IFE Science & Technology Community Strategic Planning Workshop Report

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Table of Contents:

1. Executive Summary

Fusion has incredible potential to provide energy for humanity, and interest is growing – among the public, federal stakeholders, the research community, and private industry. Inertial Fusion Energy (IFE) is a promising path towards fusion energy applications with a substantial community, existing scientific and technological basis, and U.S. leadership within the international community.

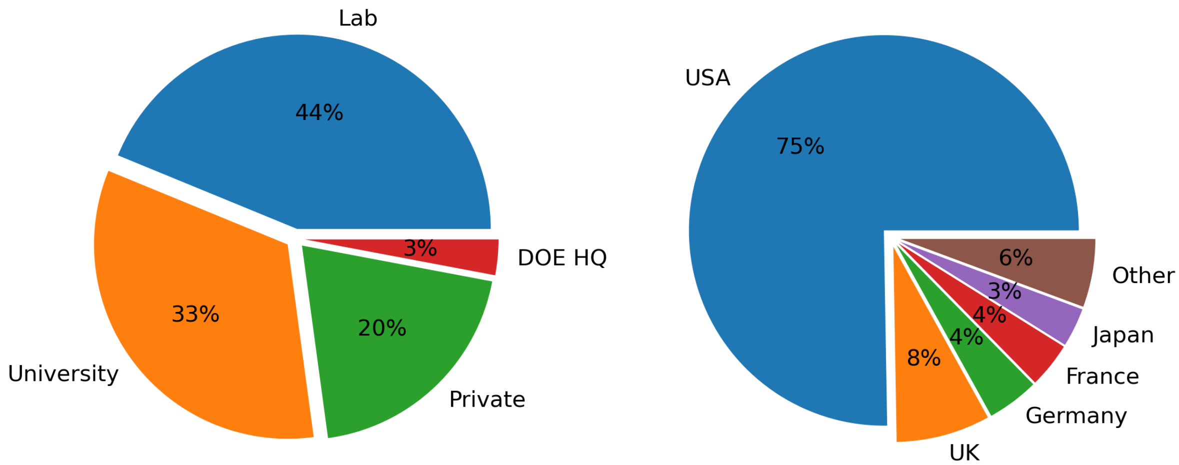
Now is the opportune time to evaluate a U.S. Inertial Fusion Energy program. While significant past work has been conducted into IFE, the lack of an established program in the last decade has hampered progress. Recent breakthrough experiments at the National Ignition Facility, producing more than a megajoule of fusion energy, clearly motivate the establishment of an IFE program now, as recommended by past studies [National Research Council 2013]. To that end the Department of Energy's Fusion Energy Science (FES) program within the Office of Science sponsored this community-led workshop. The charge for workshop attendees was twofold:

1) Assess near- and long-term research opportunities in inertial fusion energy, and the necessary high energy density physics and technologies.
2) Outline and develop a strategy for the HEDP, ICF, and IFE communities to work together.

The workshop endeavored to collect input from the *entire* community, spanning academia, national laboratories, industry, and private investors. Engaging all aspects of our community and leveraging their unique capabilities solidifies the foundation of future IFE work.

Steering and Program committees (see Appendix C) were assembled representing a diversity of institutions and perspectives to organize the workshop, which began with a kick-off meeting on November 16th, 2021. Subsequently a call for white papers was issued with over 80 submissions from the community (see Appendix B). The workshop was held from February 22 to 24, 2022, hosted virtually by LLNL. Content from the workshop is hosted on a website maintained by LLNL (https://lasers.llnl.gov/nif-workshops/ife-workshop-2022).

Participation was excellent, with over 300 registered attendees and over 200 active participants on WebEx during the majority of the meeting. Participants were predominantly from the United States and ¼ of the participants were international. They represent a wide range of institutions including national laboratories, universities, and private industry. Statistics on the workshop registrants are shown below.



Statistics on the registered participants. Left: type of institution, right: country of institution

The workshop included perspectives from sponsors, plenary technical talks, presentations of the quad charts from white-paper authors, and breakout sessions to discuss the communities perspective on critical issues for the establishment of a renewed program for IFE in the United States. Our community is energized to move boldly towards a future where we have made IFE into a reality, on a timescale appropriate to address major societal challenges including the transition to carbon-free energy.

This report summarizes:

- the technical content of the submitted white papers and workshop discussion representing the current status of the field;
- the breakout session discussions held at the workshop on key questions for the program;,
- key observations and recommendations.

2. Technical summary

The following sections summarize the technical landscape of IFE, highlighting contributions to the workshop, organized by subject area.

2.1 General and cross-cutting

A reactor is a system which must economically produce output power. During the Workshop breakout sessions, a recurring theme was the suggestion to evaluate fusion approaches at a systems level. Numerous system studies for an IFE reactor have been performed in the past (e.g. OSIRIS, SOMBRERO, LIFE, Hylife-II). This system typically requires a core in which the fusion target produces a gain G (output fusion energy over input driver energy). A fusion power system is generally characterized by the fusion gain (G = output fusion energy / input driver energy), driver electrical efficiency (η), blanket multiplication factor (M), and the efficiency of converting fusion energy (heat) into electricity (ε). It is normally assumed that the sum of all power requirements other than the driver input power is small compared to the driver input power. If f is the fraction of the gross electrical power that must be used to drive the driver, $f = 1/\eta GM\varepsilon$, and is commonly thought to be less than ≈ 0.2. For typical but not fundamental assumptions for M and ε, it is usually assumed that the product ηG should satisfy $\eta G > 10$ for an economically attractive reactor. Clearly there is an important trade-off between driver electrical efficiency and fusion target gain. Another key aspect of the fusion system is its repetition rate, which is determined by a combination of the driver technology considered, clearing of the reactor chamber, the target yield and desired electrical output of the reactor. As for conventional baseload electrical power systems, the capital cost of the plant can be amortized over the lifetime of the fusion power plant but must be cost competitive. Beyond electricity, there are other potential markets for IFE systems including hydrogen production, industrial heat, propulsion, etc. Several white papers submitted to the workshop covered these considerations in general or for specific approaches [Bangerter WP, Dunne WP, Galloway WP, Obenschain WP].

The majority of white papers covered specific important scientific or technological problems to be addressed, which will be discussed in the following sections. Several areas of cross-cutting importance emerged from the white papers and will be further mentioned in the following sections. These include the application of ‘artificial intelligence’ or ‘machine learning’ techniques to various aspects of the system [Gopalaswamy WP, Mariscal WP, Scott WP]. Workforce development in the relevant disciplines to support a robust IFE program is also key [Simpson WP].

Many white papers covered facility capabilities; while there are many reactor concepts, here we briefly identify some capabilities applicable to near-term IFE science and technology development. These include current facilities with application to IFE-relevant studies [Di Nicola

WP, LaserNetUS WP, Le Pape WP, Obst-Huebl WP, Tikhonchuk WP], and near-term future capabilities that are either in progress, planned, or proposed [Ditmire WP, Dyer WP, Heuer WP, Kodama WP, Schenkel WP].

Lastly, an important aspect to the success of an IFE program is its organizational structure, philosophy, and focus. Significant discussion at the workshop occurred on these topics and will be discussed in the breakout session summaries, and such topics were also covered in several submitted white papers [Bodner WP, Dunne WP, Tang WP].

2.2 Targets

2.2.1 Target designs

Twenty-one white papers addressed varying IFE-relevant target designs and related physics or improved modeling for predictive capability. For economic reasons, IFE applications require the product of the electrical wall plug efficiency, η, and the target fusion gain, G, to exceed a minimum of roughly, ηG > 10. [Goncharov WP, Olson WP, Albright WP]. Indeed, this requirement is a distinguishing characteristic of IFE vs ICF. For ICF, high yield is the fundamental requirement; while high gain may be a practical route to high yield, the system efficiency is unimportant. Several approaches to target design are presently being explored in the context of implosion experiments with the goal of high yield including indirect drive at the NIF, direct drive at the OMEGA facility, and magnetic liner fusion experiments at the Z-facility. The closest approach to obtaining G=1 laser indirect drive (LID), which in August 2021 achieved G = 0.7 at the National Ignition Facility, a significant milestone towards high gain. This result was obtained after nearly a decade of effort during which the indirect-drive campaigns focused on managing symmetry and stability, improving target quality and reducing variability in laser delivery [Callahan WP, Hurricane WP].

While these experiments are an important and significant milestone demonstrating ignition, significantly higher gains of the order of ~100 (assuming a wall plug efficiency of ~10%) are needed for an IFE plant. Increasing the gain in indirect drive (and also the traditional direct drive approach) can be achieved by going to bigger targets and larger laser drivers, increasing the amount of fuel used up in fusion reactions during the implosion (also known as the burn-up fraction), which in turn relies on increasing the compression or lowering the entropy of the fuel, and/or increasing the coupling efficiency. Alternate schemes that separate the formation of the hotspot from compression, such as shock and fast-ignition also hold promise of higher gains.

Varying the entropy of the target to achieve higher yields has been explored in indirect- and direct-drive on the NIF and the OMEGA laser. Larger deviations, in both direct- and indirect-drive, between predictions and observations are observed for these higher compression, lower entropy implosions that are more aligned with IFE, indicating incomplete understanding of physics. These observations indicate the need for improving predictive capability in order to extrapolate from ongoing ICF experiments on OMEGA and the NIF to a IFE-demo facility [Hurricane WP, Goncharov WP]. Research into target physics, using a variety of tools including simplistic models [Callahan WP], detailed simulations, statistical and data-analysis techniques, and focused experiments are of the highest importance. Regardless of the approach(es) that is pursued, a program grounded in experiments that systematically seeks to improve implosion performance is critical to charting the path toward an IFE pilot-plant. Each path will also require a demonstration of ignition, burn and gain at least greater than one to validate target physics.

IFE relevant target designs are closely coupled with the choice of the driver. Regardless of the driver, target designs need to be robust, tolerant of target imperfections and engineering limitations of the driver that can seed hydrodynamic instability growth and limit performance. To reduce risk, it could be beneficial for an IFE demo facility to be flexible and not be tied into one particular target design. This is easy to imagine for some approaches where multiple fusion chambers with very different illumination geometries could be driven with a single driver and a switchyard.

The different approaches to target designs are discussed below:

Laser driven designs

Laser-driven approaches offer the flexibility of different types of target designs, i.e. the choice of the laser power as a function of time, beam incidence angles, beam wavelengths, and the choice of target materials.

Traditional hotspot implosions are the most studied design in both x-ray and direct-drive. In these types of implosions, the laser launches shocks setting the main fuel layer on the desired adiabat profile that mitigates nonuniformity growth at the ablation surface while retaining the compressibility on the inside of the fuel layer. The kinetic energy of the implosion is converted into the internal energy of the hot spot where fusion reactions begin. Fuel compression and the desired velocity of the imploding shell have to be achieved simultaneously in the traditional hotspot implosions to obtain high gain. Neither x-ray nor direct-drive have simultaneously achieved high compression and high implosion velocity thus far, limiting the achieved target gain.

Direct drive couples ~4x more energy than indirect-drive at 351 nm. As mentioned earlier, higher gains can potentially be obtained by increasing coupling efficiency; at 193 nm ~6x more energy can be coupled into the target from the laser. Direct-drive is thus an attractive option for an IFE power plant. The target is also simple, comprising a spherical shell enclosing fuel. For indirect-drive on the other hand, the targets are complex, requiring a hohlraum to enclose a spherical fuel capsule. However, this same complexity can potentially shield the fuel capsule from the hostile IFE chamber environment. Aside from coupling physics, the two approaches have different perturbation growth behavior. The higher mass ablation rate for indirect-drive makes it less sensitive to Rayleigh-Taylor growth, which can significantly compromise performance. Trade-offs between the two approaches indicate that more studies are needed to choose an IFE-relevant approach.

Increasing emphasis on six broad thrust areas of research listed below will accelerate the identification of IFE relevant target designs for both these approaches. These include:

a) Identify and mitigate the seeds for hydrodynamic instability and asymmetry growth [Callahan WP, Goncharov WP, Hu WP, Hurricane WP]

b) Mitigate the hydrodynamic instability growth rates [Hu WP, Olson WP, Anderson WP]

c) Understand and mitigate Laser Plasma Interactions [Anderson, WP, Goncharov WP]

d) Model material properties such as equations-of-state, and transport properties such as opacities and heat conduction; validate these properties through targeted experiments. [Goncharov WP, Hurricane WP, Malko WP, Ogitsu WP]

e) Improve integrated modeling capabilities including the role of LPI, material properties, kinetic effects etc. [Goncharov WP, Sherlock WP]

f) Use data-driven and machine learning approaches to accelerate implosion performance improvements [Gopalaswamy WP, Mariscal WP]

A) Indirect (x-ray) drive

The target design which obtained a burning plasma is substantially different from the low-entropy design originally planned for the NIF. That design, which was based on radiation hydrodynamic simulations and predicted high gain [Hurricane WP], relied on precisely timing four shocks to set up an entropy profile in the target. Many unanticipated engineering and physics issues that compromised target performance. Getting to the G=0.7 implosion required a decade-long process where both physics and the role of engineering features were systematically studied to improve upon the designs. Continued improvement required several iterations between design and experiment to identify the limits of a design, which in turn fed back into newer designs [Callahan WP], including the Hybrid-E design [Zylstra 2022, Kritcher 2022], which resulted in a record yield on the NIF. While it is more robust and tolerant than the original NIF design, it still sits on a cliff where small changes in input have been shown to produce large changes in the fusion yield.

IFE target designs need to be robust and produce repeatable yields. Simple models such as multiple pistons on a single hotspot have been used to explain the performance of the NIF indirect-drive implosions. Using these models to extrapolate designs to the IFE relevant regime, and simulating these designs with state-of-the-art codes is the first step toward identifying IFE-relevant designs using indirect-drive [Callahan WP].

B) Direct Drive

Several design variations are being studied for laser direct drive (LDD), with the goal of identifying a robust design tolerant of uncertainties in physics and engineering imperfections that could otherwise lead to nonuniformity growth.

Traditional hotspot implosions

Proof-of-principle ignition relevant direct drive designs are primarily explored on the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics. Several gaps exist in scaling direct-drive fusion yields to IFE relevant gains. The first is the effect of Laser-Plasma Interactions (LPI) on target drive. LPI effects such as Cross Beam Energy Transfer (CBET) reduce the ablation pressure and implosion velocity of the imploding shell. The interaction of the laser with plasma waves result in energetic electrons that preheat the imploding shell reducing compression. The various LPI effects scale with the scale-length in the corona of implosions. This indicates that these phenomena need to be mitigated with increasing target size and therefore increasing driver size. Wavelength detuning, as a technique to mitigate CBET has been demonstrated on the NIF [Marozas 2018]. Varying the ratio of the beam-size to that of the target is another technique used to reduce the overlap of the laser beams and therefore mitigate CBET. This has also been demonstrated as a technique to recover implosion velocity. Further control will increase the robustness of the target design. The second effect, that of preheat of the compressed fuel from energetic electrons produced in the corona, also needs further research. Modifying the target by embedding Silicon layers in the ablator has resulted in reduced levels of preheat in OMEGA and NIF implosions. These types of studies in cryogenic, ignition-relevant implosions will continue on OMEGA.

The seeding by laser speckles onto the target surface and subsequent Rayleigh-Taylor growth is another challenge faced by direct-drive. Again, laser and target solutions have been identified. Laser beam smoothing using induced spatial incoherence [ISI; Lehmberg 1987] and advanced further by utility with excimer lasers showed nonuniformities much less than 1% could be realized. Smoothing by Spectral Dispersion [SSD; Skupsky 1989, Rothenberg 1997, Skupsky 1999] and laser beam polarization [DPR; Kato 1984, Gunderman 1990] are used at Omega for high-performing direct-drive implosions. Further research on the adequacy of these techniques for high gain designs is required to push direct-drive into the IFE relevant space. Target solutions to mitigate the effect of laser imprint include the use of low-density foams [Hu WP, Olson WP] to reduce the in-flight instability growth.

For some laser architectures the beam size can potentially be changed during the course of the laser pulse [Igumenschev 2013, Froula 2013]. This permits the necessary early-time beam-overlap reducing the seeds for laser imprint while reducing the beam overlap and thus CBET during the later parts of the laser pulse. Focal zooming, the ability to change the laser beam size during the drive pulse has been demonstrated with excimer laser technologies [Kehne 2013].

Simulations indicate that broadband laser irradiation can mitigate and even suppress LPI, as well as improve target irradiation uniformity [Zuegel WP]. A bandwidth $\Delta\omega/\omega \leq 1.5\%$ can mitigate cross-beam energy transfer (CBET) and increase the laser absorption resulting in higher drive pressures, mitigate hot-electron generation at ignition intensities, and eliminate imprint asymptotically within a few picoseconds. Broadband ultraviolet lasers promise a path to LPI-free and robust direct-drive implosions, potentially including shock ignition. Further research through simulations and proof-of-principle demonstrations are critical to chart the path to IFE.

Shock ignition

Shock Ignition (SI) has primarily been studied using the direct-drive approach [Goncharov WP] though concepts for indirect-drive have been proposed [Anderson WP]. The compression phase is separated from the ignitor phase in shock ignition. In SI designs, the fuel is first assembled by a lower-intensity pulse. A well-timed high-intensity spike laser-pulse that drives a strong shock follows this low-intensity laser pulse, increasing the hotspot pressure and temperature. SI has a significant advantage over the traditional hotspot approach as it allows for greater compression and therefore higher fusion gain for the same laser energy. The potential for high gain from SI would allow for a lower shot rate, thereby reducing the quantity of target shots per day and/or a smaller laser facility operating at the same shot rate, both of which would reduce IFE facility operating costs.

SI designs are typically slower than the traditional implosions. As a result, they are less susceptible to the short wavelength hydrodynamic instabilities than hotspot implosions. Previous research into SI experiments on OMEGA using implosions and solid spheres on both OMEGA and the NIF indicate promising results in terms of fuel assembly and the strength of the ignitor shock.

However, several LPI effects can influence the strength of the shock launched by the high intensity ignitor pulse. These are being studied in planar and spherical geometry at several facilities including OMEGA, OMEGA-EP, NIF, LMJ-PETAL, PALS, Vulcan, and LULI2000. Depending on the parameter space explored, these studies indicate losses from several mechanisms like convective stimulated Raman scattering (SRS) and two plasmon decay (TPD). Modeling reproduces the strength of the shock in solid-sphere experiments, characterized by scale lengths shorter than those in implosions. Demonstrating proof-of-principle implosions, where LPI effects might be more significant during the ignitor pulse, is a critical next step for shock-ignition.

Fast ignition

In the fast ignition (FI) fusion concept [Tabak 1994], ignition and thermonuclear burn are achieved in two separate steps: (1) the compression and assembly of high density fusion fuel, and (2) the rapid (isochoric) heating of a hot spot in the fuel to ignition conditions, allowing for propagation of a burn front into the remaining fuel. FI uses separate drivers for compression and ignition, allowing for maximal control and optimization of each. This approach to IFE avoids difficulties with conventional hot-spot laser fusion, where the same driver compresses the fuel and shock-heats its center to ignite a burn wave, requiring precise spatial symmetry, temporal pulse shaping, and timing. Rapid advances in high-intensity laser technology and its application to laser-generated ion and electron beams makes FI a promising approach for IFE. Another attractive feature of FI is the ability to manage risk by decoupling compression studies from driver studies, allowing essential R&D on drivers to be proven on smaller-scale facilities such as the various LaserNetUS sites before moving to large-scale integrated facilities. This enables greater confidence and robust risk mitigation.

For FI fuel assembly, the cold DT fuel properties are set by requirements for gain and burn efficiency. To achieve gains of 100, as needed for IFE, basic ϱR scalings [Lindl 1995] for burn efficiency indicate that dense (~500 g/cm^3) DT fuel must be assembled with fuel ϱR 3-5 g/cm^2 and a cold fuel mass of order 450-2000 mg [Albright WP]. Such targets have not been demonstrated experimentally, however computational design studies of the assembly of fuel for FI have been performed [see, e.g., Clark and Tabak 2007], providing guidance for the types of laser drivers and energies needed. If facility time were available, studies in fuel assembly using laser drivers such as OMEGA and the NIF would be valuable for retiring risk in fuel assembly, especially in the presence of reentrant cones, as needed for TNSA proton- and deuteron-driven FI and some electron FI concepts. LPI control is a common need for all laser-driven IFE approaches, including FI. Of importance in fuel assembly is controlling the various LPI processes that can arise, including stimulated Brillouin scattering (SBS), SRS, TPD, and CBET; in FI the compression driver can potentially operate at lower intensity than hot-spot designs [Albright WP]. Existing LaserNetUS are, and novel facilities such as the proposed IFE laser facility at the University of Texas, Austin, [Ditmire WP] would be instrumental in conducting studies of LPI mitigation and control for FI.

For hot spot heating, a minimum hot spot ϱR of 0.5 g/cm^2 [Atzeni and Meyer-ter-Vehn 2004] implies a minimum hot spot radius of order 10 microns, though practical considerations for beam focusing suggest radii of order 20 microns or more [Kemp WP] might be more applicable to some FI approaches. To raise DT fuel to ignition conditions (of order 10 keV), the minimum charged particle beam energy would be of order 10 kJ or more [Albright WP]. This energy must be delivered over 20 ps or less to beat hot spot fuel disassembly and losses to conduction and radiation. Assuming 10% efficiency can be achieved for generating the ion or electron beams for FI, this implies ~100 kJ or more of laser energy per pulse in the high-intensity short pulse laser beam, or, for a system operating at 10 Hz, MW-class average powers. (Note: 15-20% wall plug efficiency might be feasible using solid state short pulse lasers with complete conversion to generate ions and/or electrons; this would decrease the required average power by a factor of 1.5 to 2.) These are challenges for FI, however there is cause for optimism that these requirements can be met with focused R&D in these areas.

A robust FI research program would also be supported by recent dramatic advances in modeling and simulation using radhydro codes as well as explicit and hybrid PIC codes [Wilks WP]. The FI problem is inherently multi-scale, necessitating efficient computer models [Kemp WP, Sherlock WP]. Exascale supercomputing offers opportunities for modeling of these systems at unprecedented fidelity. PIC and hybrid PIC codes use these high performance computational resources efficiently and scale well to large numbers of computational cores. The co-maturation of these techniques and computational platforms is a distinct advantage for FI specifically and IFE more broadly.

Ion Fast Ignition

Ion fast ignition (IFI), where the isochoric heating occurs with high-intensity-laser-generated or accelerator generated ion beams, is a specific approach to FI [Wilks WP, Obst-Huebl WP, Albright WP]. Laser-generated proton or deuteron beams created through the TNSA process are the most mature (highest TRL) approach at the present time. This approach to IFI employs a reentrant cone [Key 2006] to guide the propagation of the ion beam to the hot spot. Such cones present a complication for target fabrication and fuel assembly, as well as raise other questions (e.g., plasma filling and field generation inside the cone and the associated effects on ion beam generation and transport). Alternative, lower TRL ion acceleration techniques may also be promising and worthy of investment in a robust IFE program, especially if complications from the cone prove difficult. These include the generation of high-Z ion beams using TNSA [Obst-Huebl WP] and other acceleration mechanisms such as RPA, BOA, and ISWA [Albright WP].

To realize high gain IFI, several technological hurdles must be overcome, though recent advances in laser-generated ion source technologies justify optimism that these challenges can be met within the timeline of a focused IFE program [Obst-Huebl WP]. These advances include the successful demonstration of focusing of TNSA generated protons [Patel 2003] in cone geometry [Bartal 2012], as needed for IFI, as well as the development of a variety of target conditioning techniques to increase TNSA proton generation efficiency. Several advances in the development of high-Z ion beams are also promising. Of particular note are key developments on the path for scaling ion beams to the sizes needed for IFE applications [Wilks WP, Obst-Huebl WP], such as the application of NIF-ARC facility to creating high-current laser-generated proton beams [Mariscal 2019], the successful demonstration of the beam combiner concept at NIF, i.e., a path toward the generation of high-power, high-intensity laser pulse that could, through the use of a Brillouin amplifier, convert a majority of this laser light to a 120 kJ short pulse “Mega-beam” [Kirkwood WP], and the discovery of novel laser architectures such as Tm:YLF lasers capable of sustaining MW-class average power in the short pulse beam [Tamer 2021]. Moreover, there is a plan underway to build an academic IFE high energy laser research facility at the University of Texas, Austin, that is ideally suited for IFI R&D [Ditmire WP]. These developments point to the scalability of ion source technology to larger scale, as needed for IFI.

Ion transport and WDM stopping studies would be of high importance to an IFI program [Wilks WP, Obst-Huebl WP] since ion stopping powers in these dense plasma regimes are not well understood and represent a significant source of uncertainty in terms of the sizes of drivers needed. These studies are well suited for current experimental facilities such as BELLA and other LaserNetUS sites.

Several R&D gaps exist before realization of the IFI IFE concept and addressing these gaps would be the highest priority for an IFE program in IFI. These include:

- Assembly of a cryo DT target to the required density and ρR for a capsule with a reentrant cone
- High efficiency rep-rated driver and short-pulse heater laser beam technology
- Assessment of laser-plasma instability risks in the driver and evaluation of efficacy of options for control and mitigation of LPI in IFI drivers (e.g., green light, direct drive)
- Assessment of TNSA acceleration of protons or deuterons at high laser energy within cone geometry. Demonstration that the required efficiency and focusability can be maintained at the scale needed for IFI.
- Evaluation of candidate high-intensity, high-average-power rep-rated laser options for generation of the ion beams (DPSSL, plasma beam combiner “Megabeams,” etc.)
- If TNSA proton or deuteron IFI is not possible, demonstration of necessary energy, energy spread, and focusability using alternative acceleration techniques for high-Z ions.
- Evaluation of various efficiency improvement technologies to IFI ion beam generation
- Demonstration of robustness and reproducibility of IFI ion generation schemes
- Diagnostics for assessing performance of driver and ion heater beams.

Electron Fast Ignition

The electron fast ignition approach to FI [Kemp WP] uses high-intensity-laser-generated 1-3 MeV electron beams to heat the fusion hot spot. The deposition of energy could proceed through Coulomb collisions or through other processes, such as shock heating, multi-beam kinetic processes to heat the compressed core, or hybrid ion-beam/electron-beam heating approaches. This approach has the advantage of higher conversion efficiency (laser energy to electrons in the

1-3 MeV range needed for heating) than IFI, translating to smaller required short-pulse laser driver energy (as low as 50 kJ). However, to realize these advantages, the major challenge to be overcome with this approach is to control the electron beam divergence in order to avoid the requirement of heating a prohibitively large hot spot to ignition conditions.

Novel developments experimentally and in computer simulations [Kemp WP] show that precise externally applied magnetic fields or magnetic fields from targets engineered with resistivity gradients can guide electron beams magnetically, lowering the driver laser energy requirements dramatically. If supported within a broader IFE program, a dedicated electron beam FI study to determine the limits of beam divergence control could be undertaken on facilities such as NIF-ARC, Omega-EP, LFEX, and GEKKO, and be guided by large-scale computer simulations.

R&D gaps for the electron fast ignition concept discussed in [Kemp WP] include:

- Assessment of the feasibility of efficiently generating and focusing an electron beam with the characteristics required to heat a compressed ICF core.
- Can we design, build, and demonstrate such an electron source in the Laboratory?
- Development of electron FI designs that can assemble or maintain functionality of a focused electron source in a realistic implosion.

MagLIF designs

Pulsed power targets, also known as magnetic direct drive (MDD) targets [Cuneo 2012], are typically cylindrical in shape, as cylindrical is the natural geometry for the implosion-driving magnetic field. A class of cylindrical targets that has generated a lot of interest over the past decade is that of the magnetized liner inertial fusion (MagLIF) program on the 30-MA Z pulsed power facility at Sandia National Laboratories [Slutz 2010; Cuneo 2012; Gomez 2014; Gomez 2020; Sinars 2020; Gomez Kickoff Meeting Talk].

A MagLIF target consists of a solid-metal tube called a “liner”. Contained within the hollow metal tube is the D or DT fuel. This fuel is premagnetized with an axial field that rises from 0 to 10-30 T over a relatively long timescale (several ms). Once the fuel is premagnetized, the Z machine is fired to start the implosion. The implosion-driving magnetic pressure is generated by a fast azimuthal magnetic field, which is generated by the Z machine's fast current pulse running axially along the metal liner’s outer surface. This drive pressure is transmitted through the liner wall, often resulting in a shocked liner. As the shockwave breaks out from the liner’s inner surface, and thus the liner’s inner surface begins to implode, the fuel is quickly preheated to ~200 eV by applying a few-ns, few-kJ laser pulse, supplied by the green (527-nm) Z Beamlet Laser (ZBL). The Z machine then continues to drive the liner implosion over a ~50-100 ns timescale, compressing the fuel to near solid density, and further heating the fuel to fusion-relevant temperatures (above a few keV [Hansen 2015]).

During the implosion, the preheated fuel remains hot due to the magneto-thermal insulation provided by the pre-applied axial magnetic field, which gets amplified to >1000 T during the implosion via magnetic flux compression. The flux compressed field also helps trap charged fusion products in the fuel such that the products (e.g., alpha particles) deposit their kinetic energy into the compressed fuel and contribute to fusion self heating [Schmit 2014; Knapp 2015]. The fusion burn occurs at stagnation and lasts ~1 ns.

Presently, on today's Z facility, MagLIF liners have a height of ~10 mm, an initial radius of ~3 mm, and an initial shell (or wall) thickness of ~0.5 mm. The liner material is usually a low-atomic-number metal, such as beryllium, to prevent excessive radiation losses, should some liner material mix into the hot fuel. Previous experiments have tested beryllium and aluminum liners, while lithium liners are of potential future interest.

MagLIF targets include a laser entrance hole at the top of the liner, which is covered by a plastic window. The purpose of the window is to contain the pressurized fusion fuel (gas) while also allowing the laser pulse to enter the target and preheat the fuel. This window must be thin enough and transparent enough to not absorb too much of the laser energy, while also being thick enough and strong enough to contain the pressurized fusion fuel (presently ~60 psi for an initial fuel density of 0.7 mg/cc). These windows are often made from clear plastic materials, such as polyimide, with thicknesses of 1-4 microns [Gomez 2015]. The gas fill tube (for filling the liner with fusion fuel) is attached to the bottom of the liner.

The liner's initial aspect ratio (AR) is defined as the initial radius divided by the wall thickness. The targets being explored on today's Z facility use AR~6 liners. The purpose of the relatively thick liner wall (and thus the relatively low AR) is to mitigate the deleterious effects of the magneto-Rayleigh-Taylor instability (MRTI), which can grow to large amplitudes during the implosion [Sinars 2010; McBride 2012; Awe 2013]. The initial AR value is one measure of how robust the liner is to MRTI. Simulations predict a broad optimum in fusion performance near AR=6. Note that for much higher AR values, the liner becomes too unstable to MRTI, while for much smaller AR values, the liner implosion becomes too inefficient.

Present-day MagLIF targets often have a thin dielectric coating applied to the liner's outer surface. The purpose of this coating is to tamp down the expansion and redistribution of low-density liner mass that overheats and explodes away from the liner's outer surface due to the so-called electro-thermal instability (ETI). This ETI-driven explosion and mass redistribution establishes correlated density perturbations along the liner's outer surface. These density perturbations are believed to seed the MRTI growth. The benefits of thin dielectric coatings have been demonstrated in simulations and experiments [Peterson 2014; Awe 2016].

For IFE applications, several modifications to present-day MagLIF targets could be of interest. For example, present-day MagLIF experiments require large Helmholtz-like coils to supply the pre-imposed axial magnetic field. These large, expensive coils must be replaced on every shot. Thus, a target that generates its own axial magnetic field for magneto-thermal insulation and alpha trapping would be of interest. Such targets (called "AutoMag" targets) have been explored recently at Sandia in both simulation [Slutz 2017] and experiment [Shipley 2022]. AutoMag targets consist of metal liners with helical slots removed from the liner wall, forming a solenoid-like liner. These helical slots are filled with dielectric material to contain the pressurized fusion fuel. The resulting helical liner forces the Z machine's electrical current to follow a helical path along the length of the liner and thus generate an axial magnetic field within the fuel. This axial field is then compressed as the AutoMag liner implodes.

Another important concept modification would be to find a way to use the pulsed power driver itself to preheat the fusion fuel, rather than requiring a large, expensive, auxiliary laser system such as the Z Beamlet Laser (ZBL).

Another important issue for future IFE applications is generating higher fusion gains. This could be accomplished by using a cryogenic layer of frozen DT "ice" along the liner's inner surface. The performance of such high-gain targets has been explored computationally, where single-shot fusion yields vary with the drive current. A drive current of particular interest for a future pulsed power facility is about 65 MA, where simulations predict a 7-GJ fusion yield and an overall facility gain of 70 (total fusion energy out divided by total electrical energy stored in the facility's capacitors) [Slutz 2012; Slutz 2016; Slutz 2022]. Additionally, the feasibility of fabricating such high-gain targets has been explored in theory and experiment [Slutz 2022].

Ultimately, high-gain targets would have to be physically connected to transmission lines (electrodes) that are destroyed on every shot out to a radius of several feet. Thus, for IFE applications, assemblies consisting of a pre-vacuum-pumped section of transmission line, complete with a preinstalled liner target, would have to be fabricated, installed, cleared, and replaced for every shot [Bott-Suzuki WP]. Additionally, the materials would have to be recovered and recycled to avoid excessive waste and cost (thus, these transmission lines are often called recyclable transmission lines, or RTLs). To realize an IFE power plant operating at 0.1-1 GW, these coupled high-gain target-RTL assemblies would have to be fabricated, installed, cleared, and recovered every 10 seconds (i.e., a system rep-rate of 0.1 Hz). Thus, robotics would need to be utilized. It should be noted that a Ford F-150 door, with complex stamped metal shapes, can be fabricated every few seconds using advanced robotics. Nevertheless, the engineering challenges associated with IFE target production at high rep-rates are significant and should not be understated, regardless of the IFE concept, target type, or driver technology [Bott-Suzuki WP].

In general, pulsed-power-driven cylindrical targets are advantageous in that their driver-target energy coupling efficiency can be quite high relative to other ICF/IFE concepts/drivers (see Section 2.3.3, "Pulsed Power"). However, pulsed power targets must be physically connected to electrodes, and in terms of volumetric compression, cylindrical implosions are not as efficient as spherical implosions. Thus, there are tradeoffs that must be assessed when developing full-scale IFE systems. An IFE program should explore such tradeoffs [Bott-Suzuki WP].

Heavy ion fusion designs

For heavy ion fusion, various ignition modes (hot spot, fast ignition and shock ignition) and compression (indirect and direct drive) modes have been explored. In each case, the range of the beam ions must be compatible with target geometry so that the driver beam ions stop in the target. The energy deposition, via electronic and nuclear stopping, occurs in the outer layer of the fuel capsule (direct drive), or in converter material of the hohlraum of an indirectly driven target. For HIF, the desired ion range is $0.03 < R < 3$ gm/cm^2. Heavy ions are preferred compared to protons or light ions because for a given range and desired total beam energy, the heavy ion beam pulse will have a lower current than light ions, making it easier to focus. And since the range scales approximately as the projectile Z^2, heavy ions at a given kinetic energy will have a shorter range than light ions. One feature of HIF target physics is that the challenge of LPI is absent. It has seemed unlikely that there would be instabilities strong enough to deflect the heavy ion beams significantly, especially for $E > 5$ GeV.

Early direct-drive target simulations showed a gain of $100 < G < 300$ for a total beam energy of 1-2 MJ [Bangerter WP]. As is the case for laser driven targets, the HIF direct-drive designs require more demanding beam quality and alignment tolerances than indirect drive. In the absence of a HIF target facility to advance targets, and to leverage the experimental effort on laser indirect-drive targets, the US HIF program in the 1990's chose indirect drive with hot spot ignition as a baseline. Furthermore, the two-sided illumination geometry for indirect drive targets and beam propagation was compatible with thick liquid wall protection of the chamber, a very significant attribute from an overall fusion systems perspective. However, there is a continuum of possible target designs between direct and indirect drive. Due to the high driver efficiency for heavy ion beams relative to other drivers, the gain does not necessarily need to exceed 100, but the aforementioned designs show this attribute is attainable.

The most recent indirect-drive power plant design is the Robust Point Design based on a distributed-radiator target [Yu 2003]. The input beam energy is 7 MJ with a gain of 57 with two groups of beams, 3 and 4 GeV each, impinging on the target. In a variation of the distributed-radiator design, Calahan and Tabak designed a "close-coupled" target requiring about half that energy with a gain of 130 [Callahan-Miller 2000]. The higher gain at lower input energy results in part from the requirement to focus the beam more tightly and a lower case-to-capsule ratio.

In principle, fast ignition could lead to better target performance, and for that reason fast ignition target designs have been explored in parallel with indirect drive [e.g., Basko 2002, Henestroza 2012]. The target design by Basko is the target in the RF accelerator driver design by Burke [Burke 2014], driven by ions with kinetic energy up to 20 GeV.

The stopping of ions in matter is fairly well understood. There is some uncertainty of the stopping power in hot dense matter which will certainly impact target design, and the white papers by Schenkel et al [Schenkel WP] and Malko et al [Malko WP] propose to study this with a combination of new experimental facilities and modeling. Bangerter et al [Bangerter WP] propose to integrate target physics models in a systems study code to explore target and driver concepts broadly, and to identify integrated designs with lower overall cost and robustness.

Cross-cutting physics

Advanced concepts

Additional methods to improve the yield have been proposed in several white papers. The community is beginning to study the role of externally imposed magnetic fields in trapping electrons and reducing heat conduction losses from the core thus improving yield [Moody WP]. LCLS has been proposed as a facility where the role of tunneling to potentially enhance fusion cross-sections can be studied [Glenzer WP]. Aneutronic fusion is an attractive alternative to the DT fuel cycle in the context of IFE [Melhorn WP]. The primary products are charged-particles enabling higher energy conversion, and limiting neutron damage to reactor structures. Cryogenic handling is not required as the fuel is already in a solid state. Interesting IFE relevant concepts have been proposed that combine fuel assembly with the interaction of protons accelerated by Chirped Pulse Amplification [Margarone 2022] to produce high gain. Given the advantages of p-B^{11} reactions, grounding these concepts in simulations and potentially experiments on laser facilities and extrapolation to IFE may be of interest.

Predictive simulations

Large scale multi-physics radiation hydrodynamics codes are typically used to predict and analyze performance in implosion experiments on OMEGA and the NIF [e.g. Sherlock WP]. However, results from these facilities indicate that these codes currently do not accurately predict the performance of ICF implosions. As a result codes are used to guide new designs that might improve performance and interpret experiments to identify which aspects of engineering or physics might have resulted in deviations from predictions. Several reasons for the limited code predictability exist including uncertainties in code-inputs such as seeds for nonuniformity growth, limitations in the models, or even the exclusion of processes such as those relating to LPI. Using these codes to extrapolate to IFE-relevant designs is risky without adequate benchmarking data and physics understanding. Code improvements are important to extrapolate from the current yield regime to those relevant for IFE.

A standard technique that has proven invaluable in improving models is using observations from experiments, where one aspect of physics dominates over others (e.g. Igumenshchev 2012). Systematic improvements to codes are made to codes to reproduce key observables. However, currently most codes continue to use reduced models for various effects including driver-target coupling, non-local heat conduction, etc. New and improved platforms to study isolated aspects of implosion-relevant physics, in combination with improved diagnostic techniques are extremely important for credibility in the simulation codes that are critical for the extrapolation to IFE-relevant designs from those being studied currently.

Code improvements falls into the following broad categories:

A) Improved models for static and transport properties such as opacity, thermal conductivity of materials under weakly/strongly coupled and degenerate conditions: Implosions span a range of densities from a fraction of solid from many hundred times solid densities and temperature ranges up to many millions of degrees. Under these conditions, plasmas exist in partially ionized states and can be weakly coupled. The compressed fuel, particularly for the high gain designs, exists in a highly degenerate state. While significant progress has been made in improving these models through a combination of Quantum Molecular Dynamics and Path Integral Monte Carlo simulations, uncertainties still remain in the choice of exchange correlation functions. Differences in compression between predictions and observations, particularly in the IFE relevant high compression parameter space are attributed to uncertainties in modeling material properties.
B) Improved models for driver-target coupling including laser plasma interactions such as cross-beam energy transfer in laser-driven plasmas, non-local heat conduction, radiation transport, heavy-ion energy stopping in the presence of magnetic fields.
C) Improved models for kinetic effects including non-local transport and its effect on fusion reactivity
D) Improved understanding of the inputs of non-uniformity seeds and subsequent instability growth including more accurate numerical methods that capture non-linear growth.
E) Integrated codes that combine effects in fluid-like regimes and kinetic regimes.
F) Effective use of advanced architectures such as the new High-Performance-computing architectures that include GPUs and CPUs.

These improvements are also of interest to the ICF community and taking advantage of advances in this area from ICF modeling community is of great value to IFE.

Data-driven and machine-learning approaches

Data driven [Wang WP] and machine learning [Gopalaswamy WP, Mariscal WP] approaches have the advantage that they can circumvent the current limitations in the predictive capabilities of large-scale hydrodynamic simulations, relying only on "black-box" models trained on experimental inputs and outputs. This complementary approach to improving codes is being increasingly used in ICF. Neural networks have been used in indirect-drive to explore the target-design parameter space [e.g. Spears 2018]. In parallel, a Bayesian approach that also combines simulations has been used to develop hypotheses for the observed performance in indirect drive implosions [Gaffney 2019]. Direct drive has resorted to a data-driven approach [Gopalaswamy 2019] to improve performance in cryogenic implosions on OMEGA. The direct drive approach relies on uncovering the dependencies of fusion yield on parameters such as the calculated In-Flight-Aspect-Ratio or the observed variation in the apparent ion-temperatures, or the age of the DT-fuel, using multivariate regression methods. This approach has successfully predicted yield improvements in OMEGA cryogenic implosions [Lees 2021, Williams 2021].

Given the low repetition rate of the OMEGA and the NIF lasers, significant performance improvement has been incremental and has required multi-year timescales. This also implies that the available data is relatively sparse (compared to the typical data sets required for training networks). Transfer learning methods, to develop networks with sparse data, are promising methods to accelerate progress in ICF.

Developing higher rep-rate lasers, related diagnostics and analysis tools will increase the predictive capability and robustness of these methods for IFE-relevant target-design. Accompanying rep-rates, attention should also be paid to computing hardware that can effectively integrate experiments, ML techniques, simulations, data handling, and analysis. Edge computing, using low-power computing located near data sources, is becoming increasingly prevalent at large-scale facilities (LCLS-II, CERN). Standardization of data formats is important for effective use of these methods and information sharing among collaborators.

ML/AI methods is a cross-cutting technology, being increasingly used at various ICF facilities. NIF has used these methods to identify defects in its high-power optics [e.g. Spears 2018]. Automated detection of defects in targets is being used to identify the best candidates for high-performing implosions. R&D in these areas will additionally be important for effective use of intermediate HRR facilities and charting the path towards a pilot IFE power plant.

LPI

While not applicable to all IFE approaches, LPI is a central cross-cutting challenge for all laser-driven approaches and fuel pre-heating in MagLIF type approaches. One of the important lessons learned from ICF/HED experiments on NIF and OMEGA laser facilities is that LPI reduces driver-target coupling and challenges our predictive capability. LPI are fundamental limiters of fusion performance for all laser-driven IFE approaches. Being able to predict, model, control and mitigate LPI effects is crucial for the success of the IFE program. The success of controlling LPI effects requires the development of theory/modeling capabilities, laser technologies for mitigation, modest (~shot/min) rep-rated to HRR laser facilities with precision diagnostics, strong/efficient public-private collaborations, and workforce development.

Several R&D gaps exist for laser-driven approaches and addressing these gaps would be the highest priority for an IFE program addressing LPI. These include:

<u>Improved predictive capability of LPI</u>

LPI in laser-driven IFE experiments involve complex coupling of multi-scale physics at a wide range of temporal and spatial scales, and requires linear theory, kinetic micro-physics codes, temporal/spatial enveloping and fluid/ray-based methods, and multi-physics design codes in order to model these processes properly. The key LPI challenges include controlling and mitigating CBET, SBS, SRS, and TPD for symmetry and laser-target coupling, and keeping hot electron production at an acceptable level. The mitigation of one type of LPI, i.e., CBET, may lead to an increase in laser intensities and the growth of other LPI processes such as SRS and TPD. To maximize the chances of success in a laser-driven IFE program, the community needs to extend theoretical and computational efforts to assess the full range of LPI risks and verify the proposed mitigation schemes for all laser-driven IFE approaches. Supercomputers have increased the complexity of the LPI problems we can realistically tackle today and we now have much more detailed simulations of LPI than we did in the past. If LPI is not completely mitigated, a major goal then should be to develop accurate linear and nonlinear LPI models to couple LPI effects in design codes in a self-consistent manner. Improved coupling of LPI effects in IFE design codes would also enable the efficient evaluation of various approaches to LPI control and mitigation.

<u>Controlling and mitigating LPI</u>

Control of LPI to a much-reduced level would lead to significantly reduced uncertainties in IFE design codes. To reduce spatial and temporal coherence and intensity fluctuations, beyond currently employed SSD and polarization smoothing, the most promising paths toward LPI mitigation strategies involve the use of enhanced laser bandwidth. There have been significant recent advancements in laser technology [Dorrer 2020, Weaver 2017] for the IFE program to leverage. Simulations performed to date show that low-frequency instabilities like SBS and CBET can be mitigated at bandwidths of ~1% laser frequency [Bates 2018, Seaton 2022] and high-frequency instabilities TPD and SRS can be significantly reduced [Follett 2019].

Another major recent accomplishment is rep-rated LPI experimental capability, such as ELI in Europe [Tikhonchuk WP]. High-energy, multi-beam, rep-rated laser facilities [Ditmire WP, McGeoch WP, Obenschain WP, Zuegel WP] employing enhanced bandwidth and STUD pulses [Afeyan WP], such as the T-Star, FLUX laser, and Electra facilities, have been proposed to understand LPI processes in a broad parameter space and to aid in the design of LPI mitigation schemes. A number of key physics issues for IFE can be addressed by performing scaled studies with these new rep-rated laser facilities. These include LPI control/mitigation in hot spot and fast ignition driver beams, mitigation of laser imprint and low mode nonuniformities, and maximization of ablation pressure in direct-drive settings. Rep-rated features in these laser facilities will provide platforms for probing robustly the broad parameter spaces of laser and plasma conditions relevant to IFE and for capturing the onset and nonlinear behavior of LPI.

Rep-rated precision diagnostics for LPI

In ICF/HED research, it has proven difficult to diagnose LPI in detail as standard optical and x-ray diagnostics are indirect and limited. For example, scattered light is collected with small angular aperture in limited directions, and hot electrons are inferred from x-ray emission. Moreover, plasma conditions (density and temperatures) are often inferred from rad-hydro simulation unless precision measurements such as optical Thomson scattering measurement are in place [Hansen 2021]. Therefore, it is critical that we develop rep-rated precision diagnostics. These developments will provide the community with input to employ ML [Gopalaswamy WP, Scott WP] techniques in validating LPI mitigation models and in optimizing IFE design.

LPI facilities

Although an IFE facility for demonstrating at-scale LPI control for IFE designs is yet to be built, LPI mitigation strategies can be explored immediately at small- to mid-scale existing facilities. However, the current facilities capable of addressing the identified problems are over-subscribed and industry has the potential to be the dominant driver of IFE in terms of investments for near future facilities (e.g. T-Star).

Opportunity for collaborations and workforce development

There are rich opportunities for cross-collaboration in order to leverage diverse expertise among national Labs, laser facilities, universities and industrial partners. A more streamlined CRADA process needs to be developed to increase the pace of innovation and discovery, leveraging fully the advantages of the private and public sectors.

The IFE program and private fusion companies will need improved fidelity simulation codes (including kinetic effects beyond hydro codes). National Labs have unique expertise, tools, computing resources, and diagnostics to leverage and there is a need to establish the mission areas relevant to IFE at National Labs. IFE can bring talent/workforce to NNSA labs. Partnership mechanisms and reporting requirements among industry, academia, and national Labs must be developed for a stable IFE workforce to be produced and maintained. Attraction of talent that has left the IFE field and mentoring the next generation will be needed. For these partnerships, the extent of academic publication is a key issue in the IP realm that must be clarified (or publication of some results if the experiments succeed) to be able to show benefit to the public. Agreement on publication is important in partnerships, and important for young scientists' careers, even in private industry.

Particle accelerators have been important discovery tools for high-energy physics, nuclear physics and other fields, and for the research missions of DOE BES, HEP and NP. Opportunities to leverage these large communities should continue to be explored in the context of HIF.

2.2.2 Target Manufacturing and Injection

That targets are an integral part of IFE is clear, with 66 of 79 white papers mentioning targets. Furthermore, low cost, rep-rated, mass production or manufacture or targets was seen as a definite IFE need mentioned in 35 white papers. Target manufacture or materials thereof was the subject or a portion 10 white papers. Target cost projections were provided in Alexander WP B. Manufacture of foam capsules or target parts were considered in white papers of Alexander WP B, Haid WP, Harding WP, Hu WP, Sweet WP. Additive manufacturing (AM) was part of white papers of Haid WP, Hu WP, Olson WP, and Tikhonchuk WP. Manufacturing of hohlraum parts and target assembly was discussed in the white paper of Alexander WP B. Material development was in white papers of Haid WP, Hu WP, Larson, WP, and Sweet WP. Layering of target fuel was the subject of the white paper of Boehm WP. Machine learning (ML) characterization of targets was in white papers of Alexander WP B, and Sweet WP. Target systems for laser ion acceleration experiments were discussed in white paper of Obst-Huebl. Target fabrication related papers are summarized as follows.
Alexander WP B – contained an overview of past cost studies for mass produced targets, and results of scalable technology development for coated foam shell capsules, lead (Pb) hohlraum part, robotic assembly of targets, and machine learning characterization of capsule quality. Future development pathways discussed. Cost studies indicate target costs of 10's cents for direct and indirect drive targets, and a few dollars for pulsed power targets. Foam capsules were made using micro-encapsulation using concentric nozzles with in specification yield of up to 75%.

Boehm WP – discussed using a cryogenic fluidized bed for producing solid DT fuel layers, and technologies developed to demonstrate this. Also discussed laying via wicking liquid into foam shell capsule, and showed an example of such a capsule immediately after launch from a cryogenic induction accelerator injector, where no pooling of liquid deuterium at the bottom of the capsule from launch acceleration was observed. Fuel layering development options were outlined.
Haid WP – discussed successfully making wetted foam capsule targets and other target parts using the two photon polymerization (2PP) additive manufacturing (AM) technique. AM has the ability to create structures unavailable via other techniques, such as radial gradient density in a foam capsule. The 2PP method offers sub-micron printing resolution. Also discussed were development pathways to reach the target production throughput requirements of IFE.
Harding WP – discussed development of micro-fluidic "lab-on-chip" methods of manufacturing foam capsules. Capsules were made via microencapsulation using T-junctions. Fluids were moved on chip using electrowetting-on-a-dielectric (EWOD) forces. Capsule centering of void was done using dielectrophoretic force. Capsule chemistry allowed UV light cure of the capsules.
Hu WP – discussed using a CHON material for making wetted foam capsules and showed an example of a foam capsule made by an AM 2PP technique.
Larson WP B – discussed a scalable method for manufacturing deuterated C-D polymer for use in making targets.
Obst-Huebl WP – showed a tape drive for use as high repetition rate targets, flat targets, for use in laser ion acceleration experiments at BELLA. Other target techniques for ion acceleration experiments were mentioned: cryogenic hydrogen jets, liquid jets, and supersonic gas jets.
Olson WP – showed an example of a 2PP AM wetted foam capsule made for a polar direct drive wetted foam target experiment.
Sweet WP – discussed strategies and developments for making wetted foam capsule targets for IFE. Strategies include microencapsulation followed by coating, injection molding, and outside-in manufacture (creating of foam liner inside of an already existing shell). A variety of foam chemistries were presented: resorcinol formaldehyde, divinyl benzene, GA-CH, GA-CD, and silica aerogel. ML characterization of capsules was also discussed.
Tikhonchuk WP – mentioned development of foam targets via three technologies: chemical synthesis, carbon nanotube fabrication, and AM. Examples of AM foam blocks were shown.

In laser and ion beam driven IFE, the target is injected (shot) into the reactor chamber. Targets will be tracked, and the beams steered to precisely (~~25 um) engage (hit) the target. This precise engagement of a fast moving (~50 - ~150 m/s) target is a unique feature of IFE. The anticipated shot rate is ~1 – 10 Hz. The target must survive intact both the acceleration forces of the injection, and the flight through the reactor chamber. The reactor chamber environment is harsh with the target being potentially exposed to both black body thermal radiation of ~1000°C and residual hot gas or plasma in the chamber. Not only the structure of the target needs to survive, but the precisely formed cryogenic fuel layer (e.g. DT) must survive intact until the target reaches chamber center. Indirect drive targets offer more thermal protection to the fuel layer than direct drive targets, but are more complex to manufacture. White papers that recommended development of target injectors, tracking, and beam steering included Alexander WP A, Boehm WP, Dean WP B, Dunne WP, Galloway WP, Harding WP, and Matsuo WP. Integrated target injection, tracking, and engagement were called for in Alexander WP A, Bott-Suzuki WP, Dean WP B, Dyer WP, and Harding WP. Target survival was mentioned or studies thereof called for in Callahan WP, Christopherson WP, Galloway WP, and Harding WP. The white papers on target injection, tracking, and engagement are summarized as follows.

The white paper of Alexander WP A – described full scale full speed prototype target injectors and the target placement accuracy achieved. For a gas gun with sabots for direct drive targets an accuracy (1σ) of 0.24 mrad was achieved at 50 m/s, 0.59 mrad at 400 m/s. For a linear induction accelerator (LIA) for indirect drive targets 0.14 mrad at ~50 m/s was achieved. Note these were done at room temperature and the injectors were not rep-rated. A low speed (5 m/s) target injection, tracking, and engagement demonstration with a low power laser was conducted, achieving laser to target hit accuracy of 28 μm (1σ). Development of rep-rated (fast target loading), followed by cryogenic versions was recommended for target injectors. Development of electromagnetic injector using sabots for direct drive targets was recommended. Integrated hit-on-fly demonstrations at full speed first with low power and then with full power lasers. The latter requires development of an actuated beam steering mirror such as a grazing incidence metal mirror, and integration of tracking systems into full power laser.

The white paper of Boehm WP called for development of a cryogenic target loader for the target injector, and integration of cryogenic layering system with target injection system. Also called for were studies of liquid or solid layers upon injection into a reactor chamber like environment. The white paper showed an image of a cryogenic liquid deuterium wetted foam capsule just after an 800 g launch from a cryogenic LIA; no acceleration induced pooling of liquid deuterium was observed, to the resolution of the high speed image, which was not high.

The white paper of Bott-Suzuki WP looked at reactor sub-system interdependencies and recommended development of sub-scale repetitive drive-target coupling (engagement) including injection or insertion (for pulsed power).

The white paper of Callahan WP recommended re-evaluation of target designs for robustness, including with respect to practicality of injection, survival in chamber, ability to track target and steer beams to the target.

The white paper of Christopherson WP called for addressing the issues of IFE target survival during the injection process and during the target's passage to the center of the reactor chamber.

The white paper of Dean WP B noted that most IFE technology can be developed and demonstrated at one pulsed facility including target injectors and final optics (which would include beam steering). It called for target injector and final optics development in the near and

intermediate term and recommended hit-on-fly tests (i.e. target injection, tracking, and engagement demonstration).
The white paper of Dunne WP recommends integrated (holistic) IFE reactor development, including target injection, tracking, and engagement prototype development.
The white paper of Dyer WP mentioned that the chamber for MEC-U at SLAC will be designed not to preclude adding target injection, tracking, and shooting of targets.
The white paper of Galloway WP mentions that the low shot rate of ASPEN (~1 Hz) will simplify target injection, and that the hybrid target has features that promote survival of the target during injection and during transit through the reactor chamber. Continued development of target injection was called for.
The white paper of Harding WP mentioned several methods for target injection: gas gun with sabot, gravity, and electrostatic acceleration; and notes research will be required to develop injectors that do not damage targets. Also discussed was an experimental setup to mimic cryogenic target's transit through the reactor chamber. The setup allowed for a cryogenic surface to be exposed to very hot, low density gas flow at high speed past the surface, while the surface was being diagnosed for heat flux experienced, and amount of gas condensed onto the cryogenic surface.
The white paper of Matsuo WP mentioned that Ex-Fusion Inc.'s, Japan, has an initial focus of target delivery and laser engagement. They have received a 10 Hz bead injector and laser engagement system from the Graduate School for the Creation of New Photonic Industries.

2.3 Drivers

2.3.1 Lasers

There was a lot of interest concerning laser drivers within the nascent IFE Community Workshop participants. Laser technology development for inertial fusion energy occurs through 1) development of new potential driver and/or modification of previous driver design due to improved understanding in target physics, 2) new laser technologies recently developed that can reach the scale for inertial fusion energy as well as facilities which can be utilized for examination of other aspects of laser fusion energy, 3) improvements in one or more components of the laser driver for efficiency, cost, repetition-rate, reliability, increased capability and durability. In each of the above-mentioned categories, considerable (tremendous) improvement has taken place. An attempt to discern some particular points and inclusion of the white papers submitted to the Inertial Fusion Energy Community Workshop at a high level are provided here.

1) Development of new potential driver and/or modification of previous driver design due to improved understanding in target physics

A new potential driver for IFE is the electron beam pumped ArF excimer laser, which is favorable due to the short native wavelength (193 nm) and broad bandwidth (11 THz) to limit the deleterious response of laser plasma instabilities (LPI) [Obenschain WP] for direct drive applications. The new ArF laser is based on electron beam technology developed for KrF lasers within the HAPL (High Average Power Laser) where high-energy, rep-rate, efficiency, durability, reliability and cost was previously demonstrated. Previous demonstrations of 300+ Joules, 90,000+ shots, 2.5 Hz (10 hours) continuous operation of electron beam pumped excimer laser technology was explicitly mentioned [Bodner WP]. The advance to electron beam pumped ArF also increases the projected wall plug efficiency (all driver components) by nearly 50% to an overall 10% relative to 7% for KrF excimer lasers. The driver efficiency is one of the most potent obstacles for IFE and dramatic improvements such as the advancement of ArF shows significant technical achievements can be attained in this field.

There has been recent significant success utilizing the National Ignition Facility (NIF) employing the indirect drive approach. Three indirect drive approaches (HDC, HyE & CH high foot) would benefit from increased power and energy utilizing the NIF. Development paths to access the higher laser headroom to get as high as 2.6 MJ, 600-650 TW or 3 MJ, 450 TW have been specified [DiNicola WP]. The NIF is the only present 'ignition scale' facility and demonstrates capability of high accuracy and precision laser delivery [DiNicola WP].

Development of new diode pumped solid state laser technologies for direct drive based on knowledge of target physics has been significant [Zuegel WP]. Developing broad bandwidth for direct drive applications to mitigate cross beam energy transfer (CBET), which is a significant source of laser plasma instability (LPI). There are multiple approaches to generate the necessary bandwidth, these include FLUX (Fourth-Generation Laser for Ultrabroadband eXperiments) and Star Driver [Zuegel WP]. FLUX uses optical parametric amplification in both noncollinear (NOPA) and collinear (COPA) with sum frequency generation to generate broad bandwidth ultraviolet radiation [Zuegel WP]. Star Driver is a concept to use many DPSSLs at different frequencies to provide the broad bandwidth illumination on target [Zuegel WP].

Examination of laser plasma instability (LPI) at longer wavelength in the green (2ω) with use of bandwidth or STUD pulses utilizing flashlamp pump technology was proposed [Ditmire WP]. The proposed facility would have chirp pulse amplification (CPA) capability for possible particle acceleration for fast ignition [Ditmire WP].

Diode pumped solid state laser (DPPSL) which can be modularized in a 'laser box' from the Mercury and HAPLS programs [Dunne White Paper, Haefner2 White Paper, Tang2 WP]. The key laser technologies for the development of the DPSSL development have been referenced [Tang2 WP]. The pump source for HAPLS (High Repetition Rate Advanced Petawatt Laser System) in present operation at the ELI beamlines was conceived of being capable producing 8 kJ/5ns/15 Hz pulses with a wall-plug efficiency of about 15% [Haefner2 WP].

In Japan significant progress on the laser drive capabilities are ongoing including progress toward 100 J, 100 Hz, Yb:YAG ceramic with active mirror scheme [Kodoma WP, Sentoka WP]. A 10 J, 10 Hz diode pumped cryogenic active mirror laser has already been achieved [Sentoka WP]. HYPERION (Hydrogen-production plant and Energy Reactor of Inertial-fusion) is a fast track plan with a laser driver (0.5MJ/2Hz/1MW electrical efficiency: 20%) [Kodoma WP]. Laser fusion energy has significant commercial interest in Japan [Matsuo WP].

A multi-national and multi-institutional effort utilizing electron beam pumped KrF lasers has progressed with a combination of four wave mixing techniques (forward stimulated rotational Raman scattering amplifier, seeded backward stimulated Brillioun scattering) to provide spatial and temporal compression with expected high efficiency [Galloway WP]. The novel target design with two beamlines in hybrid (indirect and drive) may limit the losses due to laser plasma instabilities reducing the constraints on the laser [Galloway WP].

The ignitor pulse in fast ignition is expected to be much smaller than the required energy for compression. Therefore the overall efficiency will be dominated by the laser energy required for compression. The difference in wall-plug efficiency between long pulse and short pulse depends on many factors. A rough estimate could be made that the wall plug efficiency for the case of solid state lasers is the same for both long and short pulse lasers because the short pulse laser will require a compressor and the compression laser drive will require harmonic generation which nominally have similar losses. Ion fast ignition utilizes a laser and generates a short pulse of ions with a couple of different methods [Albright WP]. Development of a beam combiner method that relies on ion waves to combine several nanosecond laser pulses into a single beam has reached 8 kJ into 1 ns with future laser technologies expected to produce ~60 kJ, 10 ps laser beam [Wilks1 WP, Obst-Huble WP]. Development of laser architectures, including Tm:YLF, promise orders of magnitude higher average power than presently achievable in (petawatt class) lasers [Wilks1 WP, Obst-Huble WP]. These accomplishments show promise for ion fast ignition [Wilks1, WP, Obst-Huble WP].

Examination of utilizing short pulse lasers to generate fast electrons in a fast ignition scheme by utilizing magnetic fields to keep the electrons contained shows potential [Kemp WP].

2) New laser technologies recently developed that can reach the scale for inertial fusion energy as well as facilities which can be utilized for examination of other aspects of laser fusion energy

A new fiber laser approach which possibly get to scale utilizing large monolithic large core fiber technologies with coherent pulse stacking amplification [Galvanauskas WP].

New capability of combining a high repetition rate petawatt peak power laser with hard X-ray free electron laser offers unique opportunities in laser, target and plasma technologies at relevant IFE power plant rep-rates [Dyer WP].

A new capability of utilizing high magnetic fields up to 30 T is available for laser, target, plasma and wall technologies relevant for IFE power plant rep-rates [Tikhonchuk WP].

The ability to conduct high energy density physics experiments, with extension to IFE, at a high repetition rate facility of the laser size 50-100 kJ scale for integrated target experiments was discussed [Heuer WP].

LULI2000 and APOLLON laser facilities in France offer opportunities and capabilities to aid in IFE research [Le Pape WP].

Fast ignitor laser technologies have the opportunity to spin-off and be utilized for other utilizations beyond for short pulse lasers for fast ignition IFE [Williams WP].

The ten LaserNet US facilities have different but overlapping and complementary capabilities both in laser systems and experimental facilities to assist in advancing IFE [LaserNetUS WP].

3) Improvements in or more components of the laser driver for efficiency, cost, repetition-rate, reliability, increased capability and durability.

Optics science & technology which is an essential element of laser driver development has been extended and continues to get extended farther with improved debris control and reduction of damage initiation with the high laser energy facility [DiNicola WP].

Long wavelength Diode Pumped Solid State lasers utilizing Er, Tm, and Ho have significant benefits in longer lifetimes of the upper state than ND:Glass in which a significant reduction in diode cost could be realized [Payne WP]. These long wavelength diode pumped solid state lasers could dramatically reduce for IFE DPSSL capital costs [Payne WP].

The cost and performance of diodes is a key component for solid state lasers. Significant progress has occurred since the HAPLS program ended and significant more progress is projected in the future for this key technology for DPPSL IFE applications [Haefner1 WP].

Durable solid state pulse power is an important component for development of the excimer laser approach as well as heavy ion and pulse power approaches [McGeoch WP]. Expected improved performance compared to a present device operating 200kV, 10^7 shot at 10 Hz continuously [McGeoch WP]. Wide bandgap power electronics is another key constituent component which requires durability, reliability, and cost for successful inertial fusion power plant independent driver, but has been examined for the laser option [Galea WP].

Plasma optics, including ion wave optics, to be utilized as a final optic for laser drivers allows the possibility of obtaining higher laser fluence on the last critical optics with expected minimal effect from the reactor physics for final optics [Edwards WP, Kirkwood WP]. Gas density within the reactor chamber also needs to be a consideration for laser transport to the target [Wilks2 WP].

Utilization of artificial intelligence (AI) capability shows significant improvement in potential laser control and other aspects of laser technology development for experiments at repetition rate [Mariscal WP, Scott WP].

2.3.2 Heavy Ions

Since IFE targets are small, the ion mass and kinetic energy should be compatible with stopping in an areal density consistent with the target design properties. Protons are straightforward to generate, and multi-GeV proton accelerators are common. But at low energy (<20 MeV) where the proton range is suitable, it has proven difficult to achieve the focused intensity required for ignition. Multi-GeV heavy ions allow for a much lower beam current to achieve the required power, while having the correct range. Thus, heavy-ion fusion (HIF) emerged as a promising driver for IFE in the 1970's, in parallel with laser IFE.

There were 13 white papers from 22 institutions and private entities describing research opportunities related to ion driven IFE for a variety of target designs, including heavy ion indirect and direct drive, and ion-driven fast ignition.

T. Schenkel's paper and plenary presentation (*Ion beams and Inertial Fusion Energy*) advocates for a three-pronged research program. The three research elements are: High-energy-density science experiments to address specific IFE questions (e.g., experiments at facilities coming online soon, such as FAIR, the Facility for Anti-proton and Ion Research at GSI); Modeling and simulation of beams and plasmas building on new modeling and computational capabilities; Heavy-ion driver technology development by leveraging advances in accelerator science for induction and RF accelerators. The efforts are tied together by a systems-level assessment of driver designs and specific target requirements.

The authors of the white papers addressing heavy ion fusion are motivated by the attributes of ion driven IFE: early in the HIF program, accelerator technology appeared to provide solutions to most of the difficult challenges of IFE. Large machines such as those at CERN and Fermilab had produced or stored of the order of 1MJ of beam energy. The beams from existing accelerators could be focused to the small spot sizes required by the targets. Accelerators have been shown to have very high electrical efficiency. The survivability of laser optical elements in a fusion environment had emerged as a major issue for laser IFE. Since particle beams are focused by magnetic fields rather than material optical elements, it appeared possible to design focusing elements that would survive.

Delivering the required power (>1e14 W/cm^2) for several ns with ions having a suitable range in matter has not been demonstrated. Identifying a scalable path to achieving this, and designing an accelerator driver with an attractive cost was the topic of several of the white papers. Others focused on developing a robust target manufacturing, handling and injection system capable of ≈10 Hz operation. The particular attributes and remaining technical challenges in the chamber, are addressed in two white papers [Vay WP, Bott-Suzuki WP], and noted that ion propagation in the target chamber appears compatible with thick liquid protection of the structural wall while providing a medium for tritium breeding.

This is closely related to the paper by Bott-Suzuki et al, which aim to develop sub-scale repetitive driver-target coupling test platforms for driver target coupling for laser, pulsed power and heavy ions [Bott-Suzuki WP]. The IFE-specific requirements of repetition rate and gain are emphasized, including chamber clearing for repeated shots and predictable performance. These are IFE-specific and crucial to the success of IFE. The authors note that the related IFE-specific technology development programs have been offline for a decade.

Bangerter et al. propose an integrated systems study and optimization including target performance as a function of focused beam characteristics [Bangerter WP]. Several new technologies might significantly improve the economics of HIF drivers, including new high-power solid-state switches, and the robotic fabrication of superconducting focusing magnets. Global driver system optimizations using modern computing resources would guide the development of the new technologies enabling a competitive development path.

The white paper by Burke reviews past ion-driven IFE research and advocates RF accelerator drivers to generate high-kinetic energy ion pulses for fast ignition. The paper proposes an energy-producing-industrial park on the scale of the accelerator complex at CERN with multi-GWe output [Burke WP].

Haefner et al. summarize laser-driven IFE and heavy-ion driven IFE technology development opportunities: For HIF, the opportunities center on target experiments at new accelerator facilities, detailed modeling of beams from the source through the driver and target chamber, and to leverage recent accelerator technology developments adaptable to HIF [Haefner WP].

Kaganovich et al. propose four elements to a research program: to study the neutralization of the beam space charge to allow meeting the target focusing requirements at lower kinetic energy and higher beam current; generation of high intensity negative-ion beams to circumvent electron cloud effects of positively charged beams; space charge effects in the driver; and methods to smooth beam intensity imperfections with rapidly oscillating focal spots [Kaganovich WP].

Malko et al. propose to study ion transport and stopping power in IFE relevant plasmas, focusing on present-day uncertainties of ion stopping in extreme states of matter and their effect on target gain [Malko WP].

The Spallation Neutron Source (SNS) at Oak Ridge is the highest average-power linear accelerator in the world (> 1 MW beam power). Morozov and Cousineau propose to leverage SNS experience and capabilities to benchmark codes that model high intensity and high space-charge beams. Also, the extensive experience at SNS with superconducting RF structures enables exploration for the development of high efficiency RF accelerators for HIF [Morozov WP].

By taking advantage of recent advances in particle-in-cell codes, Vay et al. aim to retire risks associated with the focusing of multiple beams in the target chamber. To date, most detailed simulations of focusing modeled one beam due to computational speed limitations and complexity. The simultaneous modeling of many beams would include all relevant physical processes: electromagnetic self fields of the beams, photons and particles emitted by target, stripping and ionization involving the background gas.

In summary, the HIF white papers cover all aspects of the driver and power plant. While HIF accelerator research has not been supported by the DOE for about a decade, impressive progress has been made with laser drivers as part of the NNSA mission. Can HIF compete? The attractive attributes are still compelling: namely the demonstrated high electrical efficiency and repetition rate of high-power particle accelerators. In addition, the focusing elements are electromagnetic fields and do not deteriorate with repeated use. What is new? In the past decade, advances in computational techniques and speed, technology and accelerator science offer opportunities to retire risk and answer open questions. New accelerator facilities coming online will enable advancing ion driver specific topics. This synergy with other research fields is very helpful. But the proponents all note that – as for all IFE approaches – good progress on HIF cannot rely solely on other research missions (NNSA, HEP, NP, BES...), but rather requires a research program with the resources to do necessary R&D specific to the energy mission. Several papers noted the opportunity to engage early with the private sector.

2.3.3 Pulsed Power

Pulsed power systems are required for all of the IFE concepts considered, including laser-driven concepts, heavy-ion-beam-driven concepts, and directly applied pulsed-power-driven concepts. In all cases, electrical energy is first stored in many capacitors, which are rapidly discharged through high-power switches to generate large bursts of electrical power. In laser-driven concepts, the electrical energy is converted into a beam of light [Boehly 1997; Waxer 2005; Haynam 2007]. In heavy-ion-beam-driven concepts, the electrical energy is converted into an accelerated beam of heavy ions [Bangerter 2014]. In pulsed-power-driven concepts, the electrical power is applied directly to the fusion target, where the electrical power is typically delivered in the form of a large-amplitude, fast-rising pulse of electrical current - e.g., the 30-MA, 100-ns current pulse on the Z facility at Sandia National Laboratories (SNL) [Sinars 2020]. In all cases, for IFE, these capacitor-switch-driver systems need to be discharged and recharged rapidly (rep-rated), with considerations for target insertion, debris clearing, and driver-target coupling in a hostile fusion environment [Bott-Suzuki WP].

In concepts where the pulsed power driver is directly applied to the IFE target, very challenging requirements are placed on the underlying pulsed power architecture. This is because many 100's of TW of electrical power must be delivered to the target chamber (i.e., many MV and many MA simultaneously). Examples of such extreme power delivery include today's 80-TW Z facility (~25 MA in 100 ns) [Sinars 2020] and possible future generators that could provide up to 800 TW of electrical power for fusion ignition systems (~60 MA in 100 ns) [Stygar 2015].

The benefit of using a pulsed power driver to directly implode an IFE target is the large driver-target coupling efficiency that can be obtained. For example, the Z facility at SNL stores 11-22 MJ of electrical energy and is capable of delivering 2-3 MJ of that energy to targets, for a coupling efficiency of >15% [Deeney 1998; Spielman 1998; Cuneo 2005]. This large efficiency is obtained by cylindrical implosion, as cylindrical geometry is the natural geometry for the implosion-driving magnetic field. That is, the large current pulse (e.g., the Z facility's 20-30 MA current pulse) is run axially along the length of the cylindrical target, which generates an azimuthal magnetic field that smoothly encloses the cylindrical target. The **J** x **B** force density (i.e., the Lorentz force, or equivalently, the magnetic pressure gradient) then acts to implode the cylindrical target [McBride 2018].

A class of cylindrical targets that has generated a lot of interest over the past decade is that of the magnetized liner inertial fusion (MagLIF) program on SNL's Z facility - see Section 2.3.1, "MagLIF Designs", for additional details; see also References: [Slutz 2010; Cuneo 2012; Gomez 2014; Gomez 2020; Sinars 2020; Gomez Kickoff Meeting Talk]. For future IFE applications, Section 2.3.1, "MagLIF Designs", discusses several potential modifications to present-day MagLIF designs, including the use of a cryogenic DT "ice" layer for achieving high-gain performance on a future, 65-MA driver. With such high-gain targets, simulations predict a 7-GJ fusion yield and an overall facility gain of 70 (total fusion energy out divided by total electrical energy stored in the facility's capacitors) [Slutz 0212; Slutz 2016; Slutz 2022].

Ultimately, high-gain targets would have to be physically connected to transmission lines (electrodes) that are destroyed on every shot out to a radius of several feet. Thus, for IFE applications, assemblies consisting of a pre-vacuum-pumped section of transmission line, complete with a preinstalled liner target, would have to be fabricated, installed, cleared, and replaced for every shot [Bott-Suzuki WP]. Additionally, the materials would have to be recovered and recycled to avoid excessive waste and cost (thus, these transmission lines are often called recyclable transmission lines, or RTLs). To realize an IFE power plant operating at 0.1-1 GW, these coupled high-gain target-RTL assemblies would have to be fabricated, installed, cleared, and recovered every 10 seconds (i.e., a system rep-rate of 0.1 Hz). Thus, robotics would need to be utilized. It should be noted that a Ford F-150 door, with complex stamped metal shapes, can be fabricated every few seconds using advanced robotics. Nevertheless, the engineering challenges associated with IFE target production at high rep-rates are significant and should not be understated, regardless of the IFE concept, target type, or driver technology [Bott-Suzuki WP].

In general, pulsed-power-driven cylindrical targets are advantageous in that their driver-target energy coupling efficiency can be quite high relative to other ICF/IFE concepts/drivers. However, pulsed power targets must be physically connected to electrodes, and in terms of volumetric compression, cylindrical implosions are not as efficient as spherical implosions. Thus, there are tradeoffs that must be assessed when developing full-scale IFE systems. An IFE program should explore such tradeoffs [Bott-Suzuki WP].

The white paper by Bott-Suzuki et al. [Bott-Suzuki WP] addresses many of these concerns from a driver-agnostic point of view, focusing on what an IFE program should look like (at least initially) to address the many common challenges between the different driver approaches. Some of the key questions brought forth for IFE drivers in general, as well as pulsed power drivers in particular, include:

- Can we develop sub-scale drivers with suitable rep-rated operation and scalability?
- Can low-maintenance switches, which are required for high energy, high repetition-rate lasers, heavy-ion beam accelerators, and pulsed power drivers, be developed that operate at-scale for millions of shots?
- What are the approaches to coupling and the chamber environment that should be considered?
- What systems are needed for target injection, tracking, laser or heavy ion beam steering, and repetitive transmission line placement in potentially turbulent gas environments?
- What chamber and driver protection schemes are compatible with coupling?
- Can current be delivered down high-inductance single replaceable transmission lines that provide standoff? What are the current transport efficiencies, and can these be modeled? What are the limits to current transport, if any?

- Can pre-pumped vacuum transmission line cassettes be installed without inducing additional current losses due to plasma physics, achieving appropriate vacuum conditions, electrode properties, and current contacts?
- What is the minimum mass that can be used to transport current to targets in pulsed power systems?
- What is the environment in the chamber following the previous fusion target event, and is the chamber clear of gas, plasma, or other debris which could interfere with driver coupling?
- How long will it take to clear the chamber and what is the environment at the time of the next pulse?
- What is the required environment for the proposed targets?
- How does the driver interact with the plasma blown off from the target and can this be simulated?
- How could these issues and others be simulated and studied in a surrogate and scaled experimental environment?

It is further noted in the white paper by Bott-Suzuki et al. [Bott-Suzuki WP] that the only feasible means to predict behavior at full-scale from sub-scale data is through well-benchmarked simulations. Therefore, one might ask, can IFE chamber environments be simulated to provide guidance for suitable scaled driver-target coupling demonstrations? Are there computational models and platforms that are up to the task of modeling the target chamber environment? If not, what new simulation tools and algorithms are required? The optimal solution for any portion of an IFE system will depend on the choices made for each other section, so can simulations aid in assessing these tradeoffs? These are the questions that a healthy IFE program will need to address.

The white paper by Bott-Suzuki et al. [Bott-Suzuki WP] ultimately advocates for a program that focuses on:

- Sub-scale repetitive driver-target coupling, including target injection, placement, or insertion
- Sub-scale repetitive drivers
- Sub-scale (but hydrodynamically scaled) IFE target chamber surrogate environments

It is noted that such a program (aimed at investigating rep-rated sub-scale experiments) would have many cross-cutting benefits, including vastly increased amounts of experimental data for general plasma physics, HEDP, large data science, and data-informed machine learning.

2.4 Reactor Technologies (Engineering/facility)

The 2013 National Academies review of IFE covers chamber technologies and materials research needs specifically for IFE. Noting that the choice of chamber technologies is closely coupled to the choice of drivers and targets, that report concluded that a coordinated chamber and blanket development program is needed, with specific R&D for liquid walls and for dry walls. Synergies with MFE fusion materials and wall technology should also be exploited. [National Research Council 2013]

IFE reactor technologies are expected to be tremendously enhanced due to the substantial research already accomplished by the MFE community [Ulreich WP]. Reactor technologies research in inertial fusion energy offers unique opportunities with potential concomitant benefit to the magnetic fusion energy (MFE) community. Specific materials, blankets and diagnostic concepts under investigation by MFE or IFE may be found to be more useful than the original fusion energy community the approach originated in. In addition to the 2013 NRC report noted above, a consistent message of community and expert panel reports to move to fusion technology and materials are exemplified in the following documentation: (i) Research Needs for Magnetic Fusion Energy Sciences (2009, Office of Fusion Energy Sciences), (ii) Fusion Energy Science Program: A Ten-Year Perspective (2015, Office of Science), (iii) Report of the Committee on a Strategic Plan for the U.S. Burning Plasma Research (2019, NASEM), (iv) A long-range plan to deliver fusion energy and to advance plasma science (2020, FESAC), (v) Consensus Study Report- Bringing Fusion to the U.S. Grid (2021, NASEM) [Snead Presentation]. Within (iv) a long range plan to deliver fusion energy and advance plasma science (2020, FESAC) lists of recommendations in technological and facility investments which will benefit the IFE community [Snead Presentation]. Vibrant fusion communities in both MFE and IFE will aid the other community in new ideas, development and evaluation. The reactor technologies is one area where this is exemplified by the similarity of the problems and ongoing solutions developed from within the fusion community. Improving and enhancing modeling capabilities with utilization of density functional theory (DFT) and molecular dynamics (MD) is an example that can enhance both MFE and IFE approaches [Custentino WP]. Technologies on PbLi blankets for high tritium extraction and corresponding design codes is another example where research benefits both the IFE and MFE community [Fuerst WP]. Utilizing modeling tools developed for light water reactors (LWRs) for PbLi blankets including RELAP5-3D exemplifies the cross-cutting capabilities of modern tools [Meehan WP]. Another example of overlapping research areas for MFE and IFE reactor blanket technologies are: (i) hydrogen isotope uptake and diffusion/permeation through blanket materials, (ii) surface chemistry at gas-solid and liquid-solid interfaces and (iii) separation of tritium from exhaust gases [Kolansinski WP]. Early and fundamental work on helium ion management under HAPL program [Snead presentation].

One difference for reactor technologies between MFE and IFE is the cyclic or short pulse nature (repetition rate). Cyclic testing and modeling of walls as well as work on increasing performance of optics in a reactor environment was conducted in the HAPL program [Snead Presentation]. Opportunities exist to make meaningful fast progress for radiation tolerant materials by utilizing artificial intelligence (AI) and machine learning (ML) [Cusentino WP]. Controlling the compositional and structural nature of materials with nanometer precision increases radiation tolerance necessary for IFE concepts [Cusentino WP]. Another difference in reactor technologies between MFE and IFE for high gain inertial confinement fusion (IFE) the amount of fuel burned is expected to be higher (20-35%) [Larsen2 WP]. Another potential difference is the impurities the tritium could be exposed to in the fuel cycle due to specific requirements of the IFE driver. All components need to be taken into account for a complete fuel cycle evaluation and modeling of the fuel cycle comprehensively with an iterative process with the target design will be critical in ensuring the fuel is both feasible and cost effective [Larsen2 WP].

IFE diagnostic capability for the progression to the final power plant and the final power plant is required. Concepts to measure ɣ-rays from behind the chamber wall could monitor the fusion yield and infer fuel and areal-density by using Compton scattering at repetition rate with utilization of Gamma-RAy Spectrometer (GRASP) [Frenje WP]. Fast x-ray imaging and tomography, particularly for diagnosing shocks through foams was reported [Gleason WP]. Development of fast hCMOS imagers, which can support fast x-ray imaging was reported [Claus WP]. Developing new diagnostic methods for plasma facing components such as ultrafast time-resolved electron diffraction would be beneficial [Mo WP]. Utilizing machine learning in developing reactor diagnostics is paramount [Scott WP, Mariscal WP]. Combining diagnostics and having data handling and data interpretation capabilities utilizing machine learning in a physics informed multiprobe instrument (PiMIX) would be beneficial for IFE [Wang WP].

Thick liquid wall protection of the reactor chamber was proposed for the HYLIFE-II power plant design for HIF [Moir 1994]. Experiments and models have explored the suitability of the thick-liquid approach, including turbulence and disruption of the liquid (fluorine, lithium, beryllium eutectic salt, or FLiBE) in the fusion environment [e.g., Elwell, 2001; Durbin, 2004]. Thick liquid walls have been utilized in designs for laser direct drive as well [Raffray 2009].

The white paper by Andruczyk focuses on pure lithium, SnLi and PbLi as a flowing liquid metal for heat removal and tritium breeding, leveraging ongoing blanket research for MFE.

The white paper by Bott-Suzuki notes the diversity of possible solutions for the blanket, including dry walls, wetted walls and thick liquid walls. Each depends on the target and driver choice.

Interest in molten salt coolant for next-generation fission reactors has grown. For example, Kairos Power [Kairos 2022] is a start-up developing fluoride-salt cooled high-temperature fission reactors. This is an opportunity to leverage private sector fission investment in the development of reliable molten salt handling techniques. And laser-IFE commercial startup Xcimer Energy includes coolant and breeding using FLiBe for breeding and heat exchange.

Blankets are an integral part of an IFE reactor chamber. The primary functions of the blanket are to breed tritium to further fuel the reactor, and to absorb fusion reaction products, primarily neutrons, producing heat that is transported to the power conversion system or process heat application. Some blanket designs, specifically those that utilize a liquid first wall, provide a chamber first wall that is self-healing with respect to ion and photon damage from target outputs. Examples of reactor design concepts that use liquid first walls are HYLIFE-II [Moir 1994, Vay WP, Fuerst WP], OSIRIS [Meier 1992], and KOYO-F [Norimatsu 2007]. If the first wall liquid is sufficiently thick (~1 m), then this thick liquid wall additionally protects the structural materials of the reactor chamber from neutron damage, which is a particular challenge for fusion reactors. The HYLIFE [Blink 1985, Meier 1985, Fuerst WP], and HYLIFE-II [Moir 1994, Vay WP, Fuerst WP] reactor design concepts are examples that use a thick liquid, first wall. A solid/dry first walls can be protected from ion and photon damage by filling the chamber with a low pressure of noble gas (e.g. Sombrero [Meier 1992] used 0.5 std torr xenon), or potentially nano-engineered armor (e.g. tungsten)(Cusentino WP) can provide for sufficiently fast helium (the threat ion) migration out of the armor to prevent exfoliation of the armor by accumulated helium bubbles. Flowing liquid first walls were recommended by white papers of Andruczyk and of Shmayda.

The tritium breeding material in blankets is typically lithium through reaction with neutrons. The tritium breeding ratio is increased by adding a neutron multiplication material, with beryllium or lead (Pb) being the most considered [Fuerst WP]. Breeding materials can be solid granules of porous ceramics (e.g. LiO_2, Li_2TiO_3, Li_4SO_4), liquid metals (e.g. Li, PbLi), or molten salt (e.g. FLiBe) [Kolasinski WP, Fuerst WP]. IFE blanket concepts have used liquid lithium (HYLIFE, LIFE [Latkowski 2011]), liquid PbLi (KOYO-F), molten FLiBE (HYLIFE-II), and solid LiO_2 granules (Sombrero) [Fuerst WP]. Magneto-hydrodynamic (MHD) forces do not play a significant role for typical IFE blankets due lack of large magnetic fields at the chamber. For MFE blanket design, the large magnetic fields at the reactor chamber often cause MHD forces to be a significant design consideration. For MFE blankets US researchers have favored liquid PbLi (e.g the Dual coolant Lead Lithium [DCLL] blanket) [Fuerst WP] with helium gas coolant and RAFM structural materials [Shmayda WP], but many options are considered. Thus, there is considerable overlap in the development needs of blankets between MFE and IFE. As reported in the Kolasinksi white paper, “7 of the 8 near-term recommendations outlined for blanket development within the recent APS-DPP-CPP report ‘will equally benefit any fusion concept including tokamaks, stellarators, inertial fusion energy and alternate concepts’”. IFE should be able to leverage blanket R&D being undertaken in support of MFE. Such work includes development in the areas of: tritium extraction from PbLi, solid breeder material examination and characterization, PbLi compatibility with RAFM steel and SiC, and simulations of PbLi behavior [Shmayda WP]. Blanket development areas recommended by Kolasinski WP include improving experimental data and modeling of hydrogen diffusion and trapping in blanket materials (breeding materials and associated containment structural materials), and quantifying surface effects (adsorption and chemisorption) associated with hydrogen recombination and release. The white paper of Shmayda recommended R&D on irradiated lithium ceramics suspended in FLiBe; particularly: microstructure and stability of Li-rich ternary oxides, tritium retention/release from Li-rich ternary oxides, leaching of lithium from Li-rich ternary oxides in FLiBe, chemical compatibility of FLiBe with Li-rich ternary oxides, and irradiation effects and chemical compatibility of structural materials for FLiBe containment.

Tritium must be extracted from the breeder material of the blanket for use as fusion fuel for the reactor. The tritium extraction system (TES) is attached to or incorporated into the blanket for this purpose. The tritium extraction efficiency should be high to avoid hold up of tritium inventory within the breeder material. This will reduce reactor on-site tritium inventory. Lower tritium inventory on-site in the reactor improves the safety posture of the reactor. The white paper of Fuerst recommends a vacuum permeator for the TES as being more efficient than the Maroni process used by the LIFE reactor and showed some of the development of the vacuum permeator. The white paper of Andruczyk recommended a lithium/lithium hydride distillation column for the TES. The HYLIFE-II used a vacuum disengage (out permeation of tritium from FLiBe mini-droplets; Moir 1994). Helium sparging/purging of PbLi, FLiBe or porous ceramics can be used to extract tritium [Forsberg 2020]. Graphite structures used with FLiBe can be used to liberate tritium as TF or T_2 [Shmayda WP]. Carbon particle beds can be used to extract tritium with alternate heating of beds to release tritium [Forsberg 2020].

A neutron transport and activation code such as MCNP is used to model neutron heating and tritium breeding in the blanket. In addition, thermal hydraulic modeling of blanket fluids is an important part of blanket design. RELAP5-3D has been used successfully to model test loops of PbLi for the DCLL blanket [Meehan WP]. Proposed close coupling of MCNP and RELAP5-3D is expected to increase fidelity of designs.

The white paper of Shmayda pointed that the development a high flux DT neutron source by Phoenix LLC/SHINE Medical Technologies LLC ($4.6*10^{13}$ neutrons/s for 132 hours) offers opportunities for testing many aspects of blankets and breeding.

The effluent from the target chamber contains DT along with contaminants from other target materials, wall materials, and chamber protective gas if used (e.g. xenon). The tritium beta decay product ^{3}He will also be present. The effluent along with tritium extracted from the blankets needs to be treated to extract the deuterium and tritium at high purity, the correct DT ratio established, and ^{3}He removed prior to be sent to the target fuelling equipment. This is the function of the Tritium Processing System [Larson WP 1, Shmayda WP]. Impurities can include tritiated hydrocarbons (e.g. methane; from carbon in targets or structural steels), triated ammonia (from nitrogen in targets or structural material), and tritiated water (from oxygen and hydrogen in targets or structural material). This adds to the complexity of the stream that the TPS handles. Equipment in the TPS must survive the aggressive tritium beta-decay environment. Pumps are being developed and qualified, now that the existing supplier Noratex has closed [Camejo WP]. There is significant overlap between the TPS for IFE and MFE. This offers an area of joint development between IFE and MFE [Ulreich WP].

3. Summary of breakout session discussion

During the workshop we held a series of breakout discussions. During these sessions the workshop participants were split into ten groups, with the intent to cover a variety of perspectives. Each session was devoted to a specific topic, with example questions posed to the community by the program committee to focus the discussion. Each group had a moderator that provided a five minute outbrief to the entire workshop afterwards. The following executive summary is intended to capture the high-level sentiment of these outbriefs with areas of consensus, or lack of consensus, noted. Each session summary is organized by the questions posed.

Breakout 1 - Program

The first breakout discussions held at the workshop centered around high-level aspects of the program.

Question 1: What is the role and unique resources of the DOE/government?

Government support clearly has a role to play in the development of IFE, and presently has unique capabilities and resources. A potential role for FES is to coordinate broader efforts in addition to directly funding work on a broad base of science and technology. Presently government-funded institutions are the only entities with relevant facilities for IFE research, especially at the ignition scale for the foreseeable future. Discussion at the workshop suggested that the DOE should organize unique system design studies, within the program, to allow for an integrated assessment of various driver-target combinations, advance the state of the art in IFE and work towards an eventual focus in the program. Workforce development is a critically important area for the DOE to lead, both for the health of the IFE program itself and broader missions of the government.

Question 2: What is the role of private-public partnerships in this program?

The community strongly supports public-private partnerships in the IFE program. The discussion highlighted several areas in which improvements could be made to strengthen the partnerships, including streamlining agreements between industry, national laboratories and academia, for example by using a consortium style model. Identifying specific technology needs that could be matured by private industry, for example diodes, was supported. Discussion groups highlighted that embracing a partnership model could balance risk, with private funding willing to take on specific, potentially higher-risk, projects in parallel with a comprehensive DOE supported R&D program. A common concern raised among the attendees was in how intellectual property and findings would be handled by private entities.

Question 3: How do we have synergy with NNSA and leverage NNSA resources?

Productive collaboration with NNSA weapons science research, especially through the ICF program, is key to the success of an IFE program given the substantial capabilities developed by NNSA. We especially encourage identification of areas of common interest that can be developed to the mutual benefit of both programs, spanning both science and technology. Substantial desire exists among the IFE community to have greater access to NNSA user facilities if such agreements can be established. Workforce development clearly benefits both programs.

Question 4: Do we need a FES-funded IFE facility(ies) or laboratory(ies) for risk mitigation? If so what is the scale, given budget scenarios?

Strong consensus emerged for FES-funded facilities as part of an IFE program, albeit with some differing opinions on the nature of these facilities. The greatest need might be in areas that are IFE specific and outside the scope of the ICF mission. The community wants to identify the S&T drivers behind any new facilities so that the return on investment is strong. It was noted that current facilities in NNSA or the LaserNet program are already over-subscribed. A likely approach is to have a staged program, where early facility investments are targeted at modest scales to reduce risk, and implement capabilities lacking in current facilities. For example, kJ-class experiments at higher repetition rate and on novel LPI physics were raised. By addressing key issues on smaller-scale facilities the program can develop a path towards credible reactor-scale demonstrations. As discussed below, a DOE-sponsored cross-institution methodology for systems studies would be beneficial to identify critical topics in need of facilities to answer questions and retire risk.

Question 5: How do we foster collaborations, e.g. between NNSA + SC + DOD labs, universities, and private industry? And collaboration between MFE and IFE?

Building strong and successful collaborations will be key to the success of the IFE program, with many productive ideas identified in this discussion. A DOE-organized cross-institution methodology for systems studies would be beneficial. A center or consortium model was suggested to foster collaborations between laboratories and universities, as well as improved models for partnerships with industry. We strongly support collaborating with and leveraging the substantial investments made by the MFE community on challenges common to the reactor concepts, for example on neutronics and materials, wall materials, blankets, tritium handling, licensing, etc. Within the IFE program we support targeted investments on technology challenges that are specific to IFE, such as: specific materials (e.g. for optics), liquid blankets, target-related technologies, superconducting magnets for HIF [Bangerter WP] and advanced high power switching (ArF, pulsed power and HIF drivers) [McGeoch WP].

Question 6: Why now? What are the roles of FES and the other agencies?

As demonstrated by the high level of participation in the workshop, the community is active and excited about the prospects for IFE. Our excitement stems from both the recent encouraging results on NIF as well as a multitude of technological and scientific developments in the past decade, and the community is ready to tackle this grand challenge. There is a clear role for FES to coordinate and steward IFE, with an aim towards identifying a feasible path(s) to a demonstration reactor. The time to start this work is now, so that the potential for impact on major societal challenges can be realized on an appropriate timescale.

Breakout 2 - Drivers

Question 1: What should the program goals be to demonstrate TRLs of drivers? How does this tie in with the whole system's TRL?

The community strongly supports taking an integrated systems approach, considering the entire plant architecture and different driver-target combinations, to assessing the status of drivers or other aspects of the program, whether through TRL or another framework that is more appropriately defined for IFE. The TRL or other criteria should be supported by technical consensus. For drivers in particular, a “beamline” style approach could be appropriate with initial milestones aimed at demonstrating relevant performance parameters towards those necessary for a reactor. Any technologies that have broader applicability can be supported and developed in parallel.

Question 2: What is the consensus, or lack of consensus, about the status of the various technical approaches?

Differing opinions on the status of the technical approaches prevents any statements at this time about whether any approach is a clear leader. This workshop was in some sense the first reassessment of IFE since the National Academies reports on IFE (2013) almost a decade ago. Within laser driver technology it is recognized that both DPSSL and excimer technology has advanced and have differing benefits and drawbacks. A better understanding of the target physics requirements, especially on LPI, can inform this discussion. It was generally thought that pulsed power and heavy-ion drivers have had less historical investment and could benefit from investments to advance their TRL. A detailed study across the various approaches that assesses how much ‘extrapolation’ is needed in operating conditions would be valuable to inform the R&D approach.

Question 3: What is your consensus on the main challenges or hurdles for each approach?

In general the discussion identified several areas of R&D that would be productive for each driver approach, including improving our understanding of the target-physics requirements. For solid-state lasers this includes research on generating bandwidth, including through new materials, and the efficiency of the system. Experimental capability at higher rep rate and energy (e.g. kJ-class) would be valuable. For excimer lasers this includes developing solid-state switches, cathodes, optics, and power supply technology towards requirements for a reactor, as well as advancing the target-physics basis on LPI and implosion physics. Other laser approaches, such as fiber lasers, would benefit from research into beam combining and energy limitations. Laser-driven fast ignition approaches have a challenge in beam generation as well as building a laser with the required characteristics, as many designs use substantially higher short-pulse laser energies than have been demonstrated. Pulse-power approaches are challenged by the mass of the target and could potentially use an OMEGA-like facility to advance the physics basis. Heavy-ion research has lacked experimental capabilities which would answer beam physics and focusing questions at scale. However, some risk can be retired with new and existing high-intenstiy facilities (e.g, FAIR, SNS) and modest research investments in accelerator components to drive down costs. It was identified that all approaches have some significant common challenges: the need for credible high-gain physics designs, drivers that operate at relevant repetition rate with necessary reliability and durability, and potential limitations from the industrial base for component production.

Question 4: What are the major accomplishments in the last 5-10 years?

The recent results from NIF – demonstration of a propagating burn – are clearly recognized as advancing the physics basis for IFE. For laser-based approaches significant technological advances have been made in the last decade. These include the implementation of several diode-pumped lasers (e.g. HAPLS) operating at higher repetition rate as well as research on increasing bandwidth or other LPI mitigation approaches. Excimer lasers have shown 11 THz bandwidth in ArF. Fiber lasers have demonstrated a commercial 100kW system. Across the laser-based approaches we recognize significant advances in the physics understanding and computational capabilities for LPI. Pulsed power has advanced MIF type concepts on Z and shown improved technology, e.g. LTD. Heavy-ion fusion has conducted experiments at the ‘beamlet’ scale at LBNL, and the implementation of solid state high-power switching technology at the Scorpius radiography facility is noteworthy.

Question 5: What can be accomplished in 5 years (sustaining, healthy program, blue sky)?

There are common technological challenges that are relevant to multiple driver approaches, for example pulsed-power technology, that could significantly advance the field. The community is supportive of conducting systems-based studies of the various approaches, with robust peer review, to guide the research program. Laser-based approaches could significantly advance the understanding of LPI physics and mitigation in the near term. Developing small or mid-scale facilities operating at higher energies and higher repetition rate, potentially including beamlet-like demonstrations, would advance the science and technology basis for all approaches. Developing a broad community working on driver technologies with collaborative mechanisms is clearly beneficial.

Breakout 3 - Targets (Physics and Fabrication)

Question 1: What should the program goals be to demonstrate TRLs of targets? How does this tie in with the whole system's TRL?

Similar to other IFE system components, the community is supportive of a systems-based approach that considers the interaction between the target physics, target fabrication, driver approach, and other reactor aspects. For example, the target physics of LPI affects the constraints placed on laser-based approaches (drivers and targets). The fabrication can potentially affect the reactor systems, e.g. carbon affecting tritium breeding or other materials interacting with the wall. It was recognized that the major challenges for target fabrication, across all approaches, include demonstrating the specifications needed for robust target performance while simultaneously tackling mass production and cost efficiency. Advancing the TRL of advanced fabrication processes would be highly beneficial for this. Target injection and tracking was also identified as an area needing improved TRL, more complex or asymmetric targets (e.g. for fast ignition) may be more challenging. The target physics is more design dependent but must also be advanced to a point where a high-gain system is credible.

Question 2: What is the consensus, or lack of consensus, about the status of the various technical approaches?

As in other areas, there is a lack of any strong consensus about the relative merit of various approaches. In part this stems from the reality that concepts exist for all driver and target approaches but they have a varying level of maturity, for example substantial investment in laser indirect drive by NNSA has advanced the physics understanding of that approach. With downselection perhaps premature, an approach that targets the highest area of risk for each approach is needed. In general the lack of relevant experimental capabilities (e.g. at higher energy and repetition rate) was discussed here as well, in addition to demonstrating driver technologies these facilities would then advance the physics and target basis of those approaches.

Question 3: What is your consensus on the main challenges or hurdles for each approach?

Some challenges for specific approaches were identified in the discussion and could guide near-term R&D priorities. For laser indirect drive the complexity of targets and potential gain. For laser-based approaches using direct drive for compression and/or ignition, understanding LPI especially with newer laser technologies (e.g. bandwidth, etc) is critical to advancing the science basis. For fast ignition the generation and transport of the ignition beam is a primary challenge. Pulsed power target physics and debris is considered a challenge, and for heavy-ion fusion the lack of relevant experiments at relevant scales. The community recognized that there are many significant challenges that apply to all approaches, for example: the needed fabrication tolerances and link with resulting performance robustness, interaction of materials in the target with other aspects of the reactor system, mass economical target manufacture (presently in the field all complex targets are made one at a time), injection and tracking of the target, and tritium handling. Credible and validated modeling that can extrapolate performance into the high-gain regime is also a general need.

Question 4: What are the major accomplishments in the last 5-10 years?

The NIF experiment with a gain of 0.7 is a major result in target physics. Significant advancements in the state-of-the-art target quality have been made, for example the recent experiments on NIF. In parallel, technology to metrologize targets has been advanced by NIF's need and revealed new information on fabrication defects and tolerances. On the target physics side we recognize that our understanding and predictive capability has advanced significantly, including on LPI and hydrodynamics, and with advanced simulation methods: the combination of particle-in-cell and fluid codes, advanced LPI models, non-local heat transport, and 3-D hydrodynamics among others. New target physics concepts have emerged and progress on short-pulse-laser generated beam sources is recognized. The community is beginning to conduct experiments at higher repetition rates. Advanced fabrication methods like additive manufacturing are quickly advancing our capabilities.

Question 5: What can be accomplished in 5 years (sustaining, healthy program, blue sky)?

For target fabrication a dedicated effort to advance the TRL of mass manufacturing techniques that can plausibly meet reactor requirements is needed. This may require a diversity of approaches to cover various target physics concepts. Deploying an injection and tracking system on a current or upcoming rep-rated facility could significantly advance the TRL of this area, with drivers also adding beam steering, for a hit-on-the-fly demonstration. On target physics the discussion raised several key physics issues that are necessary to advance the scientific basis of the approaches, which could benefit from increased capability for higher energy and higher repetition rate experiments, including with more complex targets. For example, advancing the science case for LPI control for laser-based approaches. These are considered to be scientific facilities, developed in tandem with the need for ‘beamlet’ like driver technology development. At the ignition scale, testing advanced concepts on NIF, Z, and OMEGA would advance our understanding of the requirements for high gain in an eventual demonstration facility. For HIF targets, uncertainties of energy loss in plasmas and dense matter might be addressed with existing and new ion accelerator facilities.

Question 6: What is the path towards demonstrating IFE-relevant gain (after NIF 0.7)? With robustness (e.g. to positioning, target quality, driver-target coupling, etc)?

In the near term, NIF is the only facility capable of experiments with target gain near or exceeding unity. However, in its current configuration, it is considered unlikely that NIF will demonstrate IFE-relevant gain ($\gtrsim$50). We therefore ought to leverage the physics results from the NNSA program on NIF to improve our understanding of the scientific issues and inform requirements for IFE aspects like robustness, as well as potential tests of alternative designs, supported by the IFE program, at ignition scale. Eventually, the community considers that there will be a need for a dedicated high-gain facility for IFE. It is recognized that approaches which cannot be tested at the current large NNSA-supported facilities may suffer from a lack of data needed to assess the scientific basis of these concepts.

Question 7: What are the basic physics / predictiveness issues to address (e.g. LPI, hydro)?

The community clearly considers that furthering our understanding of LPI is critical for laser-based approaches. Developing the physics basis will have the clear benefit of informing requirements for other aspects of the system, e.g. the driver technologies potentially needed for mitigation. While LPI is not relevant for HIF target physics, uncertainties remain in beam-target coupling for the ion energy loss in hot dense matter. Improved predictiveness is clearly needed across approaches incorporating state-of-the-art simulation tools to model at disparate timescales, at higher resolution, and with improved physics models. With modern high-performance computing capabilities significant improvements are possible in modeling that were not feasible a decade ago. A better understanding of scaling physics, for example leveraging the NIF database, would advance the credibility of several approaches. Lastly hydrodynamics, for example non-linear Rayleigh-Taylor growth, are a common physics challenge, across IFE approaches.

Breakout 4 - Engineering

Question 1: What should the program goals be to demonstrate TRLs of technologies? How does this tie in with the whole system's TRL?

Several discussion groups identified that an evaluation mechanism, such as working groups or a multi-institution center for systems engineering design, would be beneficial to identify technologies that are in the most urgent need of R&D. It was generally thought that many reactor technologies needed advancements through development and that a parallel development path was necessary for timely program development. An IFE technology or concept test facility was proposed, in which engineering aspects could be tested at repetition rate. Engagement with private industry to develop and provide key technologies was suggested. Collaboration with MFE on common technologies is critical to rapid development without duplicated effort, however we must also ensure that any IFE-specific technological needs are addressed.

Question 2: What is the consensus, or lack of consensus, about the status of the various technical approaches?

In general reactor technologies are considered to have relatively low TRL, with some developmental work and concept studies existing. This is due in part to the hiatus in IFE-specific R&D in the past decade. A competitive development process, with funding from the IFE base, is clearly needed to advance our readiness.

Question 3: What is your consensus on the main challenges or hurdles for each approach?

First, there is a clear sense that we should focus limited resources on challenges that are either specific to IFE or considered ‘show stoppers’ for a credible reactor design. Some specific challenges that were discussed were the use of optics in a reactor environment for laser-based approaches, chamber clearing and extraction of products/debris after a shot. The optimal first wall and blanket approaches for IFE may differ from MFE and are in need of targeted R&D investment. Collaborating with the MFE community on upcoming facilities to test such technologies is critical.

Question 4: What are the major accomplishments in the last 5-10 years?

Several systems studies for IFE have been conducted over the last several decades, and guide our current thinking, but may be outdated due to more recent accomplishments. The discussion highlighted that significant advances have been made in driver technology over the last decade, as described above; this work includes several key technologies that now appear close to some requirements for a power plant. Similarly, progress towards high-quality target mass fabrication was highlighted here as well. On reactor-specific technologies we are encouraged by recent work on hydrogen retention in liquid lithium as well as progress made by the MFE community on materials science, tritium handling, blankets, etc.

Question 5: What can be accomplished in 5 years (sustaining, healthy program, blue sky)?

An organizing structure to guide R&D investment will be key. Ideas included systems research committees or funded centers for systems studies. This would encourage a rigorous development of a modern reactor concept for any approach based on the latest technologies, and for their assessment within a common framework. At present it is considered that individual technology maturation in parallel is appropriate, especially as IFE is a more separable problem with modular subsystems. Collaborating with the MFE community on new facilities for material and blanket testing is of high value, and enables our community to focus on components that are specific to IFE systems. This can include novel plasma facing components, blanket approaches, tritium handling, and unique challenges (for example, optics protection). Diagnostic needs for IFE reactors can also be assessed throughout.

Question 6: How do we collaborate with the MFE community on common topics?

As described previously, our community considers constructive collaboration with the MFE community critical to our success, and we strongly encourage coordination with the overlapping FES research programs to both avoid duplication and emphasize common challenges, especially those at a low TRL. Some areas of common interest discussed include contaminant removal from blankets, liquid lithium systems, including safety, updating 'handbooks' on liquid salts and metals, materials science, modeling of reactor systems, tritium handling, data/control systems, and licensing. Collaborating and supporting major investments in new facilities, including the FPNS, HHF, and BCTS, is an opportunity. At the same time, we must ensure that critical challenges specific to IFE are adequately supported. These include pulsed operations, potential inclusion of specific materials in target designs (carbon, gold, etc), and the need for optics and other driver components to perform in a reactor environment.

Breakout 5 - Closing Discussion

Question 1: What is the development pathway? Should it be tied to a specific reactor concept, or focus on modularity and low-hanging fruit common to multiple approaches? Modularity, when do you combine? How tie together into a system design.

At present, the community considers it premature to focus too specifically on a single reactor concept (driver and target design combination). This motivates an IFE program with a degree of diversification between approaches with R&D aimed at advancing those approaches to the point where more credible and consensus assessments of relative merits, using common metrics, can be addressed. For driver and target concepts the full scale physics is likely limited to existing NNSA facilities in the near term, so this program can mature the necessary science and technology, for example through 'beamline' type work that mitigates risk. We also highly encourage prioritizing the advancement of technologies that are broadly applicable to common problems across multiple, or all, approaches to IFE. One suggestion was to consider a ‘concept test facility’ incorporating both flexible driver options as well as the ability to develop and demonstrate key technologies and advance our ability to work with complicated experiments at higher repetition rate.

Question 2: Is there an appropriate ‘down-select’ timescale? Do we need small / intermediate-scale facility(ies), what would they demonstrate (e.g. rep rate, fuel cycle, …) to reduce risk, or can we leverage existing capabilities? Then, what is the time scale for an IFE demo? (blue sky, or other scenarios)

The community discussion led to a variety of opinions on the ‘down select’ question. First, a general sense is that the philosophy ought to at present be open to a diversity of approaches, and in the longer term that a role for the government may be in nurturing a broad-based program at an appropriate level for risk mitigation. Simultaneously the community clearly recognizes the need to balance the urgency of this problem with the risk of prematurely focusing on one approach, with many suggesting a timeline of several years to advance the field to a point where a consensus focused program could emerge. This suggests near-term investment into ‘beamline’ like demonstrations, at modest scale. For example modular or multi-wavelength laser facilities with bandwidth, operating at higher repetition rate, to understand LPI; an intermediate scale pulsed-power facility with modern technology; or heavy-ion beam experiments at more relevant conditions. As previously discussed there is a sense of need for our community to begin conducting experiments at higher repetition rate and higher energy than presently available, and also a sense that presently existing facilities already suffer from oversubscription. Any process that results in a more focused future program ought to be widely perceived as fair with accepted criteria for assessment to determine the approach(es) most likely to succeed.

Question 3: Scale of the program. How do we deal with the fact that an IFE plant is a NIF-scale undertaking?

At present, this community needs to advance the readiness of the underlying science and technologies before a demonstration plant could be credibly proposed. Simultaneously, we must keep an eye on a timeline for such a demonstration, for example ~2040 as is the goal in magnetic fusion, which sets near-term timelines to retire risk and move towards a design stage. There is little consensus on the eventual role of the government versus private industry in the eventual construction of a power plant demonstration, yet at present there is clearly a strong consensus for the government to support a program that both advances key science and technology, supports a broader R&D base than private companies, and advances the state-of-the-art in general tools and promotes workforce development. Supporting modern systems studies, related technology development, and collaboration within FES and other parts of the DOE on reactor technologies is an area critically important for the program in the near term.

Question 4: How do we tackle regulatory issues and social acceptance?

In the discussion there were a variety of opinions on our approach to regulatory framework issues, from those who advocate this is premature or that we ought to let other communities begin the work, to those that advocated stronger engagement now. We had strong consensus that our community should actively engage on social acceptance issues, for example through outreach campaigns with local communities, recruiting advocates, promoting an educational stream, and generally conveying to the public the excitement behind fusion while not overpromising results.

Question 5: How do we use this program to promote workforce development and DEI?

The community discussion strongly supports promoting both workforce development and DEI through this program. It was recognized that workforce development actually represents a key risk factor to the community, as limited progress can be made without adequate staff. For workforce development to be successful we will need stable long-term funding, and we will need to provide opportunity to students, postdocs, and early-career scientists to perform cutting-edge research. It was raised here that current facilities are oversubscribed, and additional capacity would be beneficial. In recruiting students it was clearly recognized that the energy mission is attractive and we should lean into that excitement, including by engaging earlier in the educational process. The LLE high school program was raised as a positive example of this. Development of a robust 'pipeline' is also key to addressing DEI in our future workforce and this was strongly supported, the discussion raised the fact that starting from 'scratch' with a new program on IFE is in fact an opportunity to build a better program for the future, and we should all actively consider DEI as we do so.

Question 6: What is the future role for technologies like machine learning in developing IFE?

The community is clearly interested in the application of new technologies like machine learning to the advancement of IFE. It was generally thought that application of ML will go hand-in-hand with the development of additional capabilities for conducting experiments at higher repetition rate, as is already being done, and that the introduction of more complex experiments at higher repetition rate will greatly increase the power of ML/AI methods as a catalyst. Such applications can span both the target physics, analysis of experiments, target characterization, fabrication, selection, and insertion, as well as driver control systems where rapid optimization becomes most desirable for high repetition rate experiments. A connection with rapid or additive manufacturing for target fabrication was identified. Training and developing staff with expertise in these novel technologies will be important to the future success of their application, which may be transformative for our field.

Question 7: Is there anything important missed in the earlier discussions?

As mentioned earlier, ensuring that limitations in workforce development or in the equipment or component supply chain for industry do not limit our ability to advance the energy mission of IFE is an important consideration. Collaboration with the international community was raised as a positive aspect, while being consistent with appropriate controls on classification and export. Lastly a discussion group succinctly stated – let's get started!

4. Observations and Recommendations

Based on the content of the workshop we have summarized several recurring themes of the white papers and discussion into a short list of observations and recommendations. Since the charge of this workshop was intentionally not oriented towards assessing the relative merits of any specific approach or technology, such work is left to future reports.

1. Guide research by systems-level assessments

It is apparent that the community strongly supports guiding our efforts with system-level assessments that will guide the work and investments towards areas of particular importance for IFE systems. Several forms in which this could be formed were suggested, for example a working group on systems studies, composed of experts; creating a multi-institution consortium (or consortia), similar to the HAPL project, which have clear goals; or organizing the community around a yearly workshop or other process. In terms of technical work, this could include identifying and tackling any subsystem integration studies with high impact to the overall systems maturity.

2. Leverage the modularity of IFE

Significant interest in driver “module” type capabilities, considered an important precursor to larger-scale concept tests, was expressed during the meeting, although without strong consensus on a particular scheme or approach. Such subscale capabilities can also support a parallel program on physics topics that need to be addressed for credible scaling to robust high gain, while developing technology. That such work can be conducted at a variety of scales and in parallel embraces the modular aspect of IFE.

3. Timeline and process for focusing the program

The community is hesitant to identify a specific timeline for attempting to focus a program on a subset of IFE approaches. Simultaneously, we have a sense of urgency that dictates that the IFE program should aim for reasonable timelines for IFE to become a reality – for example a similar timeline to the 2040 goal adopted by the MFE community. A strategy for this challenging aspect of the program definition is beyond the scope of this workshop, including the fact that no specific budget scenarios were considered in detail. For future processes, this community-led workshop did have substantial discussion on the potential limitations of a strict application of standard (e.g. NASA-type) ‘TRL’ ratings to fusion approaches, which are not uniformly accepted. This potentially motivates a new methodology which is rigorous and applicable for assessing the relative readiness of disparate approaches and/or system components (e.g. wherever we use the term TRL in this report). If and when the program becomes more focused, maintaining a base level of broad research supported by the government was considered important, which leaves open the possibilities of leapfrog technologies or surprising R&D developments.

4. Building the research community

A productive and collaborative research community is critical to the success of this endeavor. IFE has some unique opportunities and challenges in this, which were discussed in the workshop. First, it is clear that a productive engagement with the science programs under NNSA are absolutely essential – including both technical areas of common interest, plus coordinating on facility use and workforce development. Given the growing investment by the private sector in fusion, it is clearly important that we have productive mechanisms for collaboration with private industry and that current mechanisms, such as CRADAs, are cumbersome or difficult to execute in a timely fashion. There is no substitute for tackling topics unique to IFE directly and systematically. Also, another recurring theme was that we strongly support and encourage productive collaboration with the MFE community on technologies and topics of common interest. Last but not least, the community recognizes that a healthy and growing workforce will be key for execution of the IFE program and we clearly support efforts to incorporate diversity, equity, and inclusion efforts in the development of our future workforce.

Appendix A: Agenda

Tuesday November 16th (Kickoff Meeting)

8:00	Kickoff and Goals	Alex Zylstra
8:15	Inertial Fusion Energy (IFE): Opportunities and Challenges	Mike Campbell
8:45	And Now on to Higher Gains: Physics Platforms and Minimum Requirements for Inertial Fusion Energy	John Perkins
9:15	High Average Power Laser Program (HAPL) with notes on earlier IFE studies and current ARPA-E BETHE IFE program	Steve Obenschain
9:45	*Break*	
10:00	Self-consistent design considerations for commercial laser fusion energy	Mike Dunne
10:30	Inertial fusion energy considerations for magnetized liner inertial fusion	Matt Gomez
10:50	Ions and IFE –A perspective from Berkeley Lab	Thomas Schenkel
11:10	N210808 and some speculations on what it implies for IFE	Omar Hurricane
11:40	*Break*	
11:50	A UK Perspective on IFE	Robbie Scott
12:10	Progress and Prospect of IFE research in Japan	Ryosuke Kodama
12:30	Focused Energy Perspective on Inertial Fusion Energy	Todd Ditmire
12:50	Call for whitepapers	Peter Seidl

Tuesday February 22nd

(Times Pacific)

7-7:10	Intro and goals		Alex Zylstra
7:10	Sponsor perspectives		
	7:10-7:40	FES	Jim Van Dam, Kramer Akli
	7:40-7:55	ARPA-E	Scott Hsu
	7:55-8:10	NNSA	Ann Satsangi
	8:10-8:25	VC (PM)	Carly Anderson
8:25-8:45	Roundtable with sponsors		
8:45-9:00	Break		
9:00-10:00	Plenary Talks		

"The Rationale for an Expanded Inertial Fusion Energy Program" Steve Dean (FPA)

"High-level requirements for an IFE development program" Mike Dunne (SLAC)

"Proposal to Build an Academic IFE High Energy Laser Research Facility as a Public-Private Partnership" Todd Ditmire (UT/FE)

10:00-10:20 Breakout organization and info

Breakout 1 topic: Program
Questions:

- What is the role and unique resources of the DOE/government?
- What is the role of private-public partnerships in this program?
- How do we have synergy with NNSA and leverage NNSA resources?
- Do we need a FES-funded IFE facility(ies) or laboratory(ies) for risk mitigation? If so what is the scale, given budget scenarios?
- How do we foster collaborations, e.g. between NNSA + SC + DOD labs, universities, and private industry? And collaboration between MFE and IFE?
- Why now? What are the roles of FES and the other agencies?

10:20-11:30 Breakouts (parallel discussion sessions)
11:30-12:00 Lunch
12:00-12:45 Breakouts
12:45-1:00 Break
1:00-2:00 Breakout out briefs
2:00-3:00 Quad chart presentations in breakout groups

Wednesday February 23rd

(Times Pacific)

7:00-8:00 Plenary talks (Drivers)

"Ion beams and Inertial Fusion Energy" Thomas Schenkel (LBNL)
"Advanced laser concepts and technologies for laser direct-drive inertial fusion energy (LDD-IFE)" Jon Zuegel (LLE)
"Inertial Fusion Energy Technology: Repetitive Driver-Target Coupling in Hostile Fusion Chamber Environment" Simon Bott-Suzuki (UCSD)

8:00-8:10 Breakout info

Breakout 2 topic: Drivers
Questions:

- What should the program goals be to demonstrate TRLs of drivers? How does this tie in with the whole system's TRL?

- What is the consensus, or lack of consensus, about the status of the various technical approaches?
- What is your consensus on the main challenges or hurdles for each approach?
- What are the major accomplishments in the last 5-10 years?
- What can be accomplished in 5 years (sustaining, healthy program, blue sky)?

8:10-9:30	Breakout 2
9:30-9:45	Break
9:45-10:45	Breakout out briefs
10:45-11:15	Lunch

11:15-12:15 Plenary Talks (Targets)

"Fast ignition inertial fusion energy using laser-driven ion beams"	Brian Albright (LANL)
"Inertial Fusion Energy Target Designs with Advanced Laser Technologies"	Valeri Goncharov (LLE)
"Target mass production for inertial fusion energy"	Neil Alexander (GA)

12:15-12:25 Breakout info

Breakout 3 topic: Targets (physics and fab)
Questions:

- What should the program goals be to demonstrate TRLs of targets? How does this tie in with the whole system's TRL?
- What is the consensus, or lack of consensus, about the status of the various technical approaches?
- What is your consensus on the main challenges or hurdles for each approach?
- What are the major accomplishments in the last 5-10 years?
- What can be accomplished in 5 years (sustaining, healthy program, blue sky)?
- What is the path towards demonstrating IFE-relevant gain (after NIF 0.7)? With robustness (e.g. to positioning, target quality, driver-target coupling, etc)?
- What are the basic physics / predictiveness issues to address (e.g. LPI, hydro)?

12:25-1:45 Breakout 3

1:45-2:00	Break
2:00-3:00	Breakout outbriefs

Thursday February 24th

(Times Pacific)

7:00-8:00 Plenary talks (Engineering)

"Common Challenges Facing Future MFE and IFE Power Plants" — Jeff Ulreich (ORNL)

"Areas of Common Need and Leverage in Near-future IFE and MFE Materials Development" — Lance Snead (Stony Brook)

"Performance Enhancements for the National Ignition Facility and Contributions to Inertial Fusion Energy" — Jean-Michel Di Nicola (LLNL)

8:00-8:10 Breakout info

Breakout 4 topic: Engineering

Questions:

- What should the program goals be to demonstrate TRLs of technologies? How does this tie in with the whole system's TRL?
- What is the consensus, or lack of consensus, about the status of the various technical approaches?
- What is your consensus on the main challenges or hurdles for each approach?
- What are the major accomplishments in the last 5-10 years?
- What can be accomplished in 5 years (sustaining, healthy program, blue sky)?
- How do we collaborate with the MFE community on common topics?

8:10-9:30 Breakout 4

9:30-9:45 Break

9:45-10:45 Breakout outbriefs

10:45-11:15 Lunch

11:15-12:15 Plenary Talks

"Accelerated Scientific Discovery with AI-driven Experiments in support of IFE" — Derek Mariscal (LLNL)

"Path to reduced-size laser fusion power plants with direct drive using the argon fluoride laser" — Steve Obenschain (NRL)

"Integrated Design of Robust System for Inertial Fusion Energy" — Debbie Callahan (LLNL)

12:15-12:25 Breakout info

Breakout 5 topic: Closing discussion

Questions:

- What is the development pathway? Should it be tied to a specific reactor concept, or focus on modularity and low-hanging fruit common to multiple approaches? Modularity, when do you combine? How tie together into a system design.
- Is there an appropriate 'down-select' timescale? Do we need small / intermediate-scale facility(ies), what would they demonstrate (e.g. rep rate, fuel cycle, …) to reduce risk, or can we leverage existing capabilities? Then, what is the time scale for an IFE demo? (blue sky, or other scenarios)
- Scale of the program. How do we deal with the fact that an IFE plant is a NIF-scale undertaking?
- How do we tackle regulatory issues and social acceptance?
- How do we use this program to promote workforce development and DEI?
- What is the future role for technologies like machine learning in developing IFE?
- Is there anything important missed in the earlier discussions?

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12:25-1:45	Breakout 5
1:45-2:00	Break
2:00-3:00	Breakout outbriefs

Appendix B: White Papers

Links to white papers / quad charts in a list. Categorization?

	Author Last Name	Institution	Paper Title
1	Albright, Brian	Los Alamos National Laboratory	Fast ignition inertial fusion energy using laser-driven ion beams
2	Alexander, Neil B.	General Atomics	Target injection, and engagement for inertial fusion energy
3	Alexander, Neil B.	General Atomics	Target mass production for inertial fusion energy
4	Anderson, Kenneth	University of Rochester	Shock Ignition: High Gain Target Performance for Inertial Fusion Energy
5	Andruczyk, Daniel	Department of Nuclear, Plasma and Radiological Engineering	The need and development of liquid metal plasma facing components and blanket using TEMHD for an IFE device
6	Bangerter, R.O.	Lawrence Berkeley National Laboratory	Systems Studies, Accelerator Design, Target Design and Enabling Technologies for Heavy Ion Fusion
7	Bodner, Stephen E.	Retired. Head of NRL laser fusion program from 1975 to 1999.	An Evaluation of Laser Fusion Energy Concepts
8	Boehm, Kurt	General Atomics	Target Layering for Inertial Fusion Energy
9	Bott-Suzuki, Simon	University of California San Diego	Inertial Fusion Energy Technology: Repetitive Driver-Target Coupling in Hostile: Fusion Chamber Environments
10	Burke, Bob		Whitepaper: Overview of IFE Workshop Submissions for Heavy Ion Fusion
11	Callahan, Debbie	Lawrence Livermore National Lab	Integrated Design of Robust System for Inertial Fusion Energy
12	Camejo, Cesar D.	Los Alamos National Laboratory	Demonstrating Pump Performance for Fusion Fuel Cycle Conditions

13	Christophers on, Alison	Lawrence Livermore National Laboratory	High gain target designs for inertial fusion energy
14	Claus, Liam	Advanced hCMOS Systems	Commercialized hCMOS imagers for IFE diagnostics
15	Cusentino, Mary Alice	Sandia National Laboratories	Radiation Tolerant Materials by Design for Inertial Fusion Energy
16	Dean, Stephen O.	Fusion Power Associates	The Rationale for an Expanded Inertial Fusion Energy Program
17	Dean, Stephen O.	Fusion Power Associates	Beyond the physics and demonstration of ignition
18	Di Nicola, JM.	Lawrence Livermore National Laboratory	Performance Enhancements for the National Ignition Facility and Contributions to Inertial Fusion Energy
19	Ditmire, Todd	Dept. of Physics, University of Texas at Austin, and Focused Energy Inc.	Proposal to Build an Academic IFE High Energy Laser Research Facility as a Public-Private Partnership
20	Dunne, Mike	SLAC National Accelerator Laboratory	High Level Requirements for an IFE Development Program
21	Dyer, G.M.	SLAC National Accelerator Laboratory	Opportunities for an Inertial Fusion Energy Program within the context of the Matter in Extreme Conditions Upgrade Project
22	Edwards, Matthew R.	Lawrence Livermore National Laboratory	Gas and Plasma Final Optics for Inertial Fusion Energy Lasers
23	Frenje, Johan A.	Plasma Science and Fusion Center, MIT	γ-ray spectrometry for diagnosing high-repetition-rate Laser Direct-Drive Inertial-Fusion-Energy implosions
24	Fuerst, T.F.	Fusion Safety Program, Idaho National Laboratory	Efficient tritium extraction from PbLi: a potential IFE breeding material
25	Galea, Christopher	Princeton Fusion Systems	Wide Bandgap Power Electronics for Inertial Confinement Fusion
26	Galvanauska s, Almantas	University of Michigan	Feasibility of fiber lasers for laser fusion
27	Galloway, Conner	Xcimer Energy	ASPEN Laser and A New IFE Power Plant Concept

28	Gleason, A.	SLAC National Accelerator Laboratory	Three-dimensional ultrafast X-ray visualization of laser-driven wetted foam targets in implosions and planar geometry to develop low-cost, rep-rated IFE targetry
29	S. H. Glenzer	SLAC National Accelerator Laboratory	X-ray Free Electron Laser Driven Fast Ignition
30	Goncharov, V.N.	University of Rochester, Laboratory for Laser Energetics	Inertial Fusion Energy Target Designs with Advanced Laser Technologies
31	Gopalaswamy, V.	Lawrence Livermore National Laboratory	Validating IFE Concepts with Machine Learning Driven Design Optimization
32	Häfner, Constantin	Fraunhofer-Institute for Laser Technology ILT and RWTH Aachen University	Status and Perspectives of High-Power Pump Diodes for Inertial Fusion Energy Lasers
33	Häfner, Constantin	Fraunhofer-Institute for Laser Technology ILT and RWTH Aachen University	Inertial Fusion Energy Drive Technology
34	Haid, Alex	General Atomics	Additive Manufacturing for Inertial Fusion Energy Target Production System
35	Harding, D. R.	University of Rochester, Laboratory for Laser Energetics	An automated IFE Target Factory based the "Lab-on-Chip" format
36	Heuer, Peter	Laboratory for Laser Energetics, University of Rochester	Accelerating the science, technology, and workforce base for inertial fusion energy with a proposed high repetition rate facility
37	Hurricane, O.	Lawrence Livermore National Laboratory	Optimism is not a strategy: A white paper on how to give IFE a fighting chance to be real
38	Hu, S.X.	Laboratory for Laser Energetics, University of Rochester	Enabling Advanced Ablator Materials for High-Gain Inertial Fusion Energy (IFE) Target Design
39	Kaganovich, Igor, D.	Princeton Plasma Physics Laboratory	Collective Effects and Intense Beam-Plasma Interactions in Ion-Beam-Driven High Energy Density Matter and Inertial Fusion Energy
40	Kazuki Matsuo	EX-Fusion Inc, Japan	EX-Fusion's challenge for the realization of laser fusion system

41	Kemp, A.	Lawrence Livermore National Laboratory	Electron-driven fast-ignition approach to IFE
42	Kirkwood, Robert	Lawrence Livermore National Laboratory	Enabling Ignition Studies and Advanced Power Plants by Development of Ultra High Fluence Beams Produced by Plasma Optics
43	Kodama, R.	Institute of Laser Engineering, Osaka University	Fast Track Approach towards Laser Fusion Energy in Japan
44	Kolasinski, R.D.	Sandia National Laboratories	Materials science R&D required for the design of inertial fusion energy tritium breeding blankets
45	Larsen, George	Savannah River National Laboratory	Highly Scalable Deuterated Polymer Development for IFE Targets
46	Larsen, George	Savannah River National Laboratory	Combined Fuel Cycle Modeling and Process Development for IFE
47	Le Pape, Sébastien	LULI, Ecole Polytechnique	Inertial Fusion Science & Technology at the Laboratoire pour l'Utilisation des Lasers Intenses
48	Malko, Sophia	Princeton Plasma Physics Laboratory	Importance of ion stopping power research for IFE
49	Matsuo, Kazuki	EX-Fusion Inc, Japan	EX-Fusion's challenge for the realization of laser fusion system
50	Mariscal, D.A.	Lawrence Livermore National Laboratory	Accelerated Scientific Discovery with AI-driven Experiments in support of IFE
51	McGeoch, M.W.	NRL Plasma Physics Division, Laser Plasma Branch	Durable Solid State Pulsed Power for ArF Direct Drive Fusion and Other Fusion Concepts
52	Meehan, Nicholas	University of Tennessee-Knoxville	Demonstration of Fusion Blanket Simulations for Anticipated Operational Occurrences with RELAP5-3D
53	Mehlhorn, TA	University of Rochester Laboratory for Laser Energetics	p-B11 ignition via ps & ns lasers: burn physics, target design, & experimental validation
54	Mo,	SLAC National Accelerator	Advance the understanding of radiation damage

	Mianzhen	Laboratory	in fusion materials using ultrafast time-resolved electron diffraction
55	Moody, J.D.	Lawrence Livermore National Laboratory	Boosting the performance of IFE targets with magnetized fuel
56	Morozov, V.S.	Oak Ridge National Labratory	Benchmarking and Validation of IFE Driver Technology
57	Obenschain, Steve	Plasma Physics Division, U.S. Naval Research Laboratory	Path to reduced-size laser fusion power plants with direct drive using the argon fluoride laser
58	Obst-Huebl, L.	Lawrence Berkeley National Laboratory	BELLA PW 1 Hz Laser Experiments for Short Pulse Laser-based Ion Fast Ignition for IFE
59	Olson, Rick	Los Alamos National Laboratory	A polar direct drive liquid deuterium-tritium wetted foam ICF target concept
60	Ogitsu, Tadashi	Lawrence Livermore National Laboratory	Theory of Quantum Effect on Degenerate Dense Plasma
61	Paddock, R.W.	University of Oxford	Potential High Gain Target Designs for IFE
62	Payne, Stephen A.	Lawrence Livermore National Laboratory	Long-Wavelength Diode-Pumped Solid-State Lasers as Inertial Fusion Energy (IFE) Drivers
63	Schenkel, Thomas	Lawrence Berkeley National Laboratory	Ion beams and Inertial Fusion Energy
64	Scott, G.G.	Lawrence Livermore National Laboratory	High repetition rate diagnostics with integrated machine learning analysis for a new paradigm of actively controlled Inertial Fusion Energy experiments
65	Sentoku, Y.	Institute of Laser Engineering, Osaka University	Research of laser fusion system based on fast ignition scheme in Japan
66	Sherlock, M.	Lawrence Livermore National Laboratory	Modeling Capabilities for Inertial Confinement Fusion
67	Shmayda, Walter T.	University of Rochester, Laboratory for Laser Energetics	Fuel Cycle for an Inertial Fusion Energy Reactor: Isotope Separation and Breeder Blankets
68	Simpson, Raspberry	Massachusetts Institute of Technology	Inertial Fusion Energy (IFE) Workforce Development: Development of a New National

			IFE Research Consortium (IRC)
69	Sweet, W.S.	General Atomics	Wetted Foam Targets for IFE Applications
70	Tang, Vincent	Lawrence Livermore National Laboratory	Initial Thoughts on Public Private Partnerships and Consortium Models for IFE
71	Tang, Vincent	Lawrence Livermore National Laboratory	Reference: History of Inertial Fusion Energy Research at LLNL
72	Tikhonchuk, V.T.	ELI-Beamlines Center, Institute of Physics, Czech Academy of Sciences	Kilojoule, nanosecond testbed development and operation for 2-omega laser-plasma interaction using novel targetry.
73	Ulreich, Jeffrey	Oak Ridge National Labratory	Common Challenges Facing Future MFE and IFE Power Plants
74	Van Tilborg, Jeroen	Lawrence Berkeley National Laboratory	Characterizing IFE dynamics with high-resolution laser-plasma-based diagnostics
75	Vay, J.-L.	Lawrence Berkeley National Laboratory	Propagation of Ion Beams in a Heavy-Ion Inertial Fusion System
76	Wang, Zhehui (Jeph)	Los Alamos National Laboratory	Physics-informed multiprobe instrument for IFE experiments (PiMIX)
77	Wilks, S.C.	Lawrence Livermore National Laboratory	Short Pulse Laser based Ion Fast Ignition for IFE
78	Wilks, S.C.	Lawrence Livermore National Laboratory	Laser Beam Propagation through Target Debris and Mitigating Gas for IFE
79	Williams, G.J.	Lawrence Livermore National Laboratory	Spinoff Technologies from the Development of Short Pulse Lasers for Fast Ignition IFE
80	Woodruff, Simon	Los Alamos National Laboratory	The SciVerse: a Metaverse for Scientists, Engineers and Scientific Outreach
81	Xiao, Steve X.	SRNL	Concept of Using Alternative Inertial Fusion Fuel
82	Zuegel, J.D.	University of Rochester, Laboratory for Laser Energetics	Advanced Laser Concepts and Technologies for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE)
83		LaserNetUS	LaserNetUS – Research Opportunities in IFE

Appendix C: Committees

This workshop was organized by the following committees

Steering committee

Mike Campbell

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Naval Research Laboratory

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Appendix D: List of acronyms

IFE Inertial fusion energy
ICF Inertial confinement fusion
HIF Heavy ion fusion
DPSSL Diode pumped solid state laser
KrF krypton fluoride
ArF argon fluoride
CPA chirp pulse amplification
COPA collinear optical parametric amplifier
FAIR Facility for Anti-proton and Ion Research at GSI, Germany
NOPA non-collinear optical parametric amplifier
HAPL High Average Power Laser Program
HAPLS High Repetition Rate Advanced Petawatt Laser System
Yb:YAG Ytterbium-doped Yttrium Aluminum Garnet
ND:Glass Neodymium Glass

Tm:YLF Thulium-doped Yttrium Lithium Fluoride
Er Erbium
Tm Thulium
Ho Holmium
AI Artificial Intelligence

MagLIF magnetized liner inertial fusion
RTL recyclable transmission line
Rep-rate repetition rate

HYPERION Hydrogen-production plant and Energy Reactor of Inertial-fusion

J Joules

Hz Hertz

W Watts

S seconds

CBET: Cross-Beam Energy Transfer
FLUX: Fourth-Generation Laser for Ultrabroadband eXperiments
HRR: High Repetition Rate
LPI: Laser-Plasma Instability
ML: Machine Learning
SBS: Stimulated Brillouin Scattering
SRS: Stimulated Raman Scattering
TPD: Two-Plasmon Decay
FI – fast ignition
IFI – ion fast ignition
TN – thermonuclear
ICF – inertial confinement fusion
NIF – the National Ignition Facility
ARC – advanced radiographic capability (on the NIF)
LLE – Laboratory for Laser Energetics
IFE – inertial fusion energy
TNSA – target normal sheath acceleration
RPA – radiation pressure acceleration
BOA – break-out afterburner
ISWA – ion solitary wave acceleration

STUD – spike trains of uneven duration and delay
DT – deuterium/tritium
DD – deuterium/deuterium
TRL – technology readiness level
PIC – particle-in-cell
Omega-EP – Omega Extended Performance laser at LLE
LFEX – Laser for Fast Ignition Experiment (Osaka University's Institute for Laser Engineering)
GEKKO – a laser facility at the Osaka University's Institute for Laser Engineering

BCTS - Blanket Component Test Facility
FPNS - Fusion Prototypic Neutron Source
HHF - High Heat Flux
MHD - Magneto hydrodynamic
LTD - Linear transformer driver
TPS - Tritium Processing System

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