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Magneto-inertial fusion and high energy density science using pulsed power

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Sandia National Laboratories

For National Academies of Science High Energy Density Science Study

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

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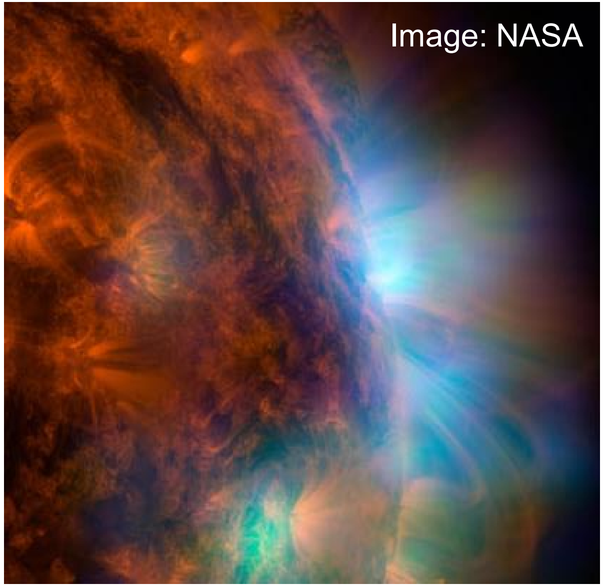
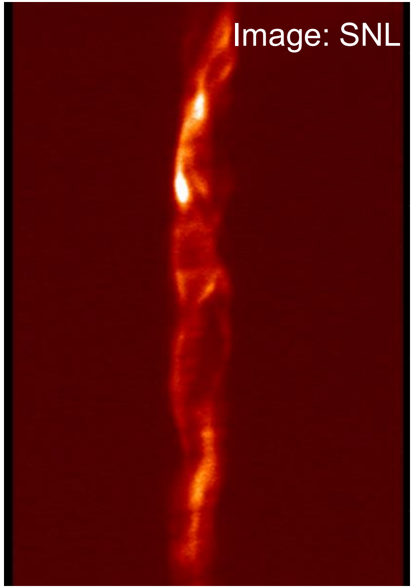
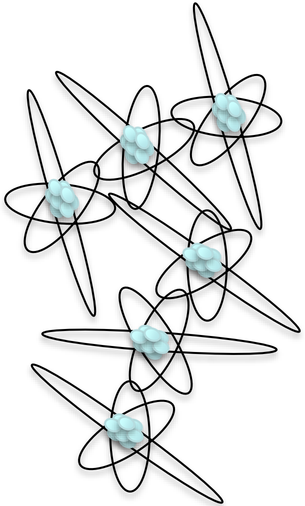


Astrophysics
10^{+9} meters
10^{+17} seconds



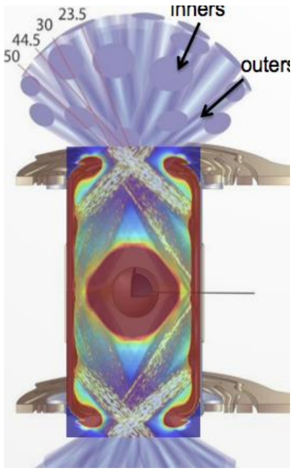
Fusion science
10^{-4} meters
10^{-9} seconds



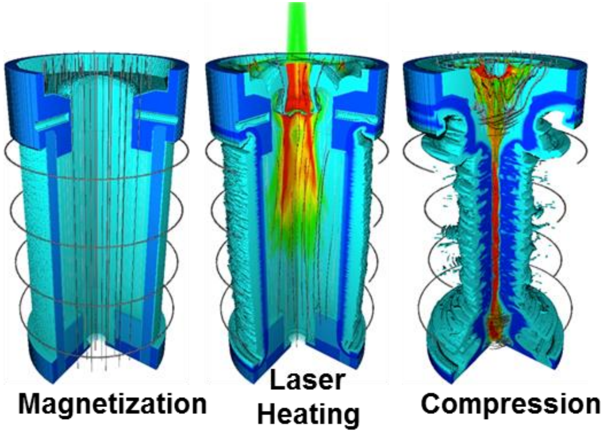
Atomic physics
10^{-10} meters
10^{-14} seconds

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

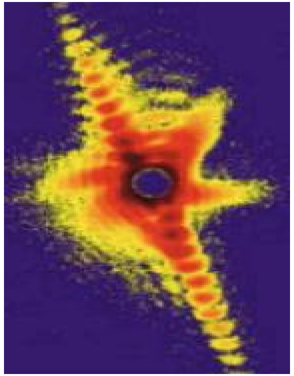
High energy density matter is created in experimental facilities that compress energy in space and time



LLNL's NIF:
422 MJ → 1.8 MJ in 10^{-8}s, 1 cm
~2 MJ/cc, ~200 TW/cc
~0.4% wall-plug efficiency

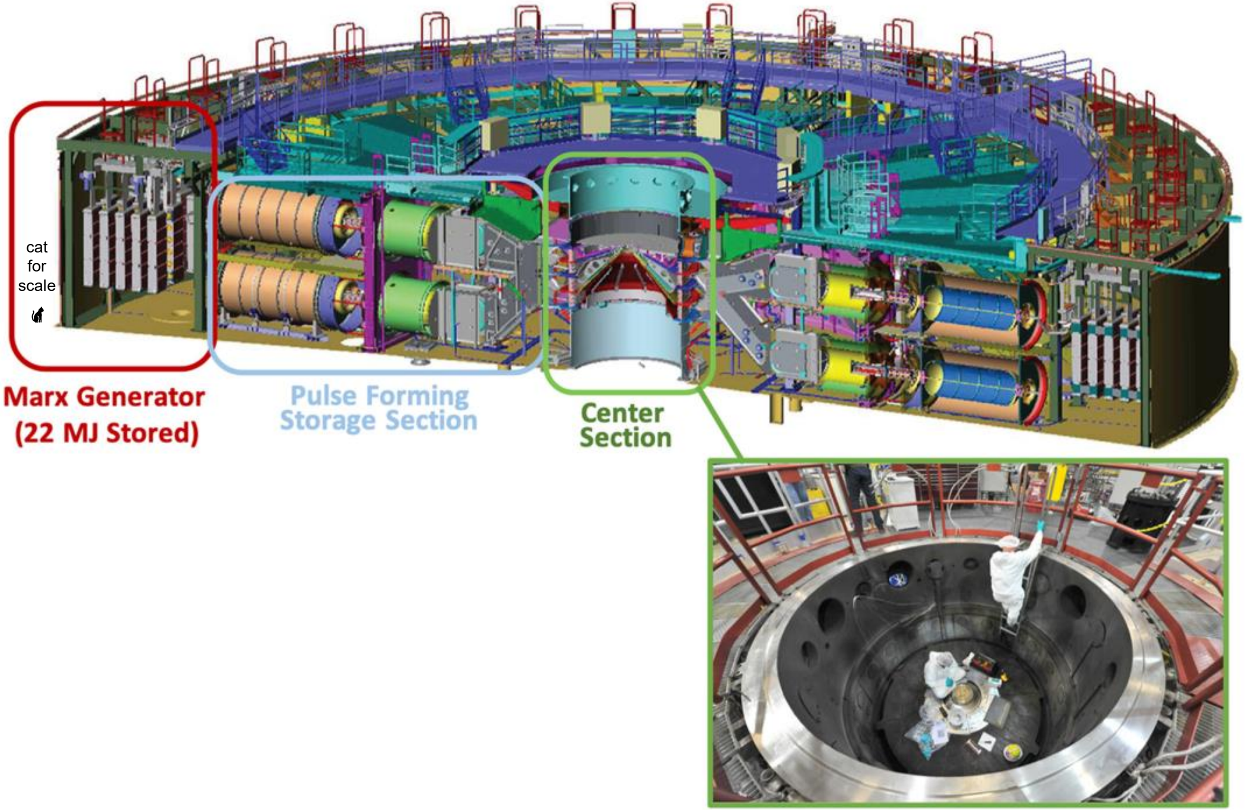


SNL's Z machine:
22 MJ → 0.5-1 MJ in 10^{-7}s, 1 cm
~1 MJ/cc, ~10 TW/cc
2 – 4% wall-plug efficiency



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)

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

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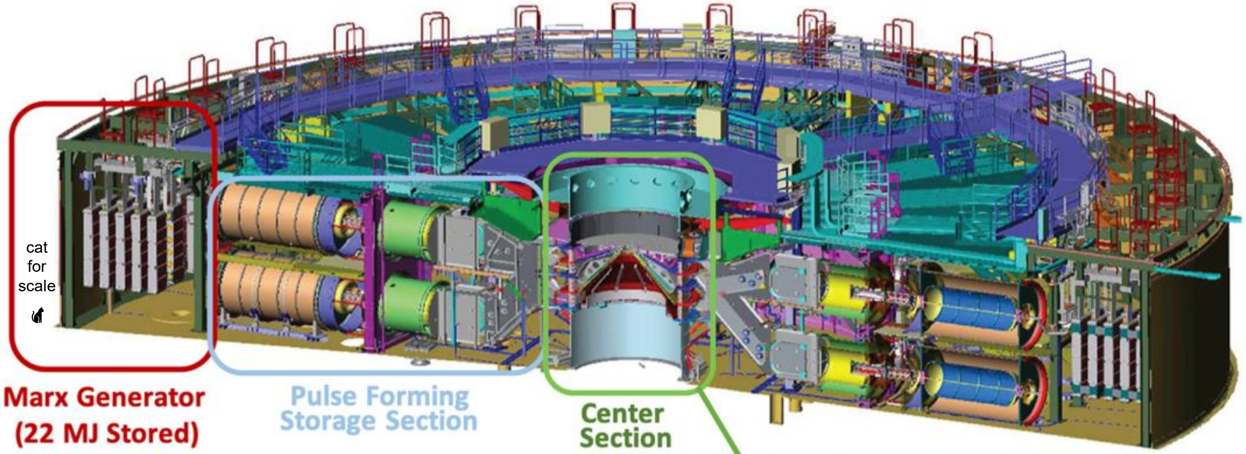
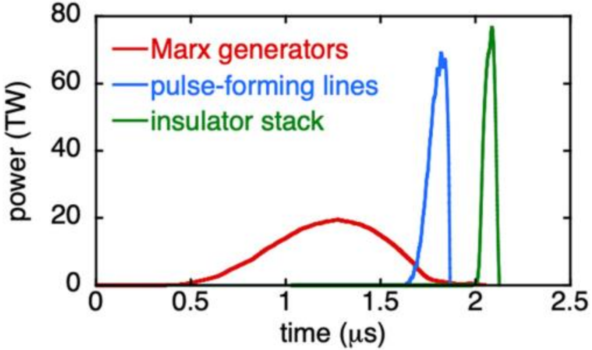
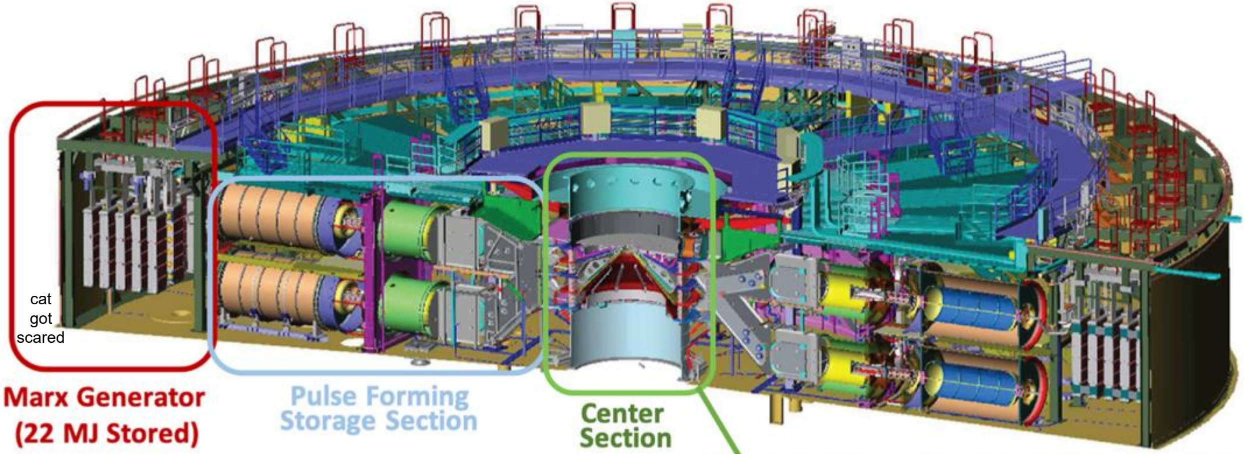
1. capacitors charge up from wall power in ~ 2 minutes (22 MJ)
2. current **j** is compressed in space and time to >20MA (>0.5 MJ to 1 cm in 100 ns)

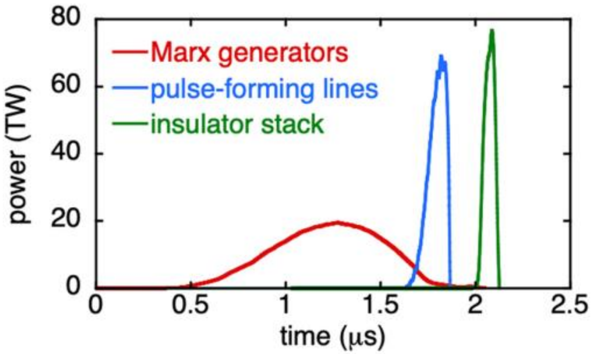




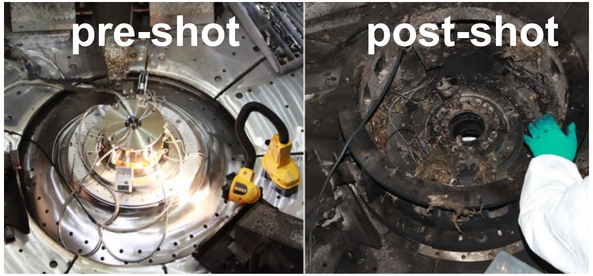
From Sinars et al, Phys Plasmas 27, 070501 (2020)

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)
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

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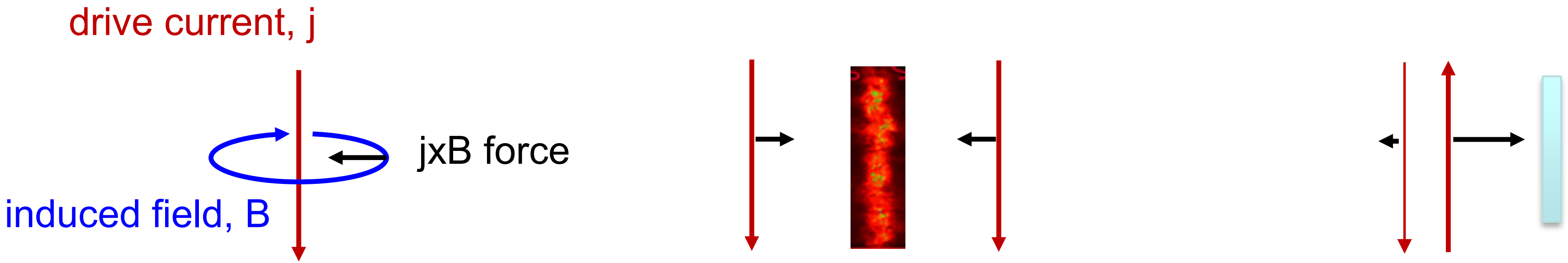
magnetic drive pressure ~ 60 Mbar $(j_{20MA}/r_{mm})^2$

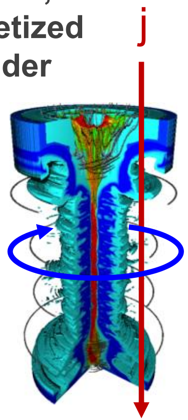


26 MA at r = 1 mm →
~100 Mbar pressures

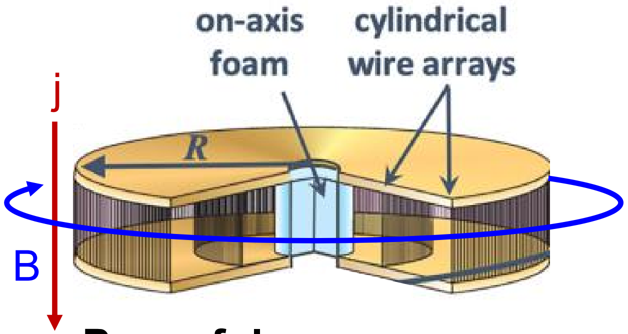
26 MA at r ~ 100 mm →
v ~ 1000 km/s

26 MA at r ~ 1 mm →
> Mbar shocks

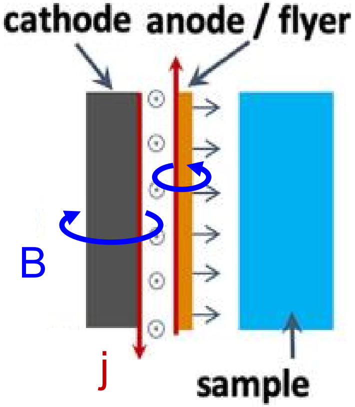
On Sandia's Z machine, we study a wide range of high energy density science using pulsed power



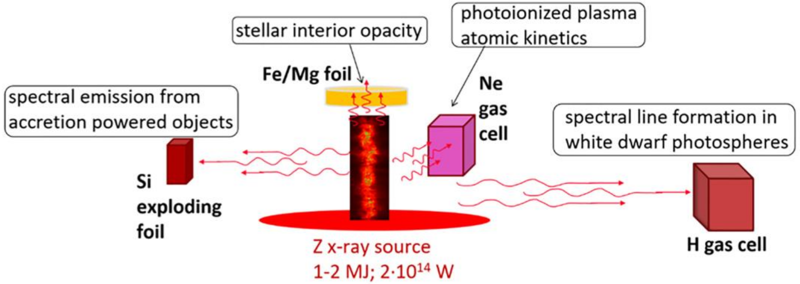
Magneto-inertial fusion
jxB heats and
compresses fusion fuel
(~1 Gbar, > kJ yields)



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



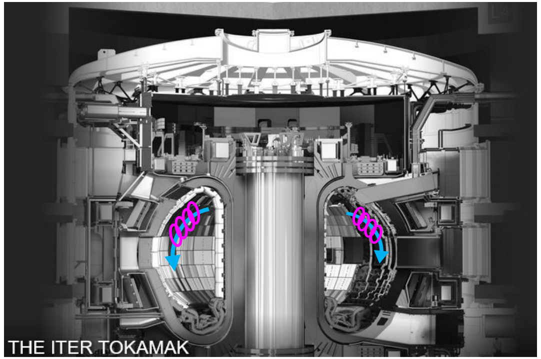
Materials science
jxB provides shock
or ramp compression
(~10 Mbar)



X-rays drive fundamental science experiments

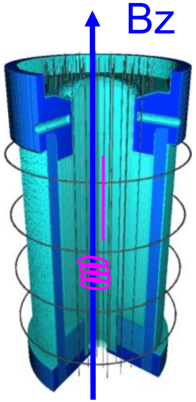
Magnetized Liner Inertial Fusion (MagLIF) combines aspects of magnetic and inertial confinement fusion

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



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

Burn requires plasma stability and high B



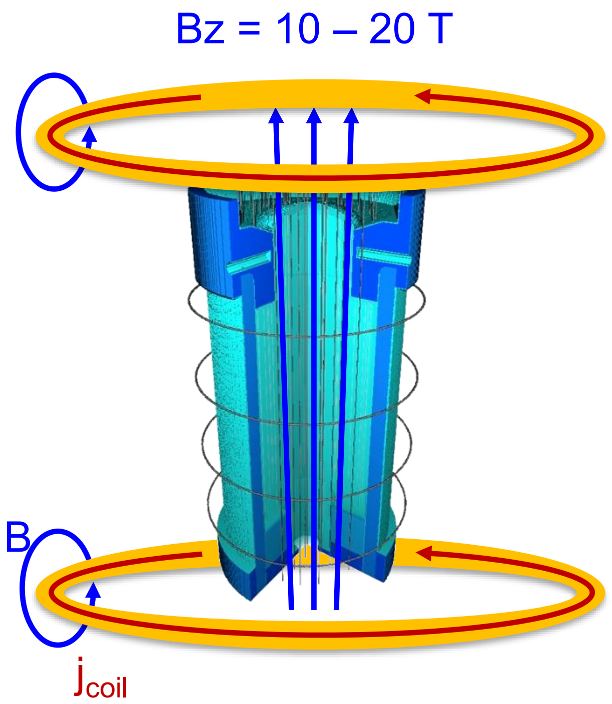
Magneto-inertial fusion (Z)
R ~ 10^{-3} m
P ~ 10^{9} bar
τ ~ 10^{-9} s
$P\tau$ ~ 1 bar-s

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

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

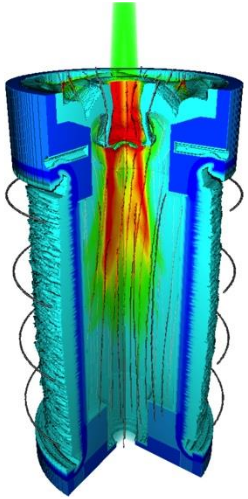
The imposed axial magnetic field prevents conduction losses that can cool the plasma below fusion temperatures

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

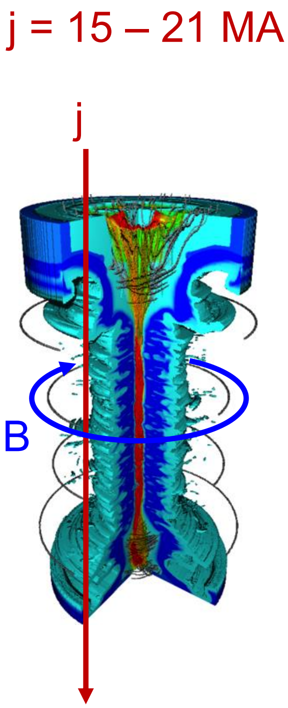


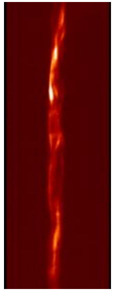
Stage 2: pre-heat the fuel

The 4kJ Z-Beamlet laser penetrates a thin window and preheats the fuel core to T ~ 200 eV, reducing the convergence required to reach fusion temperatures from pdV compressional work

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





Stage 3: compression

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

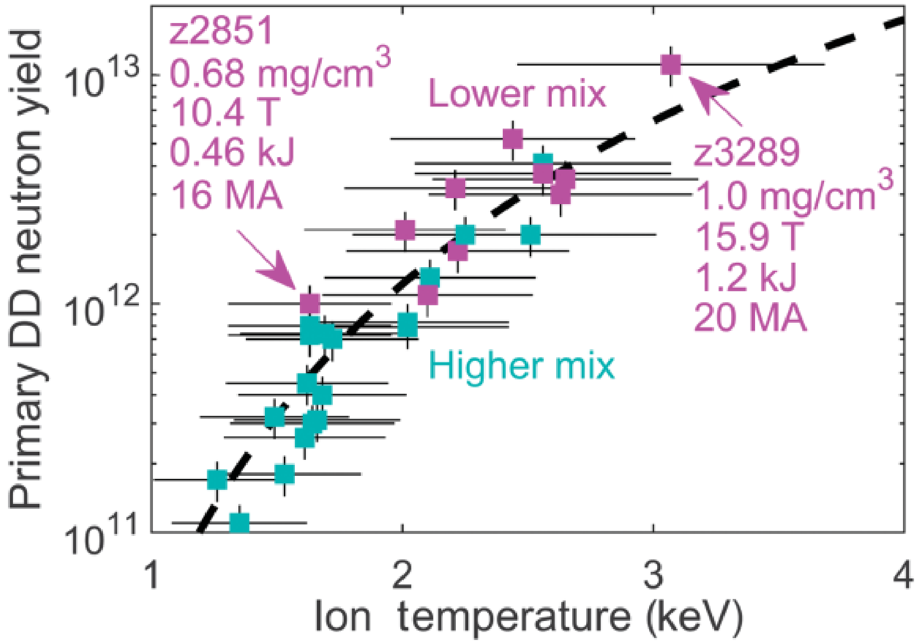
At stagnation, relatively stable plasma columns with helical structure yield ~10^{13} D-D neutrons (10^{15} D-T)

Neutron diagnostic 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



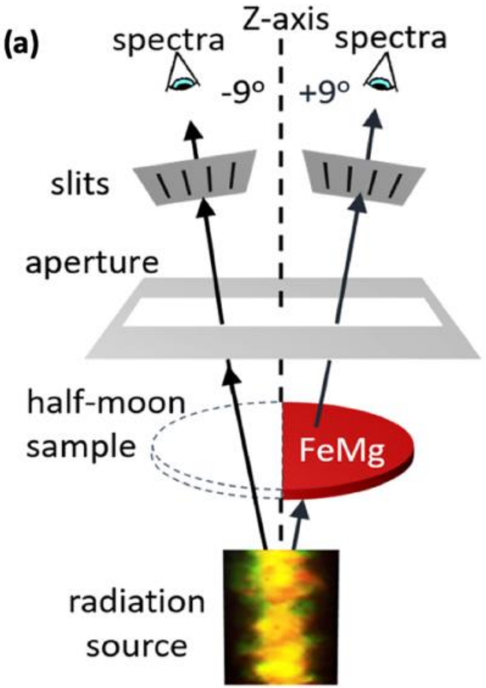
j(MA)	E_{laser}(kJ)	Bz(T)	Y(kJ)
15	0.5	10	0.2
20	1.2	20	2
22	6	30	80
60	30*	30	>1000

Z (rows 15, 20, 22 MA)

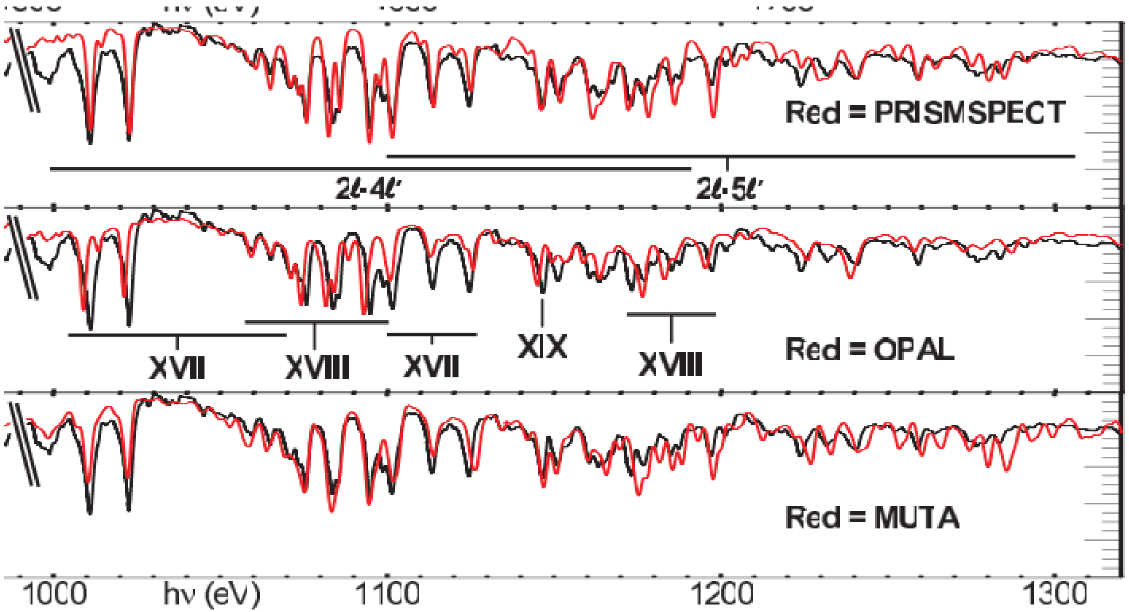
The efficiency of pulsed power opens paths to controlled high-yield fusion

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

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)

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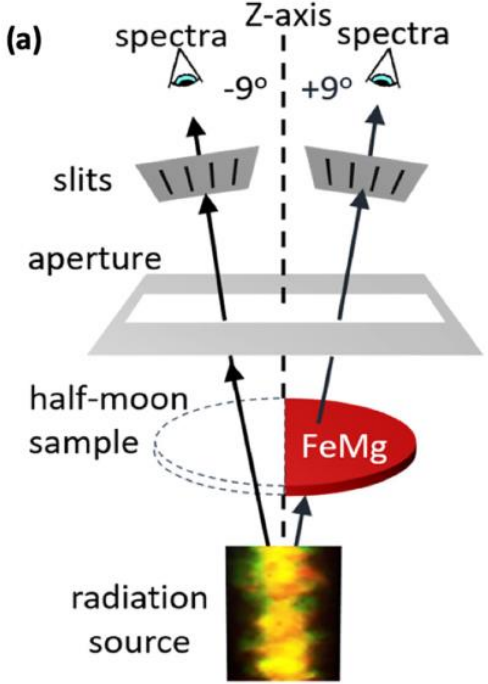
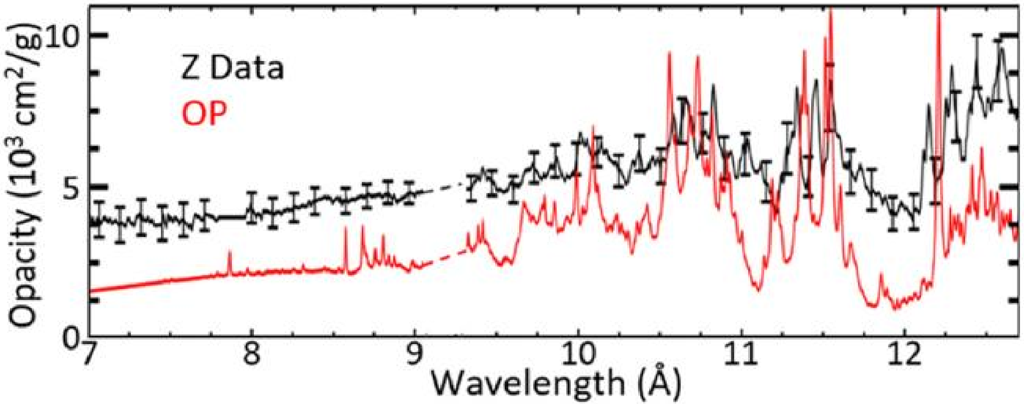


After a refurbishment of the Z machine enabled experiments at higher densities and temperatures, Bailey at al found surprising disagreement between models and experiments



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)

Key opportunities and existing gaps in pulsed power ICF/HEDP

- Z has been an engine of discovery: designed in 1996 to drive wire arrays, today 90% of Z shots are on ~5 platforms developed in the last 10-20 years. This innovation and diversity offers risk mitigation for ICF scaling and profound opportunities for fundamental science, but challenges personnel, target fab, diagnostics, & machine operation & design

- Community (esp. science of pulsed power) is small, with people/funding/historical effort 10-100x less than laser community – and mid-scale university facilities that drive innovation & support pipeline have uncertain futures

- Pulsed power drivers are inherently coupled to targets/loads through the load inductance; matching machines to loads increases efficiency (but requires people & design tools) (Even "low efficiency" PP is ~1% → high yield ICF)

- While current loss mechanisms tend to be linear and self-limiting, we do not yet have predictive whole-machine models that predict loss & attendant plasma flow to load

- Measurements of current flow at the target surface are difficult; existing simulation codes have significant & fundamental uncertainties in low-density/near-vacuum regions that are compounded by uncertainty in loss models

- Target design and diagnostic interpretation rely on constitutive data across a very wide range of temperature-density regimes in which only a handful (literally ~ 5) of true benchmarks are available

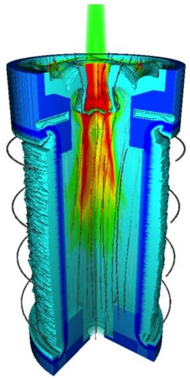
High energy density science with pulsed power relies on strong ties with larger communities

rad-hydro & PIC communities

Machine & target simulations

MagLIF preheat & x-ray backlighting

laser community



X-ray and neutron yields, images, and spectra

diagnostics community

atomic & materials science communities

Fundamental material properties

Target fabrication, advanced computing, astrophysics applications, technicians & operations

Essential collaborative communities