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Pulsed power: A “precision hammer” for high energy density science

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Sandia National Laboratories

with many thanks to many collaborators

2021 Introduction to Fusion Energy and Plasma Physics Course

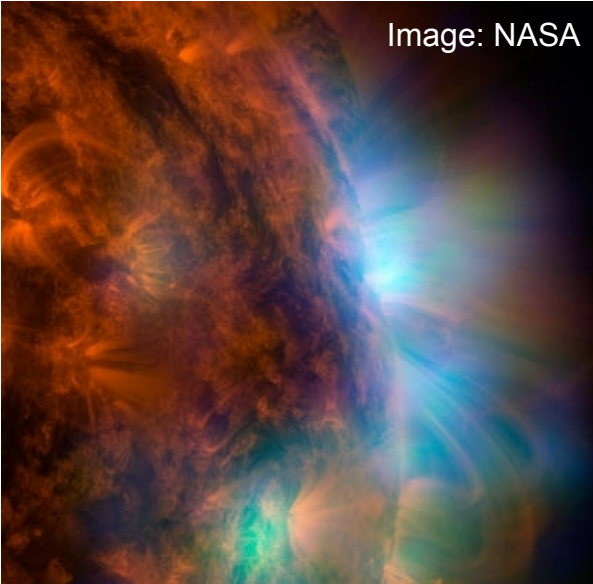
June 25, 2021



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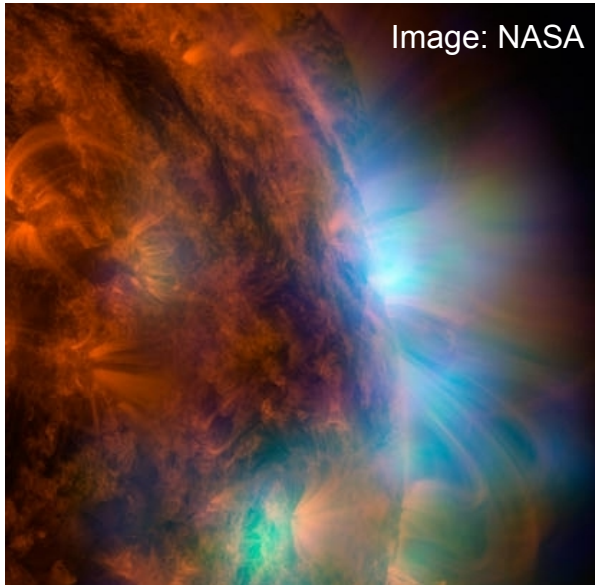
High energy density science has diverse applications and spans enormous ranges of time and length scales

Image: NASA

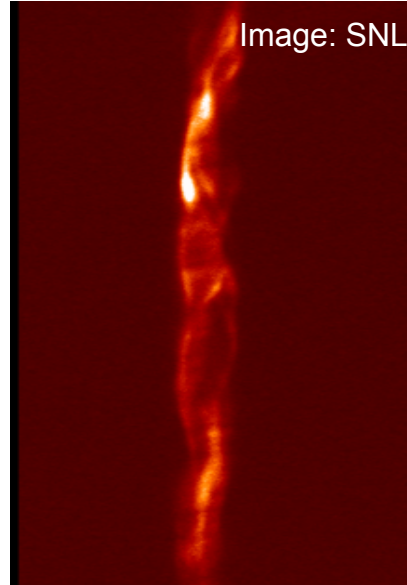


Astrophysics
 10^{+9} meters
 10^{+17} seconds

High energy density science has diverse applications and spans enormous ranges of time and length scales

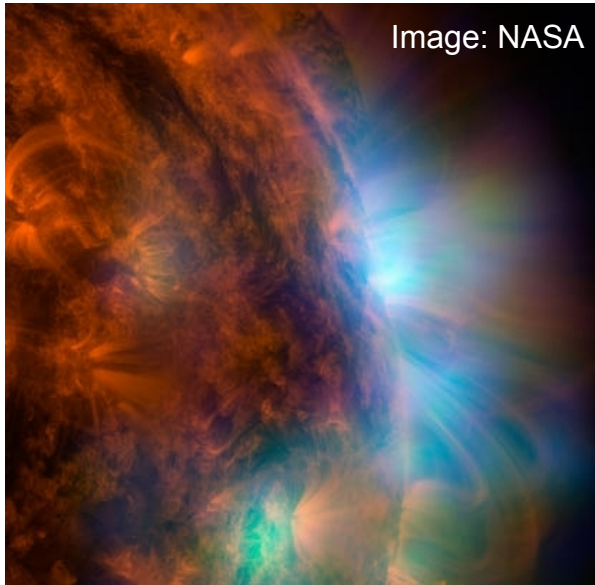


Astrophysics
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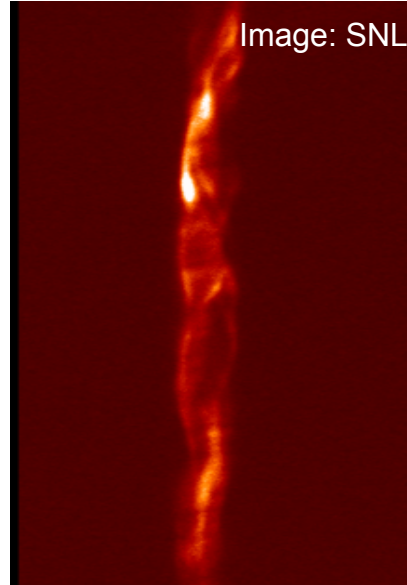


Fusion science
 10^{-4} meters
 10^{-9} seconds

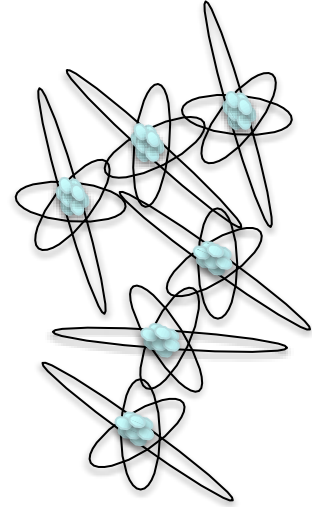
High energy density science has diverse applications and spans enormous ranges of time and length scales



Astrophysics
 10^{+9} meters
 10^{+17} seconds



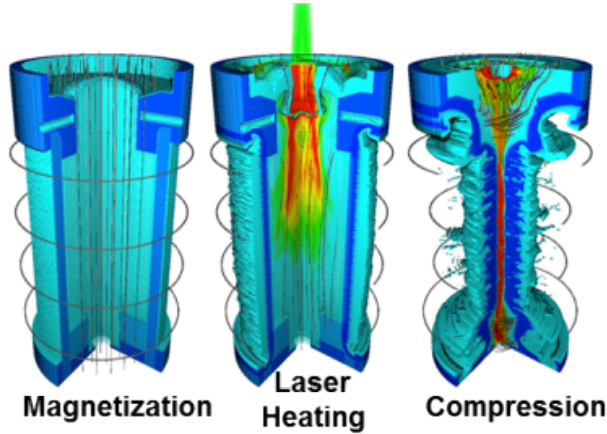
Fusion science
 10^{-4} meters
 10^{-9} seconds



Atomic physics
 10^{-10} meters
 10^{-14} seconds

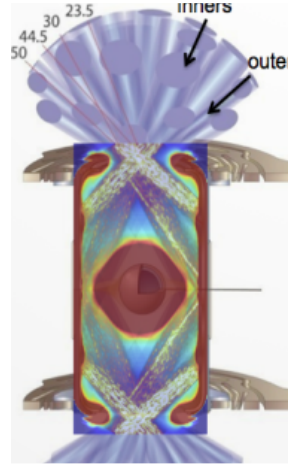
Understanding material and system behavior across scales is a key feature of HED science

High energy density matter is created in experimental facilities that compress energy in space and time



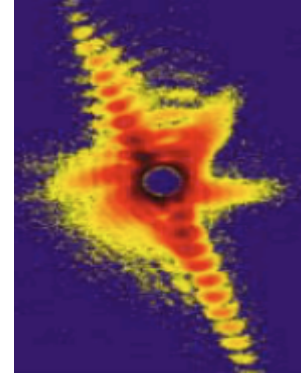
SNL's Z machine:

22 MJ \rightarrow 1 MJ in 10^{-7} s, 1 cm
~1 MJ/cc, ~10 TW/cc
~ 4% wall-plug efficiency



LLNL's NIF:

420 MJ \rightarrow 1.8 MJ in 10^{-8} s, 1 cm
~2 MJ/cc, ~200 TW/cc
~0.4% wall-plug efficiency

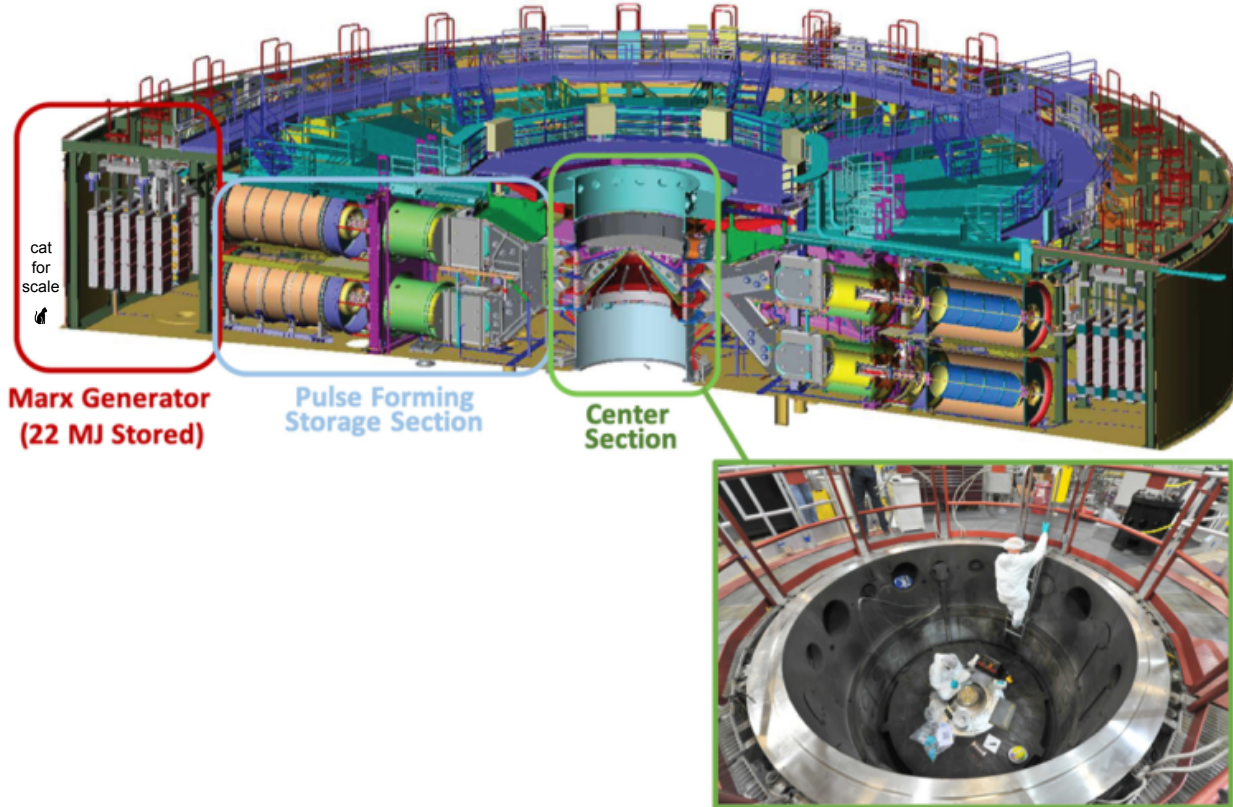


LCLS/ European XFEL:

2 mJ in 10^{-13} s, 10 μ m
~2 kJ/cc, ~20 PW/cc

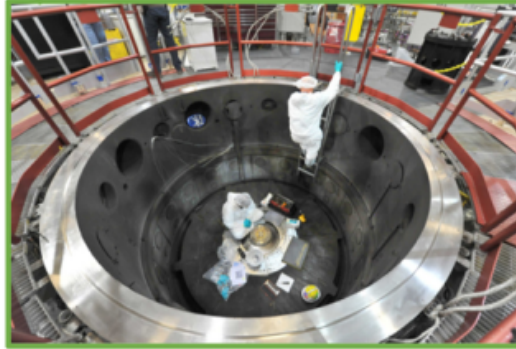
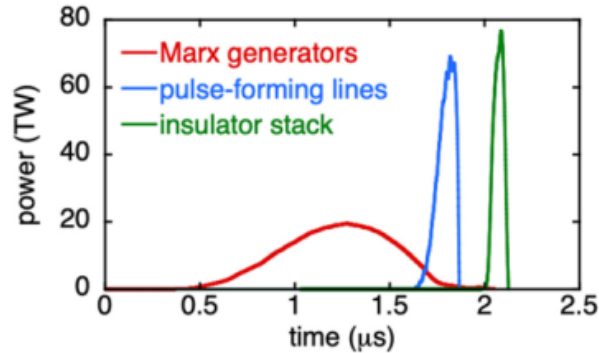
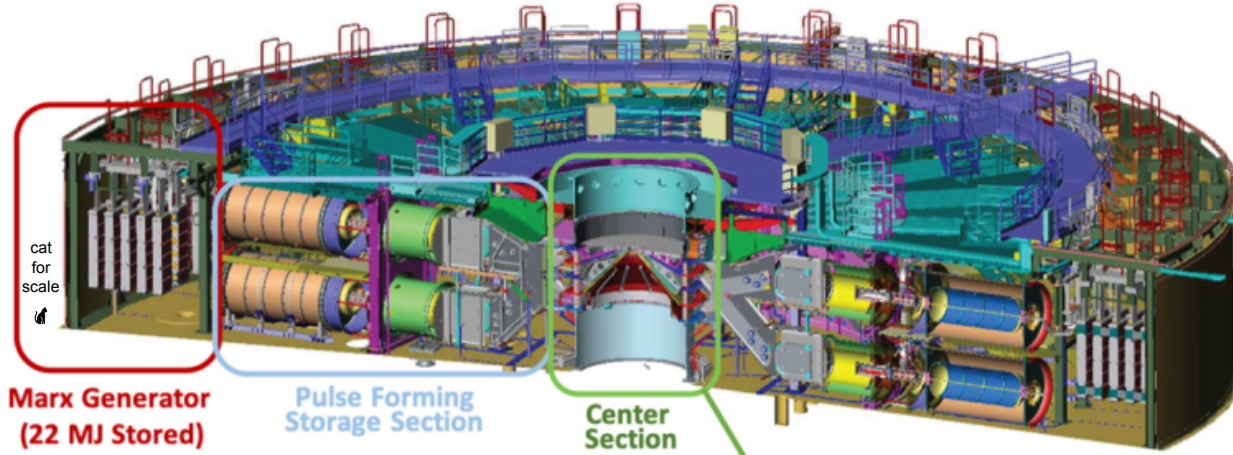
Pulsed power offers an efficient way to deliver large amounts of energy to relatively large samples

1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)

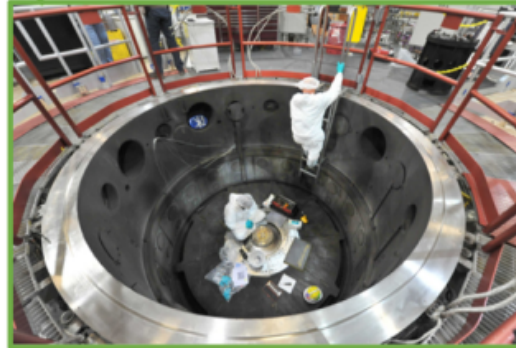
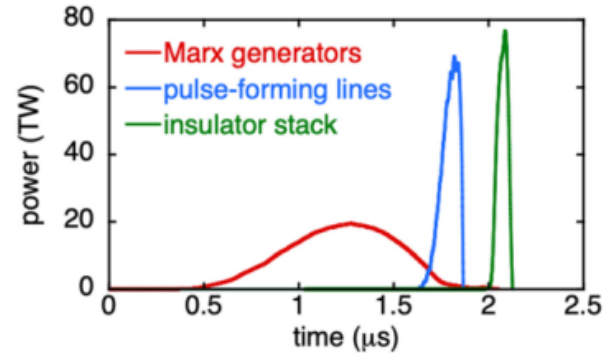
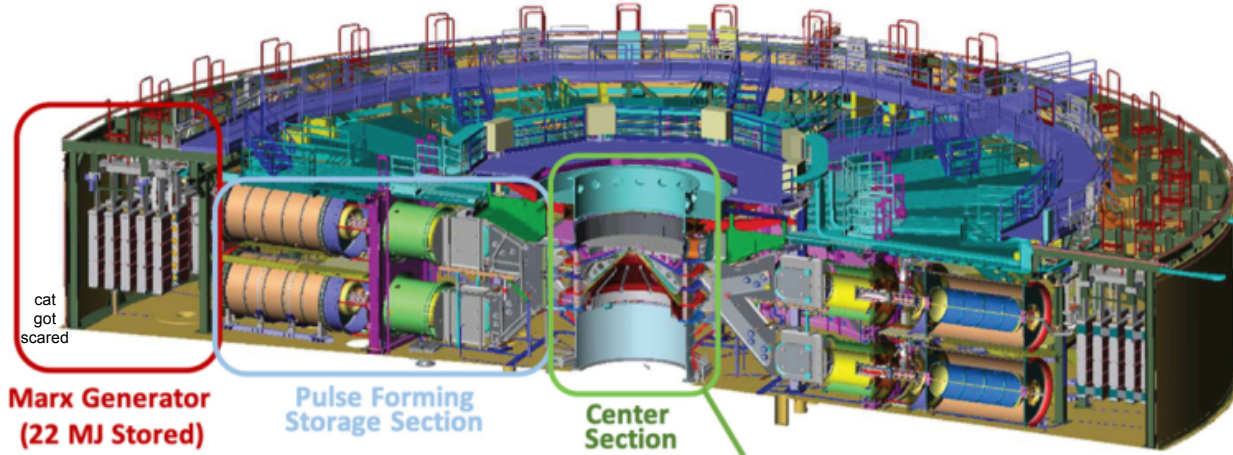


Pulsed power offers an efficient way to deliver large amounts of energy to relatively large samples

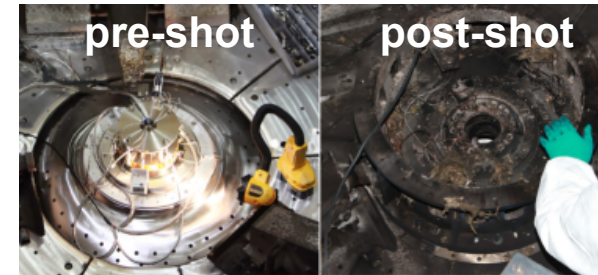
1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)
2. current j is compressed in space and time to $>20\text{MA}$ (>0.5 MJ to 1 cm in 100 ns)



Pulsed power offers an efficient way to deliver large amounts of energy to relatively large samples

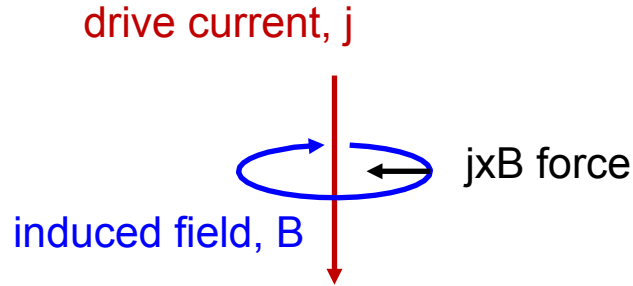


1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)
2. current j is compressed in space and time to $>20\text{MA}$ (0.5 MJ to 1 cm in 100 ns)
3. high energy density science! (the ground shakes)

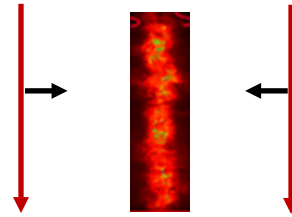


“Magnetic direct drive” uses the $\mathbf{j} \times \mathbf{B}$ force to deliver energy

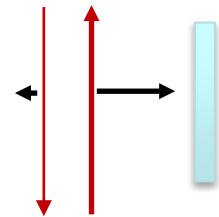
magnetic drive pressure $\sim (j/r)^2$



26 MA at $r = 1 \text{ mm} \rightarrow$
 $\sim 100 \text{ Mbar pressures}$

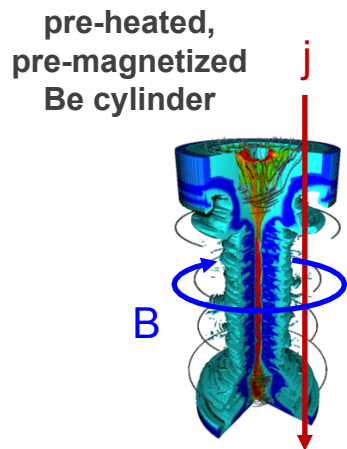


26 MA at $r \sim 50 \text{ mm} \rightarrow$
 $v \sim 1000 \text{ km/s}$

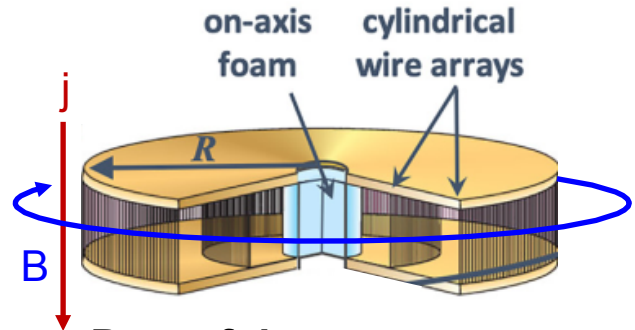


26 MA at $r \sim 1 \text{ mm} \rightarrow$
 $> \text{Mbar shocks}$

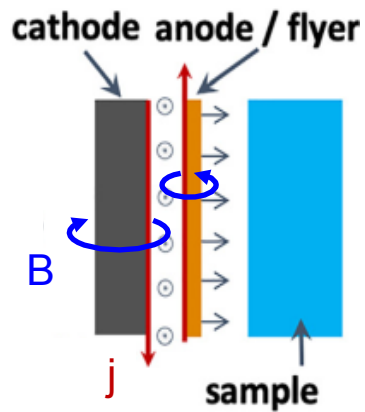
On Sandia's Z machine, we study a wide range of high energy density science using pulsed power



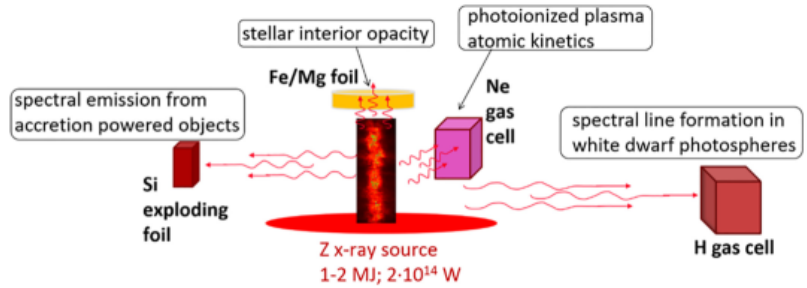
Magneto-inertial fusion
 jxB heats and compresses fusion fuel
 (~1 Gbar, > kJ yields)



Powerful x-ray sources
 jxB imparts kinetic energy
 (MJ & TW of x-rays)



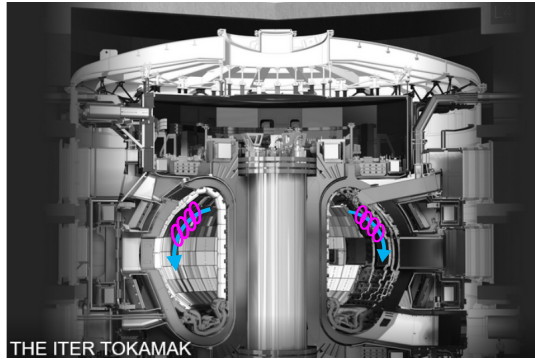
Materials science
 jxB provides shock or ramp compression
 (~10 Mbar)



X-rays drive lab-astro experiments

Magnetized Liner Inertial Fusion (MagLIF) combines aspects of magnetic and inertial confinement fusion

Lawson criterion: $P\tau > 50 \text{ bar-s}$ (and $T > 4 \text{ keV}$)



Magnetic fusion (ITER)

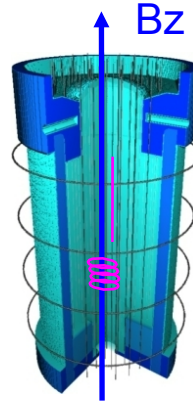
$R \sim 10 \text{ m}$

$P \sim 1 \text{ bar}$

$\tau > 10 \text{ s}$

$P\tau > 10 \text{ bar-s}$

Burn requires plasma
stability and high B



Magneto-inertial fusion (Z)

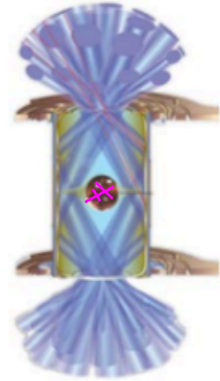
$R \sim 10^{-3} \text{ m}$

$P \sim 10^9 \text{ bar}$

$\tau \sim 10^{-9} \text{ s}$

$P\tau \sim 1 \text{ bar-s}$

Burn requires stability, high $Bz \cdot R$,
and high $\rho \cdot Z$



Inertial fusion (NIF)

$R \sim 10^{-5} \text{ m}$

$P \sim 10^{11} \text{ bar}$

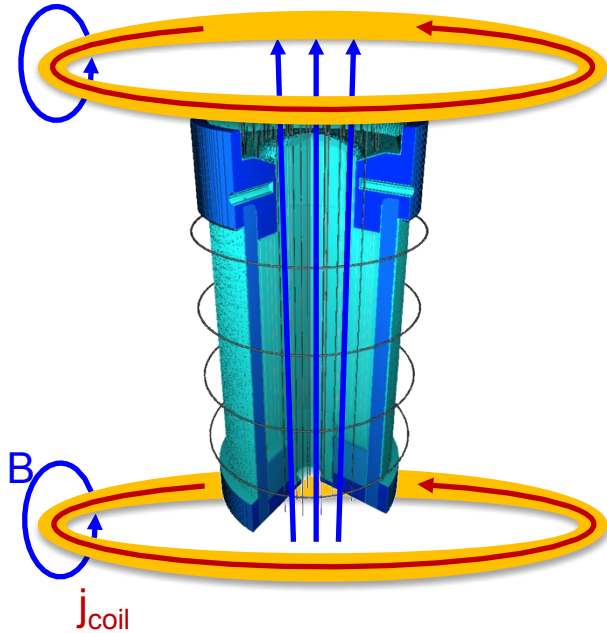
$\tau \sim 10^{-10} \text{ s}$

$P\tau \sim 10 \text{ bar-s}$

Burn requires implosion
stability and high $\rho \cdot R$

MagLIF's 3-stage design uses an imposed axial field and laser preheat to enable a relatively slow, stable implosion

$$B_z = 10 - 20 \text{ T}$$



Stage 1: pre-magnetize

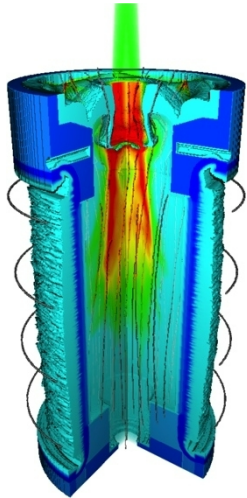
A ~1 cm beryllium liner is filled with fusion fuel and pre-magnetized using magnetic field coils

The imposed axial magnetic field prevents conduction losses that can cool the plasma below fusion temperatures

At stagnation, the imposed B field is flux-compressed to ~10 kT, effectively trapping charged fusion products

MagLIF's 3-stage design uses an imposed axial field and laser preheat to enable a relatively slow, stable implosion

$$E_{\text{laser}} = 1 - 2 \text{ kJ}$$



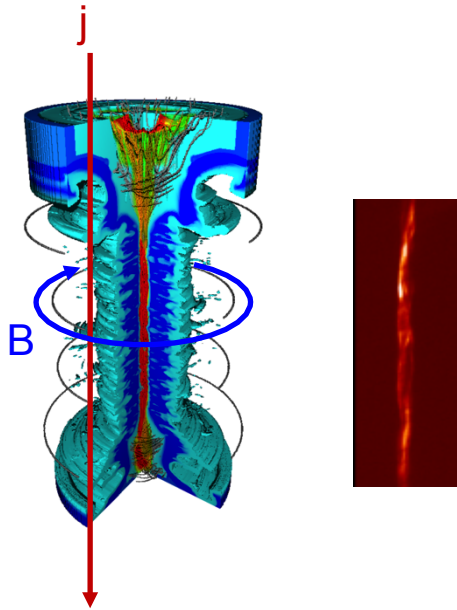
Stage 2: pre-heat the fuel

The 4kJ Z-Beamlet laser penetrates a thin window and preheats the fuel core to $T \sim 200 \text{ eV}$, reducing implosion velocities and convergence required to reach fusion temperatures

While the axial B-field effectively prevents conduction losses, even small amounts of window mix can lead to radiative losses that cool the preheated plasma

MagLIF's 3-stage design uses an imposed axial field and laser preheat to enable a relatively slow, stable implosion

$$j = 15 - 21 \text{ MA}$$



Stage 3: compression

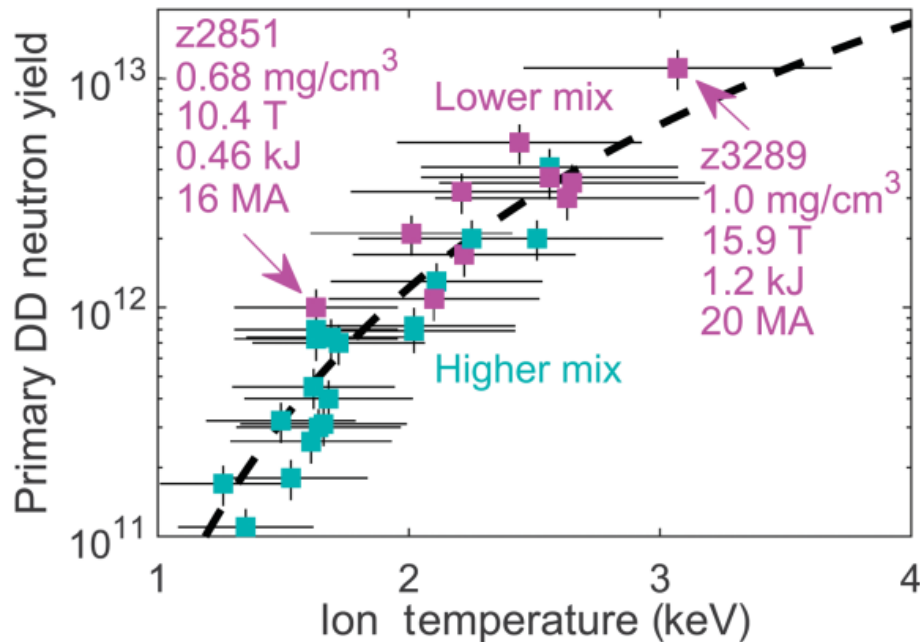
The Z machine delivers a compressional force that implodes the liner, axial field, and fuel at $v \sim 100 \text{ km/s}$

At stagnation, relatively stable plasma columns with helical structure yield $\sim 10^{13}$ D-D neutrons (10^{15} D-T or 2 kJ)

Neutron diagnostic indicate high magnetization sufficient to trap $\sim 50\%$ of charged fusion products

X-ray diagnostics indicate $T \sim 3 \text{ keV}$, $\tau \sim 1 \text{ ns}$, and $P \sim 1 \text{ Gbar}$

We can vary experimental parameters to investigate mix, stability, and yield scaling

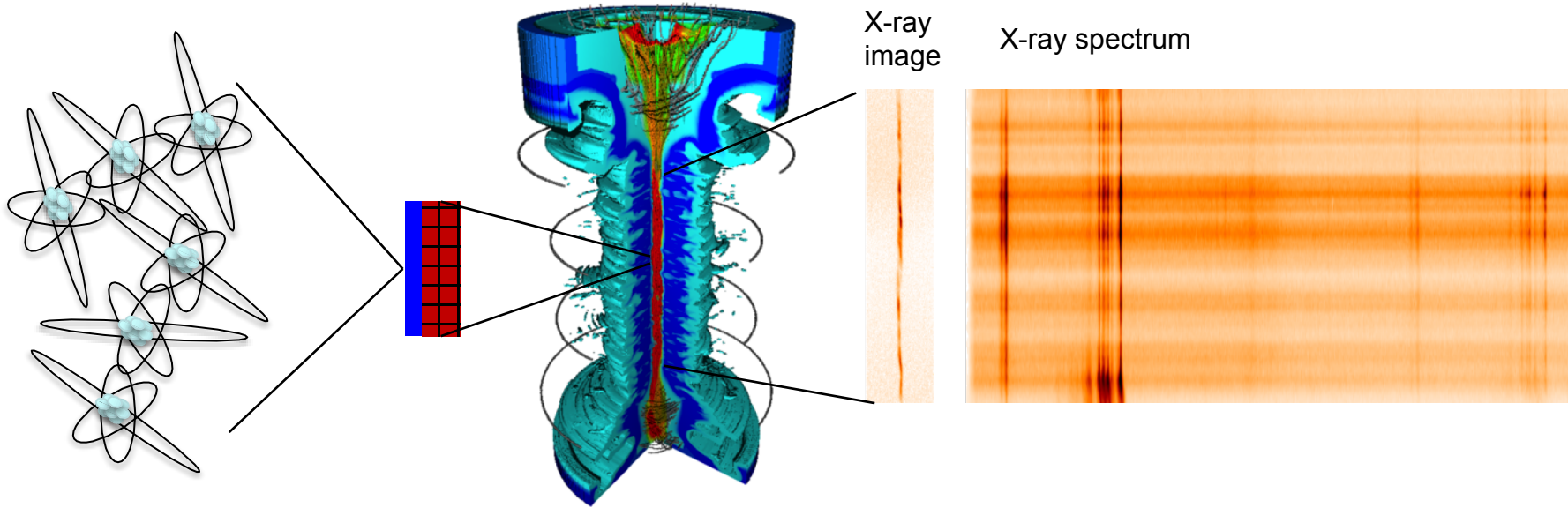


$j(\text{MA})$	$E_{\text{laser}}(\text{kJ})$	$B_z(\text{T})$	$Y(\text{kJ})$	Z
15	0.5	10	0.2	
20	1.2	20	2	
22	6	30	80	
60	30*	30	>1000	

The efficiency of pulsed power opens paths to controlled high-yield fusion

*Experiments at NIF are ongoing, along with “mini-MagLIF” at LLE

A detour into x-ray spectroscopy, which couples the very small (atoms) with the large (lab plasmas) or very large (stars)

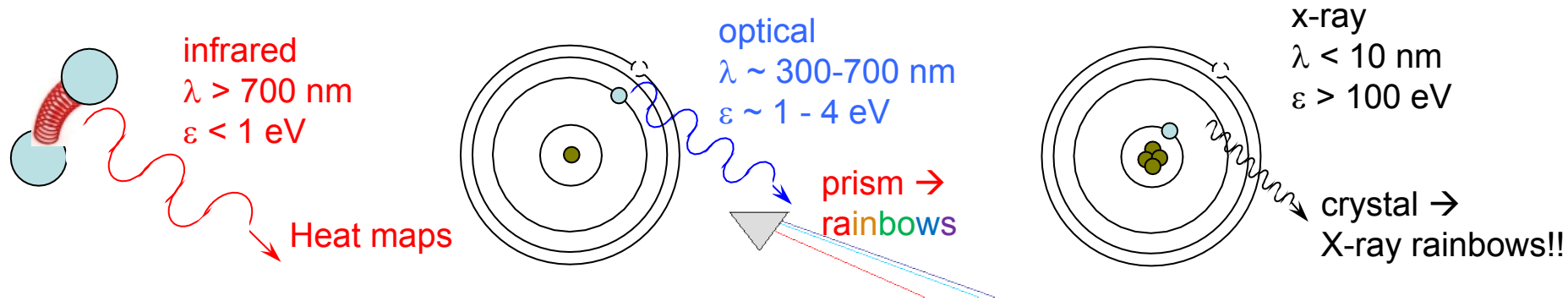


If we understand the atomic-scale response of materials in extreme conditions,

then we can more reliably predict and control HED targets using simulations...

...and we can more rigorously interpret experimental data

Spectroscopy is the science of measuring and interpreting the photons emitted and absorbed by molecules, atoms, and ions



The history of spectroscopy is intricately linked to the history of modern physics

- **atomic physics and quantum mechanics**

much of what we know about matter was learned through spectroscopy

- **astrophysics and cosmology**

“spectroscopy puts the ‘physics’ in astrophysics!”

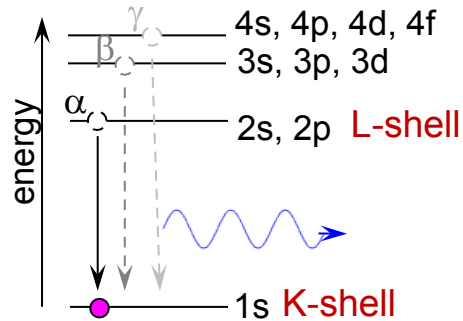
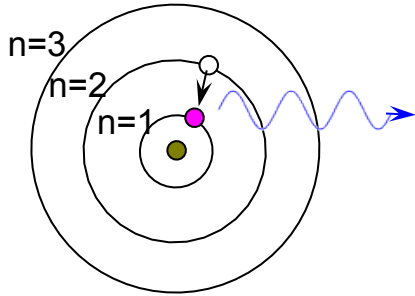
- **plasma physics and fusion research**

spectroscopic diagnostics reveal details of temperature, density, fields...

Each ion of each element has a spectroscopic “fingerprint”

Bohr model:

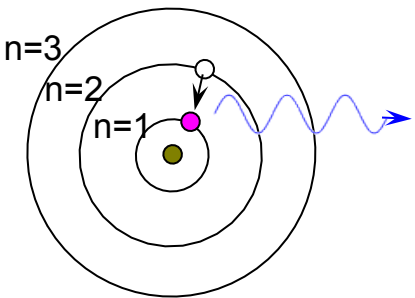
$$\epsilon_n \sim 13.6 \text{ eV } (Z_{\text{eff}}/n)^2$$



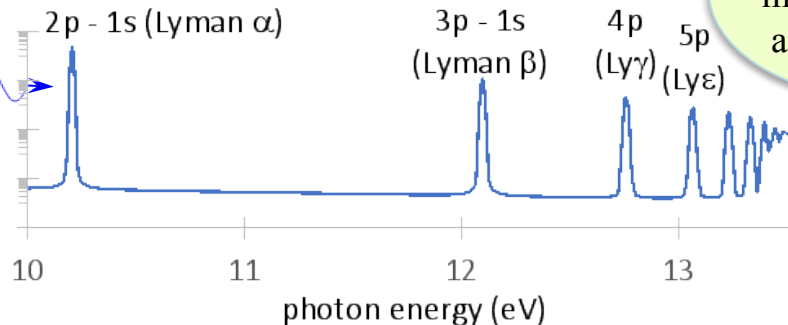
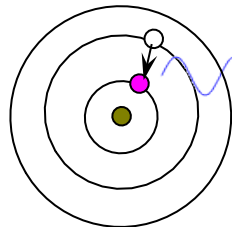
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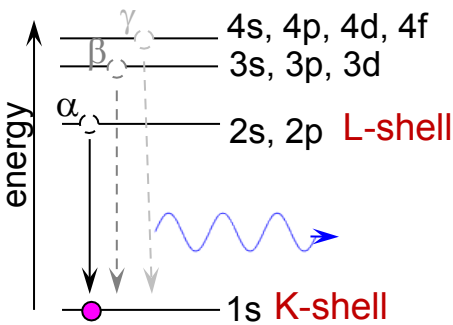
$\epsilon_n \sim 13.6 \text{ eV } (Z_{eff}/n)^2$



neutral hydrogen ($Z_{eff} = 1, n = 1$)
K-shell $h\nu = \Delta\epsilon \sim 10 \text{ eV}$



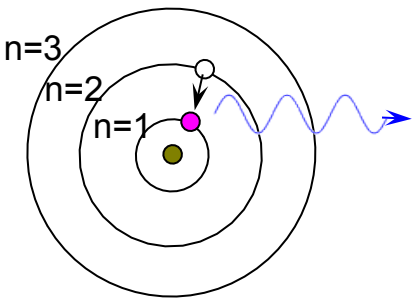
This plasma is mostly hydrogen and pretty cold.



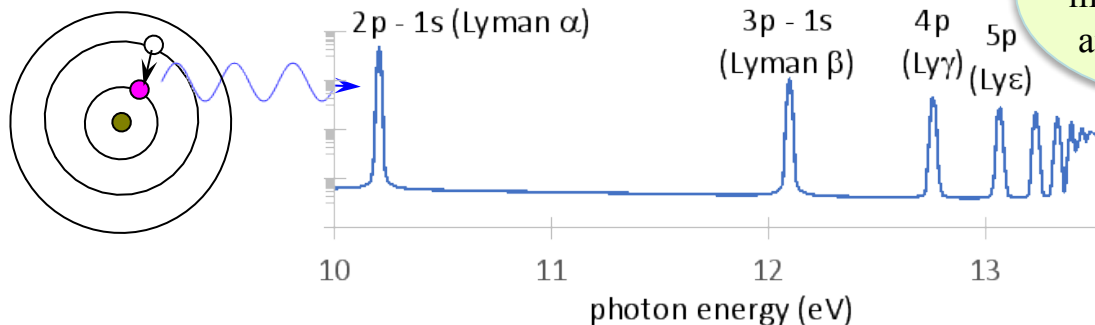
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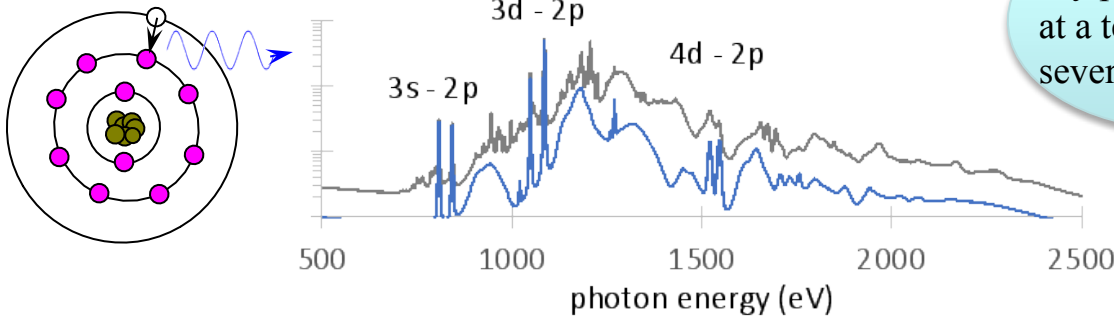
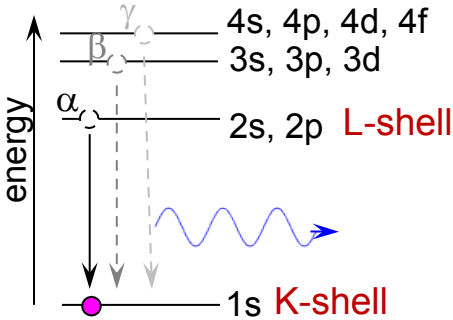
neutral hydrogen ($Z_{eff} = 1, n = 1$)
K-shell $h\nu = \Delta\epsilon \sim 10 \text{ eV}$



This plasma is mostly hydrogen and pretty cold.



neon-like iron ($Z_{eff} = 16, n = 2$)
L-shell $h\nu = \Delta\epsilon \sim 1000 \text{ eV}$

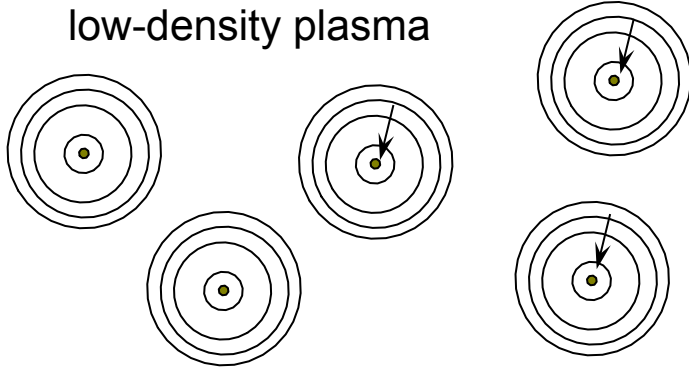


My plasma has iron at a temperature of several hundred eV!

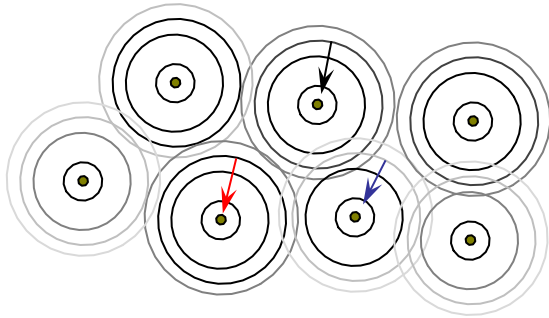


High-density environments modify electronic structure and spectroscopic signatures

low-density plasma

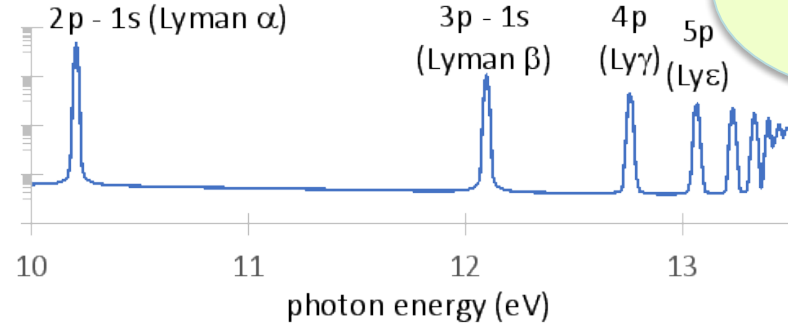
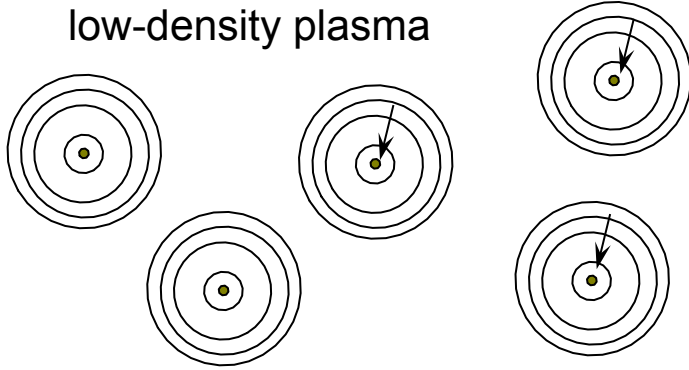


high-density plasma



High-density environments modify electronic structure and spectroscopic signatures

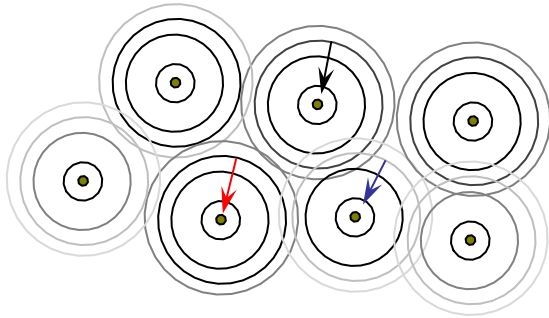
low-density plasma



yawn

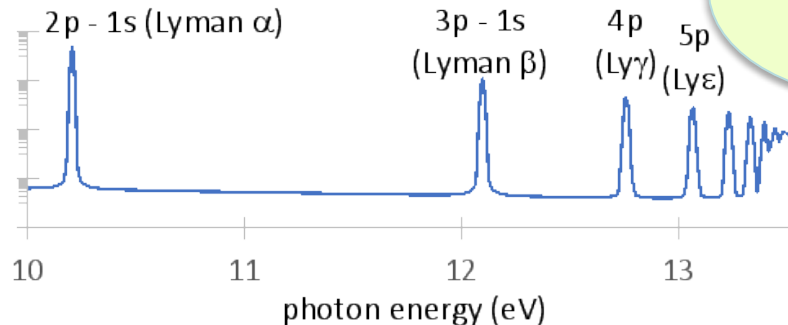
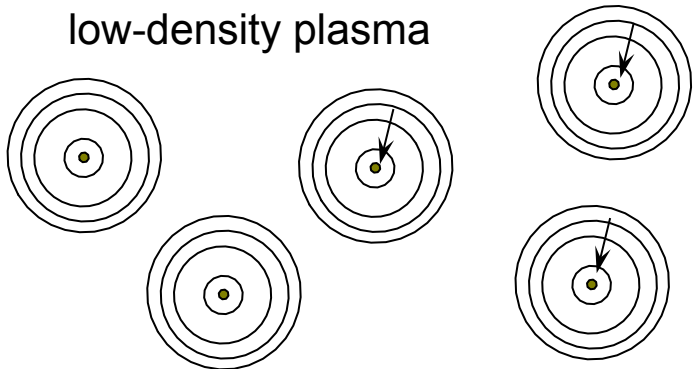


high-density plasma



High-density environments modify electronic structure and spectroscopic signatures

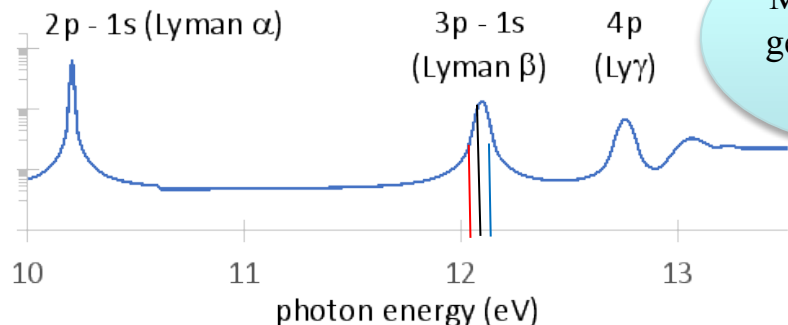
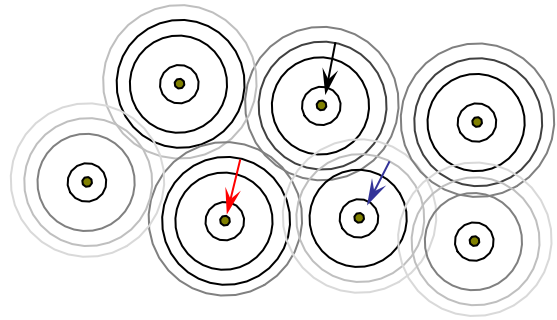
low-density plasma



yawn



high-density plasma

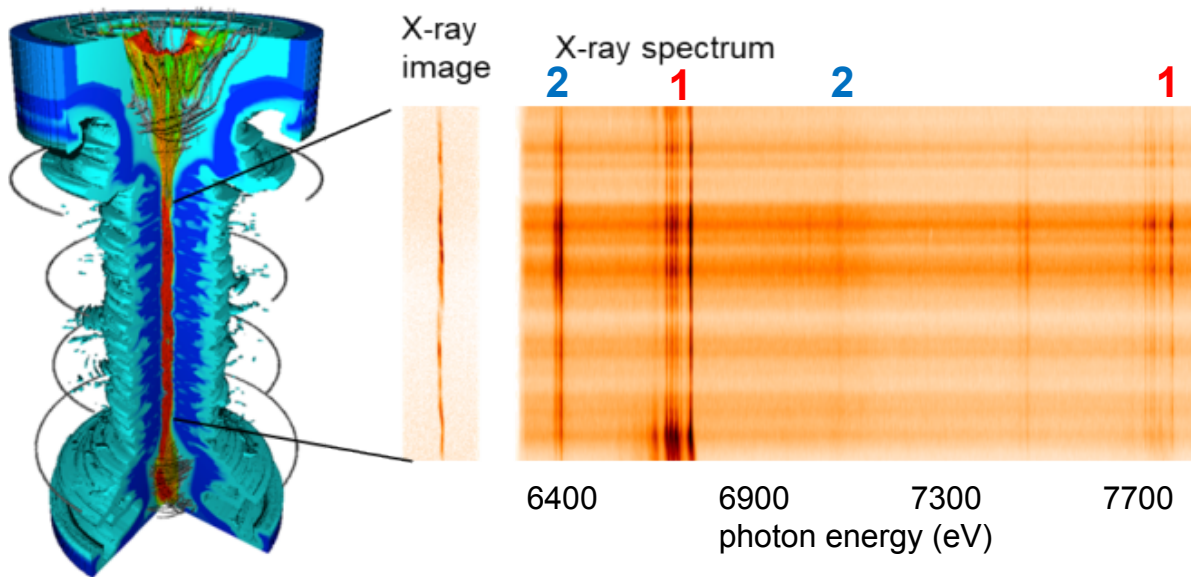


My hydrogen is getting squished pretty hard!



What does the spectrum from a MagLIF experiment tell us?

MagLIF is a Be liner with ~ 100 ppm Fe impurities surrounding a pure-D2 fuel core



1. He-like iron K-shell lines:
some of the liner mixes
with the hot fuel in a layer
with $n_e \sim 10^{23}$ e/cc and
 $T_e \sim 2000$ eV
2. Neutral iron K-shell lines:
most of the liner is cold
(~ 10 eV) and very dense
(10x solid): the iron is
photoionized by radiation
from the hot core

This plasma has
multiple elements
and big gradients.



How do we know if our atomic-scale models are reliable?

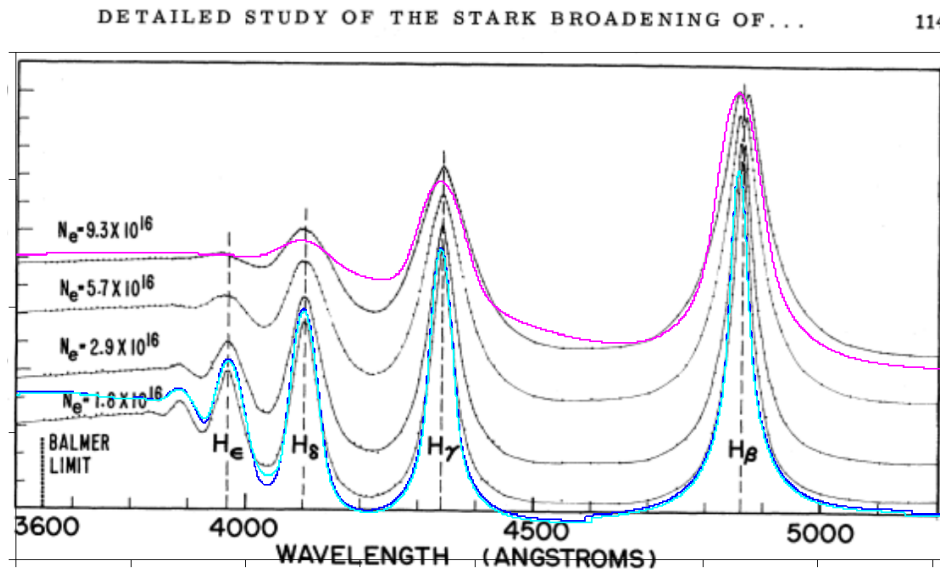
We can test them in careful, “benchmark” experiments with plasma samples that are:

1. designed to be relatively uniform
2. independently characterized
3. carefully diagnosed

Wiese, Kelleher, and Paquette, *Phys. Rev. A* **6**, 1132 (1972)

Hydrogen at $T \sim 2$ eV:

one of perhaps 5 high-quality benchmark data sets!

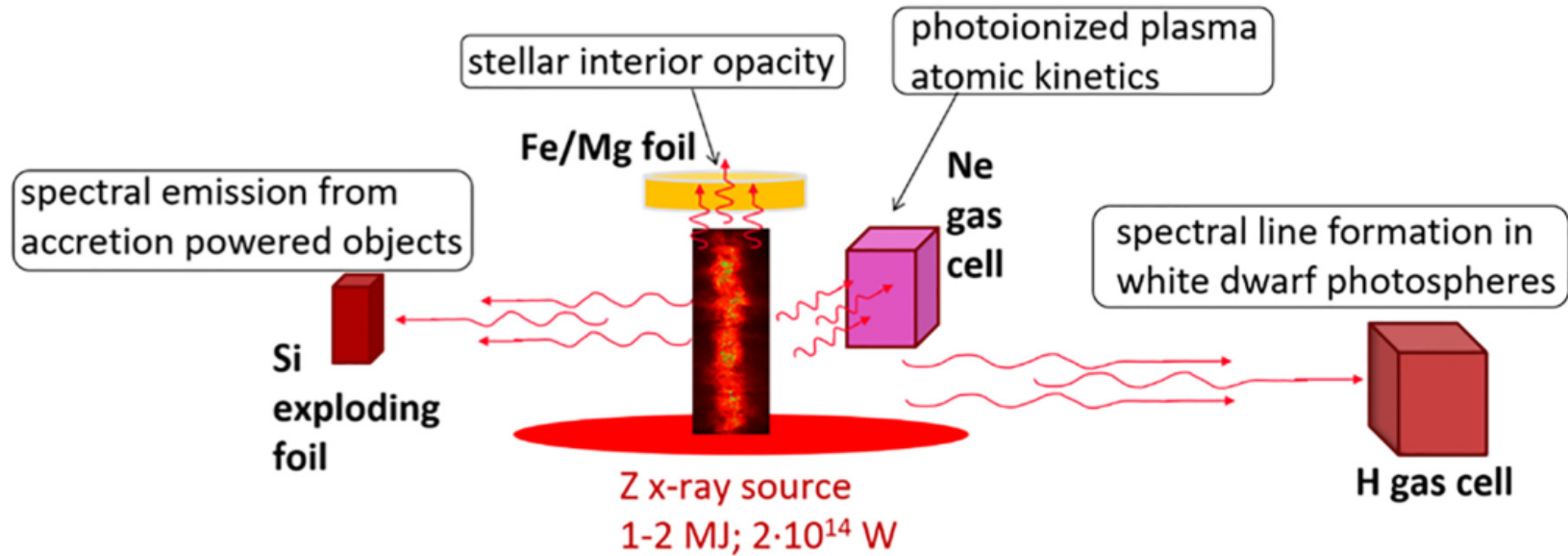


High-quality benchmark experiments are difficult but *enduring* (and highly cited!)

The closer you get to literal “benchmark” experiments (a lump of iron on your bench), the better!

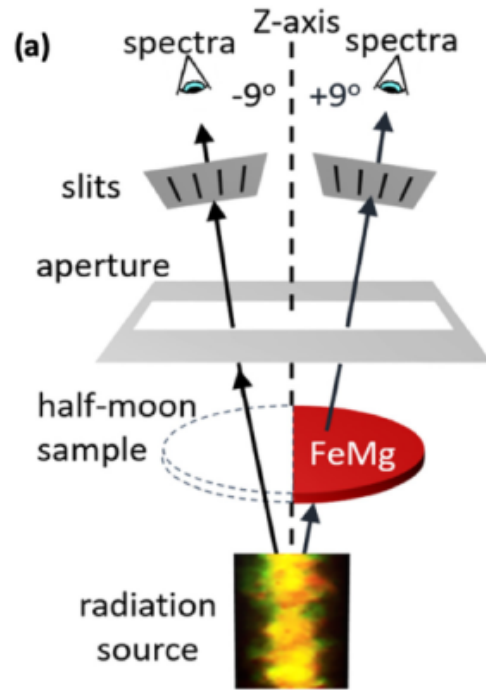
Opportunity: warm dense matter (WDM) is experimentally accessible and computationally complex

The Z Astrophysical Plasma Properties (ZAPP) collaboration aims to benchmark extreme, astrophysically relevant plasmas

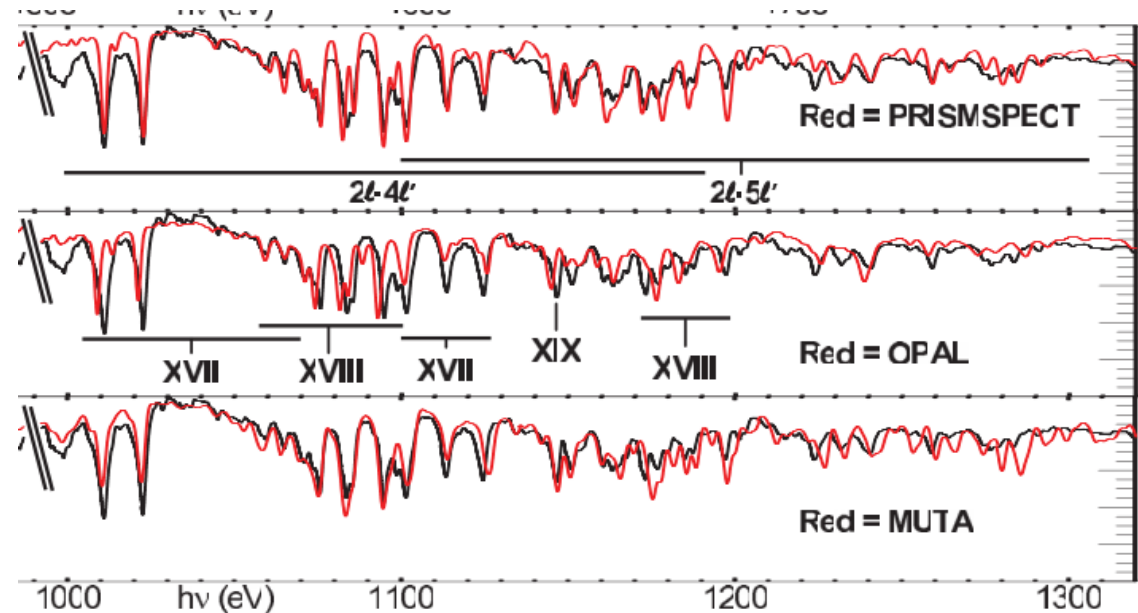


A consortium of Laboratory and University scientists use the TW x-ray powers from the Z machine to heat, photoionize, and backlight benchmark plasmas

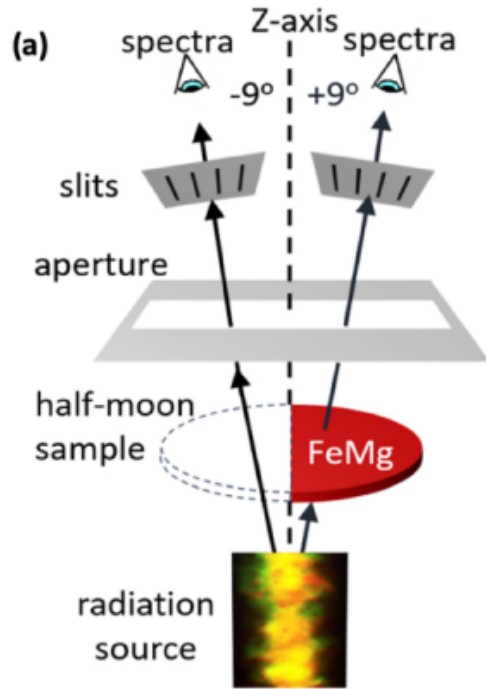
Benchmark measurements of stellar interior opacities inform models of our sun (helioseismology, elemental abundances)



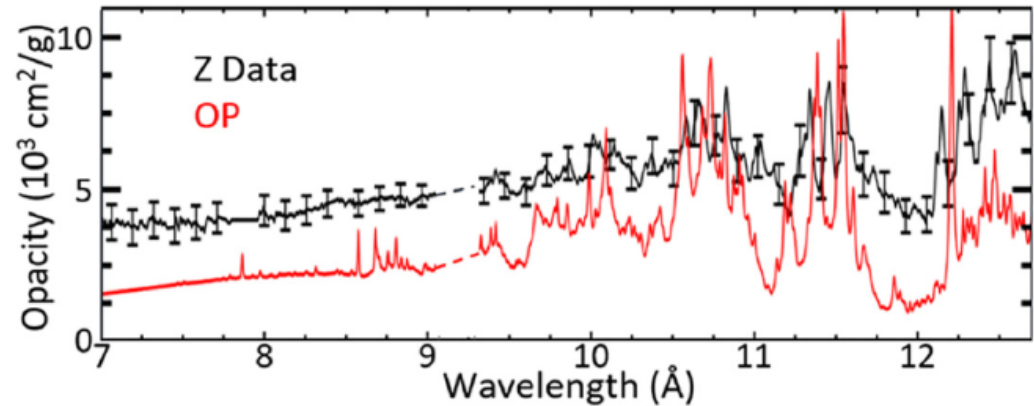
In 2007, Bailey et al found good agreement between models and experiments for iron at temperatures and densities slightly lower than that at the solar radiation/convection zone boundary:



Benchmark measurements of stellar interior opacities inform models of our sun (helioseismology, elemental abundances)



After a refurbishment of the Z machine enabled experiments at higher densities and temperatures, Bailey et al found surprising disagreement between models and experiments

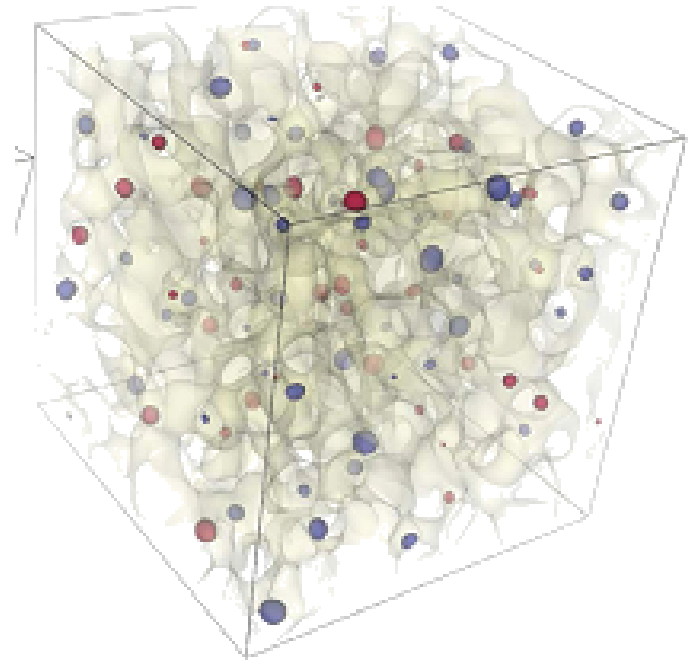


This is one of only a handful of benchmark experiments for high energy density plasmas: we will be surprised again!

Extensions of Density Functional Theory (DFT) offer a promising path for improving atomic-scale models

Density functional theory solves 3D multi-center Schrodinger equations for fixed ion positions; Zero-temperature DFT has long been used in solid-state and chemical physics to predict material structure.

Extending DFT to $T > 0$, incorporating time-dependent perturbations (e.g. X-ray free-electron laser pulses), and increasing “observable” predictions from DFT models is an exciting frontier for high energy density science!



High energy density science with pulsed power relies on strong ties with larger communities

Thanks, rad-
hydro & PIC
communities!

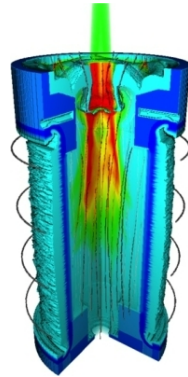
Machine & target
simulations

Thanks, atomic &
condensed matter
communities!

Fundamental
material
properties

MagLIF preheat &
x-ray backlighting

Thanks, laser
community!



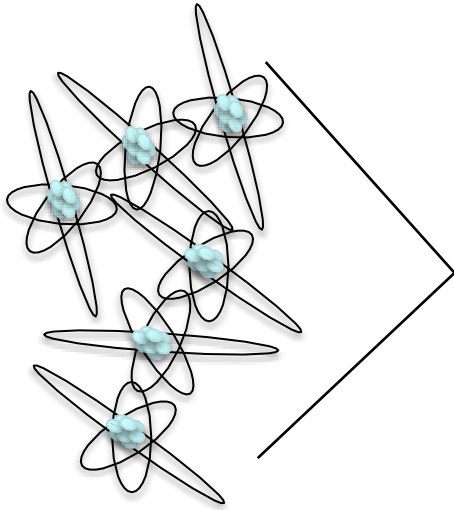
X-ray and neutron
yields, images, and
spectra

Thanks,
diagnostics
community!

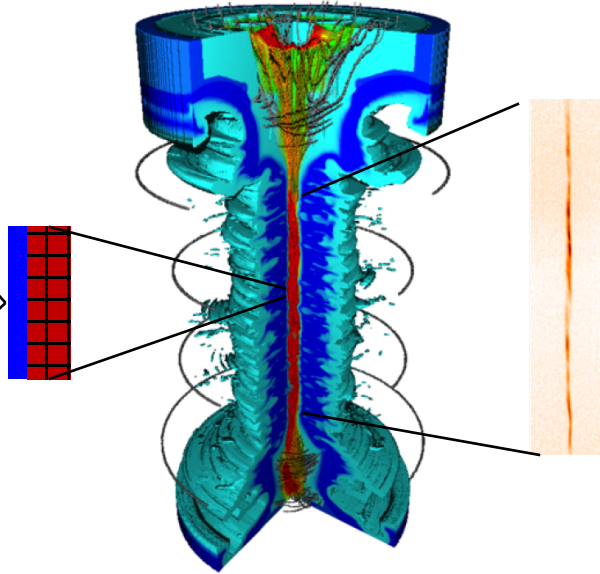
Target fabrication,
advanced computing,
astrophysics, MFE...?

Thanks, essential
(& potential)
communities!

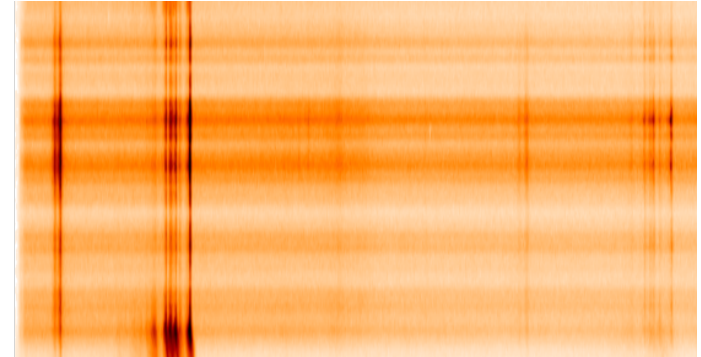
There are lots of opportunities in high energy density science: we hope you join us!



Can we accurately
model atomic-scale
processes in exotic
environments?



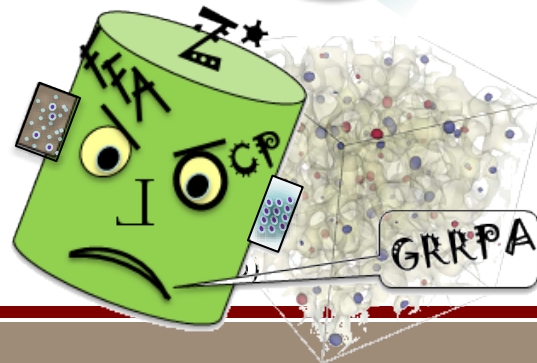
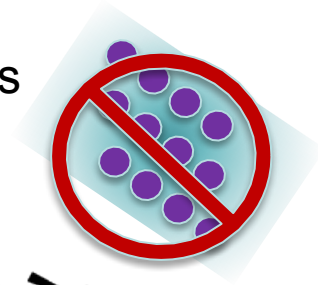
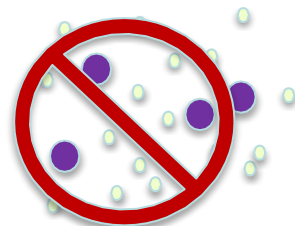
Can we reliably predict
the performance and
scaling of inertial fusion
targets?



Can we design and perform
benchmark experiments that test our
understanding and open new
windows to exotic worlds?

What's so difficult about modeling extreme conditions?

- HED plasmas are (usually) not well described by classical plasma models
 - Partial ionization complicates simple ion + electron pictures
 - Degeneracy effects invalidate classical statistics
 - Density effects distort quantum orbitals
 - Ions can be strongly coupled
- HED plasmas are (almost) never well described by solid-state models
 - Even modest temperatures can open enormous state space
 - Simplifications of ionic and electronic behavior are suspect
- Rigorous and reliable models exist, but...
 - Quantum Molecular Dynamics (QMD)
 - Time-dependent Density Functional Theory (TD-DFT)
 - Computationally expensive and difficult to extend to high temperatures, low densities, and complex ions

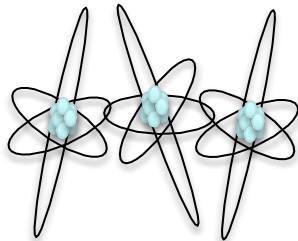


Central question: What happens to material when you squish it very hard and/or heat it quite a lot?

Experiments/Observables

Measurements from small, short-lived lab plasmas and large, distant astrophysical objects are inherently challenging

Observables (yields, images, spectra) can be difficult to interpret and may require both adequate material models and complex simulations



Simulations

“Magneto-radiation-hydrodynamic” simulations are used to design experiments and help interpret data from laboratory and astrophysical plasmas

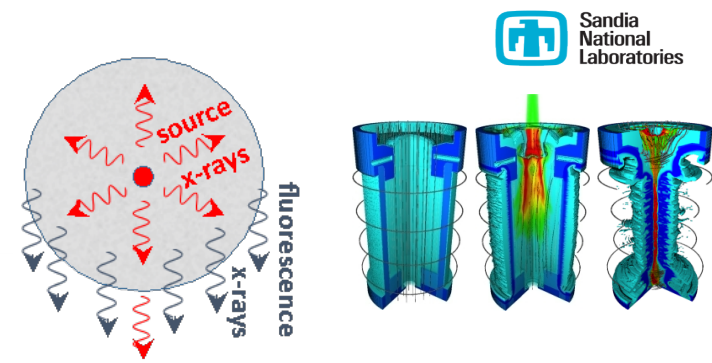
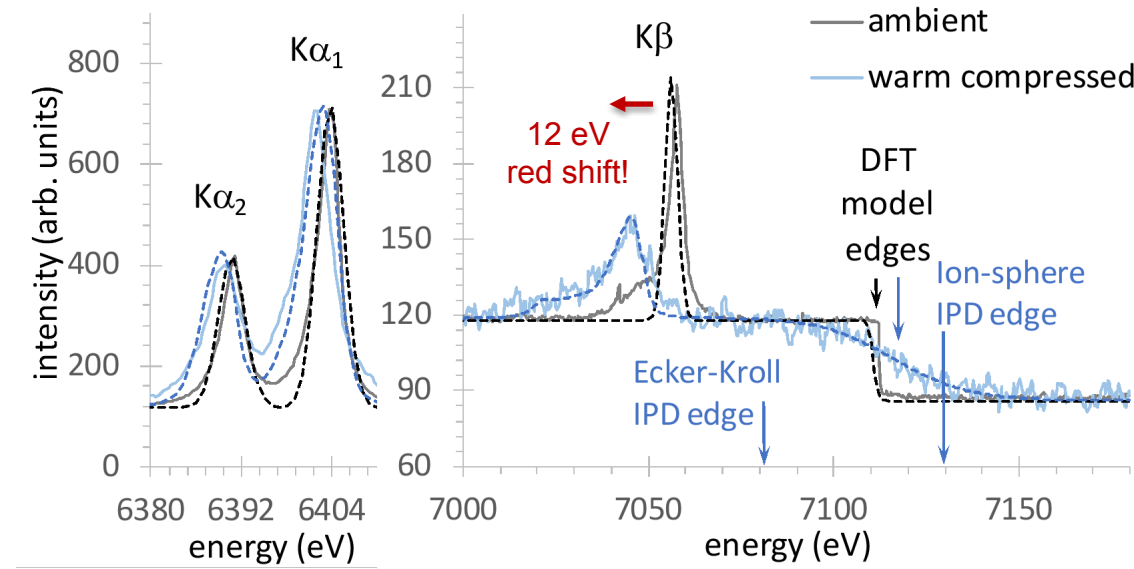
Reliable simulations themselves require extensive input from adequate material models (EOS, transport, opacity)

Additional questions:

How can we tell if our models are right?

How important is model consistency?

Observables in extreme WDM: absorption edges and fluorescence lines



Calculations (dashed lines) anchored to the K-edge of ambient data (solid gray) show good agreement with line and edge shifts and broadening due from a warm compressed MagLIF liner backlit by stagnation emission (solid blue) with $T \sim 10$ eV and $n_e \sim 2 \times 10^{24}$ e/cc.

This agreement indicates that self-consistent DFT models describe electronic structure in extreme conditions with better fidelity than ad-hoc models of density effects.