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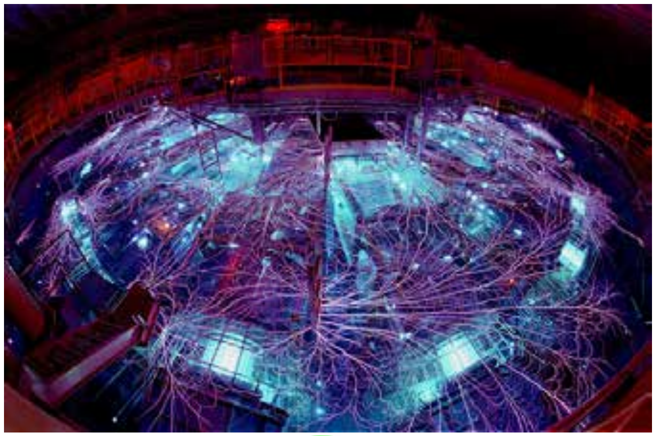

Recent progress and 5-year plan for the Priority Research Directions and Integrated Experimental Campaigns: Magnetic Direct Drive

Dan Sinars

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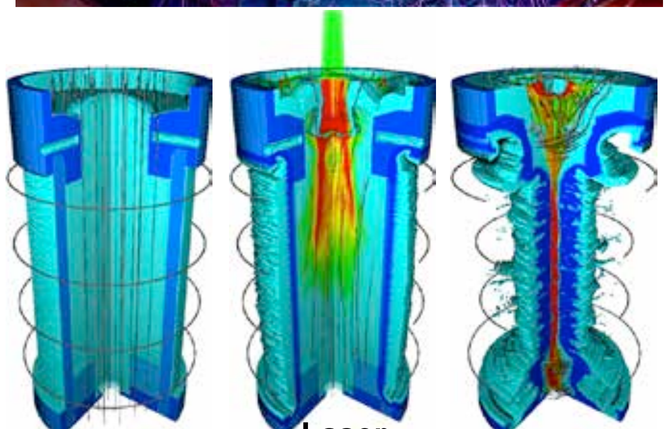

ICF Execs Meeting,
March 15-16, 2016

Lawrence Livermore National Laboratory
UNIVERSITY of ROCHESTER
GENERAL ATOMICS
Schafer
U.S. DEPARTMENT OF ENERGY
NNSA
arpa-e

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The Magnetic-driven Direct Drive effort has matured and evolved rapidly over the past 20 years—we are collectively getting better at applying pulsed power for NNSA missions!

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Year	Wire Arrays?	X-ray or direct ICF?	Specific ICF approach	Line radiation sources	Dynamic Materials	Opacity platforms
FY1996	~100%	X-ray	Many DH variants	Wire arrays	None	None
FY2001		X-ray	DH, DEH	Wire arrays, puffs	Nascent	None
FY2006	56%	X-ray & Direct	DH, DEH, Z100	Wire arrays, puffs	Strong (e.g., Pu)	Nascent
CY2011		Direct	Z100, Sierra, MagLIF prep.	Wire arrays, puffs, Z100	Strong (Pu, Ar, Kr, better pulse shaping)	Anchors established
CY2016	18% projected	Direct	MagLIF, Sierra	Z100, Wire arrays, puffs, non-thermal arrays	Strong (new platforms, techniques)	Anchors validated, extended

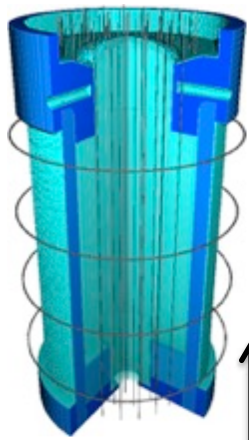
Many staff and managers at Sandia still believe we only shoot wire arrays for ICF! The situation is presumably not much better at other sites…

* DH = Dynamic Hohlraum; DEH = Double-ended hohlraum

The ICF program has been exploring multiple unique approaches to magnetic direct drive during the past 12 years, and additional variants of those

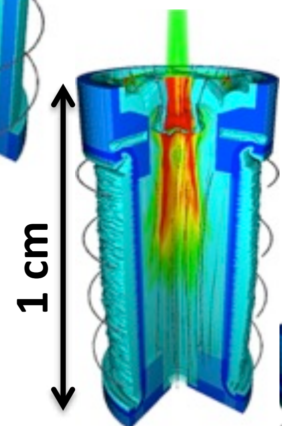
- LLNL and Sandia have jointly explored multiple magnetic direct drive approaches for 12 years on Z. This effort is continuing in 2016 and we are interested in increasing it in future years if possible.
- In 2008 Sandia began working on an new unclassified concept, Magnetized Liner Inertial Fusion (MagLIF), which was published in 2010. The first integrated experiments on these targets began in December 2013.
- MagLIF is important for Sandia as it permits us to participate in a national ICF program that is otherwise largely unclassified, allowing us to develop joint metrics, share diagnostic developments, recruit people, etc.
- There are more approaches than we have resources available to pursue. MagLIF has been prioritized at Sandia in order to keep the Sandia program visible and healthy, but all of our approaches have continued to improve their performance each year as we continue to learn.
- Despite our joint advances in the application of pulsed power for NNSA missions, progress is threatened by a decreasing shot rate on Z due to declining budgets. We did 198 shots in 9 months in FY06. We may get 140 shots in 12 months in 2016.

This talk will only discuss MagLIF examples and integrated campaigns, but the program and the PRD objectives were developed and worded with multiple approaches in mind



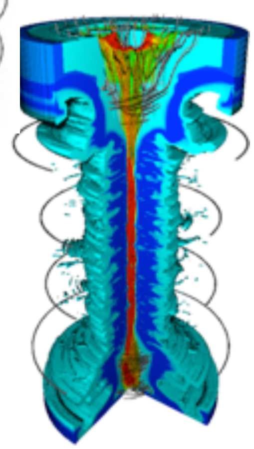
Axial Magnetic Field (10 T initially; 30 T available)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Fusion products magnetized



Laser heated fuel (2 kJ initially; 6-10 kJ planned)

- Initial average fuel temperature 150-200 eV
- Reduces compression requirements (R_0/R_f ~ 25)
- Coupling of laser to plasma in an important issue



Magnetic compression of fuel (~100 kJ into fuel)

- ~70-100 km/s, quasi-adiabatic fuel compression
- Low aspect ratio liners ($R/\Delta R$~6) are robust to hydrodynamic (MRT) instabilities
- Significantly lower pressure/density

S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

We have developed a science-based plan and structure for Magnetically Driven Implosions for the next 4-5 years that is increasingly national in scope

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~85% of effort	▪ **Study the underlying science, emphasizing MagLIF**
~10% of effort	▪ **Demonstrate desired conditions and target scaling**
~5% of effort	▪ **Develop a path to ignition and beyond**
~1% of effort	▪ **Understanding mission needs for ignition and high yield**

- **Study the underlying science, emphasizing MagLIF** (~85% of effort)
  - Primarily accomplished through Priority Research Direction teams
    - Driver-target coupling, Target Pre-conditioning, Implosion, Stagnation & Burn, Modeling, Approximations, and Scaling
  - Teams have dedicated experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)
  - Drives development of new diagnostics, simulation tools and methods
- **Demonstrate desired conditions and target scaling** (~10% of effort)
  - Primarily accomplished through integration experiments on Z
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm
- **Develop a path to ignition and beyond** (~5% of effort)
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF
- **Understanding mission needs for ignition and high yield** (~1% of effort)
  - Why does the nation need a facility capable of ~1 GJ/shot?

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- **Understanding mission needs for ignition and high yield**
  - Why does the nation need a facility capable of ~1 GJ/shot?

Program Objective 1: Demonstrate scaling of neutron yield on Z to validate our extrapolations to ignition and high yield

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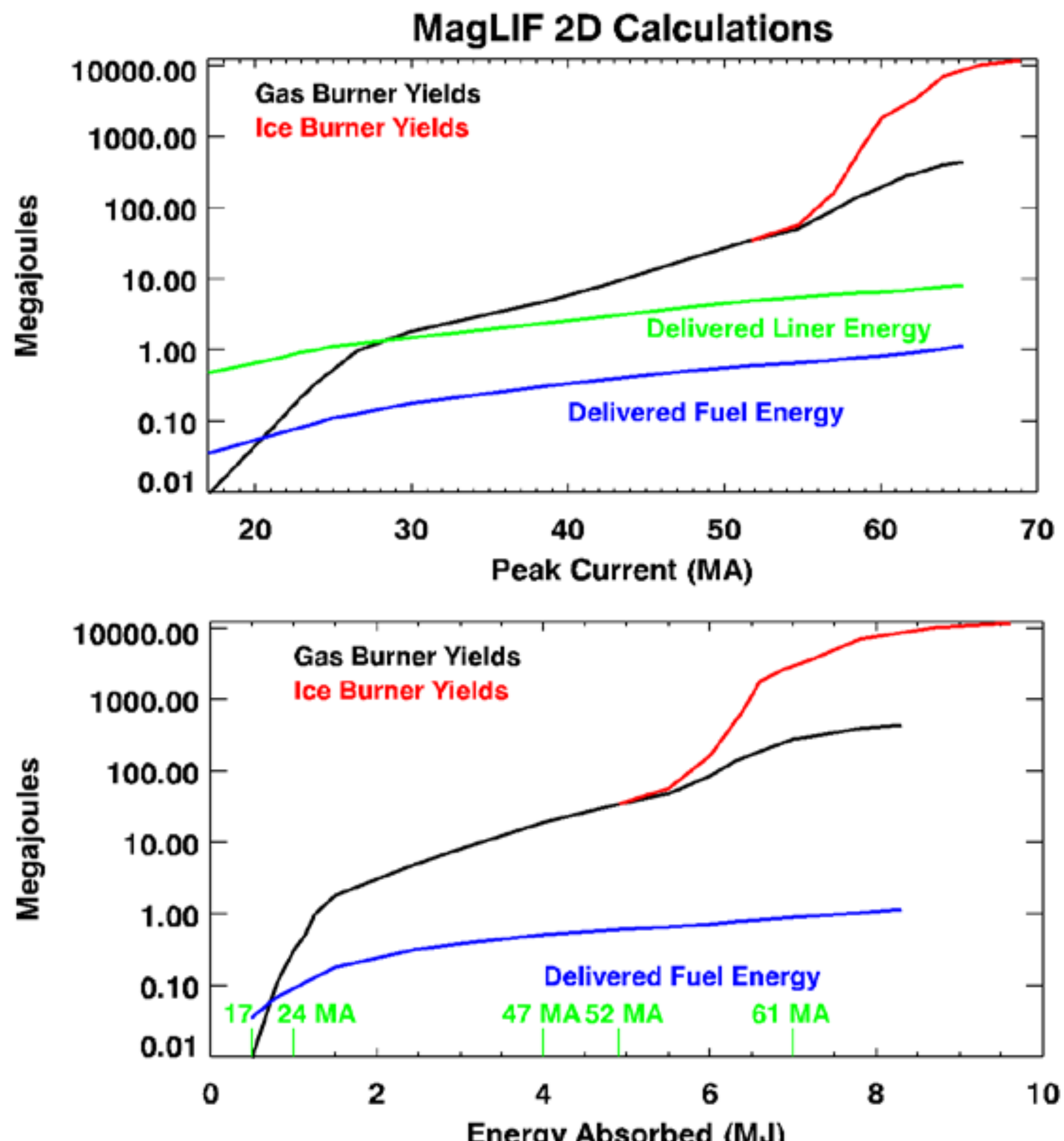
- Today's MagLIF experiments couple 17-18 MA (~0.5 MJ) to the target
- Our driver-target coupling team believes we could reach 22-24 MA using higher charge voltage & optimized load hardware.
- At 24 MA, an optimized target design with 30 T and >6 kJ of preheat is predicted by 2D LASNEX calculations to produce >100 kJ DT yield
- It is unclear today if we have the resources to implement the necessary technology or the scientific research needed to reach 100 kJ



S.A. Slutz *et al.*, Phys. Plasmas 23, 022702 (2016).

Program Objective 2: Demonstrate Pτ>5 Gbar-ns and BR>0.5 MG-cm in the fusing fuel to validate the fundamental precepts of magneto-inertial fusion

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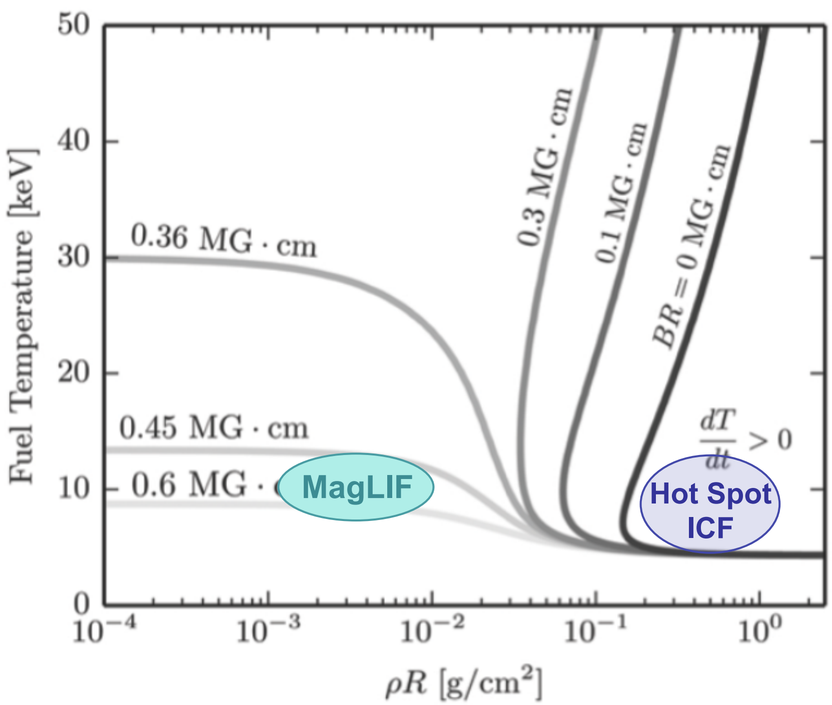
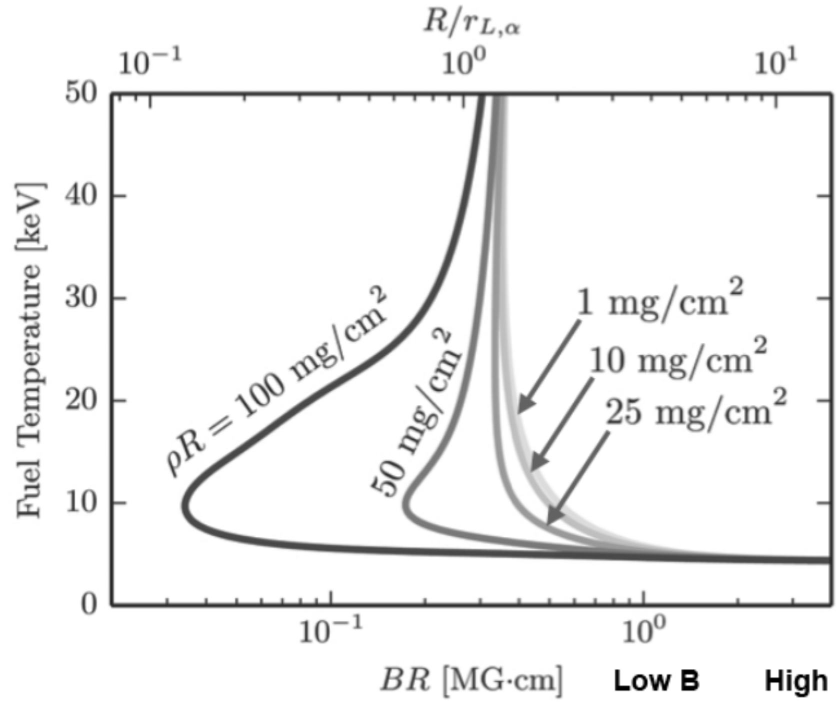
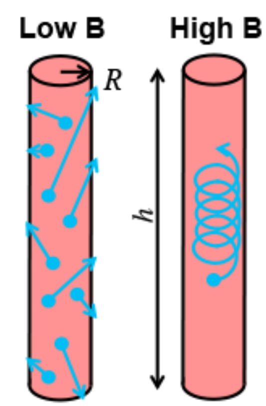






- Fraction of trapped tritons (or α's) a function of *BR*
- Effects saturate at *BR* > 0.6 MG-cm
- Lower ρR means lower P,Pτ

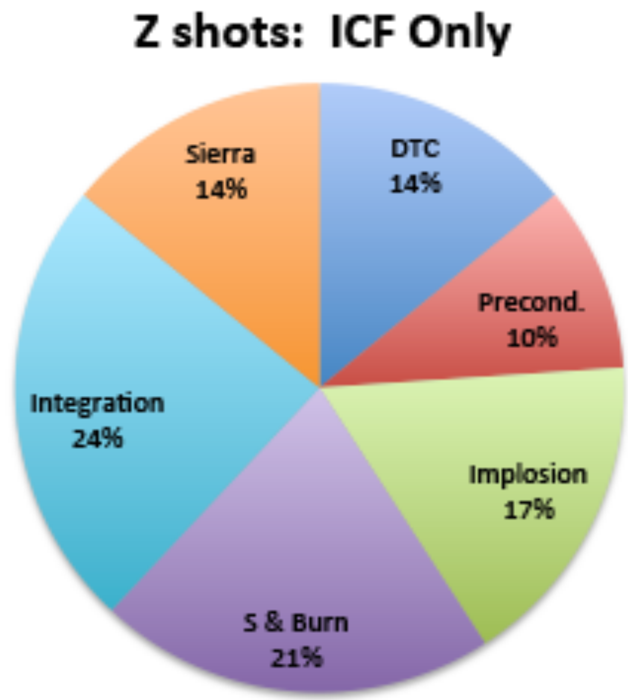
- Measurements suggest *BR* of 0.4 MG-cm at B_0=10 T
- Implosion experiments have demonstrated flux compression w/ B>1000 T

Our integration campaigns on Z are the primary way that we expect to achieve these program goals

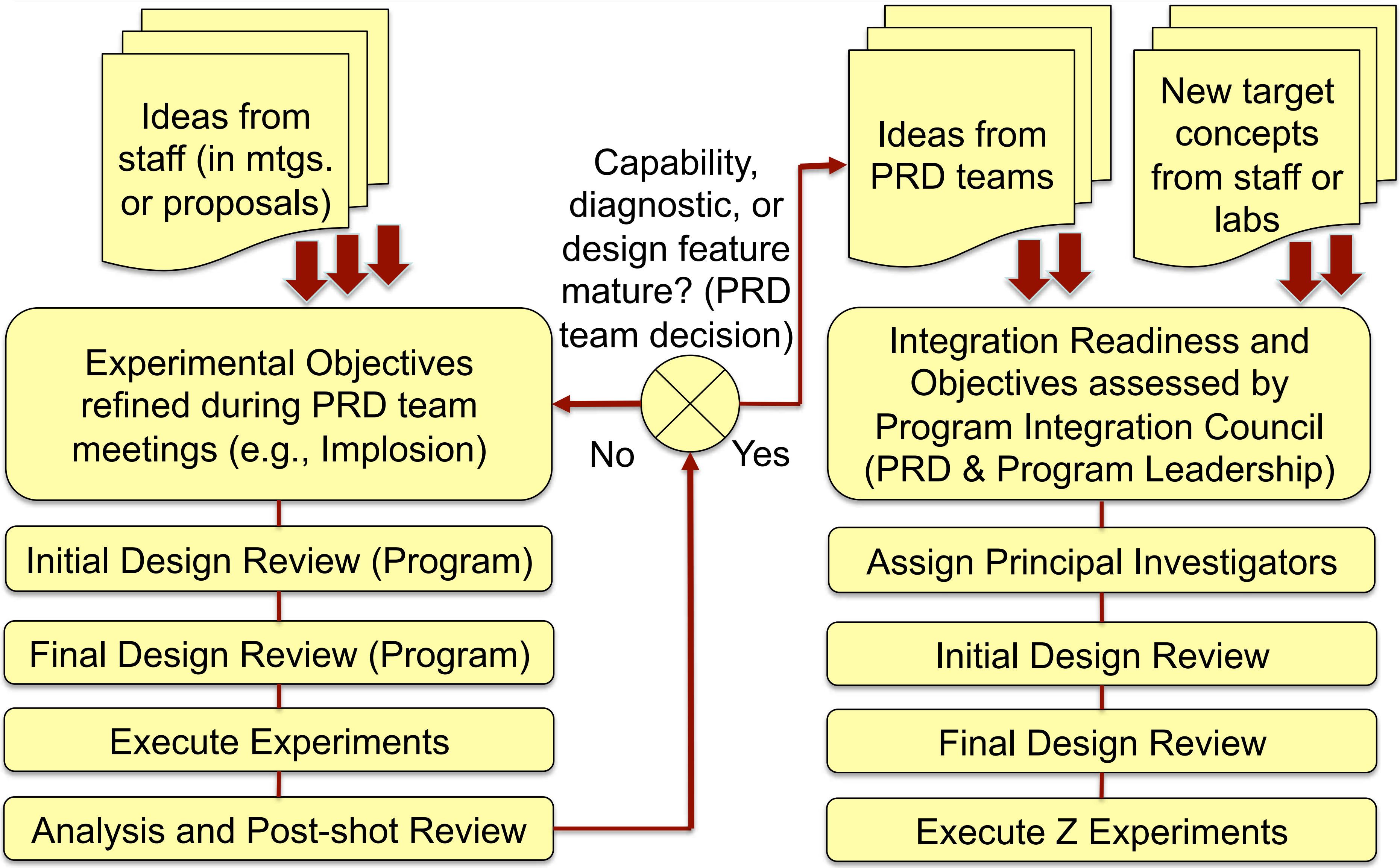
- We distinguish here between "integrated" and "integration" experiments
  - **Integrated experiment**: Any experiment combining all of the key features of MagLIF, such as Z, Z-Beamlet, magnetic field coils, gas fills.
  - **Integration experiment**: An experiment whose primary objective is to integrate in new design features or capabilities with the express purpose of demonstrating scaling, a new baseline performance, or a new target concept.
  - **All integration experiments are integrated experiments, but not all integrated experiments are integration experiments** (e.g., experiments to develop a "stagnation mix" measurement would be integrated but belong to the Stagnation & Burn PRD area).
- Integration campaigns for MagLIF will attempt to assimilate ideas developed and matured by the PRD teams, e.g.,
  - Driver-Target-Coupling: Lower-inductance hardware; higher charge voltage
  - Target Pre-conditioning: Phase plates, laser pulse shapes, higher laser energy
  - Implosion: Plastic-coated targets, thick-ended targets, Li liners, high AR liners, mix-mitigation features
  - Modeling, Simulation, & Scaling: New target designs & variants (Harding, auto-mag, etc.)

The 2016 Z shot schedule for ICF includes a mix of PRD-focused and integration campaigns

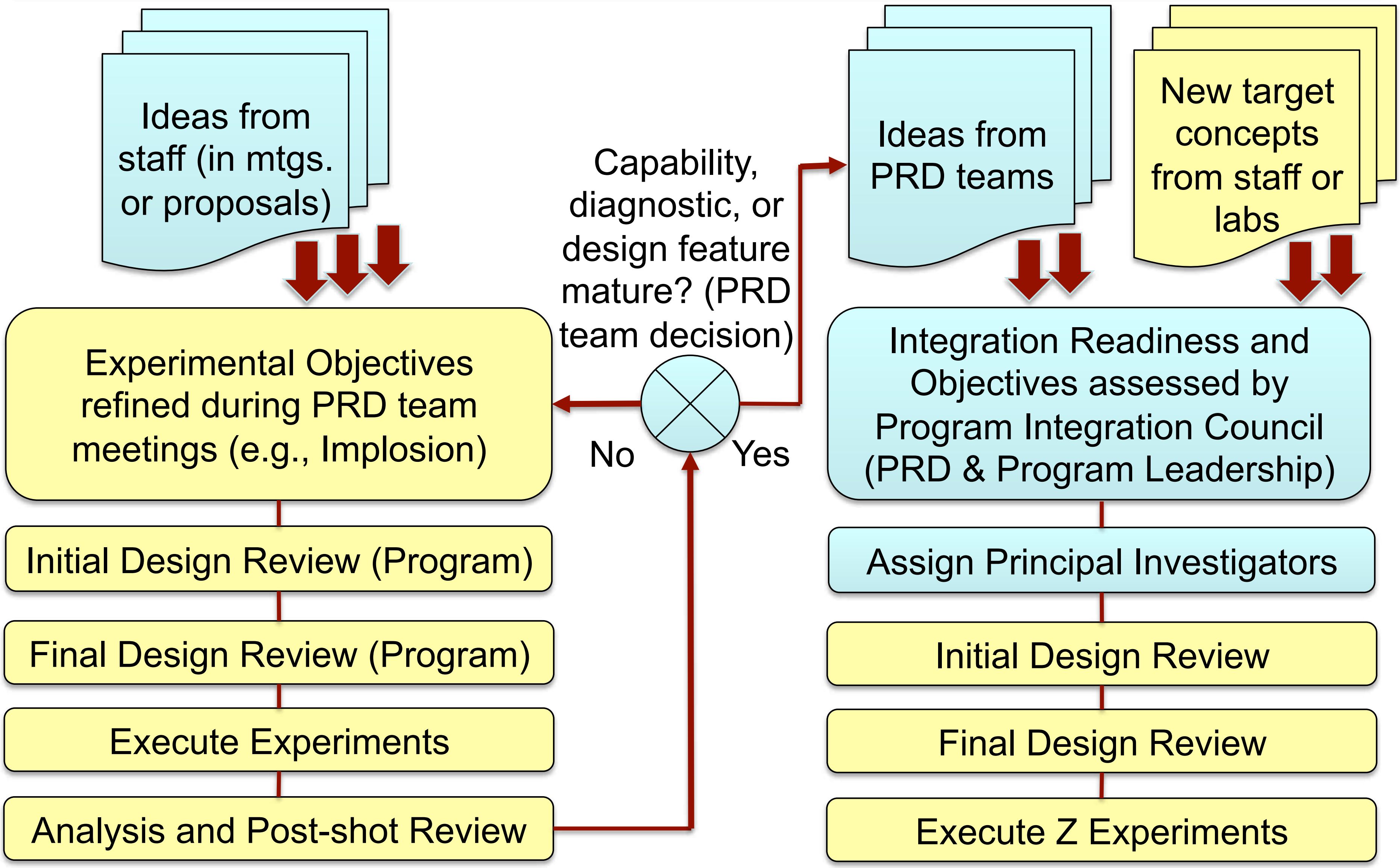
- **Sierra campaigns (joint w/ LLNL)**
  - 3 shots for Stagnation & Burn measurements
  - 7 shots for Implosion measurements
  - 0 shots for integration campaigns
- **MagLIF & general ICF campaigns (estimated)**
  - 10 shots for Driver-Target Coupling
  - 11 ZBL-only tests in the Z chamber for Target Preconditioning (7 days)
  - 12 shots for Implosion
  - 15 shots for Stagnation & Burn
  - 17 shots for Integration campaigns
    - 3 shots for plastic-coated liner integration (*ideas motivated by Implosion*)
    - 6 shots for phase plate & laser pulse shape integration (*Preconditioning*)
    - 3 shots for cryogenic target integration (*Preconditioning, Implosion*)
    - 5 shots for new target concept study
- **Z Totals: 47 PRD-aligned Z shots, 17 integration Z shots, 11 PRD-aligned ZBL tests on Z (7 days)**



We are still learning how to effectively organize our integration campaigns on Z—our proposed model is below



Sandia ICF program management is presently working on improving the stages shaded in blue



Our program has executed two integration experiments on Z since the end of the FY15 ICF Review (essentially this FY)

- Rate of ICF experiments in Q4 CY2015 slowed by the need to repair and upgrade alignment systems in Final Optics Assembly for Z-Beamlet
- Integration Objectives
  - Incorporate a 0.75 mm phase plate into a nominal baseline MagLIF target (7.5 mm tall, 10 T, 0.5+2 kJ laser energy, 3 mm ID, 1.5 mm high LEH channel, 60 psi D2 gas fill)
  - Incorporate a thinner laser entrance hole window (1.5-1.6 μm thick)
  - Incorporate the use of beryllium washers for LEH foil (lower mix)
- Experimental Objectives
  - Compare performance to most similar previous baseline MagLIF targets on z2839 (Y_{DD}=3.2e12) and z2850 (Y_{DD}=3.1e12).
- Results
  - Z2898: Y_{DD}=1-2e11; Indications of possible window mix in fuel; lower temperatures. Mix campaigns in summer will attempt to isolate sources.
  - Z2899: Failed due to a substantial current loss in power feed

CY2016 Magnetic Direct Drive integration experiments are focused on folding in advances in our understanding developed by Target Preconditioning & Implosion PRDs

Schedule name	Integration focus	Facility	Z Shots	Labs/ Contributors
Stag MagLIF16a (January)	Integrate in new phase plates for Z-Beamlet to improve laser-gas coupling. This campaign Is to leverage understanding gained on OMEGA-EP at LLE and the PECOS chamber at Sandia.	Z	2	SNL/LLE ARPA-E
Stag MagLIF16b (June)	Integrate in new phase plates and laser pulse shape for Z-Beamlet to improve laser-gas coupling. This campaign is to leverage understanding gained on OMEGA-EP at LLE and the PECOS chamber at Sandia.	Z	4	SNL/LLE ARPA-E
StagMagLIF16c (June)	Integrate in plastic-coated liners to see if it improves the three-dimensional stability of our baseline MagLIF designs. This campaign builds on years of Implosion research on Z.	Z	3	SNL
Cryo MagLIF (July)	Integrate in cryogenically cooled gas MagLIF targets. The lower pressure of the gas will enable a much thinner laser entrance hole window (better laser-gas coupling). The liner design is also changed to integrate in a thick-ended liner that eliminates the need for "cushion" end caps and thus decreases the possibility of laser-induced mix.	Z	3	SNL
Harding (assorted)	Alternative target concept exploration (includes leftover shelf shots from CY2015).	Z	5	SNL
TOTAL			17	

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~1% of effort	**Understanding mission needs for ignition and high yield** - Why does the nation need a facility capable of ~1 GJ/shot?

Each of the national Priority Research Directions has a team at Sandia and dedicated experiments to achieve a set of 5-year objectives

Research Group	Team Leaders
Driver-Target Coupling	Bill Stygar, Mike Cuneo
Target Pre-conditioning	Kyle Peterson
Implosion	Ryan McBride
Stagnation & Burn	Greg Rochau and Brent Jones
Intrinsic & Transport Properties	(treated as subset of next category)
Modeling, Simulation, & Scaling	Kyle Peterson and Thomas Mattsson

- Team leaders responsible for organizing the program of work for each of the research groups, including coordinating national research in each area

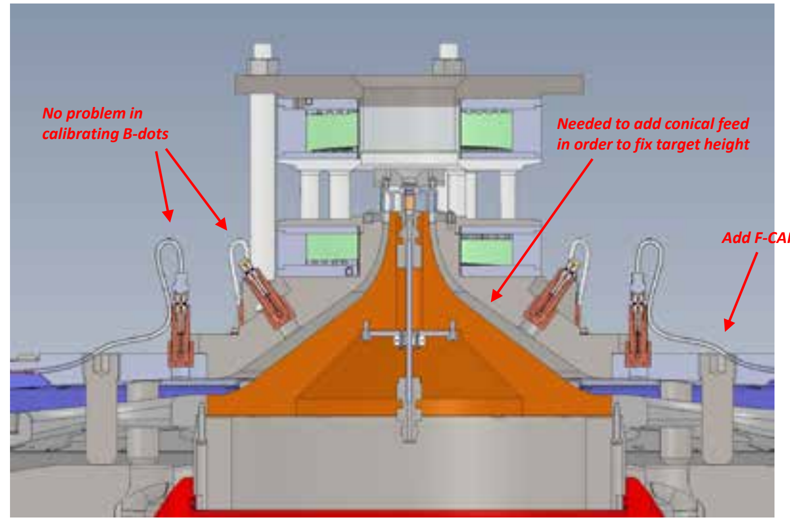
- The following slides summarize our progress to date and our key goals for the next five years in these areas

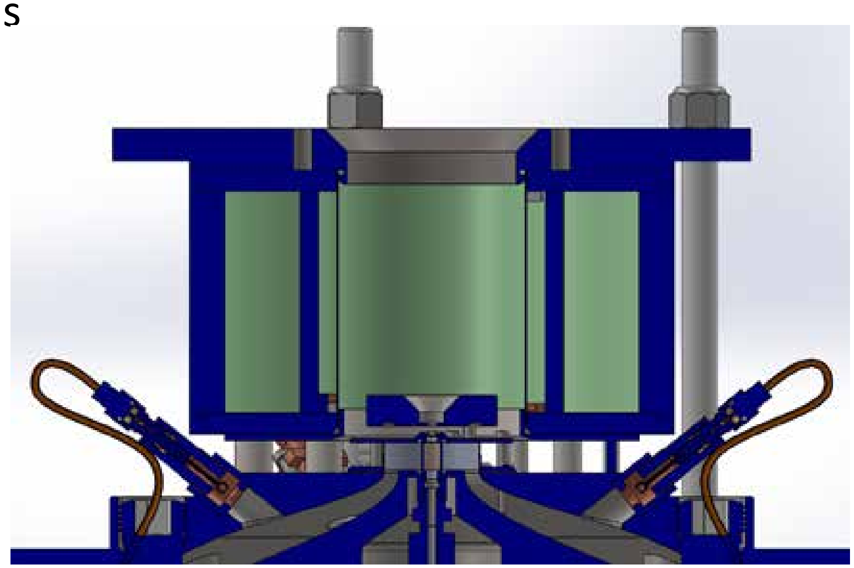
Over the next five years, we seek to accomplish the following goals related to driver-target coupling:

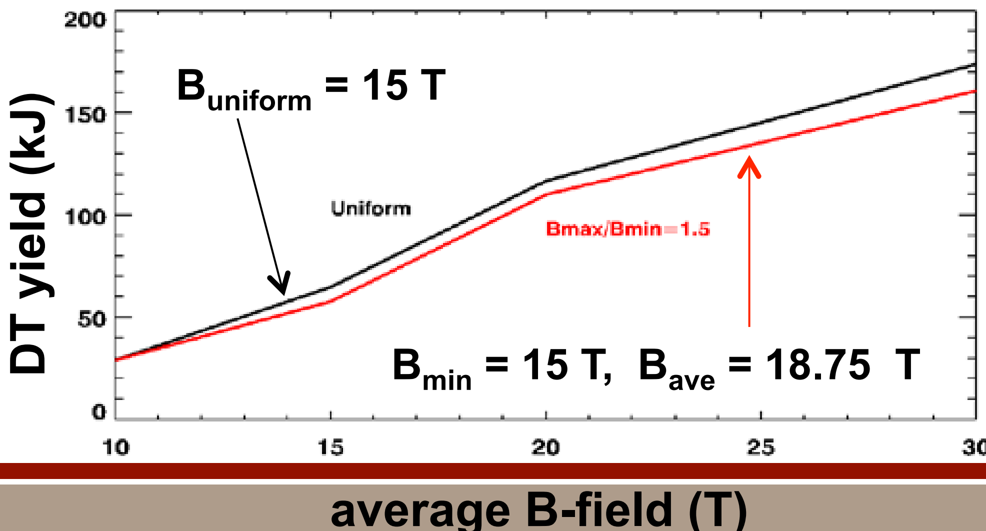
- **Deliver 24 MA to a MagLIF target on Z.**
  - To offer the potential of achieving Yield ~ E_{fuel} ~ 100 kJ.
- **Quantify the benefits to ICF loads of current-pulse shaping (affects current loss).**
  - To explore the performance space between low-adiabat implosions and stability.
- **Quantify the benefits of longer implosions (such as might be achieved by an LCM).**
  - To explore the performance space between peak current and pulse length.
- **Develop a point *pulsed-power* design of a MagLIF target for Z Next that achieves a net target gain of 1 (Likely, Yield ~ E_{target} ~ 3-5 MJ) .**
  - Gain=1 is a potential goal for Z Next that would define the driver requirements.
- **Conduct scaled power-flow experiments under conditions similar to those of Z Next.**
  - To demonstrate that Z Next will perform as expected.
- **Develop predictive (~5%) circuit and PIC models of an accelerator coupled to a variety of loads (possibly including a single integrated simulation of power flow + target?).**
  - To facilitate the design of MagLIF experiments on Z, and the design of Z Next.

The Driver-Target Coupling team has developed a path forward to achieving 24 MA on Z

- Designed 2 shots using larger-diameter convolute (better Bdot measurements, may lower losses)
- Designed 2 shots to test Load-Current-Multiplier with short-circuit load (may help Sierra, DMP)
- Designed 2 shots to test low-inductance MagLIF platform with non-uniform field. Simulations suggest that we can tolerate 50% axial variations.
- Developed a sequence of hardware and configuration changes to reach 24 MA. Tests this year may reach 22 MA. Work aided by a new physics-based TL circuit model





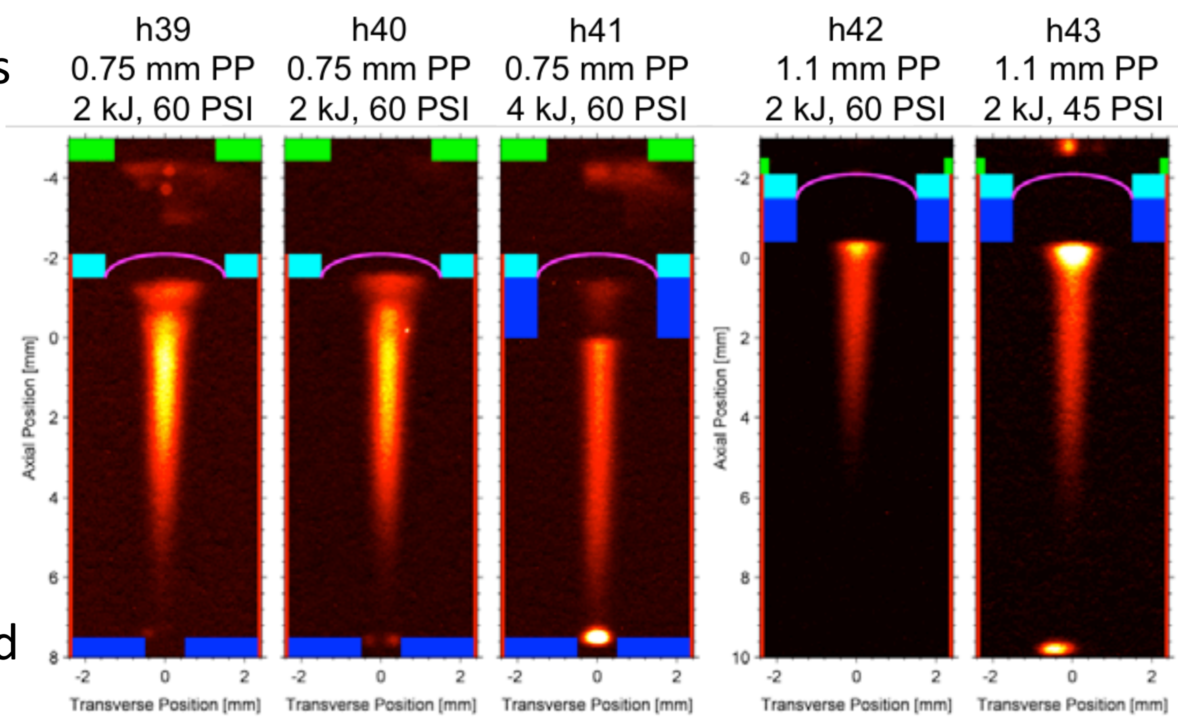


Over the next five years, we seek to accomplish the following goals related to target pre-conditioning:

- **Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel**
  - To achieve our stagnation & burn objectives
  - This includes measuring conditions created in situ on the Z facility
- **Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized "smoothed" beam profile (including an optimized pulse shape)**
  - We believe this is needed to achieve our program objectives for MagLIF
- **Minimize the likelihood and impact of laser-plasma interactions**
  - To maximize our chances of predicting performance and scaling
  - Is sensitive to fuel density, window thickness, laser intensity, wavelength
- **Characterize & mitigate any fuel contamination as a result of the heating method**
  - To minimize radiation losses throughout the implosion
  - Understand over a range of coupled energy (1-30 kJ) to predict scaling
- **Demonstrate 30 kJ heating on the NIF**
  - To reduce scaling extrapolations for a next-step facility, where >20 kJ is needed

In January we conducted successful laser heating experiments in Z using phase plates to condition the beam

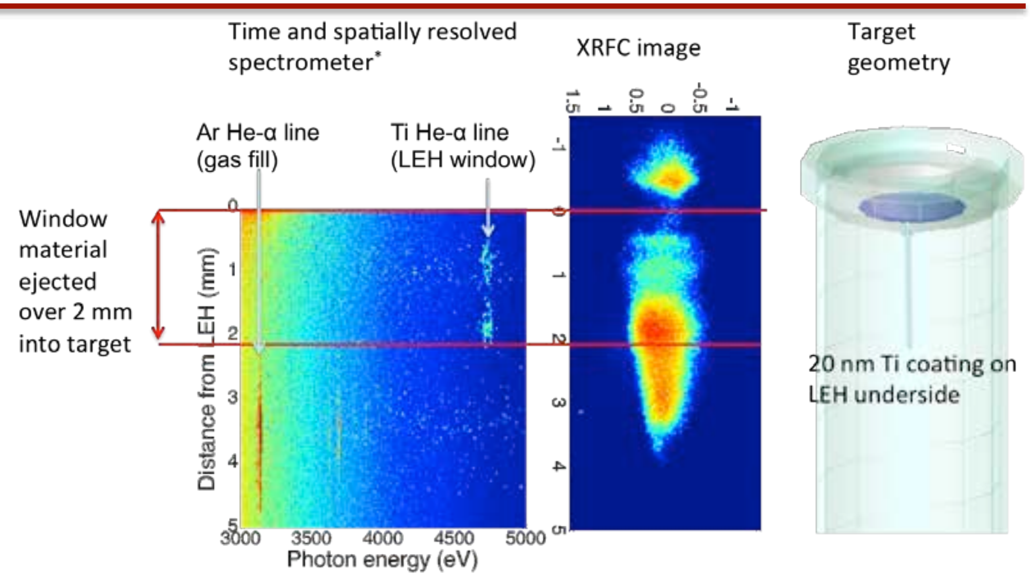
- 0.75 and 1.1 mm distributed phase plates have been procured, coated, conditioned, and characterized. Shots as high as 4 kJ with prepulse have been performed on Z using the DPPs.
- LDRD/ARPA-E supported experiments on OMEGA-EP investigated laser pulse shape (prepulse) and intensity variations.
- Results from our initial OMEGA-EP experiments have been published.*
- Developed and tested thinner LEH windows.
- Expect to have a laser co-injection system this year to enable independent control over prepulse as needed

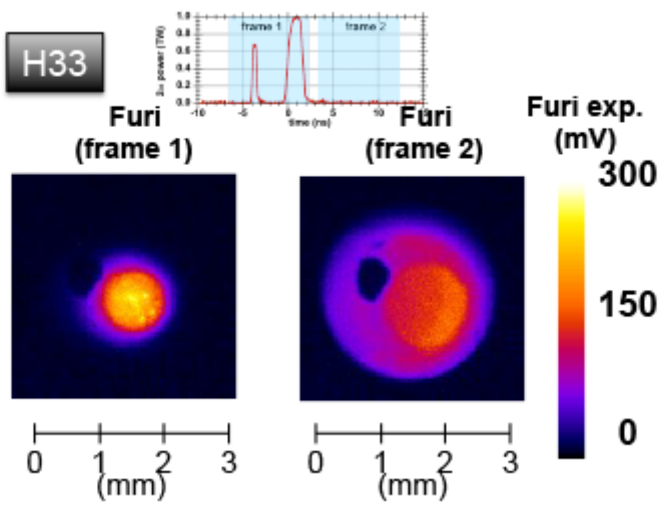


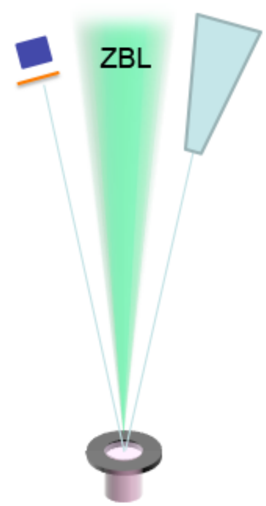
* A.J. Harvey-Thompson *et al.*, Phys. Plasmas 22, 122708 (2015).

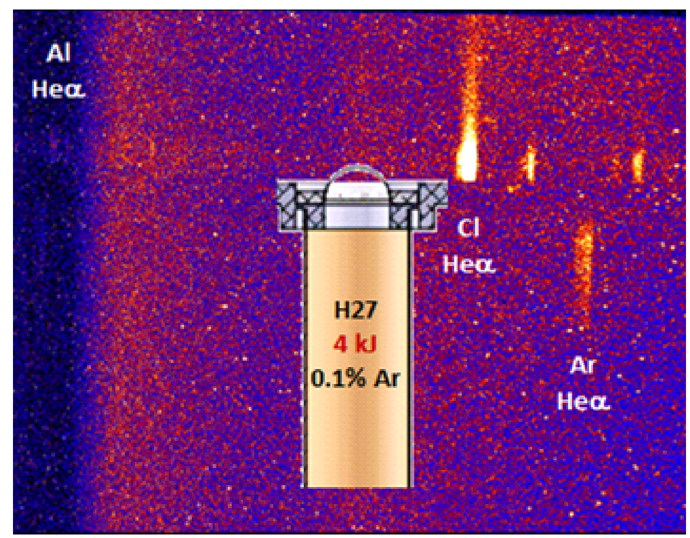
We have made progress in characterizing and mitigating fuel contamination as a result of the preheating method

- Using Ti dopant coated on the LEH window, we have started assessing window mix using OMEGA-EP
- Using Cl dopant coated on the LEH window, Al washers, and Ar dopant in the gas, we are assessing laser-induced mix using Z-Beamlet
- We are working toward time-gated axial imaging and spectroscopy to measure heating on integrated Z shots









We have made inexpensive improvements to Z-Beamlet to support MagLIF experiments in the near term

- Activated Booster Amplifier
  - Added 400J of 2ω energy (4.5kJ total)
- Upgraded Final Optics Assembly (FOA)
  - Repaired broken vacuum weld
  - Motorized up/down motion of focusing lens
- Activating co-injection to combine ZBL with sub-aperture (16 cm dia.) ZPW laser in long-pulse (2ns) mode
  - Front-end modifications complete for long-pulse operation
  - Installed optics and mounts to combine ZBL and ZPW beams
- Commissioning applied B-field system for laser experiments in Phase C target area
  - Integrated system into Phase C target area
  - Working reliably at 100kA level to produce 4T in scale-2 targets, and 8T in scale-1 targets

Over the next five years, we seek to accomplish the following goals related to magnetic implosions:

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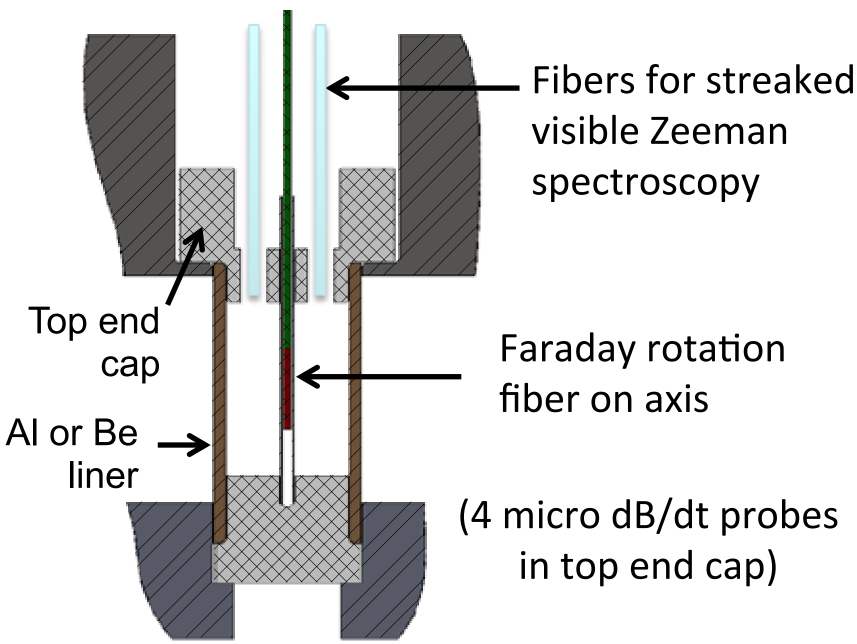
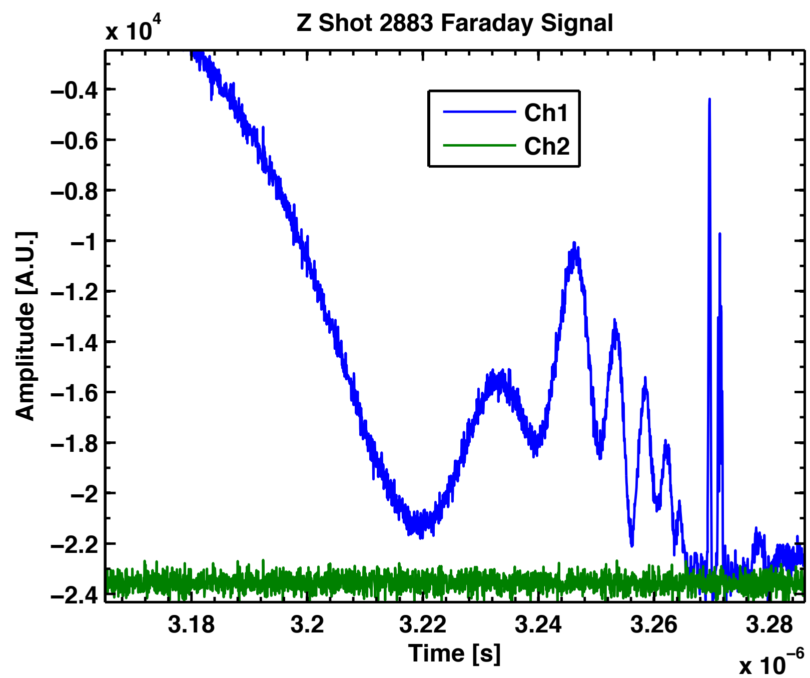
- **Determine the dominant seeds for observed acceleration and deceleration instabilities, and strategies to mitigate against them (creates more design flexibility)**
  - Accel seeds may include surface roughness, electro-thermal, or electro-choric effects
  - Decel seeds may include surface roughness, heating (blast and/or beams), or kinetics
- **Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict the integrated target performance**
  - Over a range of drive conditions (18-25 MA, 100-300 ns), magnetization (0-30 T), and relevant target designs (including Li, Be, Al liners and end cap geometries)
  - Accurate drive (current) measurements are needed for code comparisons
- **Measure the spatial distributions for temperature, density, B_z, and any contaminants in the fuel after heating and through at least CR=5**
  - Radiation and heat conduction losses are expected to be sensitive to distributions; needed to estimate energy transport out of the imploding region (radial and axial)
  - Over a range of laser preheat (1-4 kJ), magnetization (0-30 T), and target geometries
- **Experimental demonstration of a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of > 5 Gbar ns**
  - Can be achieved in a low-temperature, high-density surrogate platform

Magnetic flux compression experiments in November may have directly measured >1000 T fields (initial B=17 T)

- Three Z shots (z2882, z2883, z2885) used an on-axis Faraday rotation fiber to measure flux compression in a vacuum-filled liner implosion (topic of an invited talk at the HTPD conference this June).
- Analysis underway, preliminary work suggests >1000 T
- LDRD-funded initiative; also included micro Bdot development efforts

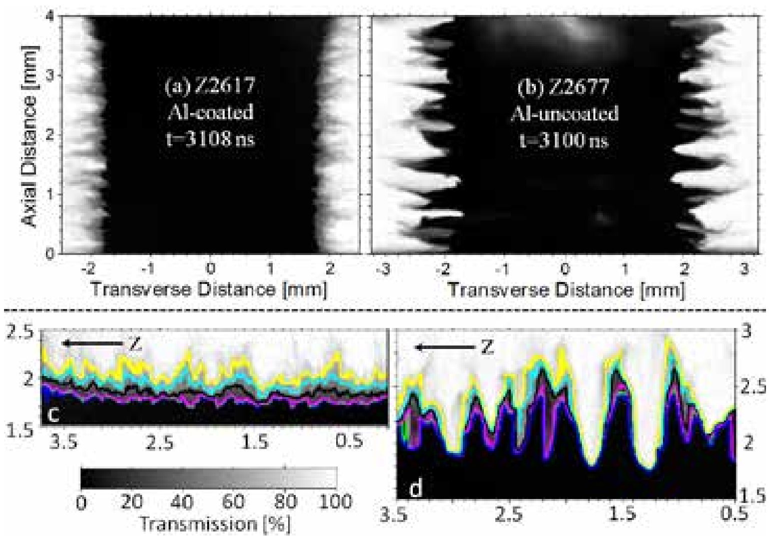
Platform developed for magnetic flux compression experiments on Z



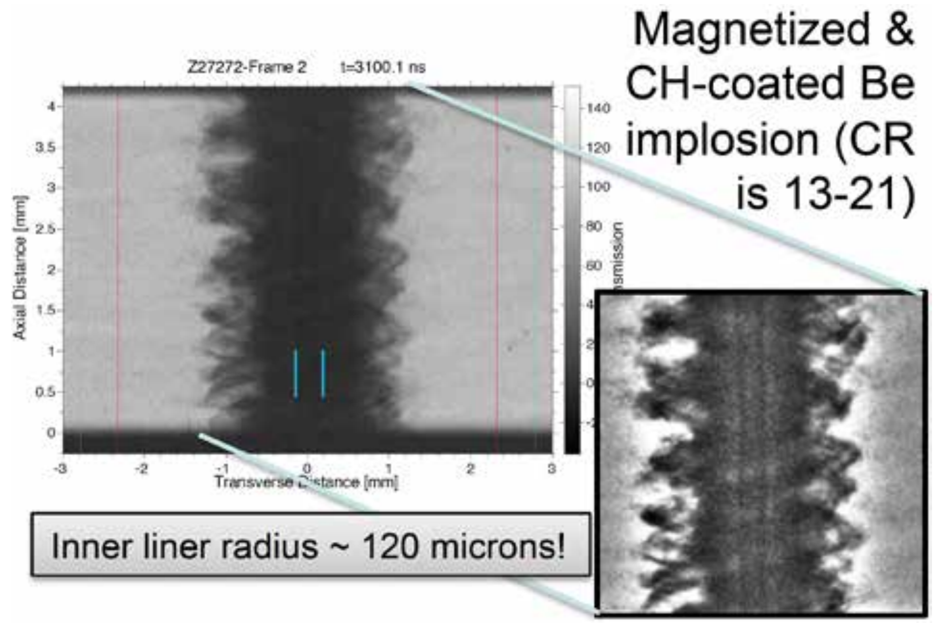


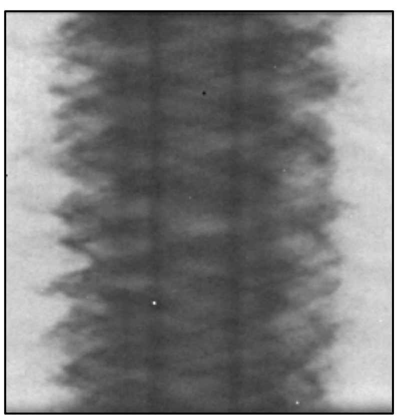
We recently published* work demonstrating the stabilizing effect of dielectric coatings on magnetically driven implosions

<u>Aluminum Results:</u>



<u>Beryllium Results:</u>



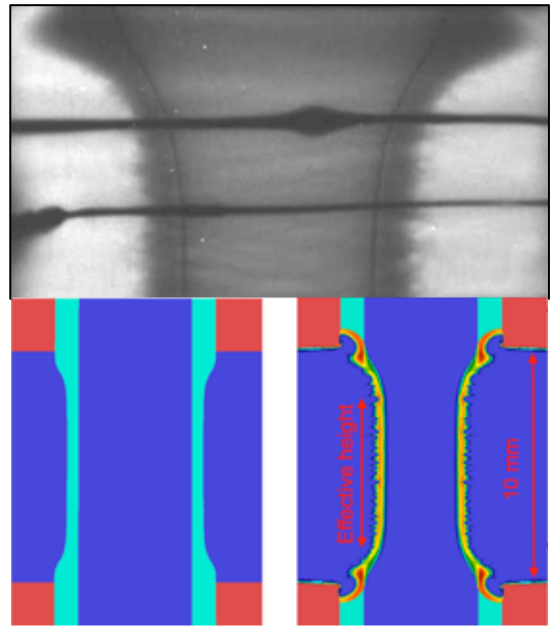


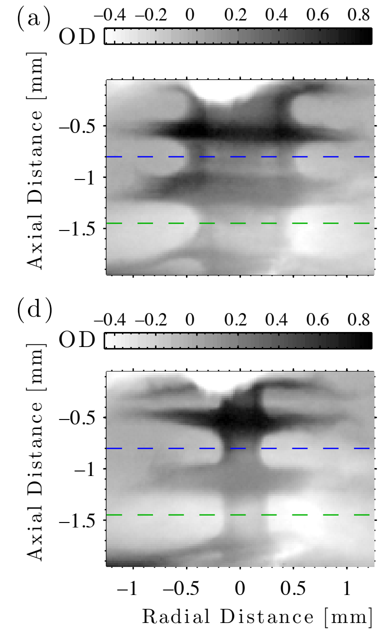
- Experiment in February fielded an AR=10.6 Be liner with a plastic coating (equivalent mass to AR=9 Be liner)
- Inner surface convergence ratio = 6.5 in radiograph
- Plastic coatings may improve stability of existing AR=6 MagLIF baseline, and may also allow faster AR=9+ liner implosions

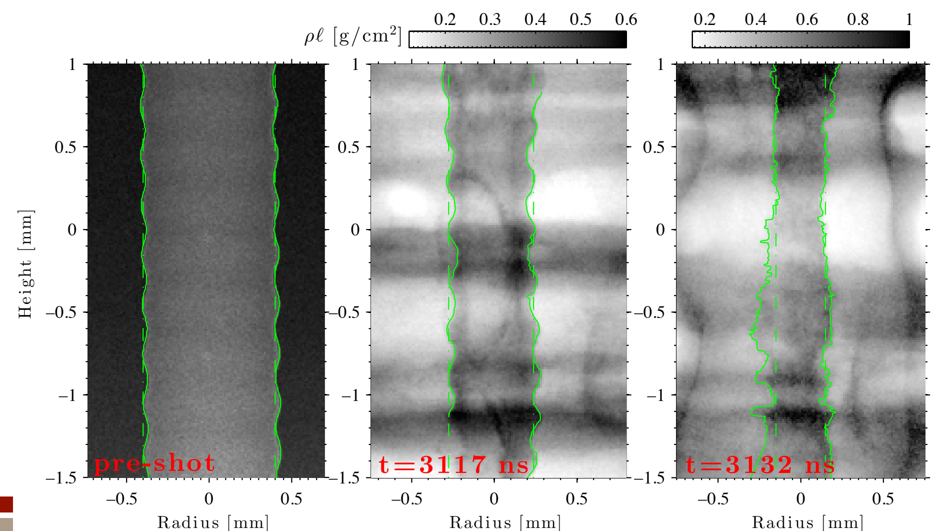
- T.J. Awe *et al.*, Phys. Rev. Lett. 116, 065001 (2016).

Implosion shots this year will continue to address several of our 5-year objectives

- Shot in February (with some current loss) began testing our ability to predict the behavior of thick-ended liners, which may reduce laser-induced mixing
- 3 shots planned to examine high P-τ stagnation, both magnetized and un-magnetized (low-T, high-density surrogate experiments)
- Additional shots planned to continue to understand deceleration instability growth, and resolve phase inversion question







Over the next five years, we seek to accomplish the following goals related to stagnation and burn:

- **Achieve a burn-averaged ion temperature of >4 keV (robust burn threshold)**
  - T_i should increase with increasing preheat energy and decrease with increasing high-Z contamination (due to radiation loss)
- **Achieve a BR > 0.5 MG-cm ($R/r_\alpha > 2$)**
  - Above this level the benefits of magnetization saturate
- **Achieve fuel pressure > 5 Gbar and $P\tau$ > 5 Gbar-ns**
  - Achieving Y ~ E_{fuel} ~ 100 kJ requires P ~ 5-10 Gbar and $P\tau$ ~ 10 Gbar-ns
  - Need to understand scaling with preheat & driver energy
- **Minimize and mitigate against radiation loss from high-Z contamination**
  - Known to vary with target geometry and character of laser heating
  - Improving liner stability and use of anti-mix layers can mitigate dynamic mix
- **Demonstrate a continuous, nearly uniform stagnation column at CR>20**
  - Discontinuous plasma assembly loses benefit of ρz and increases losses
  - Achieving Y ~ E_{fuel} ~ 100 kJ requires CR of 25, but lower stagnation fuel pressures (e.g., due to low preheat) will actually result in higher convergence
- **Determine the non-thermal component of the fusion yield.**
  - No evidence for this in MagLIF; Z pinches can have non-thermonuclear yield

The Stagnation & Burn team has made progress in understanding how to diagnose our implosions

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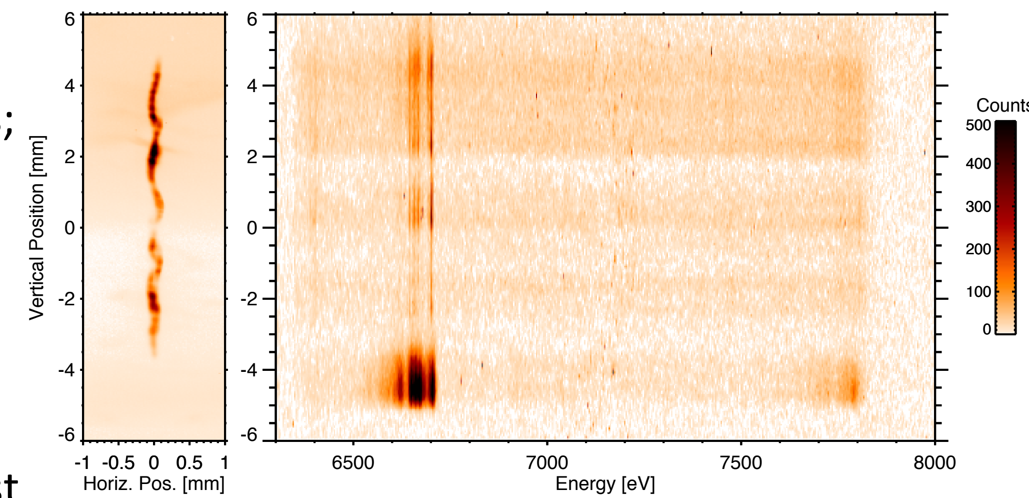
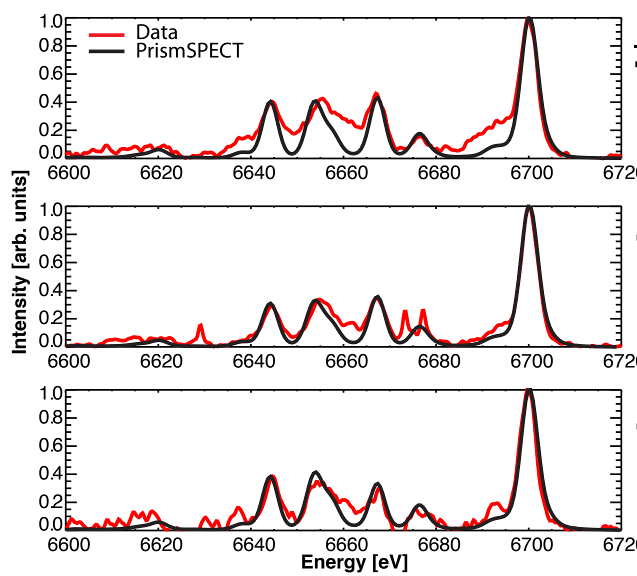
- Baseline MagLIF scans from last summer suggest neutron yield decreases with thinnest LEH windows; includes contamination from the end cap & LEH window washer
- Implemented focusing spectrometer configuration that directly measures Fe contaminants from Be liner
- Collaborated with MIT to field our first CR39 samples on Z for DD yields.
- Successfully implemented a cryogenic MagLIF preheat platform in Feb, which will be tried in integrated tests in July
- Experiments planned in 2016 will attempt to develop improved fuel contamination diagnostics, assess higher velocity (high AR) MagLIF liners, and test our ability to predict performance of MagLIF at up to 30 T





Inferred values

T_e = 1.5 keV

n_e = 1.2e23 cm^{-3}

T_e = 1.6 keV

n_e = 1.7e23 cm^{-3}

T_e = 1.4 keV

n_e = 2.0e23 cm^{-3}

CY2016 is exploring many PRD topics for the first time on Z

Title	Experimental objective	Shots	Month	Labs
TPC: Laser-only	Laser heating measurements	**6**+5*	**Jan**, Dec	SNL, LLE
Imp: Thick End	Validate dynamics models	**2**	**Feb**	SNL
Imp: High AR	Test plastic-coated AR=9 liners	**1**	**Feb**	SNL
Imp: Helical	Validate factors behind helical instabilities	**1**	**Feb**	SNL
DTC: 31-cm conv.	Can 31-cm convolute reduce current loss?	2	Apr	SNL
DTC: LCM	Test load current multiplier	2	Apr	SNL
DTC: Eddy	Study high pressure, 1D-like, large-radius stagnation	3	Apr	SNL
DTC: D-RT	Study deceleration phase	2	Apr	SNL
DTC: Low-L	Test low-inductance hardware & Bfield coils	5	May, Oct	SNL
Stag: Mix	Isolate mix sources; develop mix diagnostics	3	Jun	SNL
Stag: AR Scan	Validate scaling of MagLIF vs liner AR	5	Oct	SNL
Stag: High B	Test scaling of MagLIF targets as B0 changes	**2**+2	**Feb**, Oct	SNL
Stag: D2 puff	Contrasting stagnation conditions to validate measurement approaches	2	Mar	SNL, Weiz.
Stag: Sierra	Diagnose stagnation	3	Mar	LLNL, SNL
Imp: Sierra	Magnetic pressure vs. radius	7	Aug, Dec	LLNL, SNL

Over the next five years, we seek to accomplish the following goals related to modeling, simulation, & scaling:

- **Improve our existing codes capable of fully-integrated simulations by upgrading the MHD-based models in them**
  - All of the codes benchmarked to date as being useful for simulating all aspects of magneto-inertial fusion are based on fluid-like MHD approximations
  - Additions to the models are needed to capture more of the relevant physics, including magnetic flux loss (Nernst, Ettinghausen) and current flow in low-density plasma (“extended MHD”)
- **Investigate hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations**
  - Traditional particle-in-cell codes do not scale well to the high particle densities typical of inertial confinement fusion
  - Hybrid fluid/particle calculation techniques may allow some codes to bridge the gap into this area (e.g., LSP or other ASC codes)
- **Develop tools and experiments for validating our simulations**
  - Can be theoretical test problems (e.g., magnetic Noh problem)
  - Can be simple, highly-specialized test codes with better physics models
  - Each of the previous four areas shall generate validation data for our tools
- **We will not invest significant effort in modeling laser-plasma interactions**

We have made modest progress in our modeling, simulation, & scaling goals

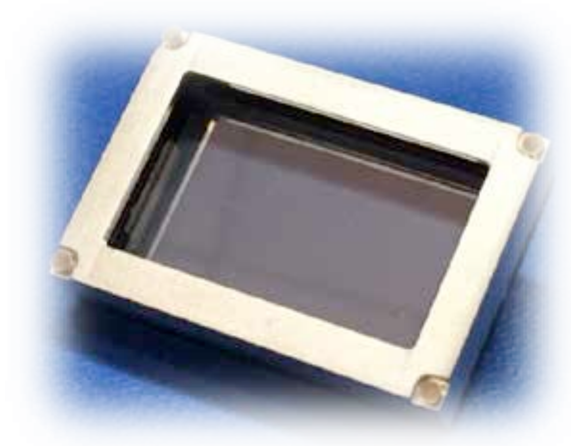
- **Improve our existing codes capable of fully-integrated simulations by upgrading the MHD-based models in them**
  - Progress: A workshop was held at LLNL last fall in which various potential code improvements were discussed. We have not yet held a follow-on workshop, however, so it is unclear whether we are making progress.
- **Investigate hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations**
  - Progress: We are proposing a ~$4.5M/year internal “Grand Challenge LDRD” at Sandia that would combine elements of our ASC program with scientists at Voss Scientific to produce an exascale-compatible hybrid PIC code. The primary emphasis would be driver-target coupling, but it could be expanded later to include target physics modeling.
- **Develop tools and experiments for validating our simulations**
  - Progress: Collaborators at the NRL continue to work on test problems and theoretical/modeling research on these topics.
- **We will not invest significant effort in modeling laser-plasma interactions**
  - We are attempting to leverage existing expertise at LLE and NIF to characterize backscatter data from Z.

The Priority Research Directions are also helping to define the main diagnostic needs for the MDI effort

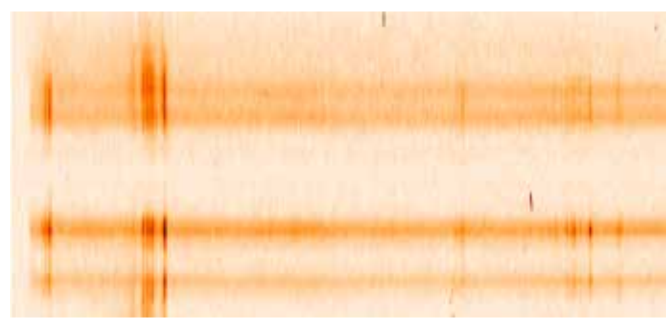
Stagnation & Burn Diagnostic Needs

- Time-gated high resolution spectra
  - hCMOS-based focusing spectrometer (1-2 years)
  - SLOS-based focusing spectrometer (3-5 years)
- Time-gated high resolution imaging
  - MCP-based in-chamber pinhole (this year)
  - SLOS-based crystal imager (3-5 years)
- Neutron Spectrum
  - Gated nTOF (this year)
  - CRS/MRS (requires tritium)
- Neutron Imaging (1-3 years)
- Reaction History (requires tritium)
- Continuum Spectroscopy
  - Mirrored diodes (1 year)

Multi-frame hCMOS Sensor



Space-Resolved Fe Spectra from MagLIF stagnation



Red: Central elements of the National Diagnostics Plan

The Priority Research Directions are also helping to define the main diagnostic needs for the MDI effort

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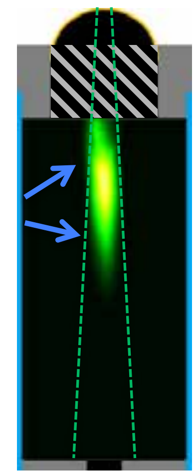
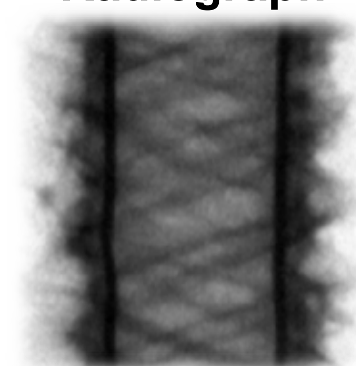
- **Implosion diagnostic needs**
  - Tandem radiography (1 year)
  - 4-frame hCMOS-based radiography (1-2 years)
- **Preheat diagnostic needs**
  - Thomson Scattering (Omega & NIF)
  - Gated LEH Imaging with hCMOS (this year)
  - Gated LEH Spectroscopy with hCMOS (1 year)
- **Driver-target coupling diagnostic needs**
  - PDV/VISAR (this year)
  - Visible spectroscopy for current flow (LDRD)

Monochromatic Preheat Image



Monochromatic Implosion Radiograph



Red: Central elements of the National Diagnostics Plan

We have developed a science-based plan and structure for Magnetically Driven Implosions for the next 4-5 years that is increasingly national in scope

Sandia National Laboratories

~85% of effort

- **Study the underlying science, emphasizing MagLIF**
  - Primarily accomplished through Priority Research Direction teams
    - Driver-target coupling, Target Pre-conditioning, Implosion, Stagnation & Burn, Modeling, Approximations, and Scaling
  - Teams have dedicated experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)
  - Drives development of new diagnostics, simulation tools and methods

~10% of effort

- **Demonstrate desired conditions and target scaling**
  - Primarily accomplished through integration experiments on Z
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm

~5% of effort

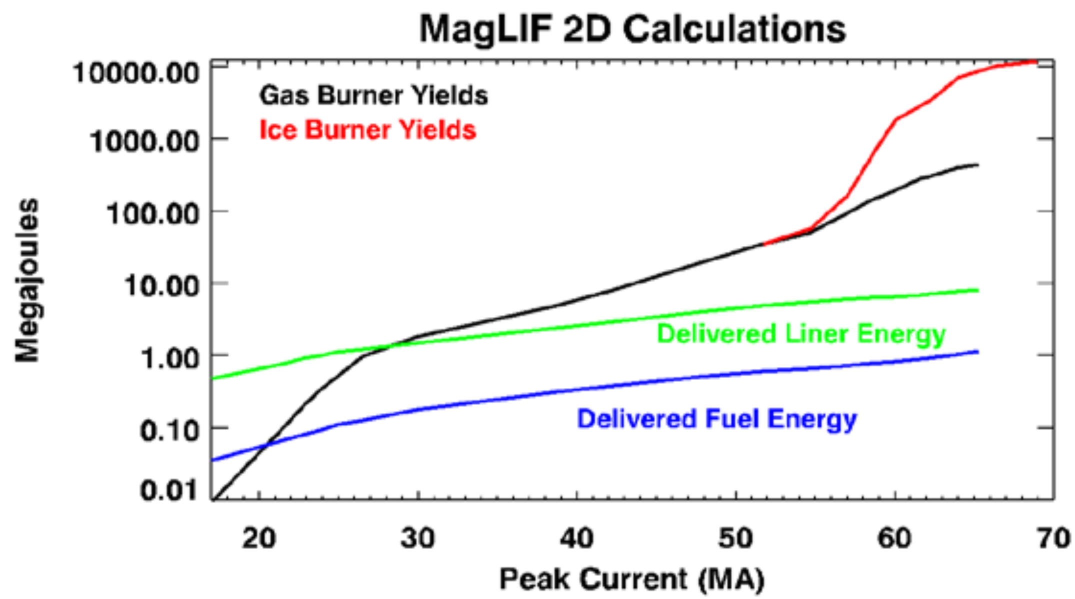
- **Develop a path to ignition and beyond**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF

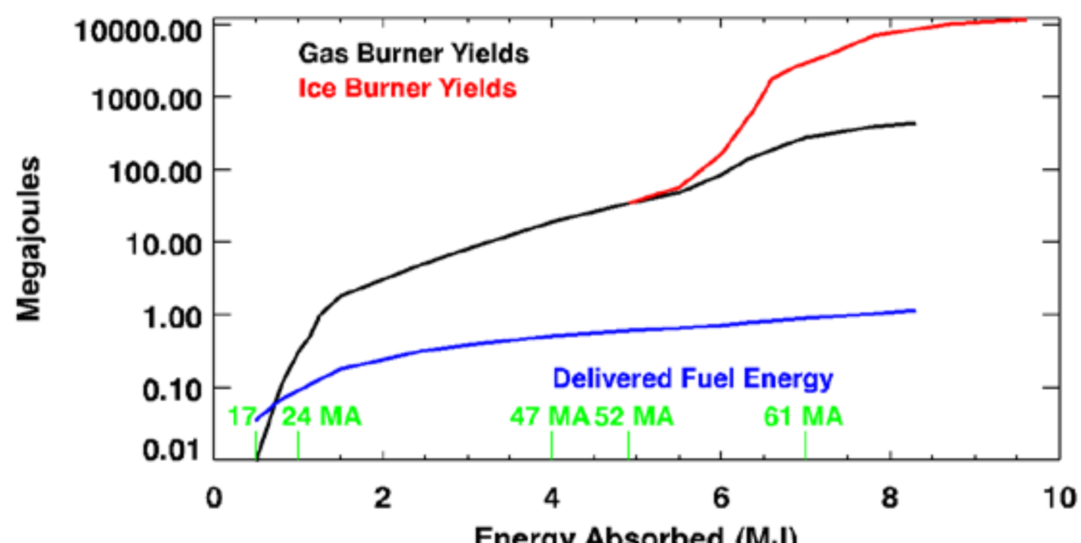
~1% of effort

- **Understanding mission needs for ignition and high yield**
  - Why does the nation need a facility capable of ~1 GJ/shot?

We are still working on validating our 2D calculations of MagLIF to understand whether they credibly scale

- Today's MagLIF experiments couple 17-18 MA (~0.5 MJ) to the target
- Our driver-target coupling team believes we could reach 22-24 MA using higher charge voltage & optimized load hardware.
- At 24 MA, an optimized target design with 30 T and >6 kJ of preheat is predicted by 2D LASNEX calculations to produce >100 kJ DT yield
- It is unclear today if we have the resources to implement the necessary technology or the scientific research needed to reach 100 kJ

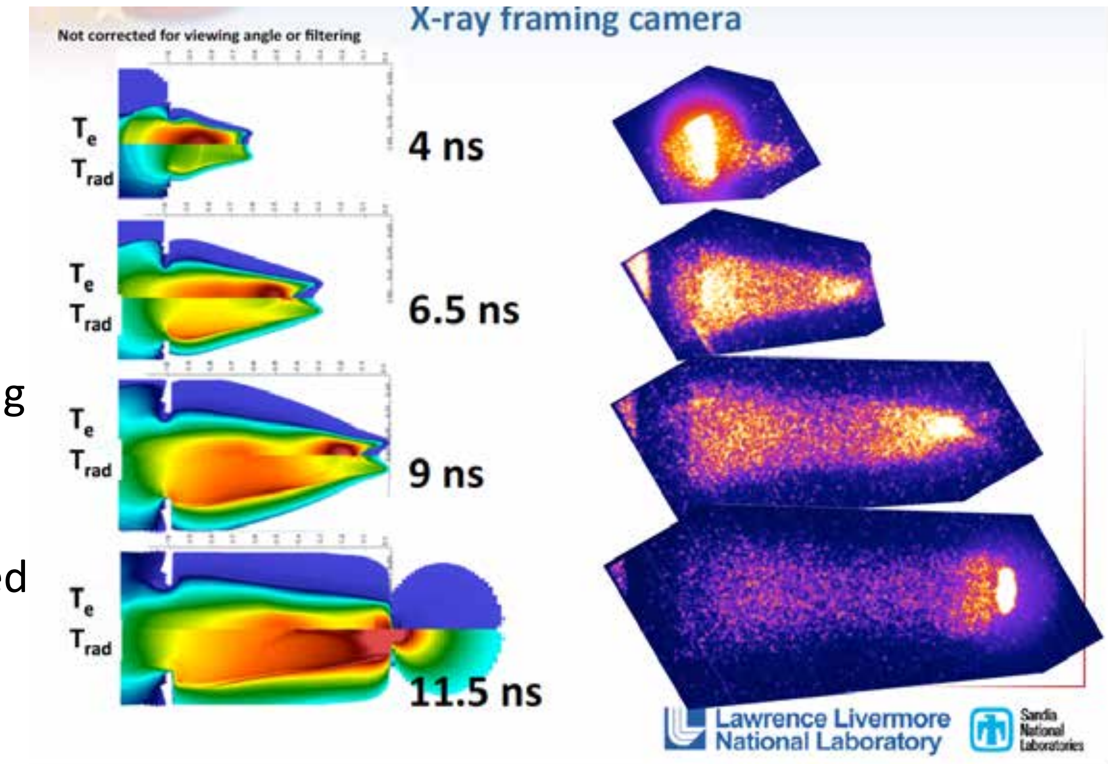




S.A. Slutz *et al.*, Phys. Plasmas 23, 022702 (2016).

In collaboration with LLNL, we recently executed our first NIF experiment to study the scaling of laser heating that would be required for an ignition or high yield target

- 1/28/2016 experiment
- Unmagnetized, 30 kJ, n_e/n_{crit}~0.1 heating experiment of a gas tube
- Quick look of data (to right) appears to show qualitative agreement with our pre-shot HYDRA simulations (propagation depth and timing of impact on far wall)
- Data analysis underway, an additional experiment planned in July 2016
- Eventual plan is to use NIF to demonstrate magnetized heating at conditions directly relevant to ignition (no scaling extrapolations needed!)



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Sandia National Laboratories

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~1% of effort

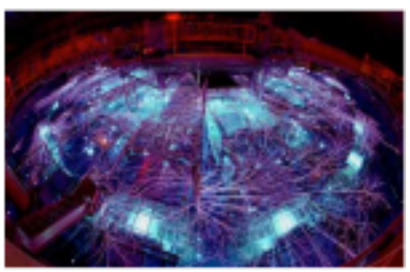
- **Understanding mission needs for ignition and high yield**
  - Why does the nation need a facility capable of ~1 GJ/shot?

Our ICF program would benefit from better understanding the value and need for ignition and high yield

- In 1988 (when I started high school) the ICF program published a multi-laboratory mission needs document for a Laboratory Microfusion Facility
  - Document claimed needs were independent of the three approaches at the time that could lead to such a facility (Laser-driven indirect drive, laser-driven direct drive, and light ion beams)
  - Are these needs still valid today? They could be viewed as not being compelling since no LMF ever built? Or was it just that the approaches were not mature enough to justify the investment?
  - There are renewed efforts and needs for hostile environment survivability across the complex. The ICF program at Sandia is seeking to better connect to those efforts (e.g., Jones/Sullivan talks tomorrow).
  - We welcome collaborations with LLNL and LANL on needs and how/whether pulsed power can contribute. If we need to develop new platforms to demonstrate the utility of pulsed power to meet these needs, let's start them sooner rather than later. Belief barriers can take time to overcome (e.g., AWE at January LANL workshop: "Magnetic fields make us nervous.")

Sandia is exploring pulsed power designs that might be capable of ignition and high yield—whether one is built and what its size is will depend on the mission needs we develop

Yield = E_{fuel}?
(~100kJ$_{DT\ eq}$)
Physics Basis for Z300

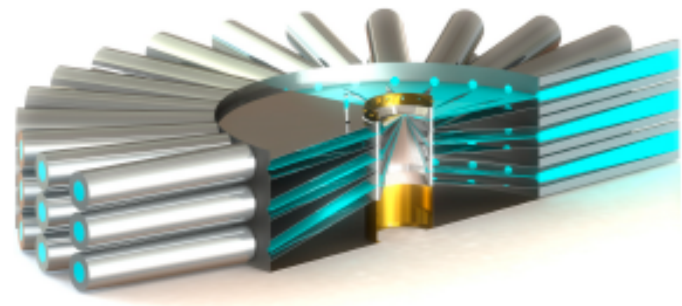


Z (“Z80”)
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

Yield = Etarget?
(About 3-4 MJ)
α-dominated plasmas

“Z300”
- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Fusion Yield 0.5-1 GJ?
Burning plasmas



“Z800”
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

Note that 1 GJ ~ 0.25 tons TNT and there will be significant radiation and activation issues, so Z800 is “bold”!

W.A. Stygar *et al.*, Phys. Rev. STAB 18, 110401 (2015).

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Sandia National Laboratories

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~1% of effort

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  - Why does the nation need a facility capable of ~1 GJ/shot?

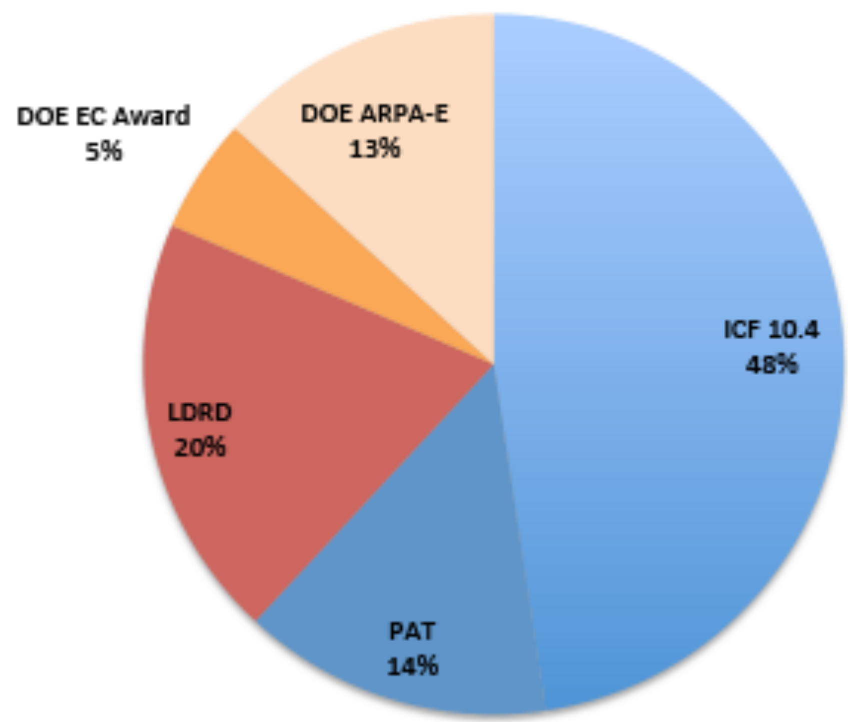
Miscellaneous Sandia ICF program business items

- Fusion Staffing
- Target Fabrication
- Tritium on Z

A significant fraction of Sandia fusion research staffing in FY16 is supported by proposal-driven funding sources

- Staff numbers are in TLEs:
  Full-time PhD-equivalent including Sandia FTEs, staff aug, contractors, and post-docs
  - PP ICF 10.4 funds 9 TLEs
  - Science PAT funds 2.7 TLEs (working on joint boost/ICF issues)
  - LDRD at Sandia funds 3.7 TLEs (fusion-relevant labor only)
  - DOE Early Career Awards fund 1 TLE
  - ARPA-E funds 2.5 TLEs
- Total TLEs at Sandia working on fusion-related research: About 19
- About 38% of our present fusion-related staffing is supported by limited-term, proposal-driven funding sources
- We are presently evaluating the affordability of a few additional TLEs to help with collaborations and experiments

Fusion-related Labor at SNL (TLEs) (non-operations; no managers)



Sandia's ICF/Science target fabrication needs have evolved rapidly and have outstripped historical capacity

- General Atomics is doing more work for Sandia than at any time in the past 20 years
  - Sandia's in-house target fabrication capability consists of load hardware and wire arrays.
  - We also used to have a captured local business for supplying DMP target panels, but lost that >5 years ago and recently switched to GA to supply these.
  - The transformation of the research program on Z from ~100% wire arrays in 1996 to ~18% wire arrays in 2016, combined with changes in our local supply chain, means that GA is now directly contributing parts and/or assembly of >82% of the experiments on Z.
- Sandia's funding allocation in the General Atomics contract for target fabrication has not kept pace with our transforming ICF/Science program
  - We rely on General Atomics to run on-site target fabrication resources and also staff and machining in La Jolla.
  - We also rely on GA for R&D for new target ideas (e.g., Li liners or coatings)
  - A significant fraction of our budget is now for thin foils, mostly from Luxel.
- A major limitation on laser heating experiments in the PECOS target chamber at Sandia is the lack of a supply chain for targets
  - Our present resources mean we can only ask GA for a few dozen targets at best
  - We have started to work with Schafer as a target fabrication supplier for Z-Beamlet

We believe that we need to demonstrate tritium use on Z to do better science & prepare for the future

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- **Even at small percentages, tritium can enhance our scientific understanding and productivity on Z**
  - In ICF, could leverage more of the diagnostics and experience developed by the larger community that is centered on measuring 14 MeV neutrons, as well as demonstrating understanding in going from pure DD to few %T
  - In effects testing work, could benefit from enhanced yields and changes in energy spectrum to test our understanding of new testing platforms under development
- **We need to develop processes and experience**
  - Tritium has never been used on a large-scale pulsed power facility
  - Multiple missions for any next-step pulsed power facility will likely require the use of tritium
    - Multi-MJ fusion yields for Inertial Confinement Fusion
    - Combined neutron/photon effects testing
    - Science campaign experiments (e.g., boost)
  - Not all of the experience with using tritium on large laser facilities is relevant—we cannot rely solely on those experiences to define requirements for a next-step facility

We plan to work towards a key decision in late 2017 regarding future tritium operations on Z

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	2015	2016	2017	2018	2019	2020	202

We believe the existing infrastructure would allow an estimated 2- 4 tritium experiments / yr. at up to 3% T

Option 0 would sustain 2 – 4 experiments / yr.
Limited uncontained experiments

Contained	D2, He3	0.1% T	1% T	3% T	3% T	3% T	3% T
Uncontained	D2, He3	D2	0.1% T	1% T	3% T	3% T	3% T

Key Decision for Tritium Operations on Z

Upgrade Option 1

Option 1
Upgrades contained experiments to 50/50
Unlimited uncontained experiments @ 3% T

Contained	10% T	50% T
Uncontained	3% T	3% T

Upgrade Option 2

Option 2
Upgrades all T experiments to 50/50

Contained	10% T	50% T
Uncontained	10% T	50% T

Potential systems requiring upgrades for options 1 & 2 include:

- Center section purging/ ventilation
- MITL tent
- HVAC
- Neutron shielding
- Tritium dedicated hardware
- Tritium capture system
- Tritium fill station

- Tests using light gas surrogates suggest a containment efficiency of 0.98. Measurements of recovery (0.99) and decontamination (0.99) give a combined 0.999998 removal efficiency
- 1st trace tritium test (contained) on Z in August

The magnetic direct drive effort will continue to evolve in 2016, both organizationally and technically

- We will complete last year's introduction of PRD teams and this year's introduction of "integration campaigns"

- This year will mark the first contributions of the new PRD teams to the program, including our first dedicated driver-target coupling effort

- We will better definine a 4-5 year program of work and priorities—we are presently trying to understand our resource needs (people, staffing, targets)

- This effort has evolved into a much more national program, and we welcome further input and collaboration

Backups

Even a few percent tritium would be of value to the magnetic drive ICF effort from a diagnostics perspective

Physics	Measurement	Tritium fuel content <0.1%	0.1%	1%
Behavior of tritium in the Z pulsed power environment	Sampling of tritium contamination, migration	FY16 LDRD	FY16 LDRD	
Scaling of yield to DT—thermonuclear?	DT yield		FY16 LDRD	
Ion temperature and non-thermal population	Precision nTOF and DT/DD yield ratio			
Liner/fuel mix	DT yield with tritiated gas fill and deuterated liner			
Fuel morphology	Neutron imaging			
Thermonuclear reaction history	Gamma Ray History/GCD, Thompson parabola			
Liner/fuel density, non-thermal effects (peak shifts)	Compact/Magnetic Recoil Spectrometer (CRS/MRS), precision nTOF			

CY2016 Magnetic Direct Drive integration experiments are focused on folding in advances in our understanding developed by Target Preconditioning & Implosion PRDs

Schedule name	Integration focus	Facility	Shots	Labs/ Contributors
Stag MagLIF16a (January)	Integrate in new phase plates for Z-Beamlet to improve laser-gas coupling. This campaign leverages understanding gained on OMEGA-EP at LLE and the PECOS chamber at Sandia.	Z	2	SNL/LLE
Stag MagLIF16b (June)	Integrate in new phase plates and laser pulse shape for Z-Beamlet to improve laser-gas coupling. This campaign leverages understanding gained on OMEGA-EP at LLE and the PECOS chamber at Sandia.	Z	4	SNL/LLE
StagMagLIF16c (June)	Integrate in plastic-coated liners to see if it improves the three-dimensional stability of our baseline MagLIF designs. This campaign builds on years of Implosion research on Z.	Z	3	SNL
Cryo MagLIF (July)	Integrate in cryogenically cooled gas MagLIF targets. The lower pressure of the gas will enable a much thinner laser entrance hole window (better laser-gas coupling). The liner design is also changed to integrate in a thick-ended liner that eliminates the need for "cushion" end caps and thus decreases the possibility of laser-induced mix.	Z	3	SNL
Harding (misc.)	Alternative target concept exploration (includes leftover shelf shots from CY2015).	Z	5	SNL
TOTAL			17	

Magnetic direct drive integration road map elements (examples—detailed plan is still being refined)

- **Laser improvements to deliver >6 kJ**: Install remaining booster amplifiers; complete co-injection of "Z-Petawatt"; increase optics size of second beam to enable 40 cm operation.
- **D-T-C improvements to deliver 24 MA**: Reduce inductance of MagLIF hardware; increase Z charge voltage to 95 kV; plasma cleaning to reduce current loss?; load current multiplier to improve current delivery to Sierra?
- **T-P improvements to improve laser coupling to MagLIF**: Optimized phase plates; optimized laser pulse shape; optimized laser energy; optimized gas fill pressure (to prevent energy from hitting bottom end cap)
- **Implosion improvements**: Plastic coatings to reduce acceleration instability growth; thick-end liners to reduce mix opportunities; liner height optimization (tradeoff in reduced end losses versus increased inductance/fuel mass; Li liners (thicker, more compressible); Li-coatings on liner inner surface to mitigate mix; Final Optics Assembly modifications to allow tandem radiography & laser-heating
- **Modeling, Simulation, & Scaling target design studies**: "Auto-magnetic field generation"; "Harding"; "Socorro"; "Mora"; closed magnetic field line implosions; alternative heating schemes
- **Diagnostic improvements**: Use of >1% tritium?; Misc. advanced diagnostics (see next slide);

Preliminary diagnostic development plan for Magnetic Direct Drive effort on Z

Stagnation	Te(t), ne(t)	hCMOS focusing spectrometer	FY17
		MLM continum diodes	FY17
		SLOS focusing spectrometer	?
	X-ray Morphology(t)	MCP in-chamber pinhole	FY16
		SLOS crystal imager	?
	T_brysk	Gated nTOF	FY16
		Far-field nTOF	FY19
		MRS (Tritium)	?
	Fusion Morphology	MagLIF n-Imaging (Tritium?)	FY17-18
	Burn History	GRH (Tritium)	FY18-19
Implosion	Liner stability at high convergence	>7keV radiography	FY16
		4-frame hCMOS radiography	FY17
	Liner stability on integrated shots	Tandem radiography	FY17
		Down-scattered n-imaging (Tritium)	?
	3-D liner stability	Multi-view radiography	FY19-20
Preheat	Te(t), ne(t) of preheat	hCMOS LEH imaging	FY16
		hCMOS LEH spectrometer	FY17
		Thomson scattering (NIF/Ω)	FY18-19
Driver-Target Coupling	Load Current	PDV/VISAR	FY16
		Line VISAR	FY17
	Plasma and field strength in feed	Streaked visible spectroscopy	FY16-17

The Magnetic-driven Direct Drive effort has matured and evolved rapidly over the past 20 years—we are collectively getting better at applying pulsed power for NNSA missions

- 1996: ~100% wire array experiments on Z, emphasis on soft and cold/warm x-ray sources for ICF and effects. No magnetic direct drive effort.
- 2001: Growing dynamic materials program effort on Z in addition to wire-array x-ray source development (e.g., double-ended hohlraums, dynamic hohlraums, K-shell radiation sources). No magnetic direct drive effort.
- 2006: ~56% wire array experiments on Z (out of 198 shots in FY06 before shutdown); ICF program exploring new ICF targets jointly with LLNL along with radiation-driven implosions; strong DMP effort including Pu; nascent platform for opacity studies; wire-array K-shell radiation sources
- 2011: MagLIF effort beginning; No x-ray driven ICF on Z for 5 years; new hohlraums and warm x-ray sources under development; robust program in DMP including cylindrical geometry; new opacity platform established
- 2016: ~18% of the shots on Z are wire arrays. Just over 2 years since our first MagLIF shots. Continued progress on other direct-drive ICF platforms by Sandia and LLNL. Robust platforms for DMP, opacity, and >10 keV x-ray sources.

We are planning on at most 15 more integration experiments in CY2016, which are mostly in June and July

- Three campaigns are essentially motivated by ongoing research driven by our Priority Research Directions (or their spiritual predecessors)
  - 4 additional Z shots for phase plate and laser pulse shape integration
    - Driven primarily by our Target Preconditioning team
    - Attempting to leverage understanding gained from laser heating experiments at Omega-EP, our Pecos chamber, and the Z chamber
    - SNL/LLE collaboration funded by LDRD and ARPA-E critical to this effort
  - 3 Z shots for plastic-coated liner integration
    - Driven primarily by our Implosion team efforts over past several years
    - Does a plastic coating improve the symmetry/performance of MagLIF?
  - 3 Z shots for cryogenic MagLIF target development
    - Integrate cryogenic gas fill to enable thinner windows (*Preconditioning*)
    - Integrate thick-end liners to reduce laser-induced mix (*Preconditioning, Implosion*)
- The fourth campaign (up to 5 shots) is investigating a new target concept

CY2016 is exploring many PRD topics for the first time on Z

Title	Science focus	Shots	Month	Labs
TPC: Laser-only	Laser heating measurements	11*	Jan, Dec	SNL, LLE
Imp: Thick End	Validate dynamics models	2	Feb	SNL
Imp: High AR	Test plastic-coated AR=9 liners	1	Feb	SNL
Imp: Helical	Validate factors behind helical instabilities	1	Feb	SNL
DTC: 31-cm conv.	Can 31-cm convolute reduce current loss?	2	Apr	SNL
DTC: LCM	Test load current multiplier	2	Apr	SNL
DTC: Eddy	Study high pressure, 1D-like, large-radius stagnation	3	Apr	SNL
DTC: D-RT	Study deceleration phase	2	Apr	SNL
DTC: Low-L	Test low-inductance hardware & Bfield coils	5	May, Oct	SNL
Stag: Mix	Isolate mix sources; develop mix diagnostics	3	Jun	SNL
Stag: AR Scan	Validate scaling of MagLIF vs liner AR	5	Oct	SNL
Stag: High B	Test scaling of MagLIF targets as B0 changes	4	Feb, Oct	SNL
Stag: D2 puff	Contrasting stagnation conditions to validate measurement approaches	2	Mar	SNL, Weiz.
Stag: Sierra	Diagnose stagnation	3	Mar	LLNL, SNL
Imp: Sierra	Magnetic pressure	7	Aug, Dec	LLNL, SNL