Exceptional service in the national interest

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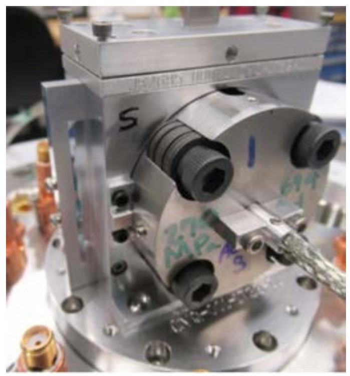
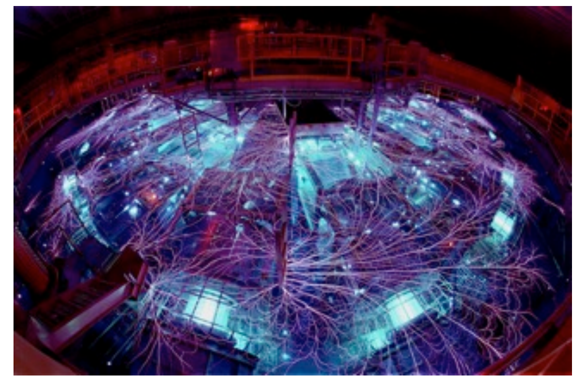




Fusion & High Energy Density Plasma Science Opportunities using Pulsed Power

Daniel Sinars, Sandia National Laboratories

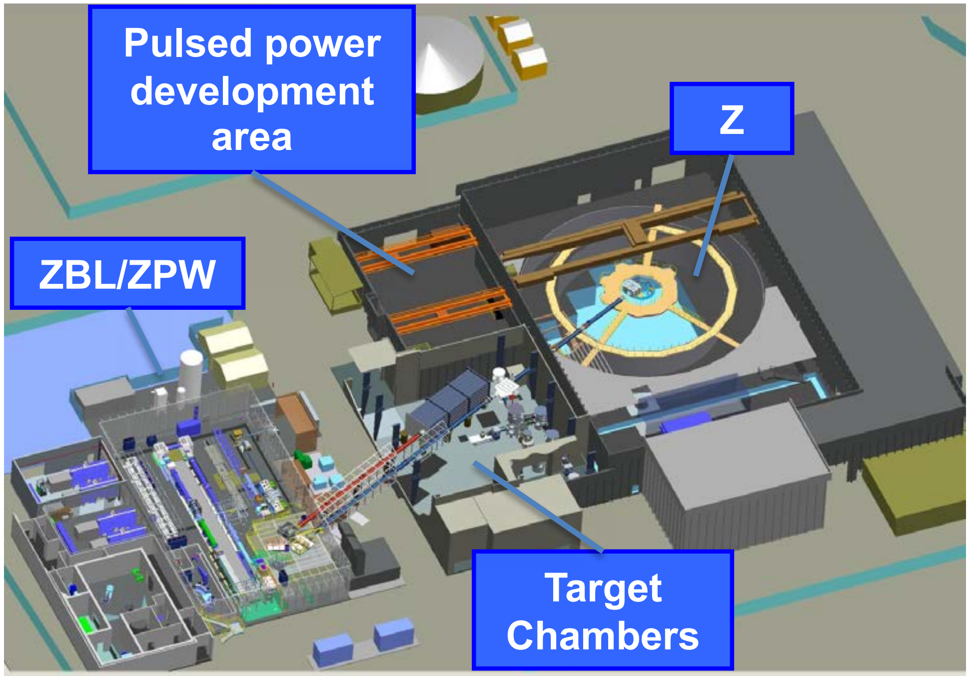
Fusion Power Associates

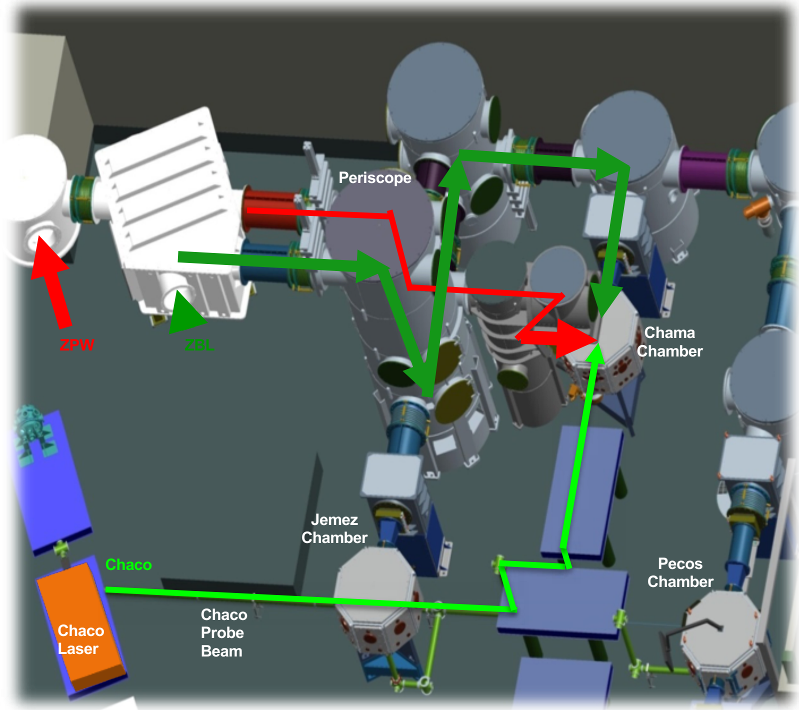
Dec. 4-5, 2018

U.S. DEPARTMENT OF ENERGY

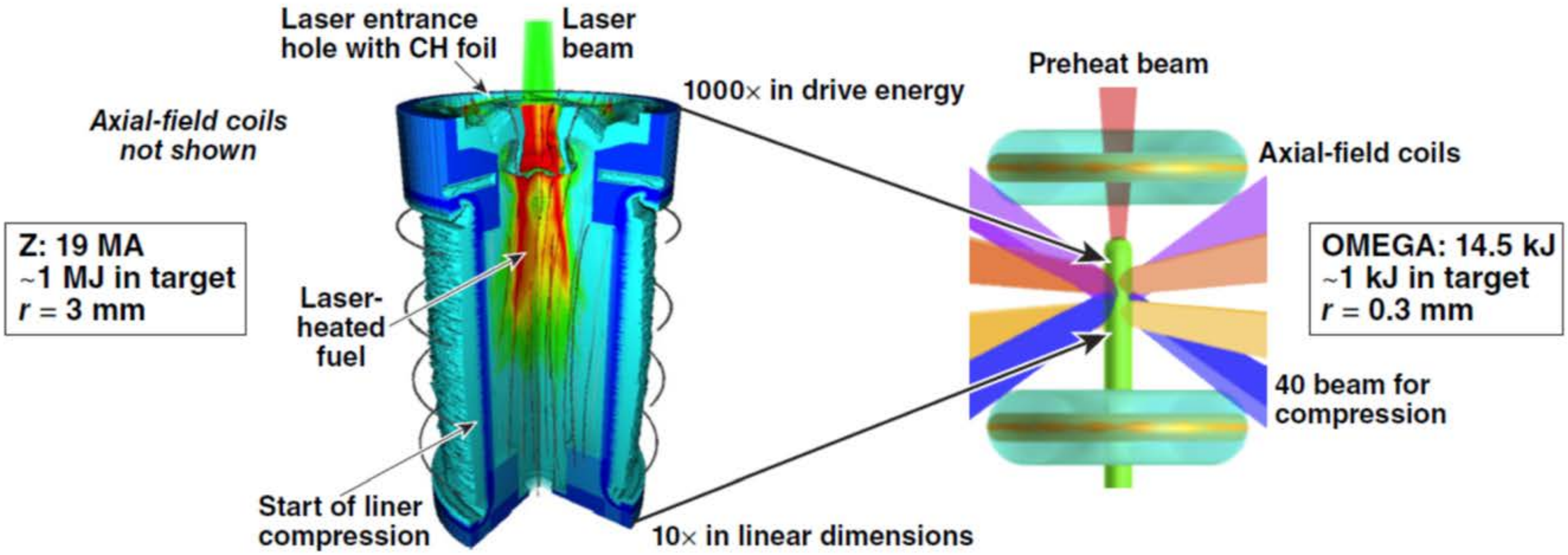
NNSA National Nuclear Security Administration

Sandia is the home of Z, the world's largest pulsed power facility, and its adjacent multi-kJ Z-Beamlet and Z-PW lasers

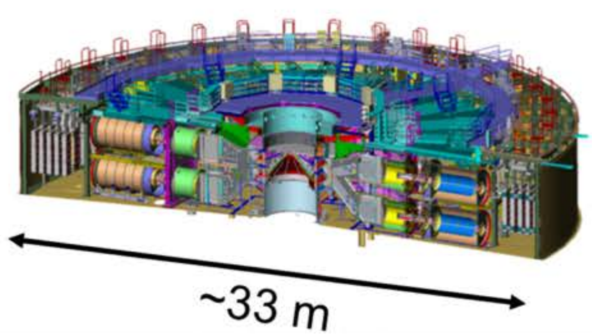




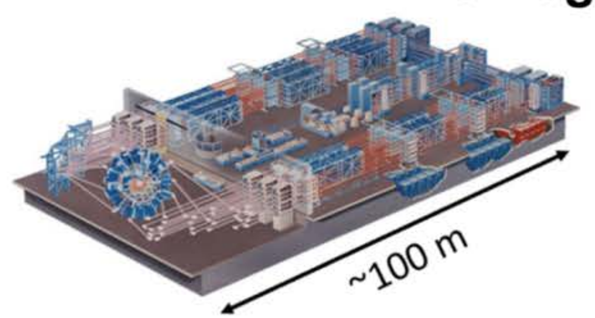
Using two HED facilities, we have demonstrated the scaling of magneto-inertial fusion over factors of 1000x in energy



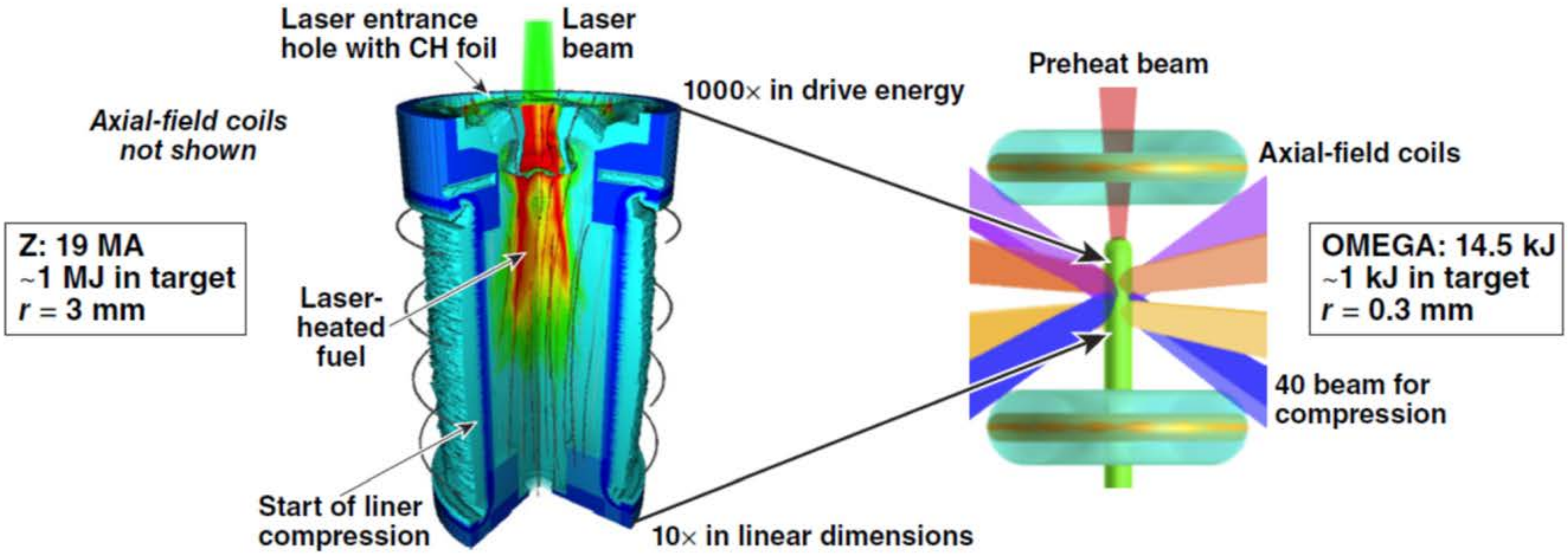
Z Facility



Omega Facility



Our fusion yields have been increasing as expected with increased fuel preheating and magnetization

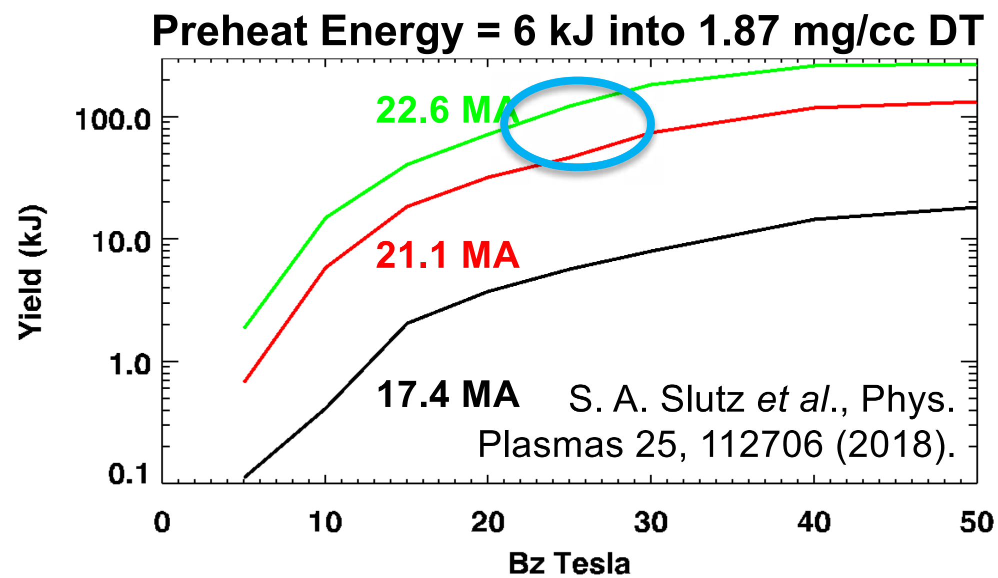


<u>Progress since 1st MagLIF in 2014</u>
- Improved laser energy coupling from ~0.3 kJ to 1.4 kJ
- Demonstrated 6x improvement in fusion performance, reaching 2.5 kJ DT-equivalent in 2018

<u>Demonstrated platform on Omega</u>
- Improved magnetic field strength from 9 T to 27 T
- Achieved record MIF yields on Omega of 5×10^9 DD in 2018

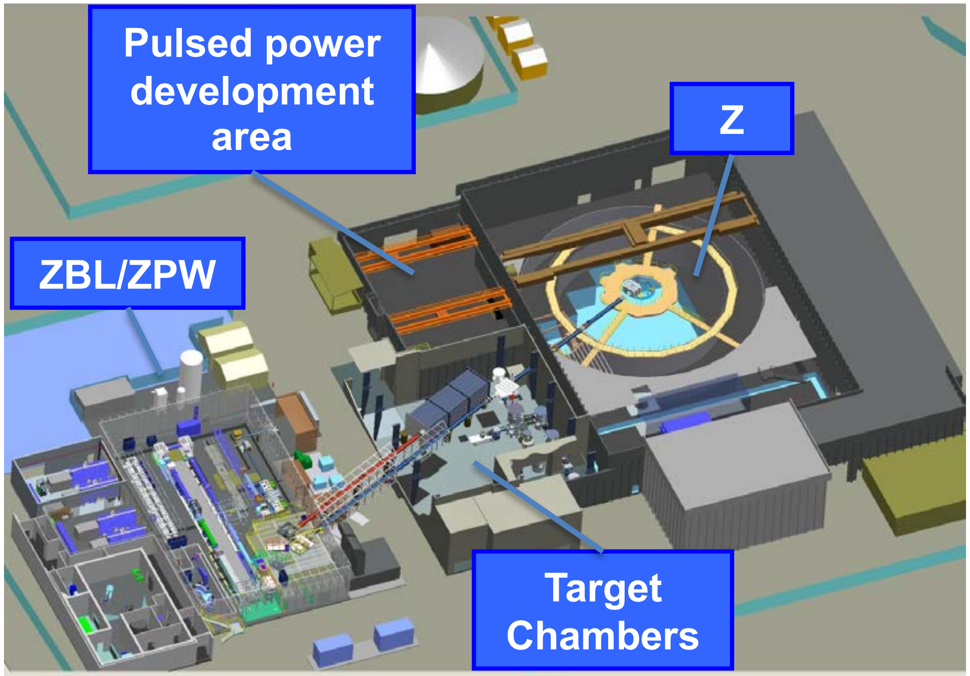
We believe that Z is capable of producing a fusion yield of ~100 kJ DT-equivalent with MagLIF, though doing it with DT would exceed our safety thresholds for both T inventory & yield

- 2D simulations indicate a 22+ MA and 25+ T with 6 kJ of preheat could produce ~100 kJ
- Presently, we cannot produce these inputs simultaneously.

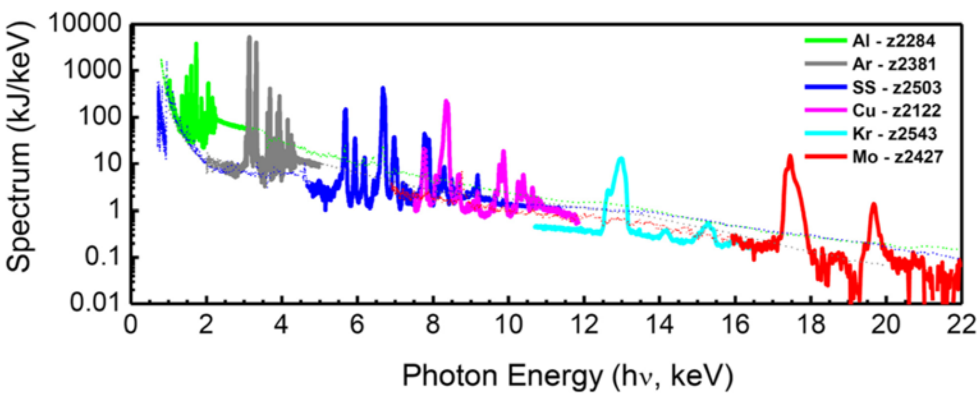


Date	Liner	D2 Fill (mg/cc)	Current (MA)	Bfield (T)	Preheat (kJ)	Yield if DT fuel was used (kJ)
2014	AR=6	0.7	17-18	10	~0.5	0.2-0.4
Aug. 2018	AR=6	1.1	19-20	15	1-1.4	2.4
2020 Goal	TBD	1.5	20-22	20-30	2-4	~10
>2020	TBD	1.5	21+	25+	6+	100

The Z facility is applied to a wide range of plasma science today, and further opportunities exist going forward

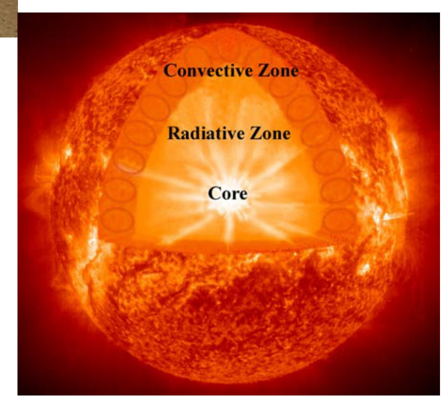


Dynamic Materials Research



Multi-keV x-ray sources

Soft x-ray sources for fundamental science



Stellar physics
Fe opacity and H spectra

The co-location of both laser and pulsed power facilities has been an enabling factor in our ability to do plasma science

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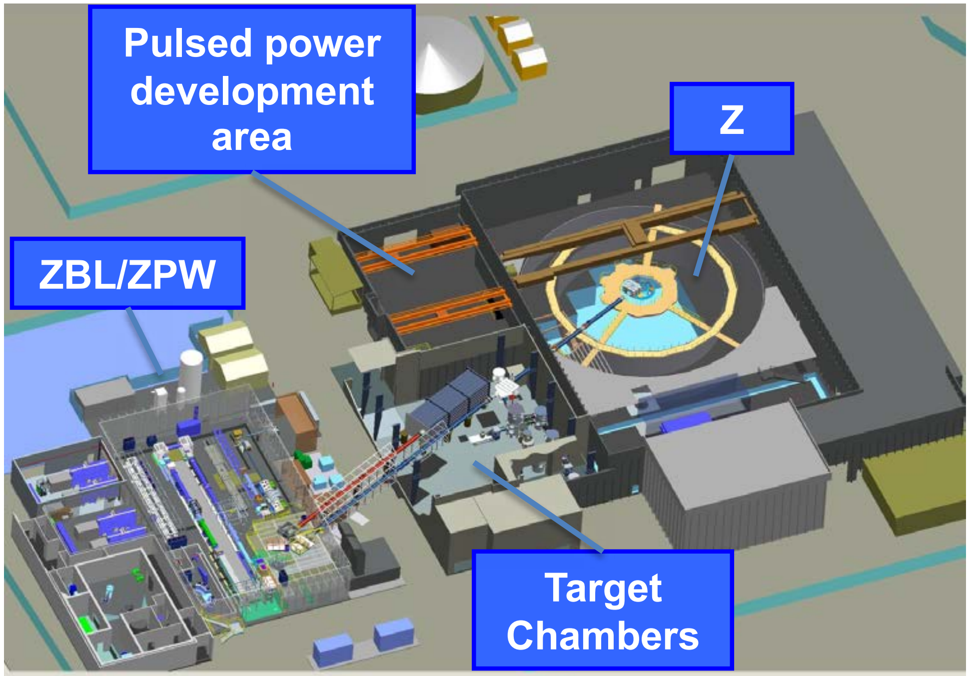
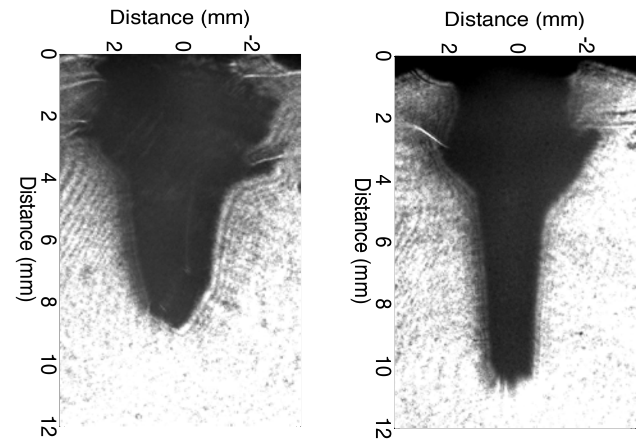
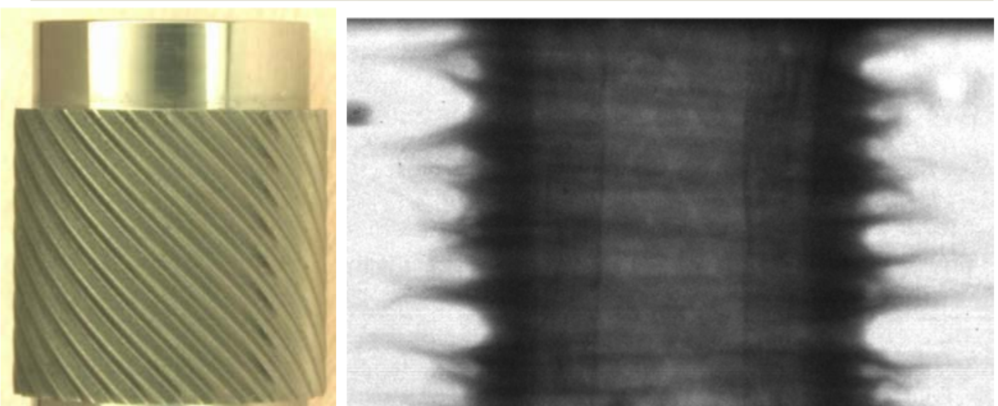
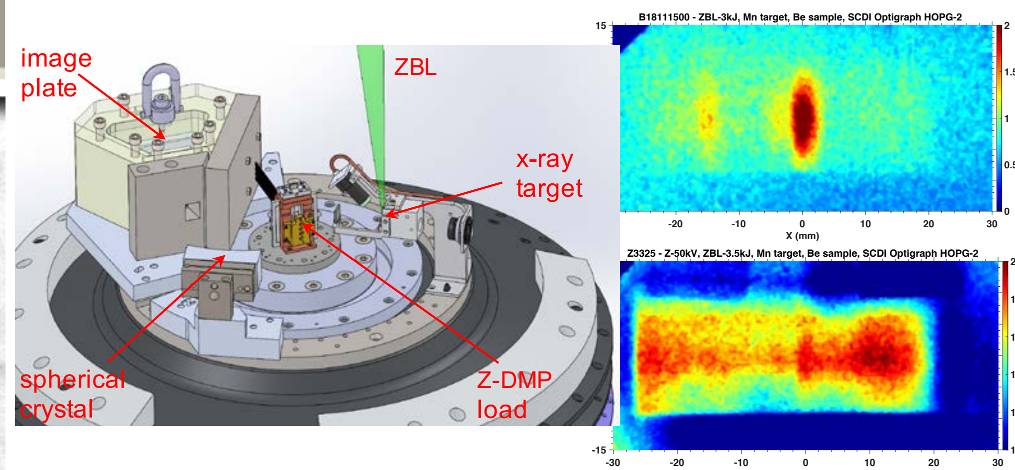




Developing plasma heating protocols for MagLIF



X-ray backlighting for implosion physics

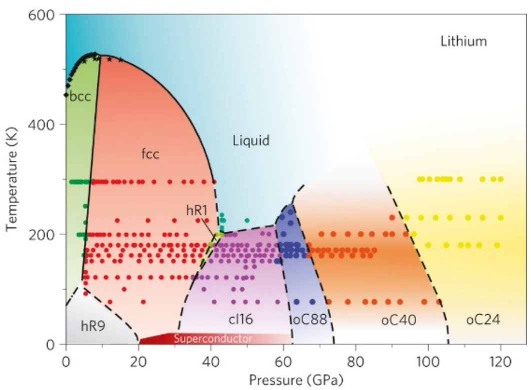


X-ray diffraction for dynamic material science

Over the next year, we will begin installing booster amps to bring Z-Beamlet to 6 kJ

Today Z is routinely used to study a wide range of multi-Mbar material science questions—pulsed power can drive large samples at relevant strain rates

- Key physics questions
  - Role of microstructure
  - Kinetics and phase transitions
  - Strength
  - Transport properties
  - Radiation shock

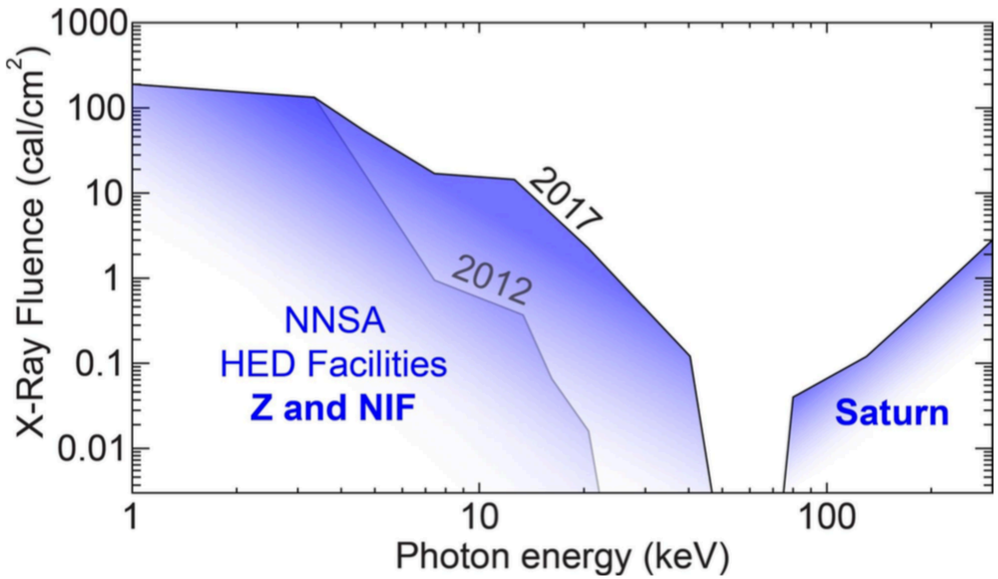


Phase diagram of lithium showing a number of solid phases with a large degree of uncertainty

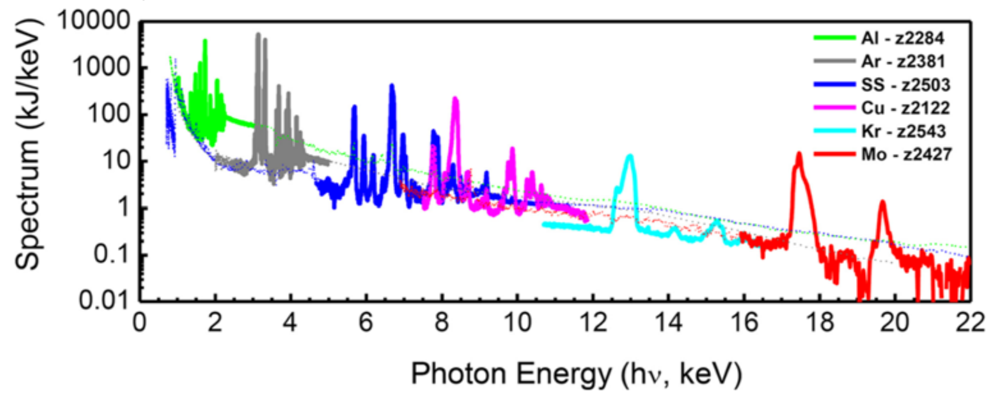
Image from electron backscattering diagnostic of grains in an additively-manufactured stainless steel. The different colors represent different grain orientations.

Image of Z explosive containment system used to contain debris from experiments with hazardous materials such as plutonium

Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV x rays



Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV yields

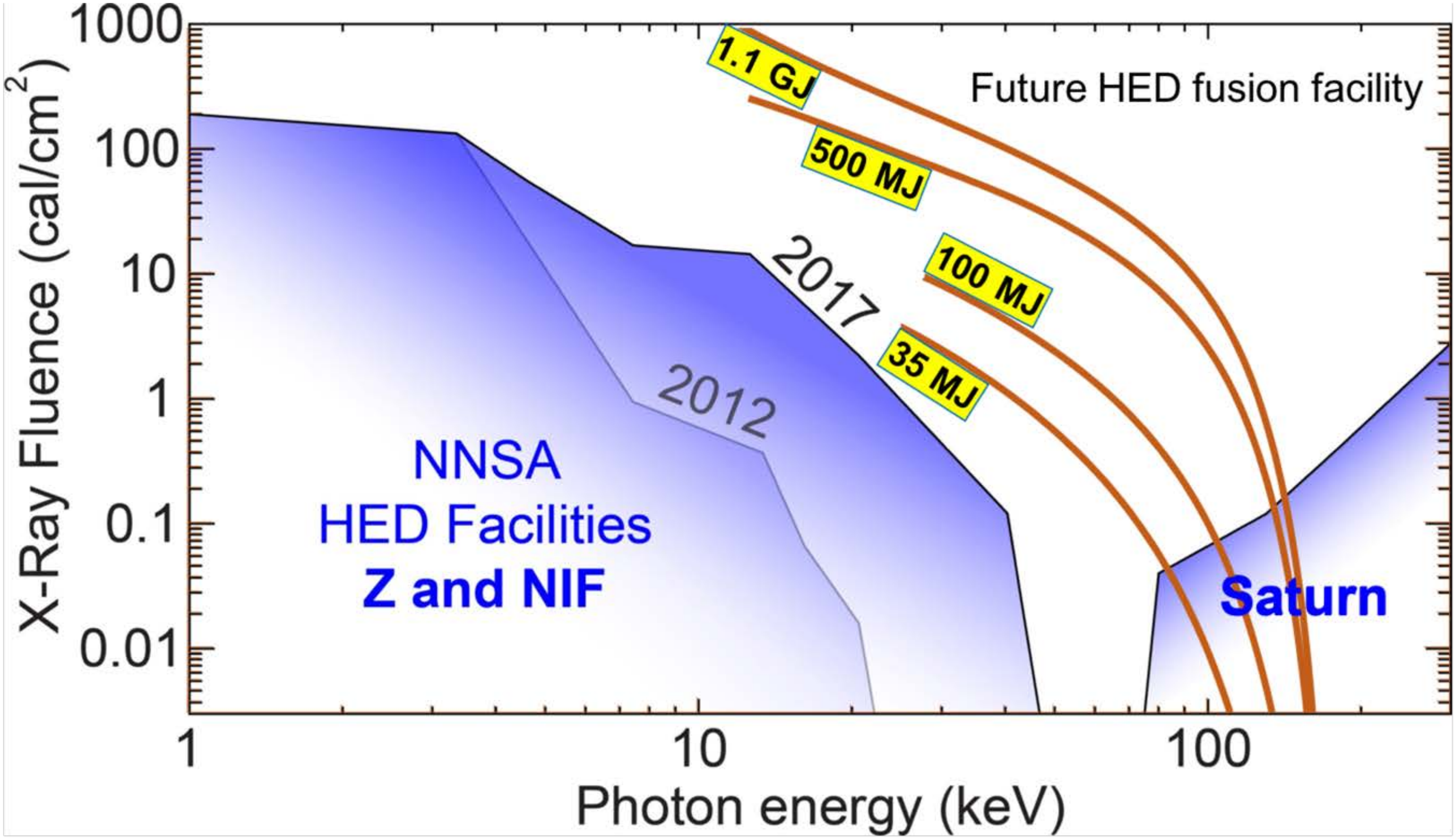


These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays

e.g., Studies of high-rate thermal degradation of polyethylene, where ~3 keV x-rays can heat ~100 microns of material at ~10^{12} K/s.
Lane & Moore, Phys. Chem. A 122 (2018).

D.J. Ampleford *et al.*, Phys. Plasmas 21, 056708 (2014).

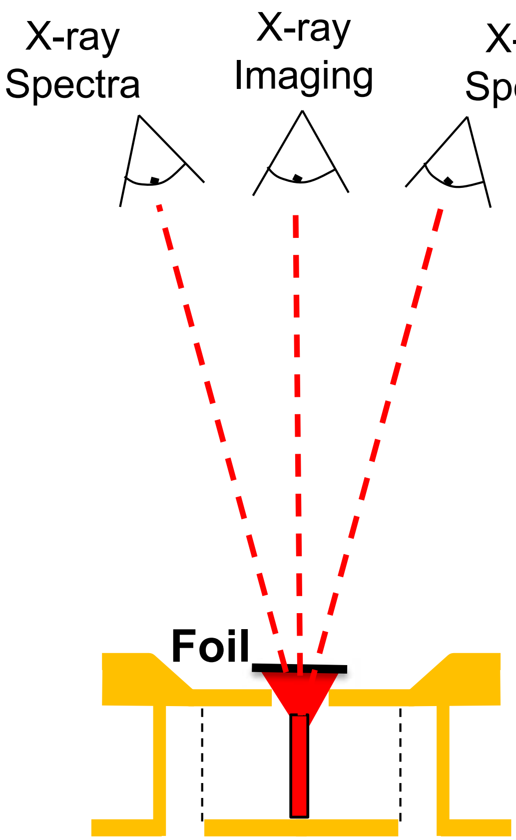
Future high yield fusion facilities could provide even more powerful sources of 10-100 keV x rays



Calculations done using MagLIF targets, but output curves are only weakly dependent on the specific target

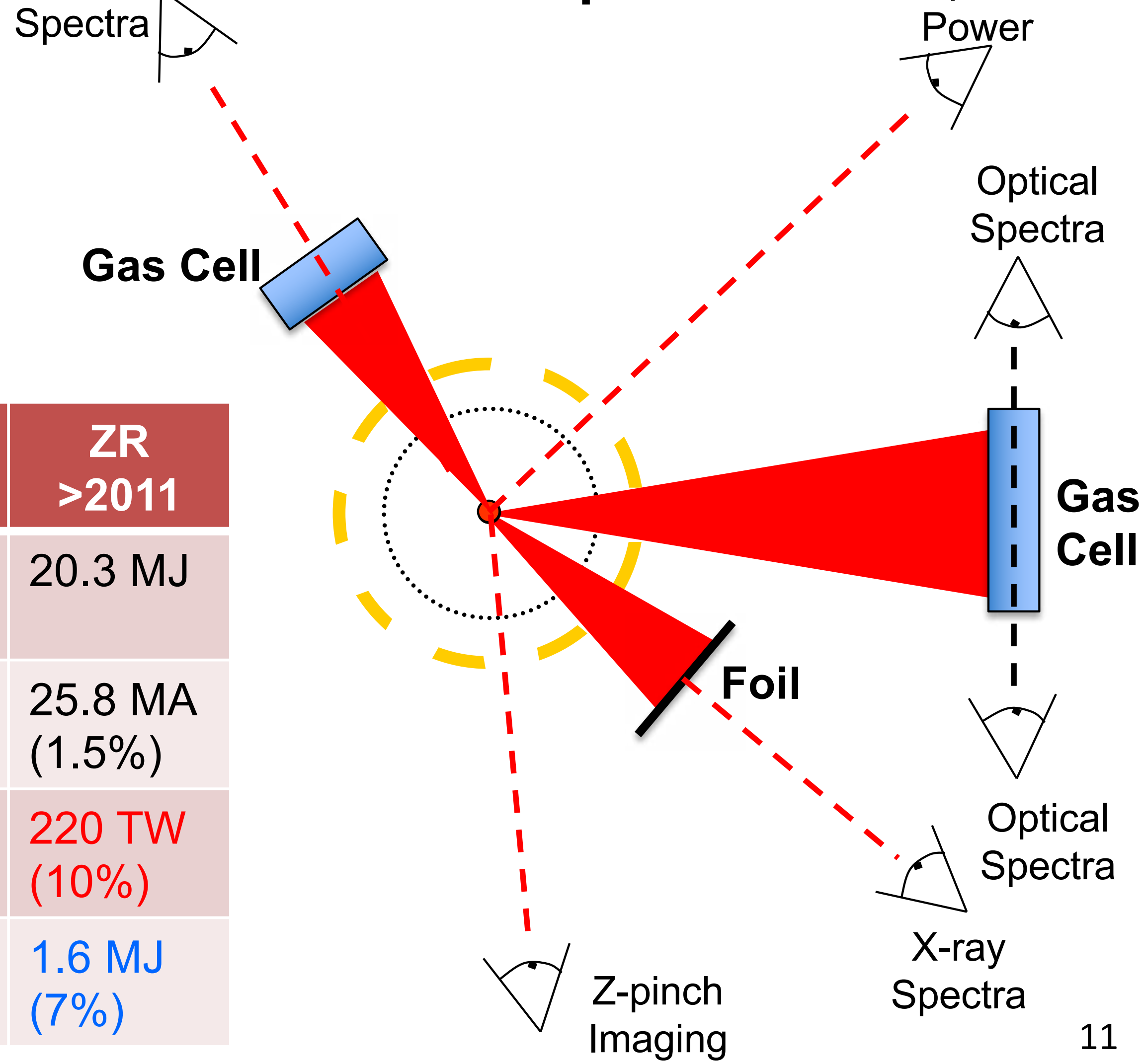
Some Z researchers use powerful soft x-ray sources to radiatively heat samples placed around the z-pinch up to T_e~200 eV, allowing multiple simultaneous experiments on a Z shot

1 Axial Experiment

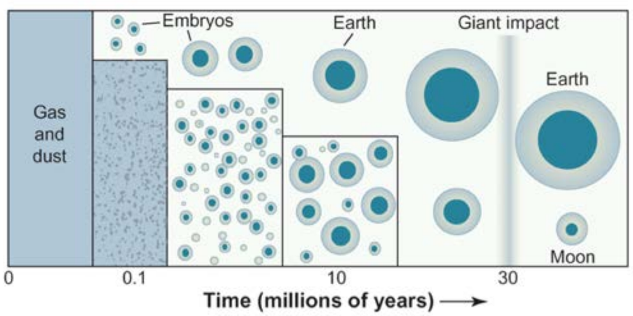


	ZR >2011
Z Marx Energy	20.3 MJ
Peak Current	25.8 MA (1.5%)
Peak Power	220 TW (10%)
Radiated Energy	1.6 MJ (7%)

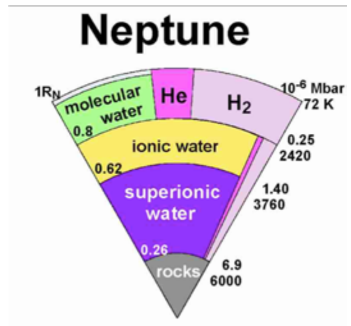
3 Radial Experiments



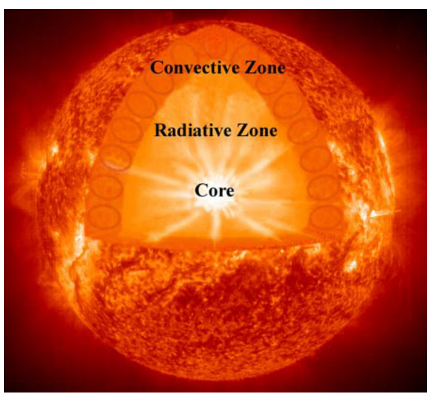
Our radiation and materials platforms are heavily used by academic partners as part of Sandia's Z Fundamental Science Program



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

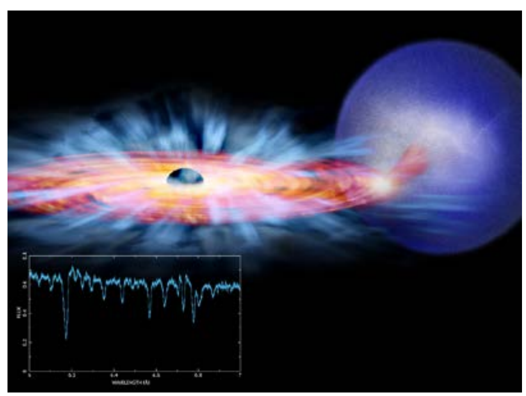


Photo-ionized plasmas
Range of ionization param. ξ

- Scientists at Sandia partner with academic researchers to study cutting-edge high energy density science
- Competitive proposal process
- NNSA provides experimental time on Z, academic partners provide their own support and some equipment
- Has resulted in great science that benefits both academic and applied research efforts on Z!

Five major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program

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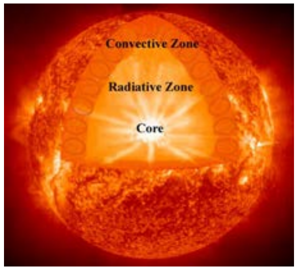
Solar Model

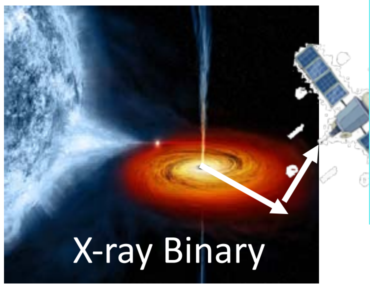


1 µg of stellar interior at R ~ 0.7Rsol

A higher-than-predicted measurement of iron opacity at solar interior temperatures

Jim Bailey, et. al., Nature **517**, 14048 (2015)

Black hole accretio



10^{-3} liters of accretion disk at R ~ 100 – 1000 km from black hole

Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources

G. P. Loisel, J. E. Bailey, et. al., Physical Review Letters **119**, 075001 (2017)

White dwarf photosphere

~0.1 liters of white dwarf photosphere

Laboratory Measurements of White Dwarf Photospheric Lines: HB

Ross Falcon, et. al., The Astrophysical Journal **806** (2015)

1.3 mg (0.8 µL) of metallic hydrogen

Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

Marcus D. Knudson, Michael Desjarlais, et. al., Science **348**, 1455 (2015).

Planetary physics

20 mg (2.5 µL) shocked iron

Impact vaporization of planetesimal cores in the late stages of planet formation

Richard D. Kraus, Seth Root, et. al., Nature Geoscience, DOI:10.1038/NGEO2369 (2015)

We are exploring a modular architecture that might scale to 300-1000 TW and is twice as electrically efficient as Z

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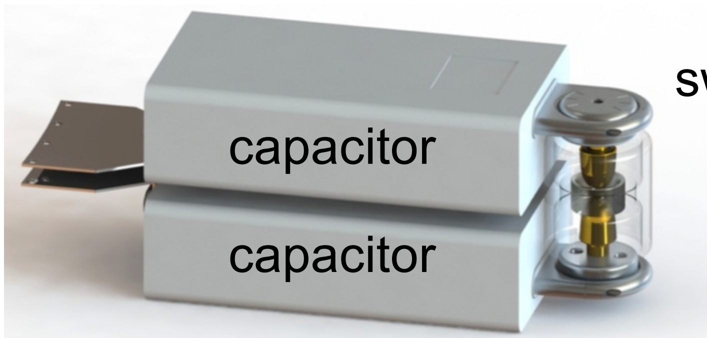
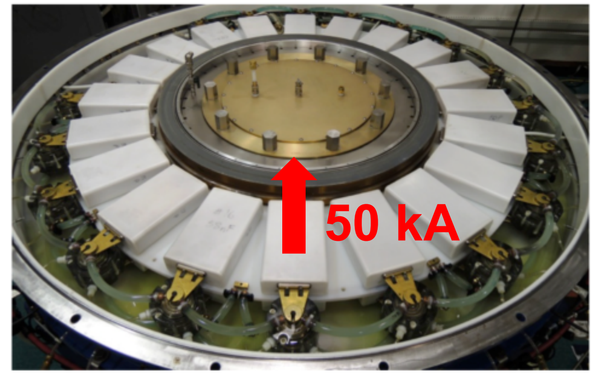
Brick – "quantum" of the next gen systems
Single step pulse compression to 100 ns



switch

5.2 GW/800 J per brick

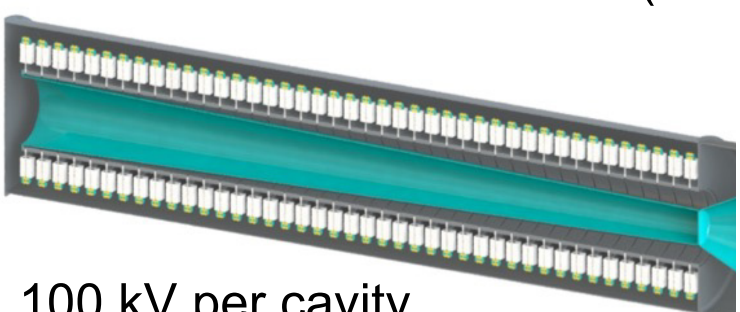
Cavity – multiple bricks in parallel



50 kA per brick

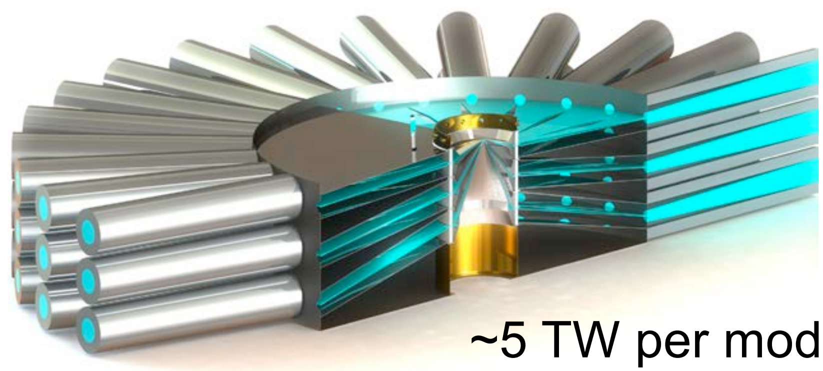
Module – multiple cavities in series

Linear Transformer Driver (LTD)



100 kV per cavity

Machine – multiple modules and levels in parallel



~5 TW per module

Next-gen machines: 20,000-200,000 bricks, 33-60 cavities/module, and 65-800 modules!

W.A. Stygar *et al.*, PRSTAB (2007); W.A. Stygar *et al.*, PRSTAB (2015); W.A. Stygar *et al.*, Proc. IEEE PPC (2017).

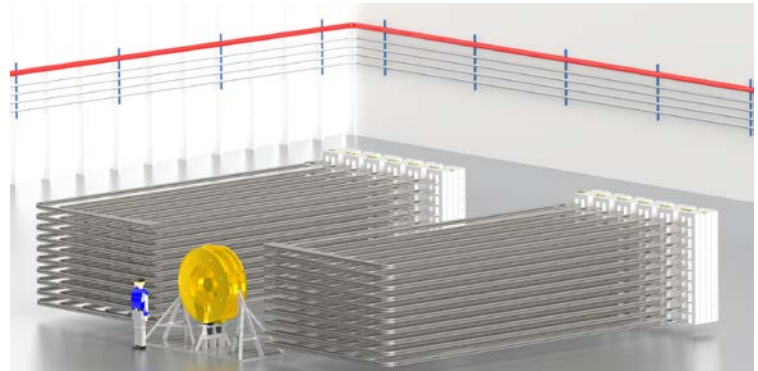
Bricks are a basis for other driver architectures, e.g., multi-MA arbitrary waveform generators for material science

Brick

Thor-72 (0.5 Mbar)

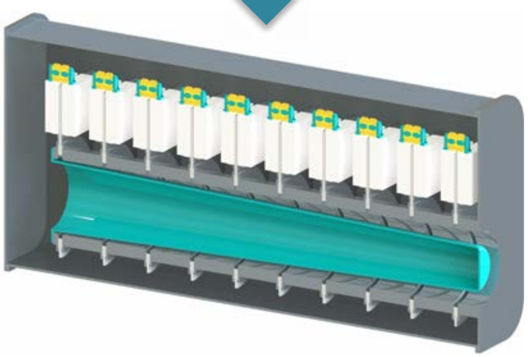
4 MA, 200 ns

Thor-240 (1.2 TW, 2 Mbar)



Reisman *et al.*, PRSTAB 18 (2015).

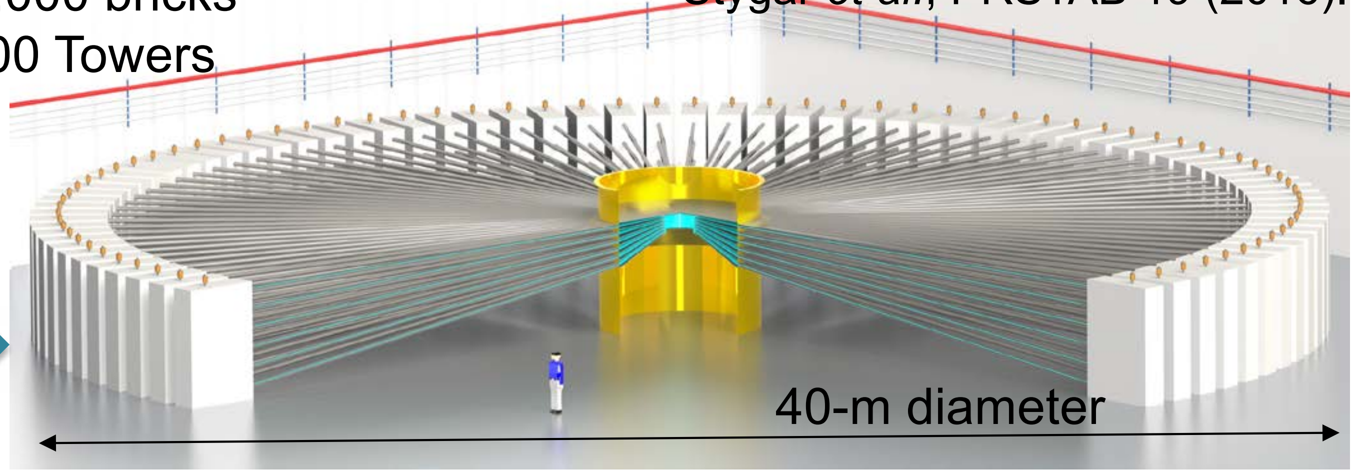
7 MA, 200 ns



10-stage Impedance Matched Marx Generator (IMG)

4,800 IMGs
48,000 bricks
800 Towers

Neptune (50 TW, 20 MBar)



Stygar *et al.*, PRSTAB 19 (2016).

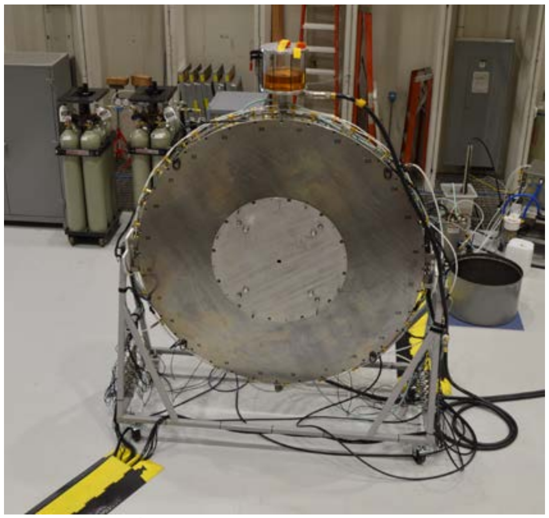
23 MA, 750 ns

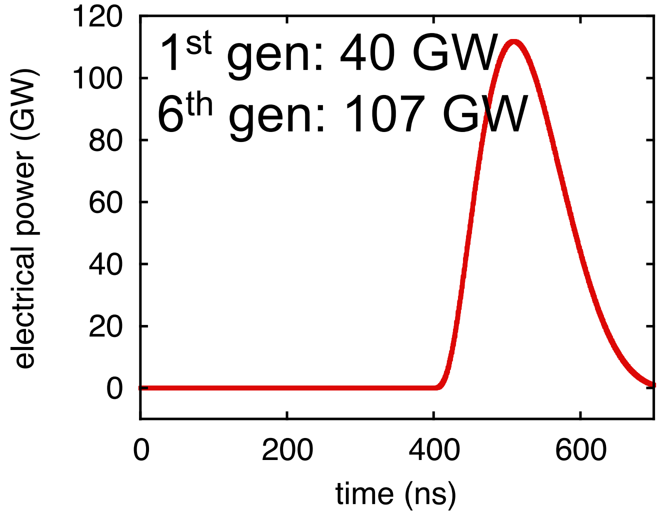
We have developed an extremely flexible pulsed power driver for materials science using cable pulser technology

- Up to 72 transit-time-isolated, independently triggered pulsed energy sources create unique pulse shapes at the load (today)
- 150-600 kbar pressures in mm-scale material samples (today)
- Recently signed a memorandum for collaborative research with UNM using this facility

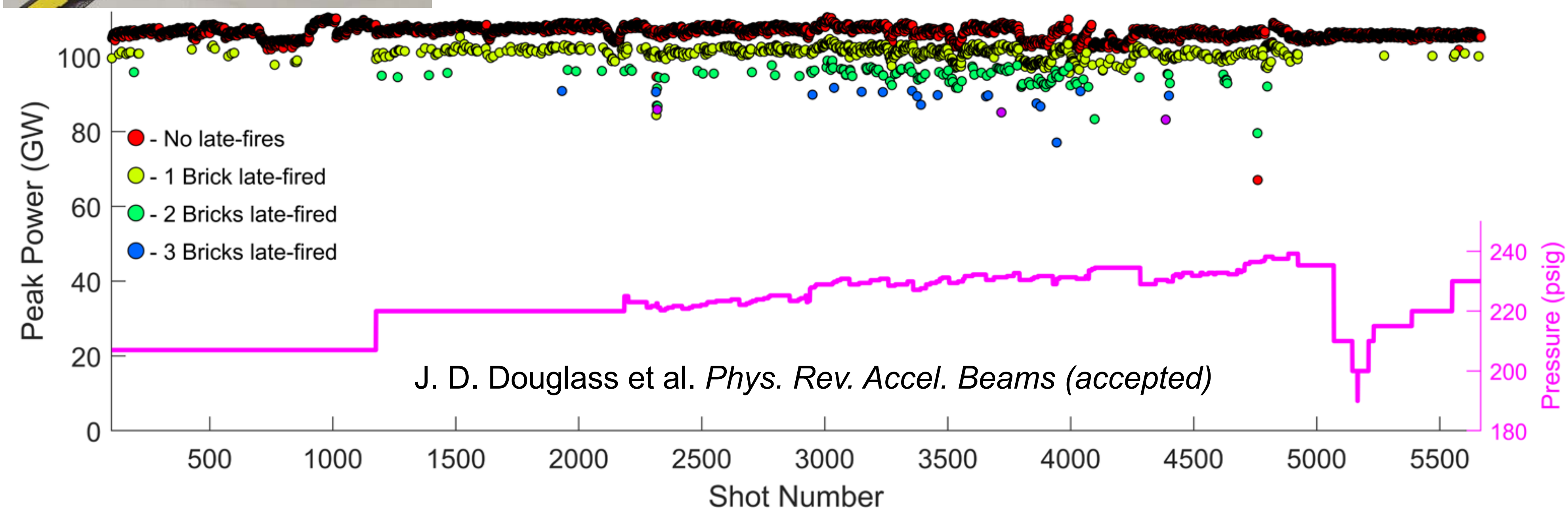
LTD Cavity: We demonstrated >4000 shots over 6 months at full voltage (100 kV) with no major configuration change or component failure

6th generation cavity



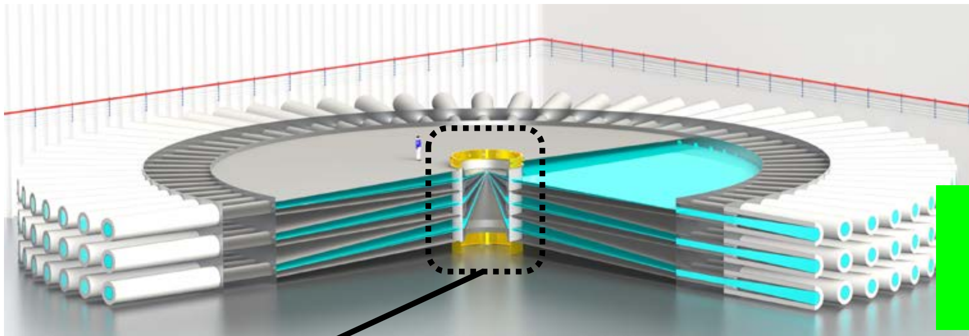


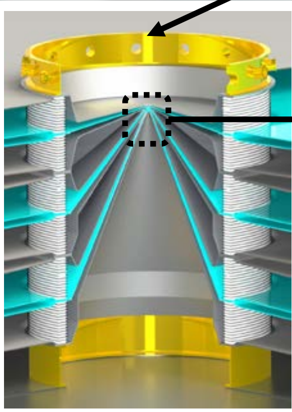
Shots	Cavity Power	Module variation (42 cavities)	Variation per 100 modules (460 TW)
2000	107 ± 1.9%	±0.3%	±0.03%
3970	106 ± 3.2%	±0.5%	±0.05%

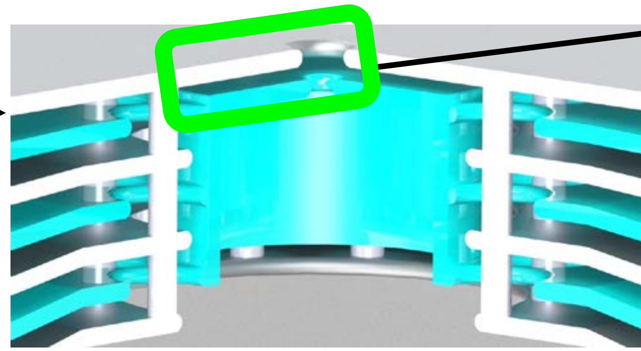


>20 years operation at 200 shots/year

We are also starting to investigate driver-target coupling physics, which is an uncertainty in going to larger machines

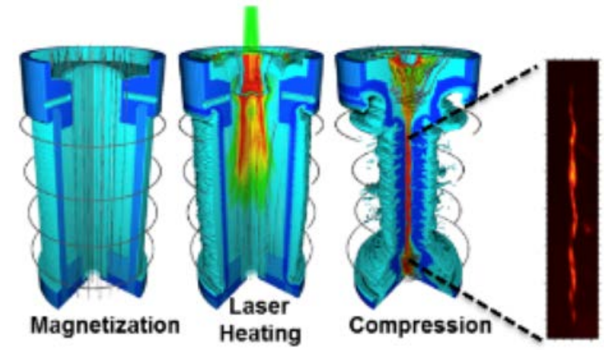






~3-5 PW
9 MJ electrical

Inertial Confinement Fusion Ignition



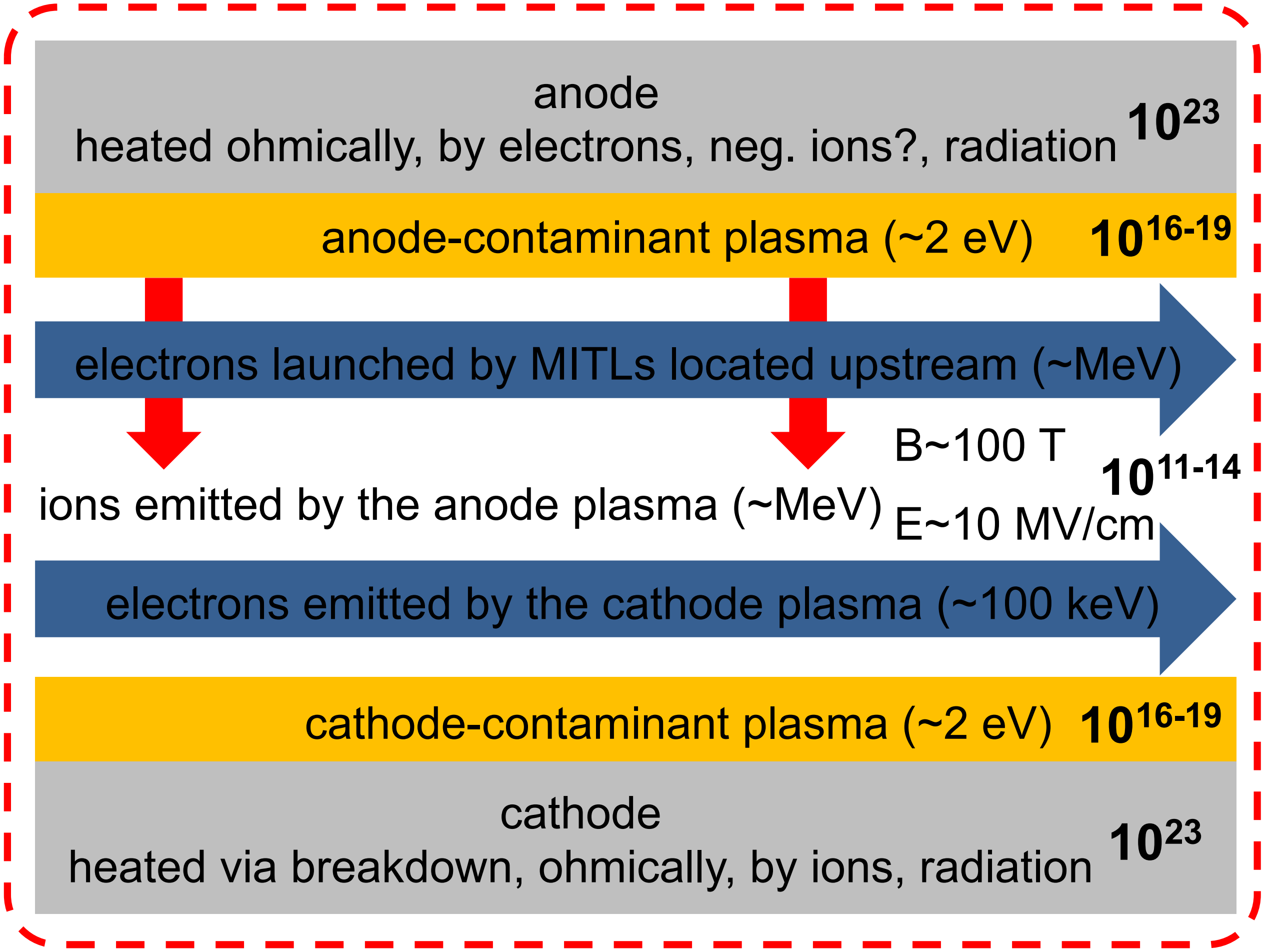
1-30 PW DT neutrons
4-5 PW soft x-rays

<u>Example driver uncertainties</u>
Electrode plasma formation/expansion
Current loss

Discovery Science Experiments

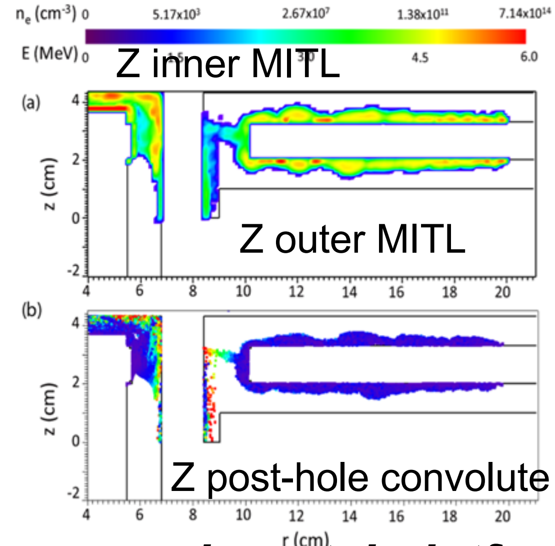
A terawatt-class power pulse generates plasmas within a vacuum transmission line

section of a “vacuum” transmission line at small radius

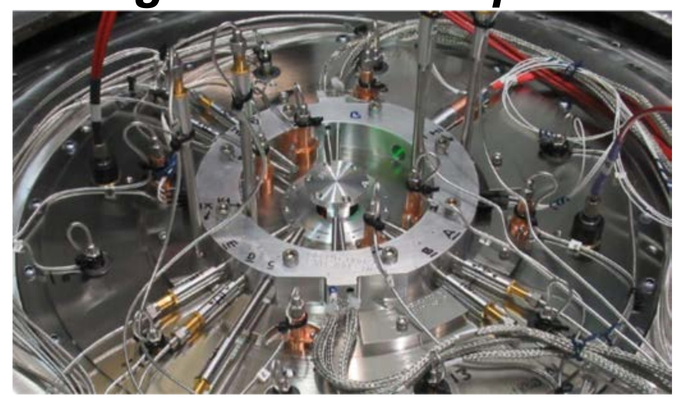


Multi-scale and non-neutral plasmas crossing PIC and Continuum regimes

Improvements to modeling

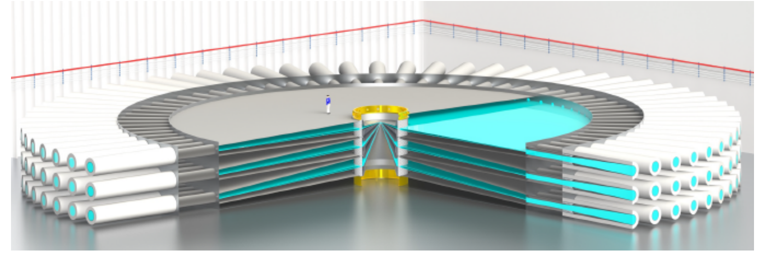


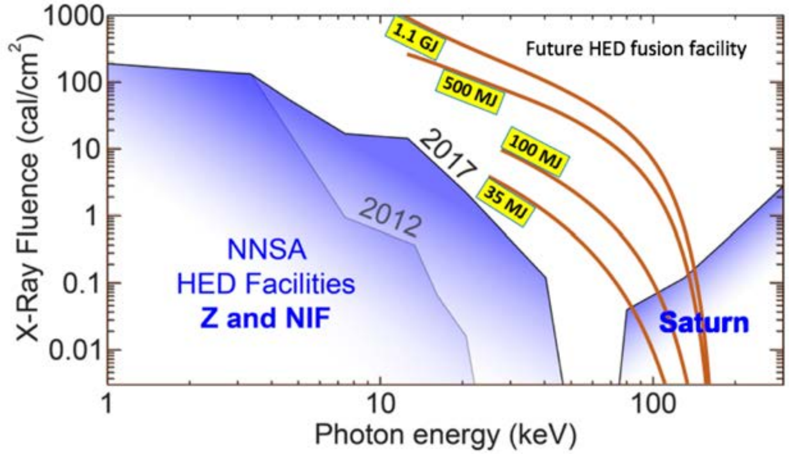
New experimental platforms & diagnostic developments



We are exploring the idea of a next-generation pulsed power facility to address multiple scientific opportunities

- **Opportunities: A Z-Next facility capable of coupling ~10 MJ to targets could address key physics gaps**
  - Achieve ~30 MJ yield; demonstrate scaling to >100 MJ
  - Provide combined neutron and x-ray environments at record fluences on test objects
  - Achieve higher-pressure capabilities for actinide dynamic material properties
  - Address critical nuclear weapon primary and secondary physics issues
- **To realize these opportunities, we are making a number of investments through 2025**
  - Demonstrating key target physics and scaling
    - Seek to increase the shot rate of Z
    - Improving our diagnostic capabilities on Z
  - Demonstrating driver technology options
  - Understanding driver-target coupling and scaling
    - Advanced models and simulations



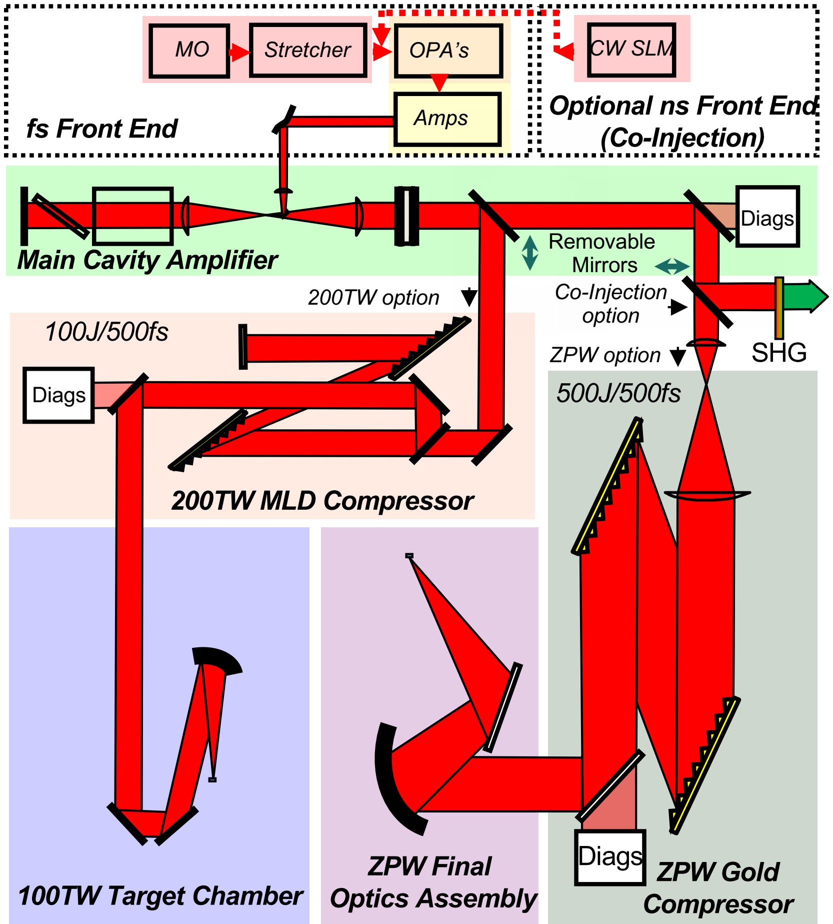


China's 10 MA Primary Test Stand

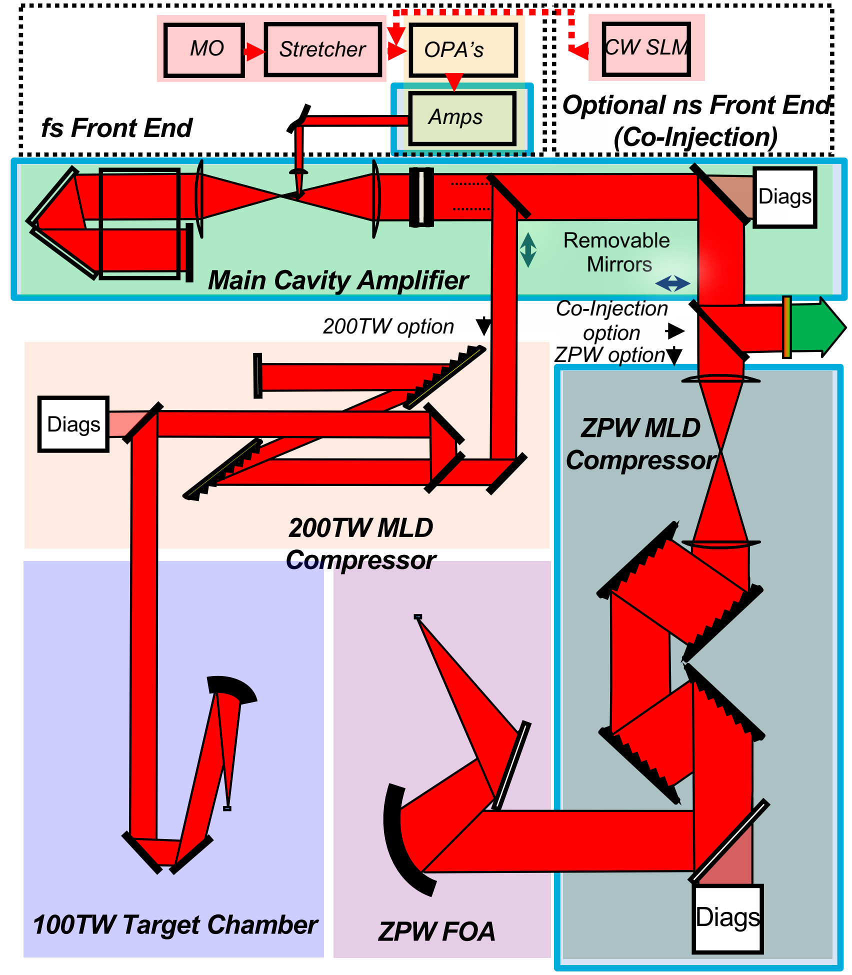
END

We are halfway through a full-aperture upgrade to Z-PW

Z-Petawatt optics before upgrade



Z-Petawatt after full-aperture upgrade



Design: Spare parts from ZBL were assembled into a 2-pass main amplifier cavity with a ***sub-apertured*** 15cm round beam

- Reduced the cost and infrastructure at the time
- Modest beam energy/size and grating technology matched
- Only top half of the 2x1 amplifiers used (as with ZBL)

- Full-aperture HEPW (1-2kJ/1054nm/500fs to 200ps)
  - High x-ray energies (>15keV) for backlighting and diffraction
- Full-aperture co-injection (1.5-2.5kJ/527nm/2ns)
  - Lower x-ray energies (<15keV) for backlighting and diffraction
  - Additional energy for heating with ZBL on MagLIF