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The Magnetically Driven Direct Drive Approach to Ignition: Responses to Questions by Panel 1 of the FY15 ICF Program Review[1]

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Long-term vision

The long-term goal of the pulsed-power based, magnetically driven target approach is to achieve high single-shot yields (0.5-1 GJ per shot). This goal may take decades to achieve, but if successful we believe it would be a key capability for the Stockpile Stewardship program, as noted as far back as 1988 in the Laboratory Microfusion Capability Phase 1 (U) study. If this approach is successful, it may be possible to achieve these yields from targets absorbing up to 10 MJ in a laboratory pulsed power facility with a stored energy of roughly 130 MJ. Such a facility would be substantially cheaper, and not as complex, than the corresponding pulsed power facility required for producing comparable yields from x-ray driven capsule targets.

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Discussion of program structure, resources, balance, and goals

Background context and concepts being studied

The magnetically driven approach to inertial confinement fusion (ICF) is closely associated with the pulsed power ICF program at Sandia National Laboratories. Pulsed power drivers discharge energy stored up in large capacitor banks to create tens of mega Ampere currents over tens to hundreds of nanosecond time scales. The majority of the research on this approach is conducted on the Sandia Z facility, the world's largest pulsed power facility, which stores up to 24 MJ and can create an 80-TW, 20-26 MA, 100-ns current pulse. A current of 26 MA at a radius of 1 mm corresponds to a magnetic drive pressure of 100 Mbar, comparable to the 140 Mbar ablation pressure of a radiation-driven capsule on the National Ignition Facility. This leads to the natural question of whether these large pressures and efficient energy coupling to targets (~0.5 MJ absorbed by target, of which ~0.1 MJ is in the heated fuel) can be useful for fusion.

It is worth noting that this is a relatively new approach for the field of ICF. In the late 1980s (e.g., see the Laboratory Microfusion Capability Phase 1 Report (U) from 1988), the national ICF program was actively pursuing four approaches to ignition, (1) Laser-driven radiation drive, (2) Laser-driven direct drive, (3) Pulsed-power-driven light-ion beam drive, and (4) Accelerator-driven heavy-ion beam drive. The first two approaches continue today. The fourth approach has effectively been put aside in recent years. By contrast, the pulsed power ICF program at Sandia has evolved considerably over the past three decades as our understanding of how to use this technology has improved.

Advances in the mid-1990s showed that pulsed power could be used to efficiently produce mega Joules of x rays from wire array Z-pinches with about 15% conversion efficiency from the energy stored in capacitor banks (e.g., 1.8 MJ radiated vs. 12 MJ stored). This, combined with technical challenges identified by the light-ion beam program, caused the pulsed power ICF program to focus on pulsed-power-driven, radiation-driven capsule implosions from 1996-2007. Multiple platforms were studied (in collaboration with scientists from both Los Alamos and Lawrence Livermore), including the "dynamic hohlraum" and "double-ended-hohlraum" platforms.

Work on pulsed-power-based, radiation driven capsule implosions on Z effectively ceased in 2007 when the Z facility was shut down for refurbishment in 2007. A key point here was that work on this approach was not stopped because it was not promising. Capsules in the dynamic hohlraum platform produced (at the time) record thermonuclear yields and the double-ended hohlraum platform demonstrated significant symmetry control and favorable scaling to high yield (e.g., 400 MJ capsule yields). It was stopped because of limited resources at Sandia to pursue both approaches and the acknowledgment that the community's understanding of the x-ray driven capsule physics could best be demonstrated on the National Ignition Facility. Should the radiation-driven capsule effort on NIF succeed, pulsed power based radiation-driven capsules could remain an attractive approach to high-yield fusion (>200 MJ).

Beginning in the mid-2000s, a joint collaboration between Lawrence Livermore National Laboratory and Sandia began investigating various magnetic direct drive concepts. As a genuinely new approach to ICF, specific concepts are being carefully evaluated before public release. The success of this research, and the impending start of the evaluation of radiation drive on the NIF, led the Sandia pulsed power ICF program to focus on magnetically driven direct drive approaches to fusion in 2008. This remains the focus of the pulsed power ICF program at Sandia today.

The majority of our effort today is centered on the Magnetic Liner Inertial Fusion (MagLIF) concept. This approach is a variant of magneto-inertial fusion (MIF) ideas that have been discussed for many years. The fundamental premise behind MIF is that the addition of a strong magnetic field can enable fusion conditions to be achieved under relaxed driver and final fuel conditions (i.e., pressure). Here a strong magnetic field is defined as a field strong enough so that the Larmor radius of the relevant particle(s) is small compared to the scale size, R, of the plasma. One can show that the key figure of merit is the product BR and that a BR>0.5 MG-cm is sufficiently large so that electrons, 1 MeV tritons, and fusion-produced alpha particles would all be strongly magnetized. Consequently, electron heat transport losses from hot plasma can be reduced and, in an igniting and burning plasma, the alpha particles produced in DT reactions can be more readily stopped and will thus deposit their 3.5 MeV energy within the plasma. This allows for a broader parameter space of fusion systems at intermediate plasma density and pressure regimes between traditional magnetic confinement fusion and ICF systems.

The MagLIF concept was first published in 2010, but integrated experiments on Z were not possible until November 2013, since Sandia first had to develop the capability to magnetize and laser heat a magnetically driven target. A 900 kJ capacitor bank was built to drive a pair of external magnetic field coils capable of producing up to 30 T, and the final optics assembly for the Z-Beamlet laser was modified to prevent a vacuum breach caused by debris damaging the optics windows. Since that time, the pulsed power ICF program at Sandia has executed approximately one integrated MagLIF shot per month on average. The integrated experimental database for this approach is therefore much smaller than for laser-based direct or indirect drive. Having said that, an extensive database of >50 implosion instability experiments exists on Z (including magnetized implosions). A growing database of laser-heating experiments also exists on multiple laser facilities across the country. Thus, progress on this approach does not rely solely on integrated experiments and we believe that significant progress can be made during the next five years.

Though the MagLIF concept is relatively new, it has benefited from many of the significant investments over the past several decades in the other two ICF approaches, laser-driven radiation drive and laser-driven direct drive. The simulation codes used to design MagLIF targets and model experimental data were originally developed for those two laser approaches (e.g., HYDRA, LASNEX) and have been adapted for use with magnetically driven targets by adding magneto-hydrodynamic (MHD) capabilities to those codes. Likewise, most of the techniques developed to diagnose the other two ICF approaches can be used or adapted for use with magnetically driven targets. Even in the area of target fabrication, a significant part of the expertise developed for NIF targets has been leveraged to fabricate magnetically driven targets.

The initial MagLIF experiments produced primary fusion yields of up to 2×10^{12} from DD reactions, secondary DT yields of up to 5×10^{10}, electron and ion temperatures of 3±0.5 keV, burn widths of 1.5±0.5 ns, from a weakly helical, continuous plasma column 5±2 mm tall and 60-140 microns in diameter. From these data and some other measurements additional parameters are inferred, including a peak fuel density of 0.3±0.1 g/cm^3, a radial fuel rho-R of about 1.5 mg/cm^2, a radial BR of 0.4 MG-cm, and a stagnation pressure of 1±0.2 Gbar. The beryllium liner surrounding the fuel is inferred to have a radial rho-R of about 0.9 g/cm^2, based on both x-ray spectroscopy and neutron scattering measurements. This rho-R compares well with the predictions of simulations. We note that the high liner rho-R is needed to provide the inertial confinement of the fuel. While much remains to be done, these initial results are promising in that they demonstrate several key aspects critical to magneto-inertial fusion: magnetic flux compression, a very high degree of magnetization in the fusing plasma, fusion-relevant temperatures (despite a peak calculated implosion velocity of 70 km/s), and contiguous fuel assembly over most of the liner height.

Resources and workforce

The pulsed power program at Sandia National Laboratories is the main source of funding for this fusion approach. The total base funding for research in the Pulsed Power Sciences Center at Sandia, $82M in FY15, is split across multiple programs within the NNSA. In FY15 the funding split as follows: $36M for Facility Operations (Z and the Z-Beamlet laser), $5M for Diagnostics, $5M for the pulsed power ICF program, $6M for Primary Assessment Technology (PAT), $11M for Dynamic Material Properties (DMP), $10M for Advanced Radiography, $5M for Secondary Assessment Technologies (SAT), and $4M for Advanced Certification (AC). Each of these eight funding sources has different program objectives, milestones, and Federal program managers. In addition, the SAT funding at Sandia is also used to pay for radiation source development in support of the Nuclear Survivability subprogram of the Engineering Program. The splits between the different funding buckets have varied every year for the past five years and will likely continue to do so over the next five.

Integrated tests of magnetically driven targets require the Z facility. At its peak in FY09, the Z facility conducted >200 shots per year. In 2015 the current projection is that we will field about 150 shots. The reduction in shot rate is commensurate with the reduction in the baseline Center budget since then. That budget has decreased every year since FY09 with the FY15 budget being 25% lower than it was in FY09 (normalized to FY15 dollars). The historical fraction of Z experiments devoted to ICF during the past five years is about 25% (i.e., 50 shots in 2009 and 40 shots in 2015). The remaining Z shots are devoted to the five subprograms of the Science Program, capability development, and the Z Fundamental Science Program.

The scientific and engineering workforce available to support integrated ICF experiments on Z is funded by the $5M pulsed power ICF program budget and a portion of the $36M Facility Operations budget. The $5M budget supports the majority of the scientists, roughly 20-25 staff and post-docs in any given year, most of whom work part time for ICF and part time on the Science Program. The Facility Operations budget supports an additional 7 ICF-centric scientists in the areas of neutron diagnostics and Z-Beamlet laser experiments. These funds also pay for ICF-specific critical infrastructure, such as cryogenics and magnetic field coil technology development. Two DOE Early Career Awards provide significant additional funding, $0.5M per year each, both of which benefit the ICF program. The ICF program also leverages significant expertise from other staff at Sandia funded by the five Science subprograms and the Facility Operations budget includes support for several dozen operations staff for Z and Z-Beamlet.

In addition to executing Z experiments, Sandia ICF scientists are currently executing MagLIF-relevant fuel heating experiments on the 2-TW, multi-kJ Z-Beamlet laser facility at Sandia, the OMEGA-EP laser facility at the University of Rochester, and the National Ignition Facility at LLNL. An additional collaboration with the University of Rochester is studying a scaled-down (in size) version of MagLIF targets using the OMEGA laser facility. Sandia ICF scientists also support diagnostics and experiments on Z as part of an ongoing collaboration with LLNL in this area.

Looking ahead to FY16 and beyond, the baseline Center budget is projected to decrease still further to $80.5M and consequently the number of Z experiments is projected to drop to about 140 experiments, and possibly lower. While the program balance on Z in FY16 is currently being discussed by senior management at Sandia and has not been approved by DOE HQ or the ICF Council, in light of the letter by the tri-lab directors and a commitment to grow the number of shots for LLNL, we are attempting to increase the fraction of Z shots in FY16 devoted to ICF from about 25% to roughly 35%. We are also expecting to conduct 4 shot days on OMEGA-EP (25-30 shots), 1-2 shot days on NIF, and >150 Z-Beamlet laser experiments in the laser target chambers. The collaboration with the University of Rochester on OMEGA will also conduct 3 shot days. The out-year budgets for FY17 and beyond in the FY16 President's Budget Request look encouraging, with a potential increase in the Center's baseline budget to ~$96M, but these should be taken with a grain of salt as those numbers have fluctuated significantly for many years. Another positive note is that ARPA-E is supporting a joint Sandia/U. Rochester collaboration for accelerating progress in magneto-inertial fusion with a $4M award spanning FY16-

17, which will include support for laser heating experiments on OMEGA, OMEGA-EP, and Z-Beamlet.

Relationship to other ICF and HED work

As noted in the previous section, both the funding and the workforce at Sandia is diversified across the Science and ICF Programs, and the majority of the ICF scientists also work part time on Science Program experiments. While this does add a great deal of complexity to planning from year to year, one advantage this has had over the last several years is that the ICF staff are very familiar with Science Program objectives and this has led to a number of new platforms for the Science Programs on Z that were originally based on ICF platforms. Some examples:

- Dynamic hohlraum source originally developed for ICF is currently being used as a radiation source for opacity (SAT) experiments and our Fundamental Science program.
- Other radiation sources developed by the ICF Program (jointly with LLNL) have been used for the LLNL "Searchlight" and "Drawbridge" campaigns.
- Magnetically driven targets developed by the ICF Program have been adapted for use as radiation effects testing platforms (Nuclear Survivability).
- Magnetically driven targets developed by the ICF Program are currently being explored as potential platforms for PAT experiments.
- Magnetically driven cylindrical targets for dynamic material property experiments on Z (DMP) were adapted from an ICF platform.
- Numerous x-ray and spectroscopic diagnostics developed to study ICF targets have also benefitted the various Science subprograms.

ICF scientists working on the magnetically driven target approach also support numerous collaborations with the University of Rochester, the Naval Research Laboratory, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory. These are summarized in a separate white paper on collaborations.

Program structure and organization

The scientific research portion of the ICF program at Sandia is currently organized around five of the "Priority Research Directions" identified as part of preparations for the FY15 ICF Review. These topical areas are described in the Table below.

Topical Area	Team Leaders
Driver-target Coupling	Bill Stygar, Mike Cuneo
Target Pre-conditioning	Kyle Peterson
Implosion	Ryan McBride
Stagnation & Burn	Greg Rochau, Brent Jones
Modeling, Simulation, & Scaling	Thomas Mattsson, Kyle Peterson

This organizational structure is relatively recent—it was implemented in March 2015. Staff typically participate in one or two of the topical areas, and each of our major collaborations in ICF have been assigned to the most appropriate topical area.

The team leaders are all managers at Sandia. Each of the topical areas are expected to host a discussion-oriented meeting once a week on topics pertinent to the area. All of the ICF shots on Z in 2016 will be assigned to one of the topical areas, which will also be responsible for all design reviews and post-shot data analysis for those experiments.

All ICF experiments on Z are expected to have a Principal Experimenter (PE) and a Principal Designer (PD). These two are responsible for determining the objectives of the experiment, for developing a target design and diagnostic set that can meet the objective, for leading pre-shot design reviews, and for analyzing and writing up the data from the experiment post-shot. Most experiments are expected to result in publications, and one of these two is expected to be the first author on any resulting publications. Many experiments have several additional key participants, especially the more complex integrated experiments. Under the current structure, the ICF program determines a proposed Z shot schedule (by calendar year) by reviewing the shot proposals and prioritizing them within overall resource and availability guidelines provided by senior management at Sandia. The ICF Council then reviews the proposed schedule and weighs in on priorities. Management at Sandia assigns a PE and a PD for each shot series when the schedule is drafted. Senior management at Sandia reviews proposed changes to the shot schedule that occur mid-year.

While the broad direction and high-level program goals are directed each year by program management, each PE and PD has a great deal of latitude within those outlines. Under the new structure, the PE and PD discuss and set specific objectives for their shots on Z during the weekly discussion sessions of their topical area. About 17 weeks in advance of their series of experiments, an initial design review is held in a separate meeting with other scientists and target fabrication personnel in attendance. About 14 weeks in advance of that experimental series, a final design review is held. About 10-12 weeks prior to these experiments, the load and target hardware drawings are finalized and sent off to production and further changes must be negotiated with management and suppliers (but are strongly discouraged). Closer to the date of the experimental series the PE is required to specify the diagnostic setup for their Z experiments, which is reviewed by facility personnel. Significant new capabilities (e.g., targets, diagnostics, hardware, infrastructure) required for a shot series often have to be developed earlier than 17 weeks out.

Prospects of achieving ignition with existing scientific capabilities and facilities

A key charge to this panel is to assess the prospects for ignition during the next five years or, if ignition were not possible, to determine what conditions would make it possible. The Panel noted that, after seeing the overview presentation for magnetic direct drive, many of the specific goals presented appeared to be related to future facilities. The orientation toward discussing future facilities is based on modeling, computational predictions, and our collective experience to date that suggest the existing Z facility is too small a driver to achieve ignition. As part of the new organizational structure mentioned above, we are currently developing a 5-year plan to build a credible case for a next-step facility that might be capable of ignition.

To clarify what we mean by ignition, here we define it as the point where the thermonuclear yield equals the energy absorbed by the target. Our target scaling designs suggest that this is approximately 3-5 MJ for MagLIF targets. The 24 MJ, 80-TW Z facility today couples about 0.5 MJ to targets.

Our present estimates suggest that it would take a 50 MJ, 300-TW facility to reach ignition. In addition to studying the physics and scaling of MagLIF targets, we are attempting to develop next generation pulsed power technology based on the Linear Transformer Driver (LTD). This architecture is fundamentally different than the traditional “Marx-based” architecture used for the Z facility and offers several advantages including the fact that it is twice as energy efficient (explaining why the next-step facility needs to be 50 MJ instead of 100 MJ). Presently there is not enough program funding for pulsed power technology to develop and build a demonstration module for a next-step facility based on this technology. We are currently utilizing internal funding opportunities at Sandia National Laboratories (e.g., Laboratory Directed Research and Development) to fund research on LTD technology.

Our predictions for the facility size needed to reach ignition are based on the best currently available models for the coupling between that driver and the target, the coupling of high-energy lasers to the target, the initiation and evolution of implosion instabilities during the acceleration stage, and the evolution of instabilities and mix during the deceleration stage. All of these effects occur in the presence of strong azimuthal and axial magnetic fields that alter the implosions and particle transport. In short, a lot of science must be done to understand how good these models really are. Ultimately, it is likely that the best demonstration of our understanding of these models will be showing that we can obtain stagnation plasma conditions consistent with our predictions at different scales. The following section of the document discusses the physics challenges broken out by the main topical areas.

Physics uncertainties, diagnostic needs, computational modeling, and 5-year goals

Summary of Five-Year Goals

This section contains several tables that summarize our five-year goals, broken up by the five main topical areas. More detailed explanations of each of the five areas follow in subsequent sections.

Table 1: 5-year goals for Driver-target coupling topical area

No.	Goal	Rationale
1.1	Deliver 25 MA to a MagLIF target on Z	Allows us to test the scaling of MagLIF targets with current up to conditions published in the original 2010 paper (Slutz et al., Phys. Plasmas) and achieve robust yields to benefit our stagnation & burn goals
1.2	Quantify the benefits to ICF loads of current pulse-shaping	Allows us to explore the performance space between low-adiabat implosions and stability, and will affect current loss in the power feeds.
1.3	Quantify the benefits of longer implosion times	Potentially higher currents (better compression) could be obtained at longer pulse lengths, but may increase risk of losses from heated plasma
1.4	Develop a pulsed-power design of a MagLIF target for "Z-next" that achieves a net target gain of 1.	Gain = 1 (Yield ~ Energy absorbed by target ~3 MJ) could be a potential objective for a next-step facility that would define the driver requirements.
1.5	Conduct scaled power-flow experiments under conditions similar to those of Z next	To demonstrate that Z-next will perform as expected
1.6	Develop predictive (~5%) circuit and PIC models of an accelerator coupled to a variety of loads	These would facilitate the design of MagLIF experiments on Z and the design of a future pulsed power facility. It may be possible to do a single integrated simulation of both the power-flow and the target itself.

Table 2: 5-year goals for Target Pre-conditioning topical area

No.	Goal	Rationale
2.1	Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel	Needed to achieve robust fusion yields, thereby enabling us to diagnose our plasmas well enough to meet our stagnation & burn goals
2.2	Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized "smoothed" beam profile (including optimized pulse shape)	We believe this is what is needed to achieve the previous goal.
2.3	Minimize the likelihood and impact of laser-plasma interactions (LPI)	Needed to maximize our chances of predicting performance & scaling. LPI is sensitive to fuel density, window thickness, laser intensity, laser wavelength.
2.4	Characterize & mitigate any fuel contamination as a result of the heating method	Early time mix is especially damaging due to the long time scales for radiation losses from the heated plasma during the implosion
2.5	Demonstrate 30 kJ heating on the National Ignition Facility	To help lay the foundation for a next-step facility, where calculations predict >20 kJ is needed

Table 3: 5-year goals for Implosions topical area

No.	Goal	Rationale
3.1	Determine dominant seeds for observed acceleration and deceleration instabilities, & develop strategies to mitigate against them	Instability mitigation can open up design space for integrated MagLIF targets.
3.2	Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict integrated target performance	Data collected to date clearly show the impact of 3D instabilities. We need to assess how important these are over a range of conditions relevant to MagLIF
3.3	Measure the spatial distributions for temperature, density, Bz, and any contaminants in the fuel after heating and through at least a convergence ratio of 5	Radiation and heat conduction losses are expected to be sensitive to distributions near the heated plasma boundary; measurements are needed to estimate energy transport out of the imploding region (both radially and axially)
3.4	Experimentally demonstrate a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of >5 Gbar-ns	Note that this goal is about demonstrating control and predictive capabilities for magnetically driven implosions, not fusion. This goal can be reached using a low-temperature, high-density surrogate platform.

Table 4: 5-year goals for Stagnation & Burn topical area

No.	Goal	Rationale
4.1	Achieve a burn-averaged ion temperature of >4 keV	This is the threshold for robust burn. We need to demonstrate that the ion temperature increases with increasing preheat energy and decreases with increasing high-Z contamination (due to radiation losses)
4.2	Achieve a BR>0.5 MG-cm (equivalent to $R/r_{\alpha} > 2$)	Demonstration of the idea of magnetic flux compression. Above this value, the benefits of magnetization saturate.
4.3	Achieve a fuel pressure >5 Gbar and $P\tau > 5$ Gbar-ns, where τ is the confinement time	Needed to demonstrate that we can reach magneto-inertial fusion relevant conditions. For context, ~100 kJ MagLIF designs require P~5-10 Gbar and $P\tau$~10 Gbar-ns.
4.4	Minimize and mitigate against radiation loss from high-Z contamination	Known to vary with target geometry and character of laser heating. Mitigation strategies may include varying the geometry of integrated targets, the fuel heating methodology, the liner stability, and/or the use of anti-mix layers
4.5	Demonstrate a continuous, nearly uniform stagnation column at a convergence ratio (CR) >20	A discontinuous plasma assembly loses the benefit of ρZ (along axial direction) and increases losses. We note that ~100 kJ MagLIF targets require a CR of 25, but lower stagnation fuel pressures (e.g., due to low preheat) will actually result in higher convergence
4.6	Determine the non-thermal component of the fusion yield	A significant portion of the yield for many z-pinches is not thermonuclear

Table 5: 5-year goals for Modeling, Simulation, and Scaling topical area

No.	Goal	Rationale
5.1	Improve our existing codes capable of fully-integrated simulations by implementing less reduced MHD models	All of the codes benchmarked to date as being useful for simulating all aspects of magneto-inertial fusion are based on highly reduced MHD models could help improve predictive capability in these "workhorse codes". Examples

		include additions such as terms needed to model magnetic flux loss (Nernst, Ettinghausen) and current flow in low density plasma ("extended MHD").
5.2	Investigate simulation tools using significantly less-reduced models to assess where the use of highly reduced models is inappropriate	While traditional particle-in-cell codes that directly treat particle kinetics don't scale well to the high particle densities of MagLIF, codes with significantly less reduced models (compared to ideal MHD) may be needed to capture key phenomena. LSP or other ASC codes could play a role in understanding this.
5.3	Develop tools and experiments for validating our simulations and demonstrating key phenomena	These can be theoretical test problems (e.g., magnetic Noh problem). They can also be simple, highly specialized test codes with less-reduced physics models than ideal MHD. Each topical area is expected to generate validation data for this purpose in physics-focused experiments.
5.4	Avoid investing significant effort in modeling laser-plasma interactions	We do not believe we can design a credible fusion target in which LPI plays a significant role

Discussion of Driver-target Coupling Topical Area

The principal goal of this topical area is to fully understand the key physics of driver-target coupling, such that verifiable predictive models for next generation power-flow to targets can be developed, and current to the target can be maximized.

A specific goal of this topical area is to develop a platform capable of delivering >25 MA to a MagLIF target on Z. This level of current is needed to demonstrate the scaling of MagLIF over a range of currents, and to ensure that we can produce robust yields that will enable the various measurements for our Stagnation & Burn topical area goals.

The team has recently developed a physics-based transmission-line-circuit model of the Z accelerator. The model has only two adjustable parameters. Predictions of the model are consistent to within 3% with power-flow measurements conducted on all short-circuit, dynamic-hohlraum, and integrated-MagLIF experiments fielded to date on Z. This circuit model suggests that it is possible to deliver 26 MA to a MagLIF liner in an integrated experiment by taking the steps outlined in Table 6.

Table 6: A possible path to achieving 26 MA currents in integrated MagLIF experiments on Z. Each row of the table represents an iteration in load hardware designs that could be developed over the next five years. Changes to the load hardware result in lower inductance, which increases the total current, but which could also affect losses in the power-flow hardware if our models are incorrect.

	initial liner radius	liner implosion time	peak liner current	final liner kinetic energy	initial feed inductance
baseline MagLIF shot (Z-shot 2591)	2.79 mm AR=6	101 ns	18.6 MA	294 kJ	6.20 nH
low-inductance feed, 80-kV Marx charge	2.91 mm AR=6	101 ns	21.9 MA	417 kJ	5.34 nH
low-inductance feed, 85-kV Marx charge	2.98 mm AR=6	101 ns	23.0 MA	452 kJ	5.30 nH
low-inductance feed, 90-kV Marx charge	3.10 mm AR=6	101 ns	24.5 MA	523 kJ	5.25 nH
low Inductance feed, 90-kV Marx charge	4.00 mm AR=10	120 ns	26.1 MA	570 kJ	4.86 nH

As indicated by Table 6, we could achieve 26 MA if we do the following:

(a) Reduce from 6.20 nH to 4.86 nH the initial inductance of the inner magnetically insulated transmission line, or MITL (i.e., the feed) that delivers current to the MagLIF liner. The reduced-inductance MITL would also use larger anode-cathode gaps to reduce current loss within the MITL.

(b) Increase the initial aspect ratio (AR), defined as the liner outer radius divided by the liner thickness, of the MagLIF target from 6 to 10.
(c) Increase the Z Marx-charge voltage from 80 kV to 90 kV.

The principal physics issues associated with this path to higher current are:

(a) Reducing the inductance of the inner MITL (and increasing its anode-cathode gaps) would increase the liner current but would require that we increase the non-uniformity of the applied *axial* magnetic field at the fusion fuel from ±0.1% to ±15%. We presently do not understand the performance space between axial-field uniformity and liner current.
(b) Reducing the inductance of the MITL may also require increasing the non-uniformity of the *azimuthal* magnetic field (by an as yet undetermined amount) at the outer liner surface. We presently do not understand the performance space between azimuthal-field uniformity and liner current.
(c) Increasing the initial liner aspect ratio from 6 to 10 would reduce the initial inner-MITL inductance and increase the liner current but would also decrease the implosion stability of the liner. We presently do not understand the performance space between aspect ratio and liner current.
(d) While increasing the aspect ratio from 6 to 10, we would also increase the initial liner radius from 2.79 mm to 4 mm and the liner-implosion time from 101 ns to 120 ns. These changes would increase by 20% the final liner-implosion velocity. We presently do not understand the performance space between aspect ratio and implosion velocity.

We propose to address these issues by developing improved theory, modeling, experiments, and diagnostics, as we describe below.

2D and 3D MHD simulations

We propose to conduct 2D and 3D MHD simulations of a MagLIF liner to develop a computational understanding of the performance space between each of the following pairs of quantities:

(a) Axial-magnetic-field uniformity and liner current
(b) Azimuthal-magnetic-field uniformity and liner current
(c) Initial liner aspect ratio and liner current
(d) Initial liner aspect ratio and final liner-implosion velocity

Results of experiments conducted on Z would be compared to predictions of the 2D and 3D simulations and used to improve the MHD models of a MagLIF target.

3D particle-in-cell simulations

We propose to develop a next-generation, fully-relativistic, fully-electromagnetic 3D particle-in-cell (PIC) model of a coupled MITL-convolute-load system. The model would be used to conduct numerical driver-target-coupling experiments. Results of the simulations would improve the fundamental physics understanding of driver-target coupling, guide the design of MagLIF experiments conducted on Z, and suggest improvements to the physics-based transmission-line-circuit model of Z.

Results of experiments conducted on Z would be compared to predictions of the PIC simulations, and used to develop a more advanced version of the PIC model of the MITL-convolute-load system.

Physics-based transmission-line-circuit model of Z

The Z circuit model would be used to simulate every MagLIF-related shot conducted on Z. Results of the shots, and the 3D PIC simulations, would be used to develop a next-generation version of the circuit model.

Integrated MagLIF experiments on Z

We propose to conduct controlled integrated MagLIF experiments on the Z accelerator to develop an experimental understanding of the performance space between each of the following pairs of quantities:

(a) Axial-magnetic-field uniformity and liner current
(b) Azimuthal-magnetic-field uniformity and liner current
(c) Initial liner aspect ratio and liner current
(d) Initial liner aspect ratio and final liner-implosion velocity

Results would be compared to the predictions of the 2D and 3D MHD simulations outlined above, and used to improve these computational models of a MagLIF liner.

Plasma cleaning of MITL-system electrodes

Presently, several megamperes of current are lost in the Z-MITL system on integrated MagLIF shots. The loss current is carried by charged particles that originate from contaminants on the surfaces of the MITL-system electrodes. The loss reduces the current delivered to the MagLIF liner.

3D PIC simulations of the Z MITL-convolute-load system make clear that the loss would be reduced by reducing the level of contamination. We propose to test this prediction by conducting controlled experiments on Z with a plasma-based in-situ electrode-cleaning system (PISCES). PISCES was recently developed by a Grand Challenge LDRD at Sandia.

PISCES may allow us to deliver in excess of 26 MA to a MagLIF liner. PISCES may also allow us to reduce the amount by which the initial liner aspect ratio would need to be increased to achieve 26 MA.

Diagnostics

The most critical driver-target-coupling diagnostics are those that measure the current delivered to the MagLIF liner. We propose to use three independent methods to determine the liner current.

Inferring the liner current from measurements at the Z insulator stack

The Driver-Target-Coupling Team have recently developed a new method to determine the MagLIF-liner current.

On every Z shot, we make precise, accurate measurements of voltage and current at the water-vacuum interface (i.e., the insulator stack) of the Z accelerator. We have demonstrated that we can use these measurements, and the physics-based circuit model of Z, to infer the current at the liner.

This method is consistent with power-flow measurements conducted on every short-circuit, dynamic-hohlraum, and integrated-MagLIF experiment fielded to date on Z.

Initial results suggest this new method can measure the liner current with an uncertainty of less than 5%. The method is compatible with every MagLIF experiment (in fact, with every experiment conducted on Z), provides the current within minutes after a shot, does not require engineering modifications to the liner, does not require an increase in either the liner or MITL inductance, does not increase the time required to install MagLIF hardware on Z in preparation for a shot, and cannot create a vacuum leak that delays a shot.

Inferring the liner current from PDV-based velocity measurements

We also propose to further develop a VISAR-based and photonic-Doppler-velocimetry (PDV) based diagnostics that could be used to infer the liner current.

The PDV diagnostic would be used to measure the rear-surface velocity of a current-carrying conductor located in close proximity to the MagLIF liner. MHD simulations would be used to infer the front-surface pressure time history from the rear-surface velocity, and then infer the liner-current time history from the pressure.

This technique requires an accurate material-physics model of the conductor, one that accounts for time-dependent material-microstructure and material-strength effects, as well as time-dependent kinetic effects on the conductor's transport coefficients and equation of state.

Inferring the liner current from B-dot measurements at the inner MITL

In addition, we propose to develop next-generation B-dot diagnostics that would be fielded in the Z inner MITL and used to infer the current delivered to the liner.

Discussion of Target Pre-conditioning Topical Area

Most of the Target Pre-conditioning topical area effort has focused on laser heating of fusion fuel for the MagLIF concept. While laser heating was thought to be the fastest way to test the magneto-inertial principles underlying MagLIF, we do not believe they are the only possible method. The group is also evaluating alternative fuel heating concepts based on pulsed power techniques. While these can, in principle, couple more energy to the fuel, they require Z shots to test their efficacy. By contrast, laser heating can be studied independently of the implosion using a number of facilities throughout the country with much higher shot rates. This allows for rapid progress in our understanding. In addition, laser based heating allows us to leverage a worldwide pool of expertise in laser produced HED plasmas.

Explanations for the five-year end state goals of the preconditioning research group follow.

Develop a robust and reproducible method to couple >2kJ of energy to magnetized deuterium fuel.

The requirements of MagLIF laser preheat are that 4-8 kJ of laser energy be deposited in an under-dense D2 (or DT) gas where the electron density is less than 10% of the critical density for the laser (i.e., $n_e < 0.1\ n_{crit}$) over a scale length of <10 mm heating the plasma to ~300-500 eV. The propagation of laser energy needs to be such that significant energy is not deposited into the liner or end caps of the target, lest ablation and mix degrade the fusion yield. Since the laser heating occurs roughly 50 ns before stagnation, there is ample time for laser-induced mix to radiate away significant energy even at fairly low dopant levels. The details of laser energy absorption in MagLIF targets are complicated by the growth of parametric instabilities and laser filamentation and spray that can occur in under-dense plasma and by interaction with the laser entrance hole (LEH) foil. To date, ICF experiments have not fully addressed the absorption and coupling of laser energy into under-dense plasmas at the conditions of interest to MagLIF. Both during and after the plasma heating, the applied magnetic field affects thermal conduction and reduces energy losses to the target walls.

At this point in time, we still do not have adequate data to ascertain the relative level of mix, mix constituents, and absolute efficiency of energy coupling to an integrated MagLIF target. Stated another way, we do not yet know the “initial conditions” for an integrated MagLIF implosion. It is absolutely critical to establish these initial conditions as soon as possible to further our understanding of the physics of MagLIF implosions. The preconditioning team recognizes that our highest priority is to develop a well characterized, robust, and reproducible method to couple >2kJ of energy into magnetized deuterium fuel. For parameters that we can reach during the next five years, the increase in neutron yield is strongly nonlinear up to about 2 kJ, so this threshold gives us a good practical breakpoint for producing robust yields and temperatures and thereby enables us to achieve our stagnation and burn goals.

In order to develop a robust and reproducible method for preheating the magnetized deuterium fuel, more well diagnosed experiments are needed that can explore design parameters and inform simulations to give an understanding of the physical processes involved in establishing the "initial conditions" of a MagLIF implosion. The most important design parameters are currently being studied experimentally: beam smoothness (spatial and temporal), laser wavelength, laser pulse shape, gas density, magnetic field strength, LEH material and thickness, and target design. The numerous parameters of significance open up considerable design space for testing and optimization. Experiments dedicated to investigating laser preheat are currently being performed at Sandia, using Z-Beamlet and the PECOS laser target chamber, and at LLE, using the OMEGA-EP and OMEGA lasers. All of these facilities enable parametric studies with multiple experiments per day.

We are also actively developing new diagnostics and capabilities on all of these facilities. One primary example is our ongoing effort to develop an in-situ time-dependent fuel temperature diagnostic during a MagLIF implosion. The goal of this approach is to obtain time-gated images and spectra of radiative emission out of the laser entrance hole using an x-ray spectrometer coupled to a hybrid CMOS camera. Spectrally resolve Ne emission lines measured throughout the implosion will be used to infer the temperature history of the fuel.

Minimize the likelihood and impact of laser plasma interactions in MagLIF target designs.

Ideally, a laser beam would couple directly to the fusion fuel via classical inverse bremsstrahlung (collisional absorption), which produces thermal electrons along well-defined laser trajectories. However, there are a number of competing ways by which lasers can interact with plasma. A laser will be reflected when the density is above the critical density, n_c, where the plasma frequency is equal to the laser frequency (n_{crit} (e/cm^3) is $\sim 10^{21}(\lambda_{\mu m})^{-2}$). Since the index of refraction is dependent on the plasma density, lasers undergo refraction, which can filament and even spray the beam. There are also a number of laser-plasma instabilities (LPI) such as Raman scattering (SRS), stimulated Brillouin scattering (SBS), and the two-plasmon decay instability (TPD). SRS can occur at electron densities less than or equal to $n_{crit}/4$ which creates energetic electrons whose effective temperature is >10x that of the thermal electrons while also scattering the incident laser light. SBS can occur at densities up to n_{crit} and can scatter the incident laser light significantly, thereby reducing the absorption efficiency. TPD, which can also generate suprathermal electrons, only occurs at densities near $n_c/4$. As mentioned above, SBS and SRS can significantly reduce the energy coupling through scattering. The growth of LPI is a strong function of the laser wavelength, intensity, local plasma conditions, and homogeneity. While the average laser intensity required for MagLIF preheating is modest ($\sim 10^{14}$ W/cm^2) the long scale length, under-dense plasma is a concern.

High power solid-state lasers are well known to have significant spatial intensity modulations that can drive the various plasma instabilities. The Z-Beamlet laser (ZBL) was originally built primarily for x-ray backlighting and therefore did not require methods to "smooth" these intensity modulations. Initial experiments using this "unsmoothed" Z-Beamlet beam to determine the fraction of the laser light penetrating though a free standing foil showed significantly lower laser transmission than predicted by the simulations. Recent experiments on OMEGA-EP, as well as on ZBL, have also demonstrated that beam propagation and fuel heating profiles cannot be predicted by our simulation codes when beam-smoothing techniques are not employed. We suspect this is the primary reason that we did not predict the poor laser coupling of energy to the fuel in our initial integrated experiments. We have therefore accelerated our plans to procure random phase plates for ZBL and the integrated MagLIF experiments on Z. Our first set of phase plates is expected to arrive in August 2015. In the meantime, phase plates have been borrowed from LLE for near-term experiments, though they are not ideal since the focal spot size is larger than we predict is optimal. Our eventual goal is to design and employ optimal random phase plates that provide a well known speckle intensity pattern to irradiate the MagLIF plasma. Additional beam smoothing such as temporal smoothing such as Smoothing by Spectral Dispersion (SSD) is not currently planned due to the cost and complexity of implementing this capability. However, future experiments planned at LLE will employ state of the art spatial and temporal beam conditioning using SSD. It is possible that these experiments will show that random phase plates alone may provide insufficient "conditioning" of the laser and unacceptable LPI results.

The hydrodynamic simulation codes used to design and interpret MagLIF experiments include the effects of inverse bremsstrahlung and refraction but do not properly account for LPI. A tremendous amount of resources are being currently devoted worldwide to study LPI physics and develop codes to simulate LPI. We intend to collaborate and leverage this knowledge as much as practical to advance our understanding of laser coupling in MagLIF. We do not intend to advance LPI simulation modeling efforts at Sandia. A guiding principle in all of our MagLIF target designs is to minimize LPI to the extent possible by avoiding plasma conditions that are conducive to the development of LPI. However, the state of the art is currently such that experiments are needed to characterize laser heating and to assess the level and impact of LPI. The MagLIF plasmas are generally outside of the parameters explored in traditional ICF in that the electron density gradient lengths are very long ($\sim L/\lambda > 10^4$) the electron temperatures are < 1 keV, and the $I\lambda^2$ is $<10^{14}$ W-μm^2/cm^2, and the plasma is intentionally magnetized.

In our current MagLIF designs, LPI and electron transport modeling is particularly complicated when the laser first interacts with the several μm thick foil covering the laser entrance hole (LEH) since this foil is initially solid with density well above the critical density, n_c = 17.5 mg/cm^3, for 0.532 μm. As a result, the MagLIF laser pulse is designed to provide a small "prepulse" of energy to this foil to start the disassembly process before the arrival of the main laser pulse. Presently, the separation of the prepulse from the main pulse is only a few ns due to limitations of the overall laser pulse length produced by Z-Beamlet. While a longer separation is needed to ensure the foil plasma density is well below n_c when the main laser pulse arrives, laser only experiments with available separation times already indicate improved penetration though the LEH foil. Upgrades are currently being performed to the Z-Beamlet facility to allow virtually arbitrary separation of the pre and main pulses by co-injecting the Z-Petawatt laser in long pulse mode along the same beam path.

Even at densities well below n_c, filamentation and SRS scattering can be problematic, particularly when the plasma scale length is long. The scale length over which LPI can occur increases throughout a MagLIF experiment as the laser propagates deeper into the gas and the LEH foil expands into the path of the laser. At the present time we have little data to determine the relative importance of LPI during the preheat phase of MagLIF experiments. As January 2015, we have just started to field basic laser backscatter diagnostics on the Z facility.

Another research direction currently being pursued to minimize LPI is cryogenically cooled targets. The first cryogenically cooled MagLIF targets will be fielded on Z in August of 2015. These designs allow much thinner LEH windows (<0.5 μm) and significantly larger LEH openings, while still containing the necessary fuel density. These targets are expected to exhibit significantly less LPI and mix contamination from the LEH mounting washer and the target channel in which the laser propagates into the fuel.

Characterize and mitigate any fuel contamination as a result of the heating method.

All fusion concepts must overcome bremsstrahlung radiation losses to achieve the required plasma temperatures. MagLIF targets are particularly sensitive to bremsstrahlung radiation losses during the implosion since tens of nanoseconds exist for the preheated fuel to radiate away its energy before stagnation. Since bremsstrahlung emission is proportional to the square of the nuclear charge, any source of contaminant mixed into the fuel can substantially increase the amount of radiation lost. It is critical to understand all sources of fuel contamination and mix in the fuel as well as when the contamination occurs.

Mix characterization and evaluation of mitigation techniques are a key focus to our preconditioning experimental campaigns on OMEGA-EP, PECOS, and ZBL-only experiments on Z. Our current approach is to utilize selective spectroscopic doping of features in the target. Multiple spectrometers are then used to infer the spatial extent and time history of mix constituents as well as relative emission levels. These measurements have already given us valuable data during the time period when the laser is on. However, doping the gas or features inside the target can have a profound impact on the very gas conditions we are trying to measure due to enhanced radiative cooling. Furthermore, measurements of the state of the gas after laser heating is extremely difficult due to the relatively low averaged plasma temperatures that must be diagnosed (<300eV). The required dopants to diagnose this range do not radiate at high enough photon energies to escape the liner walls. In order to overcome this, we are evaluating target walls with small diagnostic windows and axial spectroscopic imaging techniques along the axis once the LEH window has disassembled. Optical Thomson scattering, although challenging to implement, has the advantage of not affecting gas conditions and will be explored in the coming years as well.

Several approaches are currently being pursued to mitigate early time, laser induced mix. 1) Eliminate mid-Z and high-Z materials in the target to the extent possible. 2) Improve target designs to ensure laser heating such that the laser only heats the fuel and does not strike either the liner or the electrodes. For example, hollow beam dumps or laser exit window could be employed so that the MagLIF target is not sensitive to the laser penetration depth. Furthermore, the laser energy deposited within the fuel should be as uniform in the axial direction as possible to avoid the formation of a vortex. 3) Fire the laser later in the implosion, which would reduce the amount of time for material to mix into the fuel and subsequently radiate away energy. This option comes at the cost of efficiency since the preheated fuel would not undergo as much compressional heating. 4) Provide anti-mix layers on the inside of the liner and the electrodes. The ultimate anti-mix material is deuterium or deuterium/tritium. Within five years, we plan to test and evaluate techniques for creating either solid or liquid cryogenic anti-mix fuel layers inside a cylindrical target and understand the impact on the integrated implosion performance. Since these will require cryogenic temperatures, LiH will be tested first to investigate the efficacy of this approach.

Improve the Z-Beamlet laser to provide a multi-ns, >6kJ, well characterized "smoothed" beam profile in an optimized laser pulse shape.

We are pursuing several upgrades to the Z-Beamlet laser to improve performance, reliability, and predictability of integrated MagLIF performance as well as facilitate scaling studies. These upgrades are also necessary to achieve several of the five-year physics goals of the other MagLIF research groups.

- Initial random phase plates procured and installed to provide a significantly smoother beam profile (August 2015)
- New in-situ laser alignment system and procedure using the M8 camera which will significantly improve our alignment precision and repeatability (Dec 2015)
- Co-injection of the Z-Petawatt beam (long pulse mode) to provide significantly more laser prepulse capabilities as well as additional available energy, and new x-ray backlighting capabilities of laser preheated targets (July 2016)
- Installation of laser glass amplifiers by 2018, which will allow 6-8 kJ of energy to be delivered in a single pulse

The optimized laser pulse shape will be determined through simulations validated using experiments planned at the OMEGA-EP facility and ZBL PECOS target chamber.

Demonstration of sufficient magnetized fuel heating at energies relevant to ignition and high yield with acceptable thermal conduction losses over a relevant implosion time scale

Scaled MagLIF gas burning designs require coupling 30-40 kJ of laser energy into much higher fuel densities (4-6 mg/cc) at similar levels of initial magnetization (~15 T). Doing so without introducing unacceptable levels of contaminants that mix into the fuel is expected to be a challenge.

The National Ignition Facility provides us a unique opportunity to demonstrate all of the key physics of laser preheating required for a scaled MagLIF design. If successful, we could potentially qualify, at full scale, a preheating design that meets requirements of scaled target design. This would allow us to clearly and accurately define the laser facility that would have to be built along with any next-generation pulsed power facility on the path to ignition and burn. To enable our preheating experiments, however, facility investments at the NIF need to be made such as the development of magnetic field coils.

Preparations have already begun for our first experiments on NIF, which are scheduled to occur in January 2016. The first experiments will first focus on the study of laser preheating in dense gas and evaluate levels of LPI. A multi-year plan is currently being developed for NIF experiments in collaboration with scientists at LLNL. The plan will include the demonstration of a new experimental platform and supporting capabilities (cryogenics, magnetization, diagnostics, etc.). We believe that scaled laser heating experiments with magnetization are possible on NIF during the next 3-5 years.

Discussion of Implosion Topical Area

In contrast to the target pre-conditioning topical area, the study of the implosion phase of magnetically driven liners must be done almost exclusively on the Z facility. While some research on liner initiation instabilities is possible on 1 MA university-class pulsed power facilities, such facilities can't drive solid liner implosions unless the liner wall thickness is of order 1-10 microns, compared to ~500 microns on Z. The behavior of such liners is considerably different—note that the nominal skin depth for a ~100 ns current pulse is of order 70 microns, hence at the university scale the current penetrates the liner thickness almost immediately, and on Z it takes >10 ns before the inner liner surface moves after the outer surface has started to move. Recognizing this problem early on, the ICF program at Sandia has been doing fundamental studies of liner implosion physics dating back to 2008 and has maintained a continuous program of shots on this topic since then.

The primary question is whether we can accurately model and control magnetically driven liner implosions. Like other ICF concepts, the implosion is affected by Rayleigh-Taylor instabilities. Unlike other ICF concepts, the dominant implosion instability is the magneto-Rayleigh-Taylor (MRT) instability and because of the large skin depth of the current, the behavior of the liner is not truly a surface phenomenon. A key unknown is what the dominant initial seed for the MRT instability is. Experiments appear to show that the surface roughness can be varied in its orientation and amplitude without significantly affecting the growth rate. While the issue is still being investigated, one hypothesis that has received considerable attention is the idea that electro-thermal instabilities driven by the current flowing in the bulk material could be seeding the MRT instabilities. This has led to the idea that thick (50-70 micron) dielectric coatings on the liner surface might substantially reduce the instability growth. Early experiments along these lines seem promising and may lend credence to this idea.

Another key aspect of the liner dynamics is its three-dimensional nature when an axial seed field is present (as in MagLIF experiments). While the azimuthal field on the outside liner surface quickly exceeds any reasonable seed field produced by magnetic field coils by >100x, experiments have shown that in the presence of an initial axial field of 7-10 T the MRT instability structure fundamentally changes from being highly cylindrically symmetric to helical in nature. First, we do not fully understand why the non-magnetized structure is so highly symmetric and believe it may be related to the initial seed in some fashion. Second, we are still working on 3D models to capture this instability growth, but believe that it must affect the initial seed. Third, we don't have a quantitative understanding yet of how much this helical structure affects the stagnation physics in MagLIF. High-resolution x-ray images show a weakly helical structure, but since the compressed magnetic field in that structure can easily bend along the weakly helical path it is unclear how much impact it has. On the other hand, 3D instabilities could affect the conversion of kinetic energy into fuel thermal energy and the fuel confinement time, and we have not studied the scaling of these effects with increasing driver energy yet.

Like all ICF approaches, there will be deceleration instability growth affecting the inner liner surface during the final fuel compression stages. In contrast to the outer liner surface where MRT is the dominant instability, the inner liner surface is likely dominated by classical instabilities such as RT, Richtmyer-Meshkov, and Kelvin-Helmholtz. The inner liner surface will be affected by the blast wave produced by laser heating, which may also affect the growth of such instabilities. We have done our first focused experiments to study deceleration instabilities in 2015, and we plan to make this a major emphasis going forward. It is also unknown at this time how important kinetic effects are, such as mass diffusion and transport in the presence of multiple ion species, density and temperature gradients, and magnetic fields. There may be techniques that we can use to mitigate against such instabilities, such as including "anti-mix" layers like LiD or even frozen deuterium.

From a modeling perspective, it is important to understand the drive current in our implosion experiments. The unique power feed we are currently using that provides us with two magnetic field coils also affects our ability to field B-dot probes near the load in standard locations. As a result, there is higher than usual uncertainty in the load current diagnostics. We plan to address this going forward jointly with the driver-target coupling team to determine the current accurately and to model the circuit better for comparison to simulations.

It is possible to strongly affect the condition of the liner through shaping the driving magnetic pressure, thereby avoiding strong shocks and, in principle, maintaining the inner liner surface in a solid state for a large portion of the implosion. Longer pulse shapes may have additional benefits in terms of reduced current loss in the power feed and higher peak currents. Pulse shaping is being used by our dynamic material properties program in cylindrical geometries, but its impact for MagLIF has never been experimentally tested. Longer implosion times may impact performance negatively due to increased time for radiation losses.

As our understanding of the implosion phase improves and better predictive models become available, we could greatly open up the design space available for MagLIF. All of the experiments to date have used liners with an aspect ratio (AR) of 6, where the aspect ratio is the liner outer radius divided by its thickness. This is based on calculations that suggest such a liner will retain sufficiently large rho-R at stagnation to inertially confine the compressed fuel even in the presence of MRT instability growth on the outside of the liner. Especially if mitigation techniques for liner instability growth are successful, it may be possible to use higher AR liners. The resulting higher implosion velocity would decrease initial fuel heating requirements. Other phenomena such as end losses and so-called "wall" instabilities along electrode surfaces can also be affected by small changes in the liner design near the top and bottom (e.g., the use of compressible electrodes or slightly varying liner thicknesses near the top and bottom).

Understanding the energy losses from the fuel during compression is key. These losses can occur both axially and radially. While the magnetic field is expected to reduce radial losses, these models have not been validated at the temperatures and densities relevant to MagLIF and calculations suggest that the radial losses can be affected by small changes in temperature and density distributions near the edge of the heated plasma. Axially, the transport of electrons and heat is uninhibited by the magnetic field but it is somewhat inertially confined. Calculations suggest our baseline designs lose roughly 30-50% of the energy out the ends, which is significant but predictable—even with these losses we believe it may be possible to reach 100 kJ on Z at some point. As noted above, there may be several ways to affect the axial losses, but we have not investigated this experimentally yet since our immediate priority has been to get a stable, well-understood initial heating platform. Key to assessing these energy losses will be measuring the temperature versus time of the fuel during the compression stage, ideally to at least a convergence ratio of five. (From a practical point of view, higher convergence ratios will be increasingly difficult to diagnose due to the increasing height/diameter aspect ratio of the compressed fuel.)

Another basic question we would like to assess quantitatively is magnetic flux compression. Benchmarking our models will be important—up to 30-50% of the initial magnetic flux could leak through the liner during the compression.

With these questions in mind, the implosion team has developed a set of five-year goals (Table 3) and a draft research plan to reach those goals.

I. How to understand the seeding & evolution of 2D & 3D instability structures during acceleration & deceleration and to determine their effect on overall target performance:
   a. Obtain high-resolution early-time visible to soft x-ray emission images to better understand initialization and electro-thermal instability, and how it later affects MRT seeding; use this capability to directly observe the initiation of the helical instability structure (this could be done at a smaller scale facility, such as the Zebra generator at UNR)
   b. Measure Richtmeyer-Meshkov (and Kelvin-Helmholtz, possibly driven by the laser blast wave) near the times of laser preheating and shock breakout
   c. Obtain "3D" liner areal density profile to assess impact of helical structures on confinement quality and overall MagLIF performance; obtain this using:
      i. New tomographic radiography system [i.e., multi-views (>2)] at higher-energies (>7 keV)
      ii. New down-scattered neutron imaging capability (requires time gating and DT fuel)
   d. Measure acceleration & deceleration Rayleigh-Taylor growth (diagnose with radiography and possibly a new line-VISAR capability)

e. Demonstrate mitigation of instability growth, both in-flight & during stagnation, using target modifications (e.g., dielectric liner coatings, helical return-current paths, etc.) and pulse shaping (diagnose with radiography)
f. Determine meaningful quantitative metrics for assessing implosion performance of various liner designs
g. Obtain radiographs of an integrated MagLIF experiment
h. Determine the effects on performance of using alternative liner materials (e.g., Li) and pulse shaping to control the liner's in-flight aspect ratio and areal density (diagnose with radiography)
i. Measure and demonstrate control over the fuel adiabat in-flight using on-axis radial PDV
j. Measure the acceleration and deceleration history of liner implosions using on-axis radial PDV, multi-frame radiography, and a new long-duration (20–100 ns) streaked x-ray radiography system

II. How to understand spatial distributions for temperature, density, B_z, J_z, and contaminant mix throughout the implosion:
a. Develop end-on (viewed from top and/or bottom) diagnostics capabilities, including:
    i. Radially-resolved spectroscopy
    ii. Laser, VUV, and/or x-ray viewing and probing techniques
    iii. Minimally invasive Faraday rotation and/or B-dot probes at various radii
b. Conduct experiments to vary the spot size of the preheating beam and measure effects on the various fuel distributions
c. Pulse shaping experiments to control J_z
d. Pulse shaping experiments to assess impact on flux compression
e. Streaked visible spectroscopy experiments to look at outer surface J_z
f. University collaborations for dimensionless scaling studies, e.g., to study the inverse of a liner wall pushing magnetized fuel
g. Large surrogate experiments, possibly even planar, and possibly with viewing slots/holes cut out of the imploding targets to enable diagnostic access

III. How to understand energy transport out of the imploding region, including that due to axial mass flow (i.e., end losses):
a. Develop time-gated diagnostic techniques to image self-emission associated with mass flow out of the top of the target
b. Develop diagnostic techniques to probe mass flow out of the top of the target, e.g., laser probe/interferometer system
c. Develop diagnostic techniques to assess mass flow out of the bottom of the target, e.g., bottom-mounted PDV probes
d. Develop and field surrogate experimental platforms to study end losses

e. Measure axial radiation losses from the fuel (develop end-on views for Si diodes, PCDs, bolometers, etc.)
f. Utilize collaborations with universities and other labs, as well as surrogate platforms, to address fundamental magnetized and unmagnetized transport questions

IV. How to demonstrate a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product (where tau is the confinement time) of >5 Gbar-ns:
   a. Conduct surrogate experiments to radiograph liner dynamics and deceleration RT growth at stagnation
      i. Surrogate platform established using cryogenically cooled liquid D_2 fuel to provide a high initial fuel density
      ii. This platform enables low temperature, high density stagnation conditions with a pressure-tau product of >5 Gbar-ns (which is ignition-relevant for MagLIF) and a stagnation radius of >100 microns (which is diagnosable with our existing radiography capability)
   b. Measure a deuterium density of >100 g/cm^3 and a deuterium $\rho R > 1$ g/cm^2 using radiography
   c. Develop a new ~4-frame radiography system to measure the confinement time (tau)

We are currently in the process of mapping out a more detailed timeline for when and how we can accomplish this plan over the next five years. We believe it will be possible at a rate of about 15 shots per year over the next five years. However, such a shot rate will not be possible at the current overall rate of funding for the Z facility, as noted above.

Discussion of Stagnation & Burn Topical Area

The Stagnation and Burn topical area serves three main functions:

- Integrating the efforts of the other topical areas into a baseline system design
- Quantifying the stagnated plasma conditions, morphology, and resulting fusion production
- Studying how the stagnation plasma and resulting fusion production scale with key parameters in drive energy, preconditioning, and liner geometry.

This topical area is largely about measuring the impact of the other efforts on the production of the high-temperature, high-density, fusing plasma that is formed at stagnation. The stagnating plasma conditions will be the product of how much energy was coupled to the target, how the plasma was preconditioned, and the stability and kinetic energy of the implosion. Through improvements in instrumentation, target design, and data interpretation, we aim to develop a quantitative understanding of the dynamics that occur at stagnation in order to benchmark our simulation capabilities and assess the potential of magnetically driven implosions to achieve ignition and high yield.

We believe it is possible over the next 5-10 years to demonstrate significant fusion yield on Z of 10-100 kJ (DT equivalent) and to develop credible gas (~5 MJ) and ice burning (~ 1GJ) ignition/high-yield designs for magnetically driven implosions. Achieving these goals requires demonstrated control and understanding of the stagnation dynamics across a range of key system parameters. To this end, we have identified six high-level goals for the Stagnation and Burn effort on Z, as summarized in Table 4 and explained in more detail below. Achieving these goals requires the development and improvement of new diagnostics, targets, and modeling capabilities. The remainder of this section describes these six goals, the key physics issues, and the necessary diagnostic and target development as we understand it today.

1) **Demonstrate an understanding of how T_i scales with the preheat energy, quantify the resulting mix, and achieve a burn-averaged ion temperature of > 4 keV.**

In an adiabatic cylindrical compression with no radiative or conductive losses, the final temperature of the compressed matter scales as $T_f = T_0(CR)^{4/3}$. Thus, increasing the initial temperature decreases the necessary convergence ratio, thereby allowing for a more conservative implosion with smaller aspect ratio and lower implosion velocity. Of course, real systems have both radiative and conductive losses, and changing the initial temperature affects each of these quantities throughout the evolution of the implosion. In addition, the action of preheating the fuel can result in unintended consequences such as increasing the amount of contaminants mixed into the fuel from the walls/end-caps of the target, which may exacerbate the radiation losses. It is therefore important to demonstrate the connectivity between initial preheat temperature and final stagnation temperature. The burn-averaged ion temperature is the most relevant metric to demonstrate this connectivity since this quantity is both readily measured through the neutron spectrum and is directly relevant to the part of the stagnation plasma that is contributing to the fusion production. To date, MagLIF implosions on Z have achieved burn-averaged ion temperatures of ~3 keV. Demonstrating a temperature of >4 keV is important since this is close to the ideal ignition temperature necessary to achieve an efficiently fusing system. Future Z shot campaigns to address this goal will include measurements of the stagnation plasma under a variety of preheat conditions that include the preheat energy and method.

2) **Demonstrate understanding of how Br scales with initial axial B-field and achieve Br > 0.5 MG-cm.**

The axial magnetic field in MagLIF serves two critical functions; it decreases conductivity losses by allowing for a long dwell time between preheat and stagnation and it traps alpha particles, thereby reducing the rho-R of the fuel at stagnation. The latter requires compression of the axial magnetic field in the fuel to a value > 0.5 MG-cm in order to saturate the confinement such that the Larmor radius of the alpha particles is less than half the radius of the plasma ($R/r_\alpha > 2$). The compressed B-field also confines Tritons produced by DD fusion reactions, which go on to fuse with the deuterium background gas, resulting in a DT fusion signature of the field compression. The field at stagnation is then measured through a combination of the DT/DD yield ratio and the DT neutron energy spectrum. To date, MagLIF implosions on Z have achieved BR~0.35 MG-cm under an initial applied axial field of 10 T. Future Z shot campaigns to address this goal will include measurements of the compressed field and other stagnation conditions under a variety of initial field conditions. This will require the development of initial applied fields of ~30 T as well as an improvement of the sensitivity of the DT yield and nTOF measurements (by about an order of magnitude) to investigate the impact of initial fields down to a few Tesla.

3) **Demonstrate understanding of how stagnation pressure and Pτ scale with the drive energy and achieve P > 5 Gbar and Pτ > 5 Gbar-ns.**

Simulations of MagLIF indicate a relatively smooth increase in the stagnation pressure and resulting fusion yield as a function of the driver energy (current). That is, there is no threshold above which MagLIF yields increase dramatically. As such, we must demonstrate interesting fusion conditions on Z at 18-24 MA for the concept to scale to ignition and eventually high yield with the conceptual 40-60 MA next-step facilities under consideration. Simulations indicate that MagLIF on Z should be able to achieve stagnation pressures of > 5 Gbar over ~ 1 ns resulting in a total fusion yield of 10-100 kJ. In addition to the challenges of achieving the necessary drive energy, magnetization, and preheat, measuring the pressure of the fusion relevant plasma is also a significant challenge. The approach is to determine the pressure from measurements of the electron temperature and density through a combination of x-ray spectroscopy, x-ray imaging, and absolute power measurements. At present, the x-ray spectroscopy measurements of electron temperature are limited to time-integrated, axially resolved continuum measurements in the range of ~8-15 keV. Inferences of the density depend on the time-integrated morphology of the stagnation plasma and the absolute value of the x-ray emission, which is dominated by higher-Z contaminants in the fuel from mix. New instruments are required to measure the *absolute* x-ray emission spectrum and the morphology as a function of space *and time*. In addition, new experimental techniques are required to determine the mix fraction separate from the absolute emission level of the continuum and/or to determine the electron density separate from the absolute emission (e.g. through Stark broadening of mix species). Following development of the necessary diagnostic techniques and driver/preheat platforms, future Z shot campaigns will measure the stagnation pressure as a function of drive energy over a range of currents up to ~25 MA. In addition to the drive pressure, it is important to understand the burn duration of the plasma. Presently, this burn duration is approximated by the time duration of the high energy x-ray continuum emission at >8 keV. It would be valuable to measure the burn duration directly from the time duration of the fusion particle emission. This will likely require the use of DT fuel and the development of a diagnostic to measure the time duration of the gamma emission from DT fusion reactions.

4) **Determine the mix fraction in the fuel and how it depends on the preheat energy, liner geometry, and driver energy and demonstrate mitigation strategies, as necessary.**

Mix in the stagnation plasma can originate from multiple interfaces including the end-caps, laser entrance hole foil, electrodes, and the liner itself. This mix may be injected into the plasma at different phases of the implosion. Understanding how much mix persists at stagnation and where it came from is important feedback for refining the preheat platform and liner implosion characteristics. At present, the mix fraction is inferred from the absolute intensity of the stagnation continuum emission. However, the amount of inferred mix depends on the mix species, which is presently unknown (and could be from the Be liner or the Al end caps). More sensitive spectrometers are needed to resolve the absolute line emission from the impurities in the Be liner or Al end-cap to break the degeneracy in the mix species. Additionally, target fabrication development is needed to develop liners with inner coatings and/or buried tracer layers to better determine the origin of the mix and evaluate the mix dynamics. Future Z shot campaigns will test new diagnostics and target designs and subsequently provide quantitative determination of the mix fraction under a variety of target configurations, potentially including different preheat conditions, implosion characteristics (aspect ratio, implosion velocity, etc.), target materials, and/or locations of buried tracers.

5) **Determine how the stagnation morphology depends on the driver energy and liner geometry and demonstrate a continuous stagnation column at the necessary convergence.**

Simulations of MagLIF suggest that the fusion-relevant plasma is a continuous column that is relatively uniform without significant hot spots or other multi-dimensional structure. This morphology can be affected by instabilities and/or asymmetries in the liner implosion and may result in a significantly different structure if the late stages of this implosion are not well understood. Presently, the morphology of the stagnation plasma is measured through the continuum x-ray emission at > 8 keV with either (1) high spatial resolution (~10s of microns) and no temporal resolution, or (2) with relatively poor spatial resolution (~100 microns) and poor temporal resolution (~1 ns). New diagnostics are needed to measure the evolution of the stagnation plasma morphology with ~10 micron spatial resolution and ~100 ps temporal resolution. Such measurements will address important questions regarding how the stagnation column assembles (and disassembles). It would also be valuable to measure the morphology through imaging the fusion neutron emission, as this could be different than the high energy x-ray continuum. This will require development of a neutron imager that is about 1-2 orders of magnitude more sensitive than the existing system on Z and/or will require the use of DT fuel. Future Z shot campaigns will measure the stagnation morphology and evolution under a variety of implosion characteristics.

6) Determine the non-thermal component of the fusion yield.

Z pinches have been known to produce non-thermal ion kinetic energy distributions. This can result in enhancements in the fusion yield that won't scale in the same way as the thermonuclear yield expected from higher energy implosions. It is therefore important to determine what fraction of the measured fusion yield originates from non-thermal ions and, if possible, the ion energy distribution itself. This can be evaluated through high resolution measurements of the neutron energy spectrum and by introducing tritium into the DD fuel and comparing the enhanced DT yield with expectations based on the measured plasma conditions. This requires development of diagnostics to determine the neutron energy spectrum and the capability to use trace amounts (few percent) of tritium on Z.

Table 7 below summarizes the diagnostic and target developments needed for the Stagnation & Burn topical area.

Table 7: Summary of new diagnostic and target developments needed for Stagnation & Burn

Measured Quantity	Measurement Method	5-year Development Activities and Goals
Ion Temperature & non-thermal population	• DD spectra • DT vs. DD yields with trace tritium	• Improve nTOF to provide ±15% accuracy in T_i at Y_{DD}>5x10^{10} • Implement trace tritium on Z
Electron Temperature	• Continuum slope • Emission line ratios	• Develop diagnostics to measure T_e(r,z,t) to ±20% with dr < 50 μm, dz < 500 μm, and dt < 0.5 ns
BR	• DT/DD yield ratio • DT spectra	• Improve nTOF DT spectra to achieve ~0.15 MeV resolution at Y_{DT}>5x10^9 • Improve DT/DD yield ratio to ±30% at Y_{DT}>5x10^9 and increase the angular coverage
Mix Fraction & Electron Density	• Spectral signatures and emission amplitude	• Develop targets with tracer layers • Develop diagnostics to measure absolute x-ray emission to ±50% with dz < 500 μm and dt < 0.5 ns
Fuel Morphology	• X-ray imaging • Neutron imaging	• Develop an x-ray imager with dr < 50 um, dz < 500 μm, and dt < 0.5 ns with sensitivity to >1 GW • Develop 10-100x more sensitive neutron imager, implement T on Z
Burn Duration	• 10-15 keV x-ray history • Inferred from Te(t) • Gamma history	• Leverage electron temperature activities and goals • Develop gas Cerenkov detectors, implement T on Z

In addition to the experimental work described above, a number of model improvements and additions are needed. These activities are summarized below:

- Develop post-processing tools for synthesizing diagnostic data from simulations
- Develop self-consistent kinetic burn simulations to help validate and complement the current *BR* inferences from stationary burn models
- Develop kinetic simulations to validate and elucidate transport models used in radiation magneto-hydrodynamics (RMHD) models
- Develop models for multi-objective data analysis to self-consistently interpret spectral, imaging, and power diagnostics of stagnation

Discussion of Modeling, Simulation, and Scaling Topical Area

At present, our simulation codes have proven to be exceptional tools for developing physical intuition, designing HED, ICF, and Radiation Effects Science (RES) experiments, and essential guides to predicting scientific trends. However, lack of capability to predict the outcome of HED phenomena in general and ICF experiments in particular hampers progress. Achieving predictive capability is a challenge due to the need to model materials from solid to plasma over a huge range of spatial and temporal scales. Furthermore, compute-intensive simulations in 3D with high resolution are often required. These issues are not unique to magnetically driven implosions and are, in fact, the very same issues facing all ICF approaches. However, a unique feature of magnetically driven experiments is the intimate connection between magnetic field transport and plasma conditions.

We note that there are several levels of predictive capability:
1) Quantitative prediction of experimental observables from an entirely new design. In practice this is very difficult but not impossible depending on target complexity.
2) Post diction of an experiment including tuning shot-specific parameter, which is commonly done already.
3) Predicting the outcome of observables for a change in a target design with accuracy comparable to experimental reproducibility for that target type is occasionally accomplished for well-studied targets, however it is generally not the case. The capability to robustly predict the effects of changes to target design would accelerate experimental progress significantly.

Ideally, every particle in a magnetically driven target would be modeled by directly solving Maxwell's equations. In practice, this is not computationally tractable, and approximations are made. Currently, all of our primary design codes are based on a resistive MHD model, which is a highly reduced set of equations relative to Maxwell's equations. Our primary emphasis going forward is to improve the physical description and models in our simulation codes, essentially by usually "less reduced" models. One particular example demonstrating the need for improvement in our current MHD physical description necessitates the use of "floors", or user-defined knobs that modify the physics in low-density regions of our simulations. Eliminating the need for these floors, or at the very least reducing the sensitivity to them, is a key goal in the pursuit of predictive simulation capabilities.

There are two related approaches to improving the physical description of HED plasmas:
(1) Extend existing laboratory MHD codes to include 2-fluid and kinetic physics. That is, we propose to reduce the number of simplifying assumptions normally made in resistive MHD.
(2) Extend kinetic, e.g., particle in cell (PIC), models to recover continuum behavior described in terms of an equation of state, electrical conductivity, opacity, etc. This is akin to starting with Maxwell's equations and making some simplifying assumptions to reduce the complexity, but making much fewer approximations than

traditional resistive MHD. This is traditionally much more computationally intensive as a result.

These can be described as a (1) top-down or a (2) bottom-up approach. Each has merits and challenges associated with it. Conceptually, both of these approaches are not new [Seyler, C. E. and Martin, M. R., Physics of Plasmas, (2011), Xuan Zhao, *et al*., Journal of Computational Physics, (2014), D. W. Hewett, Journal of Computational Physics, (2003). However, high performance computing has advanced to the state to where both approaches are now realistic. In what follows we describe these approaches in turn, outline the core strategy, and give a brief survey of work in progress.

The overarching reasons for pursuing the top-down approach follows from the desire to leverage the extensive array of physics present in the design codes and shorten the cycle for algorithm and code development in order to impact experimental design and analysis. Unfortunately, this approach also comes with challenges. First, the breadth of physics in the design codes brings with it substantial code complexity, slowing development times. Second, while there are arguments which show that incorporating certain phenomena are necessary, the nonlinearity associated with the system precludes making definitive statements about what model system (generalized Ohm's law, 2-fluid 5-moment, kinetic, …) is sufficiently accurate. For these reasons, the strategy we are pursuing is a two-stage model of developing exploratory research codes, to solidify the algorithms and inform our understanding of the physics, and transferring the improved physical model to the design codes.

Significant progress has been made on the first research code development based on a reduced 2-fluid, generalized Ohm's law approximation. Closing Maxwell's equations (including the displacement current) with an Ohm's law leads to asymptotic constraints in the limit of high electrical conductivity, plasma frequency, etc. The importance of using computational algorithms that satisfy these constraints, referred to as asymptotic preserving (AP) algorithms, is well documented in the literature on radiation transport methods. Hence, an AP algorithm for solving Maxwell's equations coupled to a generalized Ohm's law has been developed and tested. Presently, work is underway to couple this algorithm for Maxwell's equations to hydrodynamic motion, resulting in a new generalized Ohm's law-based code that is consistent with the single-fluid, resistive MHD limit. When complete and the impact of this approach has been studied, these improved algorithms will be transferred to a laboratory design code.

"Bottom up" kinetic PIC modeling is a growing point of emphasis for Sandia's ICF and RES programs. The primary reason for pursuing a bottom-up approach is to significantly improve the underlying physics models used in our simulations. Unlike traditional MHD fluid descriptions, kinetic codes allow for physical effects such as non-Maxwellian particle distributions, finite mean-free-path effects, charge separation, electron inertia, etc.

We have already been coupling MHD code results into separate PIC simulations to study the stagnation and burn phase in MagLIF targets with the most realistic transport, burn, and fusion product transport [A. B. Sefkow et al., Phys. Plasmas, 21, 072711 (2014)]. PIC codes such as EMPHASIS and LSP are also beginning to be used by our Radiation Effects program to explore study kinetic effects and non-thermal radiation generation.

Presently, we are working with Voss Scientific to develop new kinetic and fluid particle simulations using the LSP code. Unlike traditional approaches to hybrid PIC modeling where ions are treated kinetically and the electrons as an inertia-less fluid, the LSP kinetics code can seamlessly transition between fluid particle and kinetic treatments for both ions and electrons based on defined constraints such as kinetic and fluid particle energies. This type of fluid treatment enables us to add key physics not available in our MHD codes (such as electron inertia and the displacement current) and to eliminate the treatment of floors in our simulations. Thus far, this support has been at a very low level, but significant progress is being made. Relatively new improvements to the LSP code now allow for solid liner simulations. We are just beginning to compare these simulations with the results of equivalent MHD simulations. Such capabilities also allow for integration of both the target physics and final pulsed power delivery sections of the Z accelerator into a single simulation. The initial results have been very encouraging and have convinced us of the need to further develop kinetic codes such as LSP.

The code landscape with respect to plasma codes is complex in terms of the number of codes at universities and the national laboratories, as well as in the range of capabilities in the different codes. We believe more work needs to done to effectively collaborate on simulation codes and tools in a broader sense between both code users and code developers. We are currently helping to organize an MHD code workshop scheduled for August 24-25, 2015 at LLNL to discuss several of the topics mentioned in this document. We will participate actively in the workshop to leverage existing code collaborations and explore where new collaborations would be effective.

Summary of Key MagLIF Publications

Papers on MagLIF design & scaling

1. S.A. Slutz et al., "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field," Phys. Plasmas 17, 056303 (2010). http://dx.doi.org/10.1063/1.3333505

2. M.E. Cuneo et al., "Magnetically driven implosions for inertial confinement fusion at Sandia National Laboratories," IEEE Trans. Plasma Science 40, 3222 (2012). http://dx.doi.org/10.1109/TPS.2012.2223488

3. S.A. Slutz and R.A. Vesey, "High-gain magnetized inertial fusion," Phys. Rev. Lett. 108, 025003 (2012). http://dx.doi.org/10.1103/PhysRevLett.108.025003

4. D.D. Ryutov et al., "Simulating the magnetized liner inertial fusion plasma confinement with smaller-scale experiments," Phys. Plasmas 19, 062706 (2012). http://dx.doi.org/10.1063/1.4729726

5. A.B. Sefkow et al., "Design of magnetized liner inertial fusion experiments using the Z facility," Phys. Plasmas 21, 072711 (2014). http://dx.doi.org/10.1063/1.4890298

6. R.D. McBride and S.A. Slutz, "A semi-analytic model of magnetized liner inertial fusion," Phys. Plasmas 22, 052708 (2015). http://dx.doi.org/10.1063/1.4918953

Papers on MagLIF-relevant implosion studies

1. D.B. Sinars et al., "Measurements of magneto-Rayleigh-Taylor instability growth during the implosion of initially solid Al tubes driven by the 20-MA, 100-ns Z facility," Phys. Rev. Lett. 105, 185001 (2010). http://dx.doi.org/10.1103/PhysRevLett.105.185001

2. D.B. Sinars et al., "Measurements of magneto-Rayleigh-Taylor instability growth during the implosion of initially solid metal liners," Phys. Plasmas 18, 056301 (2011). http://dx.doi.org/10.1063/1.3560911

3. R.D. McBride et al., "Penetrating radiography of imploding and stagnating beryllium liner on the Z accelerator," Phys. Rev. Lett. 109, 135004 (2012). http://dx.doi.org/10.1103/PhysRevLett.109.135004

4. R.D. McBride et al., "Beryllium liner implosion experiments on the Z accelerator in preparation for magnetized liner inertial fusion," Phys. Plasmas 20, 056309 (2013). http://dx.doi.org/10.1063/1.4803079

5. K.J. Peterson et al., "Electrothermal instability growth in magnetically driven pulsed power liners," Phys. Plasmas 19, 092701 (2012). http://dx.doi.org/10.1063/1.4751868

6. K.J. Peterson et al., "Simulations of electrothermal instability growth in solid aluminum rods," Phys. Plasmas 20, 056305 (2013). http://dx.doi.org/10.1063/1.4802836

7. K.J. Peterson et al., "Electrothermal instability mitigation using thick dielectric coatings on magnetically imploded conductors," Phys. Rev. Lett. 112, 135002 (2014). http://dx.doi.org/10.1103/PhysRevLett.112.135002

8. T.J. Awe et al., "Observations of modified three-dimensional instability structure for imploding z-pinch liners that are premagnetized with an axial field," Phys. Rev. Lett. 111, 235005 (2013). http://dx.doi.org/10.1103/PhysRevLett.111.235005
9. T.J. Awe et al., "Modified helix-like instability structure on imploding z-pinch liners that are pre-imposed with a uniform axial magnetic field," Phys. Plasmas 21, 056303 (2014). http://dx.doi.org/10.1063/1.4872331

Papers on integrated MagLIF experiment results

1. M.R. Gomez et al., "Experimental Demonstration of Fusion-Relevant Conditions in Magnetized Liner Inertial Fusion", Phys. Rev. Lett. 113, 155003 (2014). http://dx.doi.org/10.1103/PhysRevLett.113.155003
2. P.F. Schmit et al., "Understanding fuel magnetization and mix using secondary nuclear reactions in magneto-inertial fusion," Phys. Rev. Lett. 113, 155004 (2014). http://dx.doi.org/10.1103/PhysRevLett.113.155004
3. M.R. Gomez et al., "Demonstration of thermonuclear conditions in magnetized liner inertial fusion experiments," Phys. Plasmas 22, 056306 (2015). http://dx.doi.org/10.1063/1.4919394
4. S.B. Hansen *et al.*, "Diagnosing magnetized liner inertial fusion experiments on Z," Phys. Plasmas 22, 056313 (2015). http://dx.doi.org/10.1063/1.4921217
5. P.F. Knapp *et al.*, "Effects of magnetization on fusion product trapping and secondary neutron spectra," Phys. Plasmas 22, 056312 (2015). http://dx.doi.org/10.1063/1.4920948