Pulsed power: A "precision hammer" for high energy density science

Stephanie Hansen

Sandia National Laboratories

with many thanks to many collaborators

2021 Introduction to Fusion Energy and Plasma Physics Course

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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My path to the privilege of being paid to solve puzzles:

Wendy's

Alpha Analytical

University of Nevada, Reno

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Lawrence Livermore National Laboratory

Sandia National Laboratories

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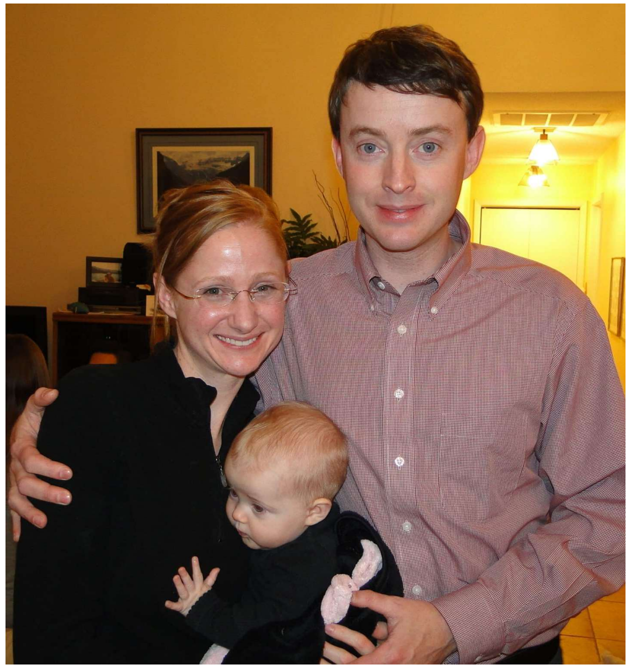

I owe a lot to family, mentors, colleagues, and friends

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

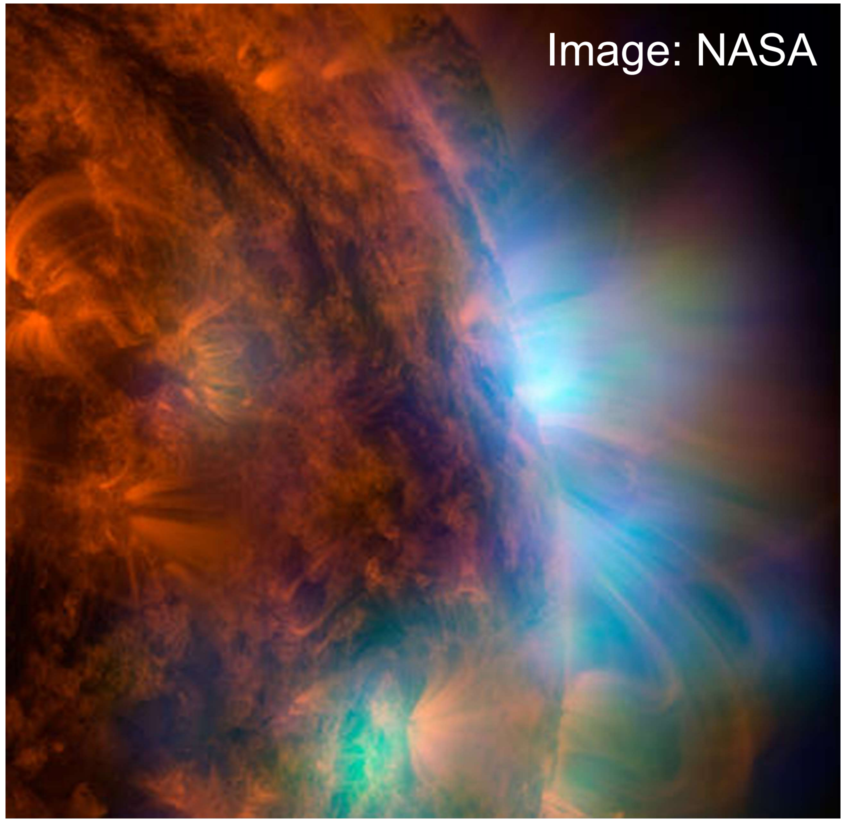
Image: NASA

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

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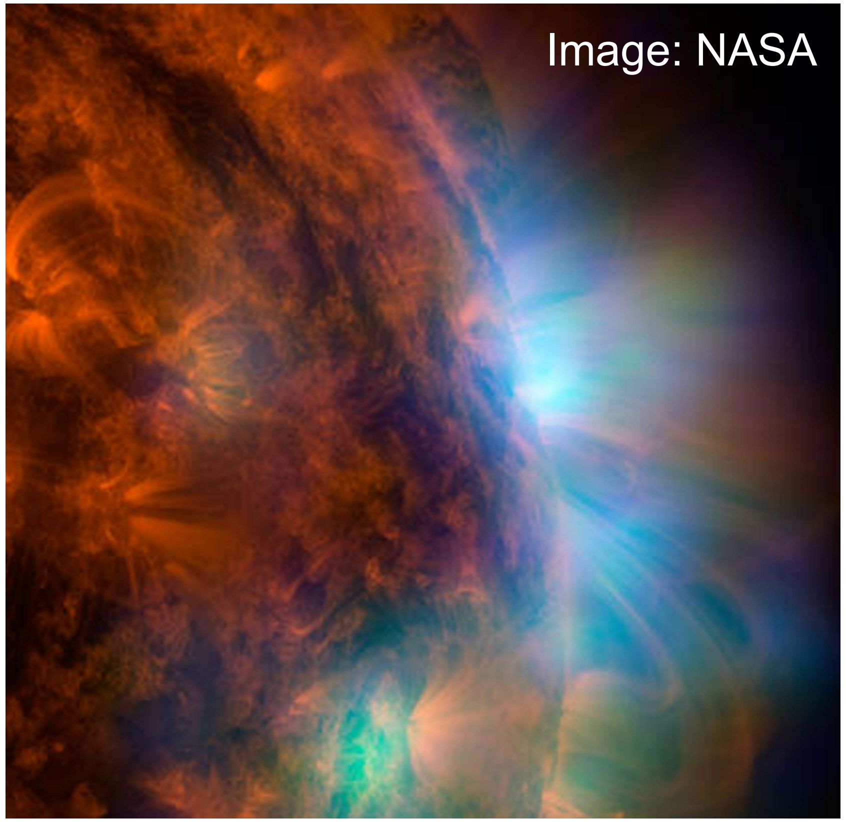
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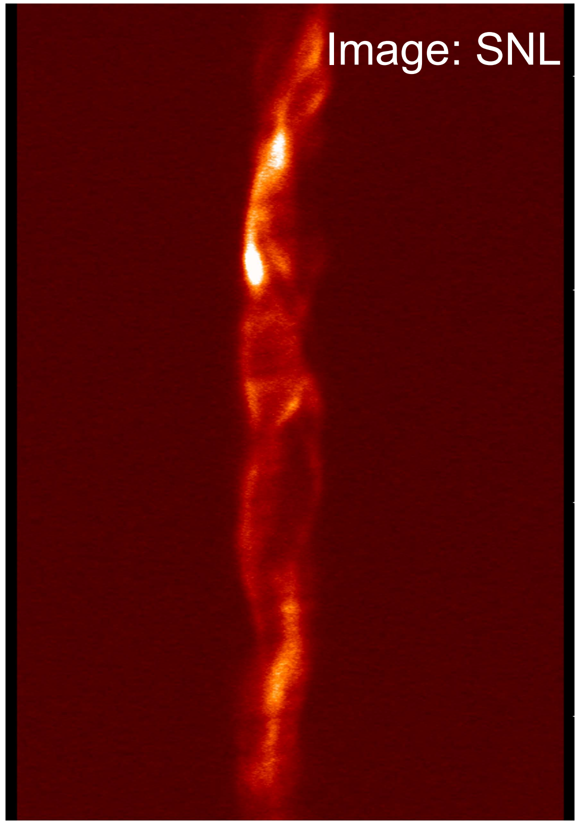
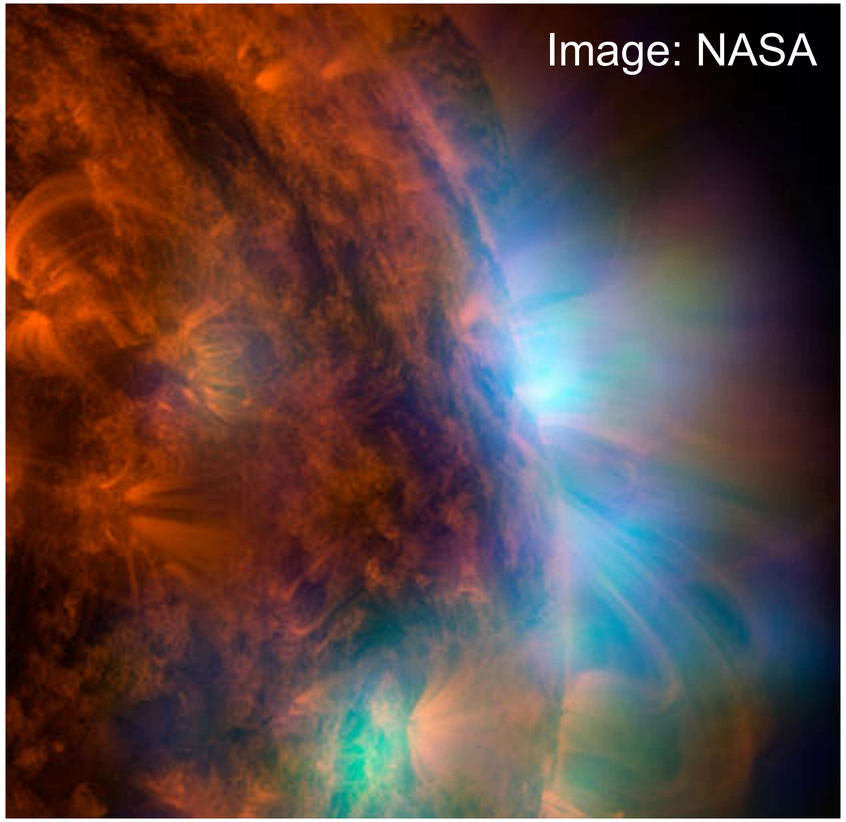


Image: SNL

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

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



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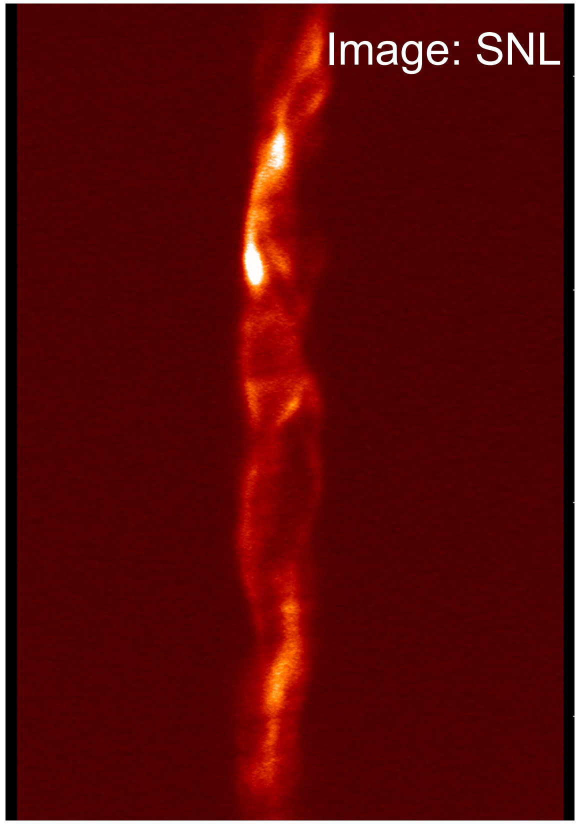

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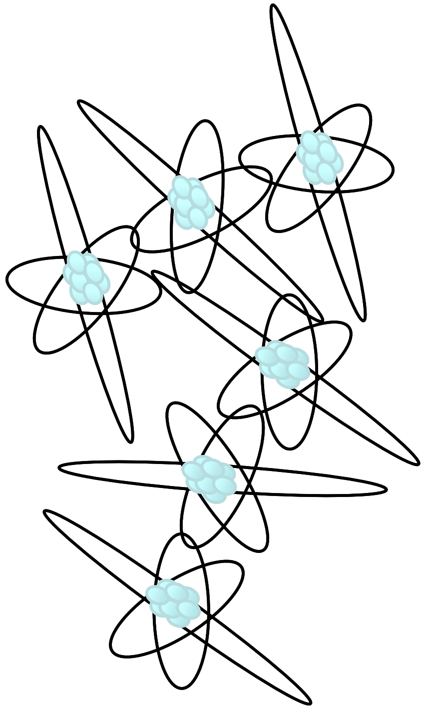
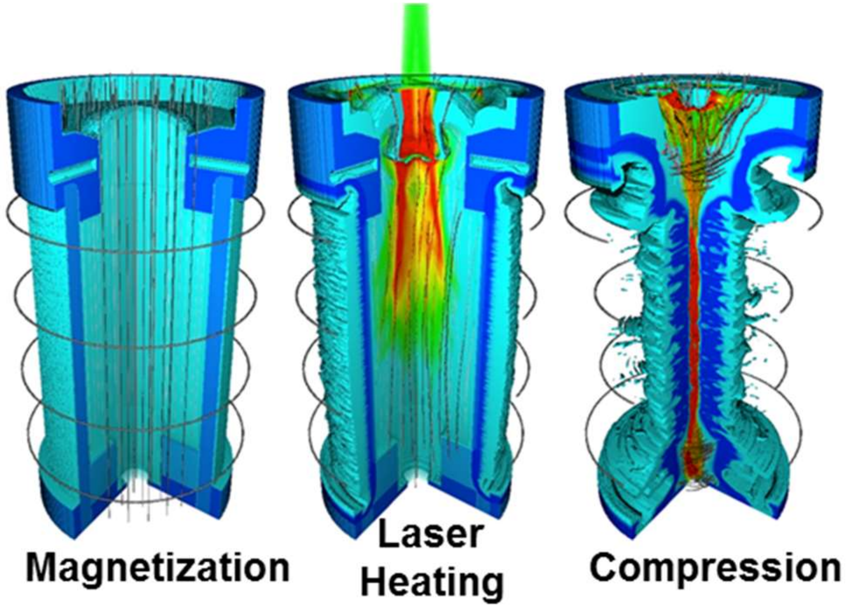
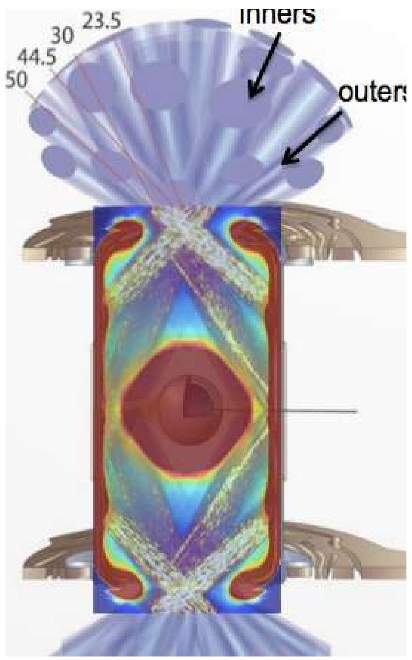


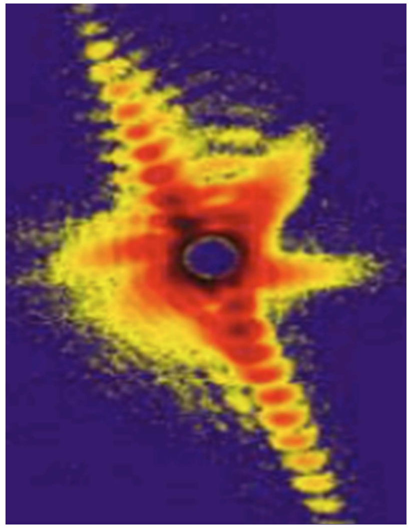
Atomic physics
10^{-10} meters
10^{-14} seconds

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





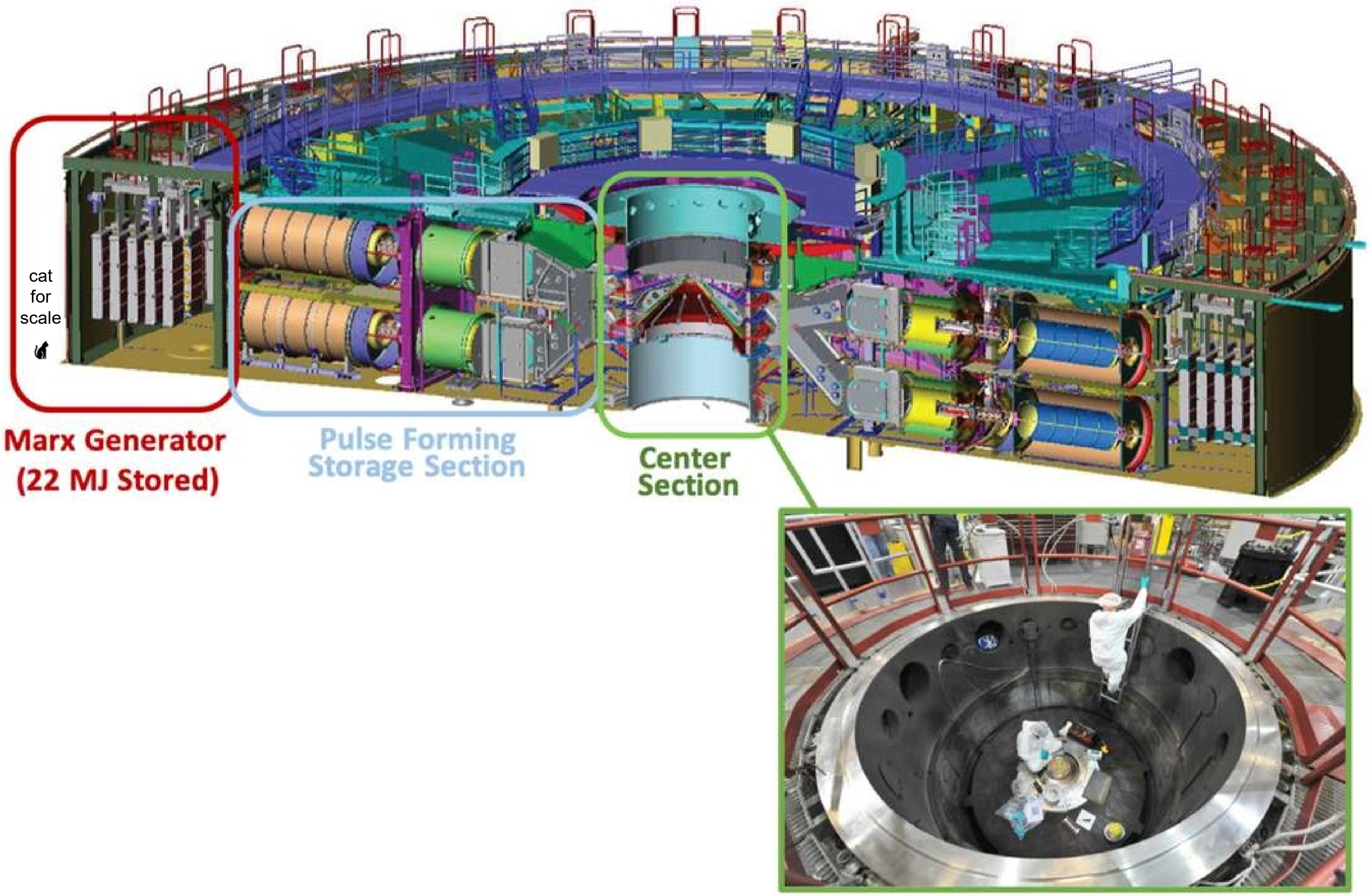


SNL's Z machine:
22 MJ → ~1 MJ in 10^{-7}s, 1 cm
~1 MJ/cc, ~10 TW/cc
~ 4% wall-plug efficiency

LLNL's NIF:
420 MJ → 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 μm
~2 kJ/cc, ~20 PW/cc

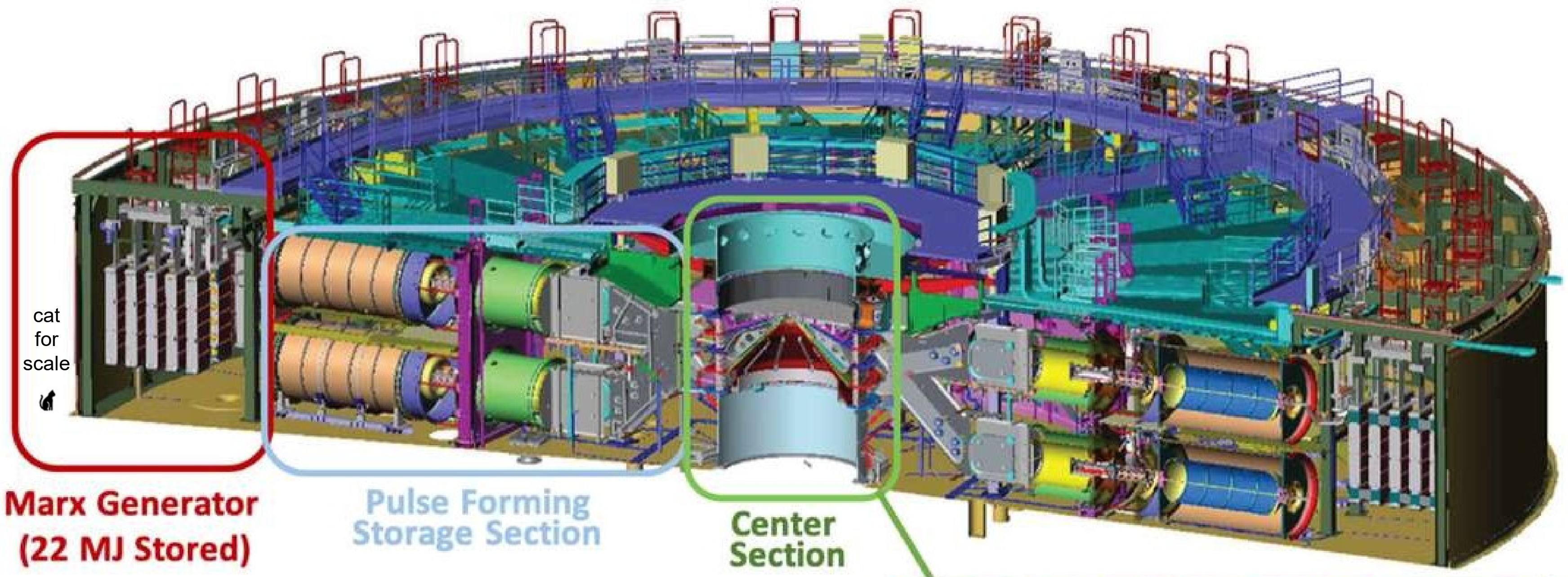
Pulsed power offers an efficient way to deliver large amounts of energy to relatively large samples

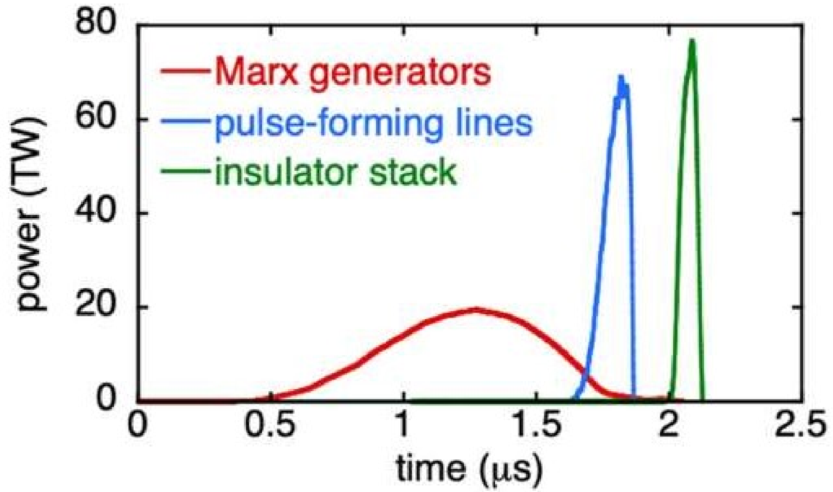


1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)

From Sinars et al, Phys Plasmas 27, 070501 (2020)

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 >20MA (>0.5 MJ to 1 cm in 100 ns)

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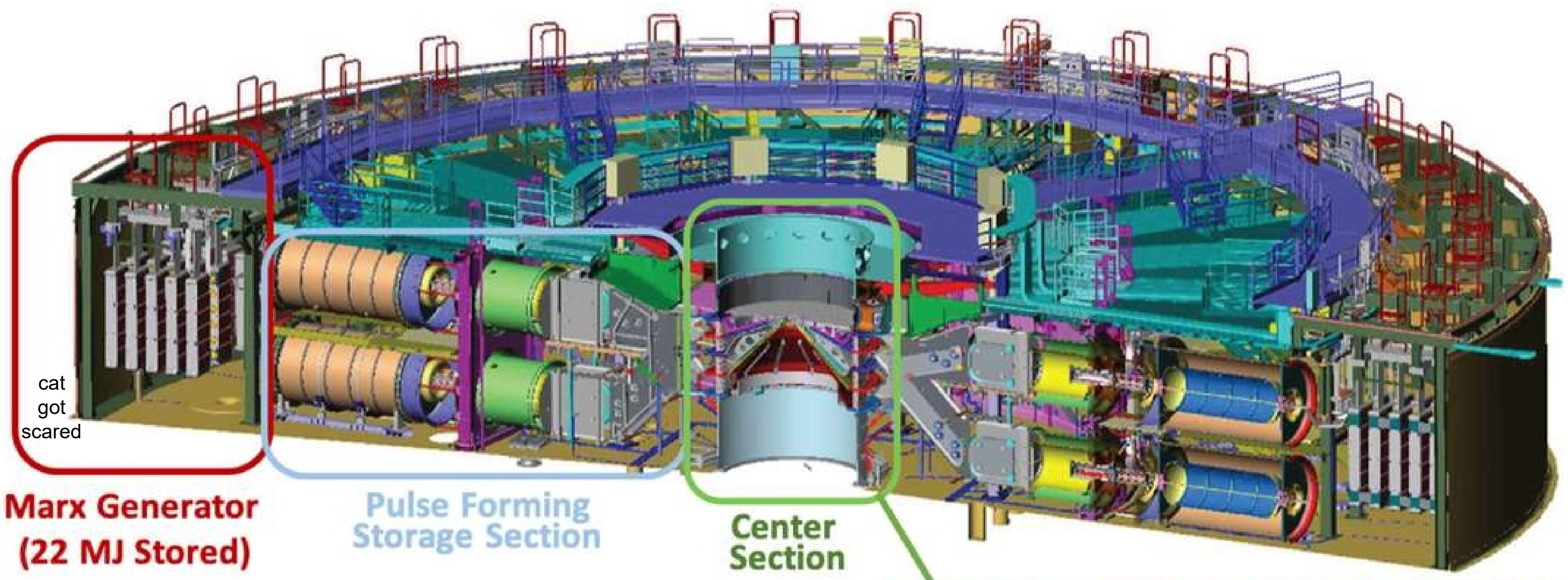
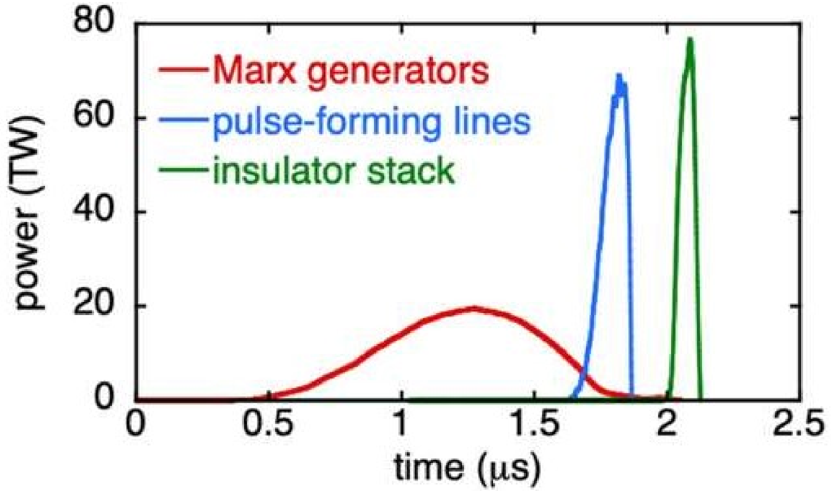
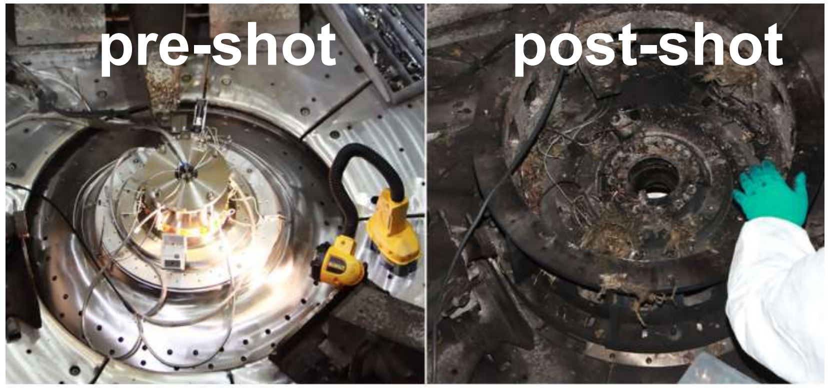
Pulsed power offers an efficient way to deliver large amounts of energy to relatively large samples





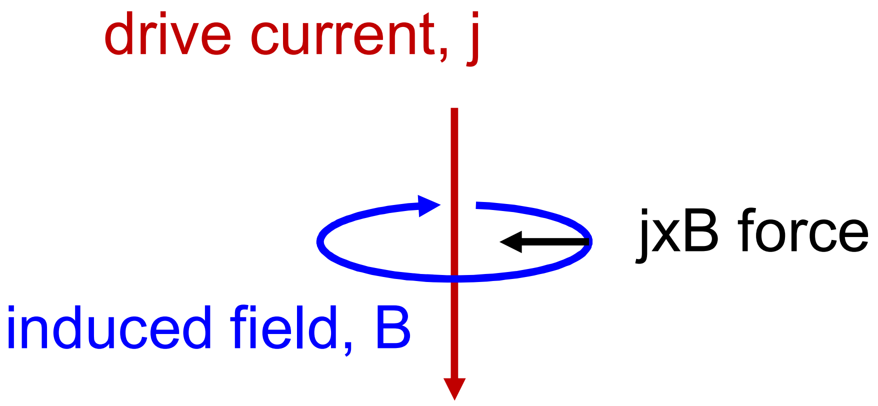
1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)
2. current **j** is compressed in space and time to >20MA (0.5 MJ to 1 cm in 100 ns)
3. high energy density science! (the ground shakes)



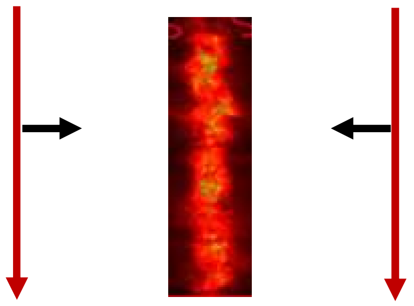
From Sinars et al, Phys Plasmas 27, 070501 (2020)

“Magnetic direct drive” uses the j x B force to deliver energy

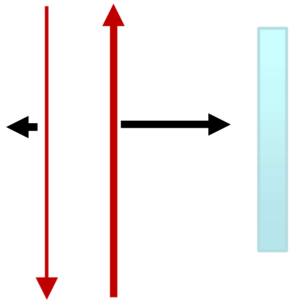
magnetic drive pressure ~ $(j/r)^2$



26 MA at r = 1 mm →
~100 Mbar pressures

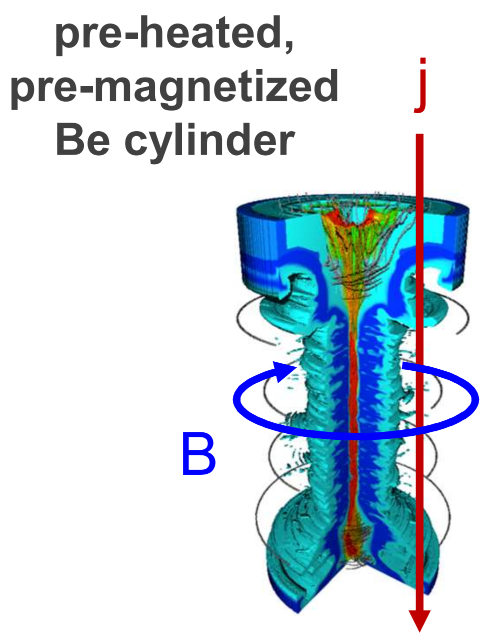


26 MA at r ~ 50 mm →
v ~ 1000 km/s

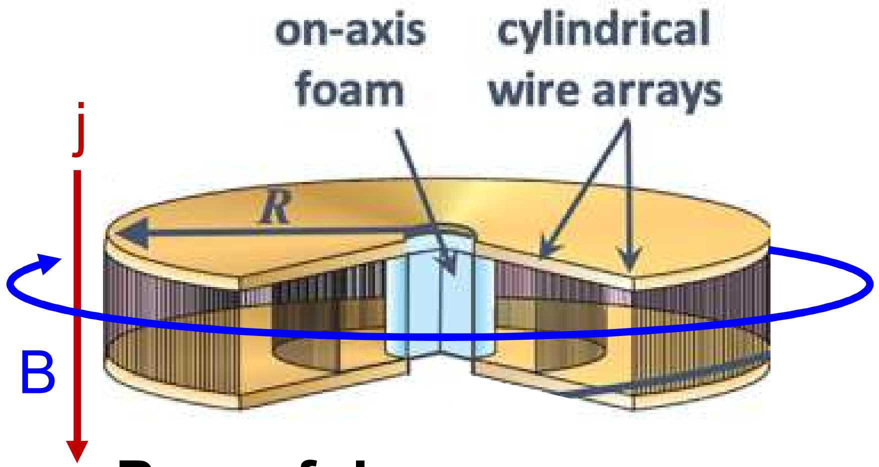


26 MA at r ~ 1 mm →
> Mbar shocks

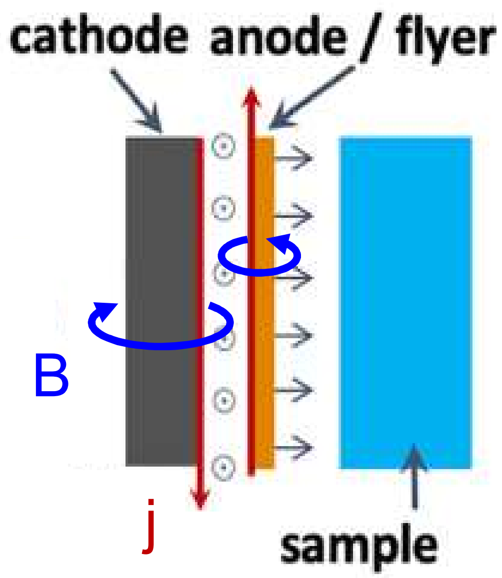
On Sandia's Z machine, we study a wide range of high energy density science using pulsed power



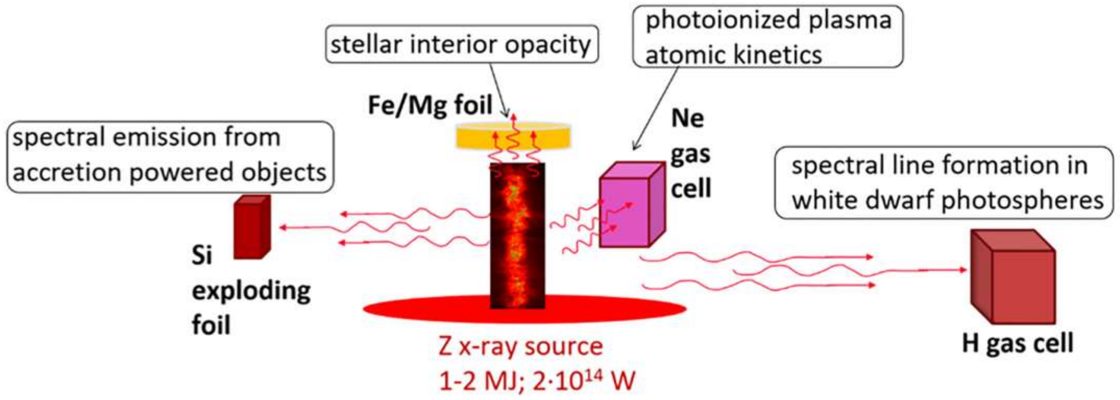
Magneto-inertial fusion
jxB heats and
compresses fusion fuel
(~1 Gbar, > kJ yields)



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



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

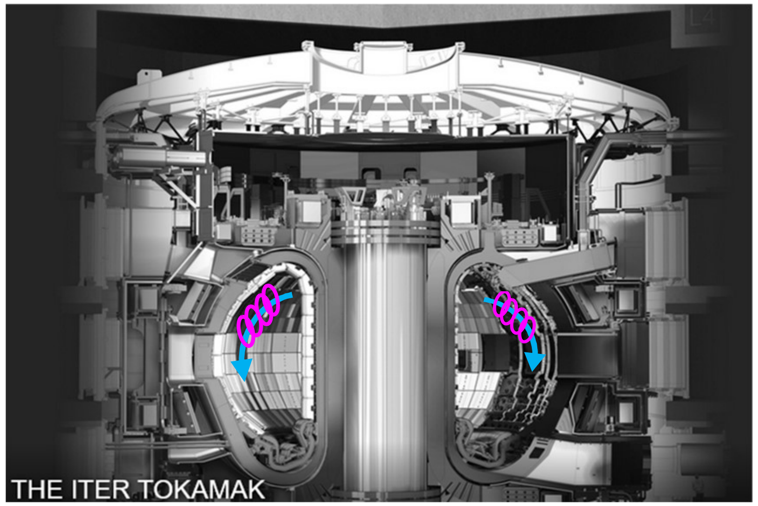


X-rays drive lab-astro experiments

From Sinars et al, Phys Plasmas 27, 070501 (2020)

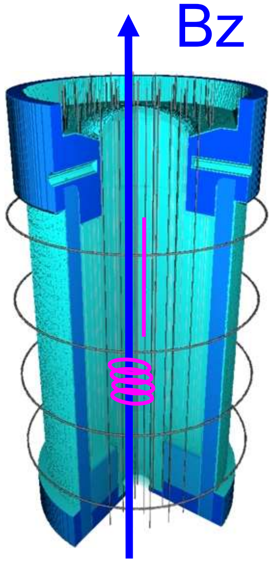
Magnetized Liner Inertial Fusion (MagLIF) combines aspects of magnetic and inertial confinement fusion

Lawson criterion: Pτ > 50 bar-s (and T > 4 keV)



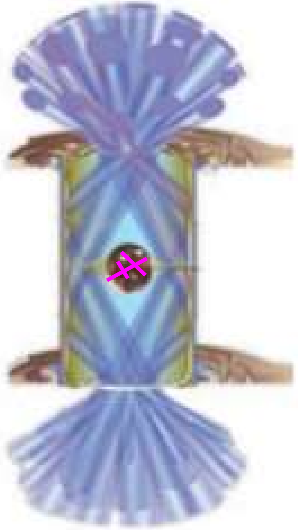
Magnetic fusion (ITER)
$R \sim 10$ m
$P \sim 1$ bar
$\tau > 10$ s
$P\tau > 10$ bar-s

Burn requires plasma stability and high B



Magneto-inertial fusion (Z)
$R \sim 10^{-3}$ m
$P \sim 10^{9}$ bar
$\tau \sim 10^{-9}$ s
$P\tau \sim 1$ bar-s

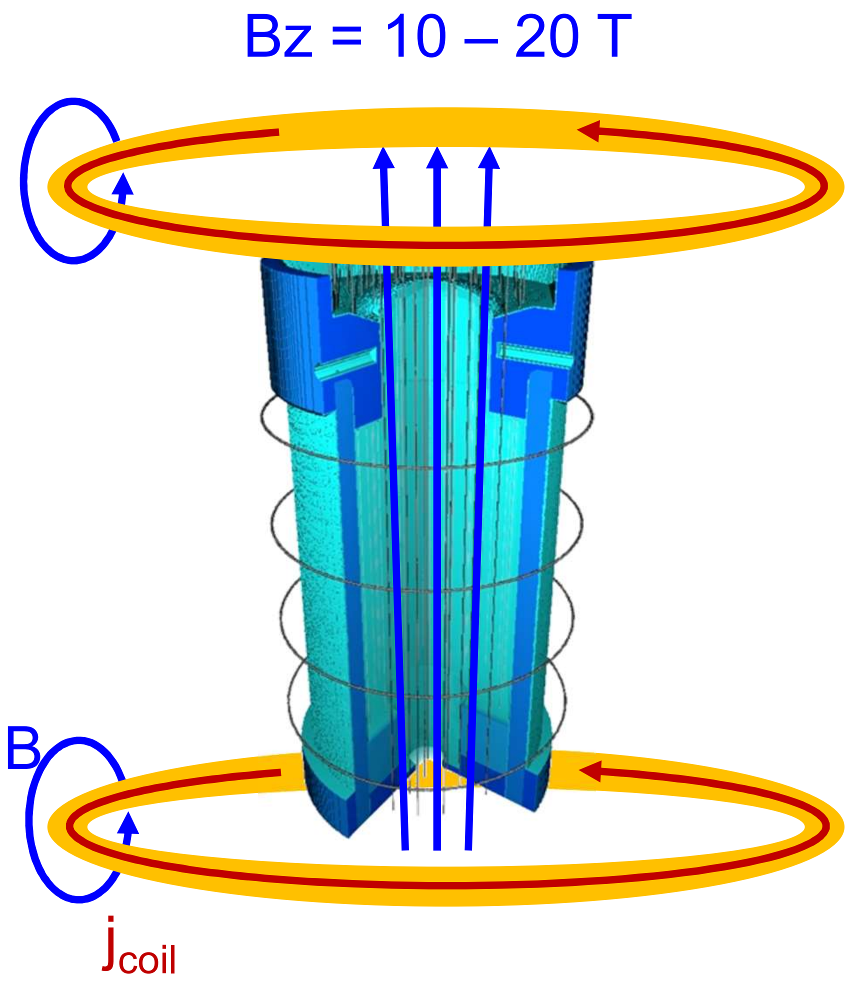
Burn requires stability, high Bz*R, and high ρ*Z



Inertial fusion (NIF)
$R \sim 10^{-5}$ m
$P \sim 10^{11}$ bar
$\tau \sim 10^{-10}$ s
$P\tau \sim 10$ bar-s

Burn requires implosion stability and high ρ*R

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



Stage 1: pre-magnetize

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

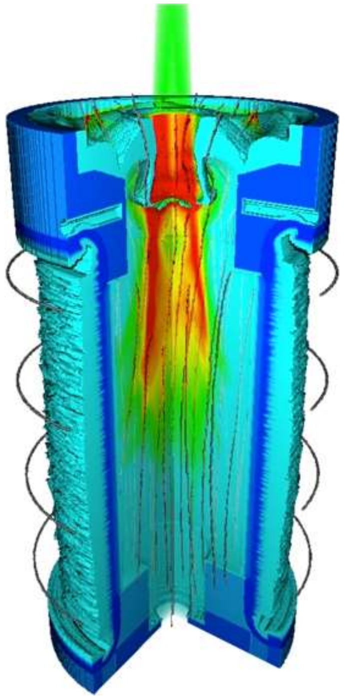
The imposed axial magnetic field prevents conduction losses that can cool the plasma below fusion temperatures

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

Images from C. Jennings (Gorgon)

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

$E_{laser} = 1 - 2$ kJ



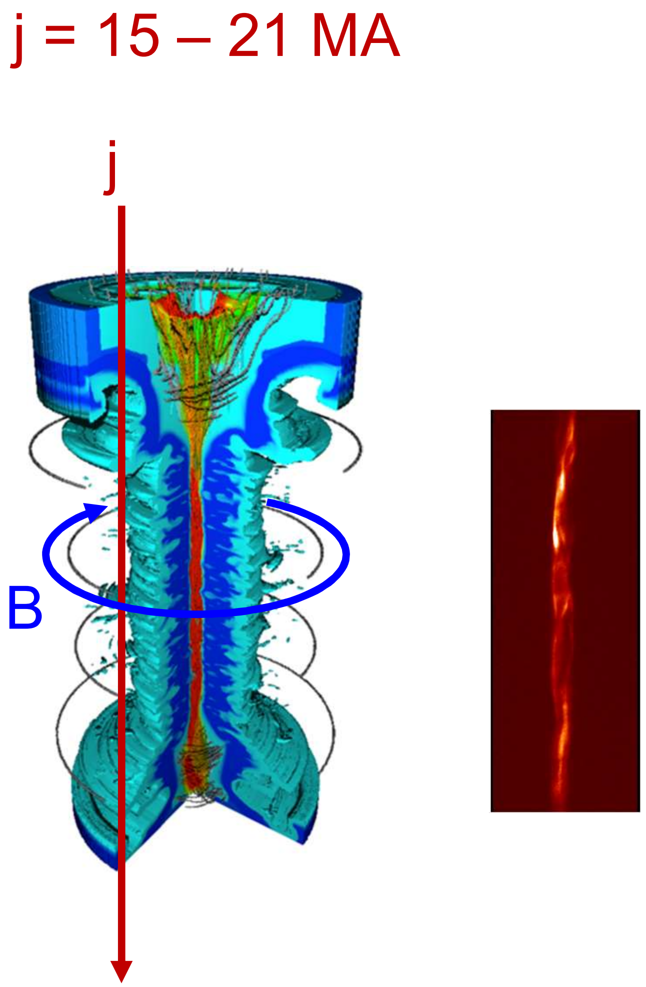
Stage 2: pre-heat the fuel

The 4kJ Z-Beamlet laser penetrates a thin window and preheats the fuel core to T ~ 200 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

Images from C. Jennings (Gorgon)

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



Stage 3: compression

The Z machine delivers a compressional force that implodes the liner, axial field, and fuel at v ~100 km/s

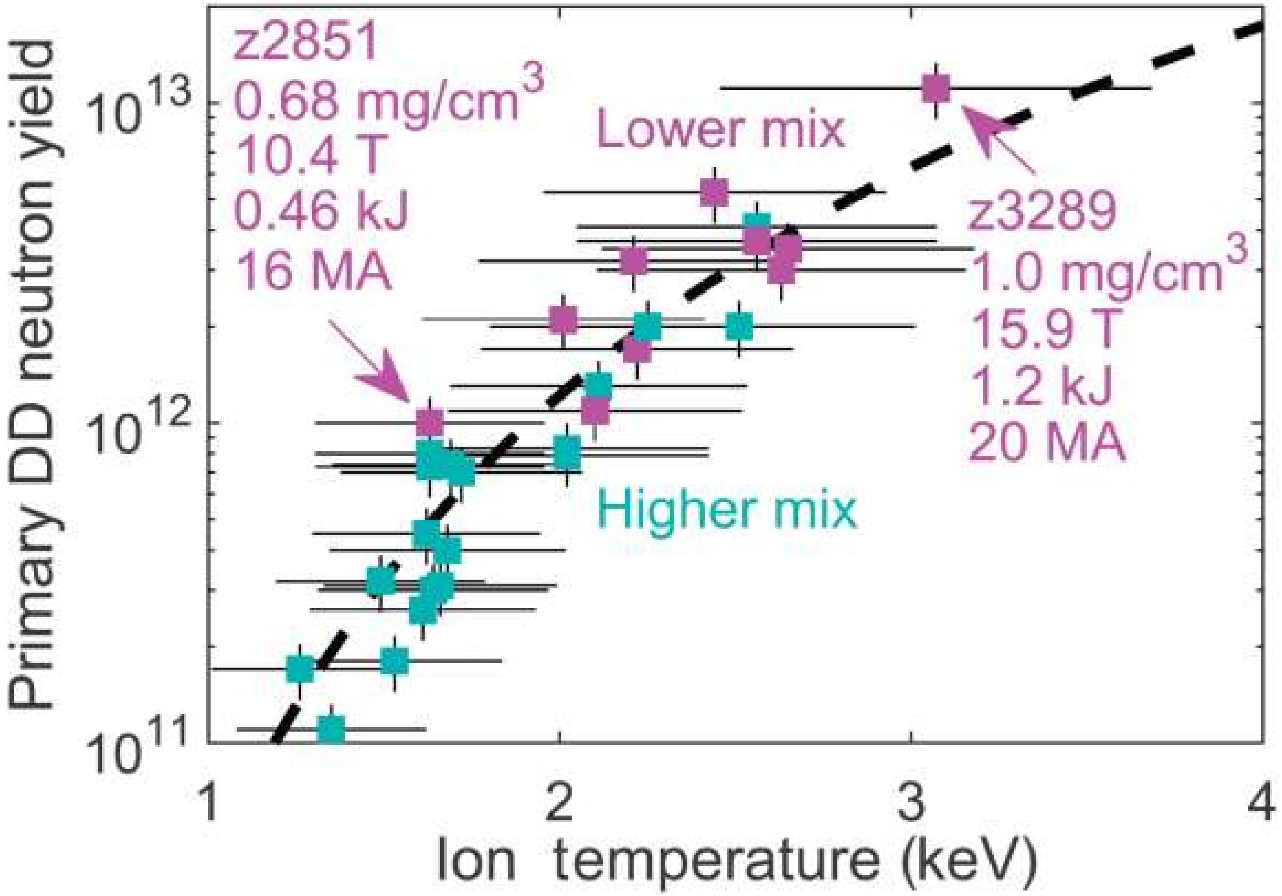
At stagnation, relatively stable plasma columns with helical structure yield ~10^{13} D-D neutrons (10^{15} D-T or 2 kJ)

Neutron diagnostics indicate high magnetization sufficient to trap ~50% of charged fusion products

X-ray diagnostics indicate T ~ 3 keV, τ ~ 1 ns, and P ~ 1 Gbar

Images from C. Jennings (Gorgon) and E. Harding (x-ray crystal imager)

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



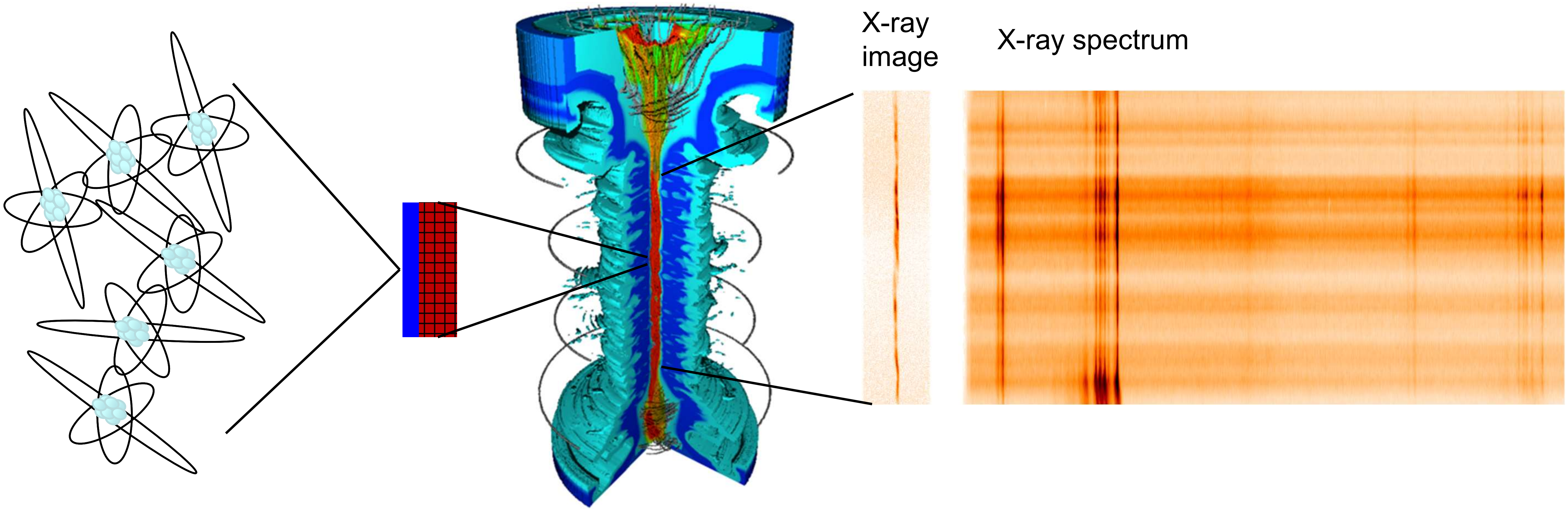
j(MA)	E_{laser}(kJ)	Bz(T)	Y(kJ)	
15	0.5	10	0.2	Z
20	1.2	20	2	
22	6	30	80	
60	30*	30	>1000	

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

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

Gomez et al, Phys. Rev. Lett. 125, 155002 (2020)

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



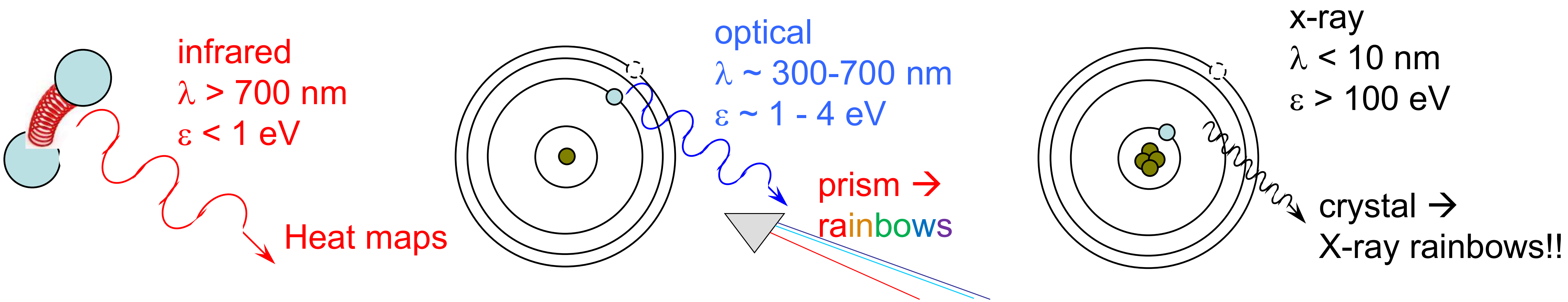
If we understand the atomic-scale response of materials in extreme conditions,

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

…and we can more rigorously interpret experimental data

Spectrum Courtesy E. Harding

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



infrared
$\lambda > 700$ nm
$\varepsilon < 1$ eV

Heat maps

optical
$\lambda \sim 300\text{-}700$ nm
$\varepsilon \sim 1 - 4$ eV

prism →
rainbows

x-ray
$\lambda < 10$ nm
$\varepsilon > 100$ eV

crystal →
X-ray rainbows!!

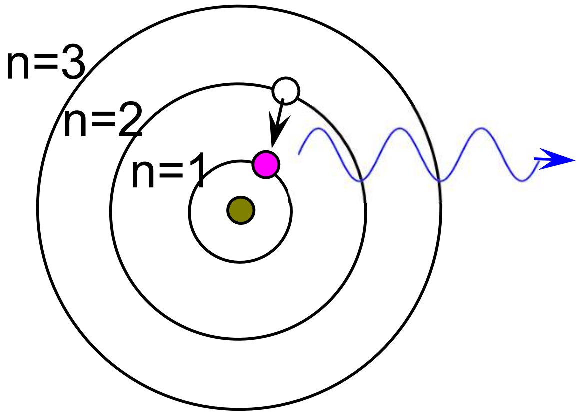
The history of spectroscopy is intricately linked to the history of modern physics

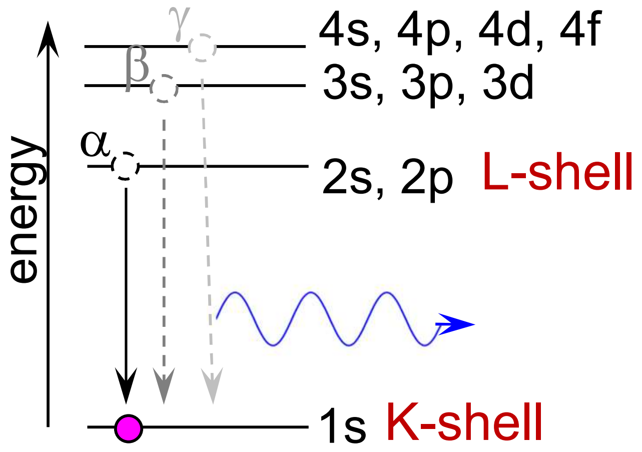
- **atomic physics and quantum mechanics**
  much of what we know about matter was learned through spectroscopy
- **astrophysics and cosmology**
  "spectroscopy puts the 'physics' in astrophysics!"
- **plasma physics and fusion research**
  spectroscopic diagnostics reveal details of temperature, density, fields…

Each ion of each element has a spectroscopic "fingerprint"

Bohr model:

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





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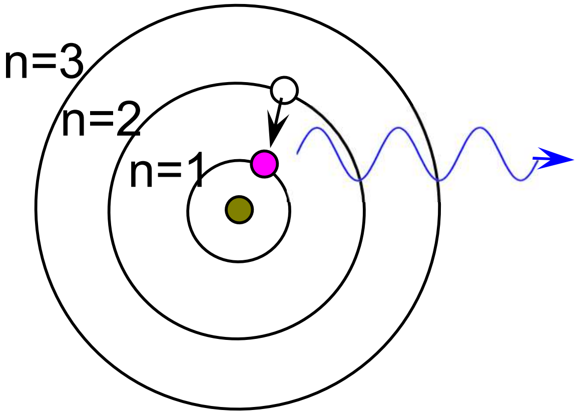
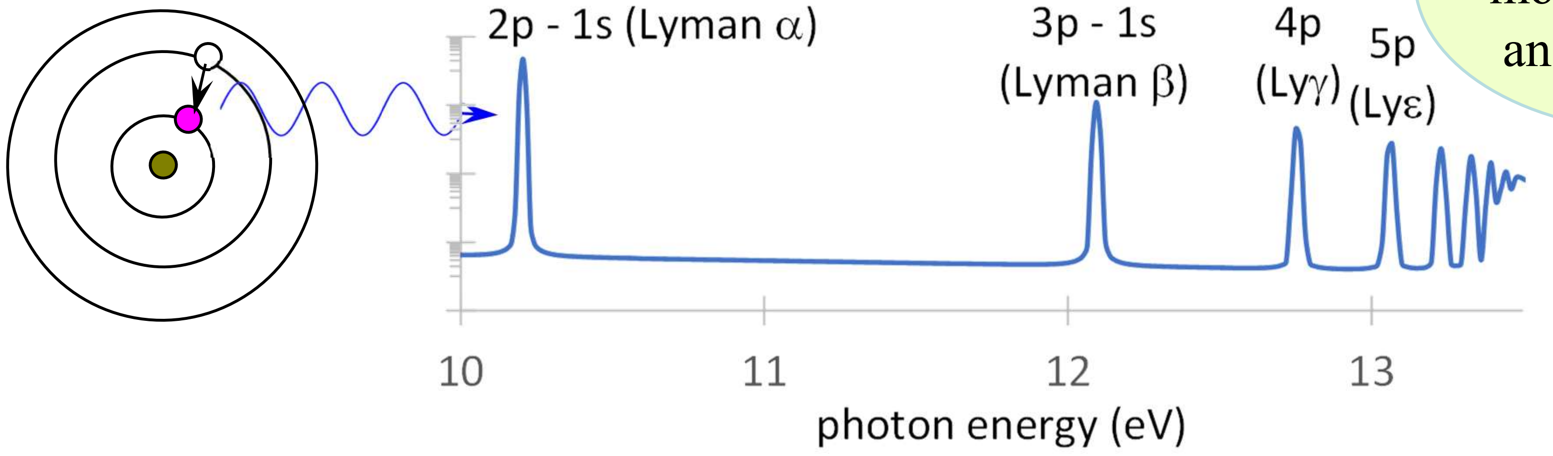
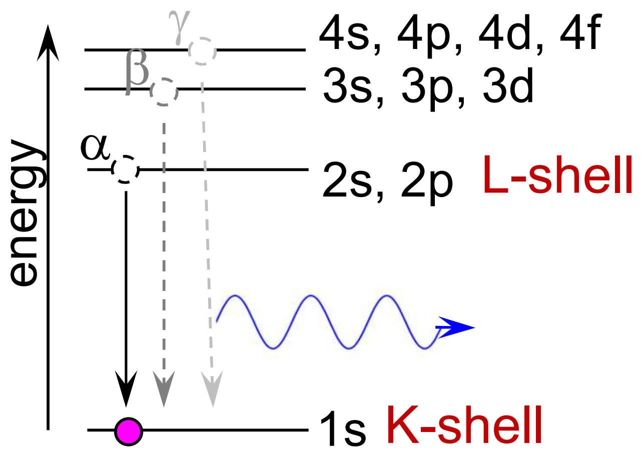
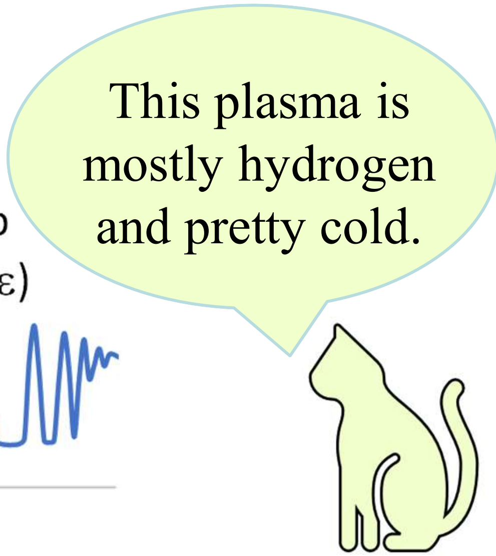


neutral hydrogen (Z_{eff} = 1, n = 1)

K-shell $h\nu = \Delta\varepsilon \sim 10$ eV







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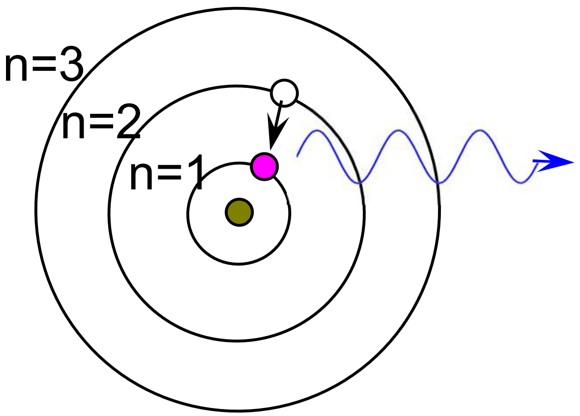

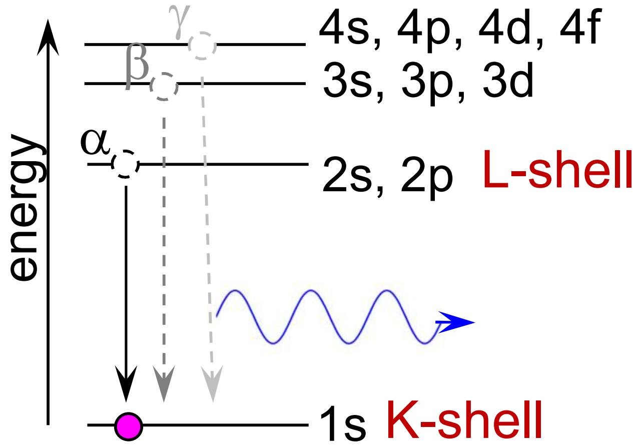

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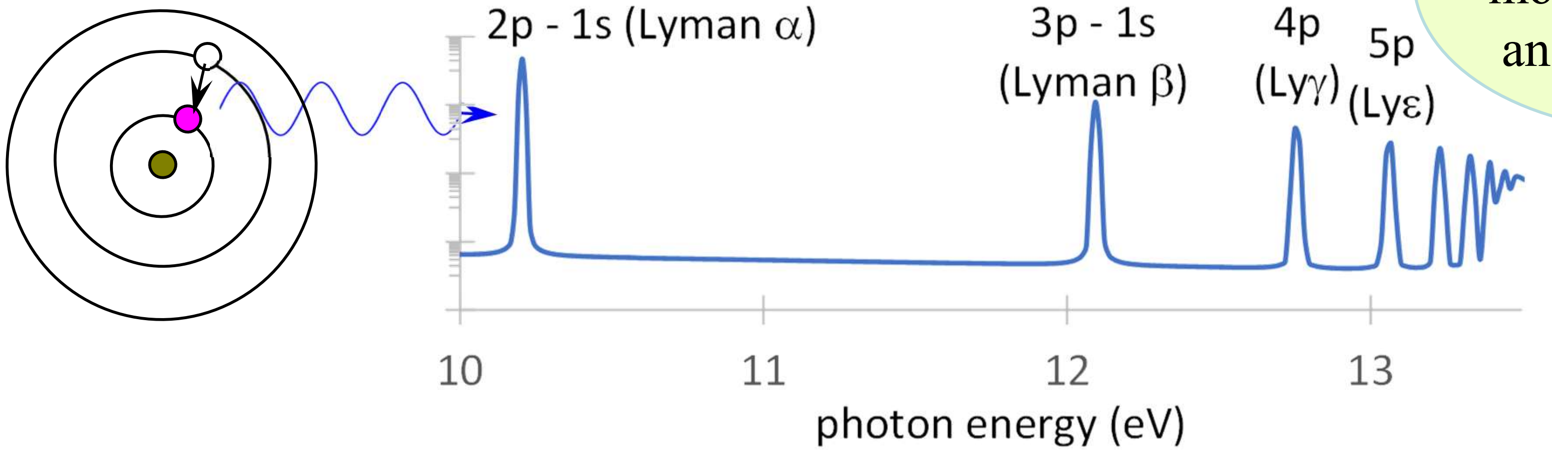
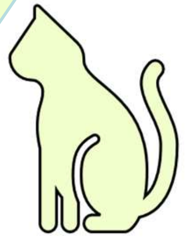
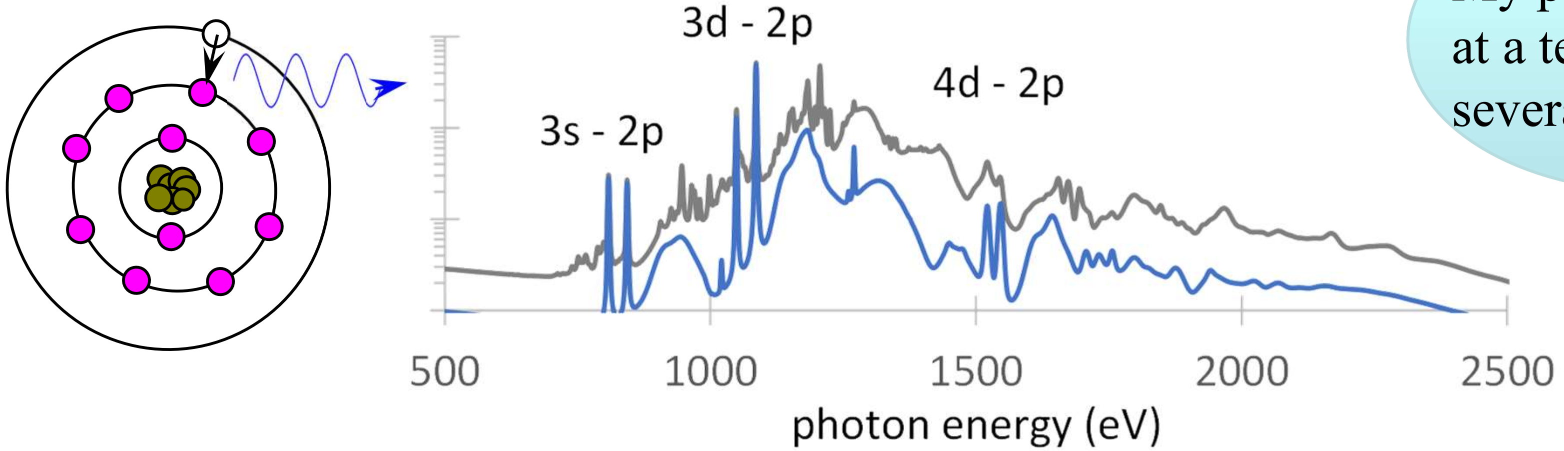


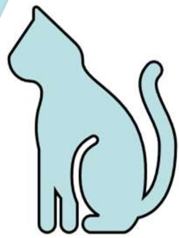


This plasma is mostly hydrogen and pretty cold.

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

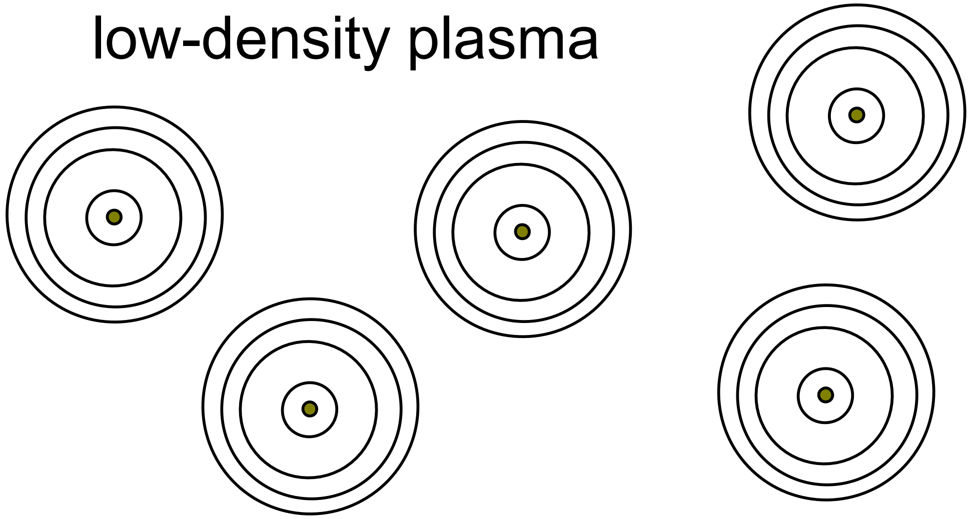


My plasma has iron at a temperature of several hundred eV!

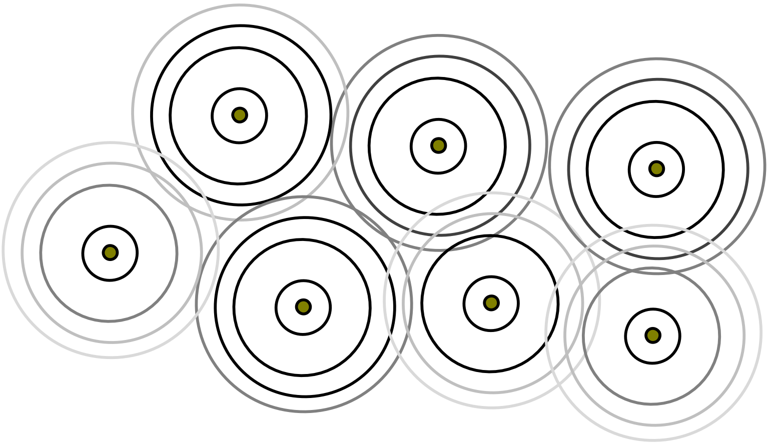


High-density environments modify electronic structure and spectroscopic signatures

low-density plasma



high-density plasma



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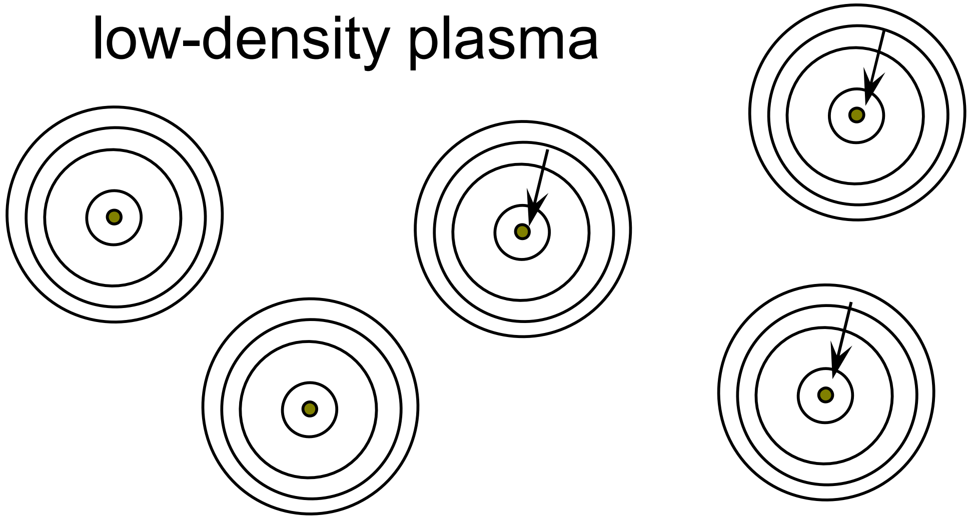

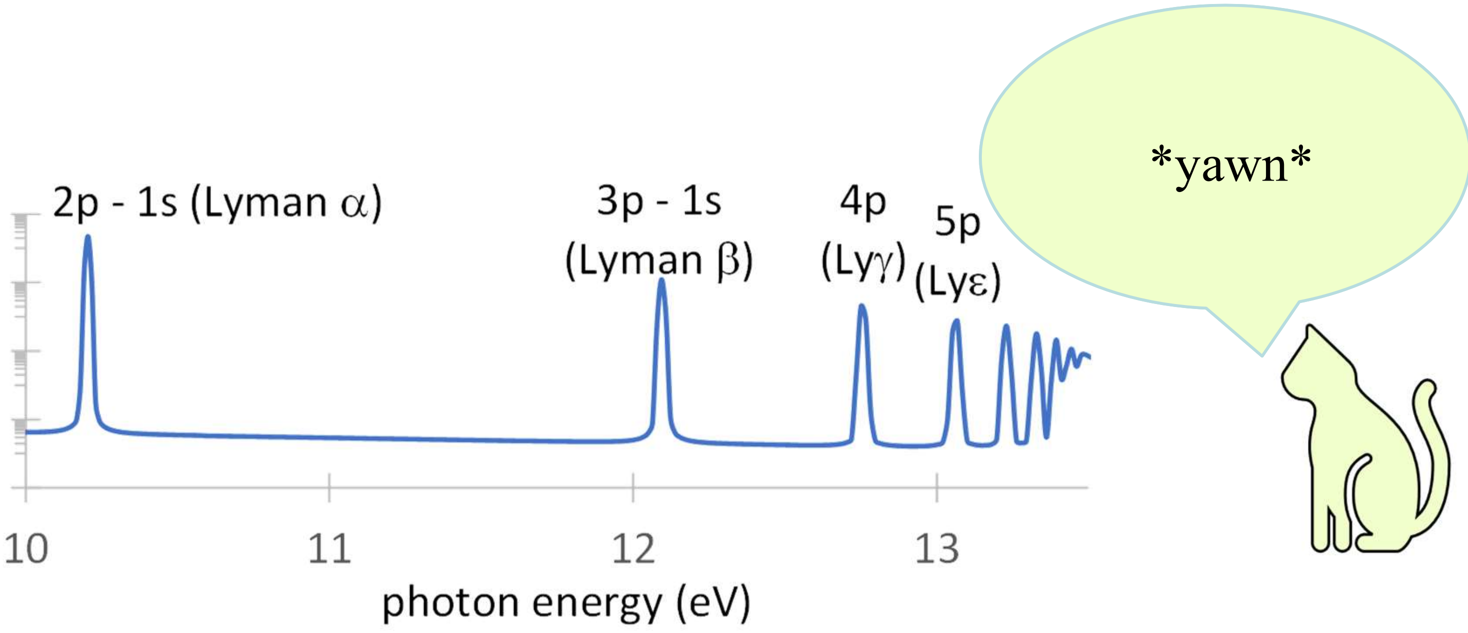

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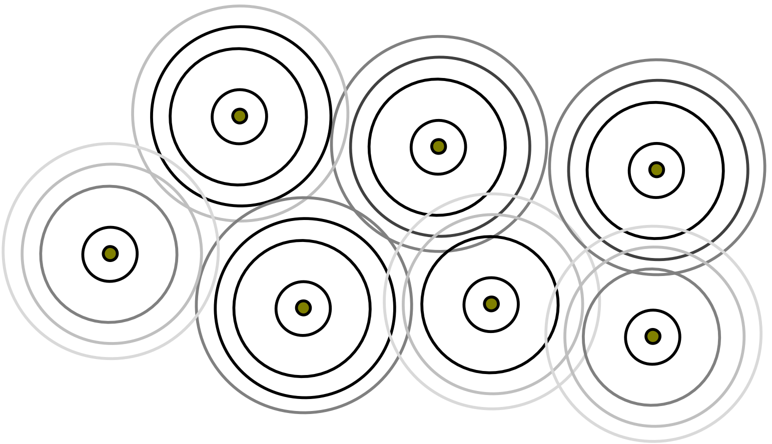

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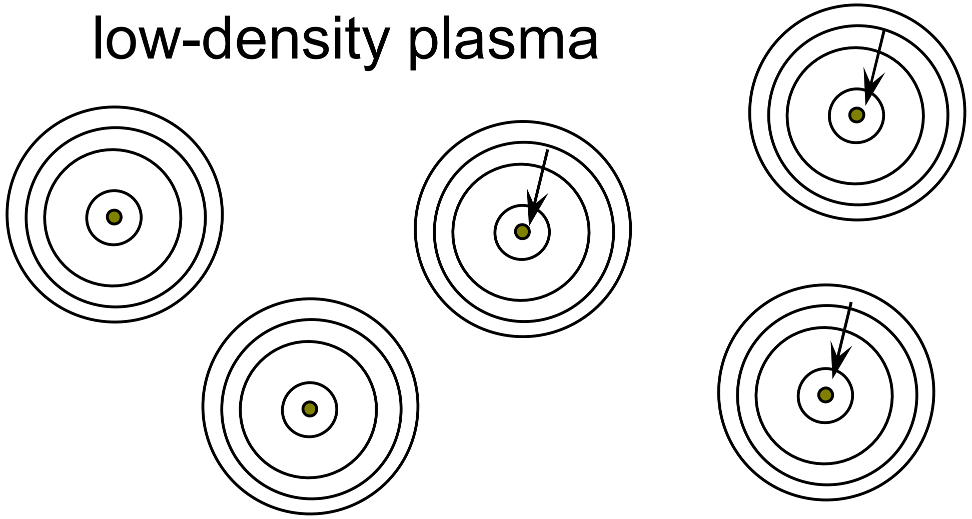
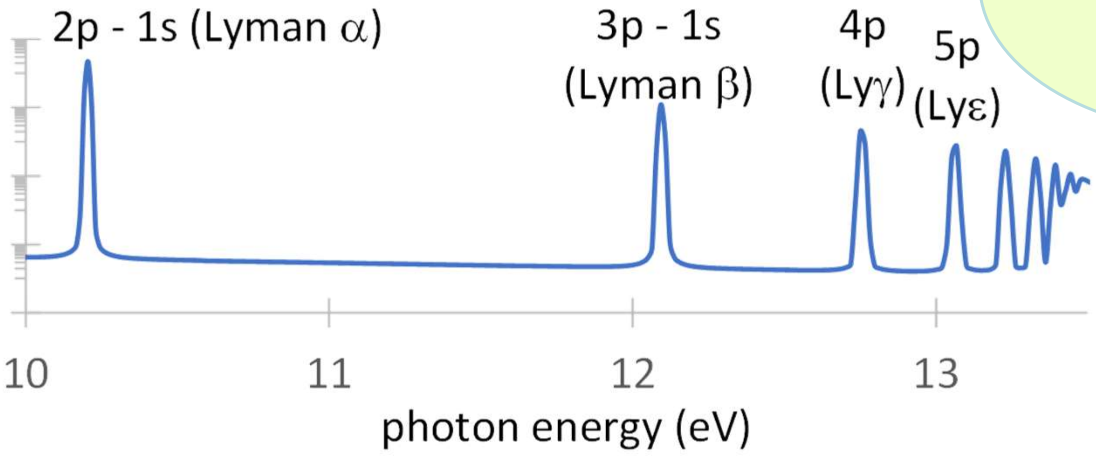
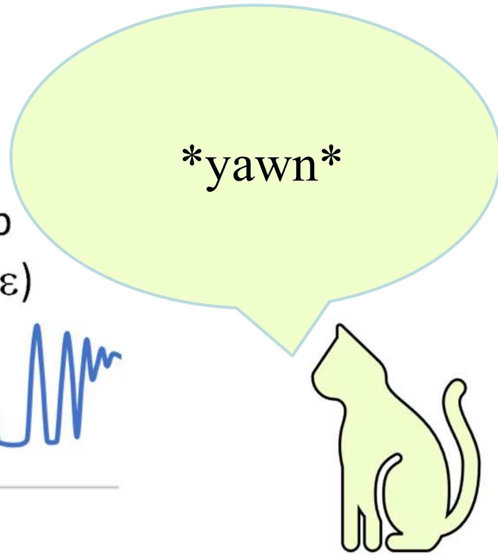
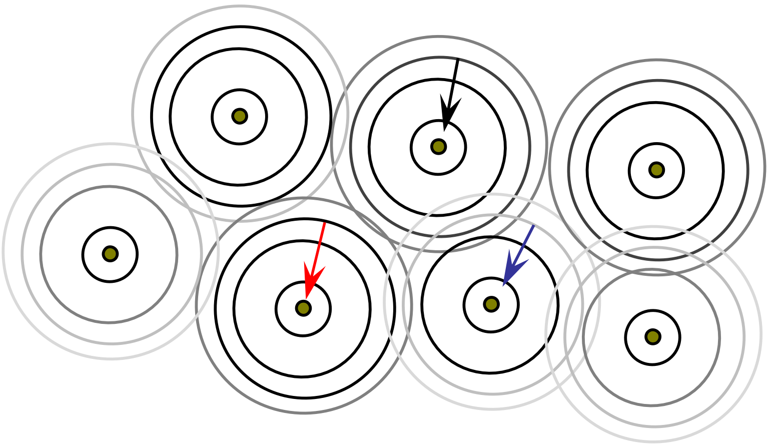
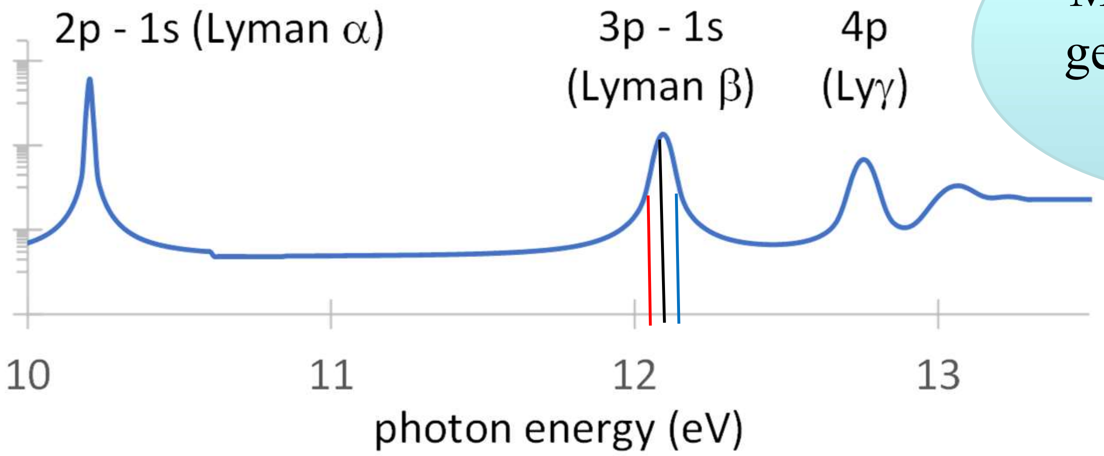


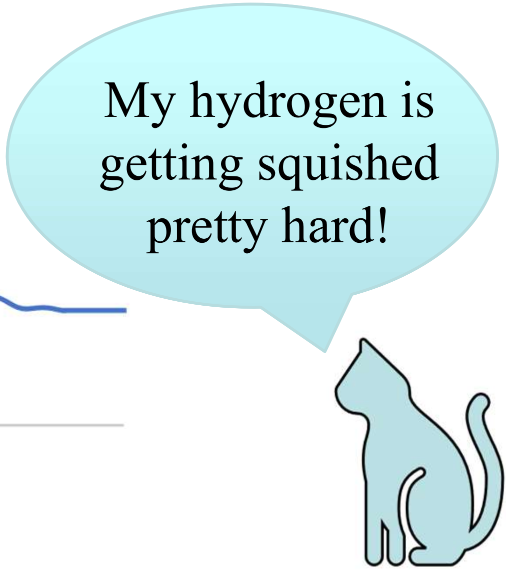




high-density plasma

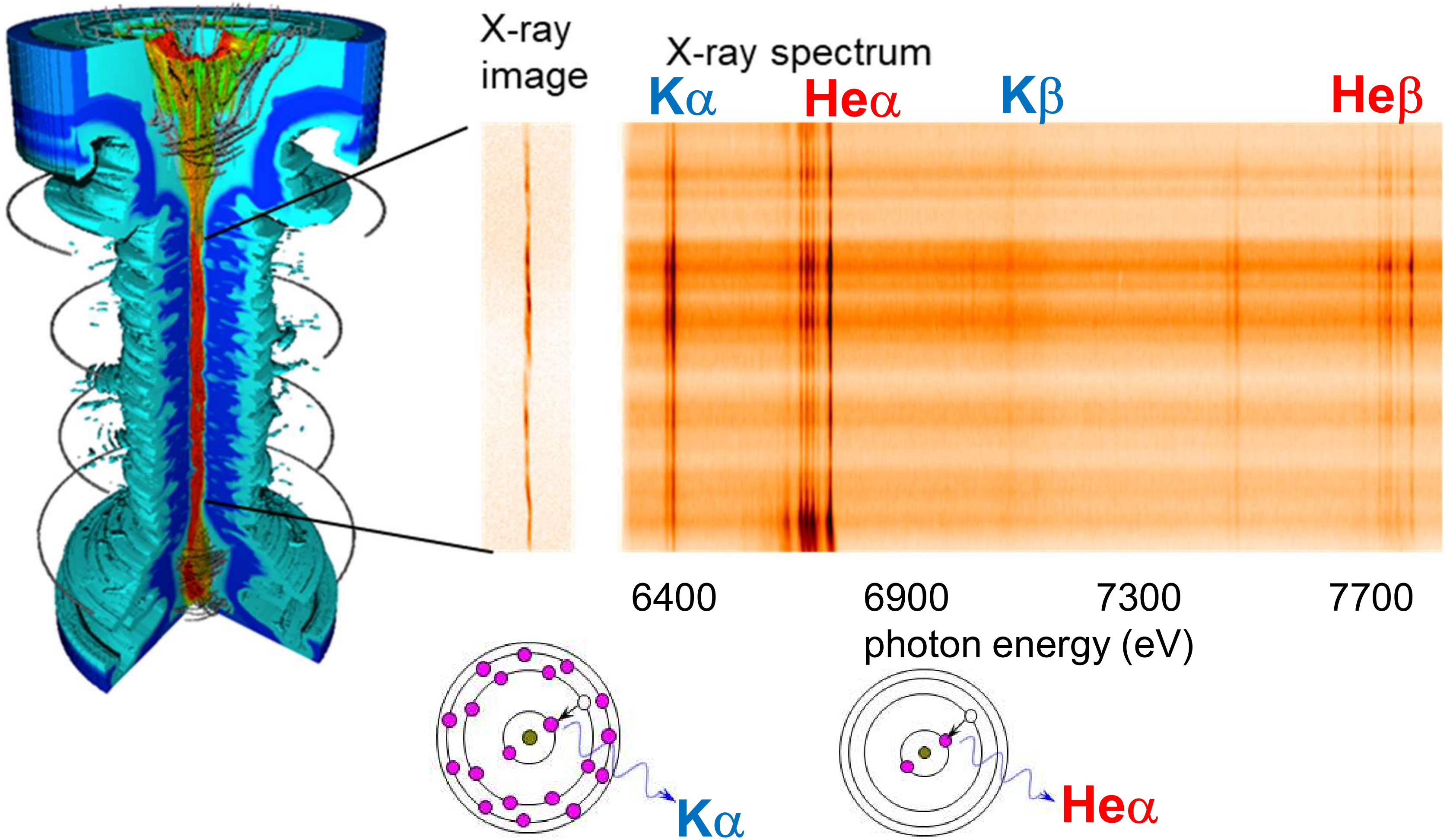






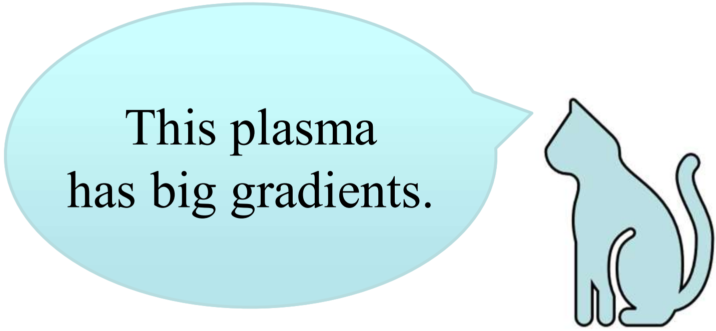
What does the spectrum from a MagLIF experiment tell us?

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



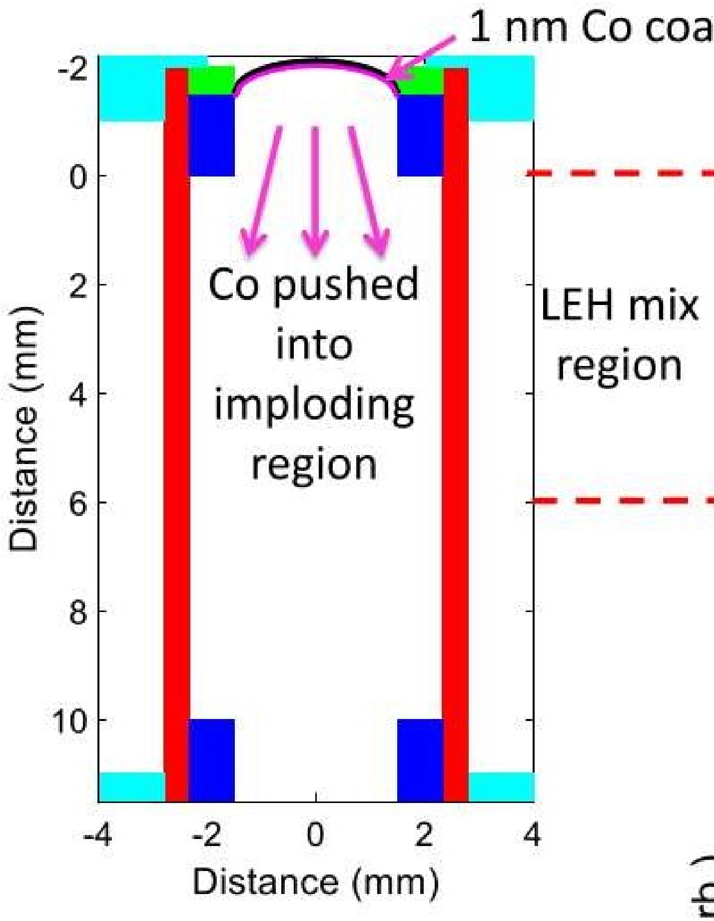
He-like iron K-shell lines: some of the liner mixes with the hot fuel in a layer with n_e ~ 2×10^{23} e/cc and T_e ~ 2000 eV

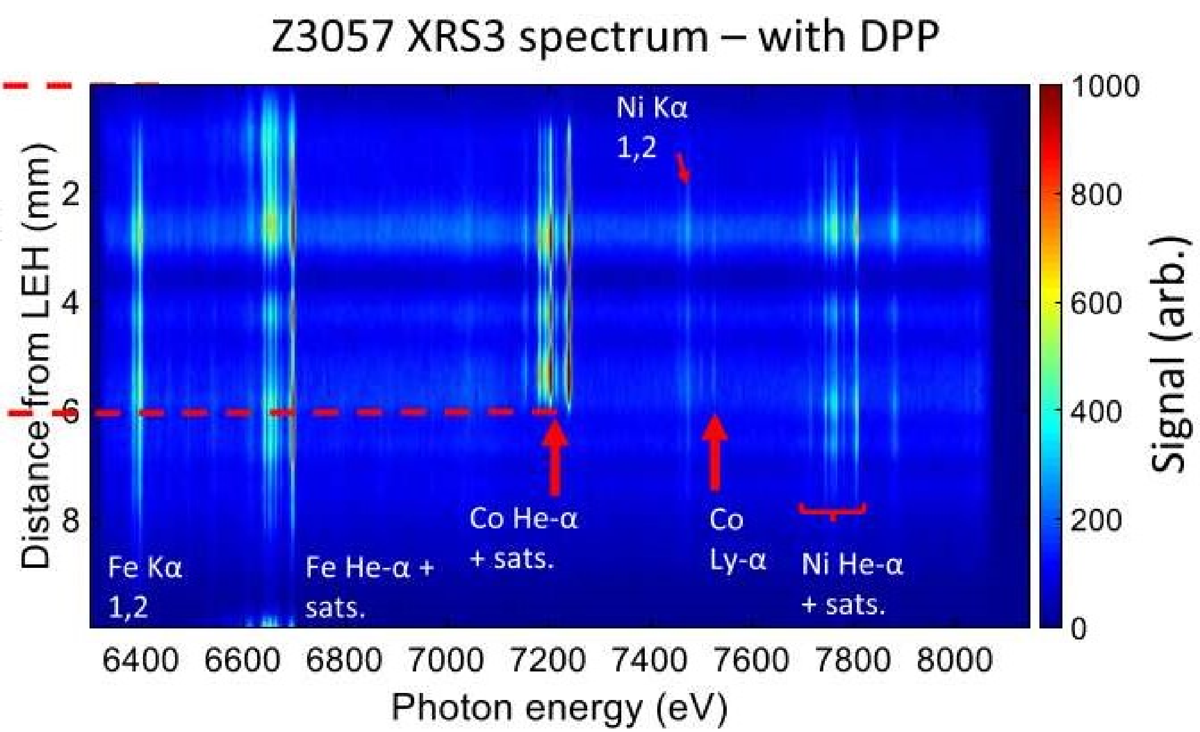
Neutral iron K-shell lines: most of the liner is cold (~10 eV) and very dense (10x solid): the iron is photoionized by radiation from the hot core

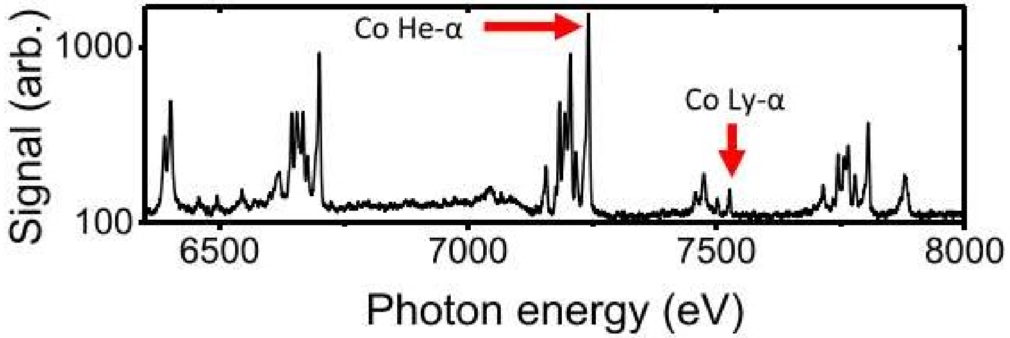


Spectrum Courtesy E. Harding

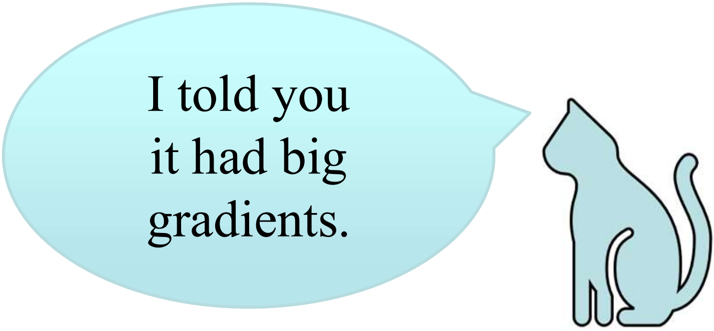
Is the whole hot core at the same conditions as the hot iron emission?




Z3057 XRS3 spectrum – with DPP



No! When we put a cobalt tracer on the window and use a smoothed, large-area beam to preheat, the window material pushed into the fuel indicates hotter (4 keV) and less dense (10^{23} cm^{-3}) plasma

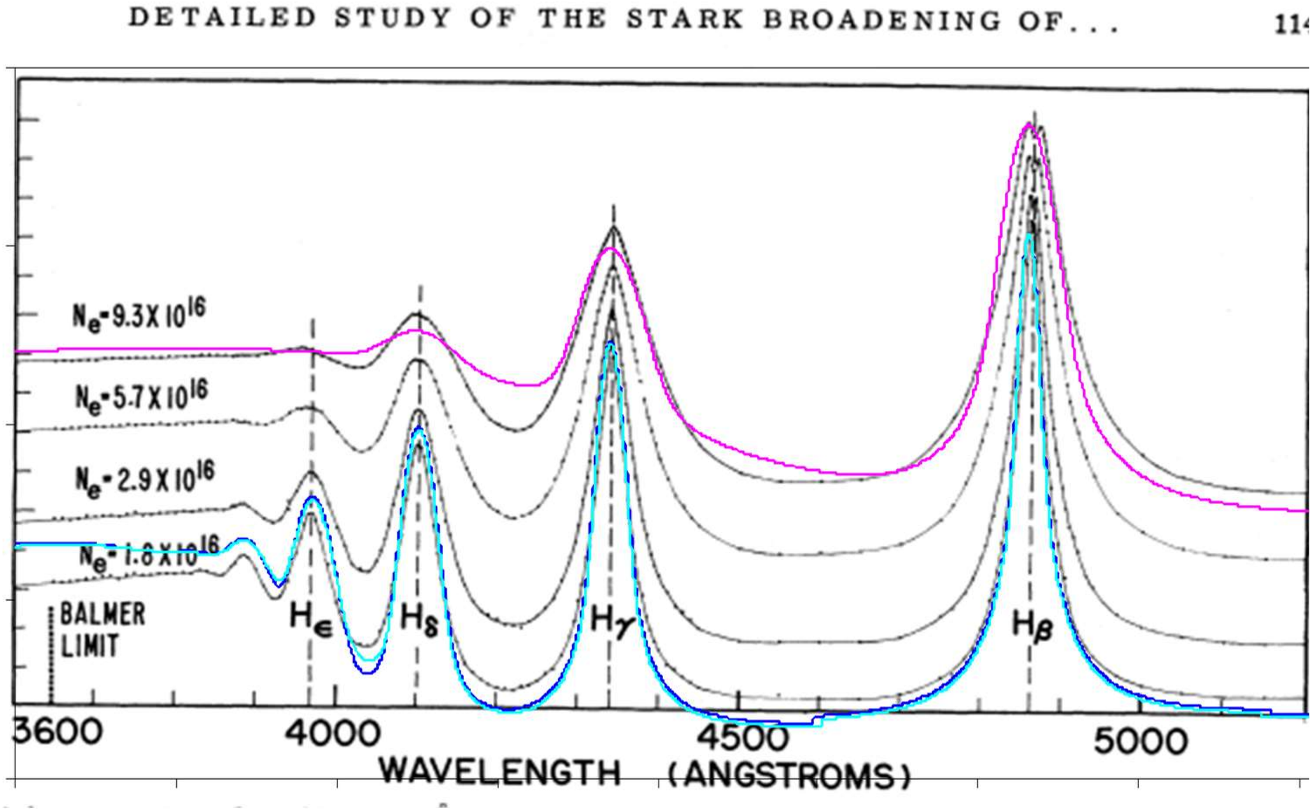


A. Harvey-Thompson, Phys Plas 25, 112705 (2018)

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 ~ 2 eV:

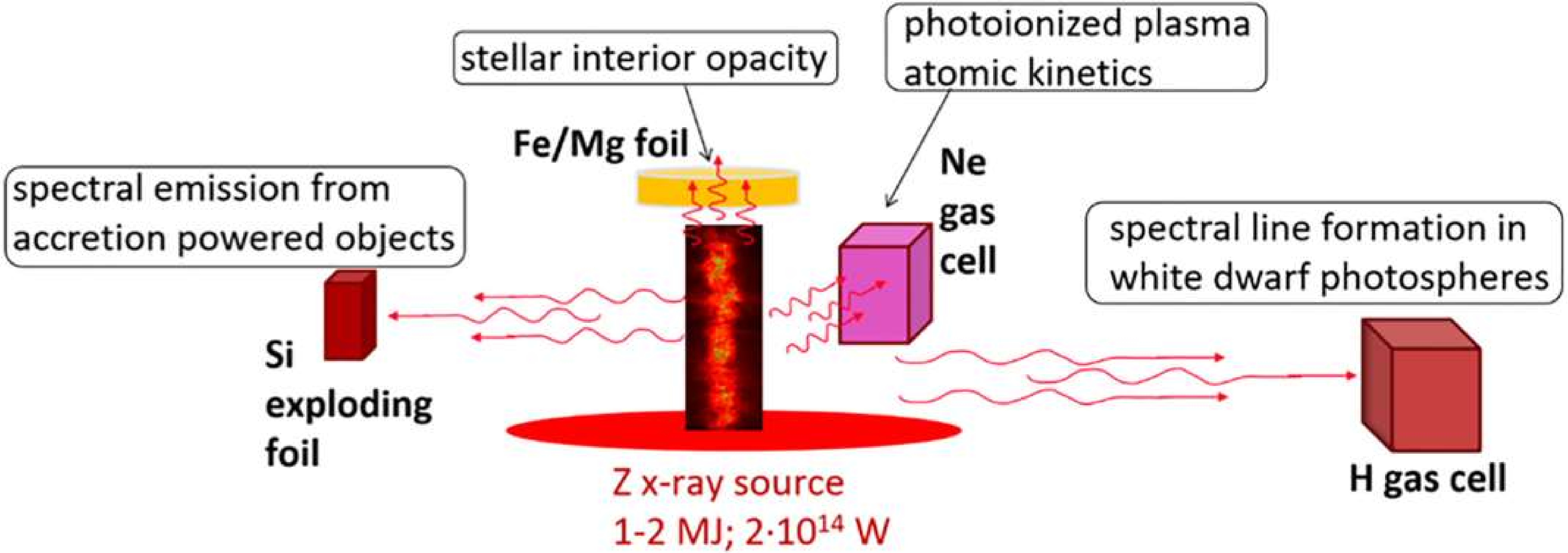
one of perhaps __5__ high-quality benchmark data sets for spectra!

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



stellar interior opacity

Fe/Mg foil

photoionized plasma atomic kinetics

Ne gas cell

spectral emission from accretion powered objects

Si exploding foil

spectral line formation in white dwarf photospheres

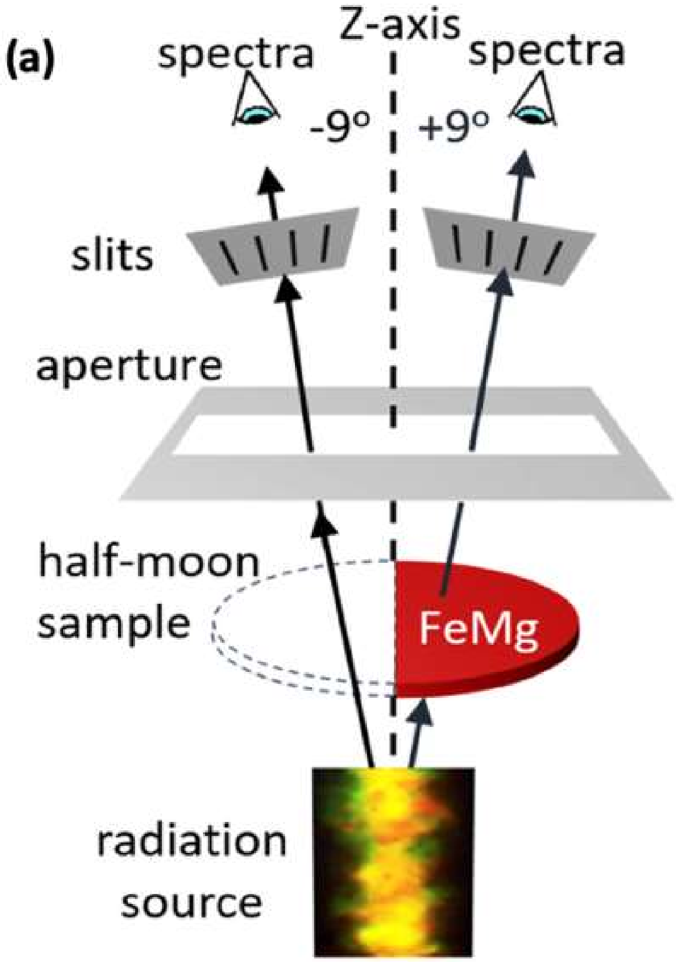
H gas cell

Z x-ray source
1-2 MJ; $2 \cdot 10^{14}$ W

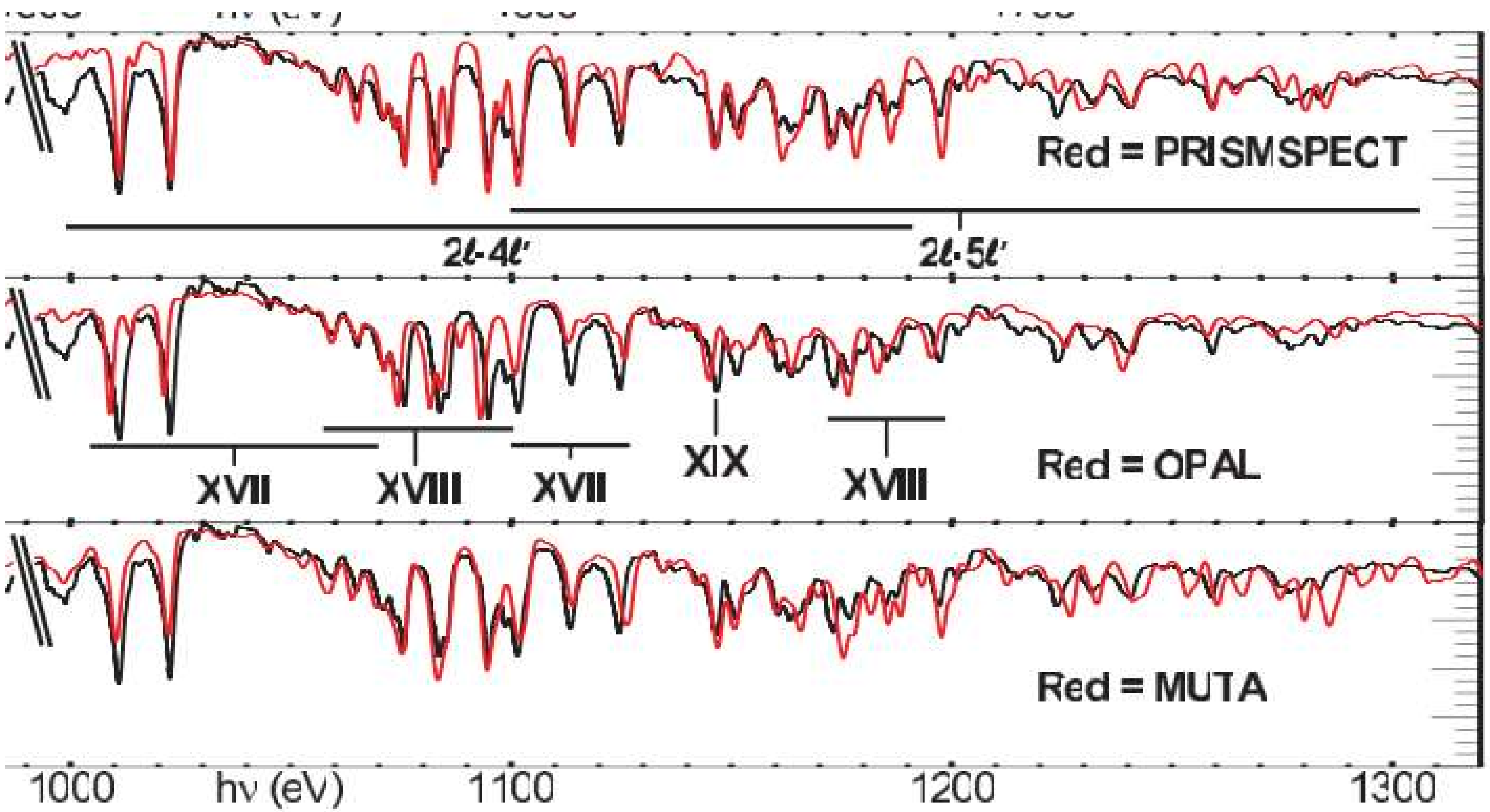
A consortium of Laboratory and University scientists use the TW x-ray powers from the Z machine to heat, photoionize, and backlight benchmark plasmas

Rochau, G. A. et al. Phys. Plasmas 21, 056308 (2014)

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

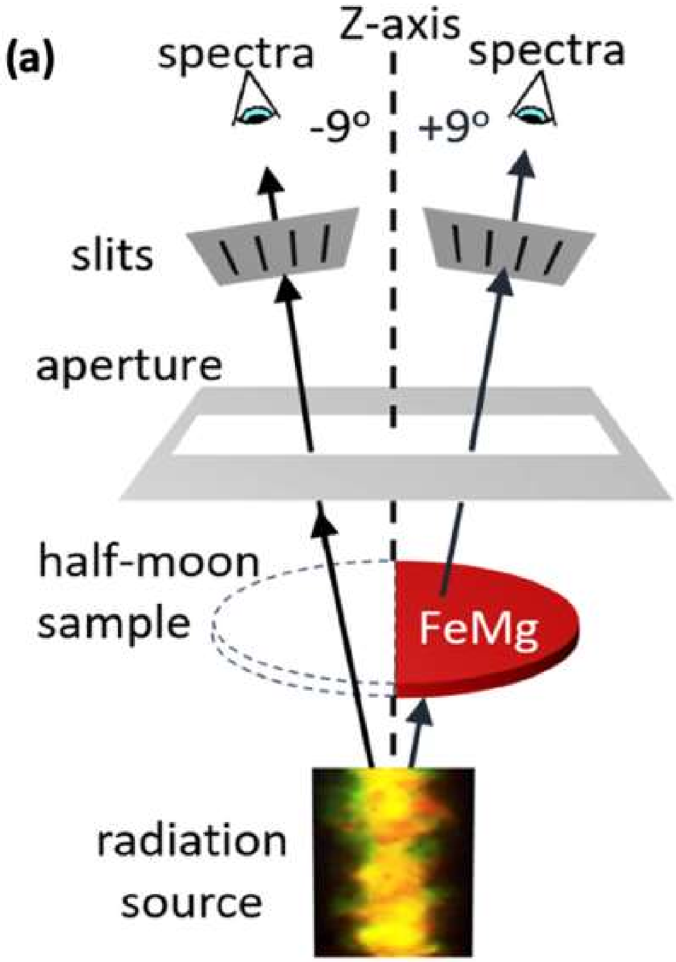


In 2007, Bailey at al found good agreement between models and experiments for iron at temperatures and densities slightly lower than that at the solar radiation/convection zone boundary:

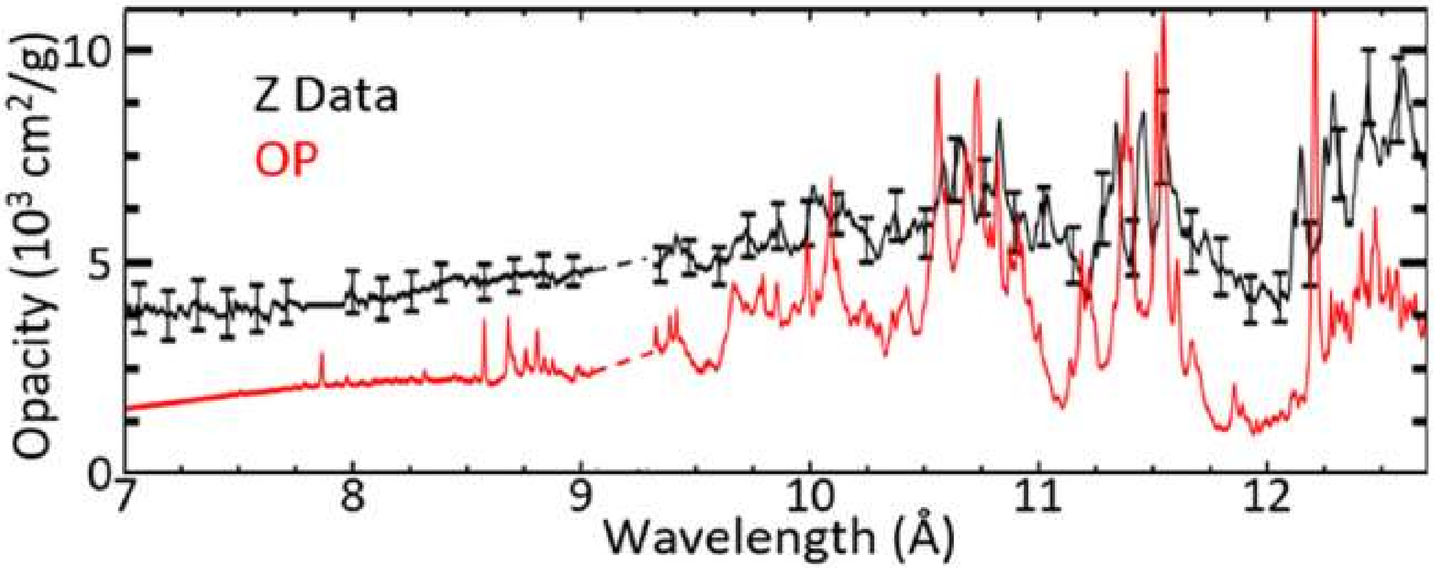


Bailey et al, Phys Rev Lett 99, 065002 (2007)

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 at al found surprising disagreement between models and experiments



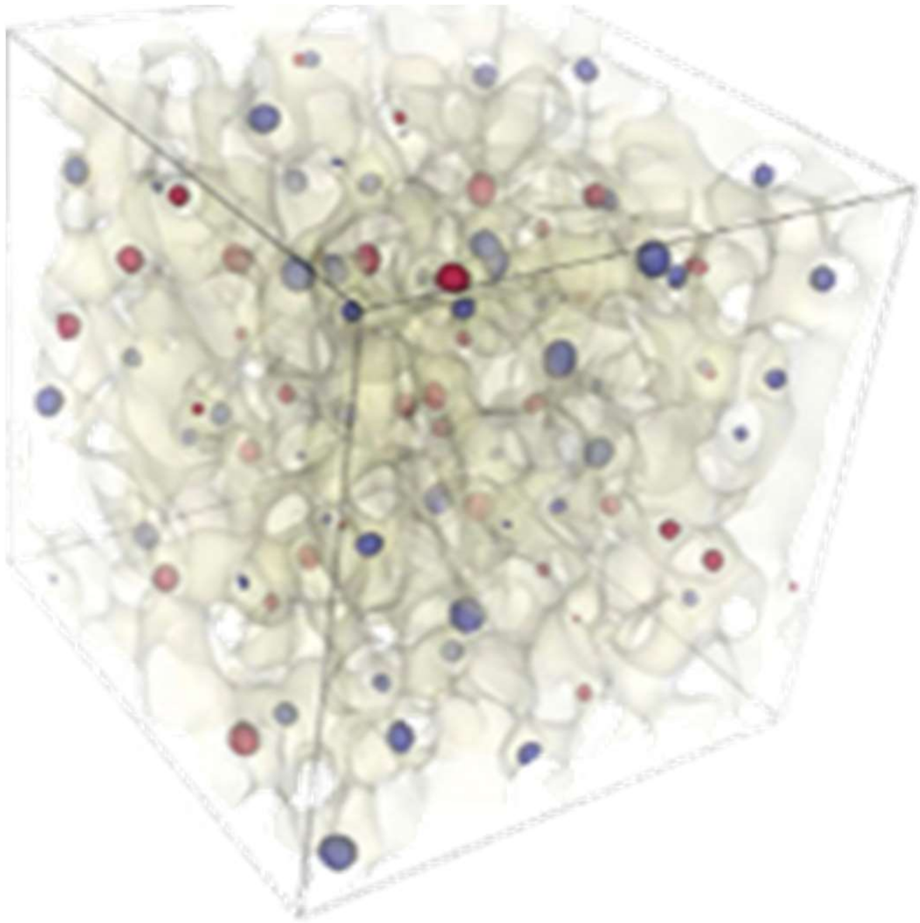
This is one of only a handful of benchmark experiments for high energy density plasmas: we will be surprised again!

Bailey et al, Nature 517, 56 (2015); Nagayama et al PRL 122, 235001 (2019)

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

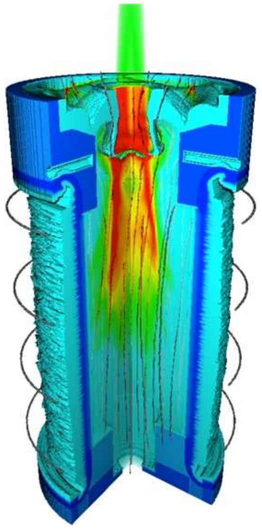
Density functional theory solves 3D multi-center Schrodinger equations for fixed ion positions; Zero-temperature DFT has long been used in solid-state and chemical physics to predict material structure.

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.



Baczewski et al, PRL 116, 115004 (2016)

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



Thanks, rad-hydro & PIC communities!

Machine & target simulations

MagLIF preheat & x-ray backlighting

Thanks, laser community!

X-ray and neutron yields, images, and spectra

Thanks, diagnostics community!

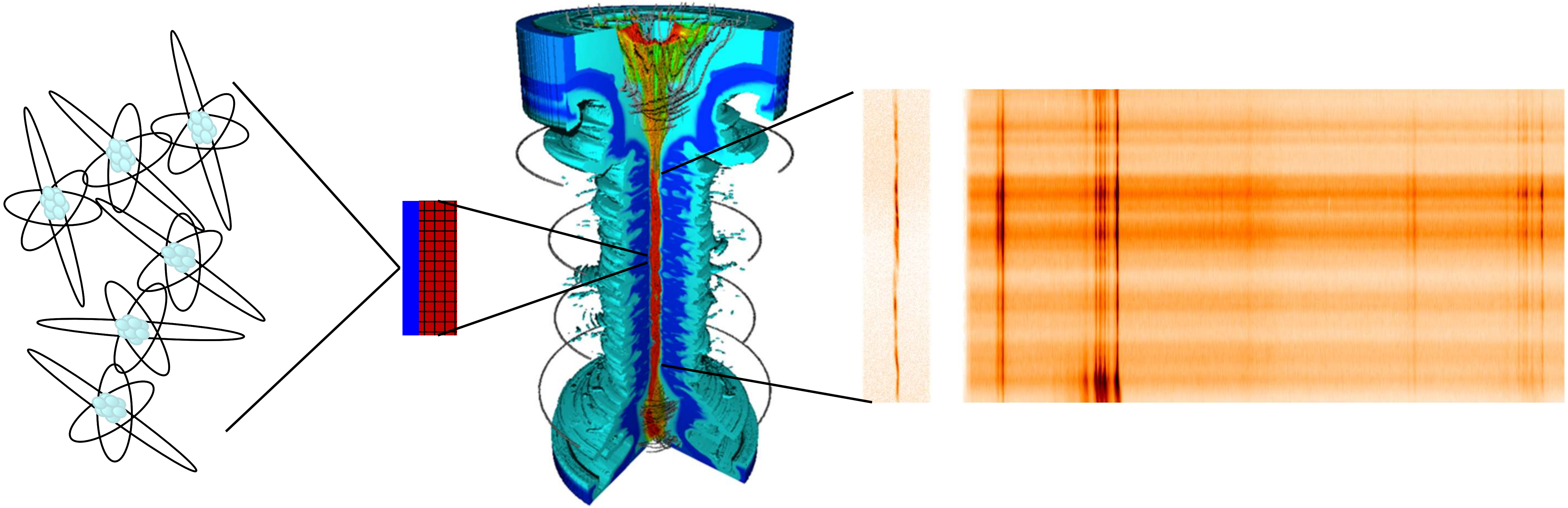
Thanks, atomic & condensed matter communities!

Fundamental material properties

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! << sbhanse@sandia.gov >>



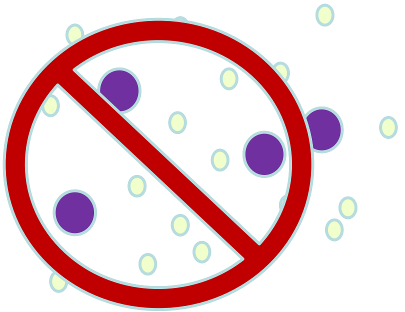
How can we accurately model atomic-scale processes in exotic environments?

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

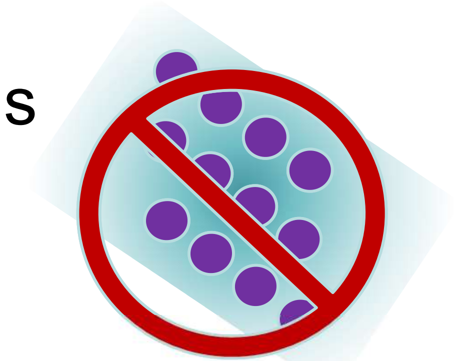
How can we design and perform benchmark experiments that test our understanding and open new windows to exotic worlds?

What's so difficult about modeling extreme conditions?

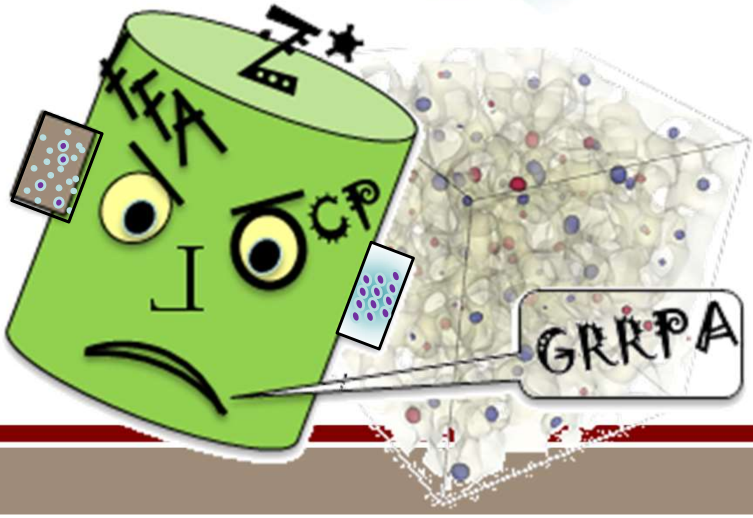
- HED plasmas are (usually) not well described by classical plasma models
  - Partial ionization complicates simple ion + electron pictures
  - Degeneracy effects invalidate classical statistics
  - Density effects distort quantum orbitals
  - Ions can be strongly coupled



- 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

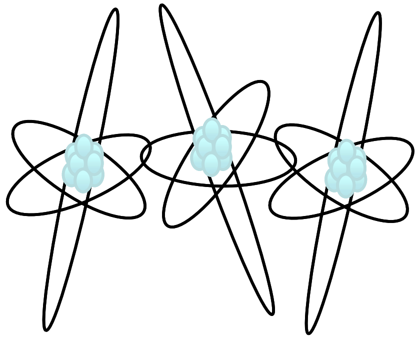


Central question: What happens to material when you squish it very hard and/or heat it quite a lot?

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

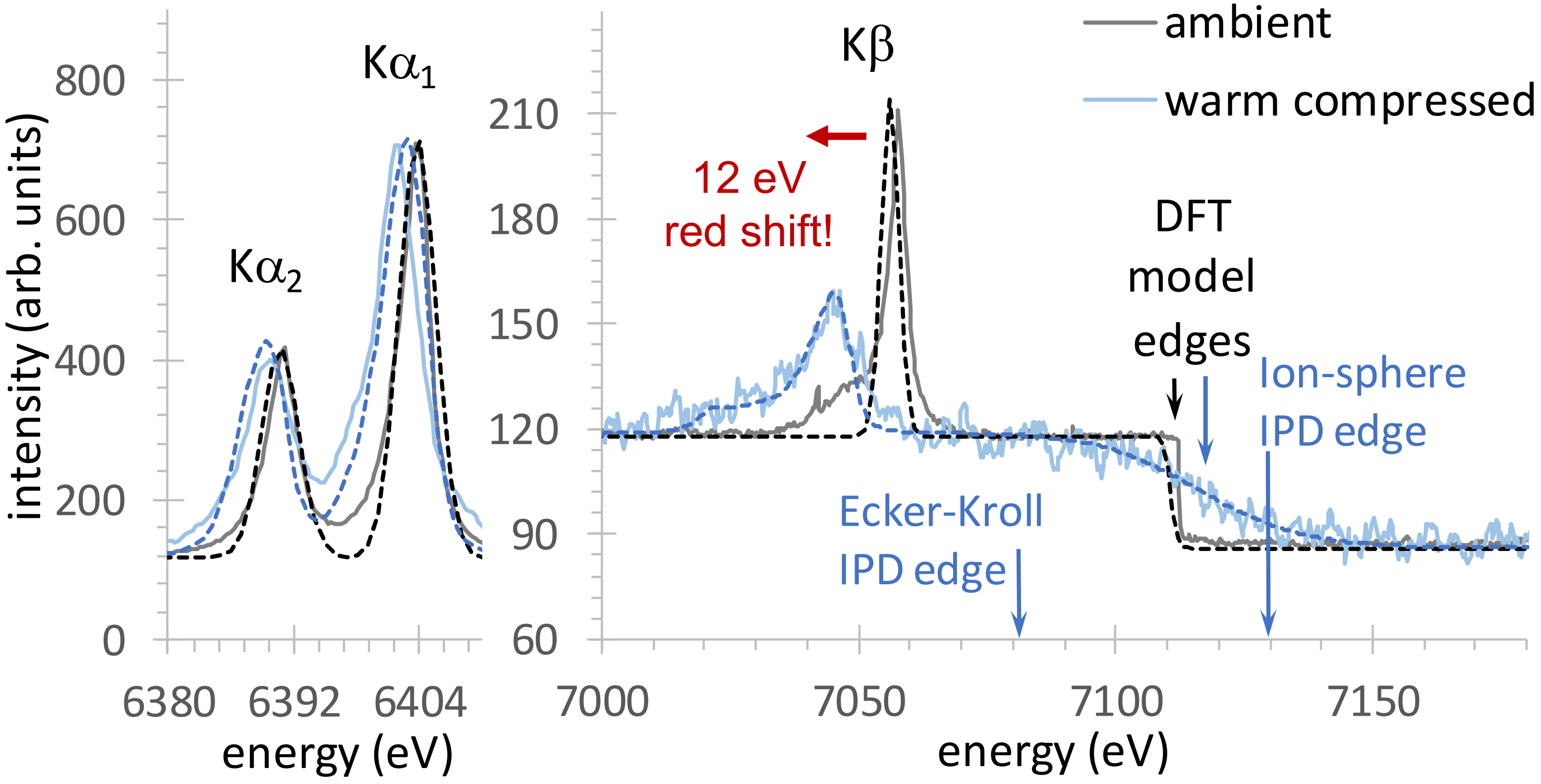
Reliable simulations themselves require extensive input from adequate material models (EOS, transport, opacity)

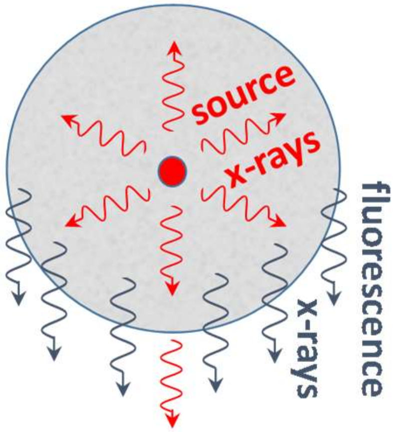
Additional questions:

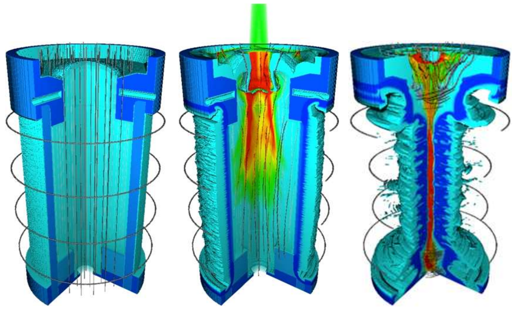
How can we tell if our models are right?

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 ~ 10 eV and n_e ~ 2x10^{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.

*Hansen et al, submitted