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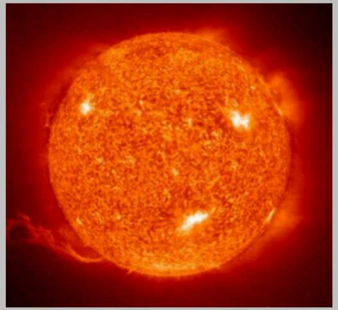

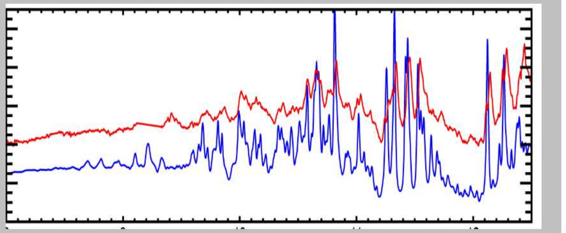

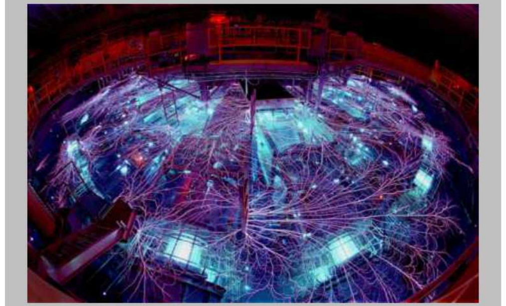

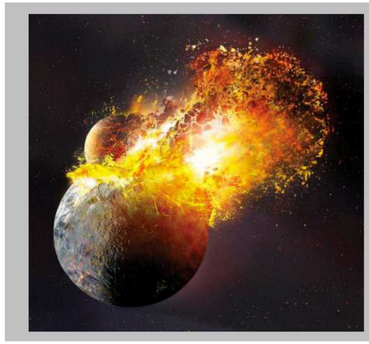

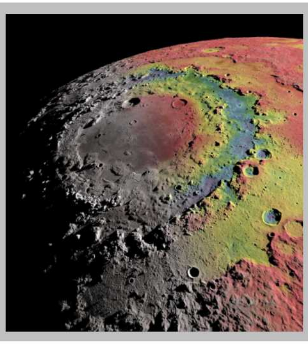

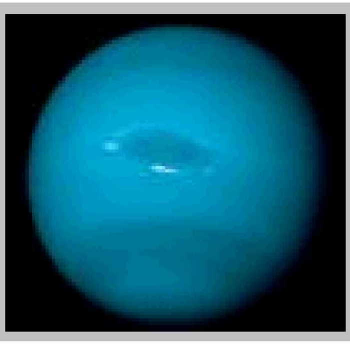

The Z Fundamental Science Program

Marcus D. Knudson

Sandia National Laboratories

Albuquerque, NM, Feb 19, 2019

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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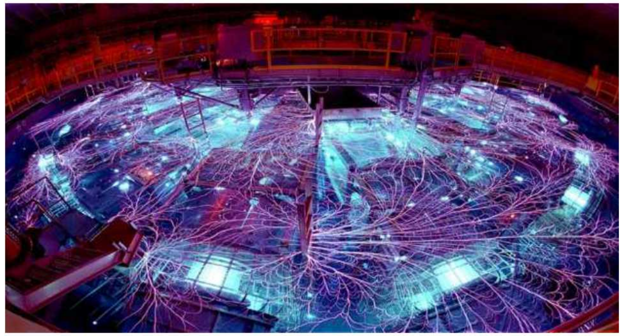
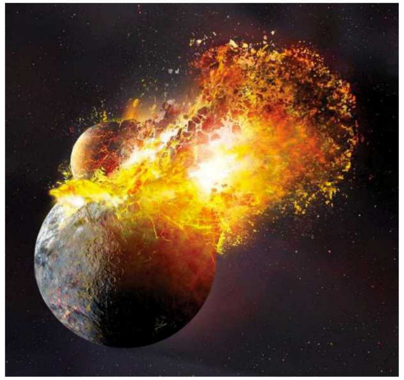
Outline

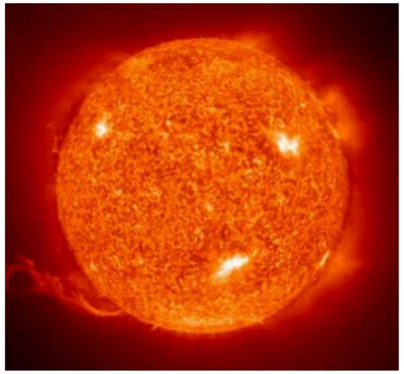
- Z – Machine
  - Z capabilities and MHD foundation
  - Z Fundamental Science (ZFS) Program
- High-pressure experiments
  - Jovian Planets and Giant Impacts
- Radiation-driven experiments
  - Opacity of iron at solar conditions
- ZFS 2019 call for proposals
  - ZFS Workshop Aug. 11-14, 2019
- Thor



Z is the most powerful pulsed-power facility in the world



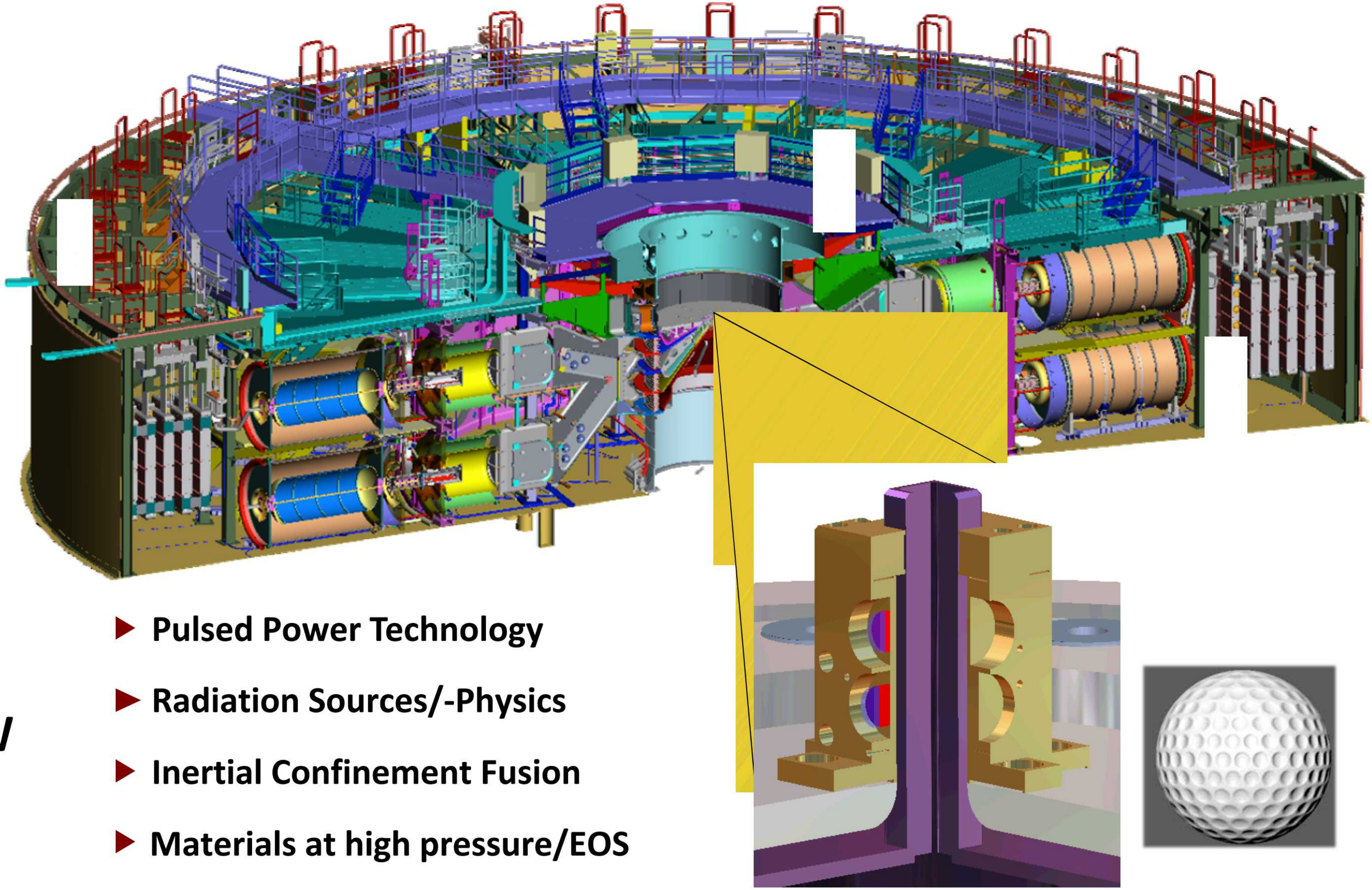
Direct measurement of iron vaporization at giant impact conditions – iron vaporizes earlier than ANEOS model.



Direct measurement of iron opacity at solar conditions – models for opacity disagree with data

Sandia's Z Machine is a unique platform for multi-purpose research on high energy density (HED) environments

Sandia National Laboratories



Acknowledgements:
Z operations, cryogenics, diagnostics, theory/ simulations, target design and fabrication, engineering, and management

I ~ 26 MA

τ ~100-1000 ns

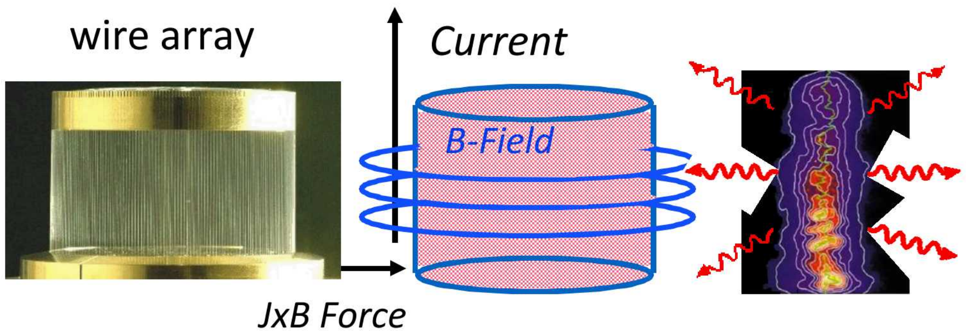
X-ray power > 250 TW

X-ray energy > 2 MJ

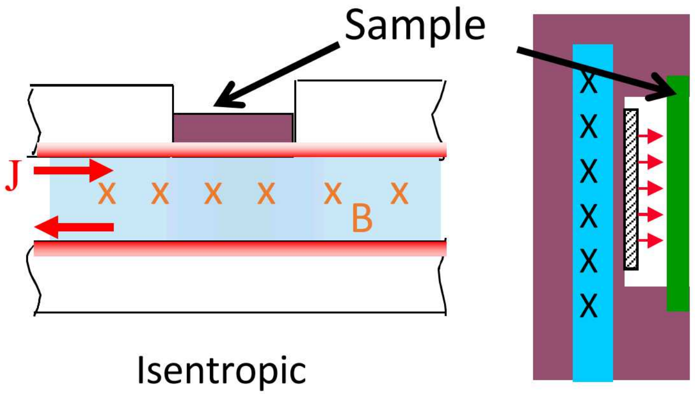
- Pulsed Power Technology
- Radiation Sources/-Physics
- Inertial Confinement Fusion
- Materials at high pressure/EOS

Magnetic fields are used to create HED matter in different ways for different applications

Radiation physics from Z-Pinch X-ray Sources



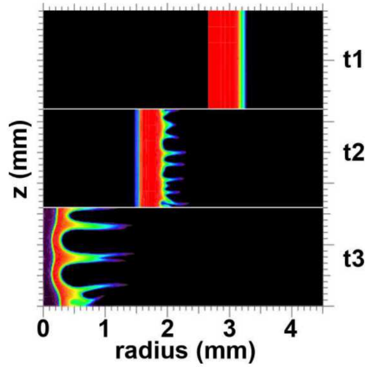
Materials Properties: EOS



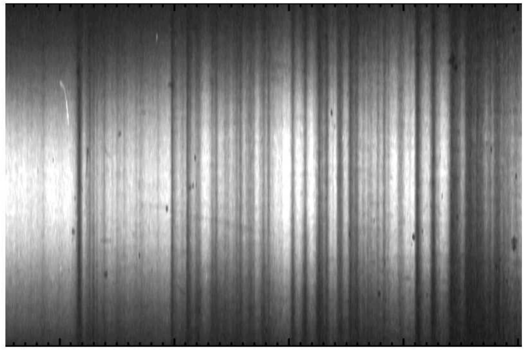
Isentropic Compression

Flyer Plate

Atomic- and plasma physics

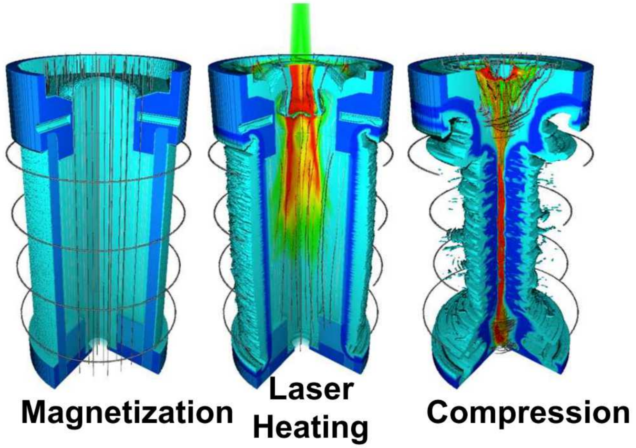


MRT instabilities



Iron spectrum

Inertial confinement fusion



The Z Fundamental Science (ZFS) Program engages a broad community and has advanced HED science

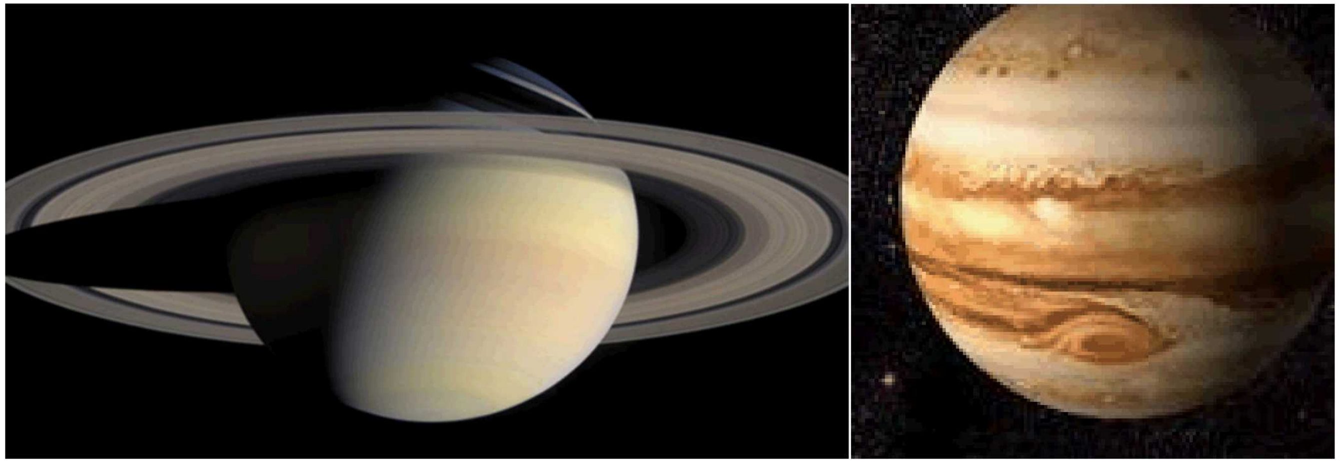
- **10 teams won shots on the 18-19 allocation**
  - Carnegie Institution of Washington
  - Lawrence Livermore National Laboratory
  - Northwestern University
  - Sandia National Laboratories
  - UC Davis/ Harvard
  - University of Rostock, Germany
  - UN Reno
  - UT Austin x 2
  - Washington State University
- **12 students are currently involved**
  - Former students have done very well
- **Resources over 7 years**
  - 60+ dedicated ZFSP shots (5+ % of all Z shots)
  - Ride-along experiments on Z program shots, guns, DICE, and THOR

- **Science with far-reaching impact**
  - Nature, Nature Geoscience, SCIENCE
  - 6 Phys. Rev. Lett, 3 Physics of Plasmas, 5 Physical Review (A,B,E)
  - About 40 total peer reviewed publications and 10 conference proceedings
  - 70+ invited presentations

- **Popular outreach**
  - National Public Radio, “All things considered”, 2014
  - Discover Magazine
    - Report on 9/16/2012
    - **Iron rain #62 in top 100 Science stories in 2015**
  - Albuquerque Journal Front Page 9/2017
  - Twice local TV coverage on planetary science

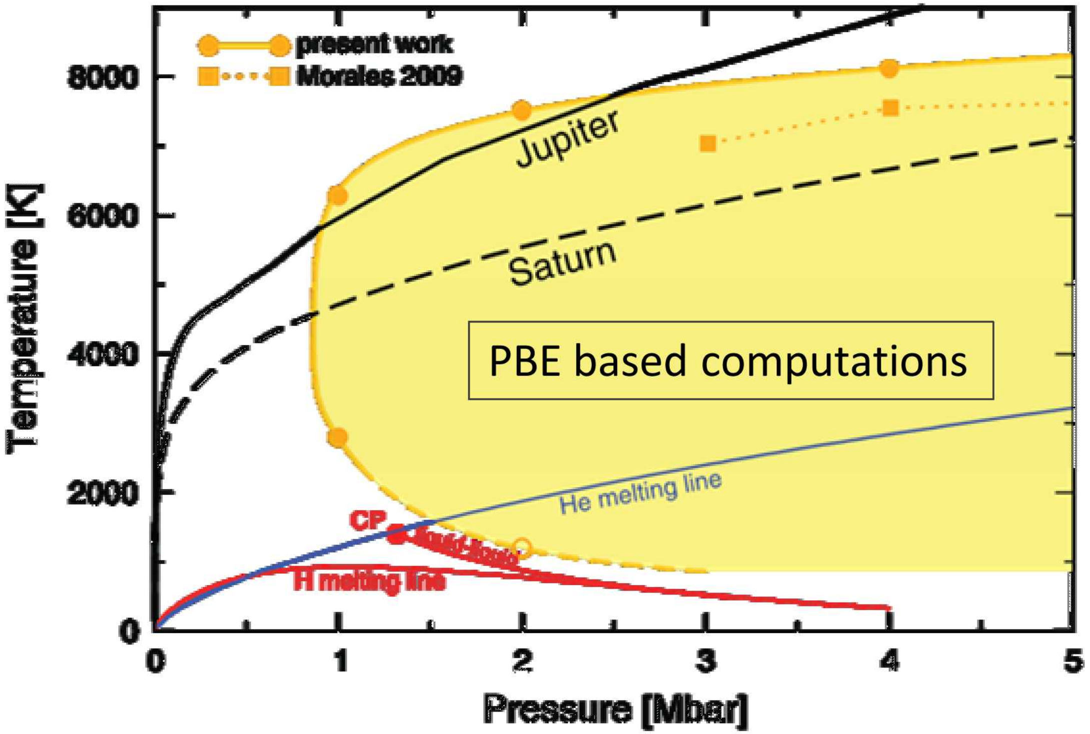
Observation of H2 metallization needed to address a planetary mystery

Why is Saturn hotter than expected?



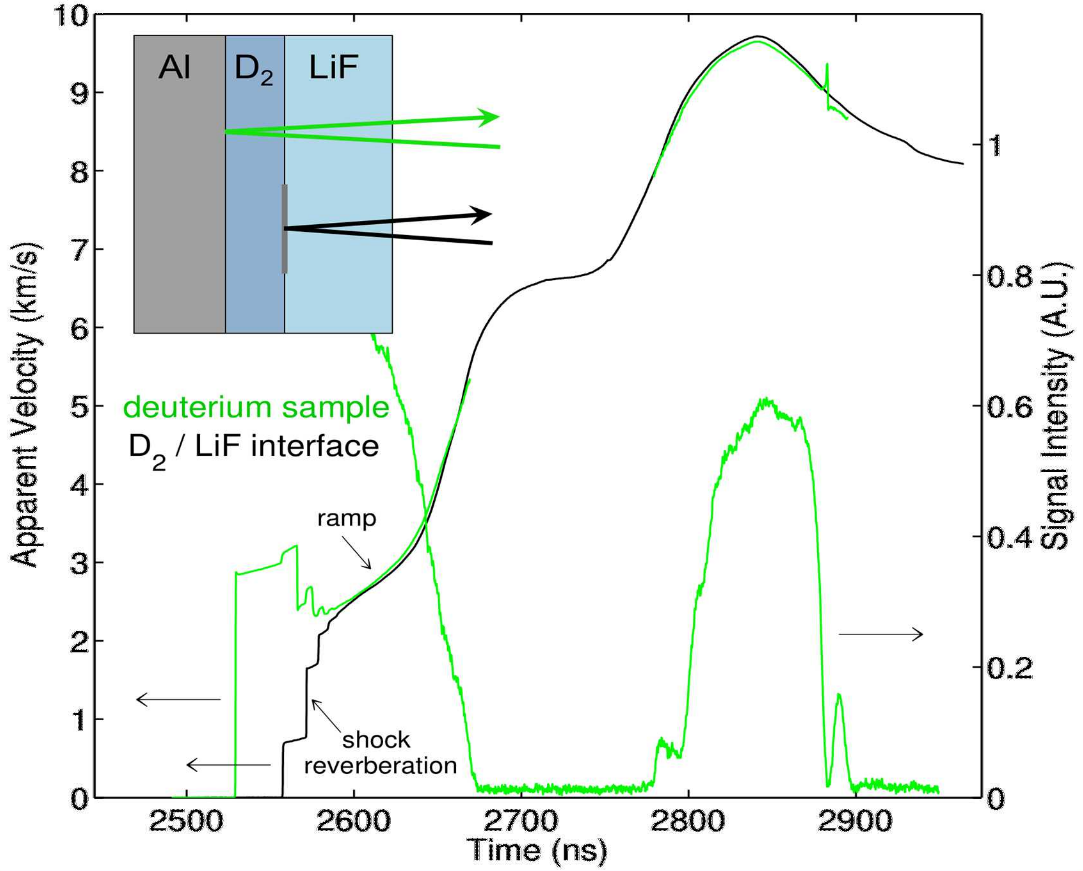
- Planets cool with age
- Saturn is much hotter than expected for it's age
- Two billion year problem using the same aging model as Jupiter

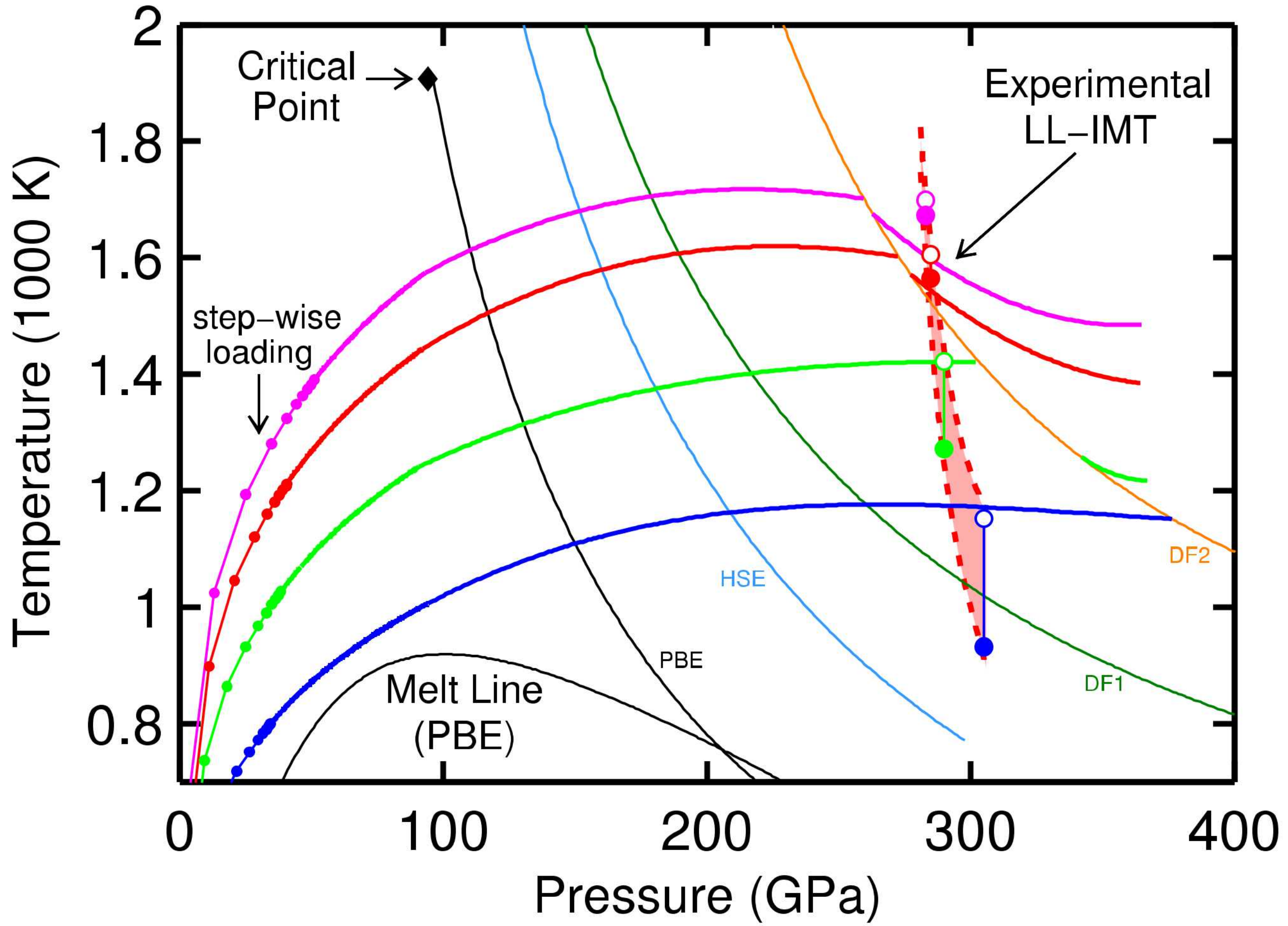
- Hydrogen metallization is linked to H-He de-mixing
- Formation of helium rain generates heat
- BUT - Jupiter would also have He rain and excess heat based on these models



Liquid-Liquid Insulator-to-Metal Transition in deuterium observed near 300 GPa

Optical absorption and reflectivity provide insight into the state of cold, dense hydrogen/deuterium

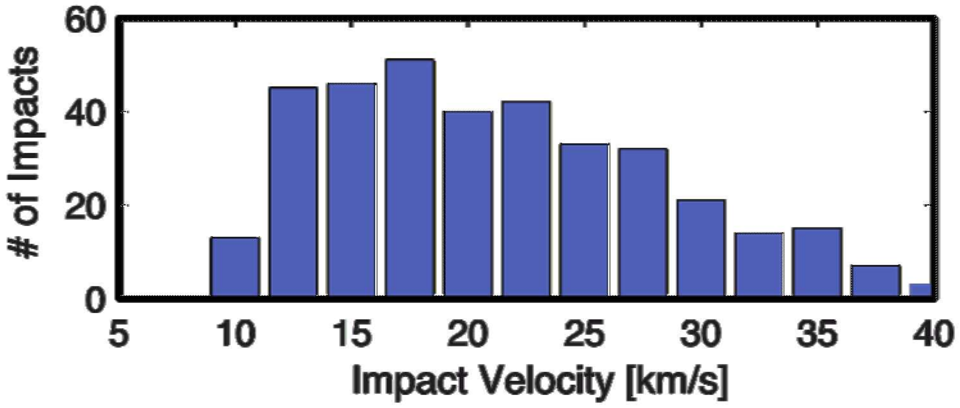


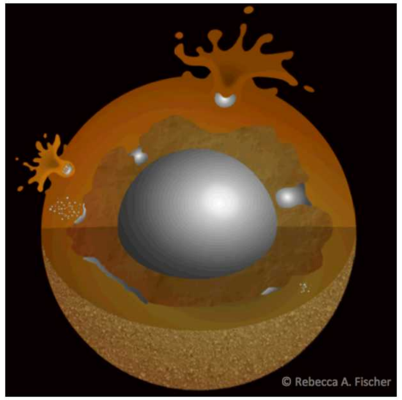


- Insensitivity to *T* suggest ρ-driven transition
- Transition *P* much higher than PBE prediction

Vaporization during planet formation and evolution is a key mechanism – large uncertainty in the onset of vaporization

Simulations of planetary dynamics suggest high impact velocities





Fluid instabilities CAN NOT sufficiently mix the incoming iron cores to explain observed iron content in the mantel or the similarity in isotopics between the earth and the moon.

Does an iron meteor:

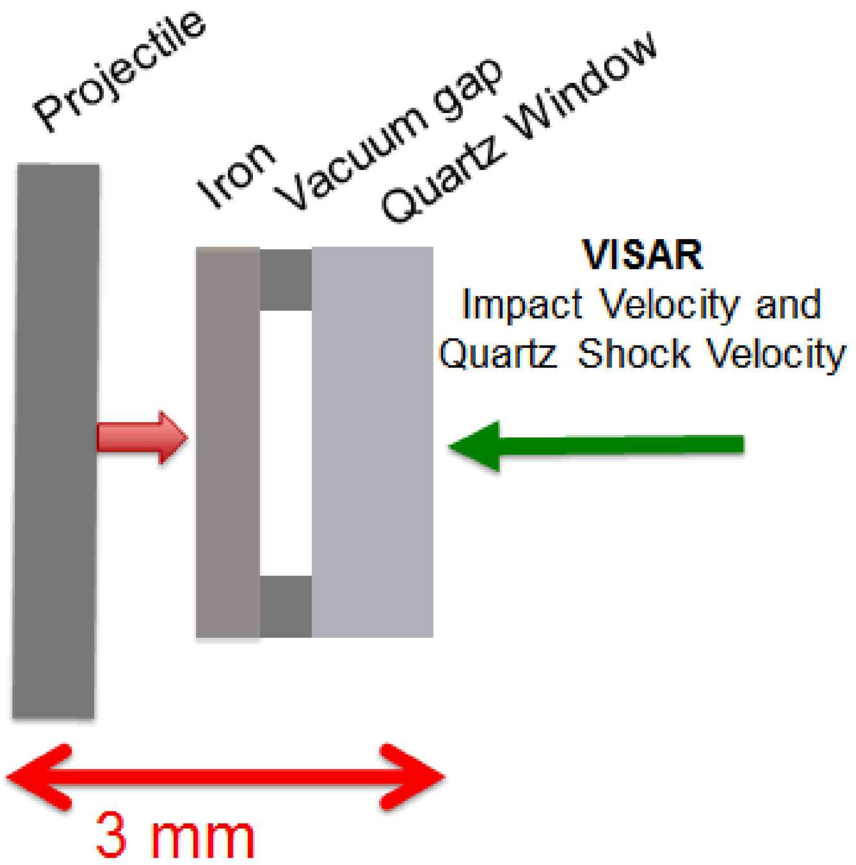
- plow into a planet as a bullet?
- splatter as a drop of rain?
- vaporize into a cloud of iron to return as iron rain?

The outcome depends on the HED properties of iron – particularly vaporization

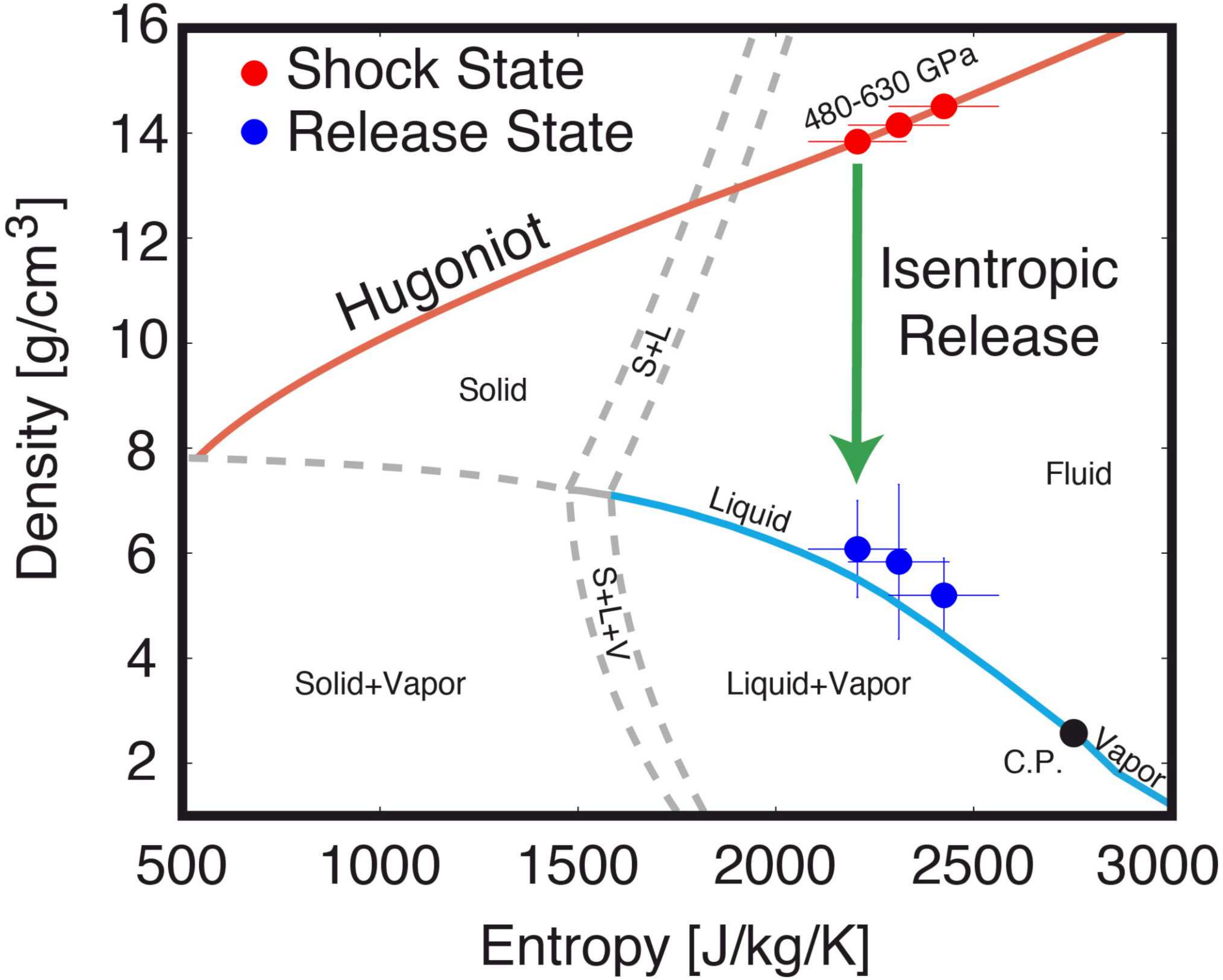
N-body simulations from Raymond et al. 2009

Z can study vaporization for states produced by planet forming impacts

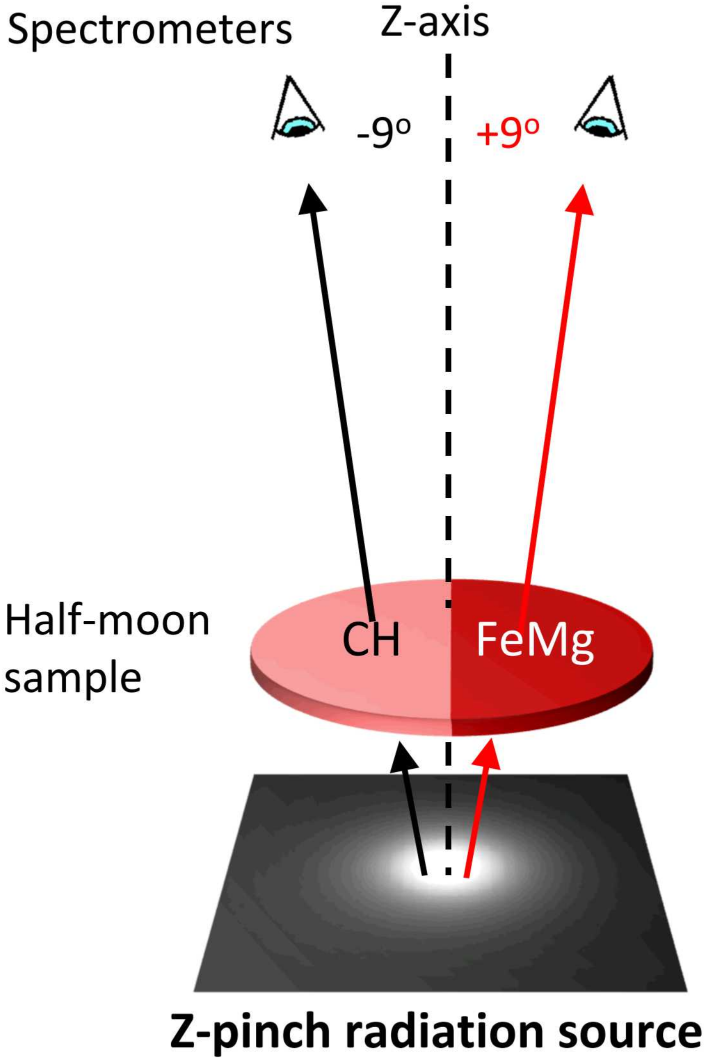
- Flyer plates on Z can exceed 40 km/s
- Liquid-vapor dome located via shock-release experiments

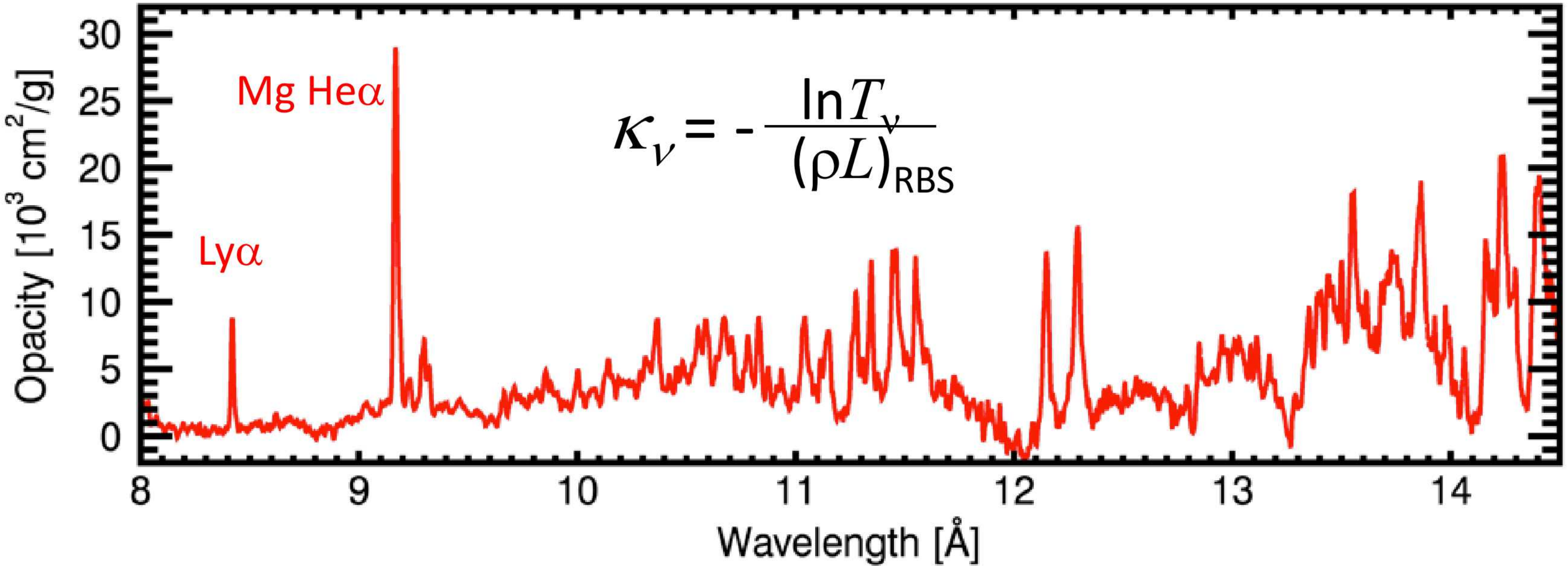


Iron Shock and Release Data



High-temperature Fe opacities are measured using the Z-Pinch opacity science platform

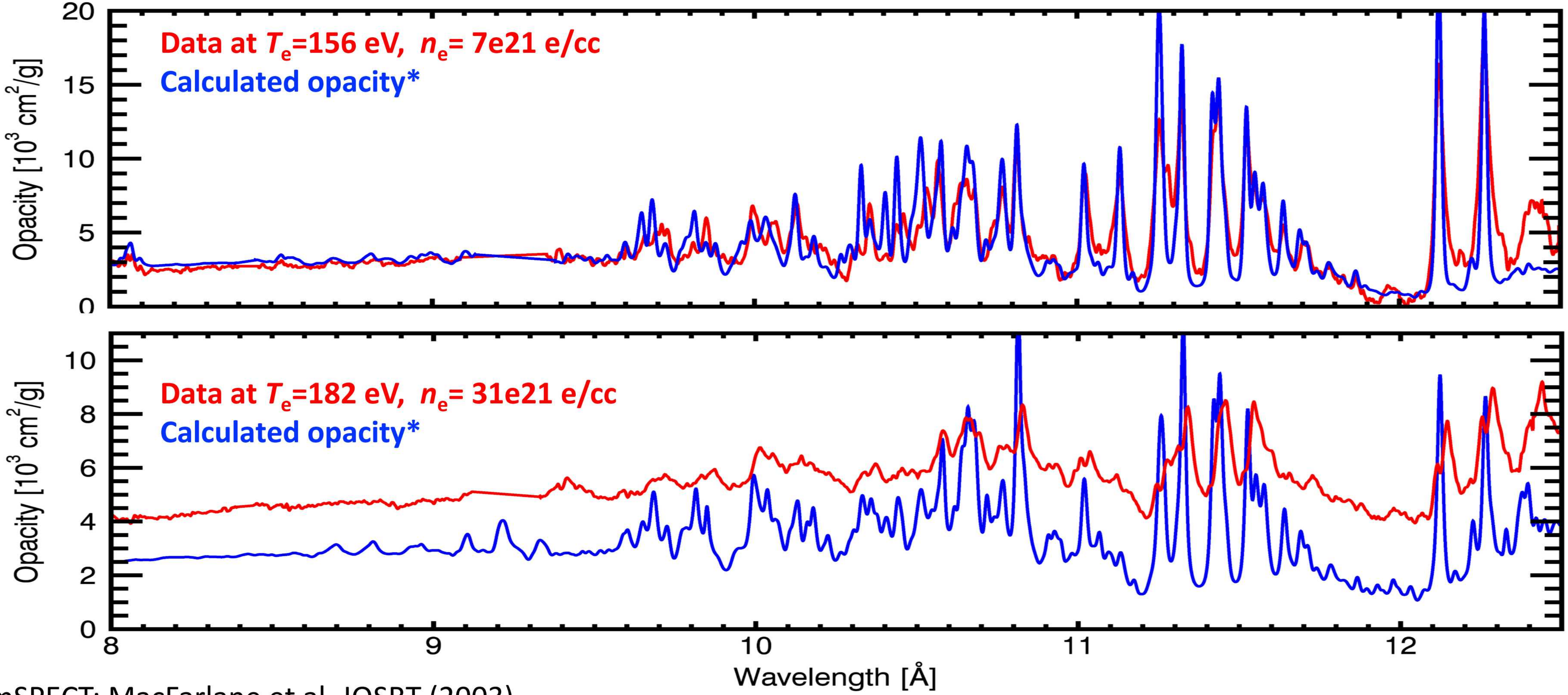




- Z-pinch energetic radiation provides uniform heating
- 350-eV Planckian backlight radiation mitigate sample self emission
- FeMg conditions inferred from Mg spectra

Modeled opacity shows marked disagreement as T_e and n_e approach solar interior conditions

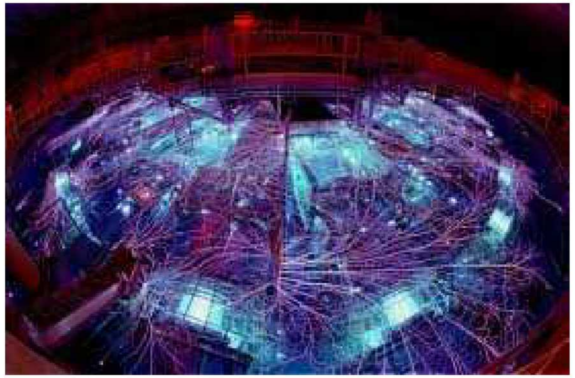
Convection Zone Base: T_e=182 eV, n_e = 90e21 e/cc

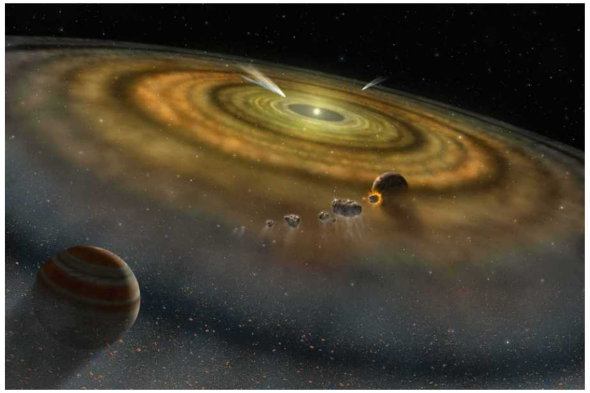


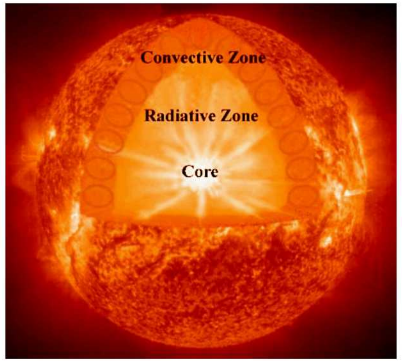
* PrismSPECT: MacFarlane et al, JQSRT (2003)

Pulsed power is exquisitely suited for HED science

- **Sandia's Z machine is ideal for Mbar material experiments**
  - Compression of solids and liquids
  - Generate conditions found in the interiors of gas giants and the Earth/super earths, other exoplanets
- **The Z machine produces MJs of x-rays**
  - Radiation effects on materials
  - Fundamental properties of matter
- **Fundamental plasma physics**
  - Spectroscopy and plasma conditions: line broadening and opacity
- **Strong integration between experiments, theory, and simulations**
  - From quantum mechanics to MHD and beyond



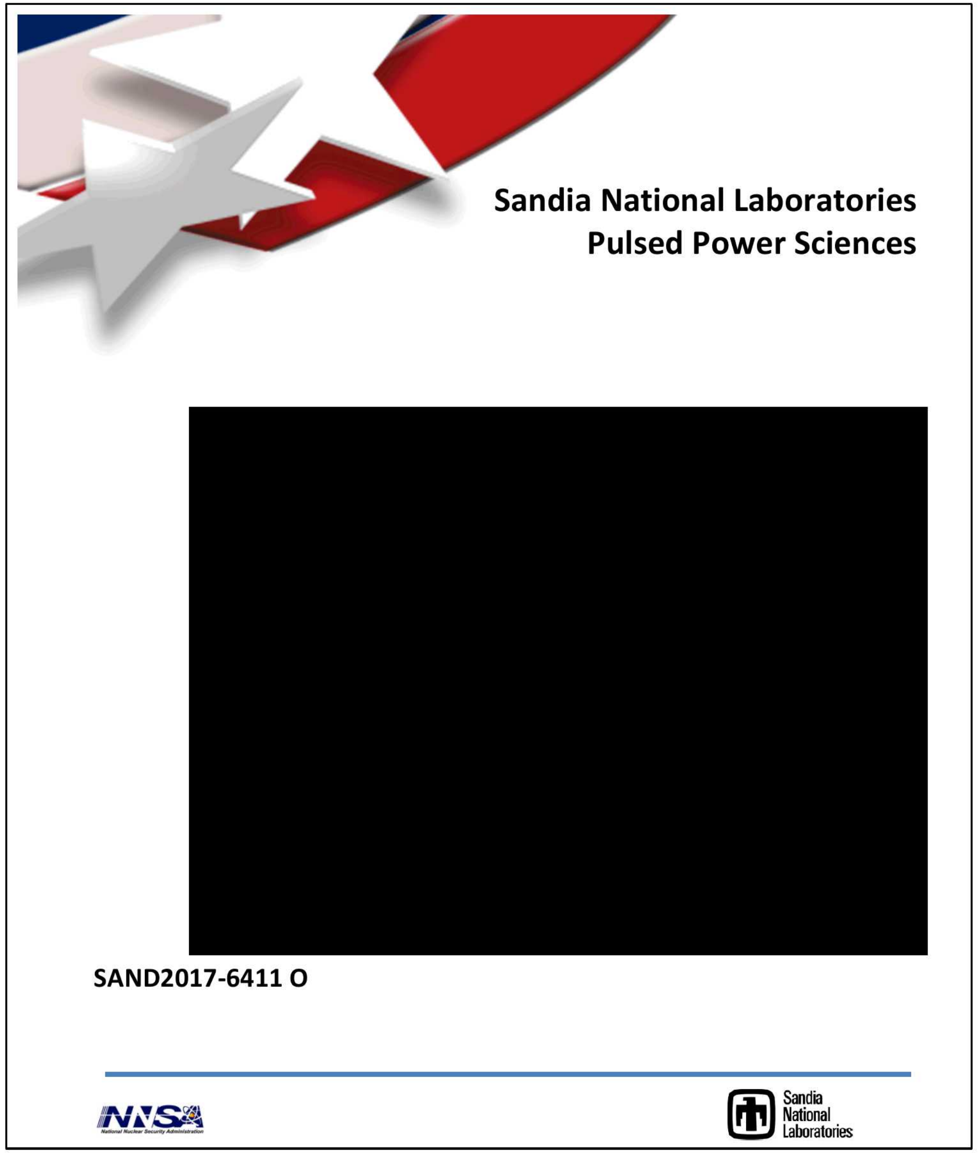




Decades of exciting HED Science research lies ahead

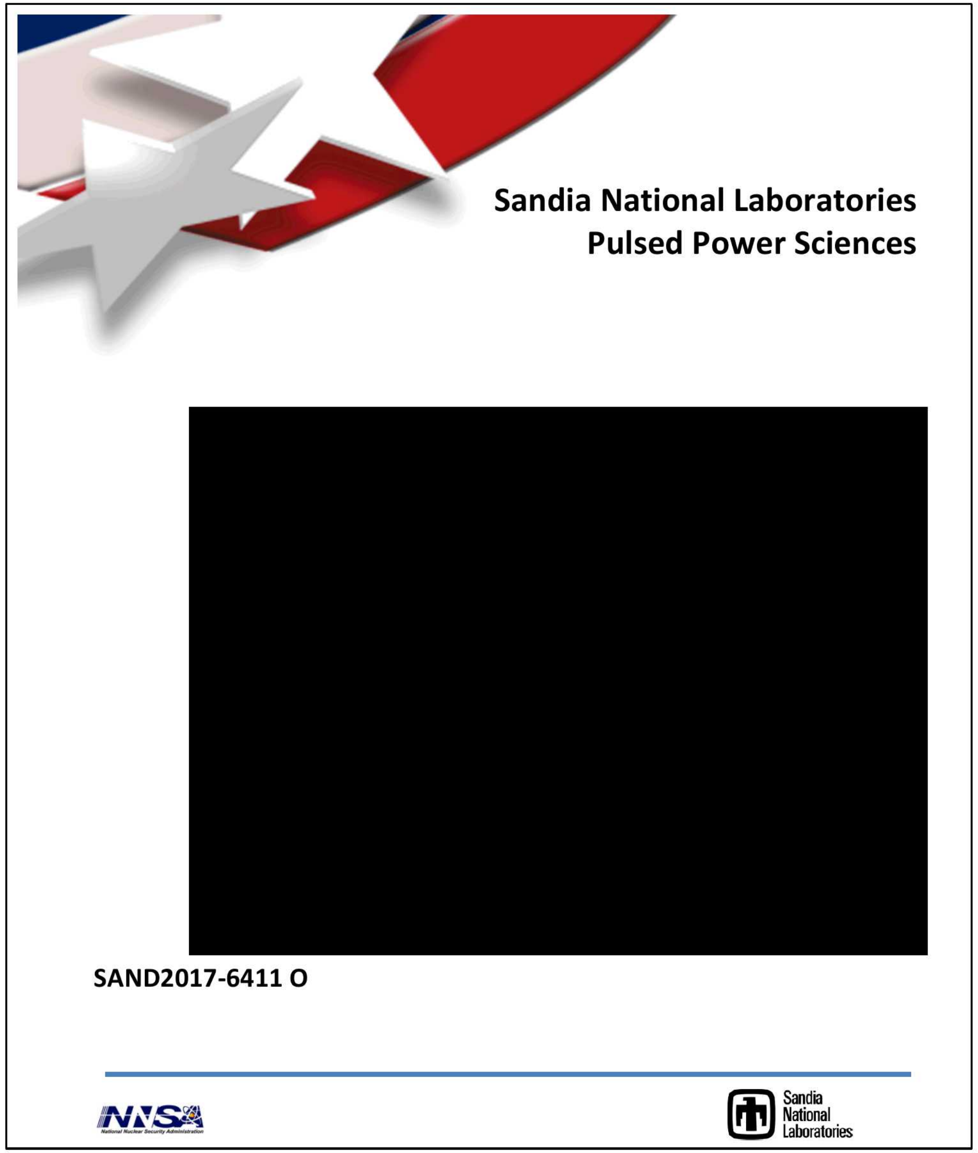
ZFS 2019 call for proposals will open in June

- **ZFSP call for proposals timeline:**
  - **June 15: call for proposals open**
  - **August 11-14: ZFS Workshop**
    - *Hotel Andaluz, Downtown Albuquerque*
    - *Interested parties please inquire at the Sandia Table*
  - **September 15: call closes**
  - **October/November: evaluation and selection**
    - *Facility review: experimental feasibility, safety, and diagnostics*
    - *Scientific review of international panel mid-November*
    - *Mid-December, distribution of shots*
  - **April 1, 2020 through March 31, 2022**
    - *Shots scheduled for successful proposals*



Proposals are evaluated by an independent, international review panel

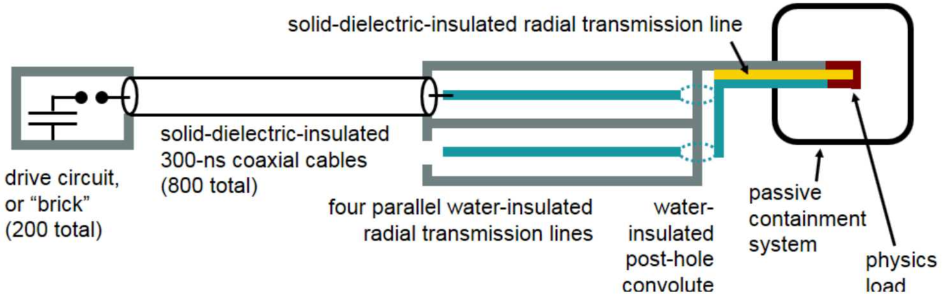
- **Applications are technically evaluated based on four scientific/technical criteria:**
  - Scientific and technical soundness and quality of the proposed method/approach, and the feasibility/likelihood of accomplishment of the stated objective
  - The overall scientific/technical merit of the project and its relevance and prospective contribution to its field of research
  - The competence, experience, and past performance of the applicant, principal investigator and/or key personnel
  - The demands of the project in terms of resource requirements (equipment, beam time, etc.) and/or other requirements (facility hardware modifications, component development, etc.) vis-à-vis competing demands.

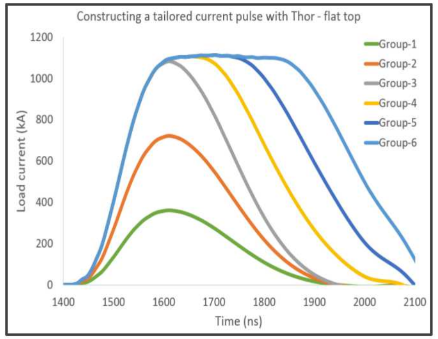


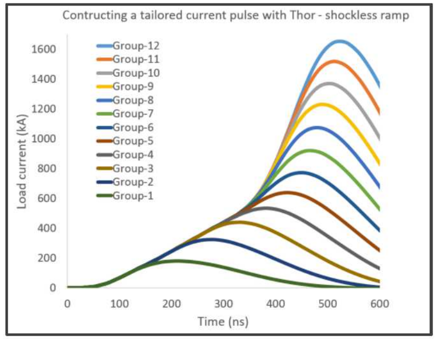
Thor: a pulsed-power driver optimized for material-physics experiments

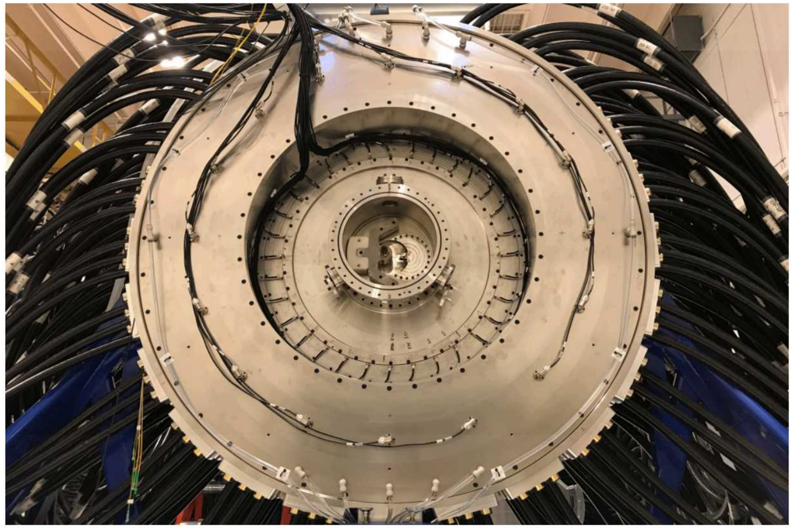
Thor design concept:

- Electrical energy is stored in many small energy storage units called “bricks”
- Switches are triggered to launch 100 ns pulses
- Pulses are summed at the load to generate a tailored current pulse









Thor is an ideal platform for the development of advanced physics-load and diagnostic concepts

- Precision control and tailoring of pulse shape
- Low experimental cost (~$1 k per shot) and high shot rate (~5 per day)
- Makes it ideal for campaigns which are too costly to run on Z