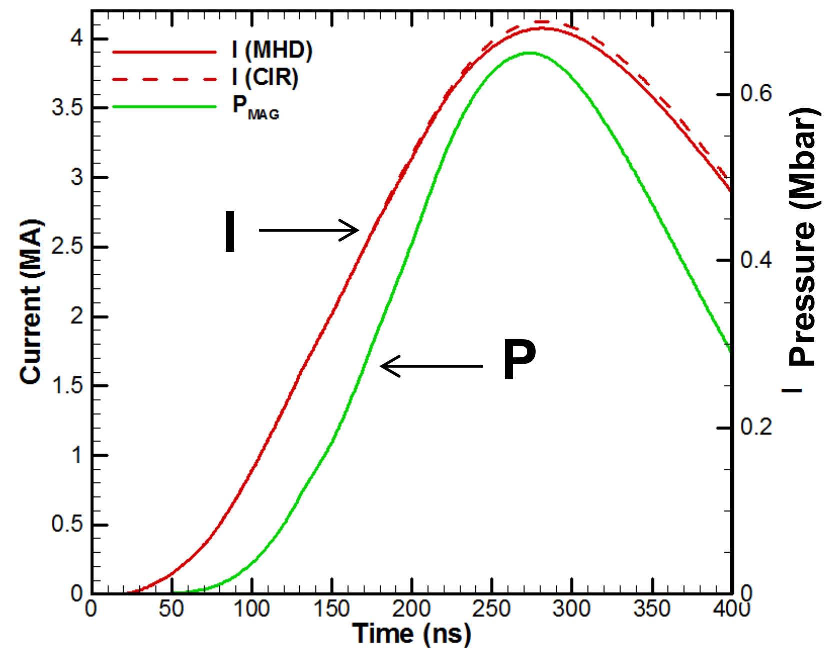




Thor can produce pressures of well over a Mbar

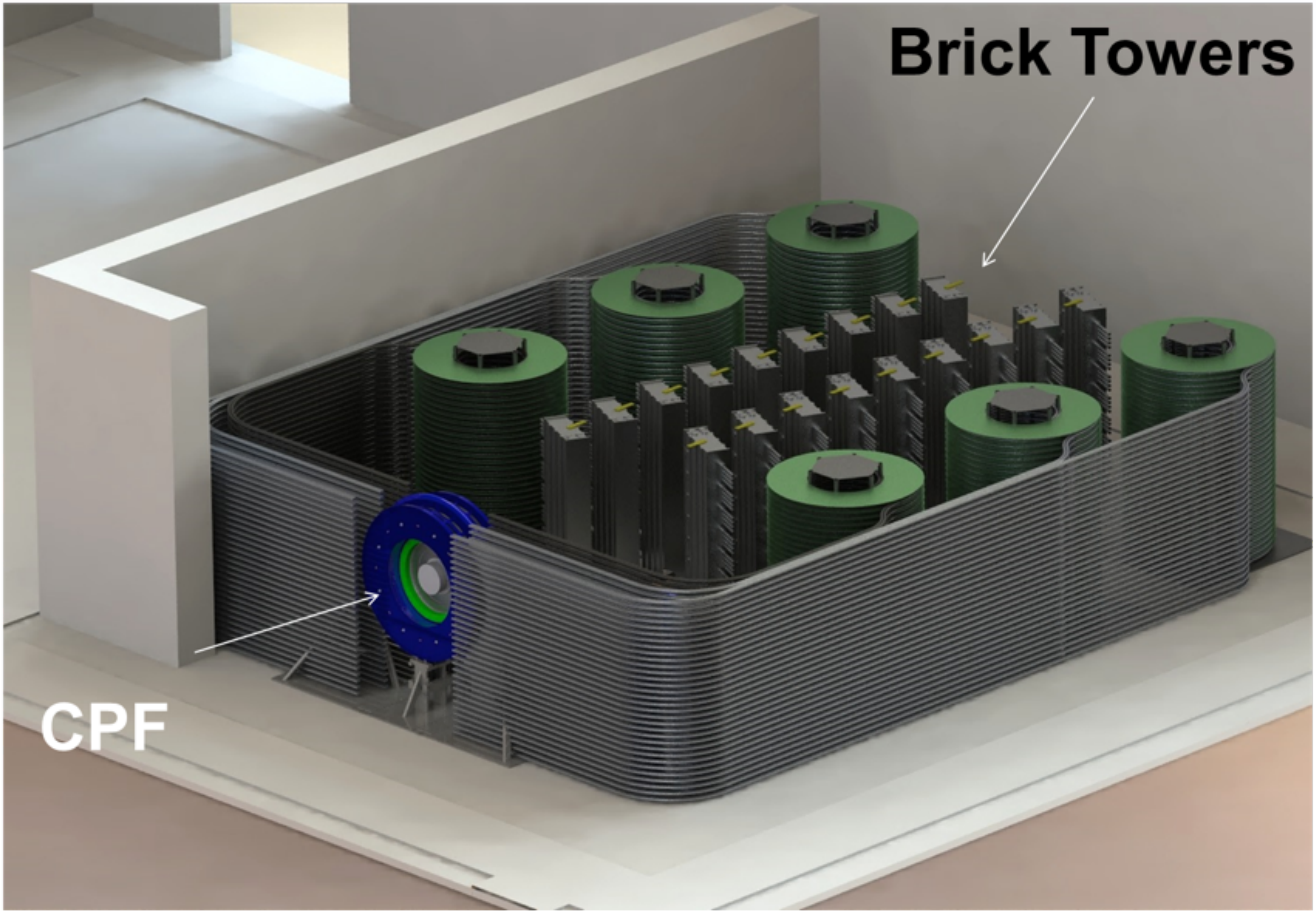
Brick #	Cables per brick	Etot (KJ)	Peak I (MA)	Peak P (Mbar)	Eload (kJ)	Eff. (%)
96	3	76.8	4.1	0.65	27.0	35
144	2	115	5.4	1.1	56.1	49
288	1	230	6.9	1.7	111	48

Thor-96
10 mm Cu panels



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

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



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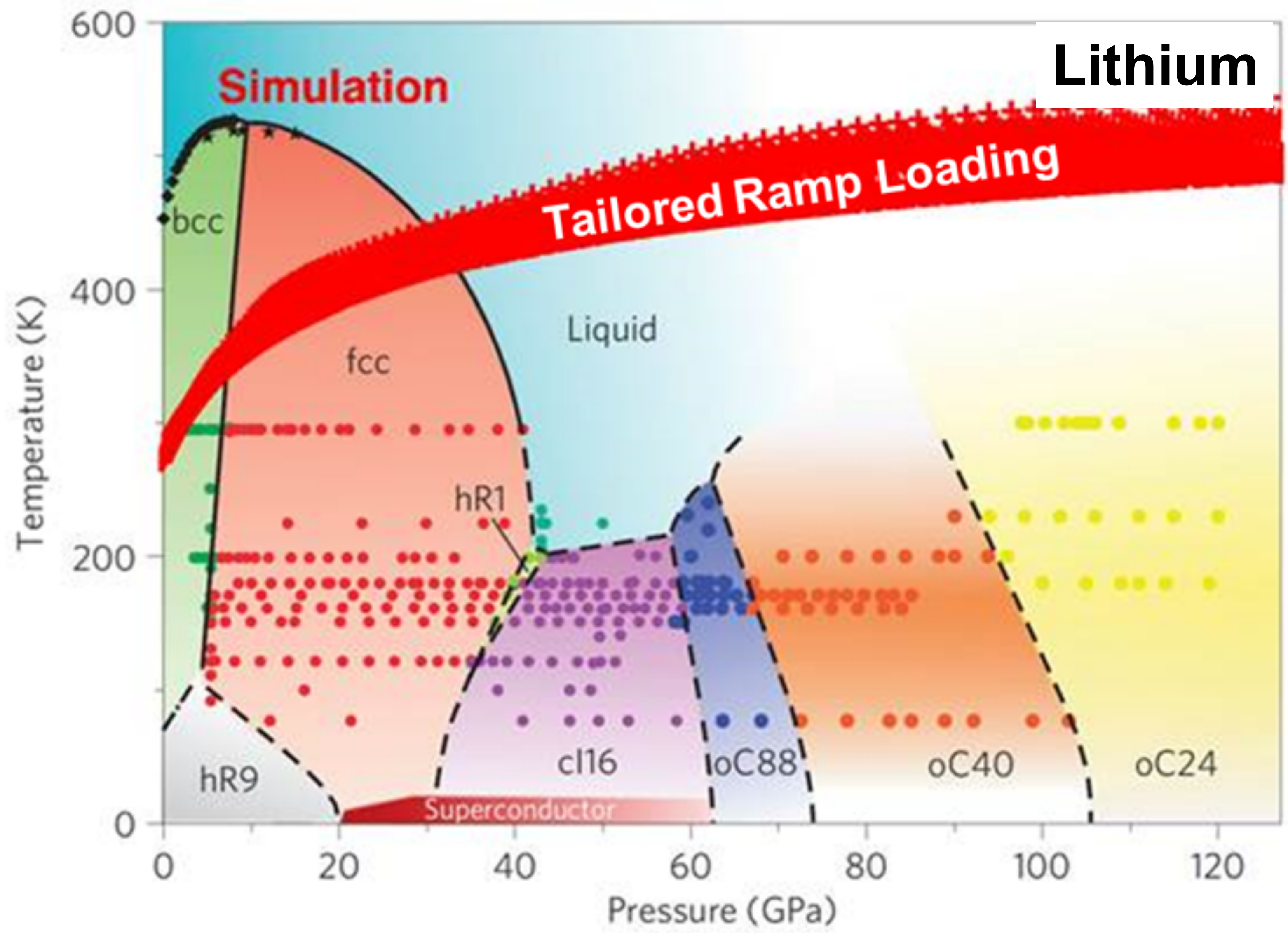
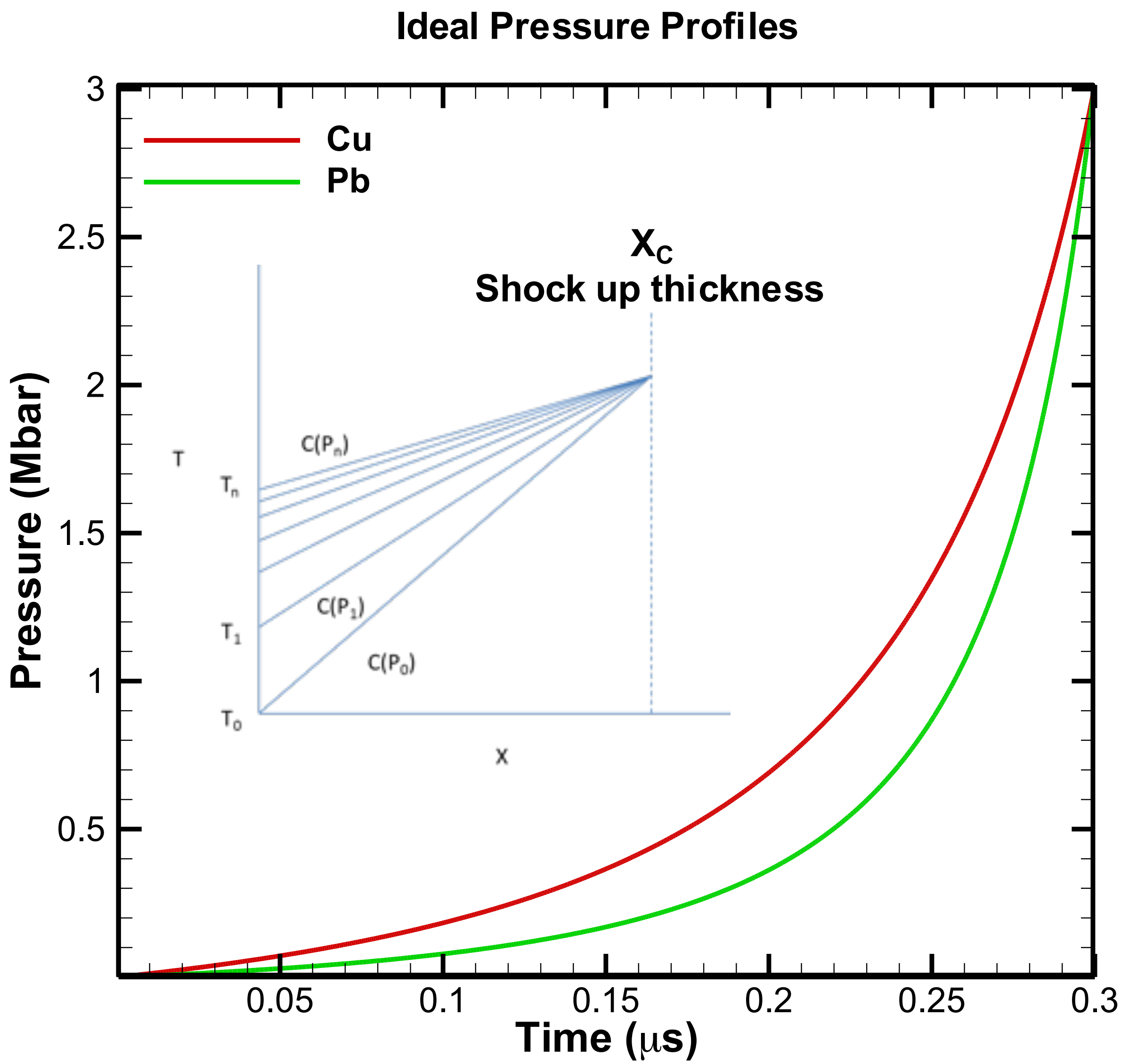
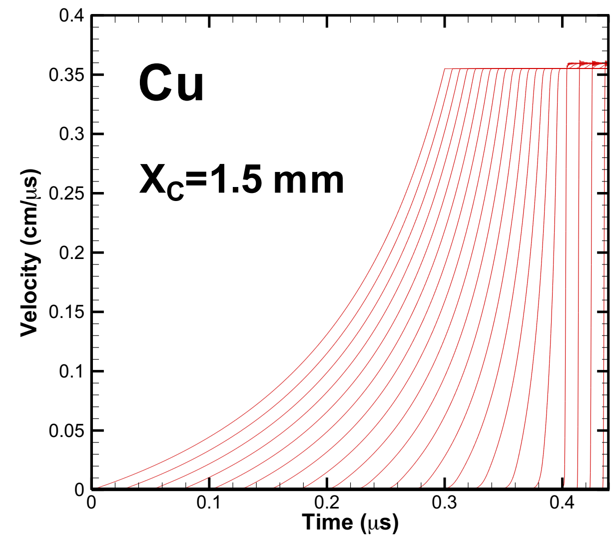
Pressure pulse tailoring enables study of many materials of interest in relevant regimes

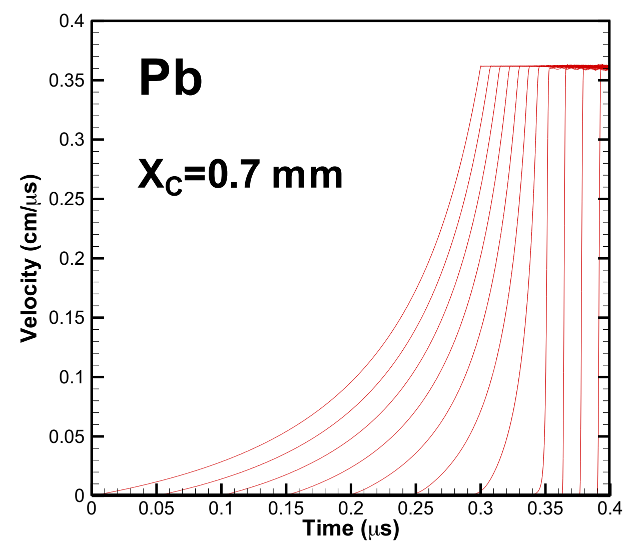


Pulse tailoring is required to maintain shockless loading



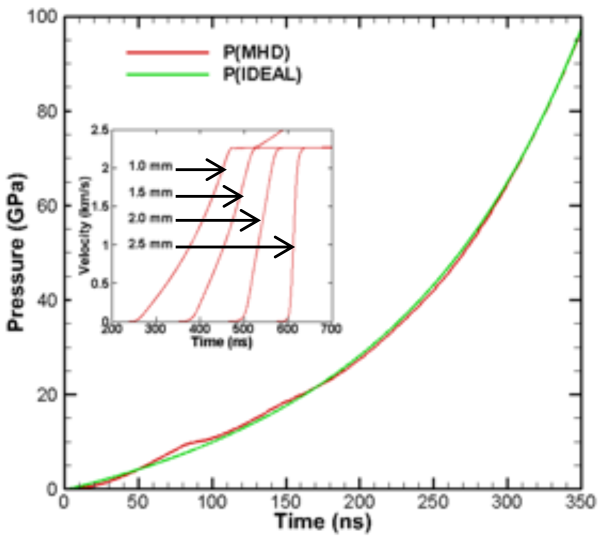
Velocity Waveforms



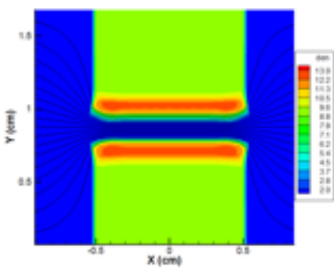


We have developed a circuit-free method to tailor the current pulse

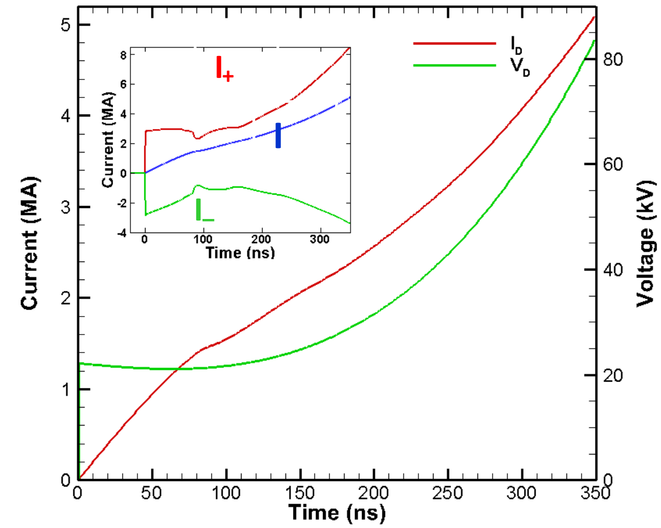
Ideal pulse for Cu/LiF Window: Xc=2400 μm



2D MHD



Find desired current and voltage



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

Form forward-going current

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

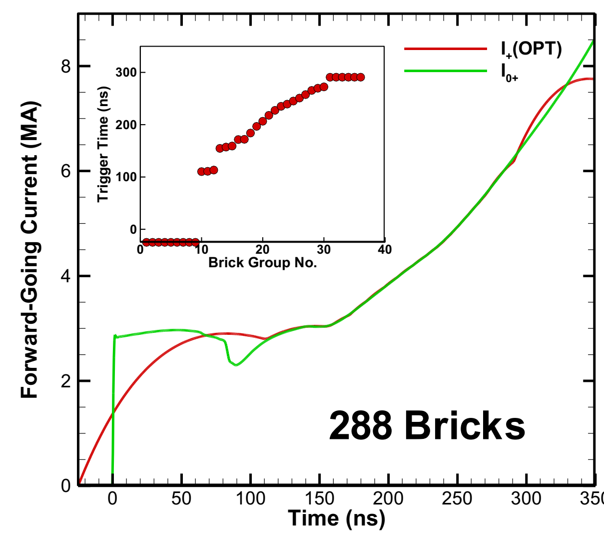
Express current as brick sum*

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

Optimize to find trigger times:

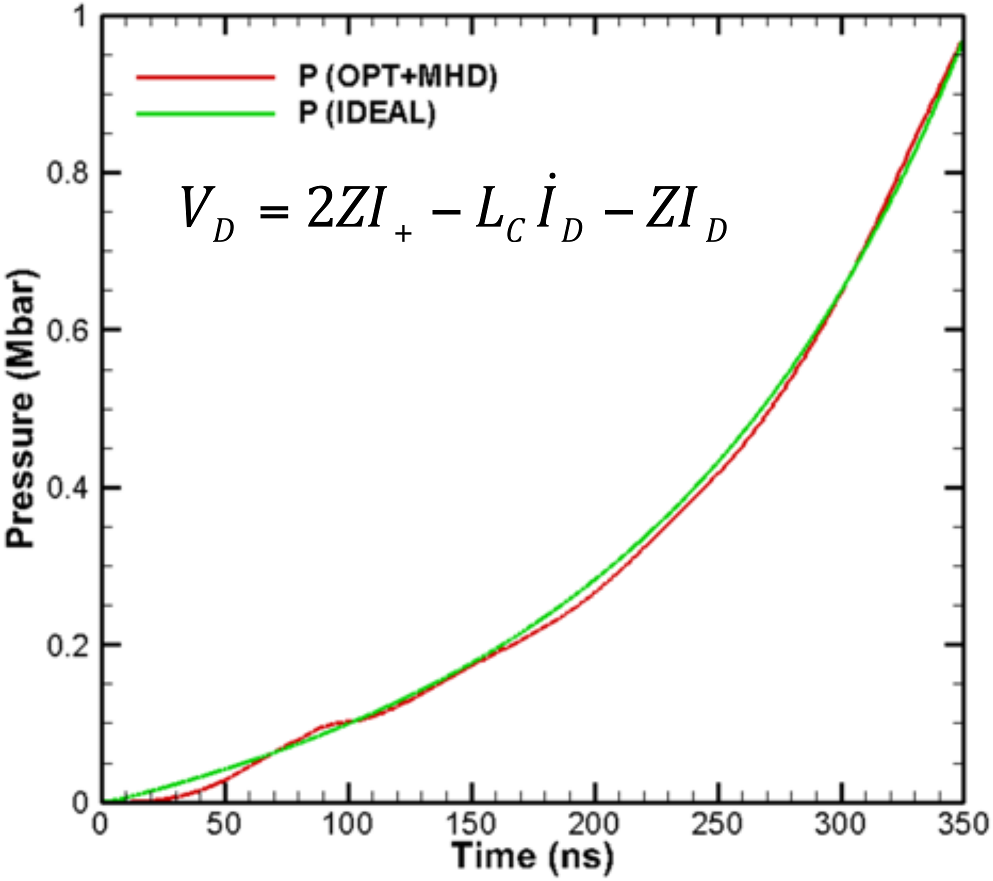
$$\vec{\tau} = \left(\tau_1, \ldots, \tau_n\right)$$

Find optimized forward-going current I_+



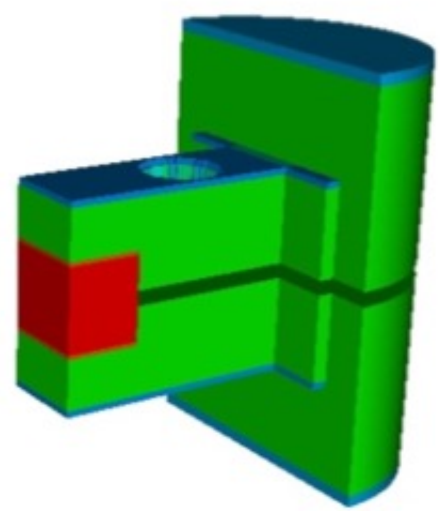
***Result of transit-time isolated transmission lines**

Optimization results are verified with the MHD code



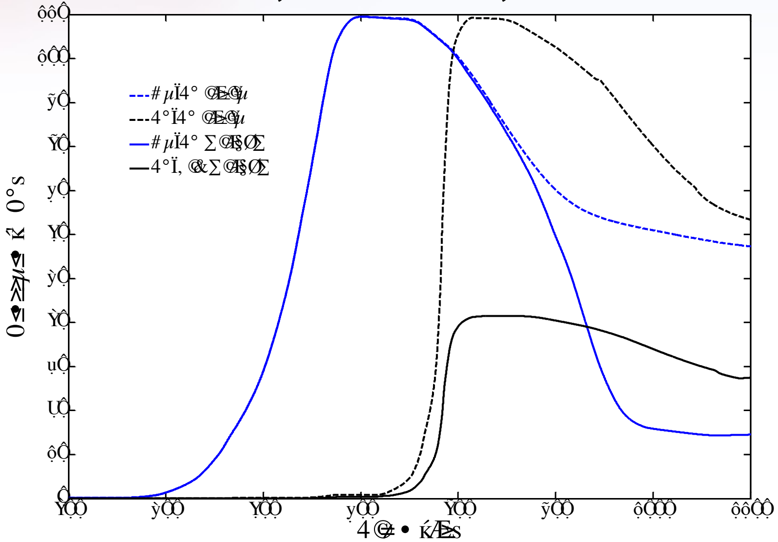
D.B. Reisman, *et al.*, PRSTAB 18, 090401 (2015)

- 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

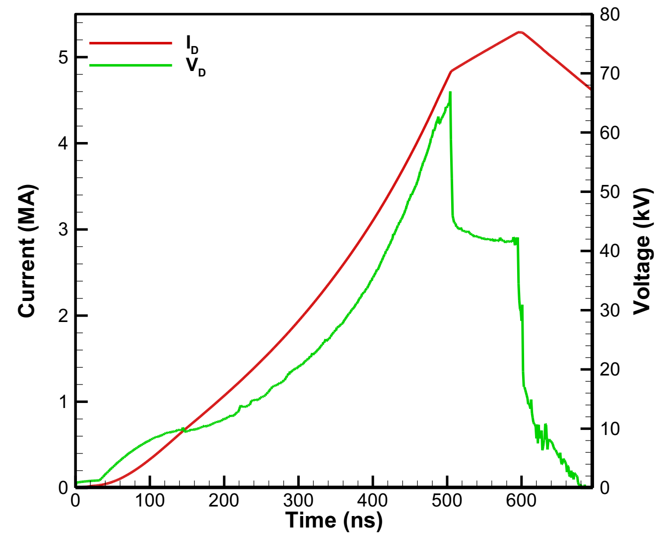


Optimization procedure is used to design 1.1 Mbar Cu/Ta strength experiments

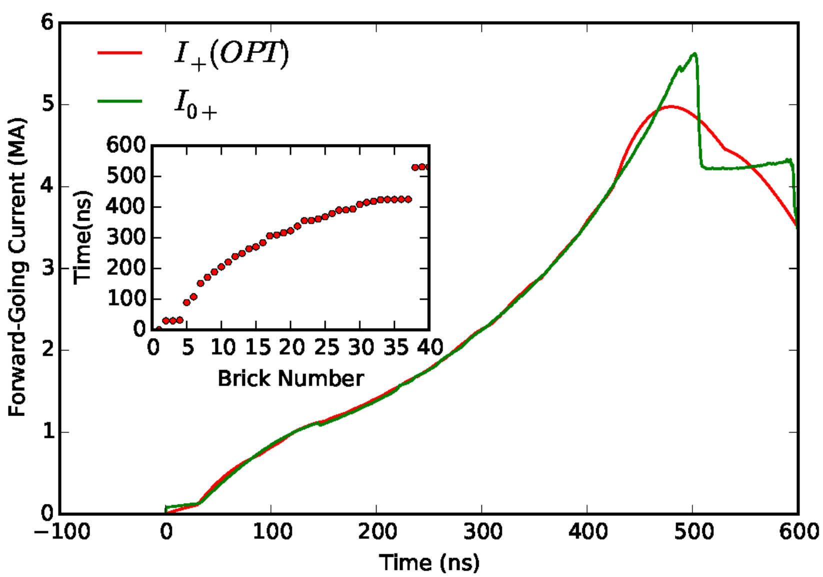
1.5 mm Cu, 0.8 mm Ta , 4 mm LiF



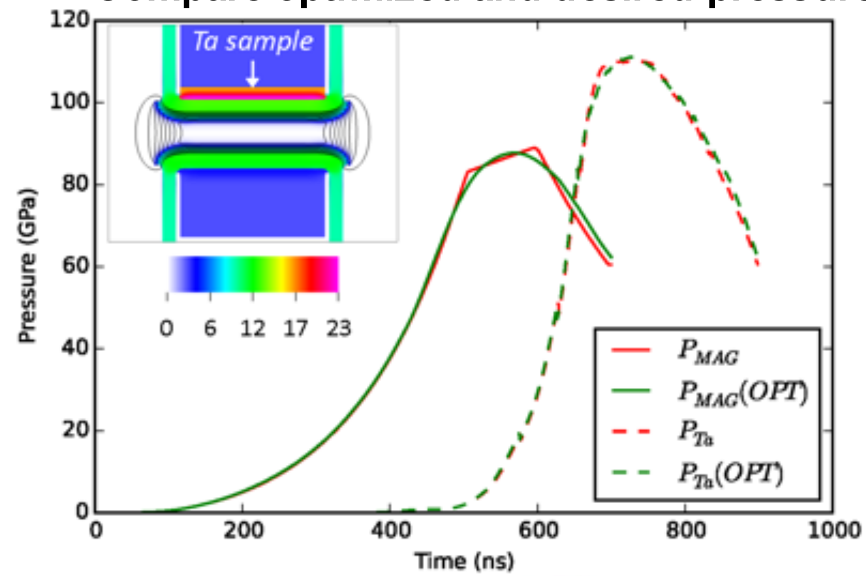
Desired voltage and current



Optimization to determine triggering



Compare optimized and desired pressures

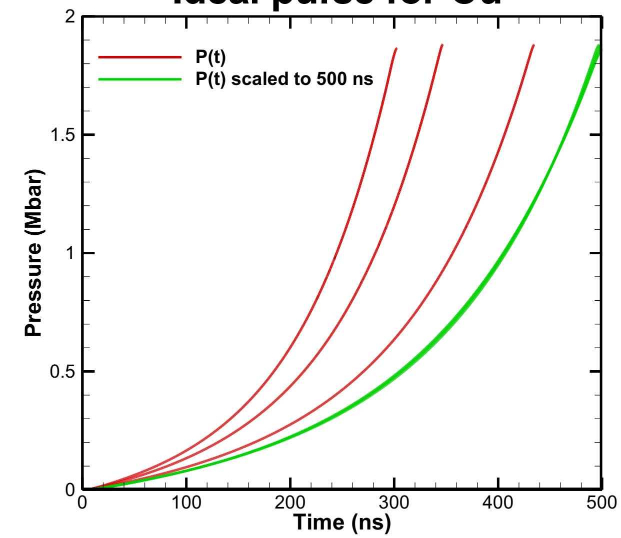


E.M. Waisman, D.B Reisman, *et al.,* Rev. Sci. Instrum. 87, 063906 (2016)

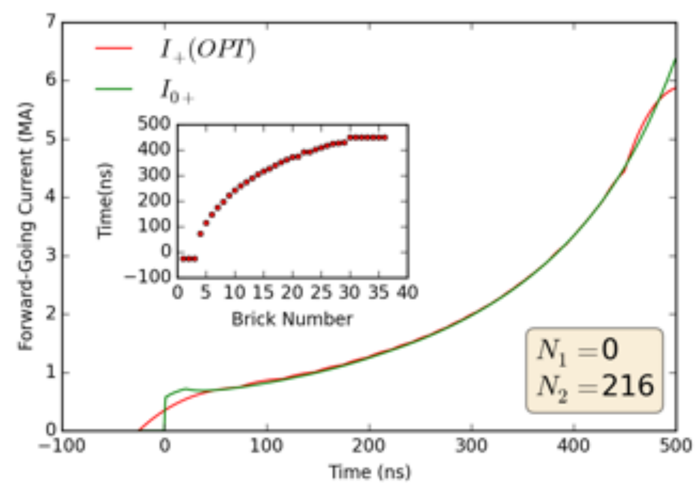
Thor's (current-adder) pulse tailoring aids the design of experiment and machine

- For a given ICE design, three conditions must be met
  - Energy, Voltage, Current
- Tailoring can be accomplished using the principle of superposition and grad-based optimization techniques (Newton, CG, etc.)
- The minimization method can be used to:
  - Design the experiment backwards, starting with the material, obtaining the pulse and triggering
  - Determine peak pressure and loading time for a given configuration
  - Determine brick and load requirements to meet certain performance levels →

Ideal pulse for Cu



Al ICE with 2-stage "Marxed" bricks



Outline

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- Neptune
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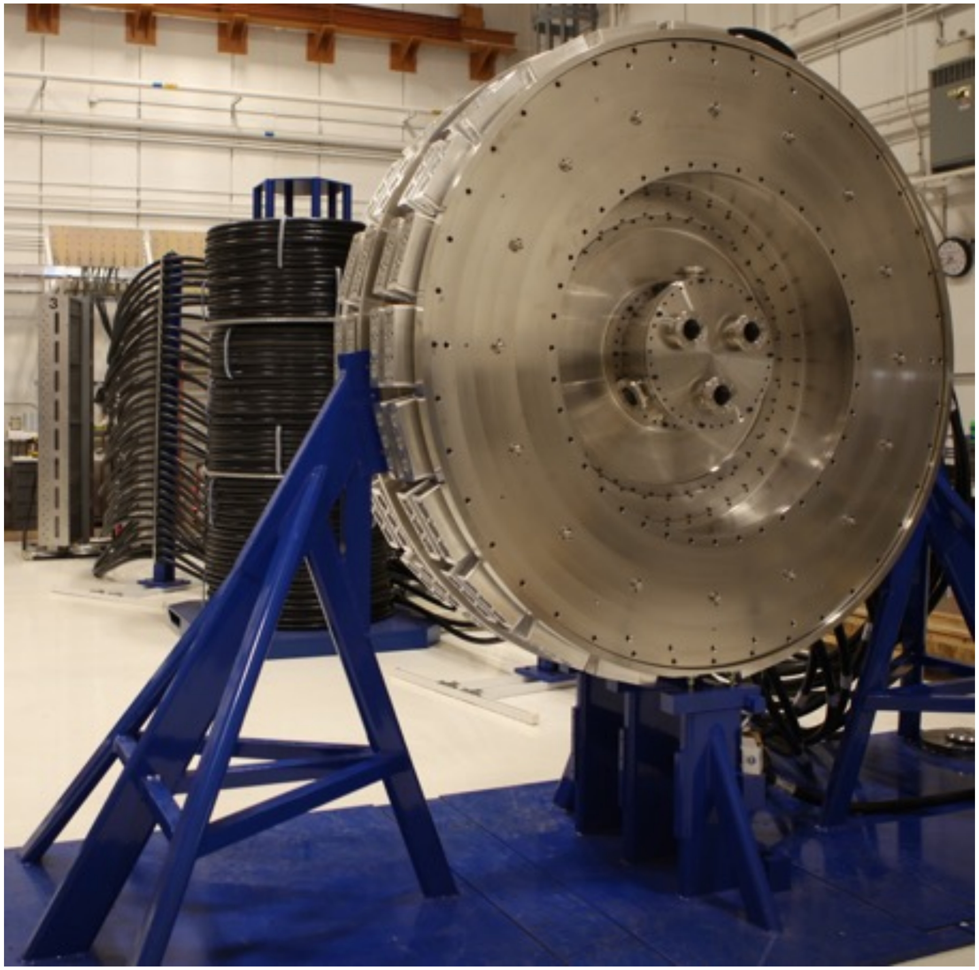
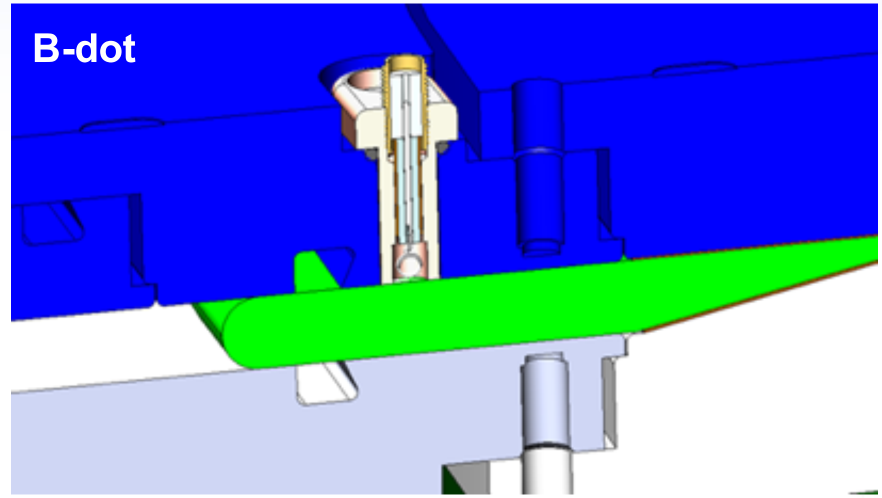
Thor-8 was commissioned in May 2016



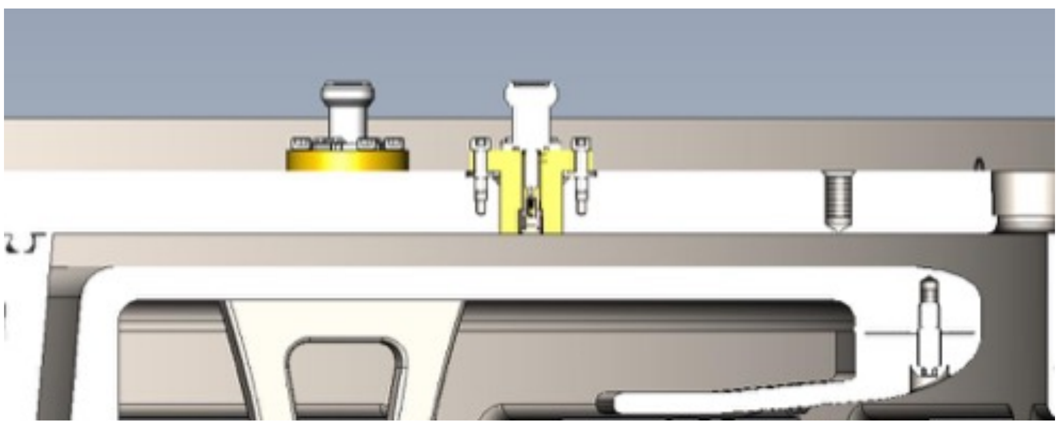
- First experiments conducted at half-voltage to non-destructively validate systems
- Experiments on Thor-16 are underway
- First load physics experiments with Thor-24 in September
- Extension to Thor-48 in FY17

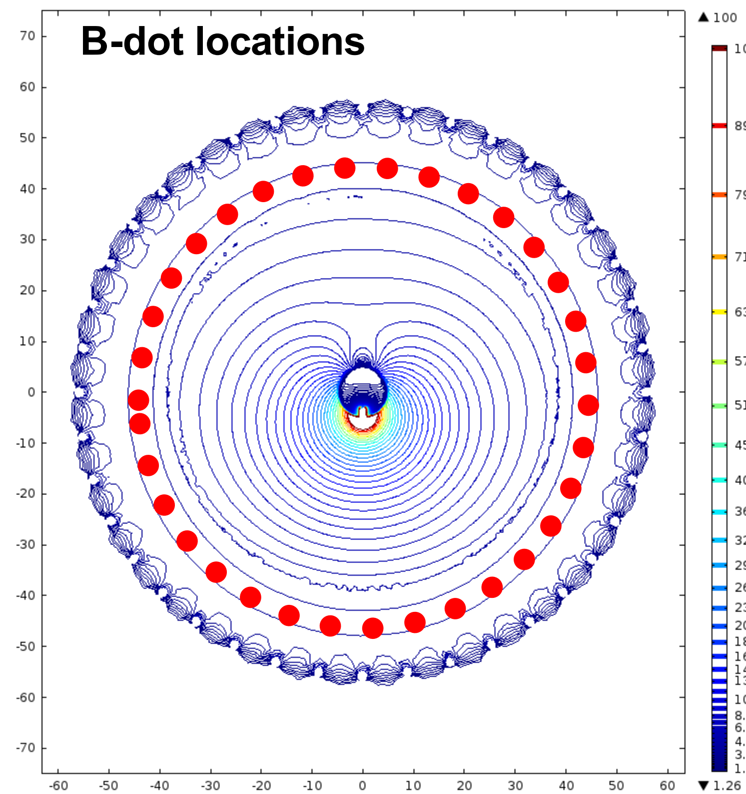
B-dots and V-dots are used to monitor current in the CPF

- B-dot located above Rexolite (R=50 cm)
- V-dots in 2 of 4 water lines
- Voltage monitors in bricks
- Free Field B-dots above load
- Compare current monitors and PDV to validate power flow

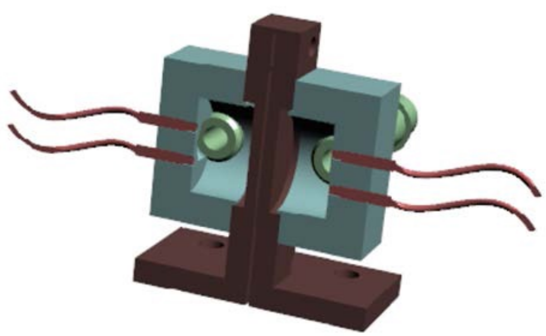


V-dot in Water Line

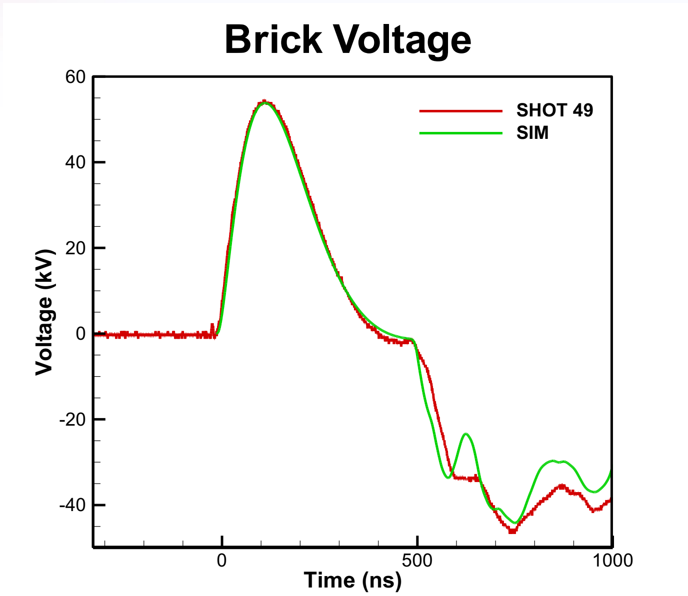


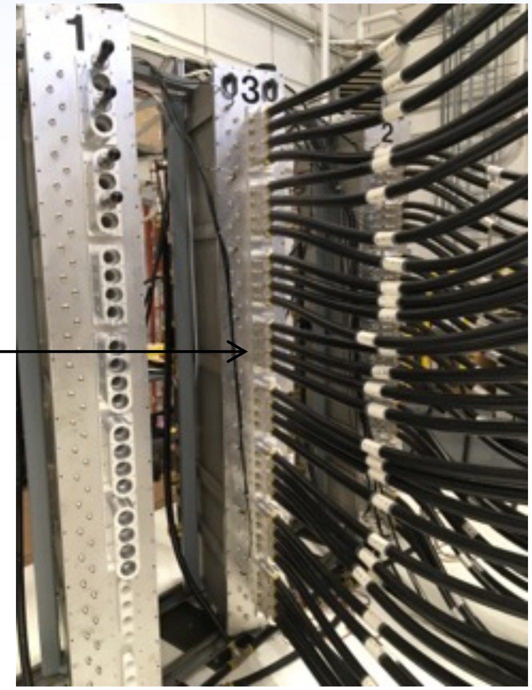


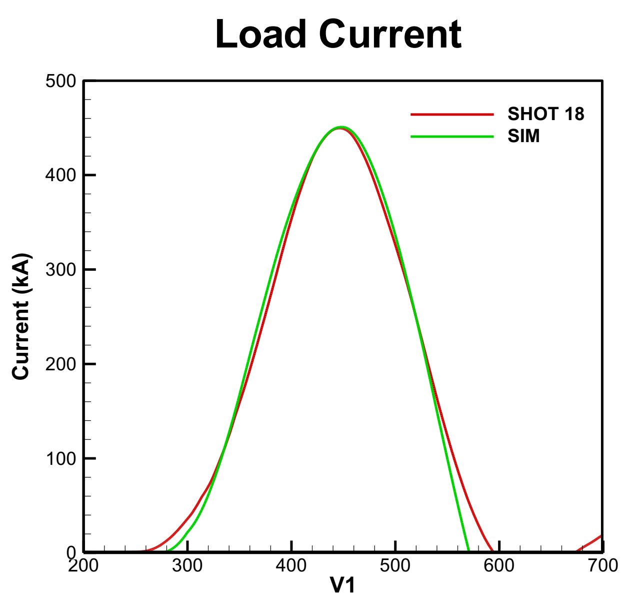
Load PDV

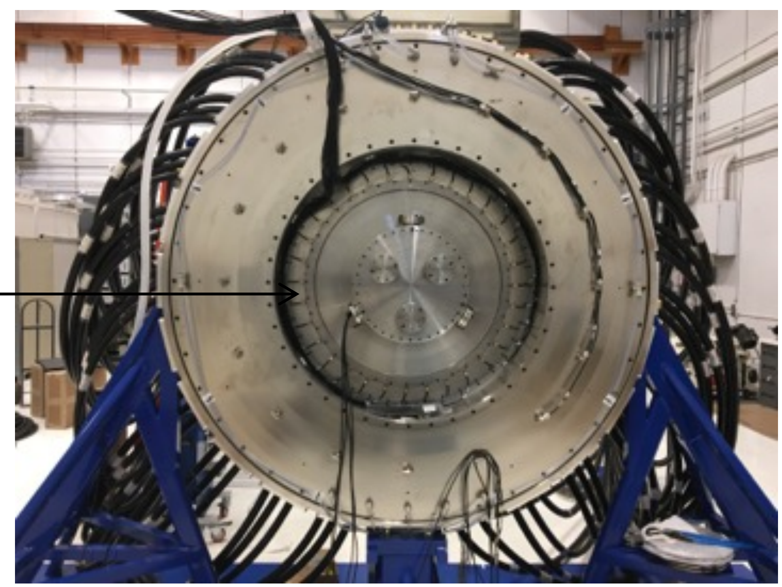


Thor-8 shots (±50 kV) – calculation comparison



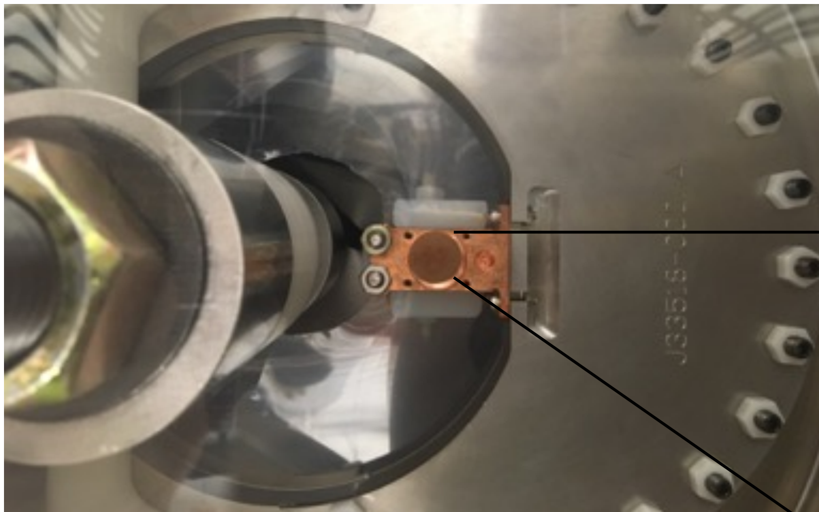


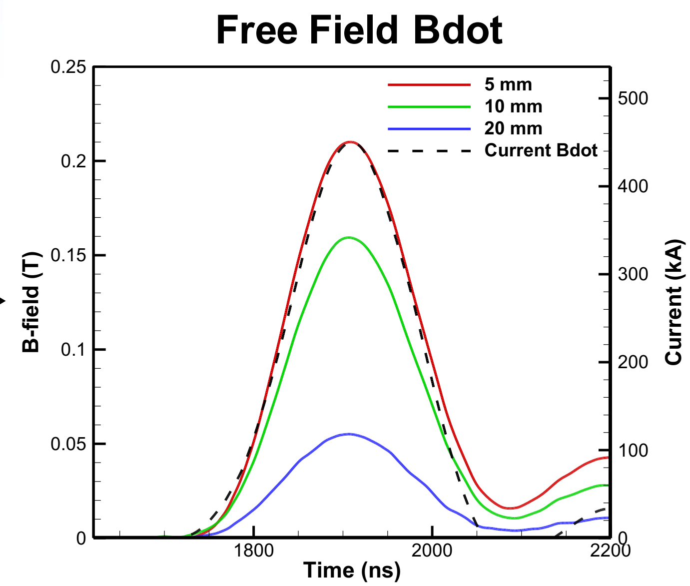


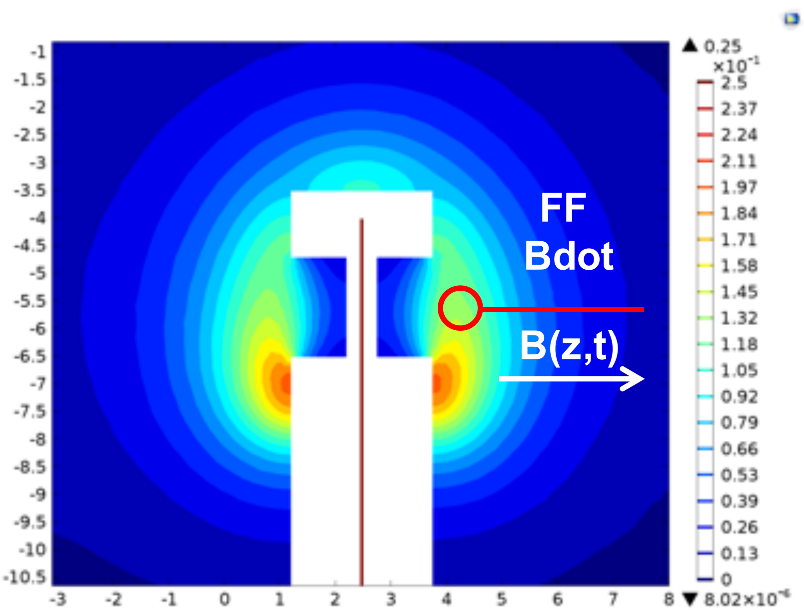


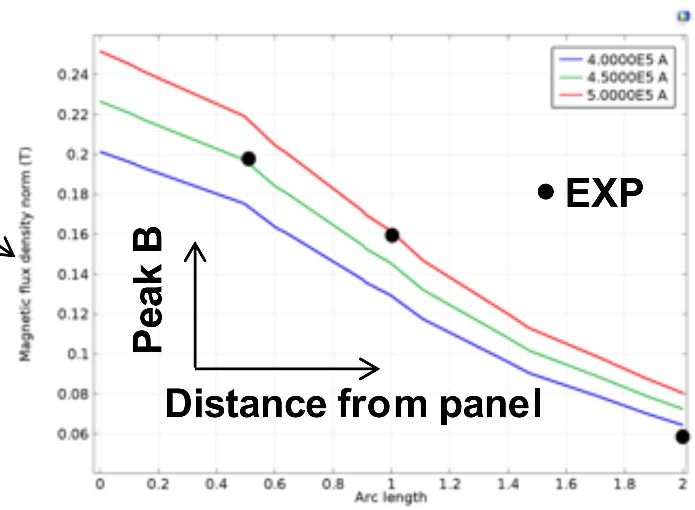
Thor-8 shots (±50 kV) – calculation comparison

Load Region





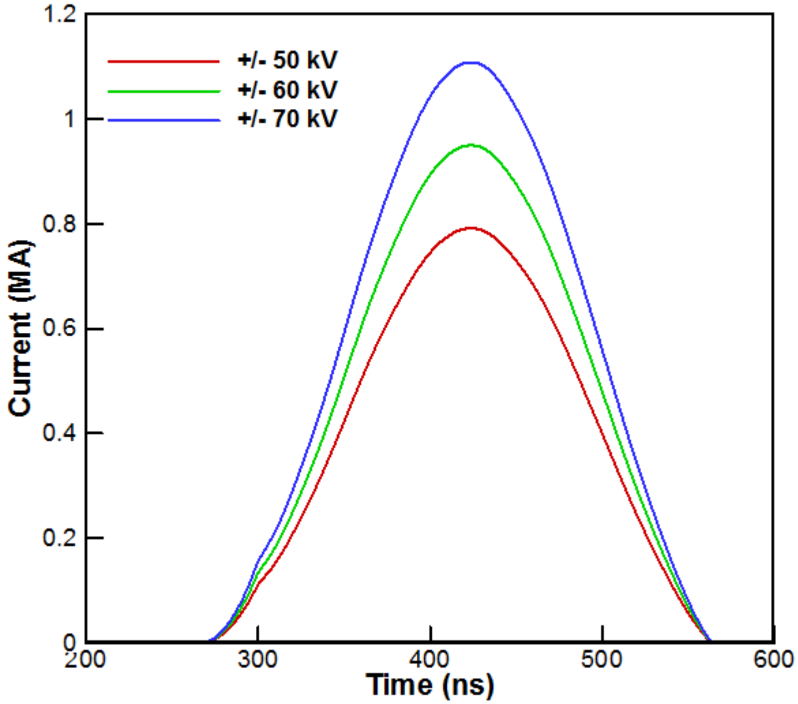




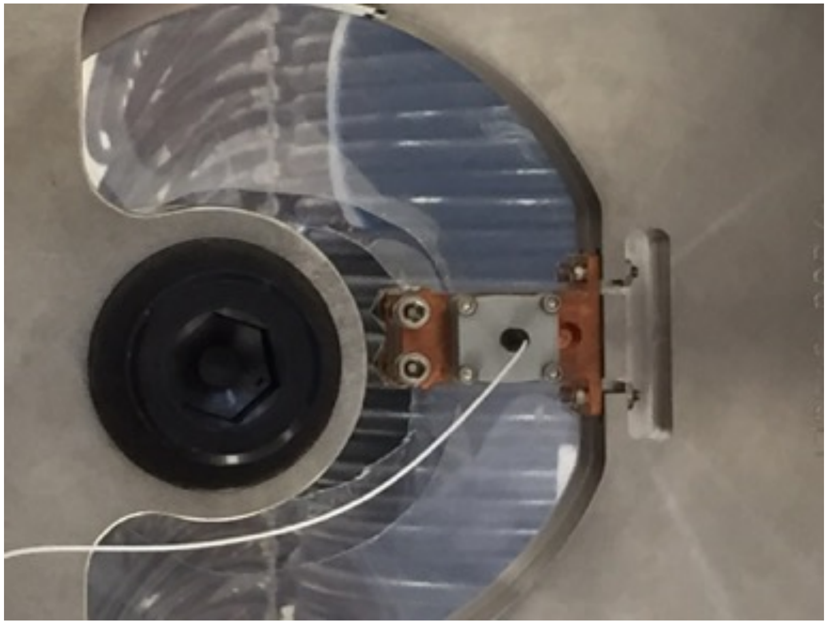
Thor-16 is being commissioned this week

Thor-16 data: coming soon

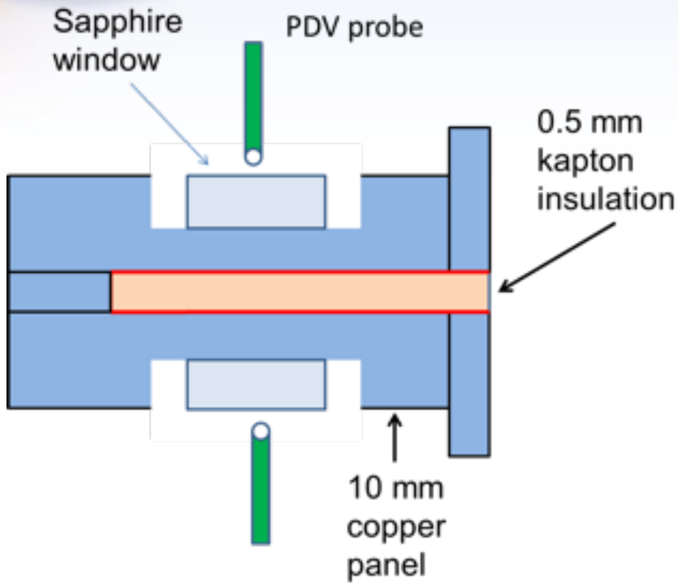
Screamer Simulated Load Current

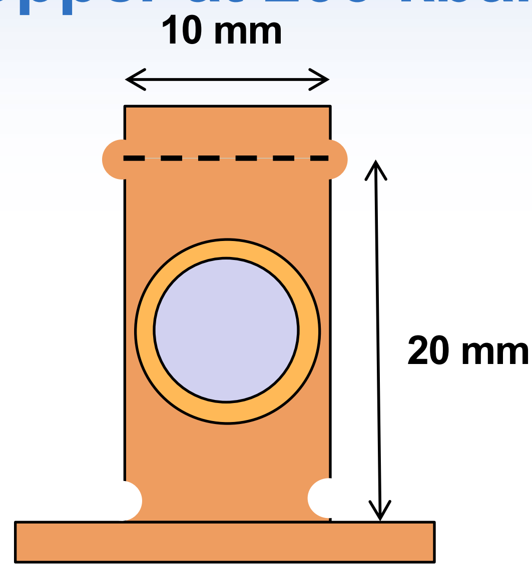


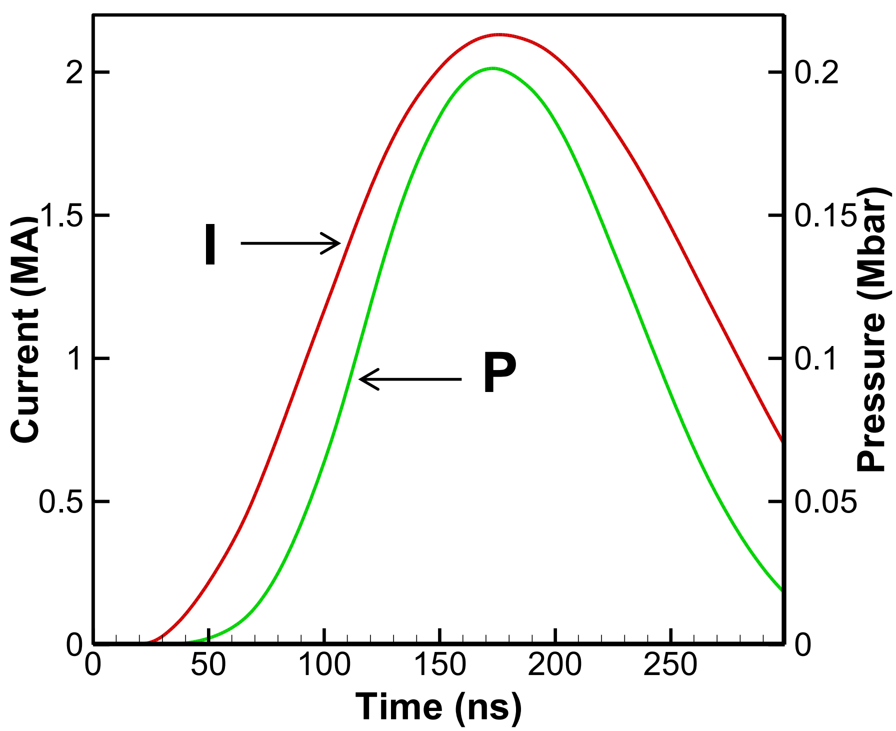
ICE Panel with PDV probe



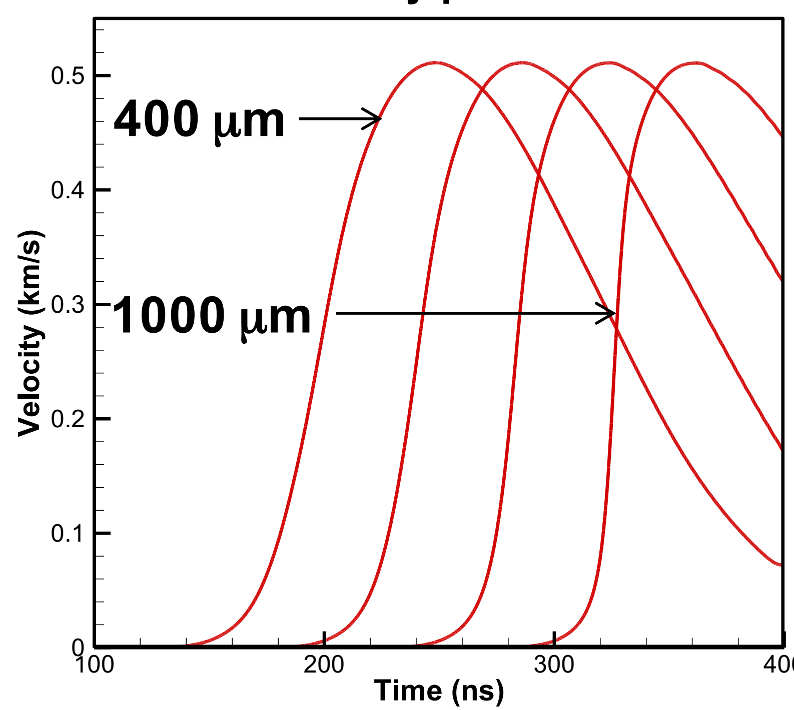
Thor-24 shot series in September: copper at 200 kbar



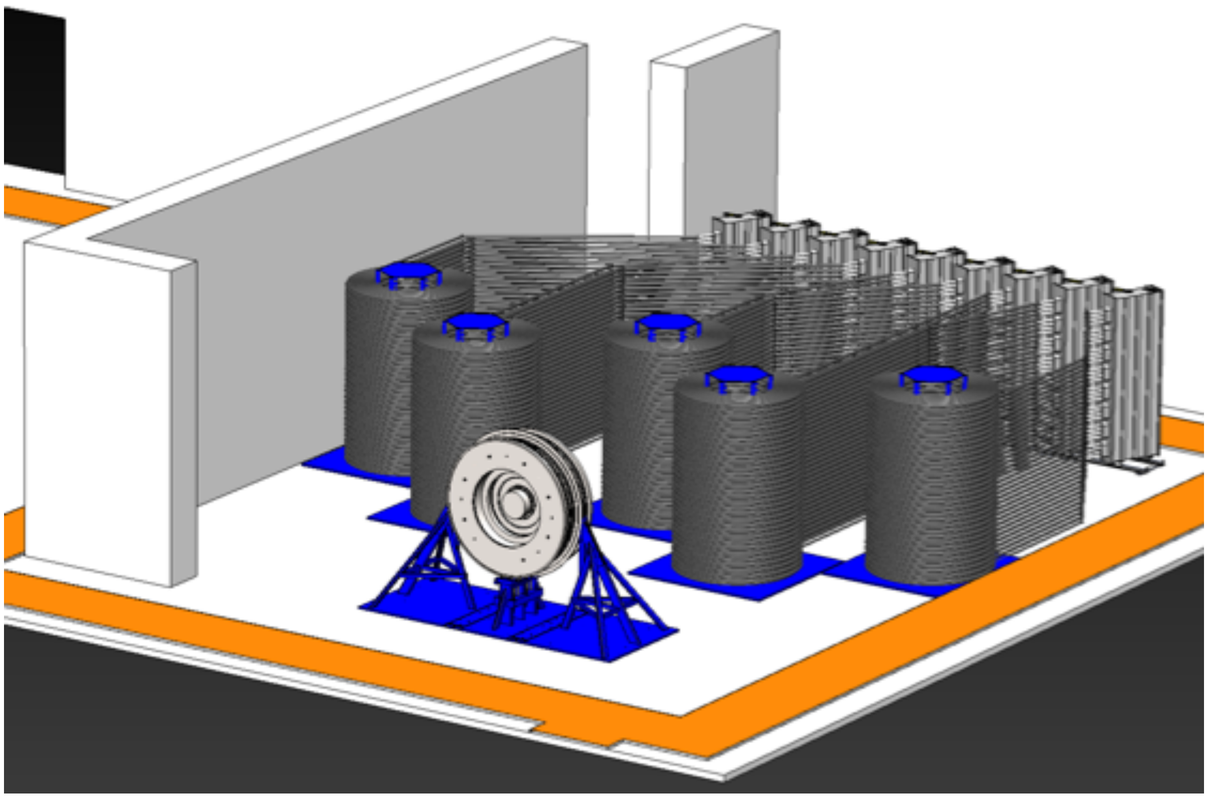


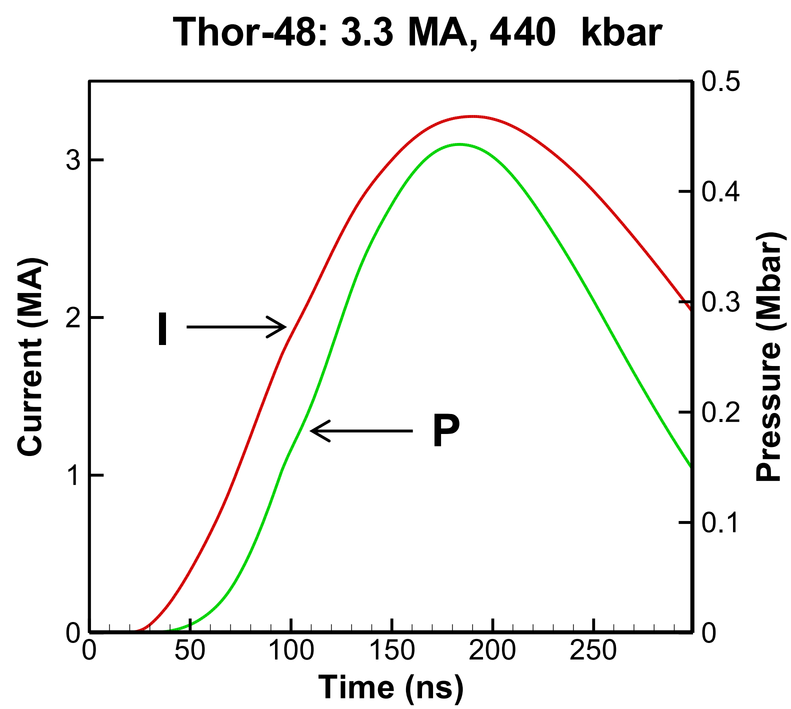


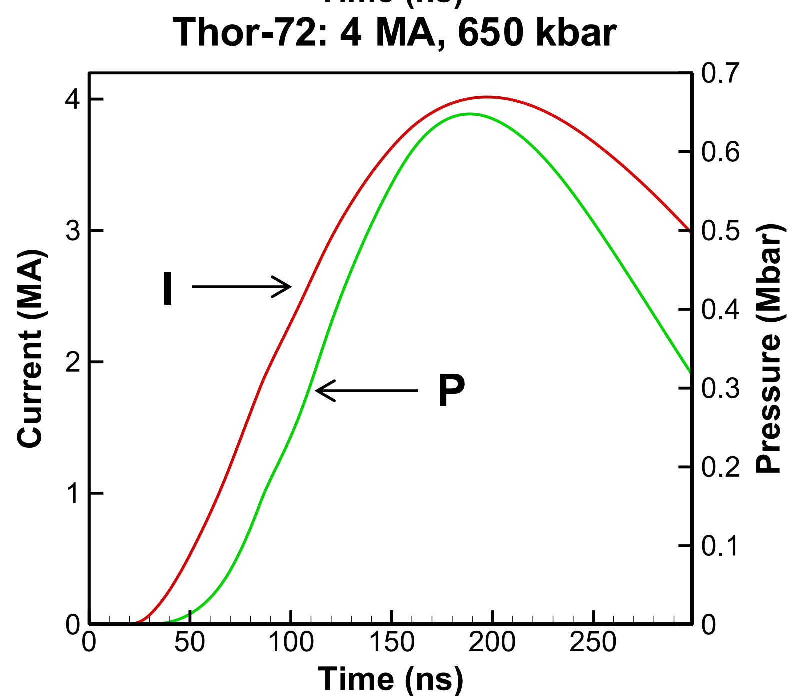
Velocity profiles



Thor-48 will be commissioned in FY17

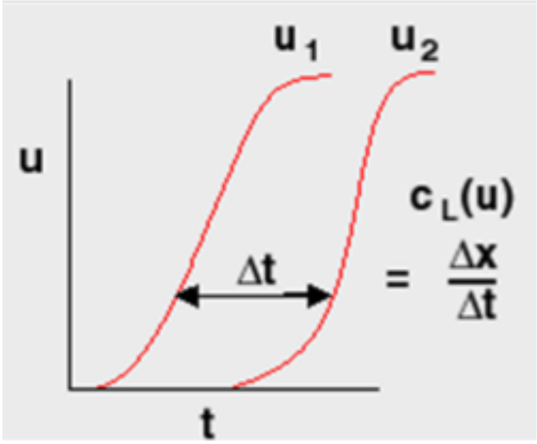


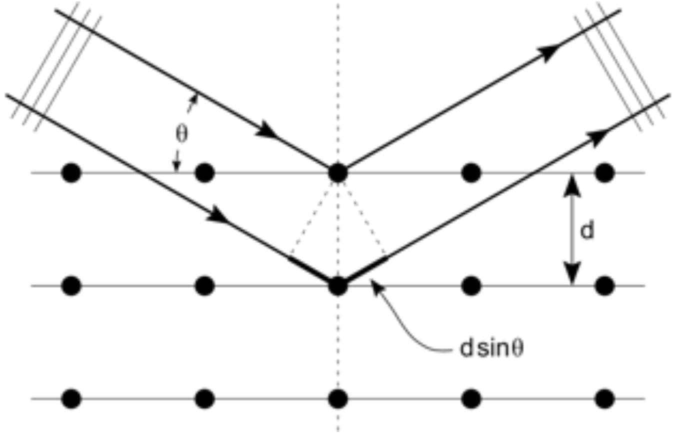




X-Ray diffraction (XRD) is beginning to be used in the dynamic materials community

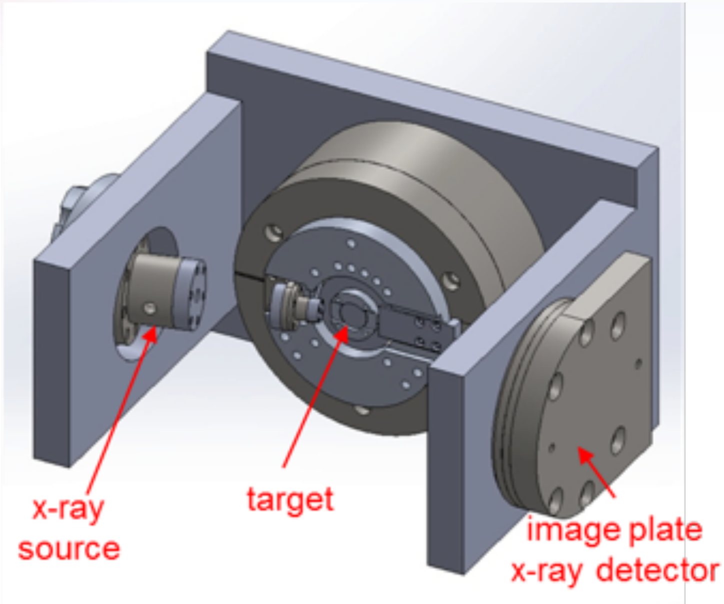
- Traditionally, dynamic materials measurements have been made of bulk properties (pressure, density, sound speed)
  - Pressure-density curves reconstructed through conservation equations
  - Phase transitions inferred through velocity waveforms
- XRD will allow us to dynamically probe *in-situ* properties of materials:
  - phase transitions
  - elastic compression of the crystal lattice – direct measurement of density
  - onset of plastic flow
  - density of crystal defects such as dislocations
- XRD for dynamic materials is currently being used/developed on multiple NNSA facilities



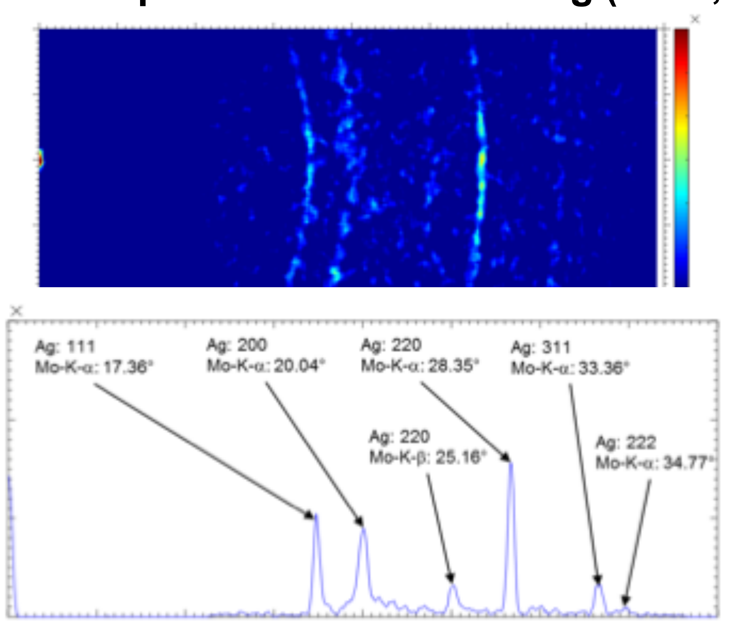


We are developing an X-ray diffraction (XRD) capability for Thor

XRD on DICE gas gun



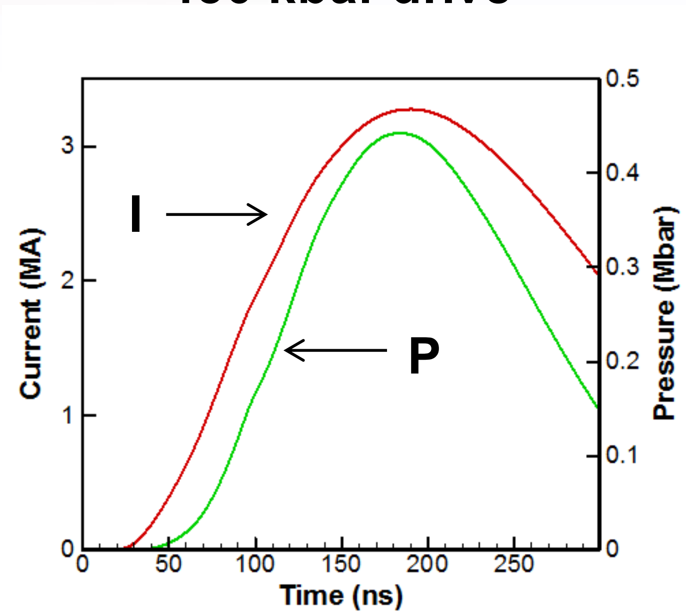
Diffraction pattern and lines for Ag (T. Ao, D. Morgan)

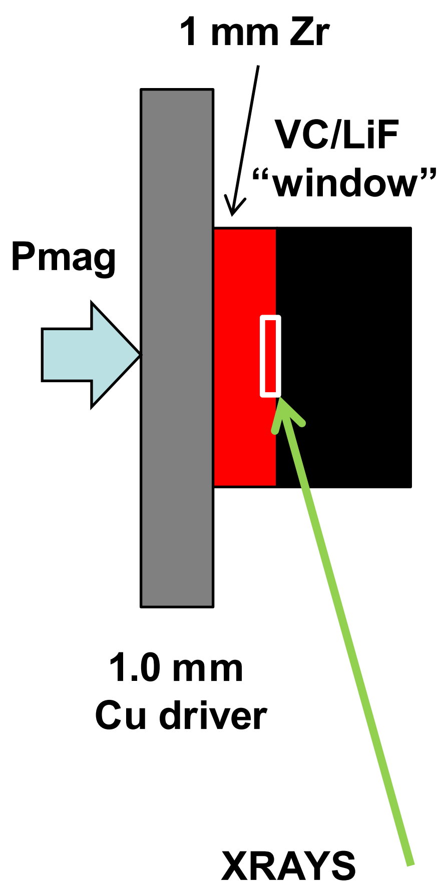


- **We will first use the NSTec compact x-ray diode system:**
  - **X-ray line emission, Mo-K-a, 17.4 keV**
  - **30 ns pulse, 15 ns pulse in FY17**
  - **Currently being used on the DICE gas gun**
  - **A modified system with a novel polycapillary optic has been developed at LLNL (B.R. Maddox)**
  - **Thor target chamber is being modified to accept this XRD system**
- **Ultimately, we wish to use a synchrotron source**
  - **Thor is configured for the DCS**
  - **Multiple XRD frames would allow a “mapping” of the phase diagrams of many materials of interest**

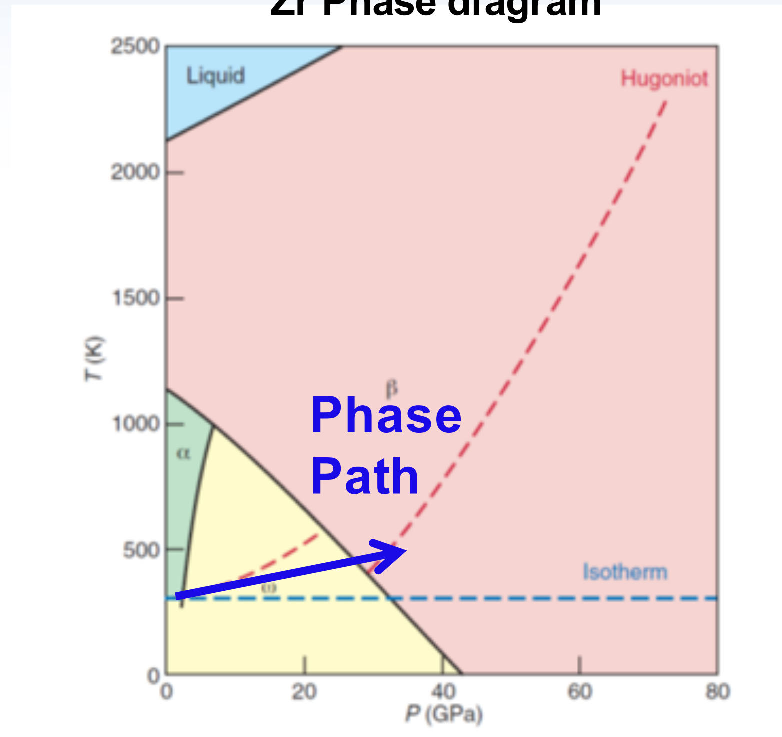
Thor-48 X-Ray diffraction experiment for Zirconium

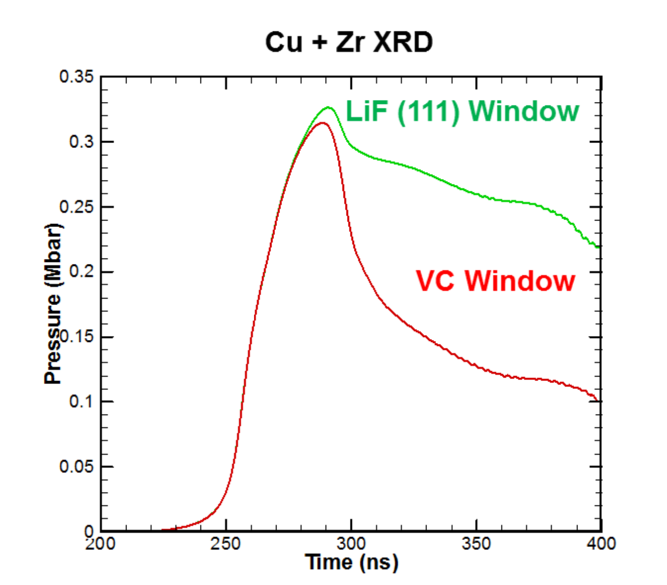
450 kbar drive





Zr Phase diagram

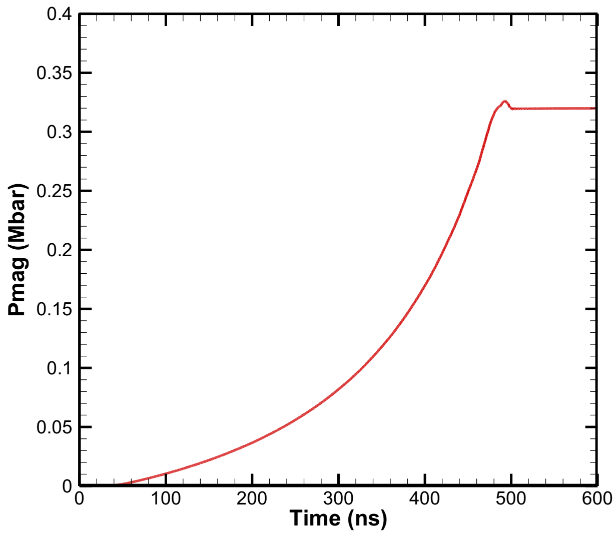


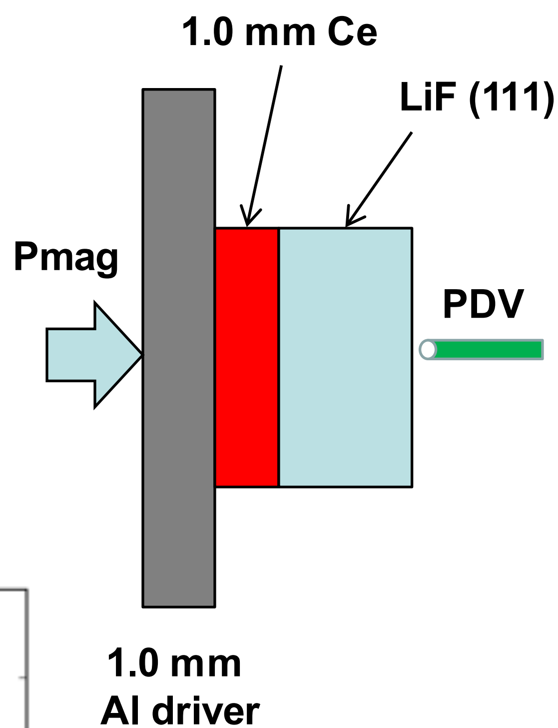


- Experiment will allow the investigation of the $\alpha \rightarrow \omega \rightarrow \beta$ phases in Zr
- Dynamic XRD data will reconnect with and extend previous work on Zr
- Will be first XRD data collected on a pulsed power driver, first ramp-driven XRD on Zr.

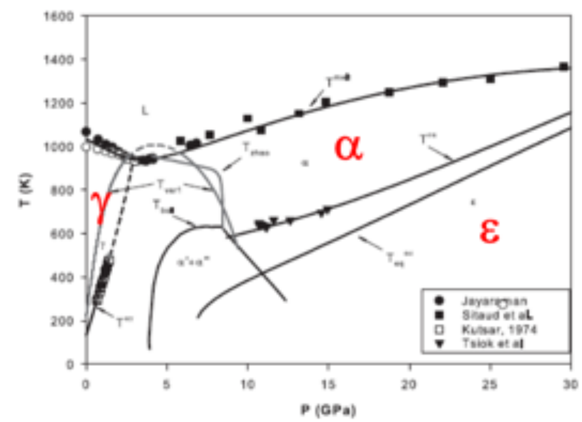
Thor-72 point design for Cerium: pulse tailoring

~300 kbar pressure pulse

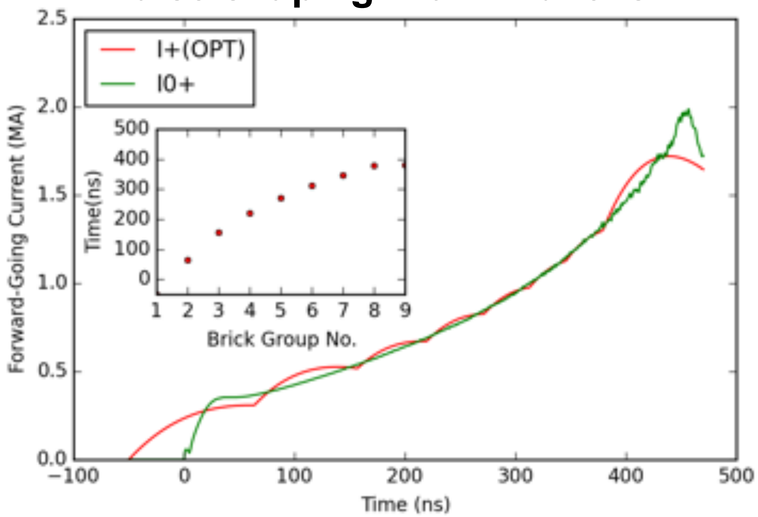




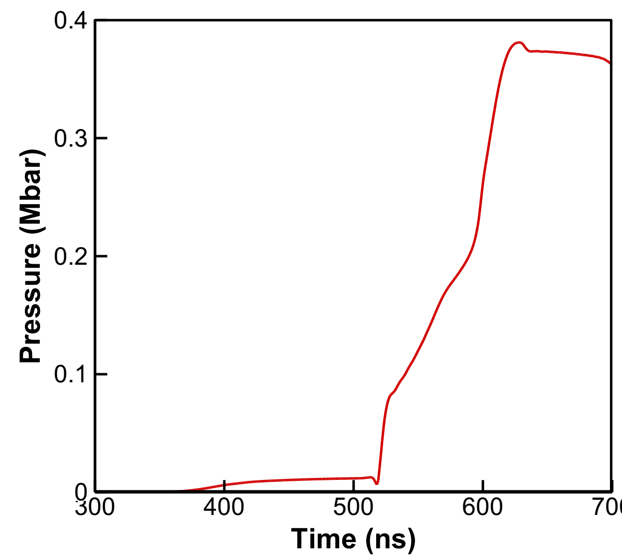
Phase diagram



Pulse-shaping with 72 bricks



Cerium pressure history



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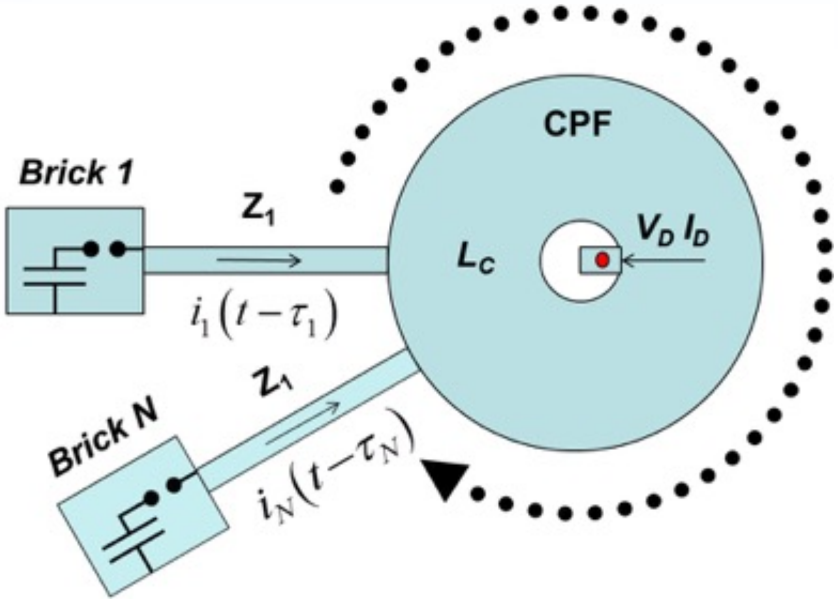
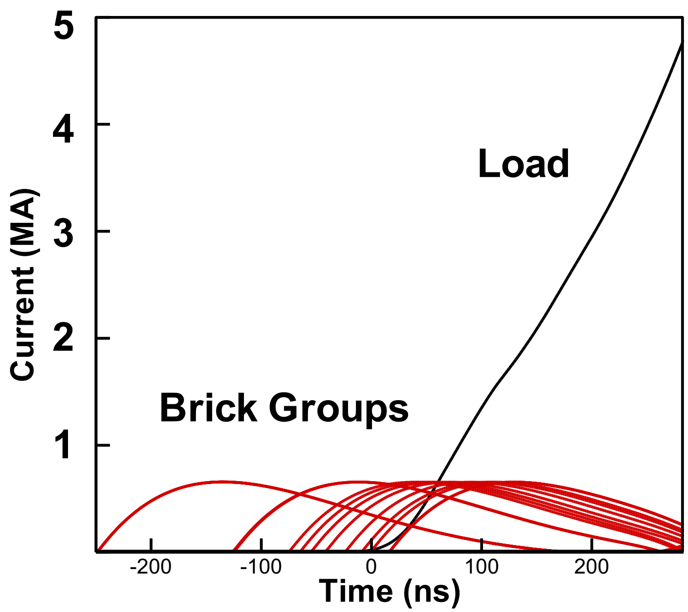
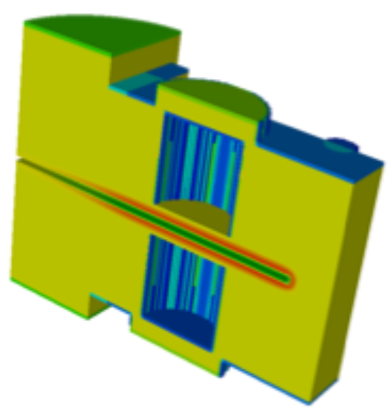
- Thor virtual experiments
- Neptune
- Conclusions

Sandia National Laboratories

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

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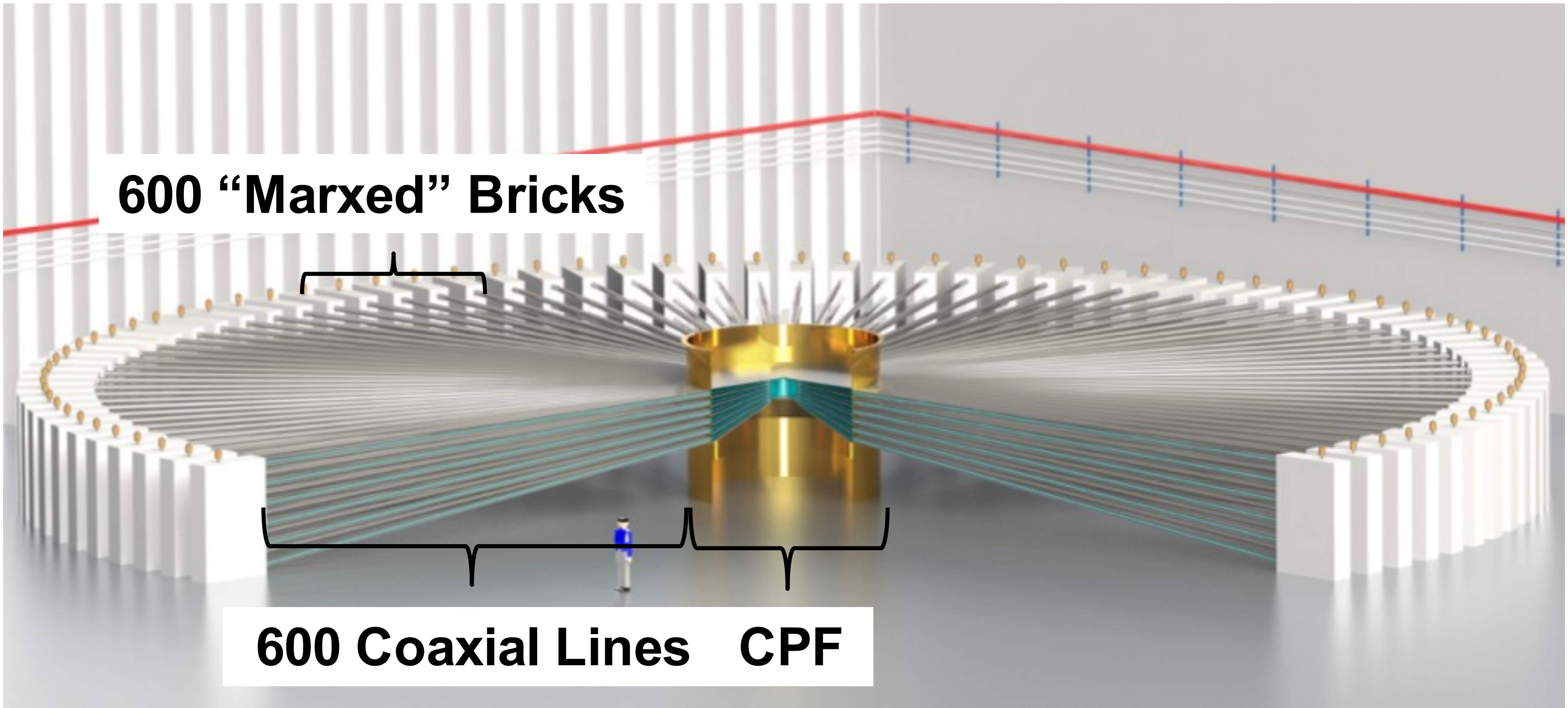
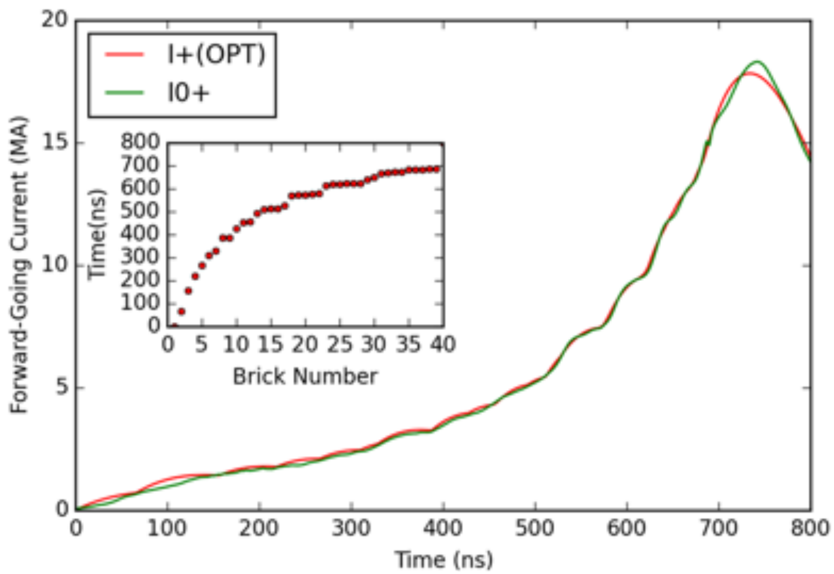
We have extend the current-adder architecture to the megajoule-class Neptune machine



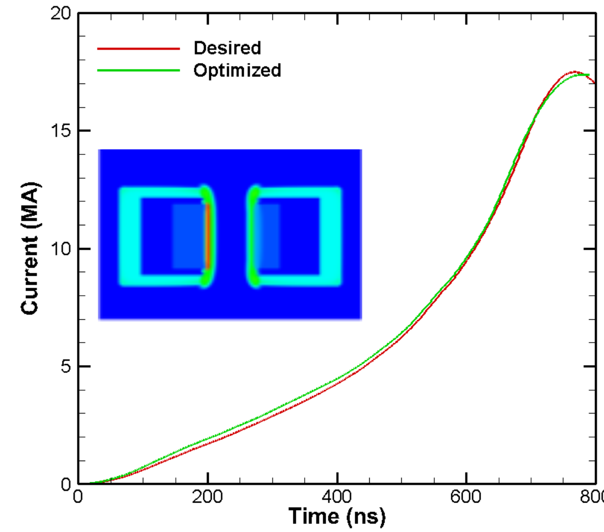
W.A. Stygar, D. B. Reisman, B. S. Stoltzfus, K. N. Austin, *et al.*, PRAB 19, 070401 (2016)

Neptune can reproduce ZR performance

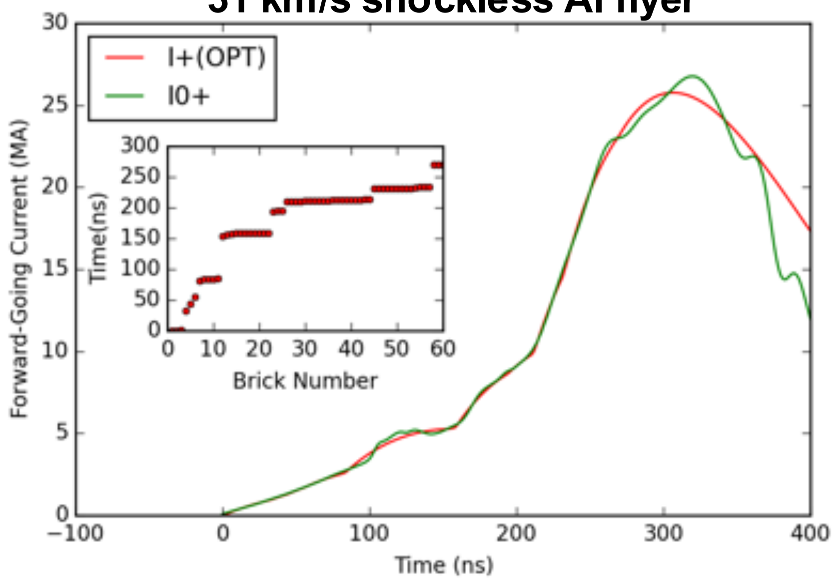
6 Mbar Ta ICE

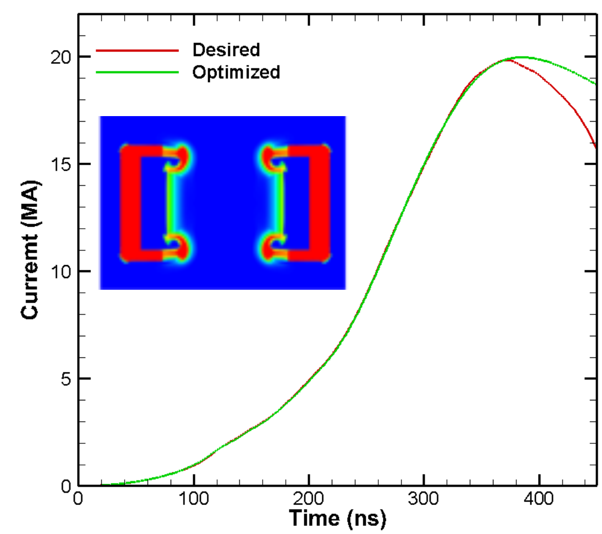


Optimized and desired current



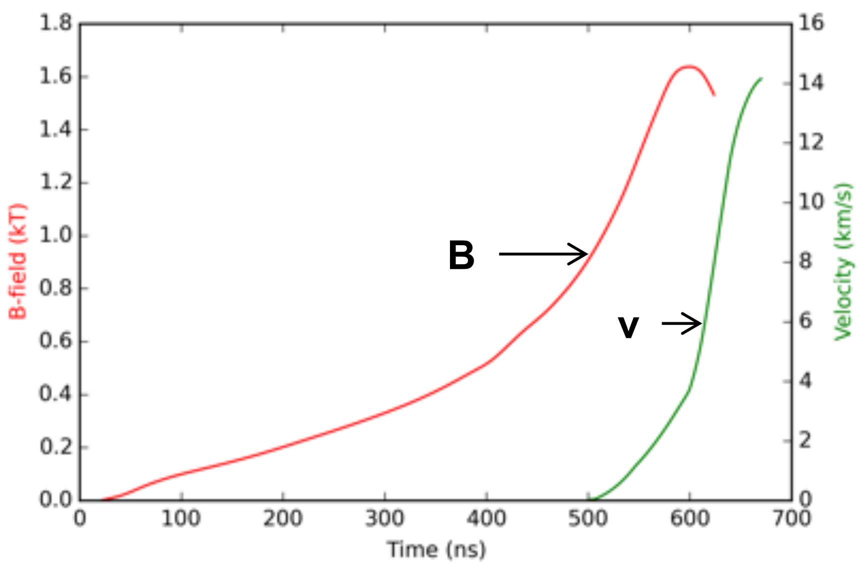
31 km/s shockless Al flyer



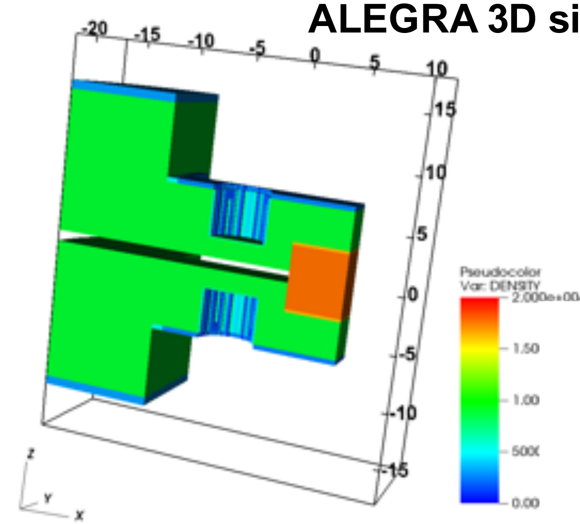


Neptune can reach 1 TPA (10 Mbar) for ICE

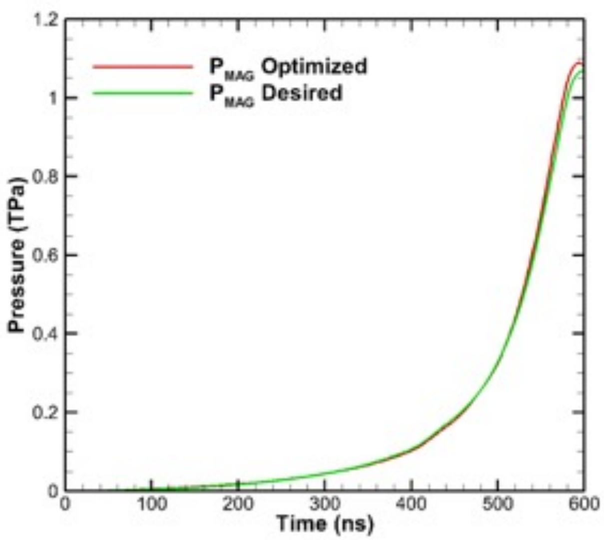
Magnetic Field and FS velocity for 1.8 mm Cu

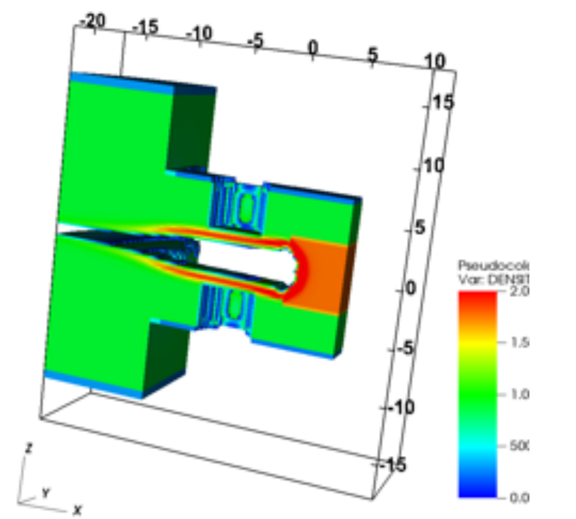


ALEGRA 3D simulation



Over 1 TPa (10 Mbar) pressure





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

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Conclusions

- We have developed a compact, low-cost platform for performing dynamic material experiments in the megabar (100 GPOa) 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

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)

Sandia National Laboratories

Thor and Neptune designs have been published in peer-reviewed journals

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 090401 (2015)

Pulsed power accelerator for material physics experiments

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We have developed the design of Thor: a pulsed power accelerator that delivers a precisely shaped current pulse with a peak value as high as 7 MA to a strip-line load. The peak magnetic pressure achieved within a 1-cm-wide load is as high as 100 GPa. Thor is powered by as many as 288 decoupled and transit-time isolated bricks. Each brick consists of a single switch and two capacitors connected electrically in series. The bricks can be individually triggered to achieve a high degree of current pulse tailoring. Because

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Conceptual design of a 10^{13}-W pulsed-power accelerator for megajoule-class dynamic-material-physics experiments

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We have developed a conceptual design of a next-generation pulsed-power accelerator that is optimized for megajoule-class dynamic-material-physics experiments. Sufficient electrical energy is delivered by the accelerator to a physics load to achieve—within centimeter-scale samples—material pressures as high as 1 TPa. The accelerator design is based on an architecture that is founded on three concepts: single-stage electrical-pulse compression, impedance matching, and transit-time-isolated drive circuits. The prime power source of the accelerator consists of 600 independent impedance-matched Marx generators. Each Marx comprises eight 5.8-GW bricks connected electrically in series, and generates a 100-ns 46-GW electrical-power pulse. A 450-ns-long water-insulated coaxial-transmission-line impedance transformer transports the power generated by each Marx to a system of twelve 2.5-m-radius water-insulated conical transmission lines. The conical lines are connected electrically in parallel at a 66-cm radius by a water-insulated 45-post sextuple-post-hole convolute. The convolute sums the electrical currents at the outputs of the conical lines, and delivers the combined current to a single solid-dielectric-insulated radial transmission line. The radial line in turn transmits the combined current to the load. Since much of the accelerator is water insulated, we refer to it as Neptune. Neptune is 40 m in diameter, stores 4.8 MJ of electrical energy in its Marx capacitors, and generates 28 TW of peak electrical power. Since the Marxes are transit-time isolated from each other for 900 ns, they can be triggered at different times to construct–over an interval as long as 1 μs–the specific load-current time history required for a given experiment. Neptune delivers 1 MJ and 20 MA in a 380-ns current pulse to an 18-mΩ load; hence Neptune is a megajoule-class 20-MA arbitrary waveform generator. Neptune will allow the international scientific community to conduct dynamic equation-of-state, phase-transition, mechanical-property, and other material-physics experiments with a wide variety of drive-pressure time histories.

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Optimization of current waveform tailoring for magnetically driven isentropic compression experiments

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The Thor pulsed power generator is being developed at Sandia National Laboratories. The design consists of up to 288 decoupled and transit time isolated capacitor-switch units, called "bricks," that can be individually triggered to achieve a high degree of pulse tailoring for magnetically driven isentropic compression experiments (ICE) [D. B. Reisman *et al.*, Phys. Rev. Spec. Top.–Accel. Beams **18**, 090401 (2015)]. The connecting transmission lines are impedance matched to the bricks, allowing the capacitor energy to be efficiently delivered to an ICE strip-line load with peak pressures of over 100 GPa. Thor will drive experiments to explore equation of state, material strength, and phase transition properties of a wide variety of materials. We present an optimization process for producing tailored current pulses, a requirement for many material studies, on the Thor generator. This technique, which is unique to the novel "current-adder" architecture used by Thor, entirely avoids the iterative use of complex circuit models to converge to the desired electrical pulse. We begin with magnetohydrodynamic simulations for a given material to determine its time dependent pressure and thus the desired strip-line load current and voltage. Because the bricks are connected to a central power flow section through transit-time isolated coaxial cables of constant impedance, the brick forward-going pulses are independent of each other. We observe that the desired equivalent forward-going current driving the pulse must be equal to the sum of the individual brick forward-going currents. We find a set of optimal brick delay times by requiring that the L_2 norm of the difference between the brick-sum current and the desired forward-going current be a minimum. We describe the optimization procedure for the Thor design and show results for various materials of interest. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4954173]

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Note: Design of 1 TPa magnetically-driven ramp wave experiments

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We have developed a new class of pulsed power accelerators for performing dynamic material experiments. Based on a "current-adder" architecture, these accelerators consist of decoupled and transit time isolated capacitor-switch units, called "bricks", which can be individually triggered to achieve a high degree of pulse tailoring for magnetically-driven isentropic compression experiments (ICE). We have also developed an optimization process for producing tailored pressure pulses, a requirement for many material studies. Using our most recent accelerator design, called Neptune [Stygar, et. al, Phys. Rev. ST Accel. Beams **19**, 070401 (2016)], we are able to design shockless ramp-driven experiments in the 1 TPa range of material pressure. We describe the design of a 1 TPa copper experiment using both our optimization procedure and a three-dimensional MHD code with a self-consistent brick circuit model.

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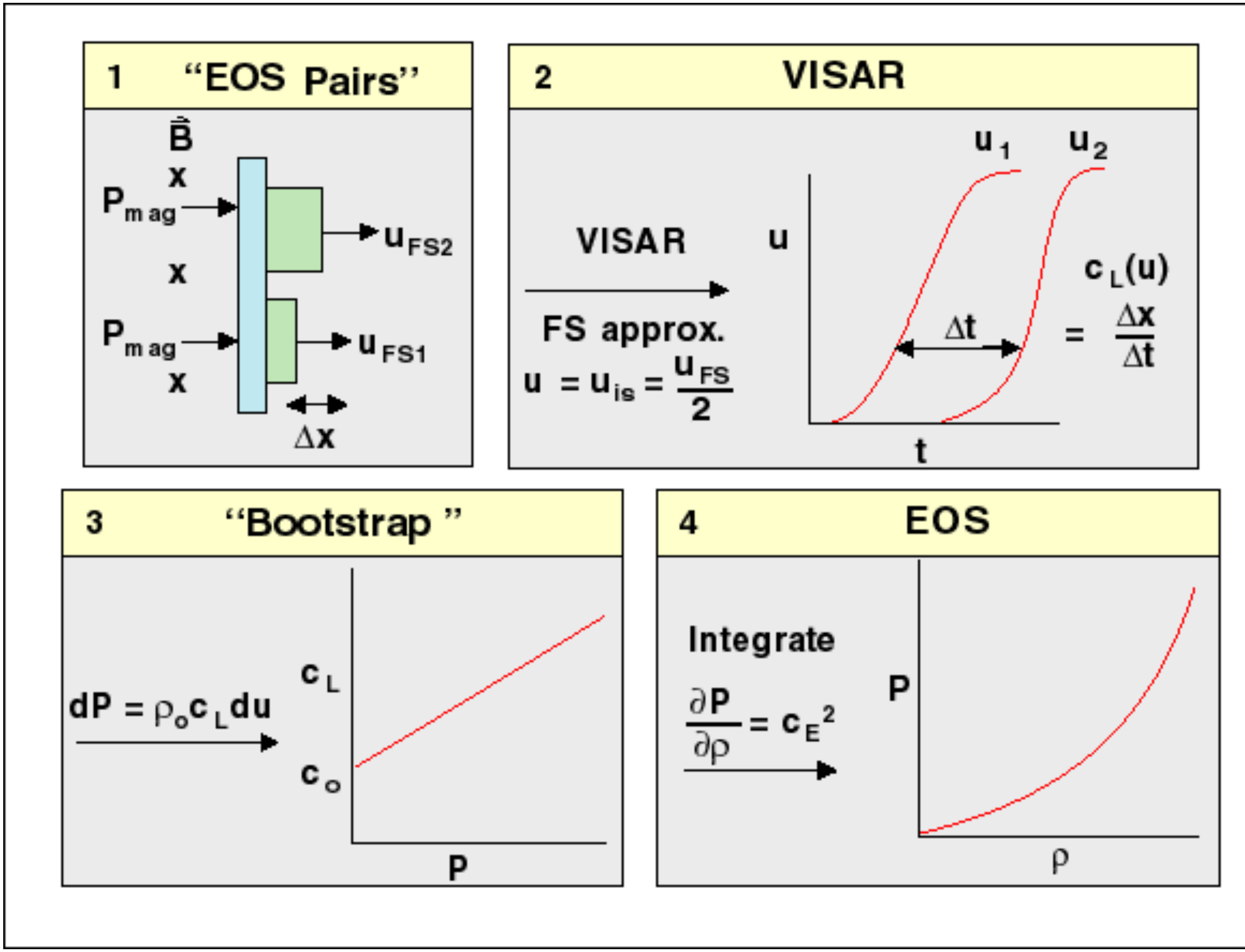
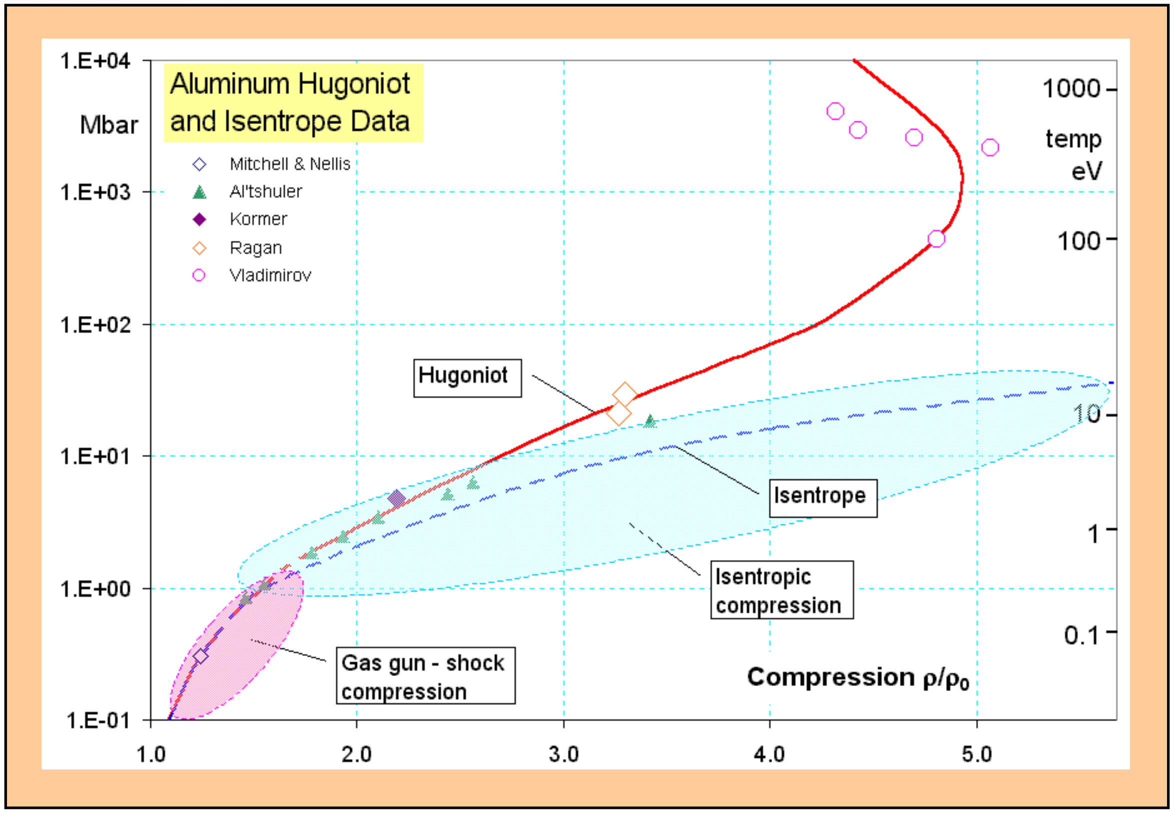
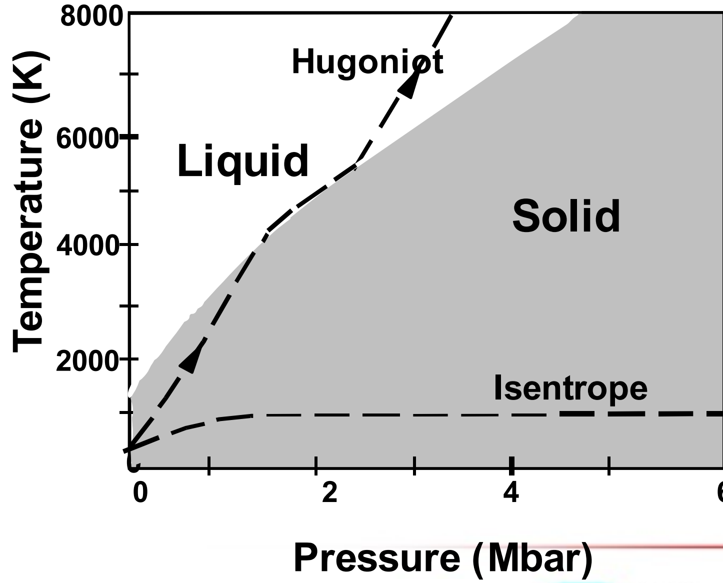
EOS is extracted from VISAR data using waveform analysis



Before 2000: High pressure EOS data are on the Hugoniot even for common materials



In 4-times compressed Al, the Hugoniot lies almost an order of magnitude in pressure above the isentrope



High pressure Hugoniot is in the fluid while the isentrope is in the solid

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