SAND2016-0758R

Technology Transfer and Outreach for SNL/Rochester ALPHA Project[1]

Version 3: 1/6/2015

This report describes the next stage goals and resource needs for the joint Sandia and University of Rochester ARPA-E project. A key portion of this project is Technology Transfer and Outreach, with the goal being to help ensure that this project develops a credible method or tool that the magneto-inertial fusion (MIF) research community can use to broaden the advocacy base, to pursue a viable path to commercial fusion energy, and to develop other commercial opportunities for the associated technology. This report describes an analysis of next stage goals and resource needs as requested by Milestone 5.1.1.

Next-stage goals and resource needs

Removing classification barriers for magneto-inertial fusion energy

A barrier to developing tools for magneto-inertial fusion energy is the Department of Energy and the National Nuclear Security Administration's existing classification guidelines. The applicability of the existing rules to the broad suite of approaches covered by the existing ALPHA program is unclear. For example, the current Inertial Confinement Fusion (ICF) program guidance from the NNSA states that targets with any dimension exceeding 1 cm are classified (this boundary is itself unclassified). Many of the ALPHA concepts exceed this spatial limit, but whether this is a problem or not depends on whether you think the ICF guidelines should apply to all (or even some) of the magneto-inertial fusion space.

A goal for Sandia is to work with the DOE/NNSA classification office to provide clearer guidance for a broader suite of pulsed inertial fusion systems. This will enable the DOE to make clear recommendations for what aspects (if any) of future magneto-inertial fusion research should be classified. This work will not require significant additional resources, but it will require broad support from the community and the Classification Office to make it happen. There is a Technical Evaluation Panel (TEP) that meets on a quarterly basis to discuss proposed changes to any classification guidance. Prior experience with this panel suggests that it will take 1-2 years for the community to accept changes. ARPA-E may be able to help this process by working with the DOE HQ personnel on the TEP.

---

[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Scale OMEGA platform to the NIF (Laser Driven MagLIF)

Under the assumption that the effort to scale MagLIF targets to OMEGA is successful, a natural next-stage goal would be to test the laser-driven version of MagLIF at the scale of the National Ignition Facility (NIF). While such targets would still absorb less energy than a comparable experiment on the Z facility, it would be a further development demonstrating the credibility of magneto-inertial fusion research and it would help engage a broader community in this area. Experimental parameters could be varied such as increasing the implosion velocity and exploring the limits of hydrodynamic stability. Furthermore, it may motivate the development of high repetition rate laser technology that could drive such targets at scales appropriate to fusion energy. As discussed below, interest in MagLIF has already helped to motivate planning for placing large external B fields (>10 T) on the NIF to enable magnetized target research.

There are two possible approaches for accomplishing this goal, which will require shot time on the NIF. The first would be to get this objective supported by the NNSA as part of its baseline approach to ICF. The second would be to make this objective part of the Discovery Science portfolio of the NIF. In either case, we would need support for the team's labor and the associated target fabrication. The ICF funding for NIF experiments does not typically cover the expenses of the research teams using it—they typically require their own grants or ICF funding support. If we assume that the existing team at the University of Rochester was leading this work then it would require an annual budget of $750-1000k. The system to place B fields on NIF is expected to receive support from the NNSA.

This effort would likely take three years to execute given a realistic number of shots per year and the need to iterate a few times. Given the schedule for the effort on OMEGA and the magnetic field system on the NIF, the earliest this effort could begin is FY18 or FY19. The sequence of events would parallel those on OMEGA: (1) establish and verify a preheat methodology, (2) establish an implosion methodology, and (3) conduct integrated scaling experiments to assess the scaling. We note that even on the NIF ignition would not be possible with this approach.

Test laser heating "at fusion scale" on the NIF (Pulsed Power Driven MagLIF)

A key goal of the current ALPHA project is to demonstrate a functional preheat capability for the Z-Beamlet laser coupling to MagLIF targets on Z, which will eventually require 6 to 10 kJ of heating to demonstrate the scaling of MagLIF from 19 to 25 MA. If Z achieves all of its objectives for MagLIF, there may be interest in demonstrating ignition and multi-MegaJoule fusion yields on a larger pulsed power facility in the future. Our current scaling studies [S.A. Slutz & R.A. Vesey, Phys. Rev. Lett. (2012); S.A. Slutz *et al.*, submitted for publication (2015)] suggest that up to 30 kJ of fuel heating may be needed at currents of ~60 MA. What this means is that in principle we can demonstrate the fuel heating at the scale needed for multi-MJ fusion yields *within 5 years* using the National Ignition Facility (one quad of NIF could supply the needed laser energy), and then use this knowledge to set requirements for a next-step facility.

A key necessity for such tests would be a magnetic field capability on the NIF that enables gas-filled targets to be magnetized at up to 30 Tesla fields. The ICF program budget for FY16 includes a small amount of money to begin working on a magnetic field capability for the NIF and a requirements-gathering workshop was held in October 2015 with participation from Sandia and the University of Rochester. It is likely that a capability could be operational on the NIF within 3 years. There is broad support for this capability both from the national ICF program and the NIF Discovery Science program.

Thus, one next-stage goal could be to demonstrate functional laser heating under conditions directly relevant to ignition-scale targets on the NIF, as a way of buying down risk and reducing uncertainties in scaling from 19-25 MA up to 45-60 MA. Such an effort would likely require about $1.5-1.8M/year to cover the labor costs at the National Laboratories. Potential sponsors for this work would be the NNSA and/or an ALPHA phase two project. Demonstrating adequate fuel heating prior to compression at the appropriate scale and lifetime is a key issue for most magneto-inertial fusion concepts today, and this work would lend credibility to the idea and significantly reduce the scientific risk associated with laser preheat.

Integrate functional laser preheating into 19-20 MA Z experiments

Our current ARPA-E grant includes funding to develop a functional laser preheat capability for Z using the Z-Beamlet and OMEGA-EP lasers, with the goal of coupling >1 kJ into the fusion fuel. It does not include funding for integrating this capability into full experiments on Z. We estimate that it will take about two years to develop a functional preheat capability (the duration of the grant) and then it will be ready for integration. Our expectation at this time is that the NNSA ICF program at Sandia will fund the Z experiments, since should such a capability be developed and shown to work well it would be used in 19-20 MA class experiments from 2018-2020. The main cost associated with the integration is the initial time and shots required to demonstrate the technique and its benefits on Z. The principal benefit of this work would be to further increase the credibility of magneto-inertial fusion. Our expectation today is that if we can successfully couple >1 kJ of energy into the fusion fuel at axial B fields of 10-30 Tesla (without significant losses during the implosion) the yield even at 19 MA should increase by 10x or more. This would be an excellent near-term starting point for scaling studies. As noted below, further scaling studies at higher currents (e.g., about 25 MA) would require more than 1 kJ to be coupled to the fuel and possibly additional research and/or capability upgrades on laser facilities to accomplish.

Demonstrate scaling from 19 MA to 25 MA

The initial integrated MagLIF experiments on Z were done with a peak current of about 19 MA and about 1 kJ of laser energy. To achieve the 100 kJ yields (or their DD equivalent) published in the 2010 paper [S.A. Slutz *et al.*, Phys. Plasmas (2010)] requires a peak current of 25-27 MA and 6-10 kJ of absorbed laser energy. (It also requires increasing the magnetic field strength from 10 T to 30 T, but this technology is being demonstrated now and poses minimal technical risk.) The initial experiments used the most direct and most conservative approach possible, which included relatively inefficient power-flow geometry in order to enable magnetic field uniformity to within ~0.1% throughout the target volume.

Simulations suggest that we can tolerate up to 50% variations because the laser heating pushes much of the magnetic flux toward the target walls, making it very insensitive to the initial conditions. By changing the magnetic field coil geometry we can optimize the pulsed power hardware design and our modeling suggests that we could achieve 25 MA currents within the next 5 years. The final piece toward demonstrating scaling on Z is demonstrating a higher level of laser heating (>6 kJ).

The hardware improvement effort has begun. We are currently working toward the development and testing of a new load hardware geometry and target that will allow us to reach 25 MA on Z with MagLIF as part of our driver-target coupling effort. This is expected to take about 6-10 shots per year for the next 3 years to achieve, which amounts to about $3.5M of effort in total, which will be supported by the NNSA ICF program on Z. In parallel, we are working on upgrades to the laser systems adjacent to Z. To reach 10 kJ, we would need to (1) install the full set of booster amplifier slabs into the Z-Beamlet laser to make it capable of 6 kJ in 4-6 ns, and (2) we would upgrade the optics for a second long-pulse laser system (known as "Z-Petawatt", but it would be used in long-pulse mode) to co-inject a full-aperture beam of ~4 kJ of energy at 1-omega. Neither of these two laser upgrades is funded at present—we are hoping that NNSA ICF funding in FY17 and beyond is sufficient to permit this. The requirements for functional laser heating developed as part of this ARPA-E effort will be critical for finalizing what is needed to demonstrate scaling from today's 19 MA experiments to 25 MA, but it is likely that there will be significant laser heating experiments necessary at the higher laser energy and power. It is difficult to estimate the total cost of this next step. The predicted yields under these conditions are 100-1000 kJ, which if achieved would be extremely motivational for both ICF and fusion energy.

Build an ignition-class "Z-next" facility

A clear next step for any pulsed inertial fusion effort claiming to be relevant for fusion energy is to demonstrate ignition and at least multi-MJ fusion yields, if not 10-100 MJ. It is our belief that the Z facility (after the investment noted above) will be capable of achieving about 100 kJ yields. Such yields, and the corresponding science underpinning it, would make a compelling case for pursuing ignition via magneto-inertial fusion methods. We estimate today that achieving ignition and ~10 MJ yields will require a ~300 TW, 45-50 MA pulsed power facility. The credibility of this estimate will be much higher if we demonstrate significant yields on Z (at ~80 TW, 25 MA) that are well modeled and understood. These yields are of interest to the NNSA at the single-shot level. While no facility was ever constructed to achieve the goal, studies in the late 1980s suggested interest for NNSA mission needs in a facility capable of order 1 GJ yields.

The cost of a multi-MJ yield facility is significant. Estimates for the pulsed power hardware alone are about $400k. However, it is likely that a new building will need to be constructed to house the pulsed power, and we do not yet have reliable estimates for the costs associated with handling tritium, beryllium, debris, radiation activation, and so on. It seems reasonable to assume that the total project cost will be >$1B. At this level, the most likely customer today would seem to be the NNSA. It is unclear whether other agencies such as the Department of Energy will be willing to invest in such a facility from a fusion energy perspective. We are currently pursuing a number of internal Laboratory Directed Research and Development initiatives to develop this project more fully. We are also using NNSA ICF and Science program funds to more carefully develop the NNSA mission needs and requirements to understand whether they are sufficiently compelling to justify the large cost of the facility.

Develop alternatives to laser heating and external magnetic field coils

As noted above, Sandia's initial MagLIF experiments were done in a very conservative geometry with the primary goal being to understand whether magneto-inertial fusion was promising. From a physics demonstration point of view, we believe that the use of large lasers and external magnetic field coils allows us the maximum flexibility and control—we can do a lot of development and testing that does not require a Z experiment. From a fusion energy perspective, however, the use of a large (~30 kJ) laser at repetition rates of 0.1-1 Hz for fuel heating might be challenging. The use of large external magnetic field coils to magnetize several cubic centimeter volumes likewise seems incompatible with 0.1-1 Hz rates.

We are currently exploring alternative methods to magnetize and heat fusion fuel prior to compression as more energy-relevant alternatives to our initial MagLIF experiments. These ideas are inherently riskier than the approach we started with and will require some development. Several of our ideas cannot be tested without using a pulsed power facility such as Z, which means the rate of progress of our understanding would be slower unless we had good models. Moreover, the classification status of some of our ideas is uncertain at this point (which is why we are emphasizing the need to revisit the classification guidance).

For example, one could use a "twisted" return-current can surrounding the MagLIF target to produce both Bz and B-theta components to the magnetic field. If the system was designed to enable significant diffusion of the field into the fuel region of the target prior to compression, this could be an alternative to the use of external magnetic field coils. In addition, such a system may have stability benefits since the external surface of the liner would experience a changing angle of rotation of the field as it imploded (caused by the changing B-theta to B-z ratio as a function of radius). One could also imagine injecting fuel that had been heated and magnetized using a variety of pulsed power methods into a liner target volume. Unlike systems with long implosion times that require closed field line geometries such as field reversed or compact toroid plasmas, the injected fuel need not have closed lines and indeed it could potentially be somewhat disordered.

This effort would largely be a target design development effort. It is one reason that our programs have emphasized understanding the underlying science and in developing predictive modeling tools. The current instantiation of MagLIF targets on Z and OMEGA are not the optimum designs for fusion energy, but they do represent a fast path toward demonstrating the credibility of this approach. It is not clear that alternatives to MagLIF will necessarily be of high priority to the NNSA, however, since they generally involve more risk and the baseline approach may be sufficient to reach the objectives of the ICF program. Thus, we feel that a robust effort in fusion-relevant target design, optimization, and associated physics studies may be more appropriate for energy-relevant agencies such as ARPA-E and/or the Department of Energy. An extended effort of ~$1.5M/year would allow computational studies to be done of alternative designs (using existing modeling tools). More effort would enable better tool development or possibly university collaborations to test some of the ideas directly. Successful modeling of the Omega and Z experiments will be essential to build confidence in our modeling.

Engage a broader university community in magneto-inertial fusion

A significant challenge for magneto-inertial fusion research is that it does not have a robust and established university community interested and engaged in the key problems of interest. The existing ARPA-E portfolio does a good job of engaging several universities that can contribute to this area, but the test capabilities of these universities is fairly rudimentary (with the exception of the University of Rochester, which has significant investment from the NNSA). Thus, doing work over an extended period of time at scales relevant to fusion energy could be a problem for universities. A second problem for university participation can be the classification guidance, applied both to experiments and to the codes capable of doing sophisticated modeling (e.g., FLASH).

There are some emerging ideas in the university community for building significant new capabilities that could be relevant to the long-term viability of magneto-inertial fusion research. One notion is to build a significant pulsed power capability (~10 MA) at the University of Rochester that could be coupled to the large lasers in the 4-beam OMEGA-EP facility (~5 kJ per beam and pulse widths from 1 ps to 10 ns). Such a facility, properly funded, could support a large university base through the model of the NNSA-funded NLUF program today. As noted above, many of the key concepts of ARPA-E could be studied on such a facility but with a higher shot rate than on larger facilities such as Z. A second idea is to build a Center of Excellence based around the University of California system. The heart of the Center could be a ~5 MA pulsed power driver and a modest (several hundred joule) laser system (moving the LANL Trident laser to UCSD is under discussion). Such a facility could again be oriented toward training students (and faculty) in skills and ideas relevant to magneto-inertial fusion.

The University of Rochester idea would likely cost in the ballpark of $100M to build and ~$10-15M/year to operate, and could well be a Department of Energy facility if sufficient support could be mustered (there is no reason that the entire University of Rochester's Laboratory for Laser Energetics could not be a DOE facility for magneto-inertial fusion and high energy density science not unlike the Princeton Plasma Physics Laboratory is for magnetic confinement fusion). The UCSD Center of Excellence would fit within the existing portfolio of NNSA Centers of Excellence, which typically run about $5M/year for 5 years.

Demonstrate driver architecture for a Z-next facility

The driver architecture proposed for a Z-next facility capable of multi-MJ fusion yields is the Linear Transformer Driver (LTD). This architecture consists of several bricks (two capacitors connected by a gas switch) in a circular array to produce voltage across a single cavity. Several cavities can be connected in series sharing a common central conductor to form a module. The output of several modules can be combined into a magnetically insulated transmission line section to deliver large currents to a target. Figure 1 illustrates the proposed LTD architecture for a Z-next. This architecture is about twice as efficient in delivering energy to a target as previous Marx-based systems such as Z and is described in a recent journal article [W.A. Stygar *et al.*, Phys. Rev. STAB (2015)].

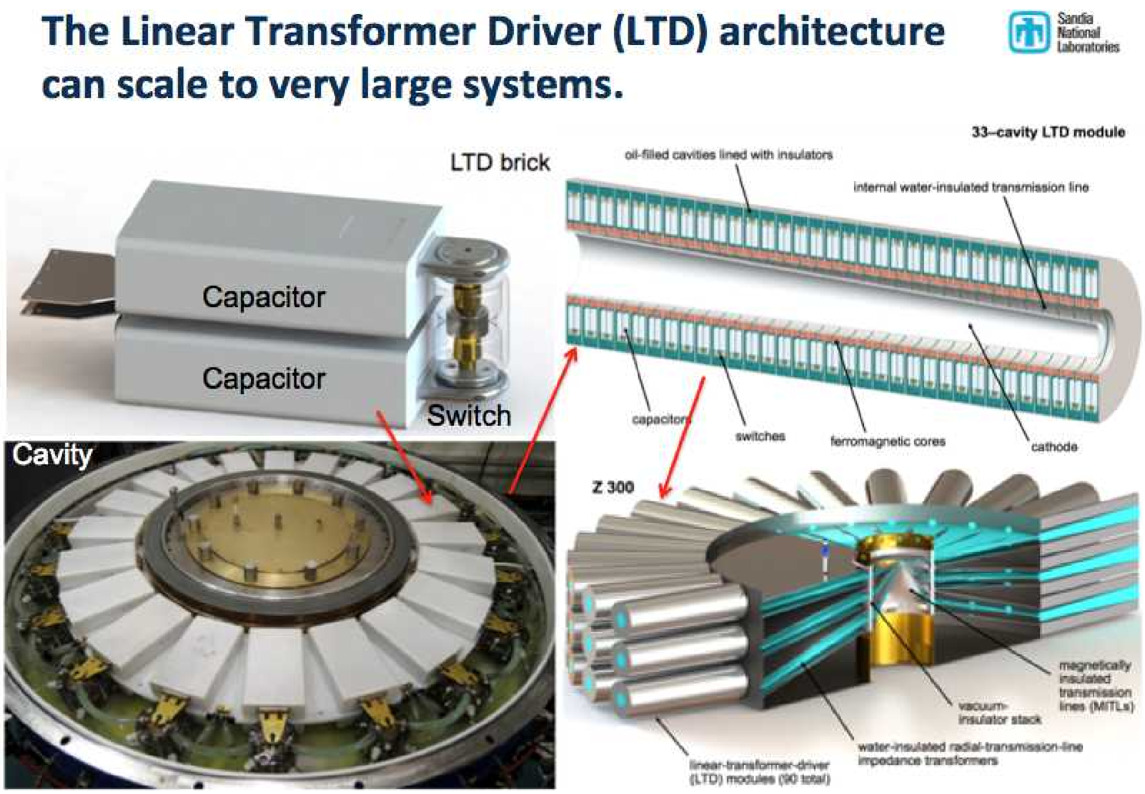

Figure 1: Illustration showing how components in Linear Transformer Driver technology scale to form a large pulsed power facility.

This driver technology has been under development for over a decade at an effort of ~$1M/year. The bricks shown in Figure 1 are the fourth generation of bricks and have been demonstrated to meet the power output (>5 GW) and lifetime requirements for a Z-next facility. Testing of the cavities using these bricks is currently underway and is going well. What remains to be demonstrated is the module and to work with industry so that the components can be fabricated at an acceptable cost while maintaining performance and reliability. We estimate that to build a 5-cavity module would require about $1.5M/year for three years. There is currently no program support for building this within the NNSA (historically Sandia spent “Campaign 3” dollars on pulsed power research but this funding is now being directed to support the Enhanced Capabilities for Subcritical Experiments effort). Our near-term plan is to seek Laboratory Directed Research and Development funding at Sandia for this effort. At one point the ARPA-E phase one call appeared to ask for the development of driver technology. If such a call should arise in the future we would propose that LTD technology development be considered with SNL, LLE and industry participation for at least some classes of magneto-inertial fusion (compression systems with 100 to 10,000 ns time scales).

Developing affordable driver solutions is critical to making progress in inertial fusion energy approaches. The traditional approach to ICF using large lasers like the NIF no longer seems likely to scale affordably to the 10-1000 MJ yield range needed for fusion energy. Due to its high energy coupling efficiency, pulsed power seems more attractive in this regard. The existing NIF stores 400 MJ of energy and might be able to achieve 0.1-1 MJ yields over the next ten years. By contrast, an 800-TW LTD facility would store about 100 MJ of energy and might be capable of a yield of order 1000 MJ, and thus the driver would be significantly cheaper (though the capabilities beyond the driver for handling such large yields would undoubtedly make it expensive). Concepts like MagLIF are critical to being able to make these more affordable drivers useful, but there will also have to be investment in the driver technology itself.

Demonstrate the use of tritium on large-scale pulsed power

No large-scale pulsed power systems have ever demonstrated the use of tritium fuel. Unlike large laser systems that typically vent their chambers no more frequently than once per month, all of the high-power pulsed power systems in the world vent their chamber after every experiment (~daily) and do manual refurbishment and target loading. This is true for facilities such as Z, and would also be true for many of the other pulsed fusion approaches in ARPA-E, at least during the development stages. Moreover, pulsed power systems often use significant amounts of water as a dielectric insulator that could potentially absorb some of the tritium. We believe that demonstrating the safe and efficient use of tritium on the existing Z facility is a necessary step to demonstrating its use on a next-step driver facility. The knowledge and experience gained on large laser facilities will not all transfer directly to pulsed power. It is likely not necessary to use 50/50 DT mixtures to achieve this goal—we believe getting to 1% T may be sufficient.

Another reason to use tritium on Z is to improve our diagnostics capabilities. The ICF community has invested a great deal of resources in developing diagnostics for the stagnated, fusing plasmas based on DT reactions that the magneto-inertial fusion community has not been able to benefit from. Our estimates suggest that even 1% T usage would enable experiments on Z to use many of these diagnostics and make better scientific measurements on MagLIF experiments. Such measurements may be important for understanding whether MagLIF is likely to scale well to higher-current facilities.

The use of tritium on Z is currently being explored as part of an existing 3-year LDRD at Sandia (FY16 is its final year). A path forward is being developed and the 2016 Z shot schedule includes one experiment using trace tritium late in the year. That experiment will use a containment system similar to that used in high-hazard dynamic materials experiments on Z. The goal is to understand where the tritium goes and how much work is needed to mitigate its spread and the hazards for the workers. Experiments within the last year with surrogate materials (DHe3) suggested that 99.4-99.8% of the T would likely be contained, but these values are at or near our detection/background limits for light gas tracer techniques. To avoid contaminating Z at low levels of tritium requires 99 to 99.9% of combined containment and purge efficiency, and at 50/50 DT mixtures we would need 99.99 to 99.999% of combined efficiency.

The existing LDRD is still estimating costs for this project. The costs will depend upon how far we want to go. The first option would sustain 2-4 experiments per year at <3% T with no major development required and would be achievable within the NNSA ICF program confines. Option two would target unlimited experiments per year at 3% T by 2020. Option three would target unlimited experiments per year at 50/50 DT by 2021. It is likely that the costs for Options two and three are significant and we anticipate making a decision along these lines at the end of 2017 after we have done a handful of trace tritium experiments. Potential systems requiring upgrades for options 2 & 3 include the HVAC system for Z, neutron shielding, a tritium capture system, new post-shot ventilation systems, and a tritium fill station. It is possible that this effort could go faster if tritium were a high priority—the 2020 to 2021 time scale is based on minimizing the perturbations to the existing shot schedule.

Explore laser-based fusion energy drivers

The National Ignition Facility is based on 192 high-power lasers. Research on taking high-power lasers to the high repetition rates for fusion energy was carried out as part of the LIFE program at LLNL and the HiPER project in Europe, based on diode pumped laser systems. An alternative approach is to use thousands of lower-power lasers, which may be easier to scale to the reliability and repetition rates needed for fusion energy. Such a system would have large system bandwidth to suppress laser-plasma instabilities and would be far more flexible and efficient than other laser concepts. One such concept has been proposed in the past, the "Star Driver," which takes advantage of multiple beamlets to provide beam smoothing and wavelength detuning to combat laser plasma instabilities such as cross beam energy transfer. If the targets at the University of Rochester are successful, as well as follow-on targets fielded on the National Ignition Facility as described above, a Star Driver type of laser facility might be exceptionally well suited for scaling the laser-driven MagLIF targets to ignition.

We would have to do more work on this option to understand the costs, but it could be an investment option for a DOE grant focused on driver technology. The "building block" of such a system would be of order one hundred joules, 50 GW and 1 kW peak and average power laser which has other commercial applications and could be developed by multiple universities and industry. A smaller version of this system could be used as the laser pre-heating source for a possible future MagLIF class energy system. Another standoff driver option that may prove to be viable with the lower intensities required for MagLIF is ion beams; the ALPHA project includes a study of new ion beam technology as a potential driver.

Both the LTD and laser-based driver development projects may realistically be viewed as second-order follow-on projects to many of the science-based scaling demonstration projects described above. The disadvantage of a linear progression of projects (science then drivers) may be the time it takes to reach a fusion energy solution. The advantage is that the country would only invest in driver development for promising approaches. This is a policy decision for the United States to make and we understand that the default position at the moment is to emphasize the science first. We include these potential projects mainly to make the full landscape clear.