Physics of Plasmas

PERSPECTIVE | FEBRUARY 28 2024

From KMS Fusion to HB11 Energy and Xcimer Energy, a personal 50 year IFE perspective

Special Collection: Private Fusion Research: Opportunities and Challenges in Plasma Science

Thomas A. Mehlhorn

Phys. Plasmas 31, 020602 (2024)
https://doi.org/10.1063/5.0170661

Check for updates

View Online
Export Citation
CrossMark

21 March 2024 03:34:24

Physics of Plasmas
Features in Plasma Physics Webinars
Register Today!
AIP Publishing

AIP Publishing

Physics of Plasmas PERSPECTIVE pubs.aip.org/aip/pop

From KMS Fusion to HB11 Energy and Xcimer Energy, a personal 50 year IFE perspective

Cite as: Phys. Plasmas **31**, 020602 (2024); doi: 10.1063/5.0170661
Submitted: 3 August 2023 · Accepted: 29 January 2024 ·
Published Online: 28 February 2024

View Online Export Citation CrossMark

Thomas A. Mehlhorn[a)]

AFFILIATIONS

Mehlhorn Engineering Consulting Services, Beaverton, Oregon 97003, USA

Note: This paper is part of the Special Topic: Private Fusion Research: Opportunities and Challenges in Plasma Science.
[a)] **Author to whom correspondence should be addressed:** Tamehlhorn97@gmail.com

ABSTRACT

Shortly after the laser was invented in 1960, scientists sought to use it for thermonuclear fusion. By 1963, Livermore had a classified laser inertial confinement fusion (ICF) program and leaders predicted scientific breakeven by 1973. In 1974, KMS Fusion, Inc. announced thermonuclear neutrons from a laser target and promised grid electricity within 10 years. Private capital was attracted, but the data fell far short of the optimistic simulations. Magnetic fusion energy has had civilian funding (DOE), while ICF has primarily received military funding (DOE Defense Programs and now NNSA). As bigger lasers have been built and better simulations performed, optimism about ICF breakeven has waxed and waned. The achievement of ignition and gain on NIF has validated ICF's scientific basis, and the DOE and venture capital funded private companies are again interested in inertial fusion energy (IFE). The new DOE Milestone-Based Fusion Development Program is creating public–private partnerships to accelerate progress toward fusion pilot plants. ARPA-E, DOE INFUSE, and DOE IFE STAR are also building a U.S. IFE program within DOE. The U.S. leads in ICF, but developing IFE is an international competition. Private companies are leading the way. HB11 Energy Pty Ltd. is pursuing the aneutronic proton–boron fuel cycle. Xcimer Energy is developing a disruptive IFE technology to achieve high laser energies at dramatically lower costs. This 50-year perspective discusses where the U.S. IFE program is headed and promising strategies for progress in establishing an effective U.S. IFE program from both public and private perspectives.

© 2024 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/5.0170661

I. INTRODUCTION

The 64th Annual Meeting of the American Physical Society (APS) Division of Plasma (DPP) (Spokane, WI–2022) included a novel four-part mini-conference[1] on the newly established Department of Energy (DOE) Public–Private Partnerships (PPP) for Fusion Energy. The Monday morning kickoff session was standing room only, with a substantial number of people spilling out into the hallway. Recent technological advances and successes in both magnetic[2] and inertial confinement fusion experiments,[3] a significant growth in venture capital (VC) funded private fusion companies, and the initiation of the DOE Milestone-Based Fusion Development Program[4] that encourages public–private partnerships as an opportunity to accelerate fusion energy research, development, and demonstration (RD&D), made this post-COVID APS DPP meeting one of the liveliest in recent memory. The mini-conference speakers included DOE fusion leaders, national lab managers and researchers, representatives from numerous private fusion companies, university professors, and supply chain vendors.

Most of the fusion sessions in the APS DPP over the past 15 years have been dominated by presentations on magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). MCF presentations include reports on experiments on existing tokamaks, such as DIII-D, EAST, JET, and K-STAR, as well as progress reports on the construction of ITER and plans for commissioning experiments. In 2018, Commonwealth Fusion Systems (CFS)[5] was formed and began reporting on their plans to build a compact tokamak fusion power plant called SPARC[6] (see Sec. III D). ICF presentations include reports on experiments on direct drive at OMEGA as well as progress in indirect drive on NIF, which succeeded in exceeding the Lawson criterion for ignition in 2022.[7] Until recently, there were a limited number of private fusion companies that were mainly exploring alternative magnetic confinement schemes and/or alternate fuel cycles, and their impact on the APS DPP was likewise limited. The exponential growth of private fusion companies during the COVID hiatus from in-person meetings, as well as the appearance of the first private IFE companies, made the mini-conference on the DOE PPP Fusion Program an exciting and timely event.

The mini-course participants were energized by the vision of finally moving beyond establishing the scientific proof of principle for

21 March 2024 03:34:24

various fusion approaches to designing and building prototype fusion power plants (FPP). The talks by the fusion companies described technological advances, aggressive schedules, and action-based plans that often called for the staged construction of increasingly more capable systems. Students were further energized by the prospects of a greatly expanded fusion job market. An additional element of this excitement was that the U.S. government had announced a bold vision for commercial fusion energy,[8] including an initiative to develop a decadal strategy to accelerate its viability in partnership with the private sector that is based on the 2021 National Academies of Sciences, Engineering, and Medicine (NASEM) report *Bringing Fusion to the U.S. Grid*.[9] A major component of developing this decadal strategy is to identify the scientific and technological gaps for each fusion energy approach, develop plans to address them, and then initiate programs to fill them that harness the collective efforts of national labs, universities, and private companies through large-scale public–private partnerships. Of particular significance to this article is that while the NASEM report was focused on tokamaks, the DOE Milestone-Based Fusion Development Program has expanded the initiative to include a varied range of approaches to commercial fusion energy,[10] including compact and spherical tokamaks; two stellarators; a magnetic mirror; a shear-flow stabilized z-pinch; and two inertial fusion energy (IFE) concepts: (1) laser fusion via high-energy excimer laser and (2) laser-driven proton fast ignition.

I was personally excited that after an almost 50-year career in inertial fusion research at national laboratories, I was seeing a convergence of public and private efforts in designing, constructing, and operating a fusion pilot plant with the goal of producing electricity in the 2035–2040 timeframe and paving the way for commercial development. Further, I have had the privilege to contribute to both public and private efforts. For example, on the public side, I was a member of the alternate concepts panel at the 2022 DOE Basic Research Needs (BRN) for Inertial Fusion Energy Workshop. On the private side, I am a member of the Scientific Advisory Board and a consultant to HB11 Energy Pty, Ltd.,[11] a company that is pursuing the aneutronic proton–boron fuel cycle. My focus at HB11 is on understanding the burn space of the proton–boron fuel cycle and using this knowledge to develop an IFE target point design that defines the laser driver and reactor chamber requirements for a fusion pilot plant. I am also a member of the Technical Advisory Board of Xcimer Energy, Inc.,[12] which is developing a disruptive IFE technology to achieve high laser energies at dramatically lower cost using an advanced KrF or ArF laser architecture. Uri Shumlak invited me to contribute this perspective article to the Private Fusion Research special edition because of my association with these private IFE companies as well as my long association with IFE. I am excited to be advising HB11 and Xcimer, as well as by the prospect that they, or one of the 43 private fusion companies listed in the most recent report of the Fusion Industry Association,[13] will leverage over \$6 billion in venture capital investment (over multiple years) to successfully build and operate a fusion pilot plant. However, my enthusiasm is tempered by my 50-year perspective on the challenges of IFE (and all fusion approaches) development, beginning with my visit in 1973 to the first private IFE company, KMS Fusion, in Ann Arbor, Michigan. Many, but not all, of these private companies have been formed and are being staffed by people who are relative newcomers to fusion research and have neither personally experienced these challenges nor know the history. Furthermore, on the public side, many of the DOE program managers and congressional staffers have had limited involvement in IFE research and could benefit from an up-to-date summary of its history. Therefore, this perspective paper has three purpose: (1) to provide a brief overview of IFE research since the early 1970s and how optimism about ICF breakeven has waxed and waned; (2) to introduce two private IFE companies, HB11 Energy and Xcimer Energy, and to describe their goals and challenges; and (3) to discuss some opportunities and challenges in plasma science and technology for IFE public–private partnerships.

The overarching goal of this article is to provide a perspective on the development of IFE fusion pilot plants and demonstration reactors within a public–private partnership framework that is informed by an overview of the ups and downs of IFE research over the past 50 years. Section II discusses the invention of the laser, the first private and public ICF research programs, and the early optimism that breakeven and energy production were on the horizon. Section III contains a brief historical overview of U.S. IFE efforts, including the High Average Power Laser (HAPL) program and the 2002 Fusion Energy Sciences Summer Study in Snowmass, Colorado. Section III A describes the 2013 NASEM Assessment of the Prospects for IFE, the failure of the National Ignition Campaign to meet its September 2012 deadline, and the resulting delay in initiating an IFE program. Section III B discusses the achievement of significant burn and gain in 2021 and 2022 on NIF and its impact on initiating a national IFE program. This includes a discussion of the DOE IFE Basic Research Needs (BRN) workshop report and its significance to the establishment of an IFE program. Section III C contains a brief discussion of the international competition in IFE. Section III D discusses the rapid increase in the number of private fusion companies, including several that have begun pursuing laser IFE in recent years. Section IV describes the challenges and research program of HB11 Energy Pty Ltd. as it pursues the alternate p-^{11}B aneutronic fuel cycle. Section V describes the work of Xcimer Energy, Inc. in developing a potentially disruptive laser technology for IFE. Section VI contains some thoughts regarding the questions posed in the call for these perspective papers about the opportunities and challenges in plasma science and technology, especially IFE, and the appropriate roles of both public and private partners. Section VII summarizes the key findings of this perspective paper.

II. ENTHUSIASM AND OPTIMISM OF EARLY PUBLIC AND PRIVATE ICF PROGRAMS

Since the earliest days of controlled thermonuclear research (CTR) in the 1950s, magnetic fusion energy (MFE) has received most of the world-wide funding for civilian fusion energy, including in the U.S. through the Atomic Energy Commission (AEC) and more recently from the DOE Office of Fusion Energy Science (FES), with only small and unsustained investments in IFE, as will be summarized in Sec. III. On the other hand, inertial confinement fusion (ICF) has received national security funding for decades from the AEC Division of Military Application (DMA), DOE Defense Programs, and the National Nuclear Security Agency (NNSA). ICF is part of the high energy density physics (HEDP) element of the NNSA Stockpile Stewardship Program (SSP).[14] The mission of the SSP is to ensure that the nation's nuclear weapon stockpile remains safe, secure, and effective without nuclear testing. The last U.S. nuclear test was in 1992, and Congress authorized the SSP in 1994.[15,16] The role of the ICF program has been to provide unique and extreme high energy density (HED) environments for the validation of computer models. The major HED

21 March 2024 03:34:24

© Author(s) 2024

platforms include the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), the Z-Machine at Sandia National Laboratories (SNL), and the Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics (UR/LLE). A long-term goal of the ICF program has been the development of a robust burning plasma platform to validate models of thermonuclear burn. Ignition on NIF has been the long-awaited first step in developing the knowledge to enable the construction of a facility with a yield of at least 100 MJ.[17] While the enabling ICF target physics for high yield and IFE will have much in common, their engineering technologies and applications will be quite different. High yield for weapons will certainly still be a single-shot operation, while IFE will require a significant repetition rate (0.5 Hz to tens of Hz) at laser wall-plug efficiencies of 7%–15% rather than the ∼0.5% of NIF and Omega.

The U.S. laser fusion program was launched shortly after the invention of the laser in 1960.[18] By 1964, the use of Q-switching for giant pulse formation was proposed by Basov[19] and Dawson[20] to heat hydrogen plasmas to fusion temperatures to fill a magnetic fusion device. By 1968, Kidder[21] was simulating the shock compression and burn of hydrogen at 10^{15} W/cm^2 focal intensities. He also outlined a laser architecture that has been systematically matured at Livermore on Argus, Shiva, and Nova, and extended by the multi-pass architecture of the NIF laser. In 1961, John Nuckolls predicted that a laser could implode a drop of deuterium–tritium (DT) fusion fuel to super-high densities (10 000× liquid deuterium) and fusion temperatures.[22] By 1963, LLNL was using a 12-beam ruby laser system[23] to perform classified experiments using AEC DMA funding.[24] There was early optimism in both the U.S. and Soviet Union that breakeven would be achieved by 1972, followed shortly by the net electrical energy production. Some of the major principles of laser fusion were declassified in 1972, and a series of foundational papers on the physics principles of direct drive laser fusion were published.[25–28] LLNL's x-ray drive approach to laser fusion was not declassified until 1992. The ICF capsule physics issues outlined in these papers, combined with their internal reports on x-ray drive, have defined the LLNL ICF research program on Argus, Shiva, Nova, and ultimately NIF.[29]

In 1969, Keeve (Kip) Siegel formed the first private laser fusion company, KMS Fusion, in Ann Arbor, Michigan, to pursue the laser fusion ideas of Keith Brueckner, a physics professor at the University of California, San Diego (UCSD). Following the declassification of laser fusion, KMS published a comprehensive theory and design paper,[30] and in 1974, they announced the first thermonuclear neutrons from experiments with D–T-filled glass microballoon targets[31] using their 2-beam laser system, a few months ahead of LLNL's announcement of neutron production on their JANUS laser system.[32] Siegel optimistically wrote to AEC Chairman Glenn Seabourg that "KMS could … bring efficient fusion power into availability within the next few years." From 1975–78, KMS received government funding for fusion research, but it became apparent that their exploding pusher targets did not scale, and their DOE funding was transferred to an ICF target fabrication contract. In 1993, KMS Fusion closed after GA and Schafer Corporation were awarded the DOE ICF target fabrication renewal contract through a competitive bid process.

The U.S. strategy for ICF that is still operative today was established during congressional budget negotiations in 1979, where the goals of the newly formed DOE ICF Program were defined as developing the technology for near-term application to nuclear weapons development and test and for long term applications as an inexhaustible energy source.[33] National security objectives were to be the primary focus, with a transition to civilian energy applications after scientific breakeven was achieved. Until that time, the commonality of ICF research to military and civilian applications was estimated to be 85%–90%. A decision to establish a separate civilian use program could only be made after scientific breakeven was achieved, and chances of achieving a commercial ICF powerplant was better known.[33]

The main lesson to be learned from this early history is that both the national labs and private companies were overly optimistic about what would be required to achieve ignition and gain in laser ICF based on very limited experimental data and 1D simulations that lacked important physics models. Further, once IFE was not viewed at the time as a viable near-term goal, KMS did not have any distinguishing derivative products or services to market. Because the main topic of this perspectives article is inertial fusion energy, a more complete history of the U.S. ICF program, including a discussion of the Nova Technical Contract (NTC),[34] the Laboratory Microfusion Program (LMF)[35] for achieving a high DT yield (>100 MJ), and a more thorough discussion of IFE research programs will be reserved for a future article. Of central importance to this article, the 1990 NAS final report[36] cautioned that the LMF was too large an extrapolation from LLNL's Nova laser and instead recommended proceeding with the construction of a 1- to 2-MJ Nd-doped glass laser designed to achieve ignition in the laboratory on the path toward high yield. Therefore, the DOE selected the NIF to advance the mission of achieving ignition and propagating thermonuclear fusion burn and to be a national user facility.[36] The decision to build NIF has determined the course of the U.S. ICF program for the past 30 years and has laid a scientific foundation for today's emerging IFE program. We shall return to a discussion of the establishment of a separate civilian use ICF program in Sec. VI. Section III looks at other activities beyond those in the core NNSA ICF program that have contributed to the IFE knowledge base.

III. A BRIEF HISTORY OF U.S. IFE EFFORTS

As mentioned above, the earliest fusion energy concepts were based on magnetic confinement (e.g., pinches, mirrors, stellarators, and tokamaks), and MFE has received most of the civilian DOE funding. Laser fusion and related ICF concepts, came later, were primarily associated with military applications and were funded accordingly. However, the promise of IFE has been one of the strongest attractors for new employees at the national labs, and a variety of limited-scope IFE projects have been pursued using internal discretionary funds, congressional plus-ups, and periodic DOE and ARPA-E funding opportunities. This section provides a brief overview of these U.S. IFE efforts.

A. HAPL program, Snowmass meeting, and FESAC and NASEM reports

The High Average Power Laser (HAPL) program[37] was a congressionally mandated IFE research program, which began in 1999, and was jointly sold to Congress by LLNL (Mike Campbell) and NRL (Steve Bodner). From 1999 to 2009, it was jointly managed by LLNL and NRL and was led by John Sethian (NRL) as a multidisciplinary, multi-institutional program to develop the scientific and technical basis for IFE based on laser drivers and direct drive targets.[38] By 2004, both NRL[39] and LLNL[40] had demonstrated repetitive operation of

21 March 2024 03:34:24

© Author(s) 2024

DPSSL and KrF lasers at 2–10 Hz for several hours at energies of 50–700 J. Other IFE technologies, including final optics (grazing incidence and dielectric mirrors), chambers, and target fabrication, injection, and tracking technologies, were developed toward the final application to a 1000-MWe pure-fusion power plant.[37] The HAPL program, which was originally funded at $10M/year and later grew to $25M/year through Congressional earmarks without the DOE support, was terminated after FY09 following the retirement of key congressional staffers,[38] putting IFE research on hold.

The IFE Roadmap (Fig. 1) from the Snowmass 2002 final report[41] was strongly influenced by the HAPL program. The roadmap was also influenced by NNSA-funded research for NIF and Z-pinches and by the small FES heavy ion fusion (HIF) program. The roadmap shows parallel development of excimer and DPPSLs, heavy ion accelerators, and shared research in target design and fabrication and IFE technologies. Integrated Research Experiment(s) (IREs) were envisioned as a step after the proof-of-principle phase I. The community consensus was that it was too early to make any down selections of driver technologies prior to the completion of phase I. The 2002 Fusion Energy Sciences Advisory Committee (FESAC) report[41] reported that it was imperative to have a strongly balanced program to develop fusion science and technology for both IFE and MFE, which would require additional funding to establish an R&D program to build a demonstration power plant within 35 years.[8] Unfortunately, additional funding was not appropriated and the HAPL investment in IFE research was not sustained. Clearly, the US would be in a much stronger position to design and construct an IFE FPP if HAPL had received stable federal funding for the last 13 years.

In 2011, the NASEM assembled a review panel at the request of the Secretary of Energy to investigate the prospects for returning to IFE, given that ignition was scheduled to be demonstrated at the NIF through the National Ignition Campaign (NIC)[42] by October 2012. However, the LLNL leaders at the time were overly optimistic and the NIC was not successful in achieving ignition, a fact that is reflected in the target physics panel final report that was released in mid-2013[43] and the full NAS IFE assessment report that was released later in 2013.[38] These reports found that there were several physics issues in indirect drive fusion that needed to be resolved to reach the ignition goal, which would likely take several years, especially since only $\sim$25% of NIF shots were allocated to ICF. Of particular concern was the substantial lack of understanding of laser plasma interactions (LPI) in NIC indirect-drive targets. Although the computational platforms and 3D codes for ICF are vastly superior to the 1D codes of the 1970s, the same over reliance and excessive optimism as to their predictive nature were one of the root causes of this delay. A 2016 NNSA report on the ICF program[44] found that the laser indirect drive program was focusing on performing integrated experiments on high-gain capsules that were predicted to perform well, despite the fact that "the codes and models are not capturing the necessary physics to make such predictions with confidence." The report also found that ignition was uncertain over the next five years because no known configuration, specific target design, or approach would guarantee ignition. Despite skepticism by some experts that NIF would ever achieve ignition, perseverance in gaining a sufficient understanding of the observed capsule performance data ultimately led to ignition. However, the almost 10-year delay in achieving ignition delayed the initiation of a national, coordinated, broad-based IFE program by at least a decade while DOE waited for ignition to be achieved.

Meanwhile, DOE FES funded a High Energy Density Laboratory Plasmas (HEDLP) subprogram, including a LaserNetUS program that

21 March 2024 03:34:24

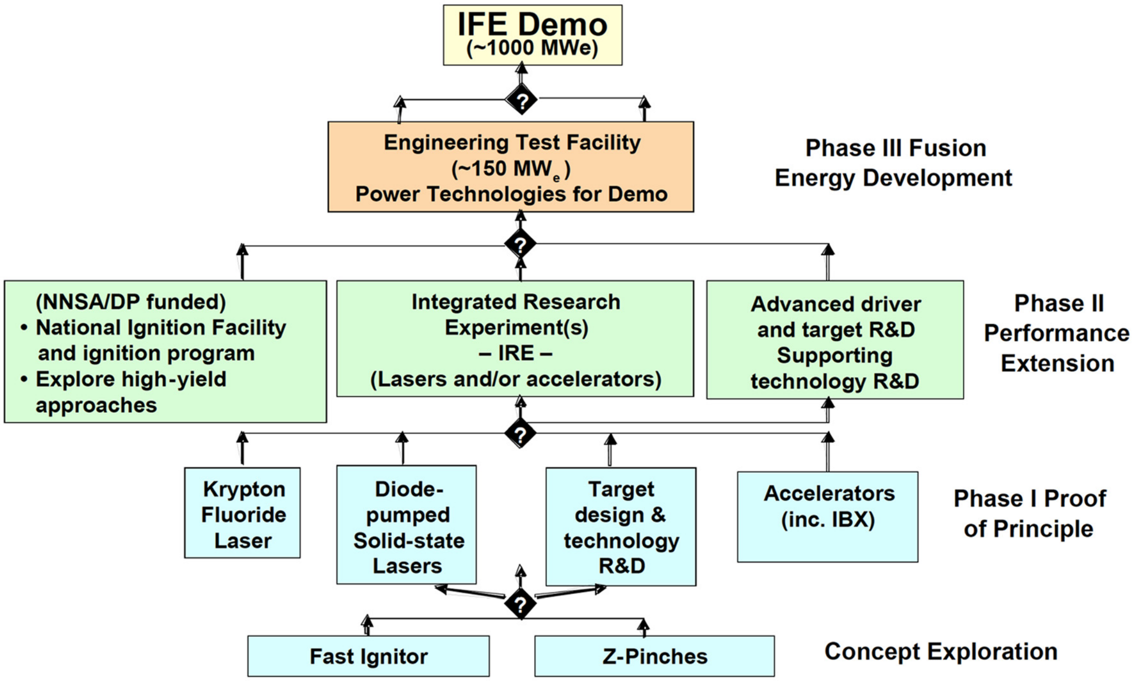

FIG. 1. IFE Roadmap from 2002 Snowmass Workshop reproduced with permission from Bangerter *et al.*, in Snowmass CO Fusion Studies, 2003. Copyright 2003 Author(s).

© Author(s) 2024

was responsive to the recommendations of the National Academy of Sciences (NAS) Report on high-intensity laser research.[45] Importantly, despite efforts to cut the budget, Congress instructed DOE Defense Programs to sustain support for ICF research for national security needs, including the pursuit of ignition via indirect drive on NIF,[46] the National Direct-Drive Program on Omega and NIF,[47] and research on MagLIF scaling on Z at Sandia.[48]

B. NIF ignition initiates DOE IFE program

On August 8, 2021, an experiment on NIF exceeded the Lawson criterion for ignition by producing a 1.37 MJ yield for 1.97 MJ of laser energy,[7] placing ICF on the cusp of ignition (laser energy breakeven). This breakthrough, coupled with a 2018 FESAC recommendation to establish an IFE program,[49] motivated DOE FES to sponsor a Basic Research Needs Workshop (BRN) to assess the status of IFE and identify science and technology priority research opportunities (PRO). The IFE Basic Research Needs (BRN) report[50] is a foundational guide for a national IFE program, starting with the $45 million in support announced in 2023 for the DOE IFE Science and Technology Accelerated Research (IFE STAR) Program hubs.[51] The BRN report was released shortly after the NIF shot on December 5, 2022 that produced 3.15 MJ of fusion energy from 2.05 MJ of laser energy,[52] exceeding the definition of ignition used by the NAS in the 1997 review of NIF.[53] It is important to note that NIF has demonstrated "Scientific Q"[54] (fusion energy output greater than laser energy to plasma) greater than 1 as opposed to the more stringent "Engineering Q" (fusion energy output greater than the energy off grid) that is a prerequisite for a power plant. NIF was built as a science facility with state-of-the-art technologies of the 1990s.

The achievement of ignition and propagating burn on NIF through alpha particle heating arguably puts IFE ahead of MFE in the experimental demonstration of fusion energy relevant results. An analysis of target alpha heating finds a yield amplification of approximately 20–30 for the N210808 NIF experiment.[55] The highest target performance to date came on July 30, 2023, when NIF delivered 2.05 MJ to a target resulting in 3.88 MJ of yield from a nearly tripling of the burn temperature, demonstrating the steepness of the performance curve when burn propagation is reached. Given that $\sim$200–250 kJ of the laser energy is coupled to the capsule and $\sim$20–25 kJ to the fuel, this gives an overall target of $Q \sim 1.9$, a capsule gain of $\sim$16, a fuel gain of $\sim$155, and an alpha yield amplification factor of 60–90. This is to be contrasted with the evidence of electron heating by alpha particles in JET DT plasmas of that show the core electron temperature to be $\sim$30% higher in the "afterglow" of neutral beam injection (NBI).[56] The highest performing D–T discharges on JET had a maximal fusion power of $\sim$12 MW when driven by an NBI power of $\sim$26 MW. The primary objective of ITER, the flagship of the international MFE program, is to attain a "burning" plasma in which the self-heating of the plasma by alphas from nuclear fusion reactions is dominant, with the goal of $Q > 10$ for inductively driven plasmas and $Q > 5$ in steady state through current drive. Full phase operation of ITER is not expected to occur before 2035.[57] A further advantage of IFE over MFE, given the world's limited supply of tritium[58] at a cost of $\sim$\$30 000/kg, is IFE's lower tritium inventory and higher utilization factor. High gain IFE targets burn up $\sim$30% of the fuel, while tokamaks have burn fractions of 1%–4%, with corresponding minimum tritium inventories of 250–500 g for a direct-drive IFE plant[59] and tritium startup inventories of 5–11 kg for a 3 GW tokamak reactor.[60]

The achievement of ignition and propagating burn on NIF is the long sought "scientific proof of concept" and has provided IFE, both public and private, with increased momentum. It is exciting that two IFE companies, Xcimer Energy and Focused Energy, were selected in May 2023 to receive part of the $46 million in funding to eight companies advancing designs, research, and development for fusion power plants from the milestone-based PPP program. To sustain and grow IFE research, it will be essential to demonstrate the significant results from the DOE PPP, INFUSE, and IFE STAR programs. However, given DOE FES' existing commitments to MFE research and its laboratories and ITER, it is likely that the private sector will remain largely reliant on VC funding if they achieve a pilot-scale demonstration of fusion within a decade.[10]

C. International competition in IFE

While the U.S. presently has the lead in ICF research, there is still a large gap in fusion nuclear technology for IFE, much of which is synergistic between MFE and IFE. Further, the U.S. lead in ICF is not guaranteed to last. China has built the 48-beam SG-III laser based on the NIF architecture, which met its goal of generating 180 kJ in 3 ns at 351 nm[61] in 2015, and forms a solid foundation for further research.[61] China has also demonstrated the capacity to deliver 10 PW peak power femtosecond pulses at their Shanghai Superintense Ultrafast Laser Facility,[62] where they are also working to deliver a 100 PW capability at their Station of Extreme Light[63] by 2023. The Germany Federal Agency for Disruptive Innovation (SPRIND) has recently approved the founding of Pulsed Light Technologies GmbH to develop infrastructure for the generation of energy from laser-driven fusion. In May 2023, Germany published a memorandum on laser IFE[64] that describes the urgency for investment and the establishment of a framework that builds and promotes a vibrant fusion energy ecosystem. European scientists are calling for a new IFE project, High Power Energy Research (HiPER) Plus, as well as more investment in the Extreme Laser Infrastructure (ELI) project.[65] Commercially, the Thales Laser Group[66] has developed a roadmap for evolving their existing product lines toward developing high-energy laser beams that have the 5–10 Hz repetition rate required for IFE applications. NIF has demonstrated that ignition and gain are possible. It is clear that the world has been energized and that there will be international competition in IFE.

D. Private fusion companies, ARPA-E, commonwealth fusion, and IFE

In 1998, TAE Technologies[67] was formed to pursue the p-^{11}B aneutronic fuel cycle using colliding beams in a field-reversed configuration (FRC).[68] FRC devices for the D–T fusion have been studied since around 1958[69] but have had difficulty scaling to adequate triple products. General fusion was established in Canada in 2002[70] to pursue magnetized target fusion (MTF), building upon concepts from the Naval Research Labs (NRL) Linus[71] imploding liner project, which began in 1971. Tokamak Energy was established in the UK in 2009[72] to develop a D–T-fueled fusion power plant based on a compact spherical tokamak using high-temperature superconducting (HTS) magnets manufactured from HTS tape containing a rare earth barium copper

21 March 2024 03:34:24

© Author(s) 2024

oxide (REBCO) superconducting material. In 2011, First light fusion[73] was spun out from the University of Oxford to pursue a projectile impact-based approach to IFE using a pulsed power driver. Helion Energy was spun out from the University of Washington in 2013[74] to develop a magneto-inertial fusion (MIF) technology to produce ^{3}He and fusion power from D–^{3}He fusion by colliding and compressing two FRCs in a central high-field coil.[75]

Increased private interest in fusion, as well as successful proof-of-concept MIF experiments from Sandia National Lab's Magnetized Liner Inertial Fusion (MagLIF) program in 2014, led ARPA-E to establish their ∼$15M ALPHA (Accelerating Low-Cost Plasma Heating and Assembly) program[76] to "enable more rapid progress in fusion research and development."[77] The ALPHA program catalyzed the formation of two private companies: (1) a team from the University of Washington launched Zap Energy in 2017 to scale shear flow-stabilized Z-pinch plasmas up to reactor parameters[78] and (2) results from MagLIF experiments at Sandia and Rochester (UR/LLE) form the basis of the MIF approach pursued by Fuse Energy Technologies (established 2019).[79]

ARPA-E's Breakthroughs Enabling THermonuclear-fusion Energy (BETHE) program[80] awarded an additional 18 projects beginning in 2020 including a follow-on project for Zap Energy and a project on a pulsed high-temperature superconducting central solenoid for revolutionizing tokamaks by Commonwealth Fusion Systems (CFS).[5] CFS was spun off from MIT's Plasma Science and Fusion Center (PSFC) in 2018 to build a small fusion power plant based on the ARC tokamak design,[81] and now, it is the biggest U.S. fusion company. The key enabler of CFS' vision was the development of high-field magnets made from a newly available superconducting material—a steel tape coated with a compound called yttrium–barium–copper oxide (YBCO). On September 5, 2021, CFS operated an HTS electromagnet up to a field strength of 20 tesla,[82] thereby establishing itself as a leader in private MFE. These HTS magnets are the key technology to enable SPARC,[6] from which CFS plans to produce the world's first net energy from a fusion device. Tokamak fusion power scales as the fourth power of the magnetic field (B^4).[83] HTS magnet technology has also stimulated a resurgence of interest in compact stellarators (Type One Energy Group[84]) and magnetic mirror devices (Realta Fusion[85]). The Fusion Industry Association, which was established in 2018, listed a total of 43 private fusion companies in their most recent report on the global fusion industry,[13] an increase in 13 from the previous year and totaling over $6 billion in investment.

There has also been a rapid increase in the number of private companies exploring various IFE approaches since First Light Fusion was formed in 2011 to explore projectile impact fusion. In 2017, HB11 Energy Pty Ltd. was formed in Australia[11] to pursue Prof. Heinrich Hora's approach to the non-thermal initiation of the p-^{11}B reaction using high-peak power lasers.[86] Marvel Fusion was formed in 2019[87] to initiate the p-^{11}B reaction using high-peak power lasers with different laser and target parameters than HB11 Energy. Fuse Energy Technologies was founded in 2019 (Ref. 79) to develop an advanced pulsed power machine to drive a MagLIF Z-pinch MIF concept. Focused Energy was established in 2021 to pursue proton fast ignition.[88] EX fusion was formed in Japan in 2021 to commercialize a laser fusion reactor.[89]

Xcimer Energy Inc.,[12] Longview Fusion Energy Systems,[90] Blue Laser Fusion,[91] and LaserFusionX[92] were established in 2022. As discussed in detail in Sec. V, Xcimer is developing a unique high-energy KrF laser architecture and associated power plant based on the HYLIFE II design. Longview is pursuing indirect-drive IFE based on the LIFE concept that was developed at LLNL.[93] Blue Laser Fusion has developed a novel high-power laser technology for pursuing the p-^{11}B reaction. It is likely that even more laser IFE companies will be established in the coming years.

Sections IV and V provide more details on the goals, plans, and challenges of two private fusion companies, HB11 Energy and Excimer Energy, where I am a scientific advisor. I note that I participated on the alternative concept panel of the IFE BRN workshop that was discussed in Sec. III B and that HB11 Energy's research on the p-^{11}B fuel cycle and Xcimer Energy's development of the ASPEN KrF laser concept are well aligned with priority research objective (PRO) 3–5: Explore alternate concepts and advanced fuels.

IV. HB11 ENERGY PTY LTD–PURSUING THE ANEUTRONIC p-^{11}B FUEL CYCLE

In January 2020, I was contacted by Prof. Heinrich Hora (Emeritus, University of New South Wales) about his theories and recent results regarding the non-thermal initiation of the p-^{11}B reaction using high-peak power lasers.[86] He then introduced me to Jan Kirchoff (Luxembourg) and Warren McKenzie (Australia) who in 2017 had formed HB11 Energy Holdings Pty Ltd.,[11] an Australian private fusion company, to pursue Hora's ideas,[94] for which they had obtained a U.S. patent (US10410752B2).[95] They invited me to join their Scientific Advisory Board, and despite my initial concerns that the theoretical predictions on which the patents were based were overly optimistic, I was intrigued by the outstanding progress in alpha yield from boron targets irradiated by high-intensity lasers that had been recently published by several independent groups[96–100] (see Fig. 2). These papers documented impressive increases in the numbers of alpha particles from 10^5 in 2005 (Belyaev), to 10^7 in 2013 (Labaune), to 3×10^{10} alpha yields/sr/J in 2020 (Giuffrida), achieved at laser intensities between 3×10^{16} and 3×10^{19} W/cm^2. I agreed to join the Scientific Advisory Board to understand and explore the

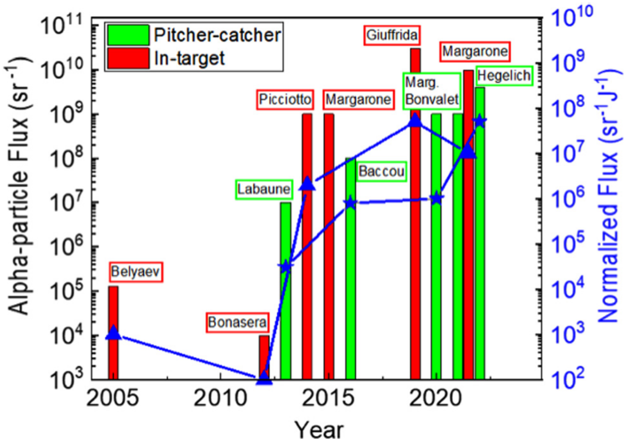

FIG. 2. Maximum alpha particle yield by year for various lasers for both pitcher-catcher and in-target irradiation geometries. Reproduced with permission from Mehlhorn *et al.*, Laser Part. Beams **2022**, ID2355629. Copyright 2022 Authors, licensed under a Creative Commons Attribution (CC BY) license.

21 March 2024 03:34:24

possibilities of the physics behind these experimental results and to see if they could scale to fusion energy production.

Proton–boron fusion is attractive because the primary reaction is aneutronic, with neutron-producing reactions in the chain at the level of ∼0.1% that produce modest neutron energies such that the activation of structural materials can be minimized. Another attractive feature for both economics and regulatory issues is that the fuel is stable, naturally occurring, abundant, and does not require cryogenic handling. This avoids the engineering challenges of the DT fuel cycle of breeding, handling, and recovering radioactive tritium, as well as the radiation damage and activation issues associated with 14 MeV neutrons. Proton–boron fusion may also enable the use of some form of direct energy conversion that operates at a higher efficiency than thermal cycles, although energy conversion technology is still an open question. Therefore, proton–boron fusion may have some technological and economic advantages over DT. However, the p-^{11}B fusion cross section is lower than that of DT and peaks at higher ion energies, resulting in a substantially higher Lawson criterion and much lower fusion gain. Therefore, the scientific challenges of the p-^{11}B fuel cycle are far greater than those for DT, and the laser requirements will be significantly larger. Further, if the larger ρR requirements for efficient p-^{11}B burn result in larger target yields, chamber containment engineering issues will need to be carefully considered. Currently, HB11 Energy is primarily focused on establishing the scientific viability of the p-^{11}B fuel cycle while beginning to build the company infrastructure in lasers, targets, and engineering that enables a corresponding IFE target point design.

A. HB11 Energy's early concept

HB11 Energy's early concept for proton–boron fusion envisioned the use of two short pulse lasers, the first irradiating the end of a cylindrical rod of B:H fuel, thereby generating a fast proton flux, which initiates p-^{11}B reactions. The second laser irradiating a capacitive coil (c.f. Fig. 2 in Ref. 101) around the fuel rod, initiating a strong magnetic field that confines the target plasma and extends the fusion reaction time. The published experiments that caught my attention were performed in either a pitcher-catcher geometry (two foils) or through direct illumination of a boron-containing single foil. In March 2022, HB11 Energy announced the publication of a paper[102] showing that it had made significant progress in its experimental program. However, the $\sim 10^{11}$ α per shot achieved on these "in-target" experiments on the LFEX kJ laser is about 10^{-4} ($Q \sim 0.01\%$) of "breakeven" for p-^{11}B (2.15×10^{15} α/kJ of laser energy). These results are consistent with my calculations of in-flight (beam fusion) reactions of protons with ^{11}B as they slowdown in the target.[103] In experiments where either the catcher is heated by an independent ns laser[104] or the direct irradiation of a thick target by an energetic short-pulse laser beam leads to ∼keV electron temperatures,[100] the thick target yields increase by roughly an order of magnitude due to the decrease in the proton electronic stopping power. However, while these alpha yields are impressive and might be useful for medical treatment or to produce certain medical isotopes,[105] as with any IFE scheme, a power loop analysis shows that target gains >100 are required for a practical fusion power plant, meaning these yields are only 10^{-5}–10^{-6} of what is needed for energy production.

This analysis is consistent with long-established knowledge that beam fusion reactions do not scale to net energy gain due to the predominance of the elastic over the fusion cross section, as discussed in Ref. 103. Furthermore, simply changing the plasma density will not improve this ratio because both components scale linearly with density until the plasma becomes degenerate and the electronic stopping power decreases. It is important to note that the predominance of elastic over nuclear reaction rates also extends to the spreading of a beam by plasma. The dispersion term in the Fokker–Planck equation for transport in plasmas describes the diffusion of a beam toward isotropy that occurs as the result of many cumulative Coulomb collisions. Around 1998, NRL was asked by the Office of Naval Research (ONR) to evaluate the colliding beam fusion reactor (CBFR) concept[68] that they had been funding at a low level for two years. The conclusion of the NRL report[106] was that, based on their Fokker–Planck analyses, the proposed CBFR equilibrium could not be "sustained for long enough to permit net fusion gain, because of the many collisional processes which occur orders of magnitude faster than fusion, and result in particle loss, energy dissipation, and or detuning of the resonant energy for the p-^{11}B reaction." It is important to keep this predominance in mind because many lower density aneutronic fusion systems utilize some form of the CBFR concepts. Further, beam-driven systems are not in thermal equilibrium, and an independent Fokker–Planck analysis has found that the minimum recirculating power to maintain this disequilibrium is substantially larger than the fusion power.[107] They found that beam-driven systems, such as inertial-electrostatic confinement,[108] migma,[109] and other colliding ion beam devices,[110] will likely not be able to produce the net power with D–T, so their use with alternate fuel cycles is even less likely. That is why HB11 has recently formed a U.S. subsidiary, HB11 Energy USA LLC,[111] to begin exploring the proton–boron burn space using the ICF design principles that were validated by the demonstration of a propagating fusion burn in highly compressed fuel on the NIF.

B. Proton–boron reactivity and non-thermal burn

A key challenge of the p-^{11}B fuel cycle is the higher radiative losses from bremsstrahlung emission due to the higher effective charge of the boron-containing plasma. Wurzel and Hsu's Lawson Criterion analysis of the p-^{11}B fusion cycle[54] asserts that fusion production can only overcome bremsstrahlung radiation losses if the electron temperature is one-third the ion temperature, although they state that they have not updated their analysis with the latest cross section data.[112] A Fokker–Planck analysis of p-^{11}B burn by Putvniski *et al.* that includes the latest cross sections finds a 20% increase in reactivity, as well as favorable kinetic modifications of the proton distribution by the up-scattering of protons by alphas, leading to a net increase in ∼30% in fusion yield,[113] such that fusion production can slightly exceed radiation losses at ion densities of 10^{20} m^{-3} and ion temperatures of 300 ± 50 keV for optimum boron concentrations of $n_B/n_i = 15\%$ and self-consistent electron temperatures. These analyses are appropriate for MFE devices where the plasmas are dilute and optically thin. HB11 is working to map the p-^{11}B burn space for high-density IFE implosions where Compton opacity[114] and radiation trapping techniques[115] could limit radiation losses and favorably change the power balance. Our approach was anticipated in 1973 at LLNL by Weaver *et al.*,[116] who were interested in the impact of non-thermal effects in laser fusion on exotic fuel cycles. They developed an infinite medium Fokker–Planck code to study non-thermal effects that could occur in p-^{11}B fusion due to energy exchange between the kinetic distribution

21 March 2024 03:34:24

© Author(s) 2024

functions of alphas, protons, boron, and electrons. They estimated net reactivity increases of 5%–15% for ICF-relevant conditions. More recently, Belloni has studied the multiplication process in high-density p-^{11}B fuel[117,118] and found similar modest increases in reactivity. The LLNL report asserted that the most promising mode for a p-^{11}B reactor was to reabsorb the bremsstrahlung photons within the burning plasma using an ICF implosion to very high densities. They also performed a limited study of the injection of 700 keV protons into the fuel and found modest 15% increases in energy multiplication factors. These simulations were performed more than a decade before the development of USPL lasers, so there is a significant opportunity to expand these simulations by exploring the fast ignition scenarios that we believe will be required to achieve ignition and propagate burn in this exotic fuel cycle.

The HB11 Energy USA LLC team has begun to map out the p-^{11}B burn space to identify where ignition and gain can be achieved and then to instantiate these parameters into a laser-driven ICF target point design. We know that p-^{11}B is less reactive than DT and will require larger targets that will require higher laser energies. Atzeni lists the ideal ignition temperature for DT as 4.3 keV with a burn parameter of 7.3 g/cm^2 at 40 keV, while for p-^{11}B, he lists no ideal ignition temperature and a burn parameter of 72 g/cm^2 at 250 keV. However, the classical definition of ideal ignition is for an optically thin system, and at such a high ρR, the system will at least have a finite Compton opacity. This fact is illustrative of the challenge of studying p-^{11}B burn. The burn for this little studied fuel cycle occurs at significantly higher density, ρR, and temperature than DT, and the physical models and databases that have been used in ICF modeling need to be carefully extended to be valid in this regime. Of course, we also need to be aware that computational models can be incomplete or misleading, so we are looking at facilities that combine long and short pulse lasers to provide data on the interaction with uncompressed and compressed B-containing fuels, testing target configurations, and optimizing proton beam generation, guidance, and delivery. Our research directly addresses the call for "maturing the evaluation of Generalized Lawson Criteria for alternate fuels and combined cycle, measuring proposed cross section modifications, and developing ignition point designs for alternate fuels (e.g., p-^{11}B)" under PRO 3.5 of the IFE BRN report.[50]

C. HB11 target physics roadmap

Our roadmap to increasing p-^{11}B reactivity and developing a target point design is detailed in Sec. 10 of Ref. 103 and will only be summarized here. Dale Welch and Carsten Thomas have developed and are verifying the accuracy of a modern update of the LLNL's relativistic Fokker–Planck model that can include up to a three-dimensional spatial dependence using the hybrid algorithms in Voss Scientific's Chicago code.[119] We have previously used these algorithms to model the laser wake field acceleration (LWA) of electrons for fast ignition,[120] as well as proton acceleration.[121] Chicago has the capability to simulate the interaction of intense lasers with dense plasmas, including the acceleration and transport of charged particles. It can further simulate the fusion reactions of the thermal and beam components of the proton distribution function within the fuel while also accounting for elastic and inelastic processes as a function of fuel isotopic composition, density, and temperature and the impact of kinetic energy exchange between the energetic plasma species. Chicago also has a multi-group radiation transport model,[122] although we are doing our initial burn space mapping assuming an optically thin plasma and a relativistically corrected bremsstrahlung emission model.[113] We are using Chicago to develop the proton fast ignition criterion for p-^{11}B, using a similar methodology that was used to study the proton fast ignition of precompressed DT.[123] We are further studying what we term a "hybrid burn" scenario where protons generated by laser acceleration both heat the B:H fuel and undergo inflight fusion reactions that produce fast alpha particles that also heat the fuel, as well as add an energetic component to the proton spectrum via up-scattering. Preliminary Chicago simulations have indicated that shorter wavelengths ($\sim$0.25 μm) may be more effective at initiating a hybrid burn than longer wavelengths, suggesting that KrF or ArF lasers, such as those being developed by Xcimer Energy and LaserFusionX, may be advantageous for the p-^{11}B fuel cycle.

Because the p-^{11}B ignition and gain burn space are likely to be found at very high densities and temperatures, we believe that developing and applying a sophisticated kinetic model will be necessary to understand the interplay between energetic species, including charged particle transport and energy loss, equilibration, and radiation processes. Max Tabak has recently joined our team as a consultant and is leading the way in developing and using analytic models, as well as performing radiative hydrodynamics modeling using Prism Computational Science's HELIOS-CR rad-hydro code[124] to investigate individual physical issues as well as model burn propagation within a single fluid approximation. Recently, our subsidiary HB11 Energy USA LLC has been awarded an FY2023 DOE FES Innovation Network for Fusion Energy (INFUSE) project,[125] specifically supporting our work with LLE Rochester and Prof. Adam Sefkow on the design and simulation of innovative p-^{11}B targets for IFE using the TriForce code for multiphysics modeling.[126] I am the PI of this INFUSE project, which enables HB11 Energy USA to gain access to the world-class expertise and capabilities available across the U.S. DOE national labs and accredited US universities. INFUSE is a DOE initiative to provide the fusion industrial community with access to the technical and financial support necessary to move new or advanced fusion technologies toward realization with the assistance of DOE-funded fusion institutions. The objective of INFUSE is to accelerate basic research to develop cost-effective, innovative fusion energy technologies in the private sector.

D. HB11 goals and international research program

HB11 Energy is working to define and achieve a set of major goals that lead to the development of a conceptual and preliminary design prior to the 2028 milestone dataset by the NASEM report and the milestone-based PPP program. HB11 Energy's intention is to build a fusion reactor under the nation-wide scheme being proposed by NASEM.

In Australia, HB11 Energy has collaborations with four universities and the nanofabrication research infrastructure facility ANFF.[127] The Australian government has supported HB11 Energy through several programs, including the Australian Research Council Linkage Program, the Trailblazer Universities Program, and the Australian Trade and Investment Commission. HB11 Energy also led the establishment of a laser coalition with a view to building a high-power short-pulse industry in Australia that will support the emerging needs of the laser fusion industry. It plans to do this by combining global linkages and Australia's existing industrial base around photonics and

21 March 2024 03:34:24

© Author(s) 2024

optical components for telecommunications and includes partners such as Thales, EX-Fusion, the Institute for Laser Engineering, BECA, and Southern Photonics, as well as many others. The coalition plans to build the first Australian petawatt laser facility for the domestic research community, as well as look to join and contribute to the U.S. IFE effort and to U.S. research infrastructure programs, such as LasernetUS. HB11 Energy has held discussions with DOE managers about Australian participation in the LasernetUS program as part of its planning process.

HB11 Energy's team building since its founding has been very international. Its network includes most of the groups involved in the early p^{11}B fusion experiments, which were in Europe as well as Japan. HB11 Energy now has personnel at the University of Bordeaux (France), University of Catania (Italy), University of Salamanca[128] (Spain), Queens University Belfast (Northern Ireland), and the Institute for Laser Engineering in Osaka (Japan), with other groups joining soon. Together with the HB11 Energy USA researchers, their collective efforts reflect most of the scientific and industrial expertise required to develop the NASEM "Conceptual Design and Roadmap" as an international collaboration.

Beyond the physics challenges that have already been discussed, HB11 Energy has already made significant progress in its experimental program, including the previously mentioned result in March 2022.[102] As a private company, it has the agility to make real progress in the "experimental evaluation of the concepts and schemes." HB11 Energy has now conducted six experimental campaigns to validate a range of parameters, including simulation performance, understanding shock-wave formation and boron fuel EOS for compression, optimizing fuel, target, and a point design for the required proton acceleration spectrum yield and angular distribution, measuring proton and alpha stopping in a hot, dense plasma, and testing the effect of magnetic fields.

In its engineering program, HB11 is addressing two critical technologies of specific interest to laser hydrogen–boron fusion: hydrogen–boron targets and laser design. HB11 has demonstrated a capability to fabricate micro- and nanostructured boron materials, including the two-dimensional borophene material, into laser targets. Future plans include a library of fabrication processes, with key processes scaled into manufacturing. Its partnership with Deakin University and ANFF provides access to world-leading boron chemists and a network of 21 laboratories with a diverse suite of fabrication tools from which processes can be designed. Through the University of Adelaide, HB11 Energy will be developing its laser design, including the manufacture of critical laser components required for its target concept, as part of an $A240 million program in which defense intends to establish a local Australian industry for pulsed lasers and components. Critically, this will be piggybacking on a greater Australian defense effort focused on short pulse lasers with many commonalities to the requirements for HB11 Energy's target design.

V. XCIMER ENERGY, INC, a POTENTIALLY DISRUPTIVE LASER TECHNOLOGY FOR IFE

In the summer of 2022, I was contacted by Connor Galloway and Alexander Valys about joining the Technical Advisory Board of their new IFE company, Xcimer Energy, Inc., because of my experience with excimer lasers at NRL, as well as my long-term experience in ICF, IFE, and pulsed power. Xcimer was founded in 2021 with initial funding from Breakthrough Energy Ventures, Lowercarbon Capital, Prelude Ventures, and others. I am personally very excited to be associated with Xcimer because their strategy is to first develop and demonstrate a potentially disruptive laser technology that could be for IFE what high-temperature superconductors (HTS) have become for MFE. As previously discussed, the resurgence of interest in MFE approaches, including Tokamaks (CFS, Tokamak Energy), stellarators (Thea, Type One Energy), and mirror machines (Realta), has been catalyzed by the breakthrough in HTS that enables higher magnetic field strengths, which enable more compact and thus lower-cost devices. Xcimer's novel laser architecture combines KrF excimer amplifiers with Raman beam combining and a novel pulse compression system using stimulated Brillouin scattering in neutral gases to achieve high driver energies (10 MJ or more on-target) at dramatically lower laser hardware costs ($20–$30/J on-target at commercial scale) than other technologies. Historically, laser ICF has been limited in available driver energy. Figure ES.1 in the IFE BRN report[50] shows that a contributing factor in ignition on the NIF was the 7% increase in laser energy to 2.05 MJ that enabled a more stable implosion of an 8% thicker shell. A 10 MJ-class laser would enable energy-rich implosions that could achieve the high gains that were predicted in the LMF program[35] and that are necessary for an efficient IFE power plant.

Xcimer's laser architecture is ideally suited to use the well-established and documented HYLIFE[129] thick liquid-wall chamber concept in a commercial reactor design. HYLIFE's thick molten salt FLiBe first wall moderates the neutron spectrum, breeds tritium (TBR ∼ 1.17), and enables the first solid wall to be a lifetime component. The large driver energy allows operation at a lower repetition rate (0.5–1 Hz) with only two small beam penetrations in the chamber. NRL has demonstrated an electrical-to-optical efficiency of 8% for KrF, and ArF may have an efficiency greater than 10%,[130] enabling a low recirculating power fraction. Xcimer's architecture combines the efficiency of pulsed power with the standoff of a laser. Xcimer's laser also enables the use of targets that operate at the same high adiabat (3) and low convergence ratio (20+) as the NIF ignition target, but with sufficient areal density to achieve robust burn propagation and high gain with hotspot ignition. Xcimer is maturing their target design through a DOE INFUSE project entitled "Simulation of Direct-Drive Hybrid Using Two Opposed Beams for Inertial Fusion Energy" with Cliff Thomas at UR/LLE.[131] The achievement of ignition and gain on NIF lends great experimental credence to the Xcimer target design. Xcimer's laser technology could also be used by other IFE companies to increase the robustness of their target yields, thereby becoming the laser of choice for the IFE community. In fact, HB11 and Xcimer have already had discussions about how the Xcimer architecture might be ideal for providing the extra energy that the p-^{11}B fuel cycle will likely need. Further, although the Xcimer architecture will be first developed to produce ns beams, the nonlinear compression techniques may also be capable of producing ps beams for fast ignition scenarios.

Xcimer's laser architecture is derived from DoD designs and research, and there is experimental data that demonstrates the fundamental nonlinear optical techniques, primarily from strategic defense initiative (SDI) research that had the goal of projecting MJs of energy into space in a pulse several microseconds (μs) long.[132–141] In particular, the KrF Large Xcimer Amplifier (LXA) is based on a design for a ground-based laser AntiSATellite (ASAT) weapon. Raman beam combiner/amplifiers were also demonstrated by Thermo-Electron Corporation and Lincoln Labs/AVCO during SDI.[142] Pulse compression by SBS was studied by LANL, which also considered windowless

21 March 2024 03:34:24

operation, which avoids serious optical damage issues, which are a limitation for solid-state lasers. The main novelty at Xcimer is the realization that in low-pressure noble gas, particularly neon at 1 atm, the SBS gain is much higher (over an order of magnitude) than expected at 248 nm due to kinetic effects, and low-pressure SBS amplifiers are not transient at ICF timescales. Operation at 1 atm also makes windowless operation feasible. Excimer lasers are attractive for IFE applications because the gaseous KrF or ArF laser medium is pumped by relatively inexpensive pulsed power that scales to multi-MJ outputs. Nonlinear SRS and SBS have been identified to enable spatial combination and temporal compression up to a factor of 3000, with fundamental wavelengths of 248 and 193 nm and large bandwidths of 5.4 and 7.8 THz, respectively, avoiding the need for KDP crystals for frequency conversion. This combination of short wavelength and large bandwidth is effective in suppressing LPI. The 3 kJ Nike KrF laser facility has been operating for more than 25 years,[143] and the Electra KrF facility has demonstrated up to 700 J at 5 pulses per second.[144] Although Nike uses angular multiplexing instead of SRS or SBS to generate laser pulses in the 1–10 ns scale, much of its durable operation is relevant to Xcimer's laser development. This includes the Orestes suite of codes, which was originally developed at NRL for the krypton-fluoride (KrF*) laser and has recently been modified to model the Electra e-beam pumped ArF* laser.[145] Xcimer is establishing a Cooperate Research and Development Agreement (CRADA) with NRL to collaborate on excimer lasers. The significant database of facility operations and testing of advanced combining and compression schemes makes me optimistic that Xcimer will be successful in demonstrating their laser technology, beginning with the SBS proof-of-principle demonstrations in their first "Phoenix" laser facility. Xcimer is targeting a Series A fund closing by Q4 of this year that would be used to construct this facility.

A. Xcimer energy selected for milestone-based fusion development program

As mentioned previously, on May 31, 2023, the DOE announced $46 million in funding to eight companies advancing designs as well as research and development for fusion powerplants toward the goal of a pilot-scale demonstration of fusion within a decade. This milestone-based fusion development program is meant to solidify U.S. leadership in fusion commercialization. Within five to 10 years, the eight awardees are expected to resolve scientific and technological challenges to create designs for a fusion pilot plant that will help bring fusion to both technical and commercial viability. This program was partially inspired by the National Aeronautics and Space Administration's Commercial Orbital Transportation Services program, which helped enable commercial space launches. This milestone program was highly competitive, with proposals evaluated by the DOE and its blue-ribbon panel of scientific evaluators. Xcimer was selected for a $9 million award, which further establishes it as a leading company in the race to achieve the first commercial fusion power plant in the United States. Xcimer's application team includes many of the brightest minds and leading institutions in the field, drawn by Xcimer's promising vision for fusion energy. The team includes partners and collaborators at the University of Rochester's Laboratory for Laser Energetics, the Naval Research Laboratory, Lawrence Livermore National Laboratory, General Atomics, Westinghouse Electric Company, Los Alamos National Laboratory, Oak Ridge National Laboratory, and Savannah River National Laboratory. I am excited to also be part of the Xcimer team toward the goal of developing a disruptive laser architecture for IFE, as well as one of the most compelling IFE power plants, whose design has the goal of minimizing engineering issues that need to be overcome to realize a first of a kind (FOAK) plant.

VI. IFE PRIVATE–PUBLIC PARTNERSHIPS: CHALLENGES AND OPPORTUNITIES

The brief historical overviews of the first 50 years of ICF and IFE in Secs. II and III have shown a recurring pattern of underestimating the science challenges of achieving the propagating burn required for ignition and sufficient energy gain for a fusion power plant because of a scarcity of experimental data and an overreliance on computer simulations. The overviews also showed an inconsistent commitment to meeting the challenges of developing IFE-enabling technologies through the unsustained U.S. investment in the promising HAPL program, the lack of follow through in funding the Snowmass IFE roadmap, and the delay in establishing a formal IFE program in DOE program until ignition was achieved. However, all these programs and plans were predicated on the predominance of public fusion funding. This section will explore how the challenges and opportunities for dealing with both the science and technology issues of IFE are changed by the rise of VC-funded private IFE companies and the emergence of private–public partnerships. Private companies are said to be leading the way, but agility, optimism, and organizational efficiencies are not a guarantee of success in the rapid development of an FPP. While the new private IFE companies have the potential to greatly shorten the time to an IFE FPP, both the public and private participants in this quest should be aware of the history to avoid repeating some of its failures.

21 March 2024 03:34:24

A. Importance of data, predictive simulation tools, and event-based roadmaps

The unwarranted optimism in ICF simulation predictions was understandable in the 1970s when the recently invented lasers were rapidly evolving, and laser-radiation-hydrodynamic codes were new and largely unvalidated against experimental data. The excessive optimism in the predictive nature of 2- and 3-D ICF codes during the NIC experimental campaign, leading to poorly performing integrated capsule implosions, might partially be attributed to the loss of an experimental platform for performing indirect drive implosions after the disassembly of the Nova laser in 1999. When the completion of NIF was delayed from 2003 to 2009, this left a 10-year gap in the validation loop between experiment and codes that resulted in the development of NIF ignition target requirements, margins, and uncertainties[146] that lacked sufficient grounding in experimental data. Further, the early NIF hohlraum experiments showed the LPI problem that had concerned the NASEM target physics panel[43] and other scientists[147] and for which some solutions were identified as part of the Nova Technical Contract.[34] Initially, these issues and past learnings were ignored, but eventually, implosion symmetry control in low-gas fill *hohlraums*[148] was a decisive factor in achieving ignition. The momentum of the integrated NIC experiments on the baseline point design was ultimately broken by the high-foot implosion campaign[149] that abandoned the pursuit of theoretical high-gain to "obtain better control of the implosion and bring experimental performance in-line with calculated performance." Ignition was ultimately achieved through data-driven

© Author(s) 2024

improvements in target design and performance, supplemented by the development of analytic models, such as the asymmetric-piston model for the impact of mode-1 shell asymmetry on implosions,[150] that provided physical insight into guiding the choice of experimental parameters.

Presently, NIF and Omega are the only lasers that can provide IFE-relevant target data and they are already oversubscribed with NNSA commitments. Further, only NIF can explore ignition, so its limited shot rate and availability for ICF experiments mean that the target physics database will only be able to slowly grow within a limited range of laser energies and irradiation geometries. Moreover, NIF's reliance on NNSA funding means that facility modifications to increase on target laser energy will happen at a slow pace. This means that private IFE companies will need to cautiously depend on simulations to develop their roadmaps and look for opportunities to get scaled validation data as soon, and as often, as possible. A recent IFE BRN white paper notes that "optimism is not a strategy"[151] because "… the same design features that make an ICF design high gain, a necessary feature for useful IFE, make it more sensitive to engineering aspects of the target and laser system (assuming laser drive) that we have less than perfect control over and more sensitive to physics where our understanding is incomplete." A recommended strategy is to seek stepwise improvements in fusion performance in a rigorous experimental program that is developed using the best available simulation tools, tied to the rigorous use of uncertainty quantification, verification, and validation (UQ/VV) methodologies and tools. This strategy is consistent with the recommendation in the NAS IFE Assessment[38] to establish "event-based roadmaps." The IFE BRN report reiterates that using existing ICF "codes to extrapolate to IFE-relevant designs is risky without adequate benchmarking data and physics understanding." Arguably, the NNSA has developed many of the best available simulation tools and databases, but some are classified, and the rest are subject to some form of export control. The availability of predictive IFE simulation tools and the best ways to improve them is one of the critical issues in formulating plans for effective public–private partnerships. It is important to also remember that ICF implosions become more forgiving of target and driver imperfections as the coupled driver energy increases. "So, higher delivered laser energies greatly reduce the likelihood of ICF implosion failure and open a larger target design parameter space…."[151] This is where Xcimer Energy's plans for developing cost-effective high-energy lasers (Sec. V) could help them realize their HYLIFE-II IFE design, as well as provide the broader IFE community with an MJ-class target driver to fill the IFE data gap.

There are also still many IFE technology gaps to be filled; lasers, target fabrication, injection, and engagement technologies need to be developed and then integrated with tritium breeding, chamber, and energy conversion technologies to create an FPP. If left to the federal government, the development of high-yield ICF within the NNSA and IFE within DOE will take decades. Likewise, the development of large-scale test facilities, such as the Fusion Prototypic Neutron Source (FPNS)[152] to understand 14.1 MeV neutron-induced material degradation, if left to the federal government, will not be operational in time to support the NASEM or milestone-based PPP timelines. To fill this specific gap in a timely fashion, either some form of PPP will need to be established between the DOE and private companies to develop an FPNS in a timely fashion or the private companies will need to use their FPPs as test stands for acquiring the data as a part of normal operation. Alternatively, to avoid first-wall neutron damage issues and tritium uptake, an option will be to use thick liquid walls, such as Xcimer's plans to use HYLIFE to protect the material wall, or to develop an aneutronic fuel cycle, such as HB11's plans to develop proton–boron fusion. Finally, the fusion community should look for synergy with the fission community and determine where scaled neutron damage experiments might be performed using fission test reactors or at radiation damage surrogate test facilities such as the Michigan Ion Beam Laboratory (MIBL) for Surface Modification and Analysis.[153]

B. Beyond IFE's basic research needs: Focus on system integrated plant design

At the system level, IFE has several advantages that need to be leveraged. As seen in the Snowmass IFE Roadmap (Fig. 1), IFE has multiple driver options that are highly modular, and systems can be built up from separable and even shared components (targets and target fabrication, injectors, trackers, tritium systems, first wall materials, etc.). As previously discussed, target gains of 100 or more are consistent with high tritium burn-up fractions (30% or more) and high fueling efficiency, so tritium inventories are modest compared to MFE, simplifying issues of tritium breeding, handling, and helium "ash" removal. The mass production of 9000–900 000 targets/day at an acceptable cost (<\$1) is challenging, but progress was made during the HAPL program, and the development of wetted foams is a high priority in the IFE BRN. The development of high energy, high average power lasers is also a formidable challenge, but IFE can look to the HAPL results, as well as for synergy with the DoD labs and companies that are developing directed energy weapons for commonalities in diode pumping and pulsed power, heat removal, optics, and related issues. This synergy could be bi-directional because the Xcimer laser design has its origins in DoD/SDI research, and their high-energy lasers could become relevant to the defense community if they are demonstrated for IFE. First-wall activation and damage issues for the DT fuel cycle can be common between MFE and IFE, and synergy should be sought. IFE also has the option of avoiding first wall issues entirely using the thick liquid FLiBe jets of the HYLIFE-II design,[129] which also has energy conversion advantages because it absorbs 100% of the fusion neutrons, particles, and associated x-rays. Alternate aneutronic fuel cycles, such as $p^{11}B$, avoid 14 MeV neutron damage and activation issues but have yet ill-defined first wall and energy conversion systems. Finally, at a system level, the IFE community could learn about system engineering from the EUV lithography community that is operating 50 kW CO_2 lasers at 50 kHz rep-rates to deliver pulse-shaped light focused to 10^{12} W/cm^2 on 50-μm tin targets that generate EUV radiation for producing chips with a 7 nm feature size. These devices also have elaborate systems to protect the expensive EUV optics and operate for $>10^9$ shots with capacity factors as high as $\sim$90%. These systems have similar features to an IFE reactor, with even tighter constraints on system packaging to be compatible with operating in the ultra-clean room environment of a chip fab.

The Snowmass 2002 roadmap (Fig. 1) portrays a tiered approach to developing an IFE Demo (FPP), supporting concept exploration for less mature technologies, the parallel development of more than one driver as phase I proof of principle beamlines, feeding into integrated research experiments (IREs), and eventually culminating in an FPP (DEMO). Continuing to develop both excimer and DPSSL laser

21 March 2024 03:34:24

© Author(s) 2024

technologies, as was done in the HAPL program, will provide real-world data for making system-level tradeoffs. Xcimer Energy is creating development and system integration roadmaps for their lasers that are consistent with this approach. With the leading role that private companies will play in developing FPPs, we may well see different plants that use either DPSSLs or excimer lasers, which will provide even more data for the economic analyses that utility companies will require. The separability of IFE reactors, as compared to MFE reactors, may be beneficial in allowing IFE companies to deliver the integrated conceptual system designs that are emphasized in the NASEM report and required by the milestone-based PPP programs. However, the IFE community will face other unique challenges because of the national security barriers to gaining access to facilities, codes, databases, and infrastructure that are still in place. As previously mentioned, the demonstration of ignition and gain on the NIF puts the IFE community on a firmer scientific footing, but the challenge will be to look beyond the science to the development of the fusion nuclear technology of the entire system.

Of even broader benefit to the fusion community would be for the milestone-based PPP program to deliver the demonstration of multiple MFE and IFE systems that can be evaluated for use in different contexts in an ecumenical fashion. This would avoid the premature down selection to a single technology that occurred in the U.S. nuclear reactor community because of the predominance of experience with water-cooled reactors by the Nuclear Navy. It is only now in the DOE Nuclear Energy Advanced Reactor Demonstration Program (ADRP) that high-temperature gas-cooled and molten salt reactors are once again being considered, and they may have real advantages in areas where access to cooling water is limited. The same mistake happened in the early 1970s when a premature focus on tokamaks halted work on the innovative confinement approaches to MFE that are now being "rediscovered." The U.S. IFE program must avoid a similar fate. All the modular IFE component technologies should be developed as much in parallel as funding allows to deliver prototype subsystems on a timely basis and to begin developing a domestic supply chain. As indicated in the Snowmass roadmap, target technology R&D should be performed in parallel with driver development, and synergy between approaches should be sought in issues such as foams, tritium, and injection/tracking technologies.

C. Beyond IFE BRN II: Facility investments, workforce, and an IFE home

At the Phase II Performance Extension level, the Snowmass roadmap shows the use of NNSA-funded experiments on NIF to provide target performance data. Today, the NNSA-funded Omega-60 laser is also being used to provide scaled data on direct drive targets, which are attractive because of their more efficient use of laser energy compared to indirect drive. However, as noted, these are NNSA facilities that, except for a limited number of days that are allocated to competitively awarded "discovery science shots," are fully utilized for NNSA experiments. Further, while in principle a researcher could request shots for IFE from this allocation, it is not clear that they would be competitive with the discovery science shots that the academic community traditionally proposes, and which play a role in NNSA workforce development. Therefore, to accelerate the development of an IFE FPP, the program needs a laser-driven target facility other than NIF where LPI, target, and burn physics issues can be addressed, preferably at the MJ or greater level. The IFE BRN report identifies such a facility as an opportunity for PPP collaborations. The report suggests that the public sector should consider PPP programs to help with both constructing and operating private-sector-led next-generation facilities that could serve the entire community. In this case, this partnership would center around a new high-energy laser facility, where a set fraction of shots would be made available to the community in exchange for public-sector support for construction and/or operations. Since a private company would be the lead for this facility, the laser should logically be a prototype of a modern DPPSL or excimer laser that is being developed for an FPP. For example, an MJ-class Xcimer laser, which would be their first integrated high-energy prototype operating at a low repetition rate, could be an attractive option. It would be desirable if the DOE National Reactor Innovation Center (NRIC),[154] or its IFE program equivalent, could assist in identifying and preparing a site. When such a facility could be built is a question of both economics and the private company's laser development project plan. Through the power of the PPP programs, it could be realized sometime in the 2030s, well ahead of when such a facility could be constructed under DOE orders.

The guiding principle behind the U.S. fusion strategy is that private industry will drive the commercialization of fusion energy, and public–private partnerships could greatly accelerate the development of all fusion energy concepts. This will require sustained advocacy and support from the White House, DOE, and Congress to meet their partnership obligations. ARPA-E, INFUSE, IFE STAR, and the milestone-based PPP program all play a valuable role on the public side of the partnership and can help enable the private companies to secure adequate VC funding by placing an imprimatur stamp of approval on the projects that are selected to receive public funds by expert review panels and informed program managers. However, what about university involvement in PPP programs? I suggest that this revitalized interest in fusion is a golden opportunity for universities, and especially engineering colleges, to engage in laser-plasma science and fusion nuclear technology development for IFE. This could take the form of a modern revisitation of the Fusion Technology Institute at the University of Wisconsin.[155] This could also be reimagined as a hub, as described in the DOE IFE STAR program, that is headed by a lead university but that partners with other universities, private companies, and even national labs. The primary product of the universities would be a skilled workforce, while the secondary product would be research, system studies, and designs.[156] Student internships from private companies would also be valuable in supporting the university programs.

The final topic to consider is identifying a single administrative home within the DOE that can be invested with the responsibility of leading a national IFE R&D program. Presently, IFE-related research is being funded by multiple departments and agencies, including the NNSA, DOE FES, and ARPA-E. The Milestone-Based PPP program involves all fusion approaches and is administered by DOE FES. The new IFE STAR program is also being administered by FES, but the Office continues to have most of its programs and funding in MFE. ARPA-E is also funding some IFE-relevant research, but the NNSA is by far the dominant force in ICF and high-yield, in keeping with its traditional funding by military organizations. However, the NNSA has a vested interest in advancing its nuclear weapon mission by building a high-yield LMF, with the attendant security issues of a primarily classified research agenda. While the NNSA may be interested in performing some research that is synergistic between the LMF and IFE FPPs, it

21 March 2024 03:34:24

© Author(s) 2024

seems unlikely that the NNSA administrators and their DoD customers will want to divide their loyalties by formally taking on an energy mission. Similarly, DOE FES has historically been identified with MFE and is responsible for the MFE labs and their experimental facilities. Perhaps, the small initial IFE efforts within FES can grow into a larger program that also takes responsibility for the proposed IFE laser-driven target facility and can grow to be on par with MFE within the Office. Another possibility would be to create an IFE office within the DOE Office of Nuclear Energy. Regardless; it seems clear that if IFE is to become a viable source of fusion power, it will need to have an administrative home within the government that has the responsibility for that mission.

VII. SUMMARY

In 1969, KMS Fusion became the first private company to pursue laser-driven IFE. Since then, IFE has gone through many periods of optimism, largely driven by theory and simulations, followed by periods of disillusionment, largely because of disappointing experimental data. Even the highly sophisticated simulations in the National Ignition Campaign were far from infallible. The experimental demonstration of ignition and gain on the NIF constitutes a pivotal point in the development of IFE. The scientific validity of single-shot ICF has been established, and private industry is stepping in to drive the commercialization of fusion energy in the United States. There are still gaps in our scientific models that need to be filled and large gaps in our technical and engineering readiness before an IFE fusion pilot plant can be built. HB11 Energy's work with the alternate proton–boron fuel cycle faces a greater challenge to initiating the fusion burn but simplifies target, breeding, and some reactor issues. Xcimer Energy is developing a potentially disruptive laser technology that could be a key enabler for all IFE companies, including HB11. Further, Xcimer's use of the HYLIFE-II reactor concept promises to simplify some of the engineering issues for their FPP. The DOE FES milestone-based public–private partnerships could greatly accelerate IFE development, but it will require a sustained commitment from all government stakeholders to realize a successful FPP and FOAK IFE power plant. Many of the ups and downs of the IFE program have been caused by a lack of continuity in funding. We would be much closer to an IFE FPP if the HAPL program had not been terminated in 2009. Private companies should work to gain access to the best available simulation tools to help develop event-based roadmaps, as described in the NAS IFE study. They should also take advantage of every opportunity to obtain experimental data that can validate or invalidate the simulations. Regardless, we must honestly assess the validity of both simulation and data, remembering Albert Einstein's admonition that "a theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it." Considering the previous 50 years of laser-fusion experiments, all IFE companies would wise to avoid overpromising to avoid losing credibility. Regardless, I am optimistic that the energy, daring, and drive of private companies will lead to an IFE FPP long before it could be realized solely through DOE funding.

ACKNOWLEDGMENTS

Thanks to Uri Shumlak for the invitation to write this perspective article. HB11 provided financial support for this article, and Warren McKenzie and Sergey Pikuz made valuable comments as well as provided input for the section on HB11 Energy. Thanks to Conner Galloway & Alex Valys for providing input for the section on Xcimer Energy. Max Tabak, Dale Welch, and Carsten Thoma have been making great progress on proton–boron burn physics, and Adam Sefkow and his TriForce team have recently joined the effort. Special thanks to my colleagues in the Nuclear Engineering and Radiological Sciences Department at the University of Michigan for continuing to support me as an adjunct professor. I could not have written this perspective without access to the University's great research library. Finally, thanks to the reviewers and editors who have patiently guided me to the present organization of this paper.

AUTHOR DECLARATIONS

Conflict of Interest

Yes, I am an advisor to both HB11 Energy and Xcimer Energy Inc.

Author Contributions

Thomas A. Mehlhorn: Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

[1] APS Division of Plasma Physics, "Mini-conference: Public-private partnerships for fusion energy," in 64th Annual Meeting of the APS Division of Plasma Physics, Spokane, Washington, 2022.
[2] Nuclear Newswire, see https://www.ans.org/news/article-3658/jet-celebrates-sustained-fusion-energy-production/ for "JET Celebrates Sustained Fusion Energy Production."
[3] B. Bishop, see https://www.llnl.gov/article/47896/national-ignition-facility-experiment-puts-researchers-threshold-fusion-ignition for "National Ignition Facility experiment Puts Researchers at Threshold of Fusion Ignition, LLNL News, 2021."
[4] US DOE Office of Fusion Energy Sciences, see https://science.osti.gov/-/media/grants/pdf/foas/2022/SC_FOA_0002809.pdf for "Milestone-Based Fusion Development program," 2022.
[5] Commonwealth Fusion Systems—CFS, see https://cfs.energy/ for "Established 2018."
[6] M. Greenwald, "Status of the SPARC physics basis," J. Plasma Phys. **86**(5), 861860501 (2020).
[7] H. Abu-Shawareb, R. Acree, P. Adams, J. Adams, B. Addis, R. Aden, P. Adrian, B. B. Afeyan, M. Aggleton, *et al.*, "Lawson criterion for ignition exceeded in an inertial fusion experiment," Phys. Rev. Lett. **129**(7), 075001 (2022).
[8] See https://www.whitehouse.gov/ostp/news-updates/2022/03/15/fact-sheet-developing-a-bold-vision-for-commercial-fusion-energy/ for "Fact Sheet: Developing a Bold Vision for Commercial Fusion Energy," 2022.
[9] R. J. Hawryluk, *Bringing Fusion to the U.S. Grid* (The National Academies, Washington, DC, 2021).
[10] See https://www.energy.gov/articles/doe-announces-46-million-commercial-fusion-energy-development for "DOE Announces $46 Million for Commercial Fusion Energy Development," 2023.
[11] HB11 Energy, see https://hb11.energy/ for "Established 2017."
[12] Xcimer Energy Inc., see https://xcimer.energy/index.html for "Established 2022."

21 March 2024 03:34:24

© Author(s) 2024

[13] Fusion Industry Association, see https://www.fusionindustryassociation.org/wp-content/uploads/2023/07/FIA%E2%80%932023-FINAL-1.pdf for "The Global Fusion Industry in 2023, 2023."

[14] See https://www.energy.gov/nnsa/articles/stockpile-stewardship-and-management-plan-ssmp for "NNSA Stockpile Stewardship and Management Plan (SSMP)," 2023.

[15] S. Drell, "Science Based Stockpile Stewardship," JASON Report No. JSR-94-345 (Mitre Corporation, McLean, VA, 1995).

[16] DOE Office of Defense Programs, "The Stockpile Stewardship and Management Program; Final Programmatic Environmental Impact Statement," Federal Register **60**(87), 22373–22376 (1995). available at https://www.govinfo.gov/content/pkg/FR-1995-05-05/html/95-11162.htm.

[17] E. Storm, J. D. Lindl, E. M. Campbell, T. P. Bernat, L. W. Coleman, J. L. Emmett, W. J. Hogan, J. T. Hunt, W. F. Krupke, and W. H. Lowdermilk, "Progress in laboratory high gain ICF: Prospects for the future," in paper presented at the Eighth Session of the International Seminars on Nuclear War, Erice, Sicily, Italy, 1988.

[18] T. H. Maiman, "Stimulated optical radiation in ruby," Nature **187**(4736), 493–494 (1960).

[19] N. Basov and O. Krokhin, "Conditions for heating up of a plasma by the radiation from an optical generator," Sov. Phys. JETP **19**(1), 123–126 (1964).

[20] J. M. Dawson, "On the production of plasma by giant pulse lasers," Phys. Fluids **7**(7), 981–987 (1964).

[21] R. E. Kidder, "Application of lasers to the production of high-temperature and high-pressure plasma," Nucl. Fusion **8**(1), 3–12 (1968).

[22] L. Wood and J. Nuckolls, "Prospects for unconventional approaches to controlled fusion," Report No. UCRL-74488 (Lawrence Livermore Laboratory, 1971).

[23] J. J. Duderstadt and G. A. Moses, *Inertial Confinement Fusion* (Wiley, 1982).

[24] J. Bromberg, *Fusion: Science, Politics, and the Invention of a New Energy Source* (The MIT Press, Cambridge, Massachusetts, 1982).

[25] J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, "Laser compression of matter to super-high densities: Thermonuclear (CTR) applications," Nature **239**(5368), 139–142 (1972).

[26] R. E. Kidder, "Energy gain of laser-compressed pellets: A simple model calculation," Nucl. Fusion **16**(3), 405–408 (1976).

[27] R. E. Kidder, "Theory of homogeneous isentropic compression and its application to laser fusion," Nucl. Fusion **14**(1), 53–60 (1974).

[28] R. E. Kidder and J. W. Zink, "Decoupling of corona and core of laser-heated pellets," Nucl. Fusion **12**(3), 325–328 (1972).

[29] NIF & Photon Sciences, see https://lasers.llnl.gov/10-years-of-dedication/laser-leadership for "45 Years of Laser Leadership."

[30] K. A. Brueckner and S. Jorna, "Laser-driven fusion," Rev. Mod. Phys. **46**(2), 325–367 (1974).

[31] P. M. Campbell, G. Charatis, and G. R. Montry, "Laser-driven compression of glass microspheres," Phys. Rev. Lett. **34**(2), 74–77 (1975).

[32] V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. Larsen, S. Glaros, G. Zimmerman, and H. Shay, "Measurement of the ion temperature in laser-driven fusion," Phys. Rev. Lett. **35**(16), 1083–1085 (1975).

[33] Gao, "Fusion—A possible option for solving long-term energy problems," Report No. EMD-79-27 (Gao, 1979).

[34] J. D. Lindl and J. D. Kilkenny, "Introduction to the Nova technical contract," United States, Report No. UCRL-LR-105820-95 (Lawrence Livermore National Laboratory, Livermore, CA, 1996).

[35] W. J. Hogan, "Missions and design requirements for a laboratory microfusion facility (LMF)," Fusion Technol. **15**, 541–549 (1989).

[36] S. E. Koonin, "Review of the Department of Energy's Inertial Confinement Fusion Program—Final Report," Report No. DE-AC0 I-89DP20 154 (National Academy of Sciences and Engineering, 1990).

[37] J. D. Sethian, D. G. Colombant, J. L. Giuliani, R. H. Lehmberg, M. C. Myers, S. P. Obenschain, A. J. Schmitt, J. Weaver, M. F. Wolford, F. Hegeler *et al.*, "The science and technologies for fusion energy with lasers and direct-drive targets," IEEE Trans. Plasma Sci. **38**(4), 690–703 (2010).

[38] R. C. Davidson and G. L. Kulcinski, *An Assessment of the Prospects for Inertial Fusion Energy* (The National Academies Press, 2013).

[39] P. M. Burns, M. Myers, J. D. Sethian, M. F. Wolford, J. L. Giuliani, R. H. Lehmberg, M. Friedman, F. Hegeler, R. Jaynes, S. Abdel-Khalik *et al.*, "Electra: An electron beam pumped KrF rep-rate laser system for inertial fusion energy," Fusion Science Technol. **56**(1), 346–351 (2009).

[40] A. Bayramian, P. Armstrong, E. Ault, R. Beach, C. Bibeau, J. Caird, R. Campbell, B. Chai, J. Dawson, C. Ebbers *et al.*, "The Mercury project: A high average power, gas-cooled laser for inertial fusion energy development," Fusion Sci. Technol. **52**(3), 383–387 (2007).

[41] R. O. Bangerter, G. Navaratil, and N. Sauthoff, "2002 Fusion Summer Study Report," in Snowmass CO Fusion Studies, 2003, Available at https://fire.pppl.gov/snowmass02_report.pdf.

[42] See https://lasers.llnl.gov/programs/pdfs/nic_execplan0605.pdf for "National Ignition Campaign Execution Plan—Revision 0, 2005."

[43] J. Ahearne, *Assessment of Inertial Confinement Fusion Targets* (The National Academies Press, 2013).

[44] NNSA Office of Defense Programs, "2015 review of the inertial confinement fusion and high energy density science portfolio: Volume I," May 2016, http://www.firefusionpower.org/ICF_HED_Review_Report_2015_Update.pdf.

[45] P. Bucksbaum, *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light* (The National Academies Press, Washington, DC, 2018), p. 346.

[46] P. K. Patel, P. T. Springer, C. R. Weber, L. C. Jarrott, O. A. Hurricane, B. Bachmann, K. L. Baker, L. F. Berzak Hopkins, D. A. Callahan, D. T. Casey *et al.*, "Hotspot conditions achieved in inertial confinement fusion experiments on the National Ignition Facility," Phys. Plasmas **27**(5), 050901 (2020).

[47] S. P. Regan, V. N. Goncharov, T. C. Sangster, E. M. Campbell, R. Betti, K. S. Anderson, T. Bernat, A. Bose, T. R. Boehly, M. J. Bonino *et al.*, "The National Direct-Drive Program: OMEGA to the National Ignition Facility," Fusion Sci. Technol. **73**(2), 89–97 (2018).

[48] M. R. Gomez, S. A. Slutz, C. A. Jennings, D. J. Ampleford, M. R. Weis, C. E. Myers, D. A. Yager-Elorriaga, K. D. Hahn, S. B. Hansen, E. C. Harding *et al.*, "Performance scaling in magnetized liner inertial fusion experiments," Phys. Rev. Lett. **125**(15), 155002 (2020).

[49] Fusion Energy Sciences Advisory Committee, see https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf for "Powering the Future—Fusion & Plasmas," 2020.

[50] US DOE Office of Fusion Energy Sciences, see https://science.osti.gov/-/media/fes/pdf/workshop-reports/2023/IFE-Basic-Research-Needs-Final-Report.pdf for "Inertial Fusion Energy: Report of the 2022 Fusion Energy Sciences Basic Research Needs Workshop," 2022.

[51] Department of Energy, Fusion Energy Sciences, "Inertial Fusion Energy Science & Technology Accelerated Research (IFE-STAR)," Report No. DE-FOA-0003044 (2023).

[52] P. Koning, see https://www.llnl.gov/article/49501/star-power-blazing-path-fusion-ignition#:∼:text=Ignition%20on%20NIF%2C%20the%20world's,of%20NIF%20(see%20%E2%80%9CAchieving%20Fusion for"Star Power: Blazing the Path to Fusion Ignition," 2023.

[53] S. E. Koonin, *Review of the Department of Energy's Inertial Confinement Fusion Program - The National Ignition Facility* (National Academy Press, 1997).

[54] S. E. Wurzel and S. C. Hsu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," Phys. Plasmas **29**(6), 062103 (2022).

[55] A. R. Christopherson, O. A. Hurricane, C. Weber, A. Kritcher, R. Nora, J. Salmonson, R. Tran, J. Milovich, S. Maclaren, D. Hinkel, and R. Betti, "Alpha-heating analysis of burning plasma and ignition experiments on the National Ignition Facility," Phys. Plasmas **30**(6), 062705 (2023).

[56] V. G. Kiptily, R. Dumont, M. Fitzgerald, D. Keeling, S. E. Sharapov, M. Poradzinski, Ž. Štancar, P. J. Bonofiglo, E. Delabie, Z. Ghani *et al.*, "Evidence of electron heating by alpha particles in JET deuterium-tritium plasmas," Phys. Rev. Lett. **131**(7), 075101 (2023).

[57] D. Kramer, "ITER appears unstoppable despite recent setbacks," Phys. Today **76**(8), 18–22 (2023).

[58] D. Cleary, "OUT OF GAS: A shortage of tritium fuel may leave fusion energy with any empty tank," Science **376**, 1372 (2022).

[59] A. M. Schwendt, A. Nobile, P. L. Gobby, W. P. Steckle, D. G. Colombant, J. D. Sethian, D. T. Goodin, and G. E. Alfred Besenbruch, "Tritium inventory of inertial fusion energy target fabrication facilities: Effect of foam density and

21 March 2024 03:34:24

© Author(s) 2024

consideration of target yield of direct drive targets," Fusion Sci. Technol. **43**(2), 217–229 (2003).

[60] A. Collaboration, M. Turner, P. Muggli, E. Adli, R. Agnello, M. Aladi, Y. Andrebe, O. Apsimon, R. Apsimon, A. M. Bachmann *et al.*, "Experimental study of wakefields driven by a self-modulating proton bunch in plasma," Phys. Rev. Accel. Beams **23**(8), 081302 (2020).

[61] W. Zheng, X. Wei, Q. Zhu, F. Jing, D. Hu, J. Su, K. Zheng, X. Yuan, H. Zhou, W. Dai *et al.*, "Laser performance of the SG-III laser facility," High Power Laser Sci. Eng. **4**, e21 (2016).

[62] Z. Gan, L. Yu, C. Wang, Y. Liu, Y. Xu, W. Li, S. Li, L. Yu, X. Wang, X. Liu *et al.*, "The shanghai superintense ultrafast laser facility (SULF) project," in *Progress in Ultrafast Intense Laser Science XVI*, edited by K. Yamanouchi, K. Midorikawa, and L. Roso (Springer International Publishing, Cham, 2021), pp. 199–217.

[63] E. Carlidge, "Physicists are planning to build lasers so powerful they could rip apart empty space," in Science New/Asia Pacific, 2018.

[64] BMBF—Bundesminsterium fur Bildung und Foschung, see https://www.bmbf.de/SharedDocs/Downloads/de/2023/230522-memorandum-laser-inertial-fusion-energy.html for "Memorandum Laser Inertial Fusion Energy," 2023.

[65] EUROfusion, https://www.laserfusion.eu/presentation-of-the-hiper-plus-project/ for "Presentation of the HiPER Plus Project."

[66] THALES, see https://www.thalesgroup.com/en/markets/specific-solutions/lasers for "information about the portfolio of high-energy solid state lasers of the Thales Group."

[67] TAE Technologies, see https://tae.com/ for "Established 1998."

[68] N. Rostoker, M. W. Binderbauer, and H. J. Monkhorst, "Colliding beam fusion reactor," Science **278**(5342), 1419 (1997).

[69] M. Tuszewski, "Field reversed configurations," Nucl. Fusion **28**(11), 008 (1988).

[70] General Fusion, see https://generalfusion.com/ for "Established 2002."

[71] D. L. Book, R. L. Burton, and A. L. Cooper, "Experimental and theoretical liner fusion studies," Report No. NRL-MR-3826 (Naval Research Laboratory, Washington, DC, 1978).

[72] Tokamak Energy, see https://www.tokamakenergy.co.uk/ for "Established 2009."

[73] First Light Fusion, see https://firstlightfusion.com/ for "Established 2011."

[74] Helion Energy, see https://www.helionenergy.com/ for "Established 2013."

[75] J. Slough, S. Andreason, H. Gota, C. Pihl, and G. Votroubek, "The pulsed high density experiment: Concept, design, and initial results," J. Fusion Energy **26**(1–2), 199–205 (2007).

[76] See https://arpa-e.energy.gov/technologies/programs/alpha for "ALPHA: Accelerating Low-Cost Plasma Heating and Assembly," 2015.

[77] C. L. Nehl, R. J. Umstattd, W. R. Regan, S. C. Hsu, and P. B. McGrath, "Retrospective of the ARPA-E ALPHA fusion program," J. Fusion Energy **38**(5–6), 506–521 (2019).

[78] K. Tummel, D. P. Higginson, A. J. Link, A. E. W. Schmidt, D. T. Offermann, D. R. Welch, R. E. Clark, U. Shumlak, B. A. Nelson, R. P. Golingo, and H. S. McLean, "Kinetic simulations of sheared flow stabilization in high-temperature Z-pinch plasmas," Phys. Plasmas **26**(6), 062506 (2019).

[79] Fuse Energy Technologies, see https://www.f.energy/ for "Established 2019."

[80] See https://arpa-e.energy.gov/technologies/programs/bethe for "BETHE—Breakthroughs Enabling THermonuclear-Fusion Energy," 2020.

[81] D. Chandler, *MIT and Newly Formed Company Launch Novel approach to Fusion Power* (Massachusetts Institute of Technology, 2018).

[82] D. L. Chandler, *MIT-Designed Project Achieves Major Advance Toward Fusion Energy* (MIT Energy Initiative, 2022).

[83] H. Zohm, "On the size of tokamak fusion power plants," Philos. Trans. R. Soc. A **377**(2141), 20170437 (2019).

[84] Type One Energy Group, see https://typeoneenergy.com/ for "Established 2019."

[85] Realta Fusion, see https://realtafusion.com/ for "Established 2022."

[86] H. Hora, *Laser Plasma Physics: Forces and the Nonlinearity Principle* (SPIE, 2016).

[87] Marvel Fusion, see https://marvelfusion.com/ for "Established 2019."

[88] M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks *et al.*, "Fast ignition by intense laser-accelerated proton beams," Phys. Rev. Lett. **86**(3), 436 (2001).

[89] EX Fusion, see https://ex-fusion.com/ for "Established 2021 in Japan."

[90] Longview Fusion Energy Systems, "Established 2022."

[91] Blue Laser Fusion, see https://bluelaserfusion.com/ for "Established 2022."

[92] See https://www-optica-opn-org.proxy.lib.umich.edu/home/articles/volume_34/june_2023/features/fusion_s_direct_drive/ for "LaserFusionX."

[93] Lawrence Livermore National Laboratory, "Igniting LIFE," *Science and Technology Review* (Lawrence Livermore National Laboratory, 2011).

[94] H. Hora, S. Eliezer, G. J. Kirchhoff, N. Nissim, J. X. Wang, P. Lalousis, Y. X. Xu, G. H. Miley, J. M. Martinez-Val, W. McKenzie, and J. Kirchhoff, "Road map to clean energy using laser beam ignition of boron-hydrogen fusion," Laser Part. Beams **35**(4), 730–740 (2017).

[95] H. Hora, "Method for generating electrical energy by laser-based nuclear fusion and laser reactor," U. S. patent application US10410752B2 (2019).

[96] V. S. Belyaev, A. P. Matafonov, V. I. Vinogradov, V. P. Krainov, V. S. Lisitsa, A. S. Roussetski, G. N. Ignatyev, and V. P. Andrianov, "Observation of neutronless fusion reactions in picosecond laser plasmas," Phys. Rev. E **72**(2), 026406 (2005).

[97] C. Labaune, C. Baccou, V. Yahia, C. Neuville, and J. Rafelski, "Laser-initiated primary and secondary nuclear reactions in Boron-Nitride," Sci. Rep. **6**(1), 21202 (2016).

[98] A. Picciotto, D. Margarone, A. Velyhan, P. Bellutti, J. Krasa, A. Szydlowsky, G. Bertuccio, Y. Shi, A. Mangione, J. Prokupek *et al.*, "Boron-proton nuclear-fusion enhancement induced in boron-doped silicon targets by low-contrast pulsed laser," Phys. Rev. X **4**(3), 031030 (2014).

[99] D. Margarone, A. Picciotto, A. Velyhan, J. Krasa, M. Kucharik, A. Mangione, A. Szydlowsky, A. Malinowska, G. Bertuccio, Y. Shi *et al.*, "Advanced scheme for high-yield laser driven nuclear reactions," Plasma Phys. Controlled Fusion **57**(1), 014030 (2014).

[100] L. Giuffrida, F. Belloni, D. Margarone, G. Petringa, G. Milluzzo, V. Scuderi, A. Velyhan, M. Rosinski, A. Picciotto, M. Kucharik *et al.*, "High-current stream of energetic alpha particles from laser-driven proton-boron fusion," Phys. Rev. E **101**(1), 013204 (2020).

[101] W. McKenzie, D. Batani, T. A. Mehlhorn, D. Margarone, F. Belloni, E. M. Campbell, S. Woodruff, J. Kirchhoff, A. Paterson, S. Pikuz, and H. Hora, "HB11—Understanding hydrogen-boron fusion as a new clean energy source," J. Fusion Energy **42**(1), 17 (2023).

[102] D. Margarone, J. Bonvalet, L. Giuffrida, A. Morace, V. Kantarelou, M. Tosca, D. Raffestin, P. Nicolai, A. Picciotto, Y. Abe *et al.*, "In-target Proton–Boron nuclear fusion using a PW-class laser," Appl. Sci. **12**(3), 1444 (2022).

[103] T. A. Mehlhorn, L. Labun, B. M. Hegelich, D. Margarone, M. F. Gu, D. Batani, E. M. Campbell, S. X. Hu, and B. Ramakrishna, "Path to Increasing p-B11 Reactivity via ps and ns Lasers," Laser Part. Beams **2022**, 2355629.

[104] C. Labaune, C. Baccou, S. Depierreux, C. Goyon, G. Loisel, V. Yahia, and J. Rafelski, "Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma," Nat. Commun. **4**(1), 2506 (2013).

[105] J. Bonvalet, P. Nicolaï, D. Raffestin, E. D'Humieres, D. Batani, V. Tikhonchuk, V. Kantarelou, L. Giuffrida, M. Tosca, G. Korn *et al.*, "Energetic alpha-particle sources produced through proton-boron reactions by high-energy high-intensity laser beams," Phys. Rev. E **103**(5), 053202 (2021).

[106] Naval Research Laboratory, "Comments on the colliding beam fusion reactor proposed by Rostoker, Binderbauer and Monkhorst for use with the p-11B fusion reaction," Report No. NRL/MR/6709-98-8305 (Naval Research Laboratory, 1998).

[107] T. H. Rider, "Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium," Phys. Plasmas **4**(4), 1039–1046 (1997).

[108] G. H. Miley, *The Inertial Electrostatic Confinement Approach to Fusion Power* (Springer US, 1997), pp. 135–148.

[109] B. C. Maglich, "The migma principle of controlled fusion," Nucl. Instrum. Methods **111**(2), 213–235 (1973).

[110] N. Rostoker, F. Wessel, H. Rahman, B. C. Maglich, B. Spivey, and A. Fisher, "Magnetic fusion with high energy self-colliding ion beams," Phys. Rev. Lett. **70**(12), 1818–1821 (1993).

[111] HB11 Energy USA LLC, "DUNS/SAM UEI: 118972177" (2023).

[112] M. H. Sikora and H. R. Weller, "A new evaluation of the ^{11}B(p,α)$\alpha\alpha$ reaction rates," J. Fusion Energy **35**(3), 538–543 (2016).

[113] S. V. Putvinski, D. D. Ryutov, and P. N. Yushmanov, "Fusion reactivity of the pB^{11} plasma revisited," Nucl. Fusion **59**(7), 076018 (2019).

21 March 2024 03:34:24

© Author(s) 2024

[114] P. Woodward, "Compton interaction of a photon gas with a plasma," Phys. Rev. D **1**(10), 2731–2734 (1970).

[115] E. L. Dewald, J. E. Pino, R. E. Tipton, J. D. Salmonson, J. Ralph, E. Hartouni, S. F. Khan, R. Hatarik, C. V. Young, D. Thorn *et al.*, "Pushered single shell implosions for mix and radiation trapping studies using high-Z layers on National Ignition Facility," Phys. Plasmas **26**(7), 072705 (2019).

[116] T. Weaver, G. Zimmerman, and L. Wood, "Exotic CTR fuels: Non-thermal effects and laser fusion applications," Report No. UCRL-74938 (Lawrence Livermore National Laboratory, Livermore, CA, 1973).

[117] F. Belloni, "On a fusion chain reaction via suprathermal ions in high-density H–^{11}B plasma," Plasma Phys. Controlled Fusion **63**(5), 055020 (2021).

[118] F. Belloni and K. Batani, "Multiplication processes in high-density H-^{11}B fusion fuel," Laser Part. Beams **2022**, 3952779.

[119] D. R. Welch, N. Bennett, T. C. Genoni, C. Thoma, and D. V. Rose, "Fast hybrid particle-in-cell technique for pulsed-power accelerators," Phys. Rev. Accel. Beams **23**(11), 110401 (2020).

[120] R. B. Campbell, R. Kodama, T. A. Mehlhorn, K. A. Tanaka, and D. R. Welch, "Simulation of heating-compressed fast-ignition cores by Petawatt laser-generated electrons," Phys. Rev. Lett. **94**(5), 055001 (2005).

[121] D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, and T. A. Mehlhorn, "Integrated simulation of the generation and transport of proton beams from laser-target interaction," Phys. Plasmas **13**(6), 063105 (2006).

[122] C. Thoma, D. R. Welch, R. E. Clark, N. Bruner, J. J. MacFarlane, and I. E. Golovkin, "Two-fluid electromagnetic simulations of plasma-jet acceleration with detailed equation-of-state," Phys. Plasmas **18**(10), 103507 (2011).

[123] S. Atzeni, M. Temporal, and J. J. Honrubia, "A first analysis of fast ignition of precompressed ICF fuel by laser-accelerated protons," Nucl. Fusion **42**(3), L1 (2002).

[124] J. J. MacFarlane, I. E. Golovkin, and P. R. Woodruff, "HELIOS-CR—A 1D radiation-magnetohydrodynamics code with inline atomic kinetics modeling," J. Quant. Spectrosc. Radiat. Transfer **99**(1), 381–397 (2006).

[125] INFUSE—Innovation Network for Fusion Energy, see https://infuse.ornl.gov/news/fy2023-awards-announced-by-doe/ for "FY2023 Awards Announced by DOE," 2023.

[126] A. B. Sefkow, "The TriForce Institute for Multiphysics Modeling." https://hajim.rochester.edu/me/sites/sefkow/research/index.html.

[127] ANFF, see https://anff.org.au/ for "The Australian National Fabrication Facility."

[128] Europa Press, see https://www.europapress.es/castilla-y-leon/noticia-compania-australiana-hb11-energy-potenciara-investigacion-clpu-salamanca-20230118135813.html for "La Compañía Australiana HB11 Energy Potenciará la Investigación del CLPU de Salamanca."

[129] R. W. Moir, R. L. Bieri, X. M. Chen, T. J. Dolan, M. A. Hoffman, P. A. House, R. L. Leber, J. D. Lee, Y. T. Lee, J. C. Liu *et al.*, "HYLIFE-II: A molten-salt inertial fusion energy power plant design—Final report," Fusion Technol. **25**(1), 5–25 (1994).

[130] A. M. Boĭchenko, V. I. Derzhiev, A. G. Zhidkov, and S. I. Yakovlenko, "Kinetic model of an ArF laser," Sov. J. Quantum Electron. **22**(5), 444–448 (1992).

[131] DOE INFUSE Program, see https://infuse.ornl.gov/awards/simulation-of-direct-drive-hybrid-using-two-opposed-beams-for-inertial-fusion-energy/ for "Simulation of Direct-Drive Hybrid Using Two Opposed Beams for Inertial Fusion Energy."

[132] V. S. Averbakh, A. I. Makarov, and I. T. Vladimir, "Stimulated molecular scattering of light in gases at different pressures," Sov. J. Quantum Electron. **5**(10), 1201 (1975).

[133] J. Murray, J. Goldhar, D. Eimerl, and A. Szoke, "Raman pulse compression of excimer lasers for application to laser fusion," IEEE J. Quantum Electron. **15**(5), 342–368 (1979).

[134] M. J. Damzen and M. H. R. Hutchinson, "High-efficiency laser-pulse compression by stimulated Brillouin scattering," Opt. Lett. **8**(6), 313–315 (1983).

[135] M. Damzen and H. Hutchinson, "Laser pulse compression by stimulated Brillouin scattering in tapered waveguides," IEEE J. Quantum Electron. **19**(1), 7–14 (1983).

[136] A. Hunter, R. Hunter, and T. Johnson, "Scaling of KrF lasers for inertial confinement fusion," IEEE J. Quantum Electron. **22**(3), 386–404 (1986).

[137] J. P. Partanen and M. J. Shaw, "High-power forward Raman amplifiers employing low-pressure gases in light guides. I. Theory and applications," J. Opt. Soc. Am. B **3**(10), 1374–1389 (1986).

[138] M. R. Osborne, W. A. Schroeder, M. J. Damzen, and M. H. R. Hutchinson, "Low-divergence operation of a long-pulse excimer laser using a SBS phase-conjugate cavity," Appl. Phys. B **48**(4), 351–356 (1989).

[139] C. Higgs, J. A. Russell, D. W. Trainor, T. Roberts, E. D. Ariel, B. E. Player, M. J. Smith, and L. C. Bradley, "Adaptive-optics compensation in a Raman amplifier configuration," IEEE J. Quantum Electron. **26**(5), 934–941 (1990).

[140] M. J. Shaw, C. J. Hooker, and D. C. Wilson, "Measurement of the nonlinear refractive index of air and other gases at 248 nm," Opt. Commun. **103**(1), 153–160 (1993).

[141] I. C. E. Turcu, M. C. Gower, and P. Huntington, "Measurement of KrF laser breakdown threshold in gases," Opt. Commun. **134**(1), 66–68 (1997).

[142] Thermo Electron Technologies Corporation, "Single pulse excimer ground-based laser ASAT concept definition study for Air Force Weapons Laboratory," Report No. TTC-1588-R under contract No. N00014-88-C-0763 (1989).

[143] S. P. Obenschain, S. E. Bodner, D. Colombant, K. Gerber, R. H. Lehmberg, E. A. McLean, A. N. Mostovych, M. S. Pronko, C. J. Pawley, A. J. Schmitt *et al.*, "The Nike KrF laser facility: Performance and initial target experiments," Phys. Plasmas **3**(5), 2098–2107 (1996).

[144] S. Obenschain, R. Lehmberg, D. Kehne, F. Hegeler, M. Wolford, J. Sethian, J. Weaver, and M. Karasik, "High-energy krypton fluoride lasers for inertial fusion," Appl. Opt. **54**(31), F103–F122 (2015).

[145] T. B. Petrova, M. F. Wolford, M. C. Myers, and S. P. Obenschain, "Modeling of the NRL electra electron-beam pumped argon fluoride laser," IEEE Trans. Plasma Sci. **51**(6), 1392–1403 (2023).

[146] S. W. Haan, J. D. Lindl, D. A. Callahan, D. S. Clark, J. D. Salmonson, B. A. Hammel, L. J. Atherton, R. C. Cook, M. J. Edwards, S. Glenzer *et al.*, "Point design targets, specifications, and requirements for the 2010 ignition campaign on the National Ignition Facility," Phys. Plasmas **18**(5), 051001 (2011).

[147] S. E. Bodner, "Time-dependent asymmetries in laser-fusion hohlraums," Comments Plasma Phys. Controlled Fusion **16**, 351–374 (1995). http://inis.iaea.org/search/search.aspx?orig_q=RN:27012485.

[148] A. L. Kritcher, C. V. Young, H. F. Robey, C. R. Weber, A. B. Zylstra, O. A. Hurricane, D. A. Callahan, J. E. Ralph, J. S. Ross, K. L. Baker *et al.*, "Design of inertial fusion implosions reaching the burning plasma regime," Nat. Phys. **18**(3), 251–258 (2022).

[149] O. A. Hurricane, D. A. Callahan, D. T. Casey, E. L. Dewald, T. R. Dittrich, T. Döppner, M. A. Barrios Garcia, D. E. Hinkel, L. F. Berzak Hopkins, P. Kervin *et al.*, "The high-foot implosion campaign on the National Ignition Facility," Phys. Plasmas **21**(5), 056314 (2014).

[150] O. A. Hurricane, D. T. Casey, O. Landen, A. L. Kritcher, R. Nora, P. K. Patel, J. A. Gaffney, K. D. Humbird, J. E. Field, M. K. G. Kruse *et al.*, "An analytic asymmetric-piston model for the impact of mode-1 shell asymmetry on ICF implosions," Phys. Plasmas **27**(6), 062704 (2020).

[151] O. Hurricane, D. Callahan, A. Kritcher, and A. Zylstra, "Optimism is not a strategy: A white paper on how to give IFE a fighting chance to be real," in paper presented at the IFE Workshops 2021, 2022.

[152] DOE Fusion Energy Sciences, see https://www.federalregister.gov/documents/2023/03/27/2023-06176/fusion-prototypic-neutron-source-fpns for "Fusion Prototypic Neutron Source (FPNS)," 2023.

[153] Michigan Engineering, see https://mibl.engin.umich.edu/ for "Michigan Ion Beam Laboratory for Surface Modification and Analysis."

[154] US DOE Office of Nuclear Energy, see https://www.energy.gov/sites/prod/files/2019/08/f65/NRIC_Fact_Sheet.pdf for "National Reactor Innovation Center—Establishing the Test and Demonstration of Advanced Reactor Concepts."

[155] G. L. Kulcinski and R. W. Conn, "The conceptual design of a tokamak fusion power reactor, UWMAK-1," Report No. UWFDM-90 (University of Wisconsin Fusion Technology Institute, 1974).

[156] D. G. Whyte, C. Paz-Soldan, and B. Wirth, "The academic research ecosystem required to support the development of fusion energy," Phys. Plasmas **30**(9), 090604 (2023).

21 March 2024 03:34:24

© Author(s) 2024