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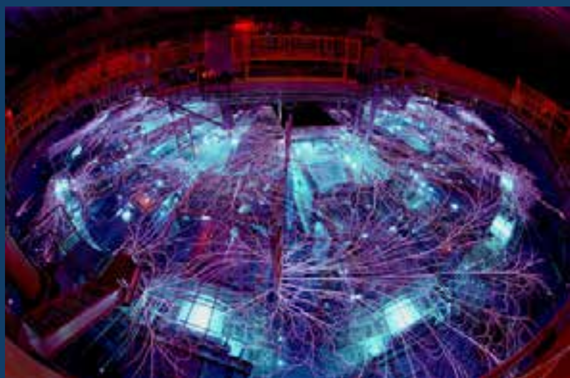

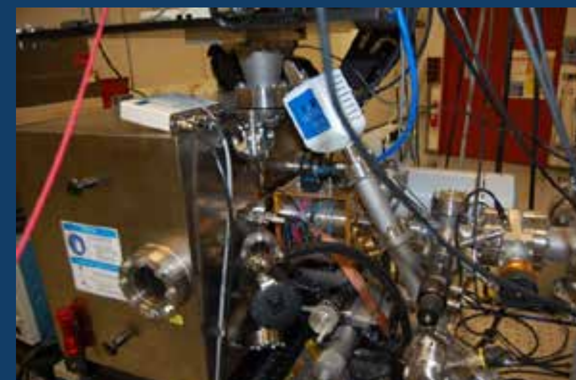

Meeting the 2020 ICF Program Goal: Determining the credible physics scaling to multi-MJ fusion yields for the Magnetic Direct Drive approach

Daniel Sinars, Senior Manager

Radiation and Fusion Physics Group (1680)

GENERAL ATOMICS

Schafer

UNIVERSITY of ROCHESTER

Lawrence Livermore National Laboratory

Radiation Effects and High Energy Density Sciences Research Foundation External Review, May 16-19, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

arpa·e

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The transition of the Sandia ICF (and HED) programs from wire arrays to magnetic direct drive still poorly understood by many people not closely coupled to our ICF program

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Year	Wire Arrays? (All Z shots)	Magnetic X-ray Drive or Magnetic Direct Drive?	Main ICF target concepts being studied
FY1996	~100%	X-ray	Many dynamic hohlraum variants
FY2001		X-ray	Dynamic Hohlraums (DH) & Double-ended hohlraums (DEH)
FY2006	56%	X-ray & Direct	DH, DEH, "Z100"
CY2011		Direct	"Z100", Sierra, MagLIF preparations underway
CY2016	18% projected	Direct	MagLIF, Sierra

Your help in communicating this shift from wire arrays is appreciated!

A key element of our strategy is to focus primarily on MagLIF through 2020, with a parallel track joint with LLNL.

- While there are a variety of interesting target concepts for Magnetic Direct Drive, we don't believe we can carry them all forward. The FY15 Review commented: *The present program has insufficient experimental opportunities and lacks availability to a sufficient number of designers and experimentalists to thoroughly evaluate more than one design.*

- LLNL and Sandia have jointly explored multiple magnetic direct drive target concepts for 12 years on Z. We will continue to collaborate at 3-4 weeks/year.

- MagLIF will be the central focus of the ICF effort at Sandia, despite its relative immaturity (first experiments just over 2 years ago). As an unclassified concept, it allows us to participate more directly in the national program landscape.

- There is some risk in the focus on MagLIF, as noted in the FY2015 review: *This is a cause for concern as there would be a limited selection of mature alternatives if current performance limitations ultimately prove insurmountable. Given the current constraints, it is not immediately clear how alternative designs that go beyond simple variations on a theme could grow from a nascent idea to a viable alternative.*

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

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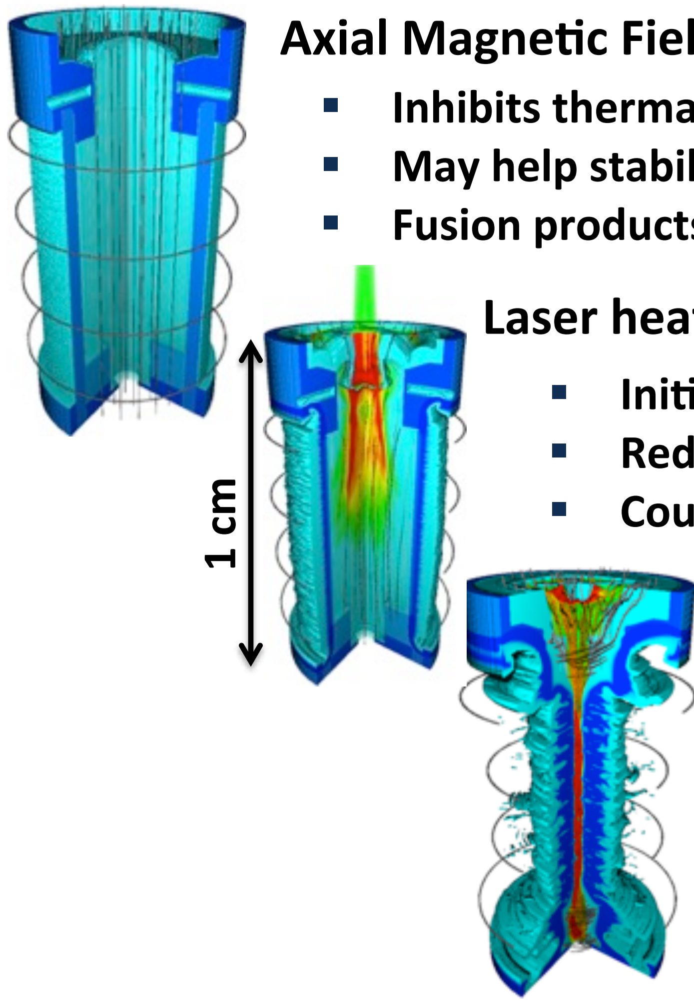


Axial Magnetic Field (10 T initially; 30 T available)

- 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

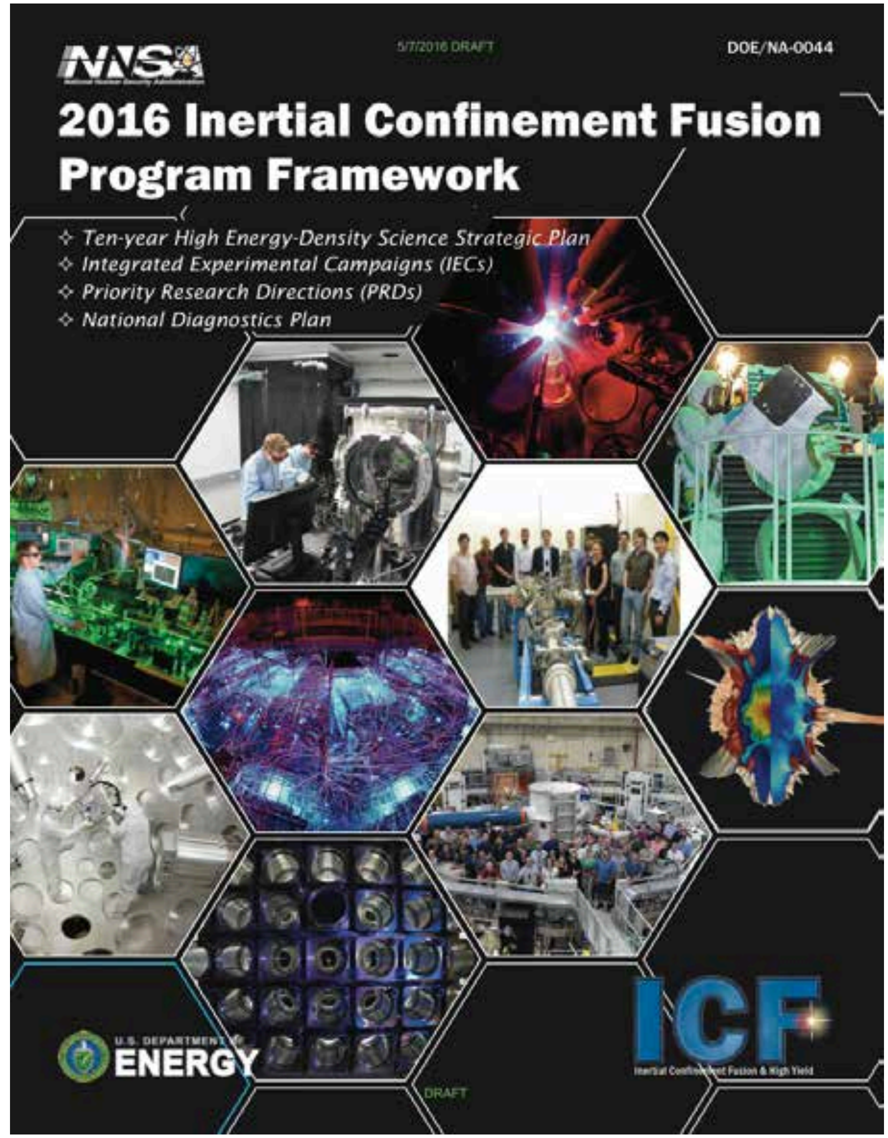
Magnetic compression of fuel (~100 kJ into fuel)

- ~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).

Sandia's ICF plans and strategies in MDD are well aligned with the national ICF program in structure and priorities

- Major program elements
  - 10-year HED Science Plan
  - Integrated Experimental Campaigns (IECs)
  - Priority Research Directions (PRDs)
  - National Diagnostics Plan
- Last year we created ICF working groups at Sandia for five of the six PRD areas
  - These groups carry out the science, not just on Z but also on Omega, Omega-EP, and NIF
- This year we are paying more attention to how we approach IECs
  - More focus on how ideas flow from PRDs into the IECs



Our ICF plan emphasizes the science using Z, Ω, and NIF, and tests our integrated models using Z, with the goal of assessing the credibility of any extrapolations to ignition

~85% of total effort (Z,Ω,NIF)

- **Study the underlying science, emphasizing MagLIF**
  - Primarily accomplished by the 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 target performance over available range of conditions**
  - 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, and assess its credibility**
  - 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

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

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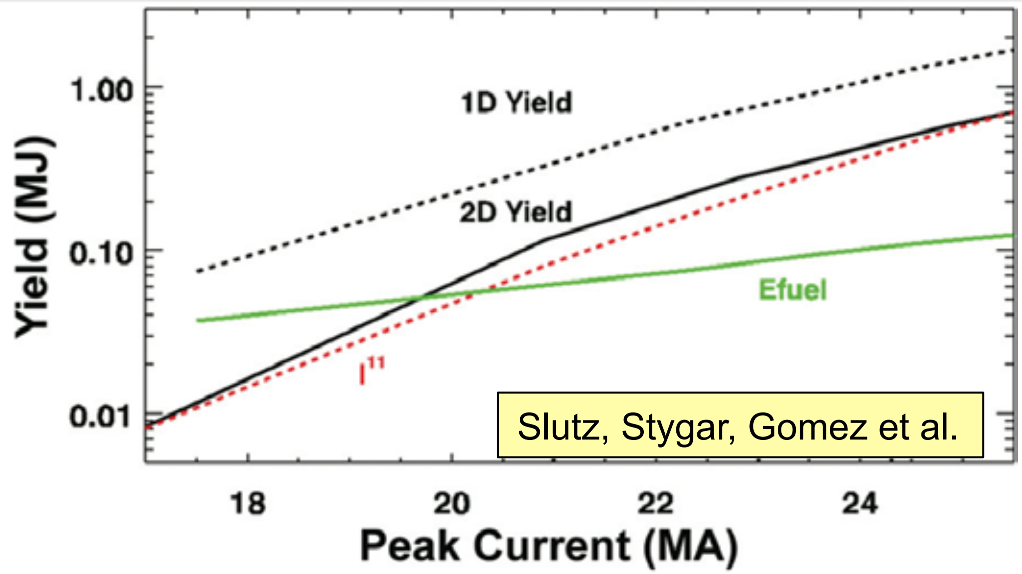
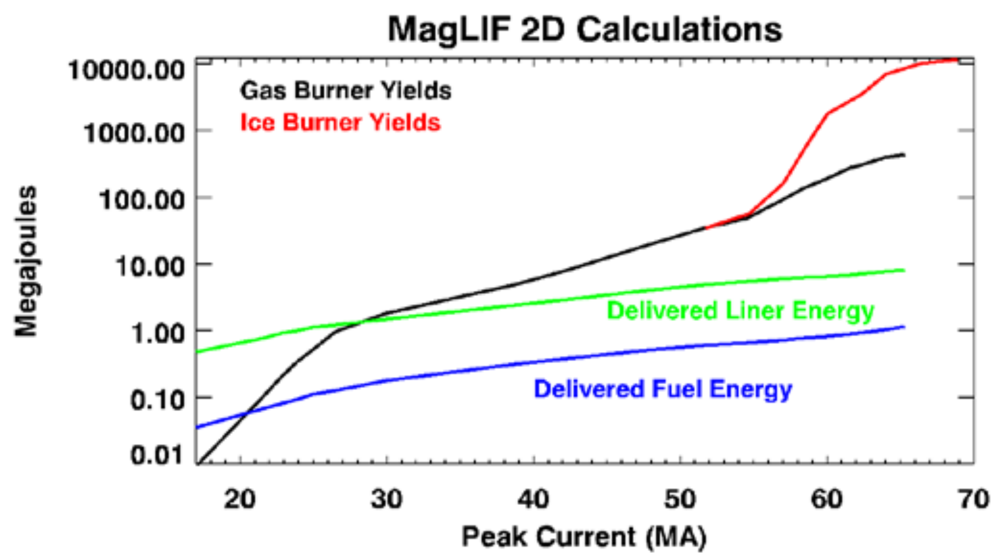
MDD Approach Goal 1: Demonstrate MagLIF target yields over the range of available parameters on Z (up to 24 MA)

- Initial MagLIF experiments coupled 17-18 MA to the target.
- Our driver-target coupling team believes we could reach 22-24 MA using higher charge voltage & optimized load hardware.
- During the next four years we will use integrated experiments to determine if predictions of >100 kJ yields are valid
- Significant investments are needed to actually reach 100 kJ (e.g., 50/50 tritium on Z, 95 kV short pulse capability, higher shot rate)

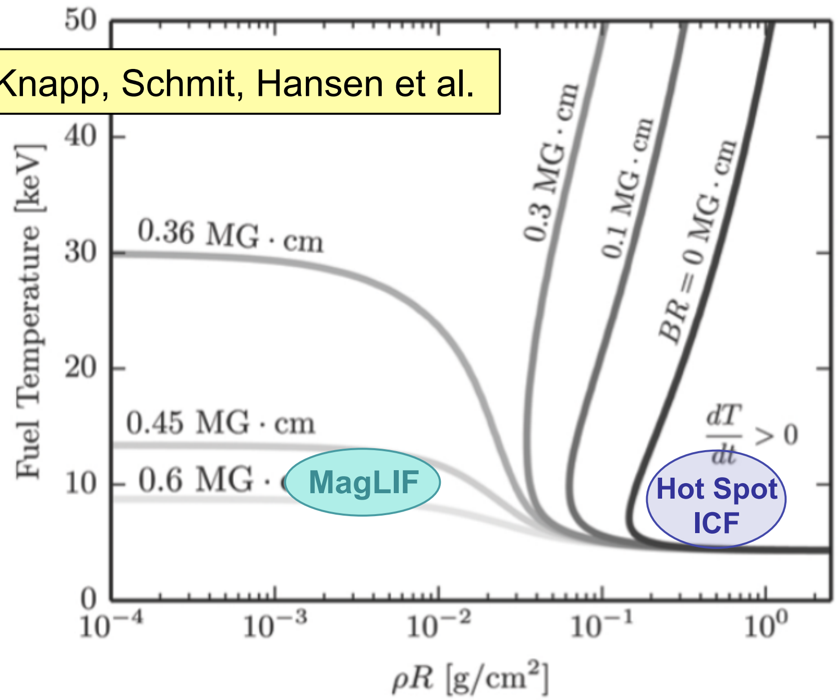


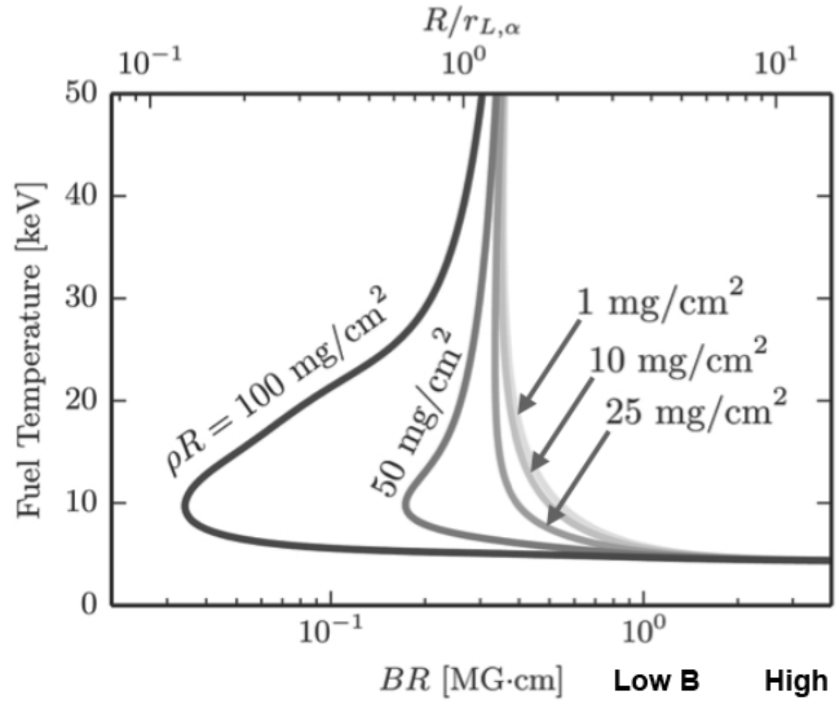


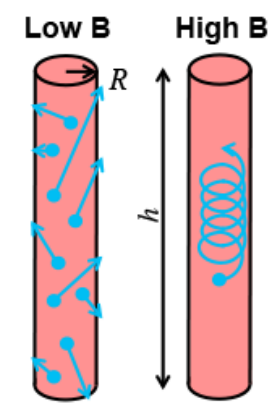
S.A. Slutz *et al.*, Phys. Plasmas 23, 022702 (2016).

MDD Approach Goal 2: Demonstrate Pτ>5 Gbar-ns and BR>0.5 MG-cm in the fusing fuel to validate the precepts of magneto-inertial fusion (not just about yield)

Knapp, Schmit, Hansen et al.







- 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>800 T

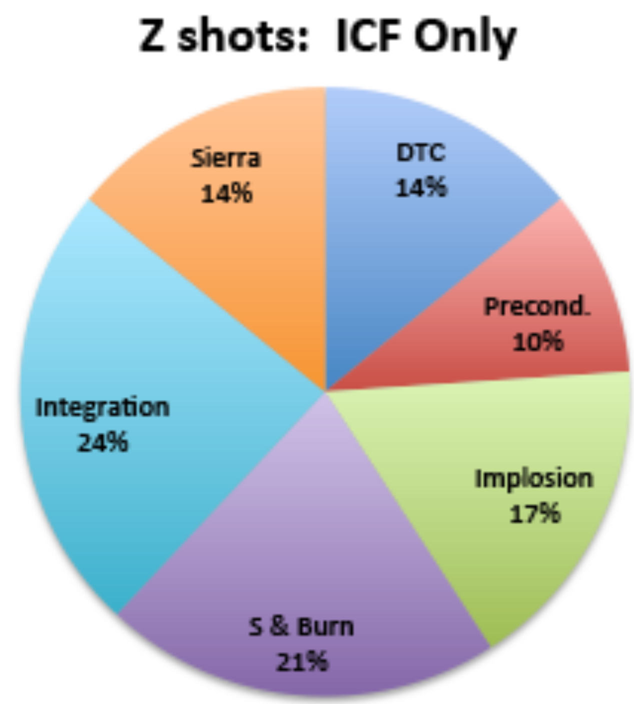
Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al.*, Phys. Plasmas (2015).

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

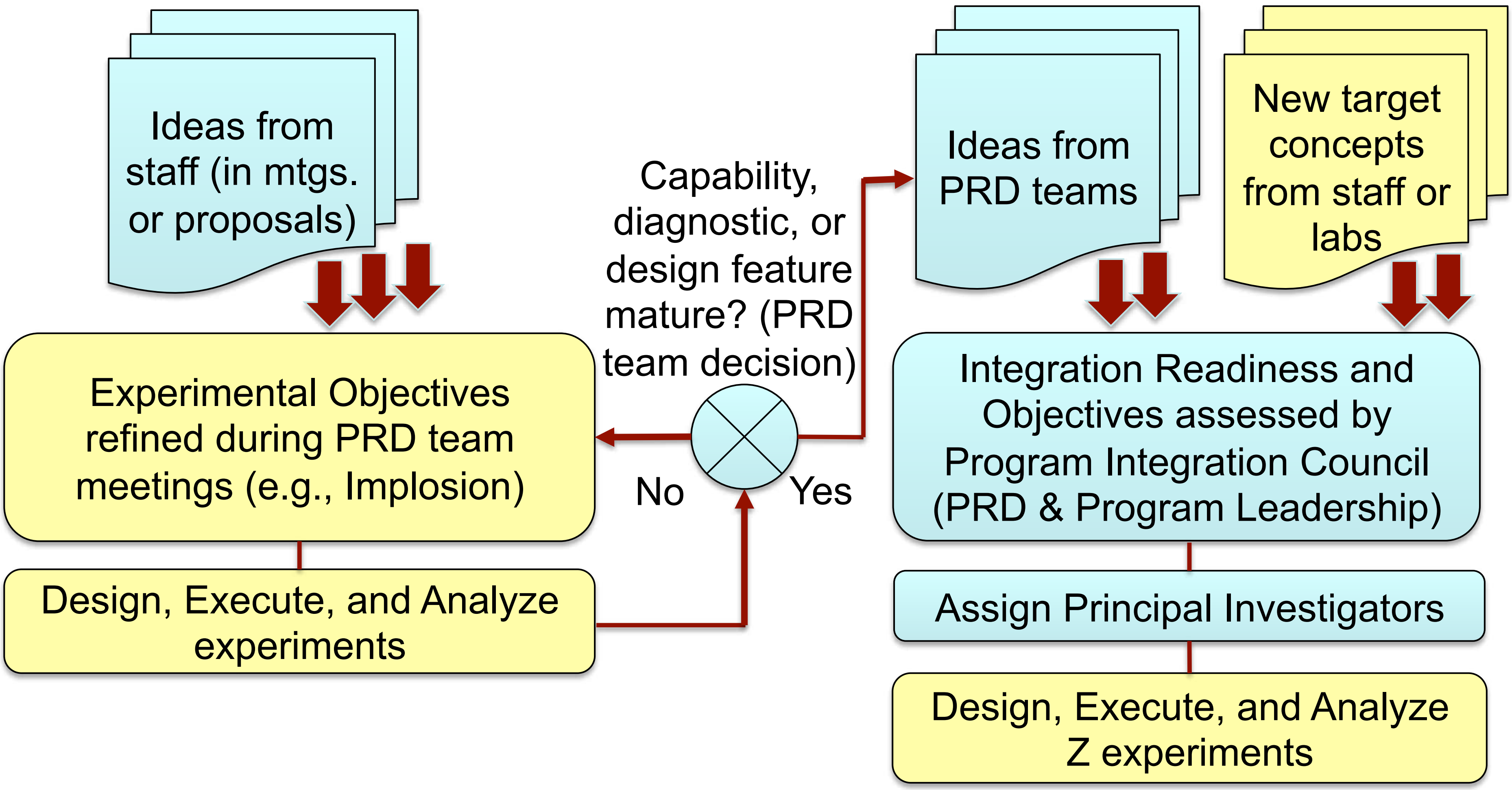
- We distinguish here between "integrated" and "integration" experiments
  - **Integrated experiment**: Any experiment combining all of the key features of MagLIF, such as Z, Z-Beamlet, magnetic field coils, gas fills.
  - **Integration experiment**: An experiment whose primary objective is to integrate 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**
- Integration campaigns for MagLIF will attempt to assimilate ideas developed and matured by the PRD teams

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

- **Sierra campaigns (joint w/ LLNL)**
  - 10 shots (3 weeks)
- **MagLIF & general ICF campaigns (estimated)**
  - 11 ZBL-only tests in the Z chamber for Target Preconditioning (7 days)
  - 47 Z shots for the PRD campaigns
  - 17 Z shots for Integration campaigns
- While the percentage of ICF shots on Z is higher this year than last year, this is still 2-4x fewer shots than available for Laser Indirect Drive or Laser Direct Drive



Sandia ICF program management is working on improving the coupling between PRD and Integration experiments



Our program has executed two MagLIF integration experiments on Z so far this fiscal year

- We executed few ICF experiments last fall in order to allow us to repair the 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; Achieved lower temperatures (increased mix?)
  - 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

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Schedule name	Integration focus	Z Shots
Stag MagLIF16a (January)	Integrate in new phase plates for Z-Beamlet to improve laser-gas coupling.	2
Stag MagLIF16b (June)	Integrate in new phase plates and laser pulse shape for Z-Beamlet to improve laser-gas coupling.	4
StagMagLIF16c (June)	Integrate in plastic-coated liners to see if it improves the three-dimensional stability of our baseline MagLIF designs.	3
Cryo MagLIF (July)	Integrate in cryogenically cooled gas MagLIF targets. Includes MagLIF design optimization to take advantage of lower fill pressure (less mix?)	3
Harding (assorted)	Baseline & scaling of an alternative concept	5
TOTAL		17

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We established teams and team leaders for the science organized around the Priority Research Directions. They are focused on 5-year science & performance goals.

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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:

Scientific goals

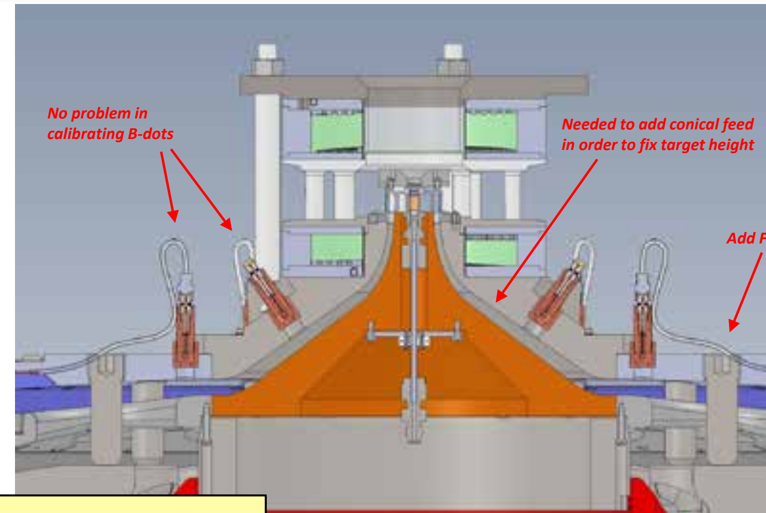
- **Develop predictive (~5%) circuit and PIC models of an accelerator coupled to a variety of loads (possibly including a single integrated simulation of power flow + target?).**
- **Conduct scaled power-flow experiments under conditions similar to those of Z Next.**
- **Quantify the benefits to ICF loads of current-pulse shaping (affects current loss).**
- **Quantify the benefits of longer implosions (such as might be achieved by an LCM).**

Programmatic goals

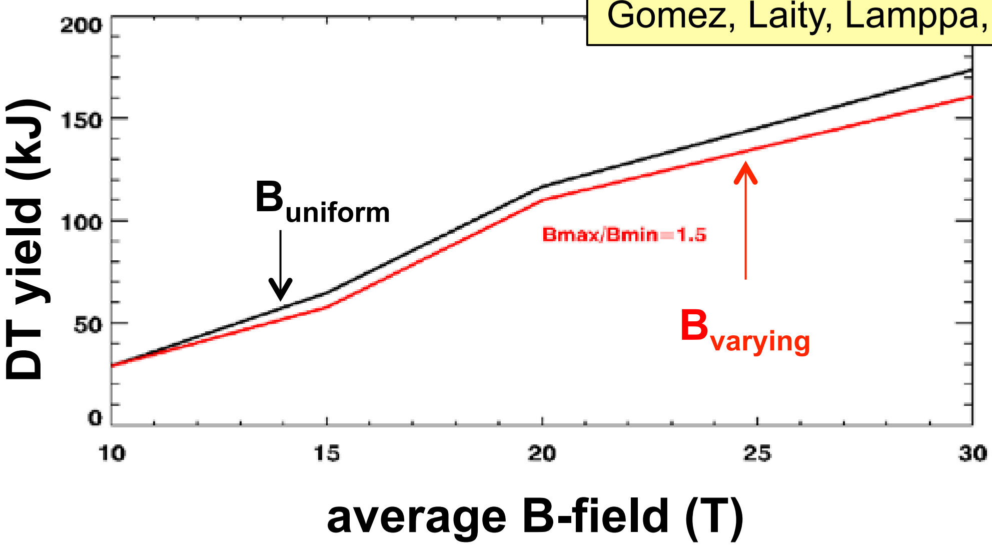
- **Deliver 22-24 MA to a MagLIF target on Z.**
- **Develop a point *pulsed-power* design of a MagLIF target for Z Next that achieves a net target gain of 1 (Likely, Yield ~ E_{target} ~ 3-5 MJ).**

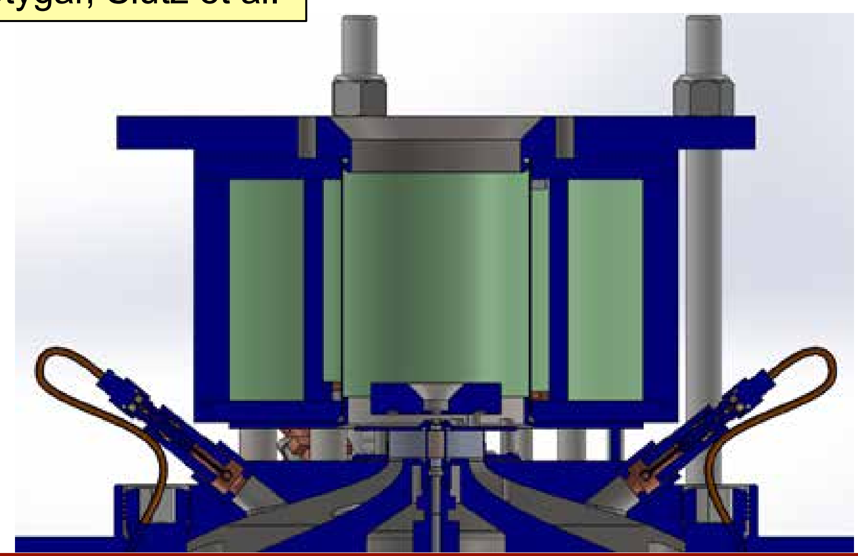
The Driver-Target Coupling team is exploring new load hardware designs as a way to increase the current and test our predictive circuit models

- Original hardware configuration optimized for magnetic field uniformity, but this may not be necessary
- Lower-inductance hardware sets could increase the current delivered to the load, enabling our program goals



Gomez, Laity, Lamppa, Stygar, Slutz et al.





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

Scientific goals

- **Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel**
- **Characterize & mitigate any fuel contamination as a result of the heating method**
- **Minimize the likelihood and impact of laser-plasma interactions**

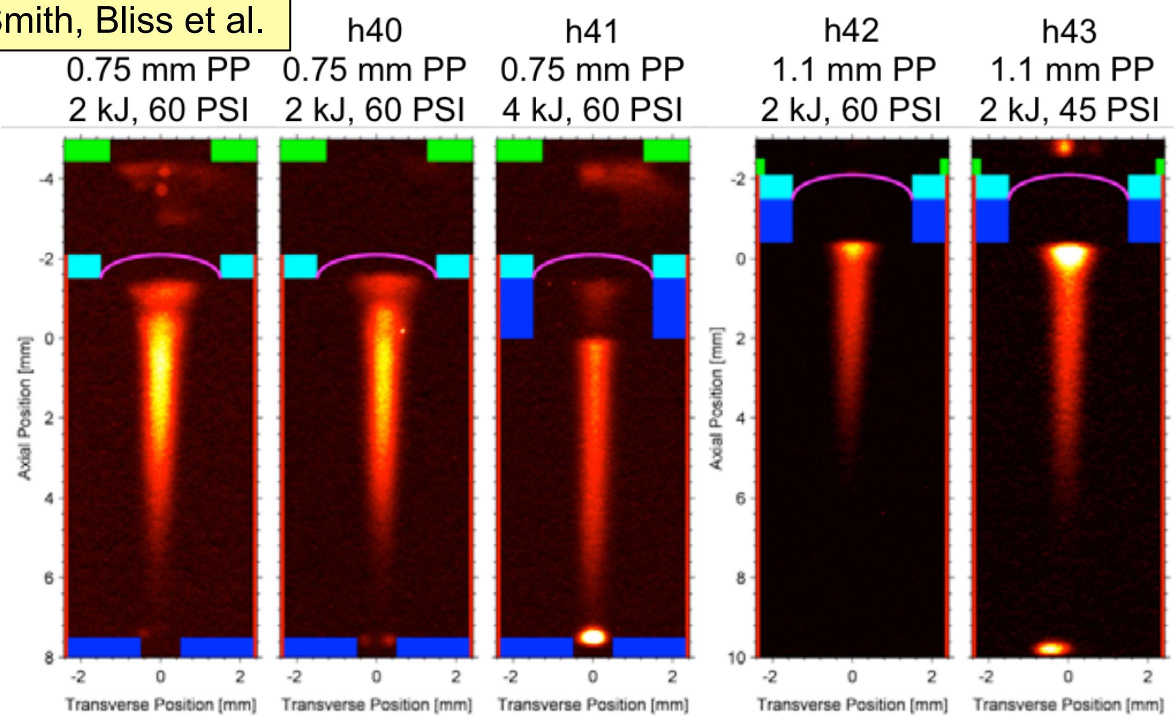
Programmatic goals

- **Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized "smoothed" beam profile (including an optimized pulse shape)**
- **Demonstrate 30 kJ heating on the NIF**

In January we increased the penetration depth of the laser into the fusion fuel using new 0.75 and 1.1 mm phase plates

X-ray pinhole camera images of fuel emission

Geissel, Gomez, Smith, Bliss et al.



- LDRD/ARPA-E supported experiments on OMEGA-EP are investigating laser pulse shape (prepulse) and intensity variations.
- Results from our initial OMEGA-EP experiments have been published.*
- Team is also making progress on cryogenic targets (400 nm windows).

Awe, Sefkow et al.

* 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

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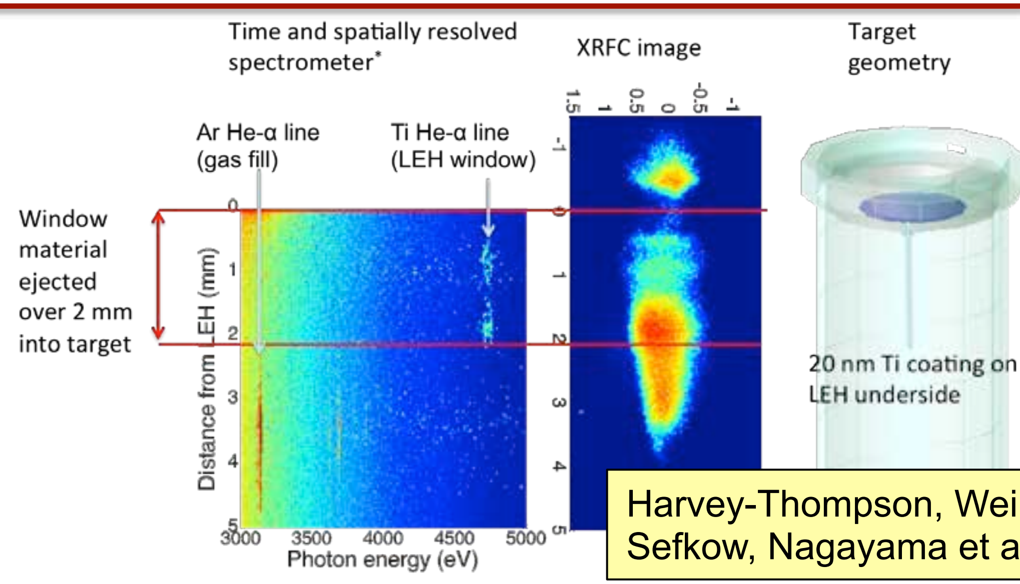
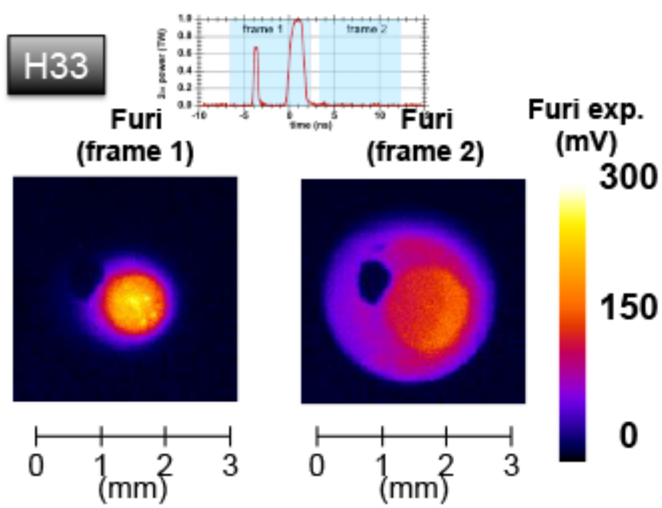
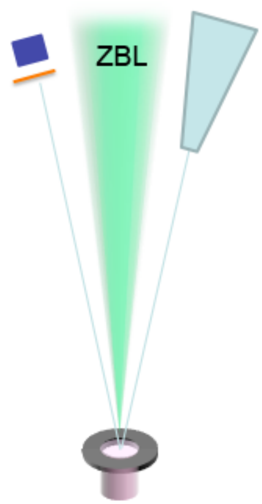
- We are learning how to place and measure spectroscopic tracers to diagnose mix and conditions from the window, the washer, the liner, and the fuel
- We are working toward time-gated axial imaging and spectroscopy to measure the fuel temperature vs. time during integrated Z shots

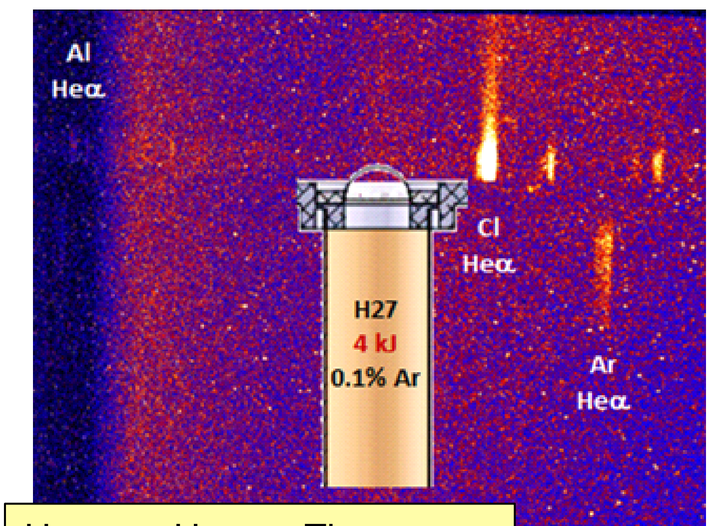


Harvey-Thompson, Wei, Sefkow, Nagayama et al.





Geissel, Porter et al.



Hansen, Harvey-Thompson, Peterson, Geissel et al.

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

Riley, Porter, Geissel et al.

Rambo, Schwarz, Speas, Kellogg et al.

Smith, Speas, Shores et al.

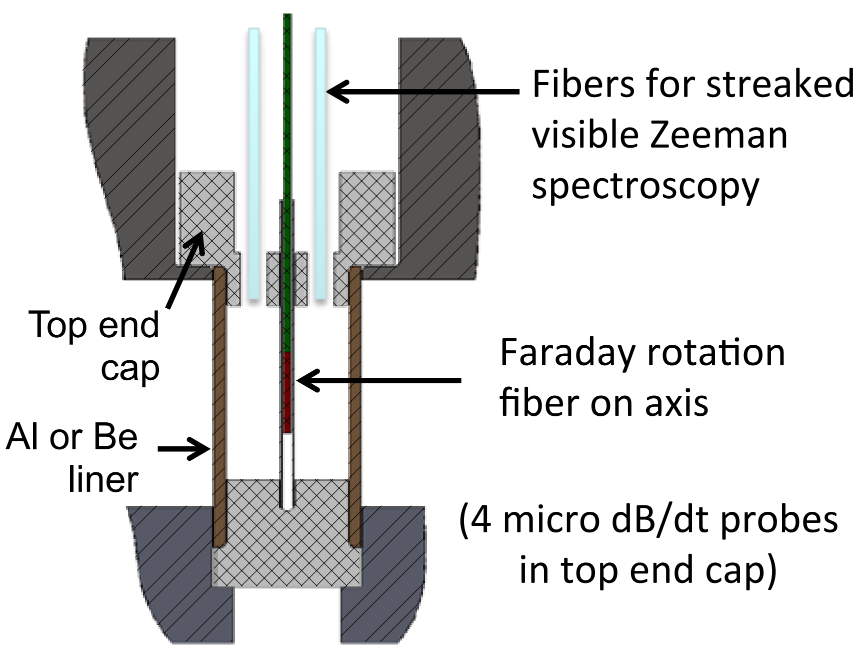
Over the next five years, we seek to accomplish the following goals related to magnetic implosions:

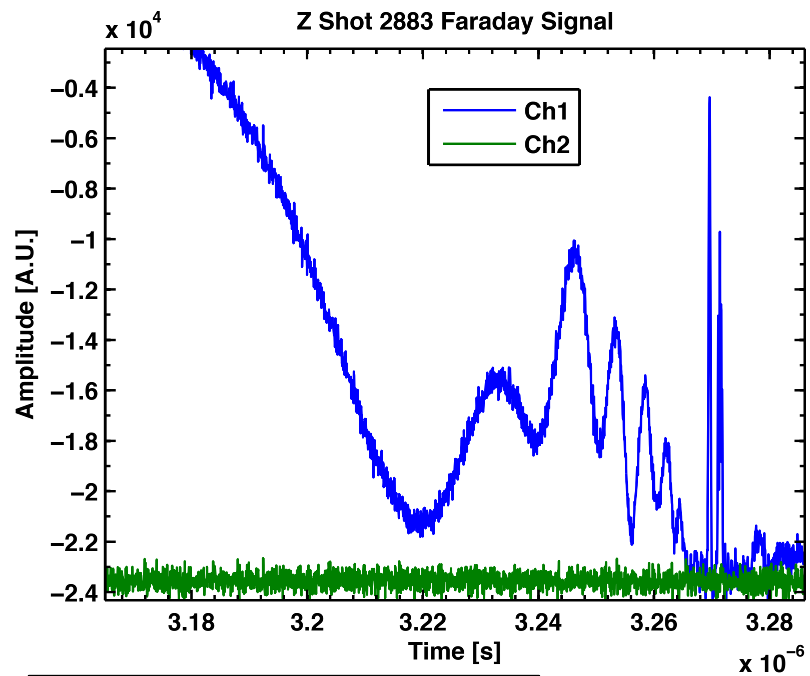
- Determine the dominant seeds for observed acceleration and deceleration instabilities, and strategies to mitigate against them
- Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict the integrated target performance
- Measure the spatial distributions for temperature, density, B_z, and any contaminants in the fuel after heating and through at least CR=5
- Experimental demonstration of a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of > 5 Gbar ns (also "1D physics")

Magnetic flux compression experiments in November may have directly measured >800 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).
- LDRD-funded initiative; also included micro Bdot development efforts

Platform developed for magnetic flux compression experiments on Z





McBride, Bliss, Intrator et al.

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

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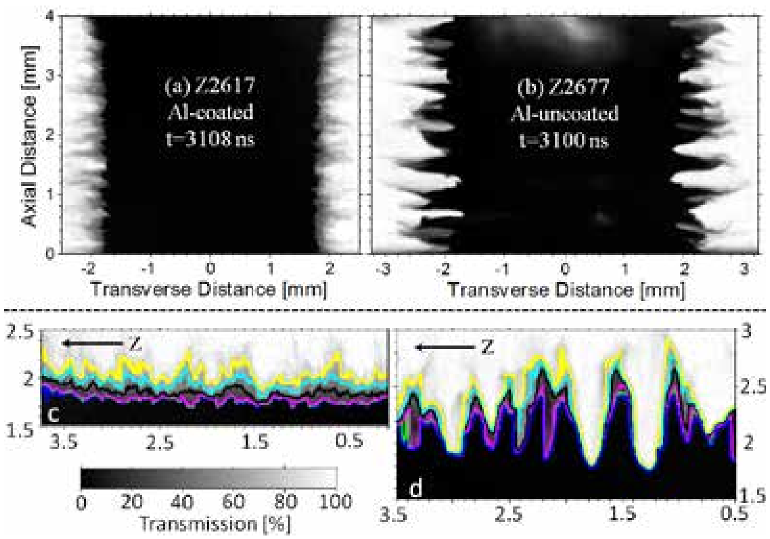
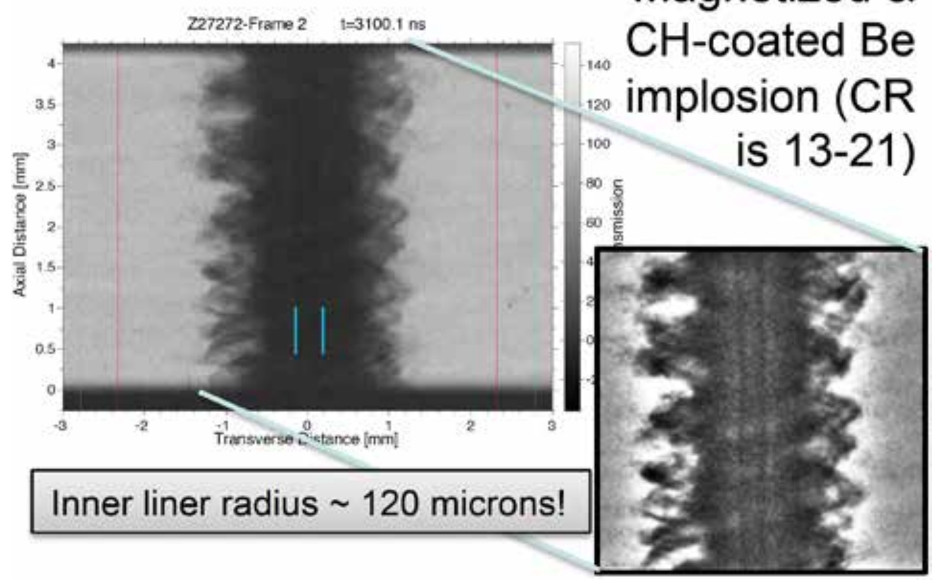
Aluminum Results:



Awe, Peterson, Yu et al.

Beryllium Results:

Magnetized & CH-coated Be implosion (CR is 13-21)



Late time radiography demonstrates that high aspect ratio liners can achieve more stable implosions with coatings

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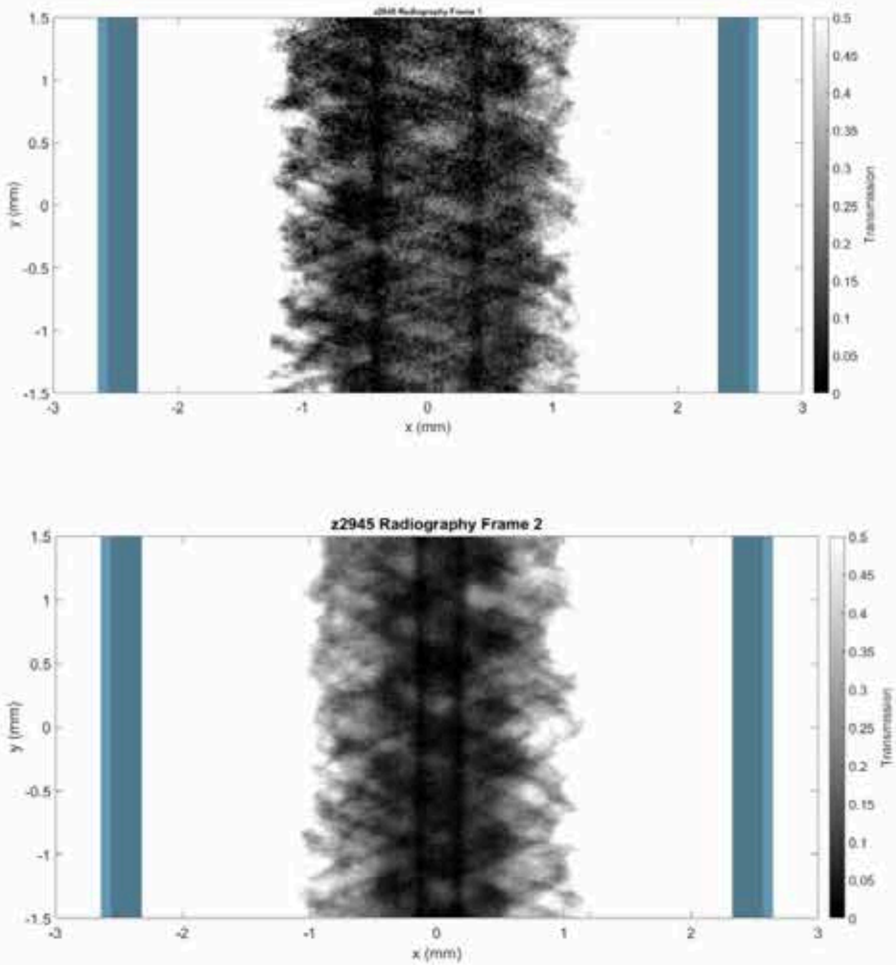
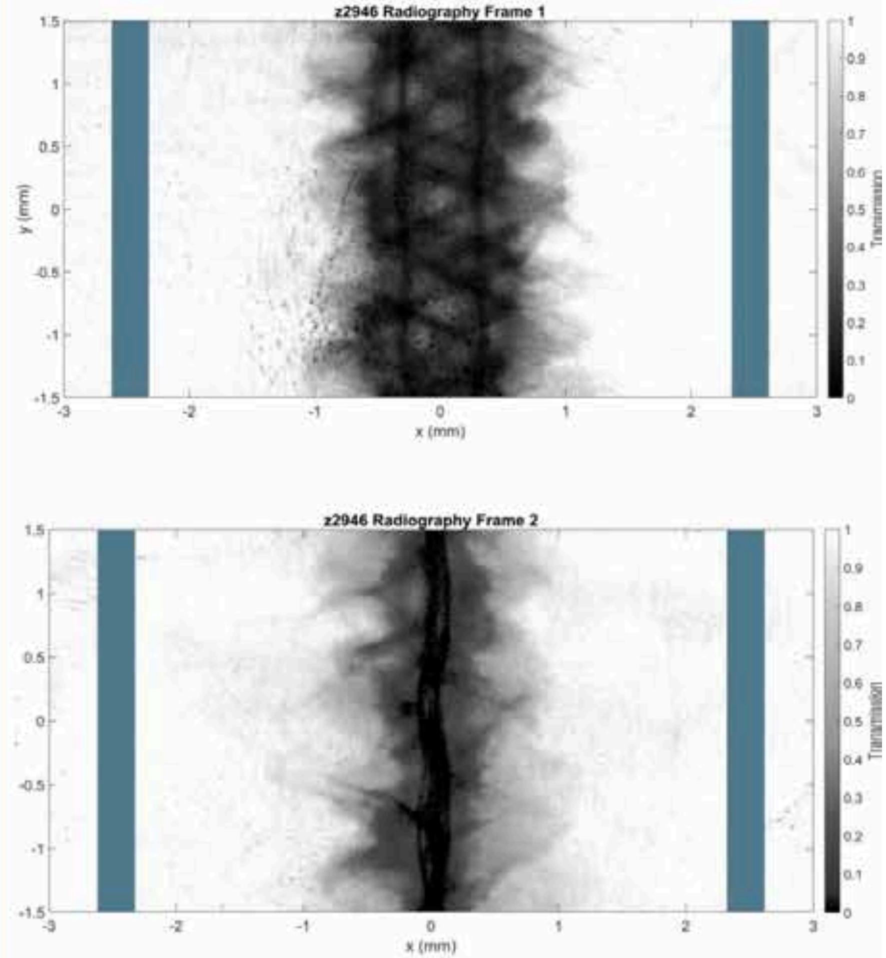
Coated liner

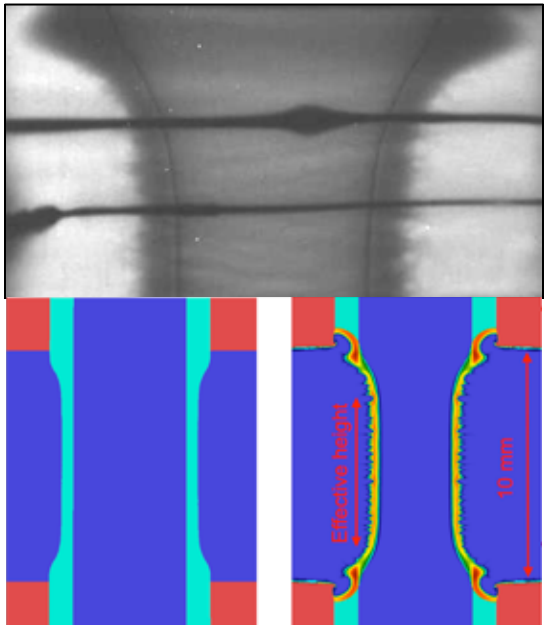


Uncoated liner



Ampleford, Rosenthal, Jennings et al.

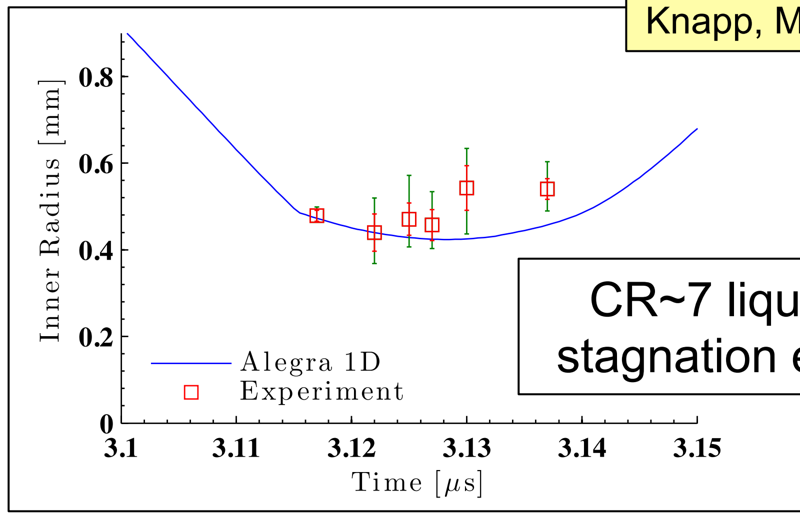
Other implosion experiments this year are exploring our ability to diagnose and control liner implosions



Shaped liners to control electrode/end effects

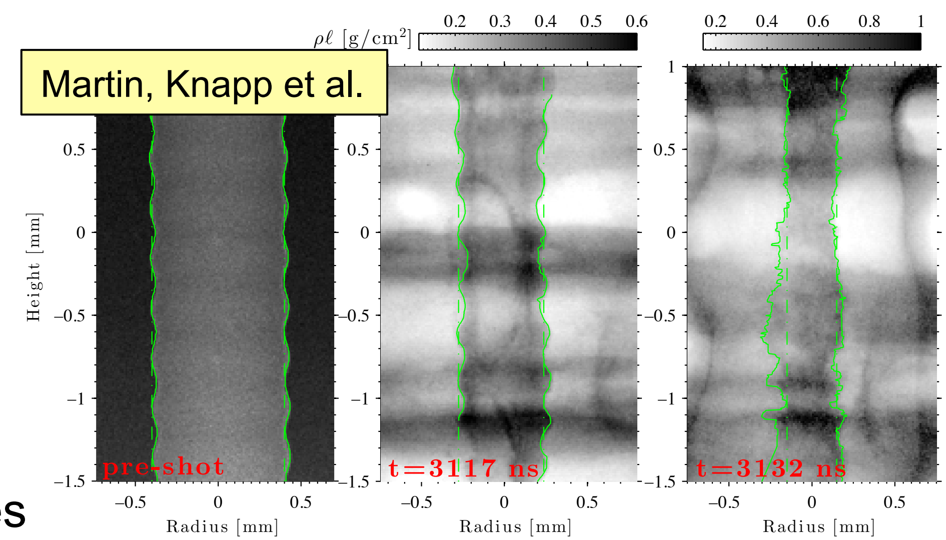
Sefkow, Ampleford et al.

Knapp, Martin et al.



CR~7 liquid D2 "1D" stagnation experiments

Martin, Knapp et al.



On-axis rods to study deceleration instabilities

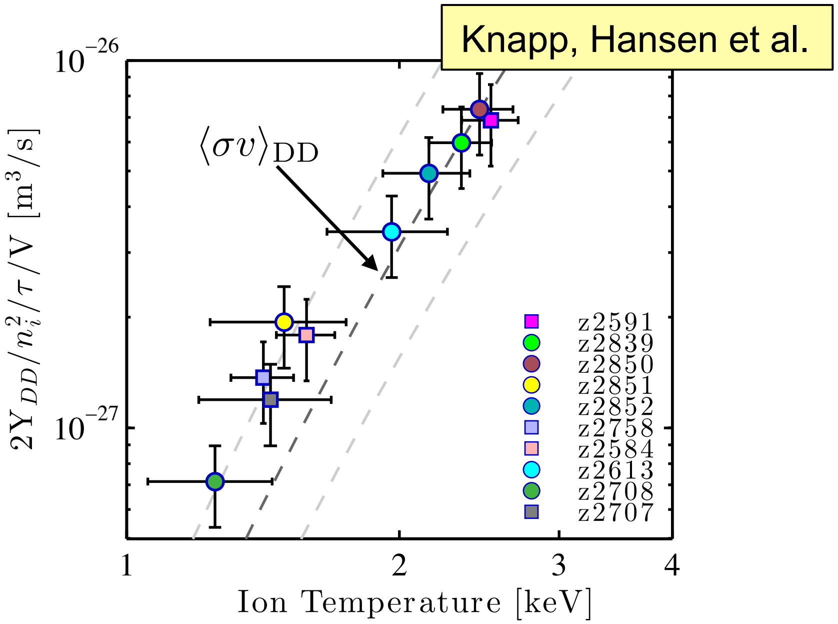
Over the next five years, we seek to accomplish the following goals related to stagnation and burn:

Note: Implicit in these goals is developing the ability to make these measurements, which is where we are spending a lot of effort today

- **Achieve a burn-averaged ion temperature of >4 keV (robust burn threshold)**
- **Achieve a BR > 0.5 MG-cm (R/r_α > 2)**
- **Achieve fuel pressure > 5 Gbar and $P\tau$ > 5 Gbar-ns**
- **Minimize and mitigate against radiation loss from high-Z contamination**
- **Demonstrate a continuous, nearly uniform stagnation column at CR>20**
- **Determine the non-thermal component of the fusion yield.**

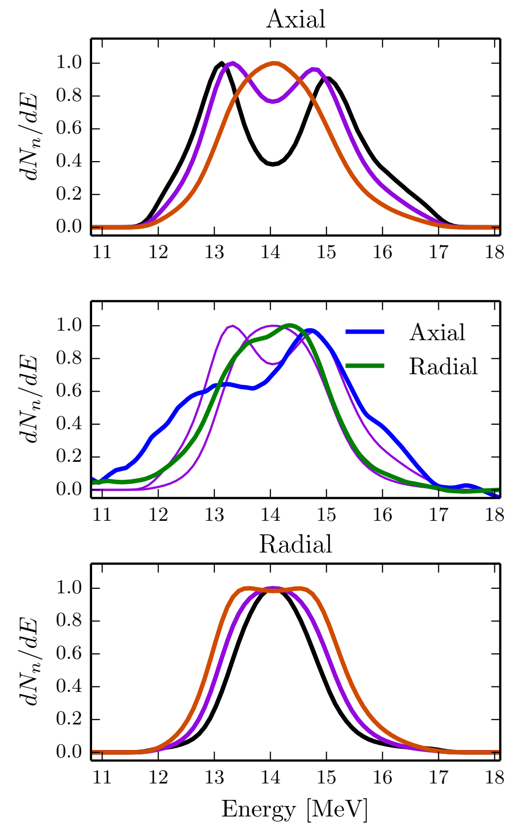
The Stagnation & Burn team is focused on diagnosing and understanding key elements of magneto-inertial fusion

Thermonuclear neutron generation



- Isotropic, Gaussian DD neutron spectra
- DD neutron yields = 3e12
- Ion temps = 2.5-3 keV
- Electron temps = 3.1 keV
  (from x-ray spectroscopy)

Magnetic flux compression

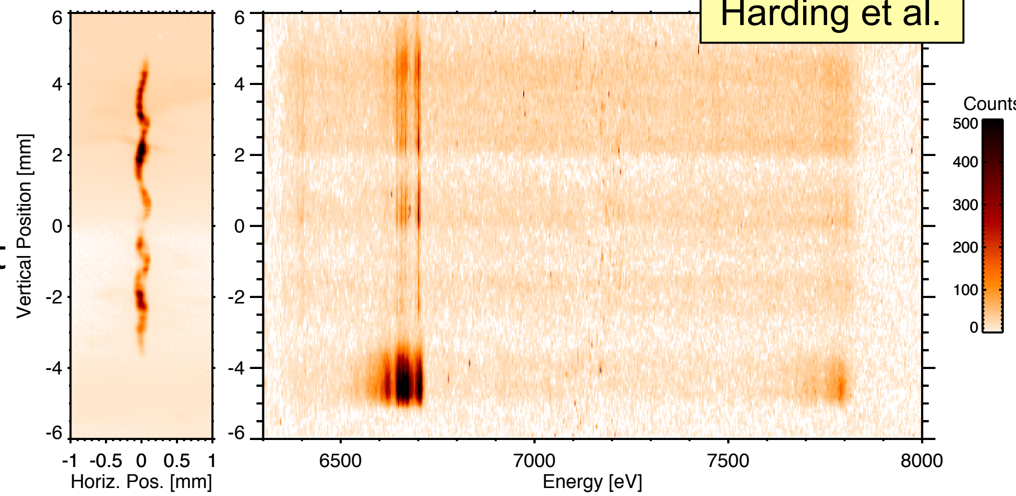


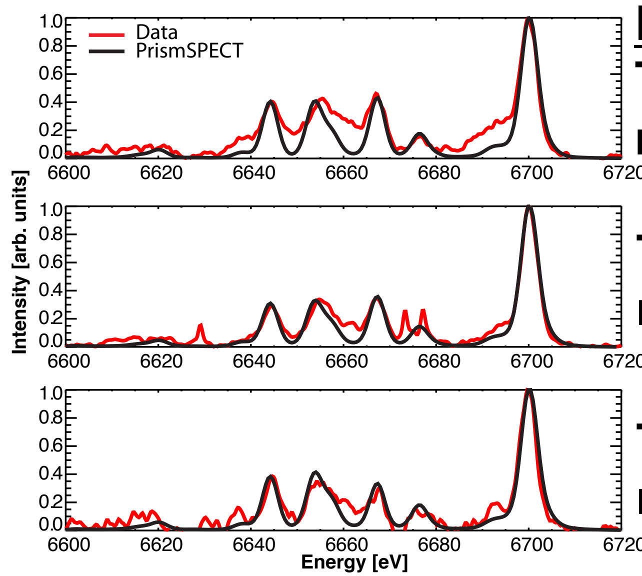
Knapp, Schmit et al.

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

- 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

Harding et al.





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}

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 (Rovang poster)

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	2015	2016	2017	2018	2019	2020	202
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

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

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

See also poster by Rovang *et al*.

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

- **Improve our existing design codes capable of fully-integrated simulations by improving and extending the MHD-based models in them**
- **Invest in new hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations that captures new physics**
- **Develop tools and experiments for validating our simulations**
- **Avoid investing significant effort at Sandia in modeling laser-plasma interactions, but support a national effort in this area**

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

- A workshop was held at LLNL last fall in which various potential code improvements were discussed.
  - All of our integrated MagLIF design tools are developed and supported by LLNL.
  - We have not yet held a follow-on workshop, however, so it is unclear whether we are making 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.

- Collaborators at the NRL continue to work on test problems and theoretical/modeling research on these topics.

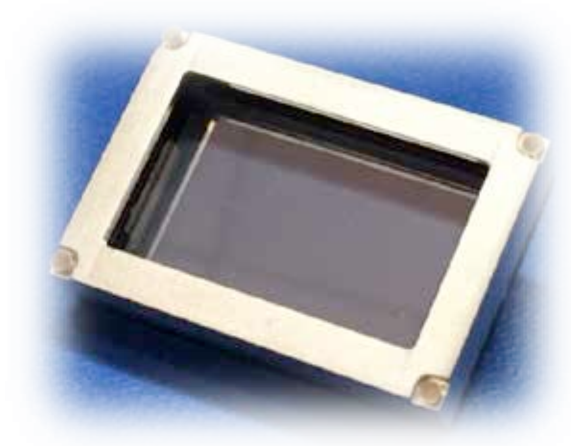
- We are attempting to leverage existing expertise at LLE and NIF to characterize backscatter data from Z, Omega-EP, and NIF.

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

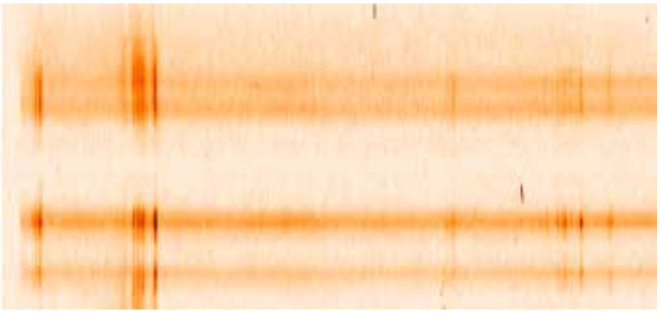
Stagnation & Burn Diagnostic Needs

- 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

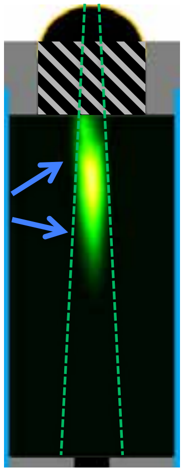


Red: Central elements of the National Diagnostics Plan

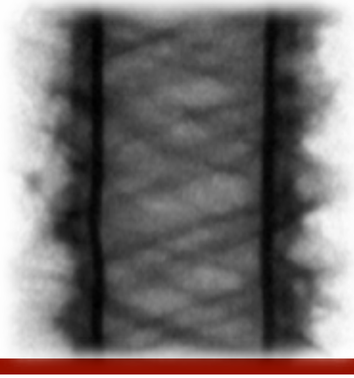
The Priority Research Directions are also helping to define the main diagnostic needs for the MDD effort

- **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

Our ICF plan emphasizes the science using Z, Ω, and NIF, and tests our integrated models using Z, with the goal of assessing the credibility of any extrapolations to ignition

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~85% of total effort (Z,Ω,NIF)

- **Study the underlying science, emphasizing MagLIF**
  - Primarily accomplished by the 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 target performance over available range of conditions**
  - 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

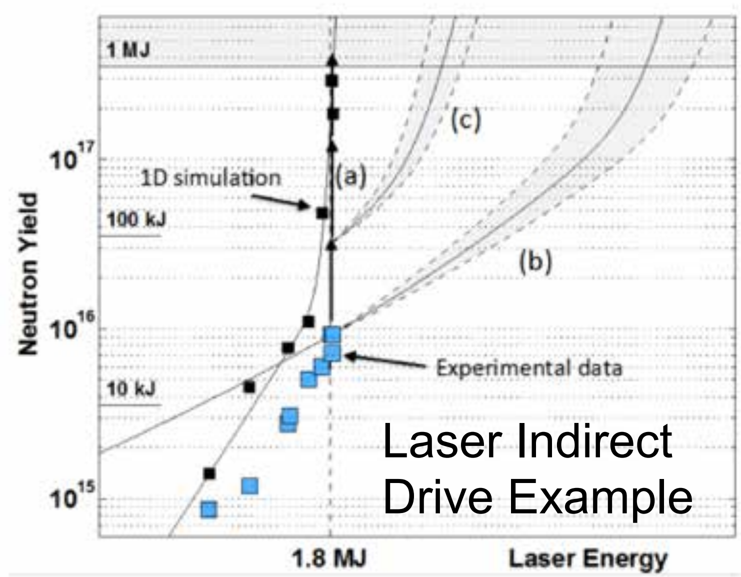
- **Develop a path to ignition and beyond, and assess its credibility**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF

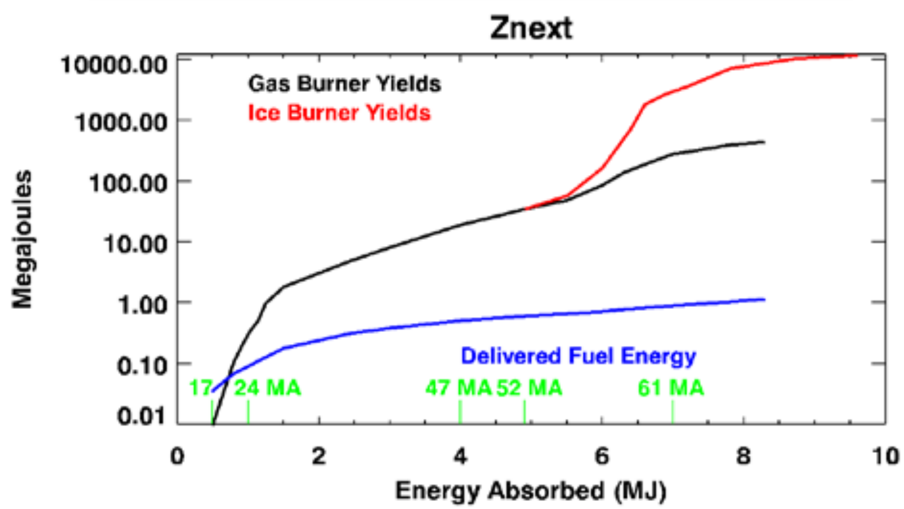
~1% of effort

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

The ICF community is presently discussing what it means to "credibly extrapolate" to multi-MJ yield

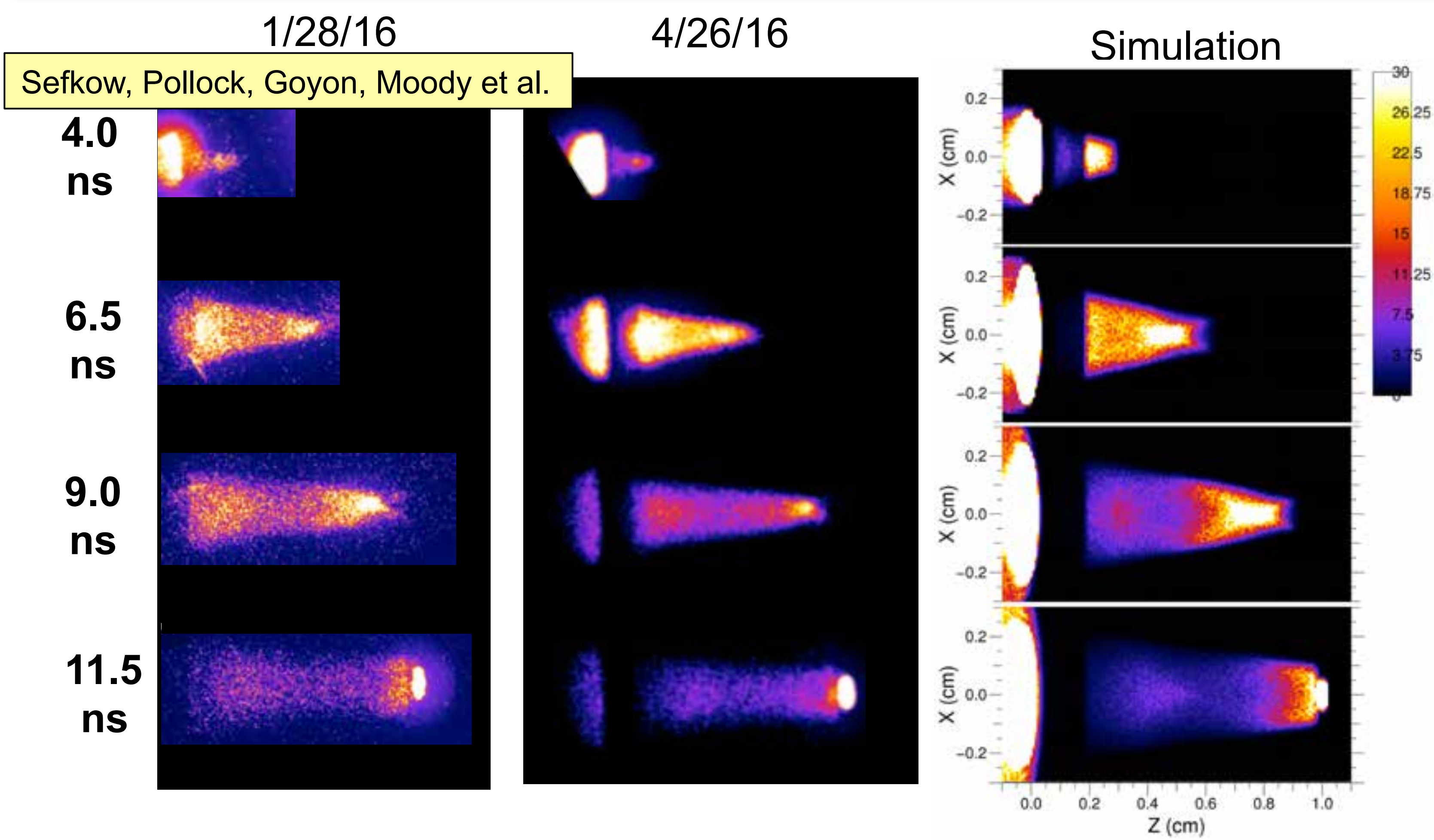
- Yields from all approaches are below our best predictions. All approaches will follow two paths in next 5 years
  - Improve target physics to improve the yields
  - Find "1D-like", well-understand base camps and determine the ignition energy requirements
- The credibility of any extrapolation from today's results will be based on
  - Target performance scaling over the accessible range
  - Validation of the physics models underpinning the extrapolations
- The ICF Framework document calls for the creation of Devil's Advocate Red Teams to help community understand our logical cases





Slutz, Stygar, Gomez et al.

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



- Unmagnetized, 30 kJ, n_e/n_{crit}~0.1 heating experiment of a gas tube
- NIF has started working on magnetic coil development

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~1% of effort

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

The laboratories will need to update the mission need for high yield (beyond ignition)

- In 1988 (when I started high school) the ICF program published a multi-laboratory mission needs document for a Laboratory Microfusion Facility. These mission needs have not really been updated since then. Needs loosely binned as
  - Secondary weapons physics
  - Primary weapons physics
  - Nuclear survivability
- Excerpted comments from the FY2015 Review

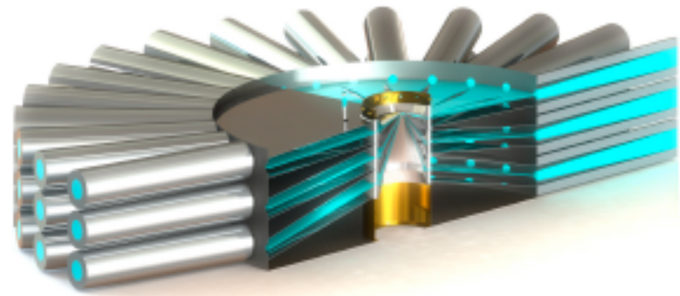
Ignition is an important step toward multi-megajoule fusion yield, not an end in itself.

The pursuit of high yield will <u>test the innovation of designers i</u>n ways that few other technical pursuits can. Higher yields enable experiments to test the validity of current nuclear weapon codes in temperature, pressure, and density regimes closer to nuclear weapons operating conditions, serving as a key means to train the new generation of nuclear weapons scientists and engineers who have no experience preparing, fielding, or observing an actual nuclear explosive test.

<u>High yield must remain a long-term goal</u> for the ICF Program, even if ignition is not reached on the NIF. In an extended era without nuclear explosive testing, driving towards a fusion source of 500 megajoules or greater will be essential for the health of the program.

Sandia is exploring pulsed power designs that may be capable of ignition and high yield—whether one is built and what its size is will depend on mission needs & MDD credibility

Fusion Yield 0.5-1 GJ?
Burning plasmas



"Z800"

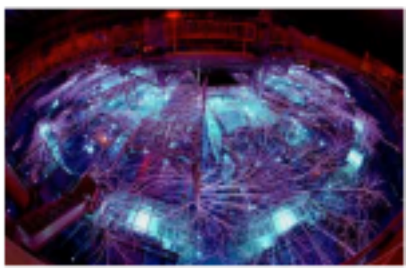
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

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

"Z300"

- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

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



Z ("Z80")

- 80 TW
- 33 Meter diameter
- 26 MA
- 22 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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~1% of effort

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

We believe our program is aligned with key concerns discussed in the FY15 ICF Review. Do you?

Excerpted comments from review:

The MDD Program's highest priority is to demonstrate laser beam propagation and heating on Z which must include collaborations with LPI and laser experts across the complex.

A comprehensive diagnostic plan for characterizing plasma properties during MagLIF preheating and during implosion must be developed, with a focus on understanding stagnation.

There is a need to develop further a diagnostic plan for the MDD effort to characterize plasma properties during preheating and implosion, with a focus on understanding mix.

The MDD Program would benefit from the inclusion of LPI experts from across the complex to aid understanding of the laser plasma interactions of the preheat beam.

The program could use more 3-D modeling to develop mitigations of instability features in the implosion. This would complement the fielding of improved diagnostics of axially resolved imaging, spectroscopy, and x-ray scattering to measure the conditions and allow for comparison with simulation data. Simulation tools and models (including reduced models) with magnetic fields will need to be developed and tested with focused experiments.

Some specific FY2015 ICF Review recommendations that we would like your thoughts and priorities for

A second beam line would enable simultaneous laser preheating of the target and radiographic backlighting…. A cost and schedule estimate for the development of a second beam line on Z should be prepared for consideration.

The ability to add tritium or 3He to the fusion fuel … should be a high priority.

Shot opportunities on Z should be increased. The MDD Program should dedicate more experiments for understanding and optimizing the power flow in the driver-target coupling, and understanding the scaling of MagLIF performance as a function of design parameters such as current, fuel preheat, magnetic field, fuel density, liner aspect ratio, and liner material over as large a range as possible at the Z Facility.

There should also be more experiments that pursue alternative concepts to MagLIF.

There is an opportunity to explore alternative indirect drive designs with larger absorbed energies on a future larger-scale pulsed-power facility. … This capability would enable a logical transition from LID to MDD in the future, should the SSP pursue "high-yield" fusion at laboratory scale.

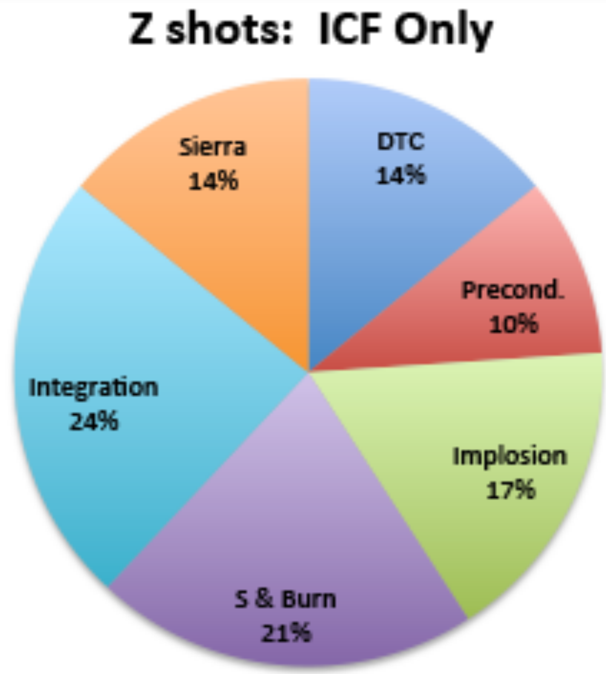
Backups

Draft Phases described in Integrated Experimental Capabilities Framework document being prepared this month

- Phase 1 (FY16-18): Complete initial capability to conduct MagLIF experiments at 22 MA on Z using a seed magnetic field of 30 T and laser preheating with an energy of 6 kJ
  - Improved load hardware being tested now, to be integrated in FY17-18
  - 30 T coils exist in laboratory, to be integrated in FY17
  - 4.5 kJ available now; install booster amplifiers in FY17 for 6 kJ integration in FY18
- Phase 2 (FY18-20): Optimize ICF target performance and demonstrate neutron yield scaling over the available conditions, with a goal of achieving 100 kJ DT equivalent. In addition, demonstrate magnetization (BR) in excess of 0.5 MG-cm and a pressure-time product of 5 Gbar-ns in MagLIF targets
  - Tritium decision point in 2018 (Option 0, 1, or 2?). Integration in FY18-20.
  - Optional: Modification of FOA to allow tandem radiography + heating.
  - 10 kJ laser heating, requires increase of beam size for second beam to 40 cm, should also help with diffraction effort

How many shot weeks could we use in ICF going forward?

- **Sierra campaigns (joint w/ LLNL)**
  - 10 shots in FY16 (3 weeks)
  - LLNL would like 4 weeks going forward
- **ICF PRD experiments**
  - 2.5 weeks for Driver-Target Coupling
  - 1 week for Pre-conditioning
  - 2.5 weeks for Implosion
  - 3 weeks for Stagnation & Burn
- **ICF Integration experiments**
  - 4 weeks (1 per quarter) for MagLIF
  - 2 weeks for other (Harding, Socorro, Mora, Tritium, other new capabilities)
- **ICF Total: 19 weeks requested**
  - As with FY16, some of these are dual-use with PAT (both integration & PRD)
  - We are proposing here to move Tritium back under ICF from RES category
- **Additionally, we are proposing to continue work on other facilities**
  - 2 shot days/year on the NIF
  - 3 shot days/year on OMEGA-EP
  - ~120 experiments/year on Z-Beamlet



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			

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