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To measure and model the properties of warm dense matter

Pierre-Alexandre Gourdain

Adam Frank, Patrick Knapp, David Meyerhofer

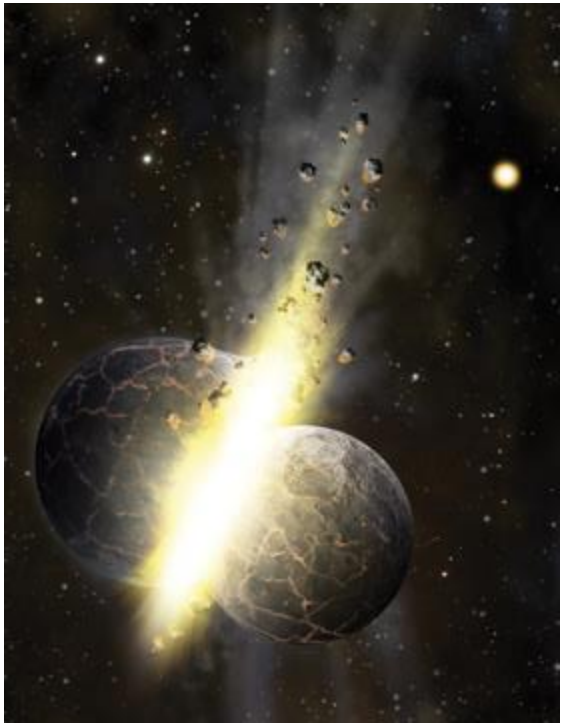
Outline

- Introduction
- Research frontier and scientific challenges
- Advancing the frontier of plasma science
- New research tools and capabilities
- Impact and conclusions

INTRODUCTION

Warm dense matter: “solids” under extreme conditions

- Warm dense matter is a whole new state of matter which bridge the gap between solids and plasmas
- The properties of warm dense matter are mostly unknown
- New physical models are required to describe properly warm dense matter
- Warm dense matter is key to understanding the evolution of gas giants, Mega-Earths or planetary collisions



Kathleen Cantner, AGI

What is warm dense matter? Where do we find it?

Definition

- 0.1 to 10 times solid density
- 0.1 to 100 eV in temperature

Problems:

- Ions are strongly coupled (beyond the plasma physics model)
- Electrons are degenerate but with a finite temperature (beyond the scope of condensed matter physics)

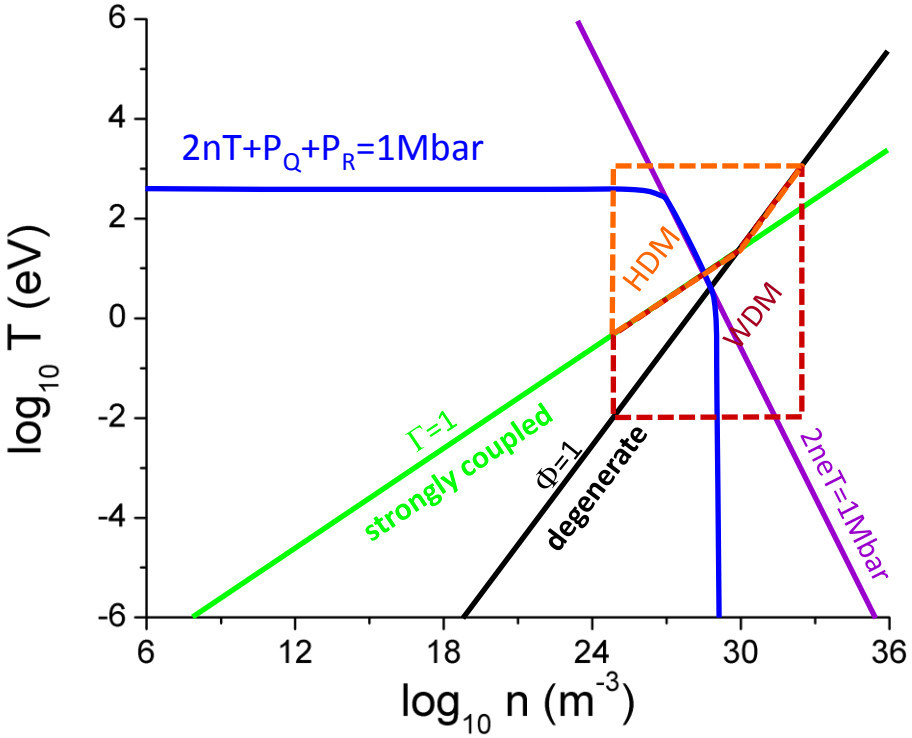
Where it can be found

- Core of gas giants
- Core of mega earths
- Planetary collisions
- Early stages of inertial fusion targets

End game:

- Defining the properties of warm dense matter to predict the evolution of **macroscopic** systems under extreme conditions

The realm of warm dense matter



Warm dense matter (WDM) is:

- Strongly coupled
- Degenerate

Hot dense matter (HDM) is:

- Classical matter
- In the Mbar range

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RESEARCH FRONTIERS AND SCIENTIFIC CHALLENGES

Research frontier

- Warm dense matter properties are virtually unknown
- Warm dense matter models require new mathematical approaches
- New techniques are required to produce and study warm dense matter

Experimental challenges

- Getting uniform warm dense matter samples
- Avoiding mixed states (warm dense matter +gas or plasma) caused by material expansion
- Measuring the properties of warm dense matter requires bright x-ray sources

Theoretical challenges

- Well established theories (plasma and condensed matter physics) do not apply to warm dense matter
- Perturbation theories cannot be used due to the non-adiabatic nature of warm dense matter produced by lasers isochoric heating
- Only macroscopic models can be used in practice to understand the evolution of warm dense on macroscopic

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ADVANCING THE FRONTIER OF PLASMA SCIENCE

Producing warm dense matter

Present methods

- Heavy ion beams
- High intensity laser
- Coherent light sources

Required innovations

- High rep rate
- Higher energy flux
- Larger illumination area

NDCXII

OMEGA EP

LCLS-SLAC

Diagnosing warm dense matter

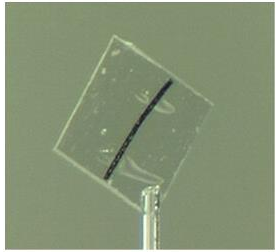
Present methods

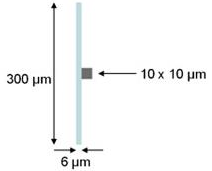
- X-ray sources:
  - High intensity laser
  - Coherent light sources
  - X-pinches
- Detectors:
  - Scintillators
  - Image plates
  - Gated intensifiers

Required innovation

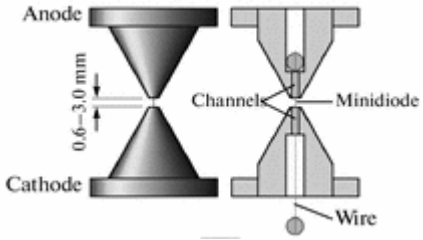
- X-ray sources
  - High rep rate
  - Higher energy flux
- Detectors
  - Higher sensitivity
  - Higher resolution

20 keV source: K. Vaughan HEDP (2013)





5 keV source: T. C. Shelkovenko et al. Plasma Phy. Rep. (2015)



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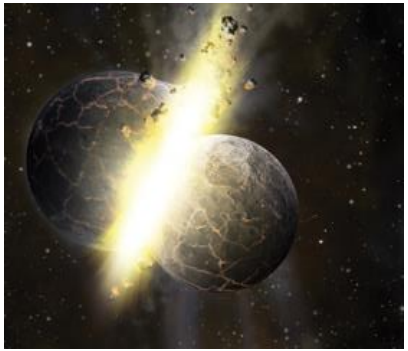
Modeling warm dense matter

Present methods

- Density functional theory
- Classical molecular dynamics
- Magneto-hydrodynamics (e.g. Lee-More-Desjarlais resistivity)

Required innovations

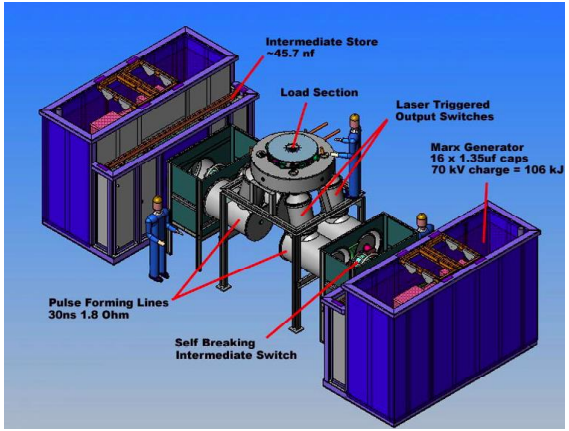
- Develop parallel ready approaches to present approaches
- Finding macroscopic approaches to handle microscopic effects



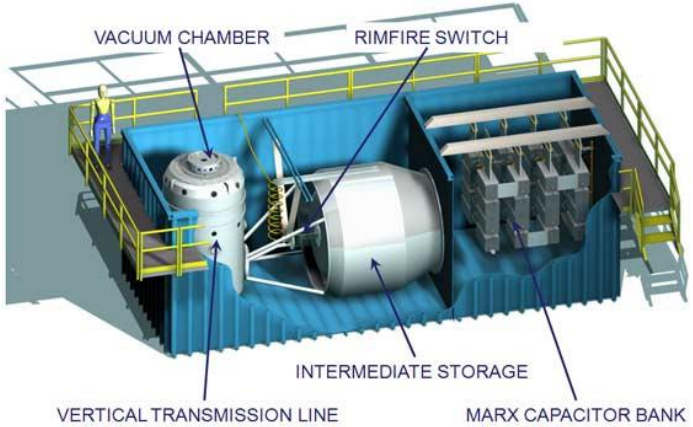
NEW RESEARCH TOOLS AND CAPABILITIES

University pulsed-power machines: I~1MA, dI/dt~100ns

COBRA: Cornell University

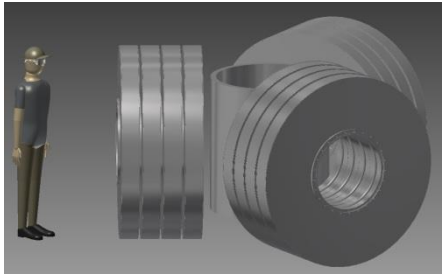


ZEBRA: UN Reno



MAIZE: UMich Ann Arbor

HADES: Uni. of Rochester



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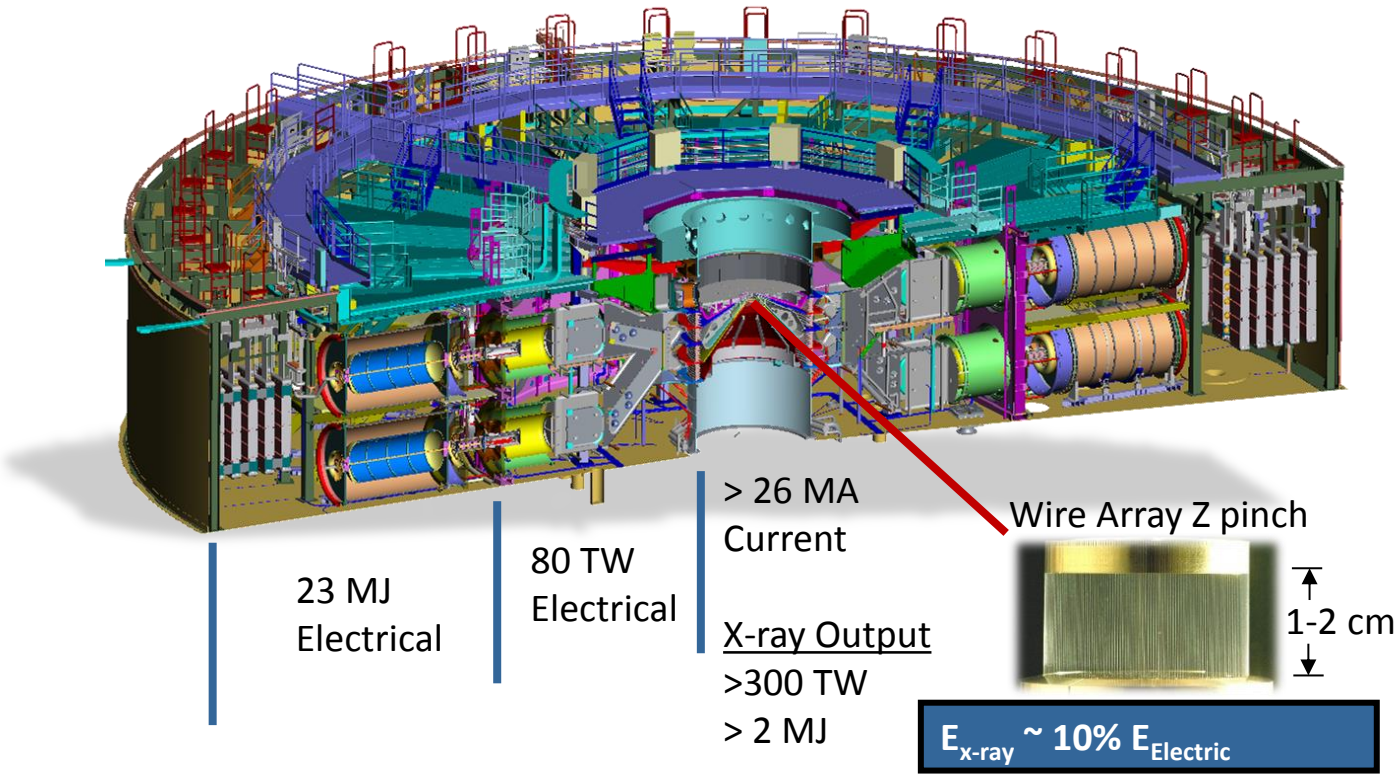
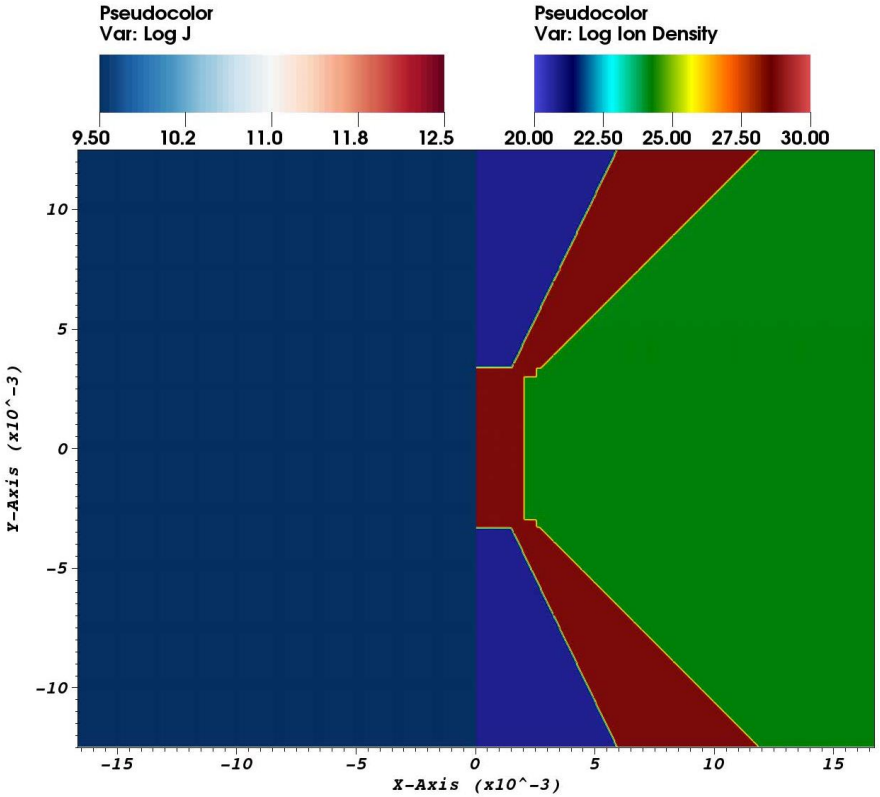
THE pulsed power machine: Z-machine: I~26MA, dI/dt~100 ns



Why producing warm dense matter with pulsed-power generators?



- More energy available than lasers
- Formation process yields quasi-neutral warm dense matter
- Large volume warm dense samples (best diagnostic capabilities)
- Smaller geometrical gradients

Gourdain at al. PPC (2014)

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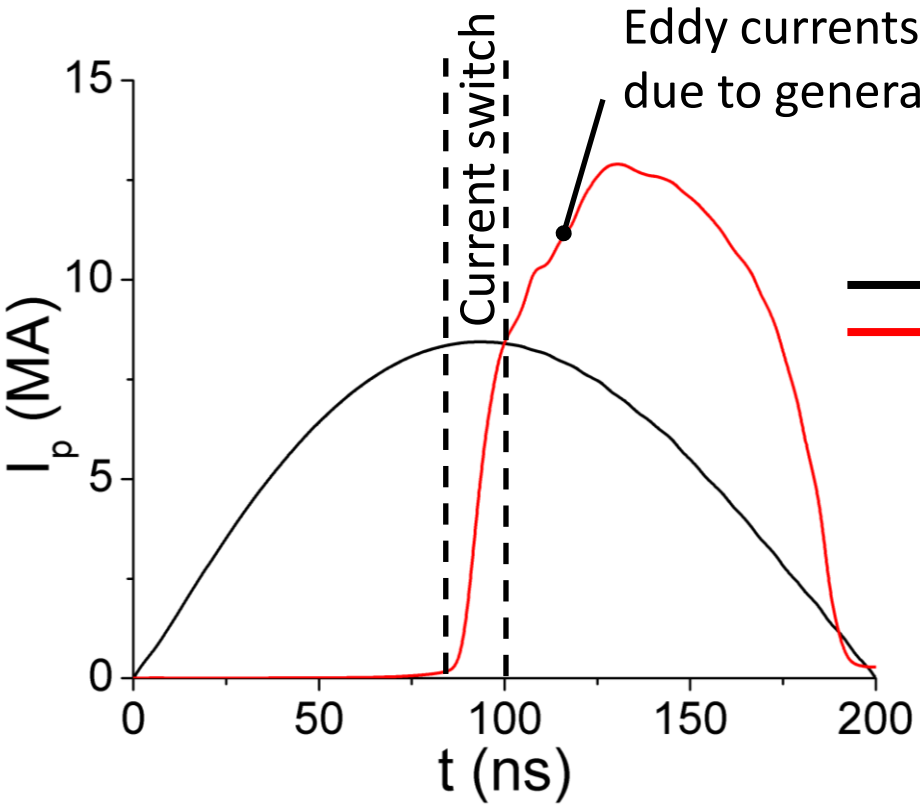
Fast current rise using plasma closing switch at 10MA



Eddy currents driven inside the rod due to generator current decay

Total discharge current

Rod current

High plasma conductivity promotes strong eddy currents inside the rod.

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Advancing the frontier of plasma science

- Can we design robust, experimental research platforms capable of generating high quality warm dense matter samples and diagnose them with great precision?
- Is it possible to develop **macroscopic** theories capable of capturing the microscopic, quantum nature of warm dense matter and incorporate these theories into numerical simulations that can predict the static and dynamic behavior of large systems?

New research tools

Experiments

- Design new experimental platforms to generate warm dense matter
- Couple pulsed power machines (compressor) to high intensity lasers, laser plasma acceleration or coherent light sources (diagnostics)
- Improve x-ray sources and detectors

Simulations

- New methods to encapsulate microscopic properties into macroscopic quantities
- New paradigms to handle non-equilibrium quantities
- More computational power is required but to handle more compact physics models NOT to compute first principle models using “brute force”

Conclusions

- Warm dense matter is at the frontier of plasma science “literally” at the frontier of plasma and condensed matter physics
- Warm dense matter science will help us understand the formation and evolution of gaseous giant planets, mega-earths or planetary collisions
- Impacts
  - The efficient, high energy density drivers required to produce warm dense matter can be used to generate HEDP or to develop inertial fusion energy.
  - High resolution, high gain gated x-ray detectors are essential to warn dense matter studies but are also indispensable to high energy physics or medicine.
  - The innovative physical models and numerical algorithms capable of predicting the properties of warm dense matter will yield new physical paradigms which can find applications in statistical mechanics or solve other types of multi-body problems.