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Thor: Modeling of a Megabar Class Pulsed Power Accelerator

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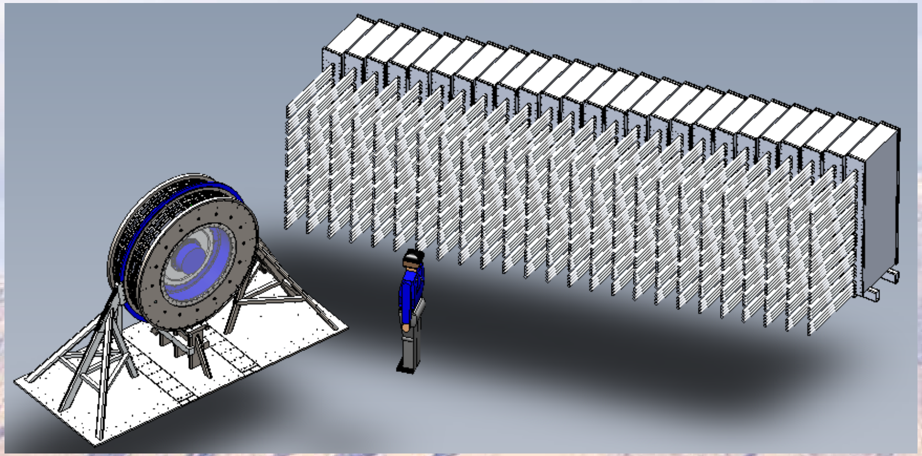

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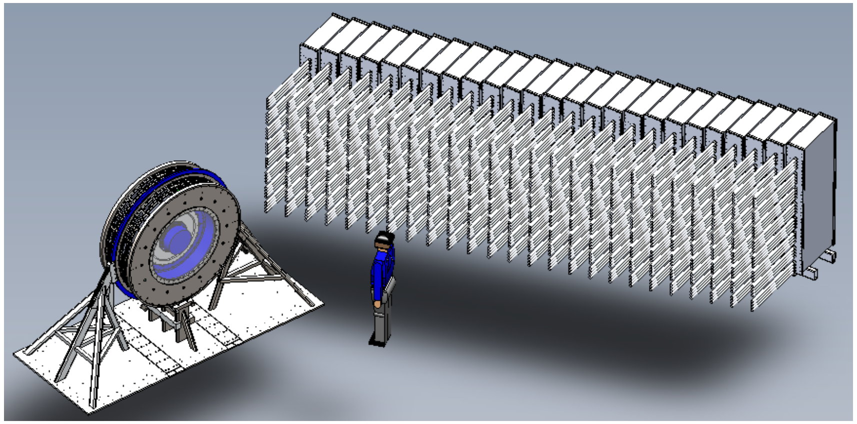
Abstract

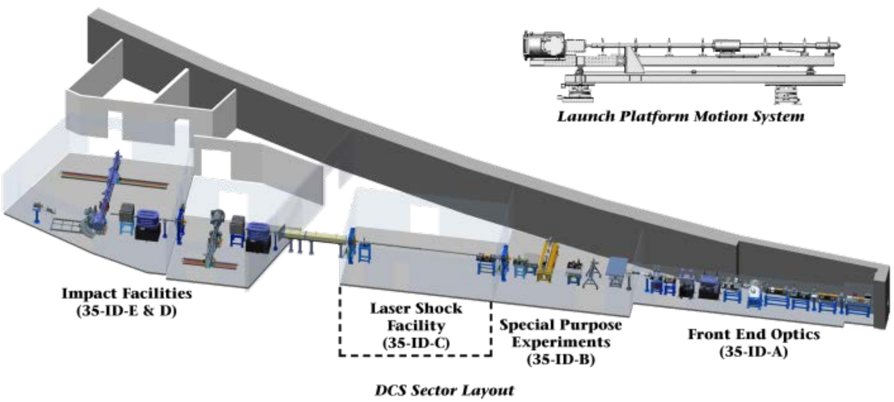
- Thor is a compact, economical machine to drive megabar-class shockless compression material physics experiments and multi-mega-ampere HEDP experiments for the physics community. It is capable of driving peak currents up to 7 MA with rise times of 200-500 ns, resulting in material pressures between 1 to 5 Mbar depending upon the load design, and incorporates a pulse tailoring capability required to maintain shockless loading of many materials. Thor is modular in nature with 200 capacitive bricks triggered in groups by independent, decoupled switches. The current pulse at the load is a simple linear combination of the 200 time-shifted basis pulses. This enables a variety of experiments including shockless compression experiments using smooth ramped pulses, shock-ramp compression experiments using tailored pulses, and strength measurement experiments using flat top pulses. This paper overviews the Thor design and describes an equivalent circuit model of the machine that drives MHD simulations of the load region. 3D ALEGRA MHD simulations explore topics such as the uniformity of the magnetic field along the stripline load and the design modifications to improve uniformity. Optimized current drives and simulations of the aforementioned applications are also presented.

What is Thor?

Thor Concept



Dynamic Compression Sector



- Thor[1] is a compact modular scalable pulse power machine designed to:
  - Take advantage of the throughput of small pulsed power machines such as Veloce[2] and GEPI[3],
  - Be more economical than large machines such as the Z accelerator and its proposed successors[4],
  - Be based upon the capacitive brick technology of linear transformer driver (LTD) accelerators[5],
  - Greatly expand the ability to tailor current pulses for material science and HEDP experiments.
- Thor is intended to be sited at the Dynamic Compression Sector (DCS) of the Advanced Photon Source (APS) at Argonne National Laboratory[6,7].

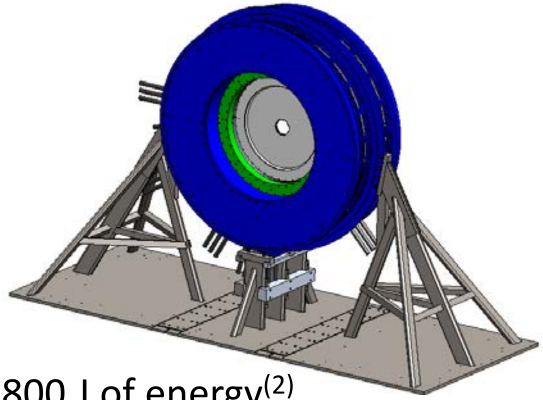
1. D. Reisman, et al., *Thor: a 100-GPa pulsed power accelerator for material-physics experiments*, PRSTAB, (in preparation), 2015.
2. T. Ao, J. Asay, S. Chantrenne, et al., Rev. Sci. Instrum., 79, 013903 (2008).
3. A. Lefrancois, P.-Y. Chanal, G. LeBlanc, et al., IEEE Trans. Plasma Sci., 39 (1) 288, (2011).
4. W. Stygar, M. Cuneo, D. Headley, et al., PRSTAB, 10, 030401 (2007).
5. J. Woodworth, J. Alexander, F. Gruner.et al.,, PRSTAB, 12, 060401 (2009).
6. Y. Gupta, S. Turneaure, K. Perkins, et al., RSI, 83, 123905 (2012).
7. For the DCS see http://dcs-aps.wsu.edu/home/ and for the APS see http://www.aps.anl.gov/ .

Thor's design is modular and scalable

LTD capacitive brick

Heliax Coax Cable

Central Power Flow (CPF)

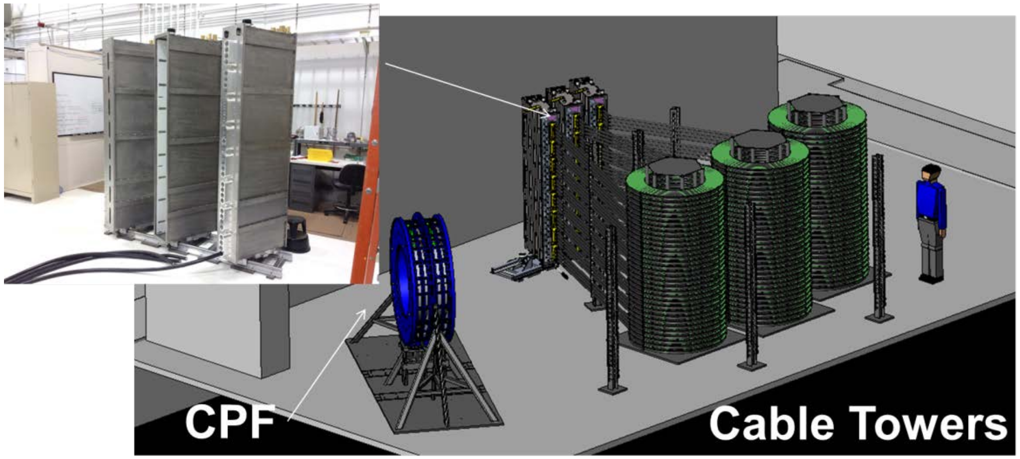


- Thor stores its energy in as many as 288 capacitive bricks(1)
  - Each brick has 2 80-nF capacitors charged to ±100 kV providing 800 J of energy(2)
  - Bricks are trigger by a 240-nH, 0.37-Ohm HCEI switch(2)
  - Bricks are assembled into 8-brick towers and the towers are triggered in groups
- Coaxial cables deliver the energy and current from the bricks to the CPF
  - Cables are 10.8-Ohm transmission lines having ~300-ns delay times
  - Cables isolate the many pulses from each other allowing superposition of currents at the load
- A central power flow (CPF) region combines the energy and current from the many lines
  - Cables attach to 1 of 4 water-insulated radial parallel-plate transmission lines
  - The 4 levels are combined using a 40-post double-post-hole convolute (DPHC)
- A dynamic stripline load is located at the center of the CPF
  - Loads feature either 15x30-mm or 10x20-mm aluminum or copper stripline panels

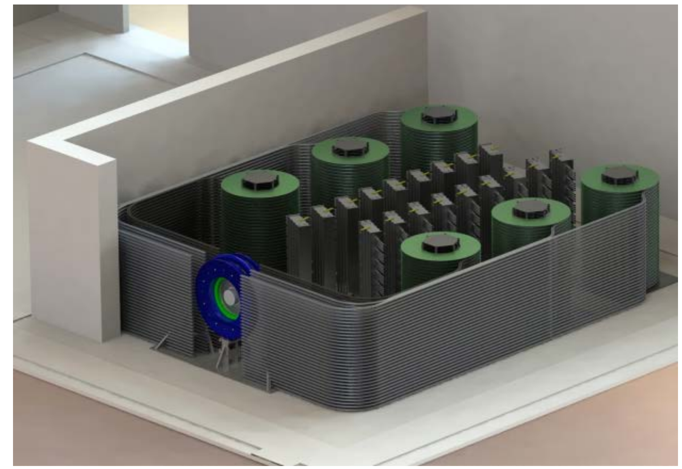
1. D. Reisman, et al., *Thor: a 100-Gpa pulsed power accelerator for material-physics experiments*, PRSTAB, (in preparation), 2015.
2. J. Woodworth, et al., *Low-inductance gas switches for linear transformer drivers*, PRSTAB, 12, 060401 (2009).

Thor is built in stages designated by the number of bricks driving the system up to 288 bricks

Thor-24



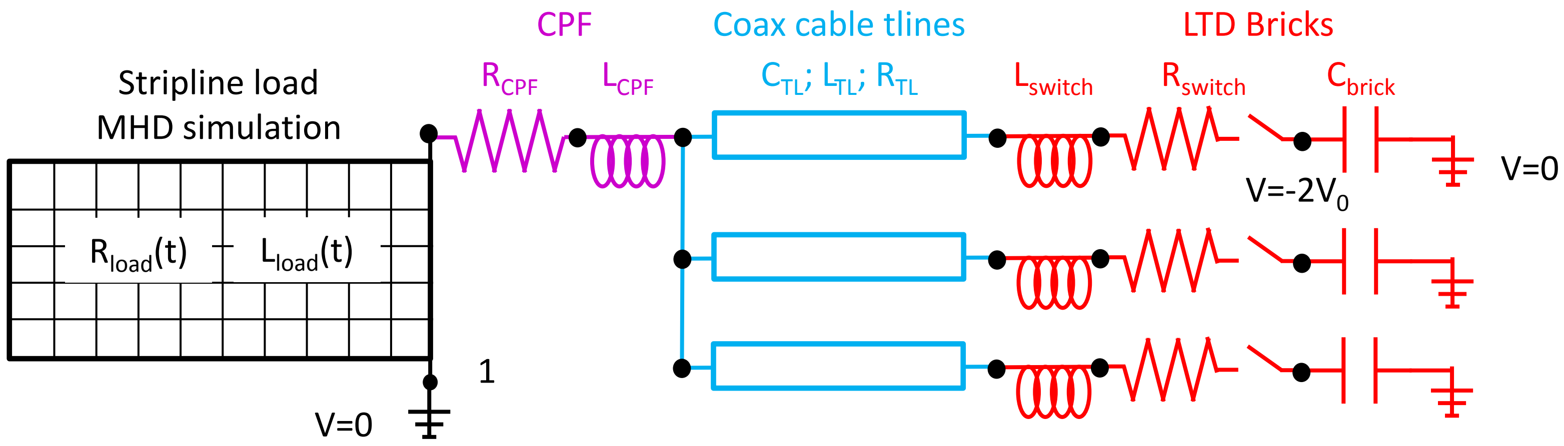
Thor-144



Schedule	Bricks	Cables per brick	E stored (KJ)	Peak I (MA)	Peak P (Mbar)	E load (kJ)	Eff. (%)
CY15	24	3	19.2				
CY16	96	3	76.8	4.1	0.65	27.0	35
	144	2	115.2	5.4	1.1	56.1	49
	288	1	230.4	6.9	1.7	111	48

Circuit model represents Thor as an equivalent circuit solved by ALEGRA[1,2] or by Screamer[3]

- **Circuit model has 4 principal components:**
  - **LTD bricks, coaxial transmission lines, central power flow (CPF), and the stripline load**
- **There may be hundreds of LTD bricks and coax cables (up to 4 per brick)**
- **LTD bricks are triggered in $N_{triggers}$ groups**
- **Thevenin equivalent circuit collapse many bricks and cables into scaled components**
- **Equivalent lumped circuit model:**



1. A. Robinson, et al., *Arbitrary Lagrangian-Eulerian 3D Ideal MHD Algorithms*, Int. J. Numer. Meth. Fluids, 65, 1438, 2011.
2. T. Haill, et al., *Validation of ALEGRA MHD to Model Confined Electrical Discharges*, Paper SEA2013-89, Proc. ICOLSE, Seattle, WA, Sep. 18-20, 2013.
3. M. Kiefer and M. Widner, *Screamer – A Single-line Pulsed-Power Design Tool*, Digest Tech. Papers 5th IEEE PPC, 685 (1985).

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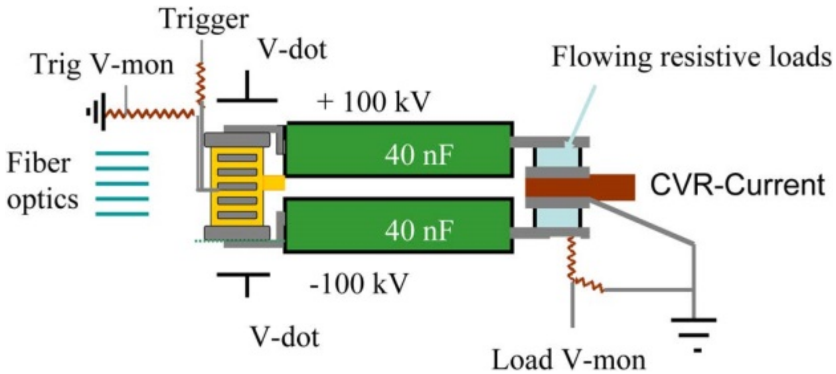
Thor’s LTD bricks are simple LRC circuits: single bricks are well tested and modeled

LTD capacitive brick

LRC circuit from Ref. 1



Single brick testing

- Multiple bricks may be combined in parallel if they feed a common load
- A common load can be the lumped equivalent of N_{coax} coaxial cables

- Single brick parameters
  - Two capacitors in series
  - One inductive switch
  - One resistive trigger
  - C_0 = 80 nF
  - L_0 = 240 nH
  - R_0 = 0.67 Ohm
  - V_0 = ± 100 kV

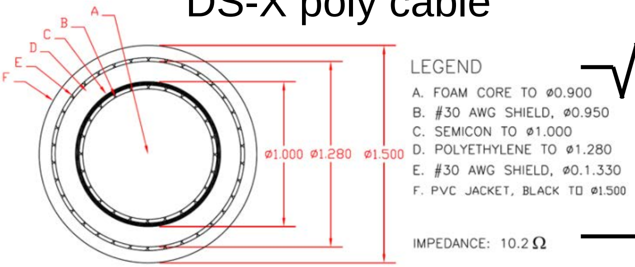
- Lumped brick parameters
  - $C_{brick} = C_0/2$ = 40 nF
  - $L_{brick} = L_0$ = 240 nH
  - $R_{brick} = R_0$ = 0.67 Ohms
  - $V_{brick} = V_0 \cdot 2$ = 200 kV

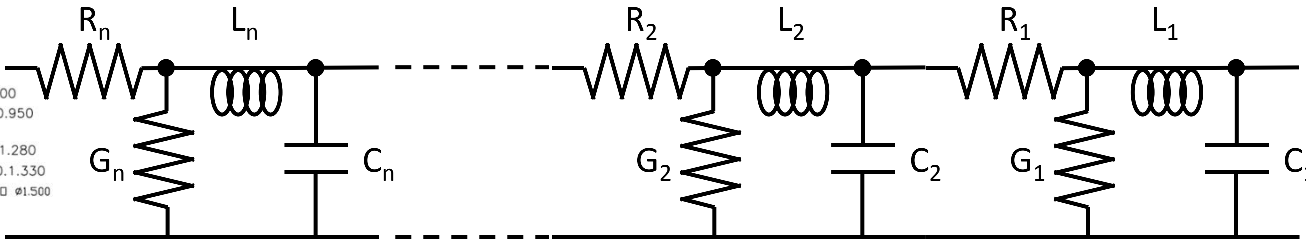
- N_{brick} bricks in parallel
  - $C_{brick} = C_0 \cdot N_{brick} /2$
  - $L_{brick} = L_0 / N_{brick}$
  - $R_{brick} = R_0 / N_{brick}$
  - $V_{brick} = V_0 \cdot 2$

1. J. Woodworth, et al., *Low-inductance gas switches for linear transformer drivers*, PRSTAB, 12, 060401 (2009).

Thor’s coaxial cables are modeled as transmission lines

DS-X poly cable





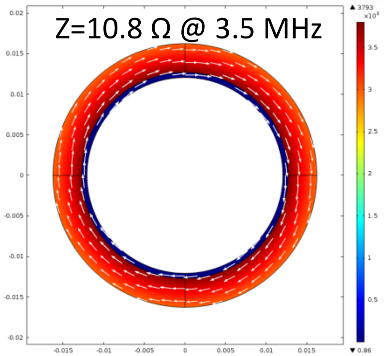
- **ALEGRA models transmission lines as a set of inductors and resistors in series and a set of capacitors and conductances in parallel[(1)]**
- **Total length is divided into N segments depending upon desired time resolution**
- **Lossless transmission lines have zero resistance, i.e., inductors and capacitors only**
- **The properties of Thor’s coaxial cables have been measured[(2)]**

- Inductance/length
  - $L' = 19.5$ nH/ft
- Capacitance/length
  - $C' = 0.165$ nF/ft
- Resistance/length
  - $R' = 5.0$ mOhms/ft
- Impedance
  - $Z = (L'/C')^{1/2} = 10.8$ Ohms
- Wave speed
  - $v \approx (L' \cdot C')^{-1/2} = 0.557$ ft/ns
- Delay time / length
  - $t' \approx 1/v = 1.79$ ns/ft
- Total length
  - $d = 60$ m $= 196.8$ ft
- Total delay time
  - $t = d/v = 353$ ns
- Resolution
  - $t_{res} = 10$ ns

1. P.A. Rizzi, *Microwave Engineering Passive Circuits*, Prentice Hall, Upper Saddle River, NJ, 1988.
2. Alpha-Omega Power Technologies LLC, September 2014.

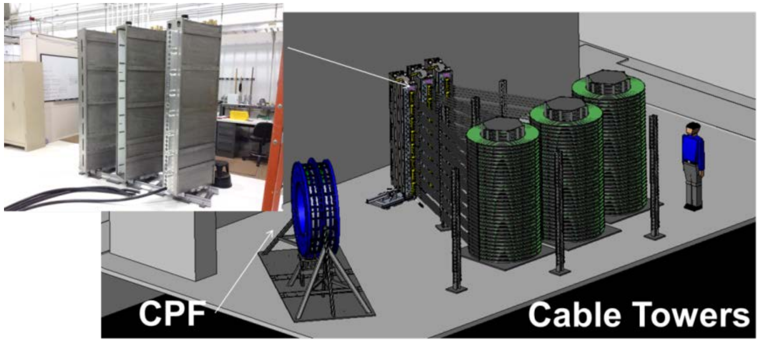
Thor's LTD bricks and cables are assembled into towers which form a triggering unit for pulse shaping

DS-X poly cable



Single-brick multi-cable

Thor-24 with 72 cables

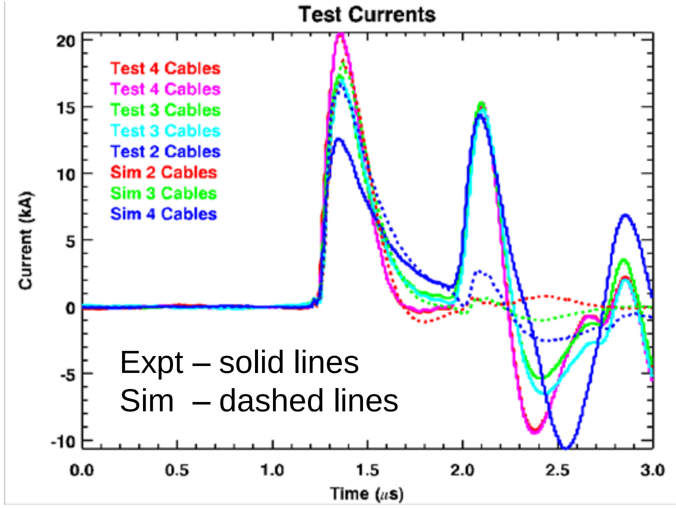


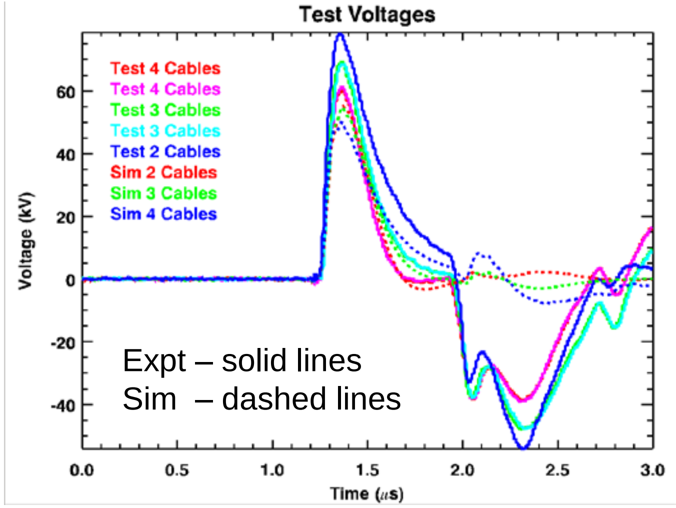
- Multiple cables may be combined in parallel if they feed a common load
- A common load is the central power flow (CPF)
- A tower of 8 bricks will form a triggering unit
- Multiple towers may be triggered simultaneously

- Single cable parameters
  - $C' = 80$ nF/m
  - $L' = 240$ nH/m
  - $R' = 0.67$ Ohm/m
  - $Z = (L'/C')^{1/2} = 10.8$ Ohm
  - $v = (L' \cdot C')^{-1/2} = 0.170$ m/ns
- $N_{coax} = N_{brick} \cdot N_{cables/brick}$ lumped cables
  - $C_{coax} = C' \cdot N_{coax}$
  - $L_{coax} = L' / N_{coax}$
  - $R_{coax} = R' / N_{coax}$
  - $Z_{coax} = (L_{coax}/C_{coax})^{1/2} = Z / N_{coax}$
  - $v_{coax} = (L_{coax} \cdot C_{coax})^{1/2} = v$

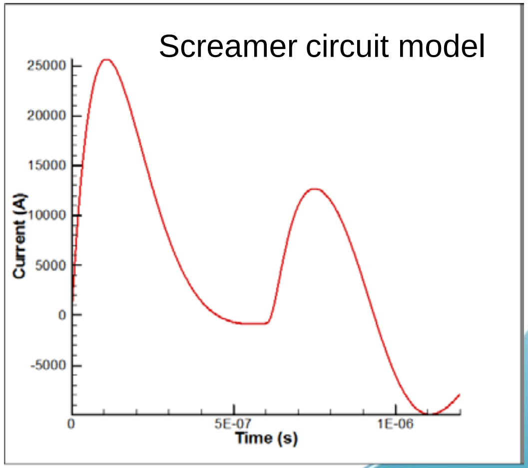
Thor testing of single brick with multiple cables provides data for circuit model validation

Comparison of experiment to ALEGRA circuit model





- Tests are conducted at charge voltages of 25 to 100 kV and with 1 to 4 coax cables
- Load resistance was altered to provide various levels of reflection and capacitor reversals of 15 to 60%
- Better knowledge of precise experimental setup will improve ALEGRA simulations and improve late time reflection modeling



Current-adder architecture allows us to use TEM waveguide theory to construct forward current into CPF

- **Total voltage and current entering a cable is the sum of the forward and backward waveforms**

$$V_C = V_{C+} + V_{C-} \qquad I_C = I_{C+} - I_{C-} = \frac{V_{C+}}{Z_C} - \frac{V_{C-}}{Z_C}$$

- **Forward voltage and current are computed from the total voltage and current entering cable**

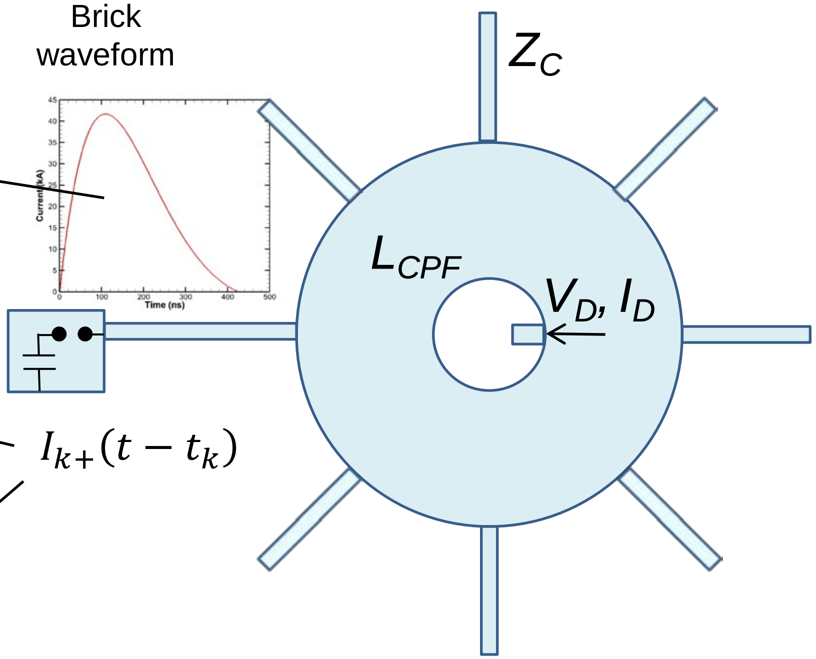
$$V_{C+} = \frac{1}{2}(V_C + I_C Z_C) \qquad I_{C+} = \frac{1}{2}\left(\frac{V_C}{Z_C} + I_C\right)$$

- **Forward current in each line is time shifted according to trigger time and cable length and summed to yield the total forward current into the CPF**

$$I_+ = \sum_{k=1}^{N} I_{k+}(t - t_k - l/c_{coax})$$

- **Desired load current and voltage and energy also yield the total forward current into the CPF**

$$I_{0+} = \frac{1}{2}\left[\frac{V_D + L_{CPF}\dot{I}_D}{Z} + I_D\right] \qquad Z = Z_C/N_{cables}$$

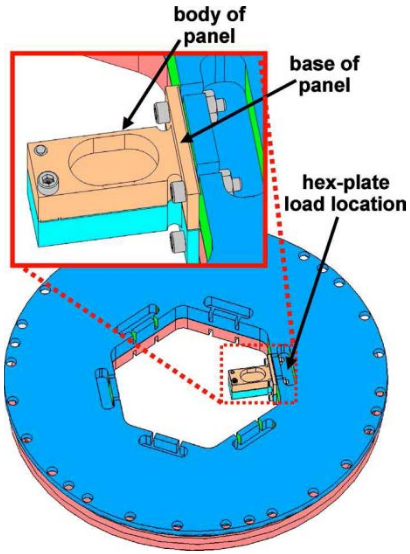


- **Optimization procedure[1] determines trigger times by minimizing the L_2 norm of difference between I_{0+} and I_0, i.e., $I_{0+} \approx I_+$**
- **The open circuit voltage computed from the CPF forward current may drive forward MHD simulations**

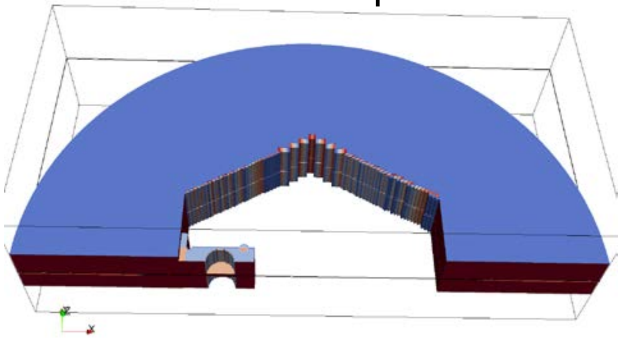
$$V_{oc} = 2\,Z\,I_+$$

1. E. Waisman, et al., *Optimization Procedure for the Thor Megabar-Class Pulsed Power Accelerator*, Paper PPP-O-12-6, IEEE Pulsed Power Conference, Austin, TX, May 31 – June 4, 2015.

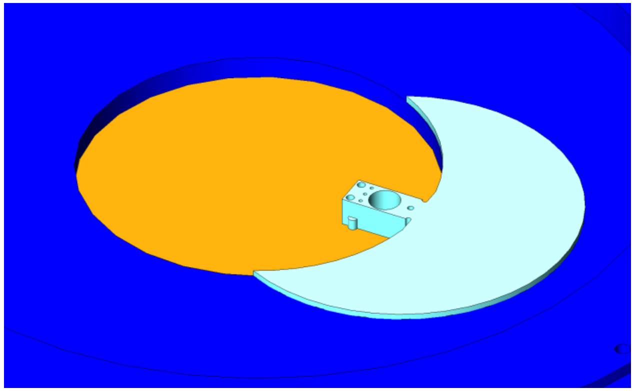
3D ALEGRA MHD modeling illuminates load deformation and provides scaling information for lower dimensional simulations



ALEGRA 3D MHD half-symmetry simulation with Veloce hex-plate load



Proposed Thor load design with circular hole for stripline load



- Thor load designs are very similar to Veloce[1] load designs due to similarity of machine parameters
- ALEGRA 3D simulation may be driven by:
  - Equivalent circuit model, or
  - Open circuit voltage based upon TEM waveguide theory at input to CPF

Open circuit voltage:

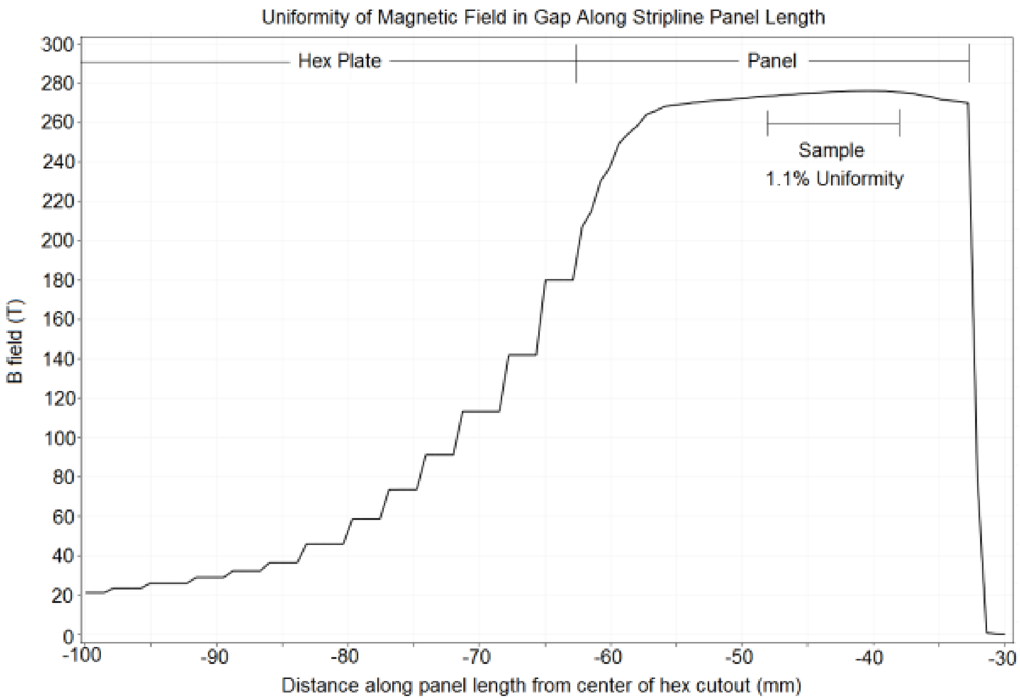
$$V_{oc} = 2\, Z\, I_{+}$$

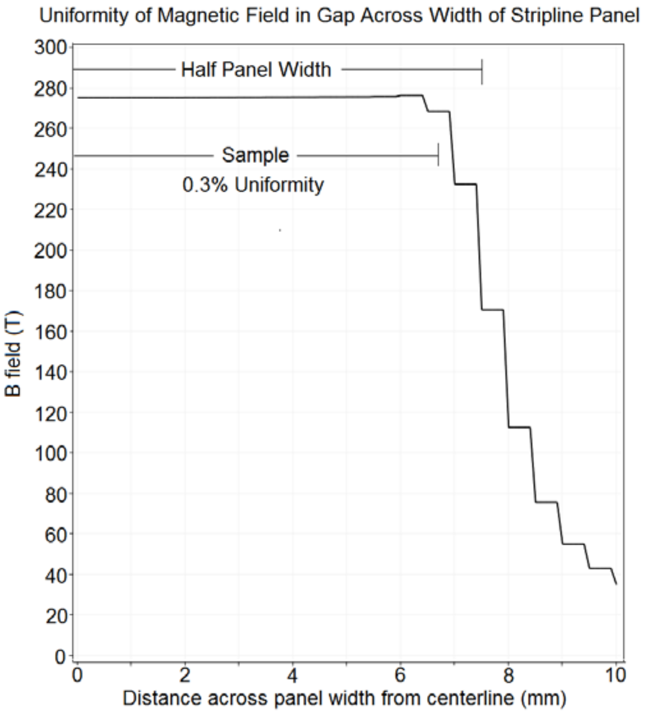
Forward current:

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

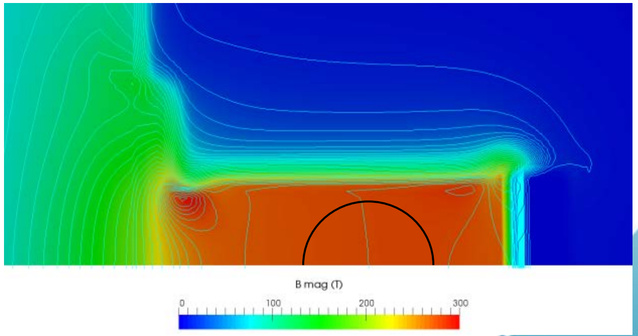
1. T. Ao, J. Asay, S. Chantrenne, et al., *A compact strip-line pulsed power generator for isentropic compression experiments*, Rev. Sci. Instrum., 79, 013903 (2008).

3D ALEGRA MHD modeling shows the magnetic field uniformity is on the order of 1% at 350 ns into an experiment



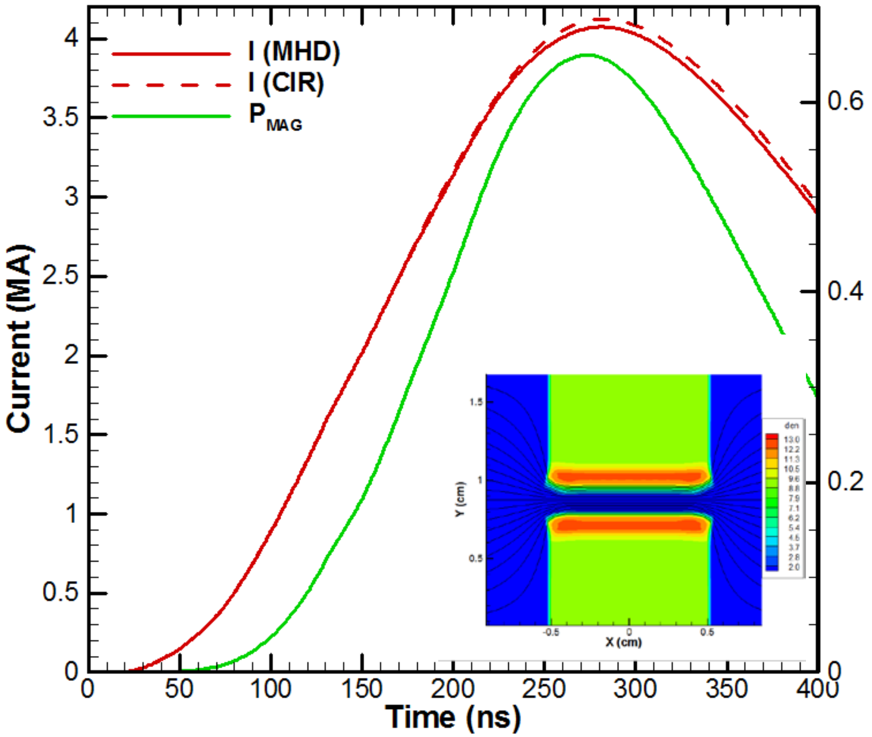


- Lineouts are taken along the length and across the width of the panels at mid gap

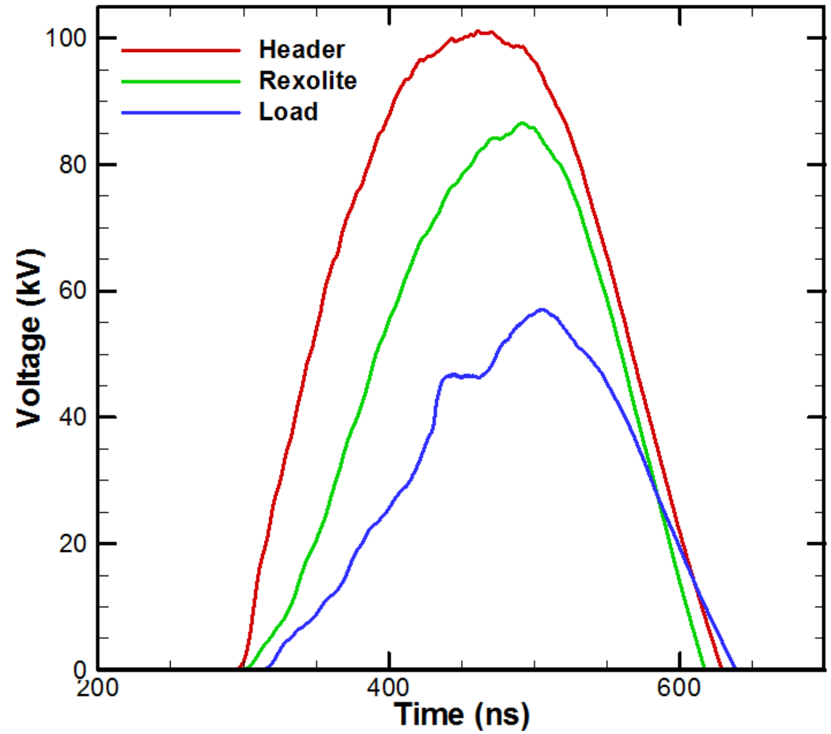


Thor-96 performance is examined with 2D MHD modeling performed with Trac II and ALEGRA

10 mm Cu panels
96 Bricks



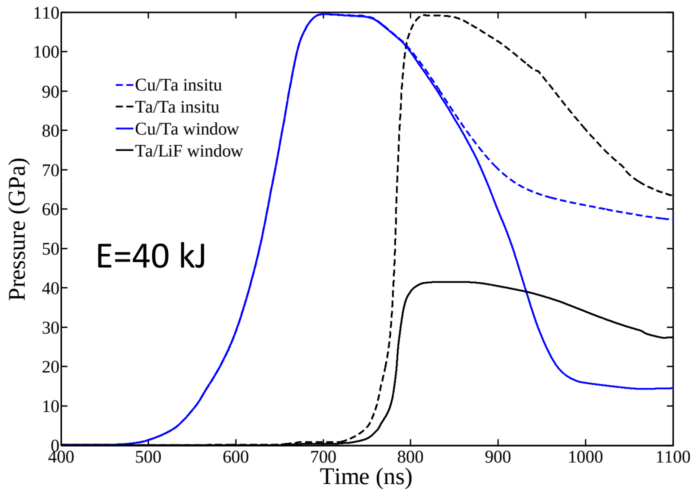
Voltage on each CPF component



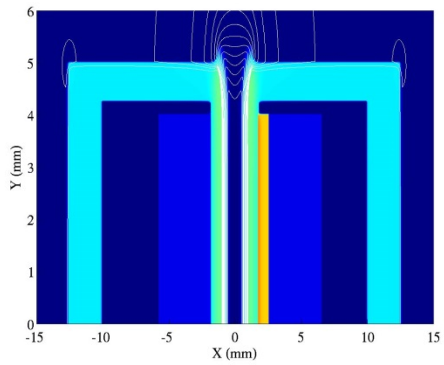
MHD Modeling: ○○○●

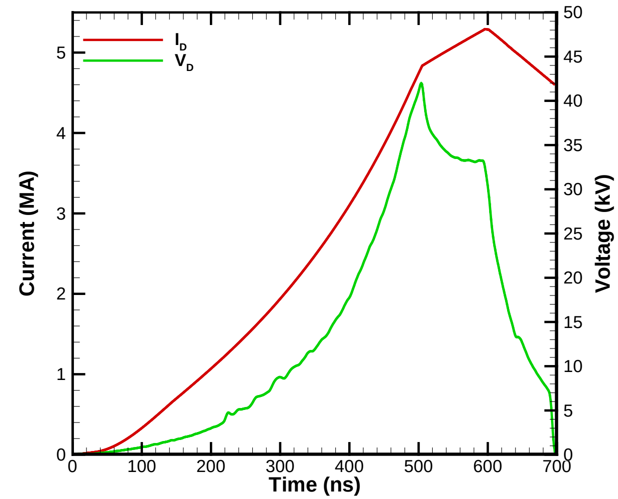
Current optimization and 2D MHD simulations providing design for 1.1 Mbar Cu/Ta flat-top pulse for strength experiments

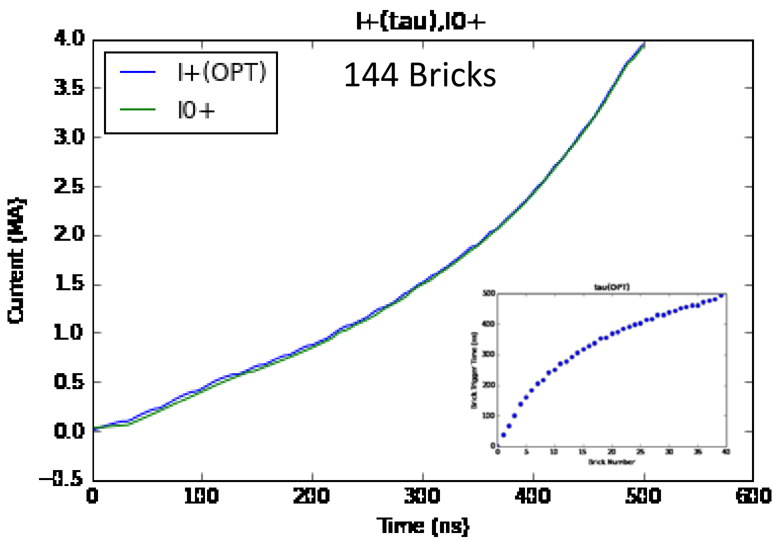
1.5 mm Cu, 0.8 mm Ta , 4 mm LiF

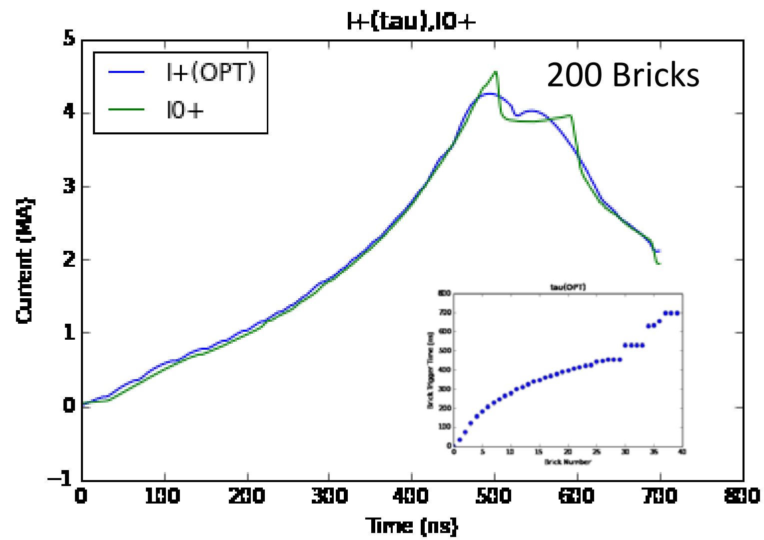


ALEGRA 2D





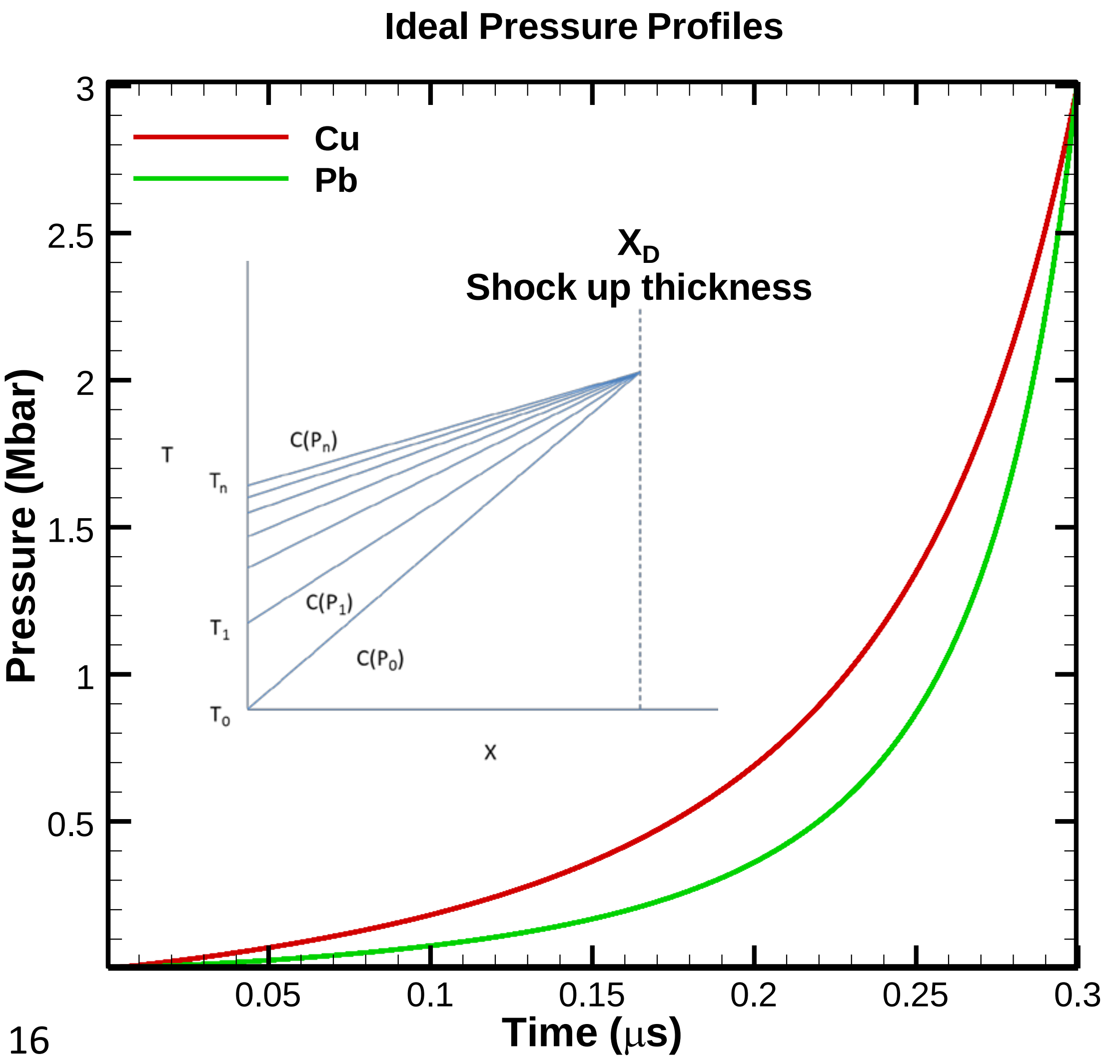


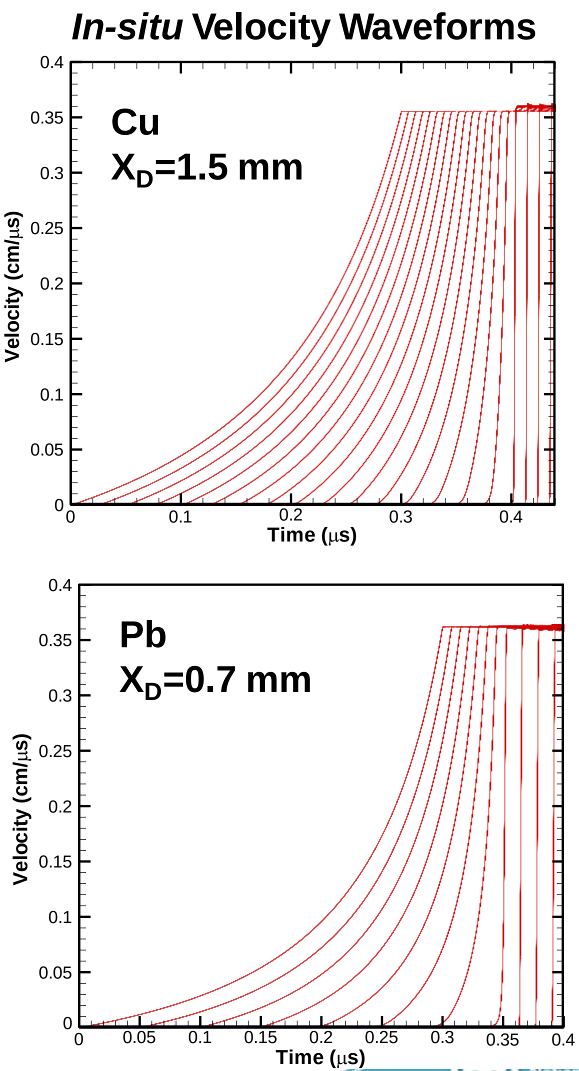


Ramp wave is well-matched

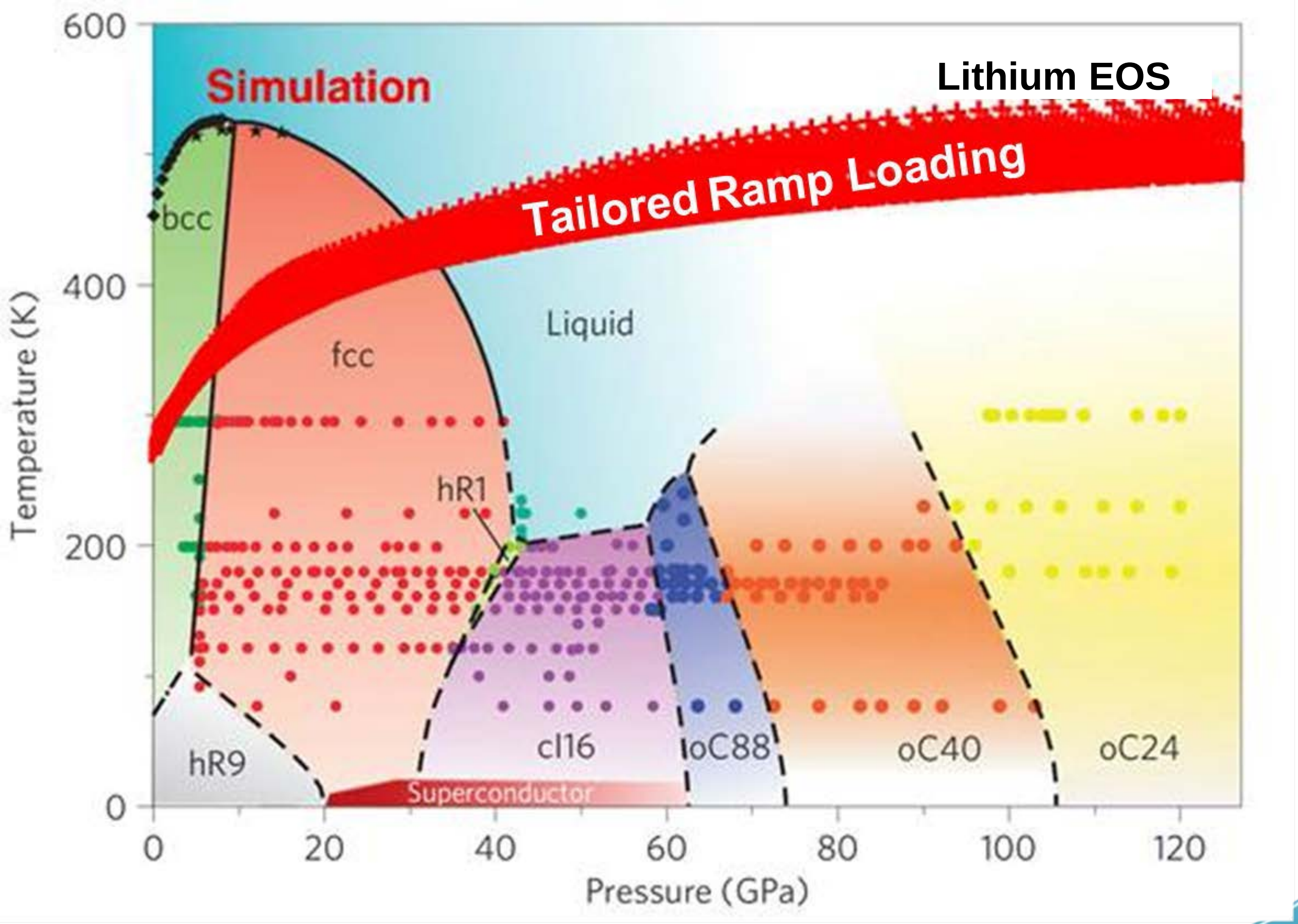
Ramp & slope change is more difficult
May need higher freq. brick component

Current pulse tailoring and MHD optimization are required for shockless compression of the sample being tested



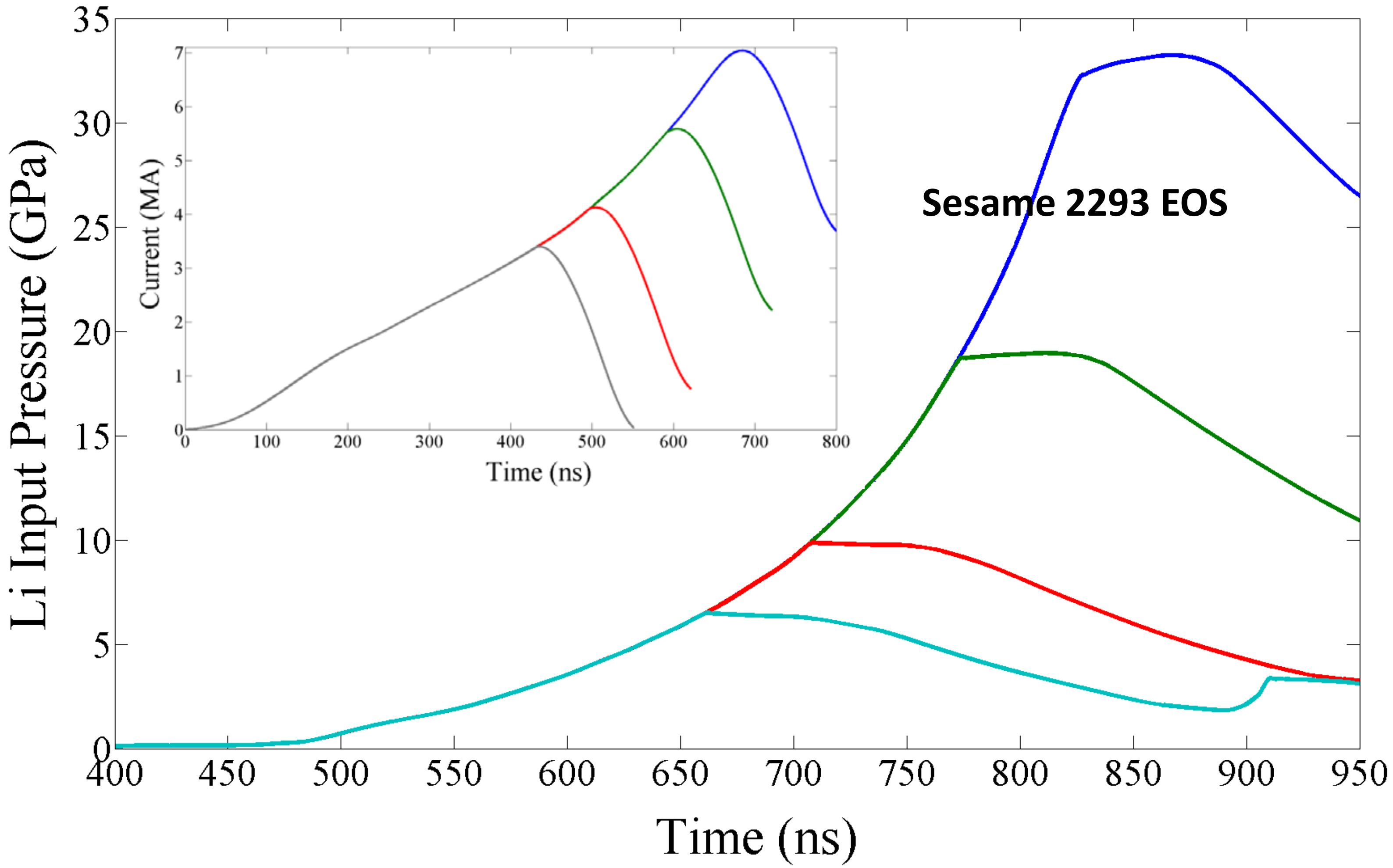


Shockless compression of lithium probes the melt transition boundaries and complements experiment and theoretical results of others



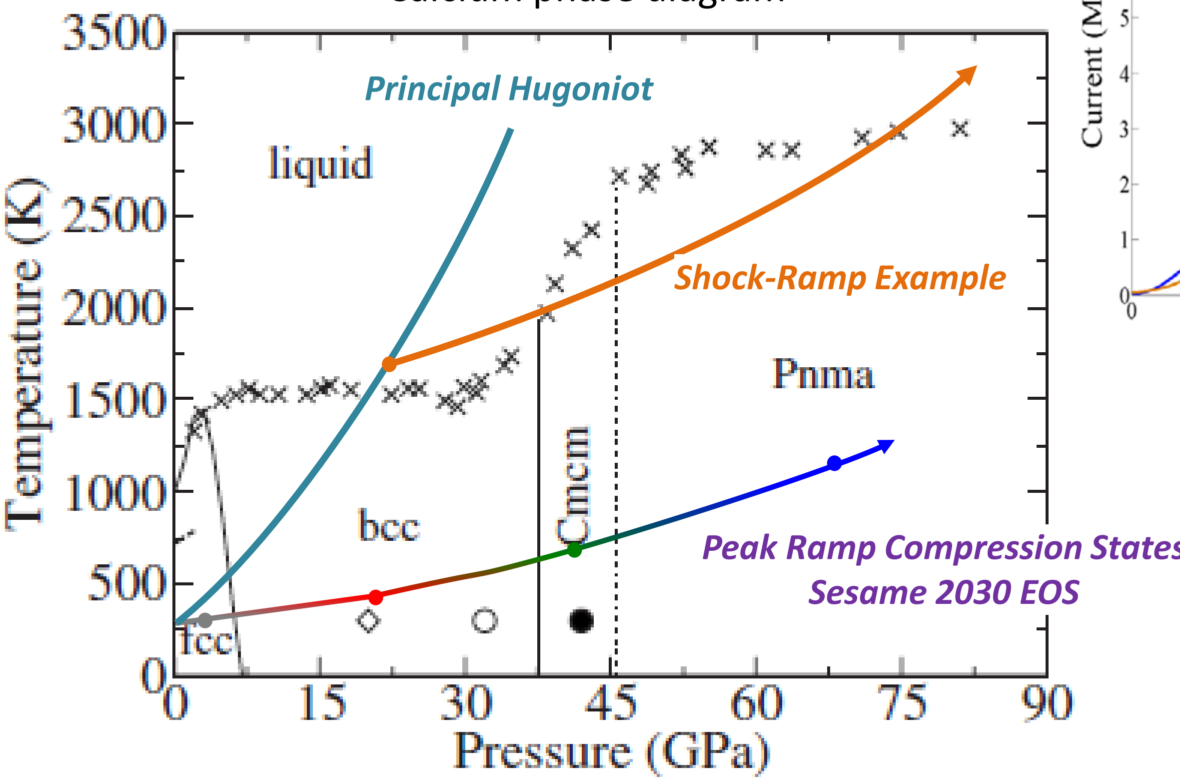
1. C. Guillaume, et al., *Cold melting and solid structures of dense lithium*, Nature Science, 7, 211 (2011).

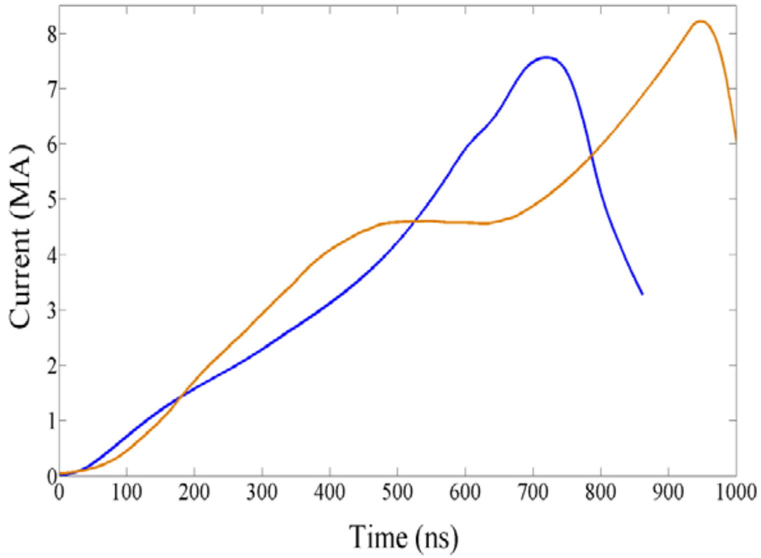
Tailored flat-top ramp loading can probe the melt boundary to about 33 GPa



Tailored ramp and shock-ramp current profiles may drive calcium through several phase transitions

Calcium phase diagram

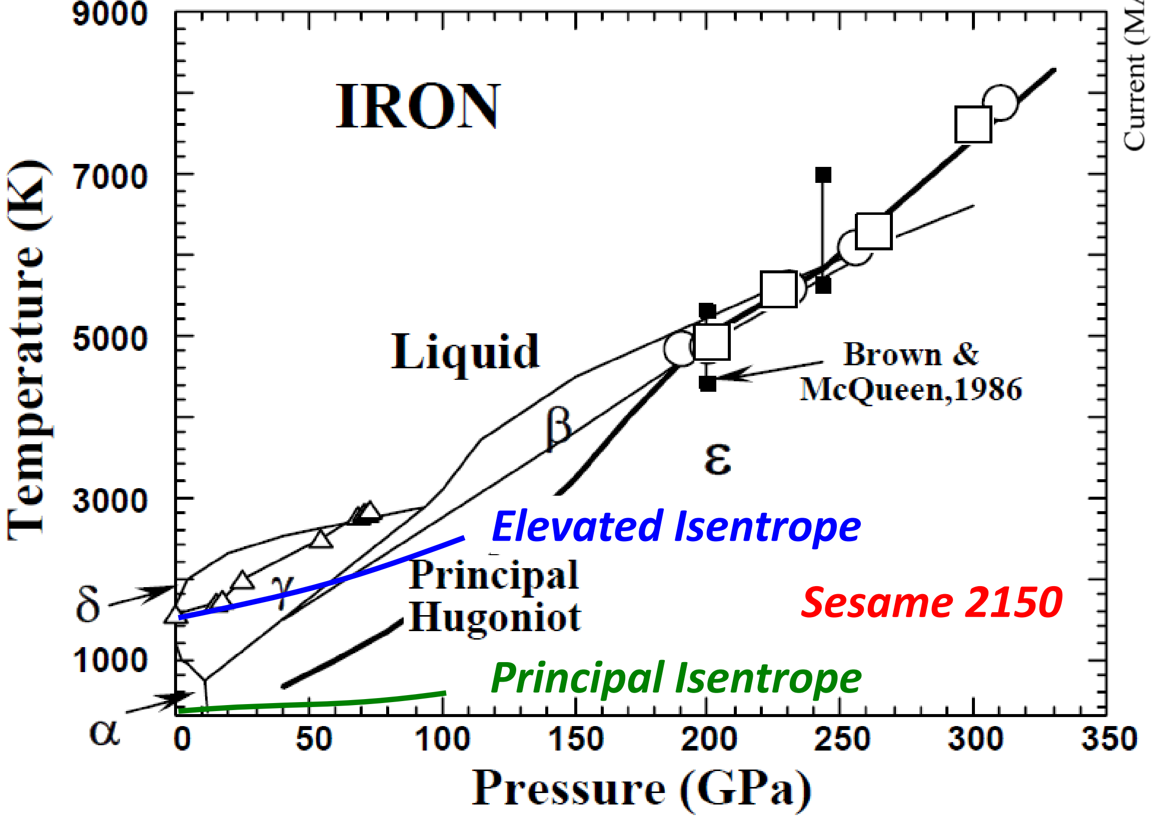


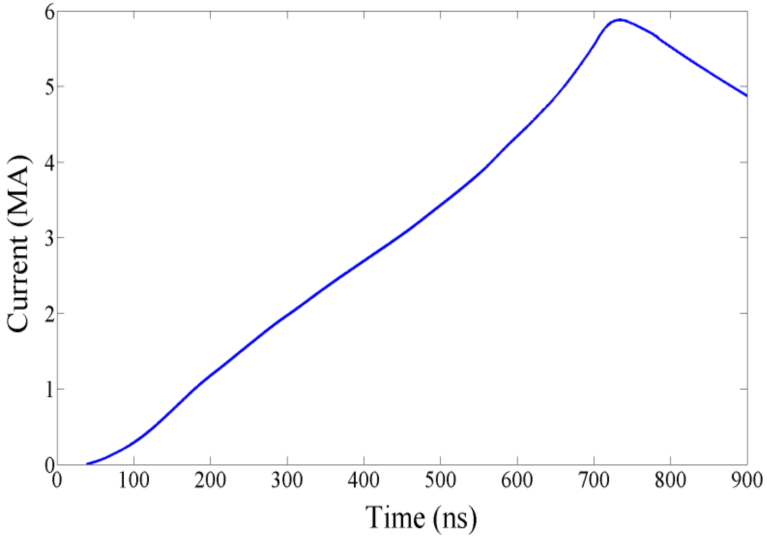


1. A. Teweldeberhan and S. Bonev, *High pressure phases of calcium and their finite temperature phase boundaries*, Phys. Rev. B, 78 (14) 140101 (2008).

Applications: ○○○○●

Preheated ramp compression experiments allow access to the γ-ε and possibly the γ-β-ε transitions





1. A. Ahrens, et al., *Shock temperatures and the melting point of iron*, AIP SCCM-1997, CP429, 133 (1998).
2. J. Nguyen and N. Holmes, *Melting of iron at the physical conditions of the earth's core*, Nature, 427, 339 (2004).

Conclusions

- Thor is under development as a compact modular scalable pulse power machine
- Current pulse tailoring is achievable through the use of many independent, decoupled switches to deliver shaped current pulses to the load
- All aspects of Thor are modeled through the use of various codes such as ALEGRA, Trac II, Screamer and others
- Points designs for several applications are in development
- 3 year schedule
  - FY14: Thor design and testing of 1 brick system
  - FY15: Thor-24 fabrication and testing, validation of MHD modeling
  - FY16: Thor-96 fabrication and commissioning, first materials science experiments

Collaborators

- Thor designers
  - P. D. Gard, SNL
  - R. J. Hickman , SNL
  - D. V. Morgan, SNL
  - D. W. Johnson, SNL
- Experimentalists
  - C. S. Alexander, SNL
  - T. Ao, SNL
  - M. D. Furnish, SNL
  - M. D. Knudson , SNL
  - S. Root , SNL
  - C. T. Seagle , SNL
  - L. Schulenburger , SNL
- Suppliers
  - W. R. Cravey, Alpha-Omega Power Tech
  - D. A. Goerz, Goerz Engineering
  - J. A. Goldlust, Dielectric Sciences
  - R. B. Spielman, Idaho State University