

Retrospective of the ARPA-E ALPHA fusion program

C. L. Nehl,¹ R. J. Umstattd,^{2,*} W. R. Regan,^{2,**} S. C. Hsu,^{2,†} P. B. McGrath²

1: Booz Allen Hamilton, McLean, VA 22102

2: Advanced Research Projects Agency–Energy, U.S. Department of Energy, Washington, DC 20585

* R. J. Umstattd is presently affiliated with Fusion Industry Association, Gaithersburg, MD 20879

** W. R. Regan is presently affiliated with X, the Moonshot Factory, Mountain View, CA 94043

†Corresponding author email: scott.hsu@hq.doe.gov

Introduction:

In 2014 the Advanced Research Projects Agency—Energy (ARPA-E) of the U.S. Department of Energy (DOE) launched a new research program on low-cost approaches to fusion-energy development[1]. The “Accelerating Low-Cost Plasma Heating and Assembly” (ALPHA) program set out to enable more rapid progress towards fusion energy by establishing a wider range of technological options that could be pursued with smaller, lower-cost experiments, short development and construction times, and high experimental throughput. Mainstream fusion research generally refers to magnetically or inertially confined fusion, both of which require expensive facilities for reasons briefly described below and explored in more detail in several books[2][3]. ALPHA focused on magneto-inertial fusion (MIF), a class of pulsed fusion approaches with fuel densities in between those of magnetic and inertial fusion[4], [5] [6]. This paper presents a brief background on the origins of the ALPHA program, the results achieved by ALPHA-funded teams, and a look ahead to potential next steps for low-cost fusion development.

Origins

ARPA-E’s mission is to develop transformational new energy technologies[7]. While DOE has pursued fusion energy as a potentially transformational opportunity for decades, ARPA-E had not supported any work in fusion prior to the ALPHA program. This was in part due to a perception that fusion was inherently the realm of “big science” and that ARPA-E, which runs relatively small, targeted, short-term programs across a wide spectrum of energy technologies—did not have a role to play in that development. In launching ALPHA, ARPA-E sought to change this dynamic and bring new players into the field – both in terms of the kinds of teams doing fusion development (e.g., smaller groups and private startups), and in terms of the sources of funding (e.g., private investors). The ALPHA program was also a way for ARPA-E to address a longer-term problem in energy development with a targeted program. The motivation and timing for the ALPHA program were driven by three major factors:

- 1) analysis suggesting the potential for lower-cost pathways with fuel densities between those of the mainstream approaches of magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) [8], [9],
- 2) significant experimental results from magnetized inertial confinement fusion [10] and from the Magnetized Liner Inertial Fusion (MagLIF)[11] program that supported this analysis, and
- 3) growing private sector investment in fusion[12][13], opening an opportunity for new approaches if they can achieve performance gains at costs compatible with private investors.

1: Potential for lower-cost pathways: The overwhelming majority of fusion research funding is currently devoted to major programs in MCF (principally the ITER collaboration and supporting plasma science in

conventional tokamaks), and in ICF (principally laser-driven systems such as the National Ignition Facility, NIF, in the U.S.). ITER and NIF are each multi-billion dollar facilities, and the costs are driven in large part by performance requirements that are intrinsic to their respective approaches. ITER, which will operate as a long-pulse device with an ion density of approximately 10^{14} cm^{-3} , requires an exceptionally large vacuum vessel and magnet set to contain a plasma of sufficient size to meet and exceed Lawson conditions, and the costs of the vacuum vessel and magnets are correspondingly large[14]. NIF, a pulsed device that compresses targets to ion densities greater than 10^{26} cm^{-3} , requires exceptionally high power and power density to overcome the thermal losses (hundreds of TW peak power), and the cost of a MJ-class laser and optics systems to deliver sufficient energy in a sufficiently short time to the target system drives high costs for the machine[15]. ITER and NIF are the leading facilities within MCF and ICF, respectively. For the purposes of burning plasma research (as in ITER) or ignition and propagating burn (as in NIF), these “big science” projects have arguably the lowest scientific risk for achieving their respective goals. However, there are a wide range of alternative approaches spanning the full range of parameter space for fusion plasmas, including many that lie near the middle of the ten-plus orders of magnitude in ion density between MCF and ICF[8]. In fact, there are a number of analyses suggesting that some of these intermediate-density approaches with very high magnetic fields (megagauss or higher) may be able to achieve Lawson conditions at significantly lower costs than the mainline MCF or ICF approaches. The reasoning behind these analyses varies – from an optimal balance between the minimum size/energy of a plasma against the minimum power to overcome thermal losses[8], to an optimum magnetic field in the megagauss range for sizing plasma and pulsed power components[9], to the power density of the fusion core matched to practical reactor scaling [16], but they each suggest that the space in between ITER and NIF may be less costly to explore than the MCF and ICF extremes.

2. MagLIF experiments constituting proof-of-concept for MIF: The analyses referenced above have developed over decades, but there has been relatively little exploration of the concepts that might fall in this range, and thus little experimental data or validated models to offer more detailed support. However, in 2014, Sandia completed their first integrated shots of the MagLIF experiments, which used the Z-machine to implode a pre-heated and magnetized cylindrical D plasma target [17]. The experiments reached peak ion densities exceeding 10^{22} cm^{-3} and multi-keV temperatures, producing significant DD neutron yields from thermonuclear fusion[11]. These results – which came very early in the first campaigns, and have subsequently been exceeded – represent the first significant experimental evidence to support the claim that intermediate-density, magnetized fusion approaches could be significantly lower in cost than MCF or ICF [18]. The MagLIF experiments were performed on a multi-purpose pulsed power machine that is more than an order of magnitude lower in cost than the single-purpose ICF machine NIF[19]. While the MagLIF results do not represent a new record in fusion yield, the very fact that these experiments produced high yield in early experiments on a non-purpose built, relatively low-cost machine suggests that this is an area of fusion research that warrants further exploration.

3. Increased private interest in fusion: At the same time that these scientific developments were taking place, there was also a growing movement of private investors taking increased interest, and devoting significant private resources, to fusion development. In the years leading up to the ALPHA program, hundreds of millions of dollars were invested into private fusion companies, led by Tri Alpha Energy (now TAE Technologies) in the U.S., Tokamak Energy in the U.K., and General Fusion in Canada[12], [13]. Acknowledging the extremely high technical risks and long timelines associated with fusion, the interest

and appetite for private investors to participate in fusion development signals an opportunity to bring in new players and expand the field. A central thesis of the ALPHA program was that we could expand the field if we could offer more options for fusion development that could be developed at funding levels compatible with private investment (i.e., tens to hundreds of millions of dollars for R&D, not several billion for scientific proof of concept). When combined with (1) compelling arguments for low-cost pathways and (2) experimental evidence supporting those arguments, ARPA-E determined that this could offer transformational opportunity to change the trajectory for the field.

Based on this combination of factors, ARPA-E launched the ALPHA program to explore “intermediate-density” fusion approaches with peak ion densities ranging from 10^{18} - 10^{23} cm⁻³[1]. This is a range that includes a diversity of approaches, but all share the common attributes of a magnetized plasma (a “target”) that must be compressed in a pulsed fashion (using a “driver”) to reach high density and temperature. Some examples include magneto-inertial fusion (MIF, sometimes called magnetized target fusion, MTF), which utilize an imploding conductive liner to compress a fusion plasma, and stabilized dense Z-pinches, which use direct pulsed power to assemble, compress, and heat a column of fusion fuel. The focus on intermediate-density approaches reflected the opportunity for low-development cost in a range that was relatively under-explored as compared to MCF and ICF approaches.

Beyond the focus on approaches in the intermediate ion density range, the ALPHA program set specific goals for the cost (<\$0.05/MJ delivered driver energy, measured over full driver life), engineering gain (>5 for product of driver efficiency and projected fusion gain), and shot rate (hundreds of shots in ALPHA program, path to >1 Hz operation) of the proposed plasma systems, all with the purpose of achieving rapid experimental progress in the near term, and enabling economical fusion power reactors in the long term[1]. These constraints ruled out many destructive experimental approaches that, such as the use of explosives for compression. Recent progress in pulsed power technology, such as the continued development of wide bandgap devices for high current/high voltage solid-state switches[20][21], [22] and linear transformer drivers (LTD)[23], [24] offer promise that pulsed fusion approaches can achieve high efficiency, low cost, and high repetition rate. ALPHA teams were permitted to use “legacy” pulsed power machines to demonstrate performance, but each had to justify that the current and voltage levels, and the required timescales and profiles for discharge could be compatible with eventual efficient operation at high repetition rate (e.g., 1 Hz).

Out of this competitive solicitation, a portfolio consisting of nine teams was selected for award in the ALPHA program. There was a diversity of approaches within the program, including pulsed magnetic compression, MIF with piston-driven liquid liner compression, MIF with high velocity plasma jet compression, and stabilized Z-pinches. There were also projects in the portfolio performing applied

ALPHA: Portfolio of teams and approaches










Pulsed magnetic compression  Helion Energy	Stabilized Z-pinch (direct pulsed power)  UNIVERSITY of WASHINGTON	Plasma jets for high velocity liner implosion  Los Alamos NATIONAL LABORATORY
Piston-driven liquid liner implosion  NumerEx	“Plasma rope” for stable plasma target.  SWARTHMORE	Scalable MEMS-based accelerator for plasma heating  BERKELEY LAB
Staged Z-pinch (direct pulsed power)  MFT Clean Energy	Underlying science and scaling of MIF  GENERAL INSTITUTE OF ATOMICS	Underlying science of MIF at fusion conditions  Sandia National Laboratories

Figure 1: List of lead organizations and approaches selected in the ALPHA program.

scientific studies relevant to the densities, magnetic fields, and plasma/liner interface environments encountered in this range of fusion parameter space. The program also included some exploratory efforts on new components that could be broadly enabling for new fusion concepts. For the purposes of discussion, we group those projects as “Integrated Concept” teams, which developed integrated plasma and compression systems to produce thermonuclear fusion plasmas; “Driver” teams that developed technologies for liner compression systems that could be applied to MIF concepts (but did not integrate the drivers with plasma targets during the ALPHA program); “Applied Science” teams that performed experimental and simulation studies to better inform intermediate density fusion plasmas and MIF; and “Exploratory Concepts” that developed novel plasma configurations and driver components. (Note that these groupings were not categories of the FOA, but are rather post-hoc descriptions of the general thrusts within the program. There is some overlap within these groupings, insofar as all teams performed some level of exploratory work and applied science.) The following section describes the goals, progress, and status for each of the individual projects.

ALPHA projects and results

i. Integrated Concept Teams

University of Washington/Lawrence Livermore National Lab: Sheared-flow Z-Pinch for Fusion

The University of Washington (UW), along with its partner Lawrence Livermore National Laboratory (LLNL), developed a variant of the Z-pinch that exploits sheared flow in the axial direction to mitigate the $m=0$ and $m=1$ instabilities that plague Z-pinch plasmas. The concept builds upon prior work in the ZAP and ZAP-HD

experiments which demonstrated that a Z-pinch initiated from a high velocity plasma gun experiences a shear flow from $r=0$ at the center of the Z-pinch axis to $r=R$ at the plasma edge[25], [26][27]. In those experiments, it was shown that at sufficiently high velocities (typically observed as $\sim 10\%$ of the Alfvén velocity times k , the axial

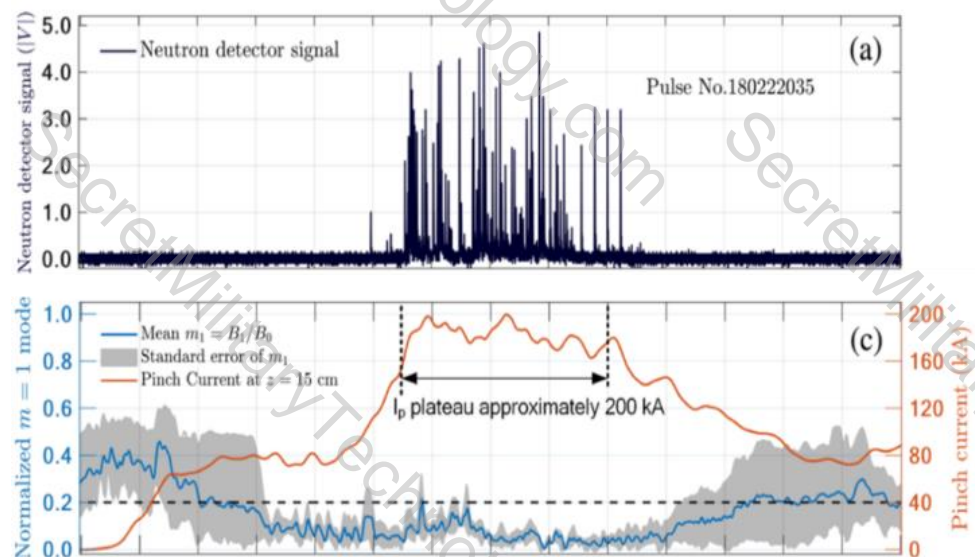


Figure 2: Results from the University of Washington Sheared flow Z-pinch. Top: Signal observed on the scintillator detector, which shows neutron producing during the stable (quiescent) period. Bottom: Normalized magnetic field fluctuation amplitude for the $m=1$ mode, as measured at multiple locations, which shows that the plasma is relative stable for about 5 μ s. Note that the quiescent period aligns to the time in which neutrons were detected. Figure adapted from PRL 122, 135001

wave number) from the plasma gun, the shear in the plasma was able to suppress the growth of sausage and kink modes in a Z-pinch over a stable period about 700X the expected instability growth time in a non-sheared Z-pinch, at densities of 10^{16} - 10^{17} cm⁻³ and temperatures of 50-80 eV[26]. Under the ALPHA program, the UW/LLNL team sought to determine if this shear stabilization mechanism scales to fusion conditions, specifically by pushing the current to 100's of kA, thereby increasing the density to $\sim 10^{17}$ cm⁻³ and temperature to ~ 1 -2 keV. As shown in figure 2, and as summarized in a recent paper, the team was able to demonstrate experimentally that the sheared-flow Z-pinch at high currents (approximately 200 kA) exhibited stability for 5-20 μ s, several orders of magnitude longer than the characteristic growth time for sausage and kink instabilities[28]. At these currents, plasmas of 20% Deuterium/80% Hydrogen reached densities of 10^{17} cm⁻³ and temperatures estimated at 500 eV-1 keV, and reproducibly generated neutron yields $>10^5$ for 5- μ s periods, and observed a scaling of neutron emission with the square of the deuterium ion number density, which suggests thermonuclear origin[28].

The UW/LLNL team also performed extensive MHD and PIC simulations of the sheared-flow Z-pinch system. As the system pushes to higher currents, temperatures, and densities, the plasma will approach kinetic conditions, and at the outset of the project it remained an open question as to whether the shear stabilization demonstrated in the ZAP and ZAP-HD experiments would hold in the kinetic regime. PIC simulations from LLNL suggest that the shear stabilization mechanism will remain effective at the high currents projected for fusion conditions. [29] [30] This is a valuable addition to the existing literature on sheared flow Z-pinch stabilization. To review it was theoretically predicted that the kink ($m=1$) mode would be stabilized when the flow shear ($\partial V_z/\partial r$) exceeds $0.1kV_A$ (0.1 times the axial wave number times the Alfvén wave velocity) [25]. This prediction was later verified experimentally, which set the stage for further development of the sheared-flow Z-pinch[31]. Fully kinetic PIC simulations have also shown the suppression of instabilities in sheared flow stabilized Z-pinch plasmas at scales ranging from current experiments up to reactor-scale[29].

Based upon the promising results of the research under the ALPHA program, the team from UW launched a new company, Zap Energy, and has won a follow-on award from ARPA-E to push the sheared-flow Z-pinch to higher currents, possibly necessitating improved materials and designs for high-current-density electrodes, and refinement of timing and current profiles for plasma initiation and for stabilization at increased densities and temperatures[32].

Helion Energy – Magnetic Compression of Field Reversed Configuration (FRC) Targets for Fusion

Helion Energy is developing an MIF concept for the compression of an FRC plasma using high power pulsed magnetic coils. The concept builds upon prior work at UW and at MSNW LLC, and utilizes the dynamic formation of two FRCs, accelerated towards each other and merged in a central chamber[33]–[35]. A high power magnet coil surrounding the central chamber compresses and heats the FRC. In prior experiments, such as the “Grande” experiment at MSNW, the merged and compressed FRCs reached high temperatures and densities. Based upon empirical scaling relationships from the LSX experiments at UW in the 1990's[35], [36], the Helion team has projected that fusion conditions are achievable in a relatively low-cost machine with increased trapped flux in the FRCs, and increased peak B-field from compression [37]. However, these projections from the relatively low density, steady state

conditions of LSX must extrapolate to several orders of magnitude higher in ion density, as well as significant increases in other experimental parameters, and there is limited theoretical or simulation-based understanding of the FRC to confidently make those projections. The ALPHA-supported research sought to increase the trapped

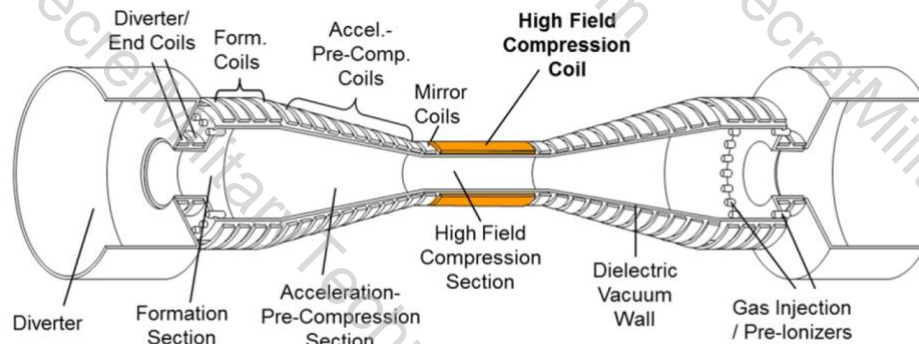


Figure 3: An early depiction of the Helion approach. Image reproduced from Nucl. Fusion 51 (2011) 053008

flux in the FRCs by a factor of 2 and then compress it to a peak magnetic field of 20 T, providing experimental data in the higher density regime, as well as an experimental basis for performance projections for compressed FRC targets in fusion conditions. The experiments (in keeping with prior nomenclature, the updated machine was named “Venti”), proved to be challenging, particularly with the mechanical structure and pulsed power system for the central compression coil (designed for 10 T, but ultimately operated at 8 T), and for keeping the highly compressed FRCs on-axis in the relatively small radius of the central chamber. Even with the aggressive experimental goals, the team was able to conduct over 900 FRC compression shots, and the team observed DD fusion neutrons. As the team reported to the an independent review team (JASON) in 2018, Helion’s integrated system achieved a density of 8×10^{16} ions/cm³, a final magnetic field of 8 T, a final radius of 6 cm, and an energy confinement time at maximum compression of 4×10^{-5} s [38] While this data is encouraging, further experimental measurements of the plasma parameters are necessary to validate these claims. Significantly, the team believes they showed that the micro-scale confinement and macro-scale stability scale as expected. Separate from the ALPHA award, Helion is also pursuing increased performance for a larger scale compressed FRC system. Beyond their technical progress, Helion has also successfully secured private investment (much of it prior to their ALPHA award).

MIFTI, along with partner UCSD, is developing the “Staged Z-Pinch” MIF concept, which delivers high current pulsed power to an annular shell of high atomic number gas (e.g., Ar or Kr), which then compresses at high velocity on a cylindrical target of magnetized D-D fuel[39][40] [41] [42].

The geometry of the Staged Z-Pinch is very similar to Sandia’s MagLIF, in that both are cylindrical magnetized plasma targets, and are compressed radially by a high-Z liner. However, there are important differences for MIFTI’s Staged Z-Pinch concept. First, there is no laser pre-heat of the MIFTI target, instead the pre-compression heating in the plasma target is provided by the initial shock of the imploding high-Z liner at the interface with the (stagnant) low-Z fuel target. Another key difference is that

the liner in the Staged Z-Pinch is an annular gas puff, as opposed to a solid metal liner as in MagLIF. The gas puff allows for more rapid experimentation, as each shot does not require replacement of the liner hardware, and in the course of the ALPHA project, MIFTI routinely complete 10’s of shots per day (albeit at current levels >10x lower than MagLIF shots on Sandia’s Z-machine). The Staged Z-Pinch concept has been described in a number of simulation-based studies, and was explored in limited experimental work at UC Irvine in the 1990’s. The goals for the ALPHA project were to demonstrate the Staged Z-Pinch at fusion conditions utilizing the 2 TW (up to 1.2 MA) Zebra pulsed power machine at the Nevada Terawatt Facility at The University of Nevada Reno[43]. Hundreds of shots were completed, exploring a range of parameters for initial magnetization in the target, ion density (both in the target and in the liner), and using different liner species (principally Ar and Kr). Through the course of several campaigns on Zebra, the MIFTI team was able to produce consistent and repeatable shots with neutron yields exceeding 10^9 , with top-performing shots (Kr liner imploding on target with initial axial B-field of 10 kG) exceeding 10^{10} neutrons[44][41]. The neutron yields appeared to have an isotropic and repeatable distribution suggestive of a thermonuclear origin, although direct measurements of temperature and neutron spectrum are necessary to fully establish that the yield is predominantly thermonuclear in origin[45]. It is worth noting, that the neutron time-of-flight diagnostics showed a signal with the timing and magnitude that would be expected for D-T neutrons. If this can be verified, it would indicate secondary fusion events from tritium produced in the D-D fuel, as had been shown on MagLIF experiments at Sandia. In addition to the Zebra experiments, the team also completed a series of shots on the Cobra pulsed power machine at Cornell University for increased diagnostic access, especially for imagery to assess the stability of the inner surface of the liner during the implosion. These experiments were not able to utilize D fuel, and thus did not offer insights on fusion performance. Most of the simulations for the Staged Z Pinch were performed in MACH2, and as noted in the literature, there are disagreements over the extent of heating seen in MACH2 simulations of the Staged Z Pinch. In particular, simulations in

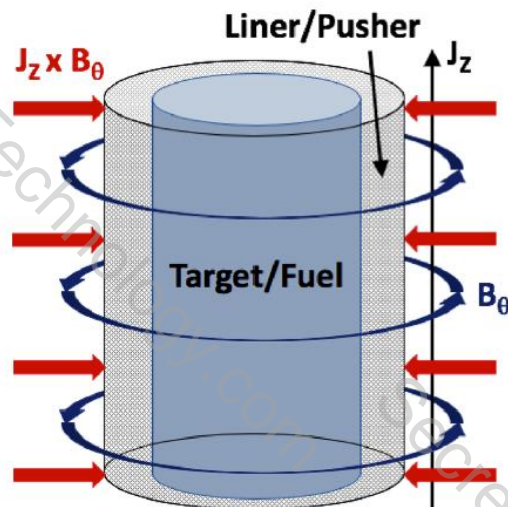


Figure 4: Schematic of a liner-on-target Z-pinch, reproduced from Phys. Plasmas 26, 032708 (2019).

MHRDR show significantly lower levels of heating during the implosion, and suggest that the Staged Z Pinch will not extend to fusion breakeven[45]. The MIFTI/UCSD team also performed 1D HYDRA results, which were consistent with the MACH2 results showing shock heating followed by adiabatic compression, but additional work in 2D and 3D simulations will be required to properly assess the disparity between different codes. The latest analysis suggests that the major code discrepancies arise due to the differences between Lagrangian versus Eulerian numerical methodologies. Additional experiments with improved diagnostics for time-resolved data on temperature and density, and exploration of different implosion initial conditions, are needed to improve understanding of the Staged Z-Pinch[45] and its potential for scaling to net-gain fusion.

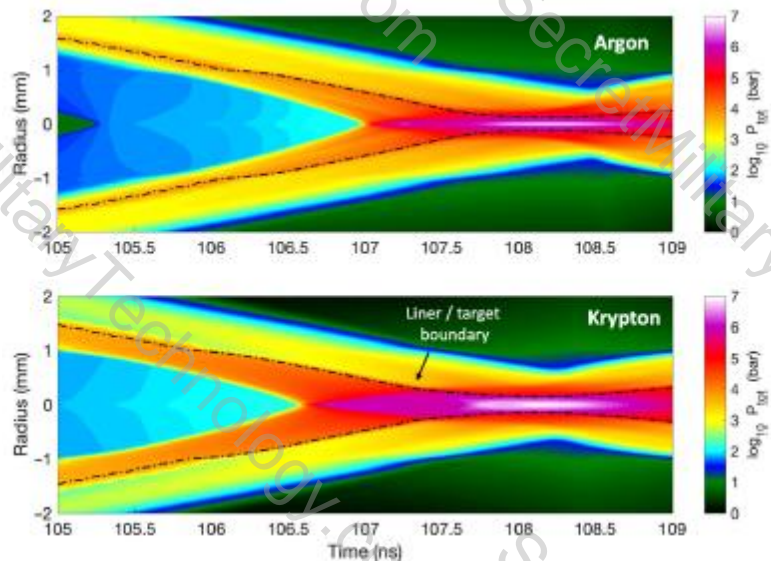


Figure 5: Total plasma pressure in the staged Z-pinch as a function of time and radius near stagnation for Ar and Kr plasma shells compressing a deuterium target. Plots made with MACH2, a single-fluid radiation-MHD code. Figure reproduced from Phys. Plasmas 26, 052706 (2019).

ii. Drivers

Los Alamos National Laboratory/HyperV Technologies: Plasma Liners For Fusion

Los Alamos National Laboratory, along with HyperV Technologies and other partners, are developing a new MIF driver technology that is non-destructive, and should allow for more rapid experimentation and progress toward economical fusion power[46]. The team designed, built, tested, and deployed multiple plasma guns to produce hypersonic jets that merge to create a section of an imploding plasma liner, to support the development of the plasma-jet-driven magneto-inertial-fusion (PJMIF) concept [47][48]. Because the guns are located several meters away from the fusion burn region (i.e., they constitute a “standoff driver”), the plasma gun components should be protected from damage during repeated experiments. By project completion the team should better understand the behavior of plasma liners as they implode in order to demonstrate the validity of this driver design, optimize the precision and performance of the plasma guns, and obtain experimental data in a 36-gun experiment on ram-pressure scaling and liner uniformity critical to progress toward an economical fusion reactor.

The project team designed, built, and tested seven state-of-the-art coaxial plasma guns, and used them to merge up to seven hypersonic plasma jets to form a section of a spherically imploding plasma liner [49] [47]. The team assessed two key scientific issues of plasma-liner formation via merging plasma jets: (i) shock heating leading to a degradation in the sonic Mach number of the merged jets, which would cause overly large spreading in the subsequently formed plasma liner leading to low calculated 1D energy gain [50] for the PJMIF concept, and (ii) degree of uniformity for the liner formed by discrete jet merging. For (i), ion shock heating was measured in two- and three-jet merging experiments [51], which benchmarked simulations showing that the liner-average Mach number remained above approximately 10. For (ii), the first six-jet merging experiments were quite imbalanced due to large mass imbalance among the six jets[49]. An upgrade to the gas-valve design allowed for mass balance across seven jets of better than 2%. The more balanced jets led to the formation of a section of the plasma liner in good agreement with simulations [47], [52]. Several upgrades to improve the gun precision, reproducibility, and maintainability were required and subsequently implemented, and testing is underway to qualify this second gun iteration to be the basis for a 36-gun, fully spherical plasma-liner-formation experiment. The additional gas-valve and gun-design iterations led to a substantial delay in the construction and fielding of the 36-gun experiment, which the team still hopes to execute.

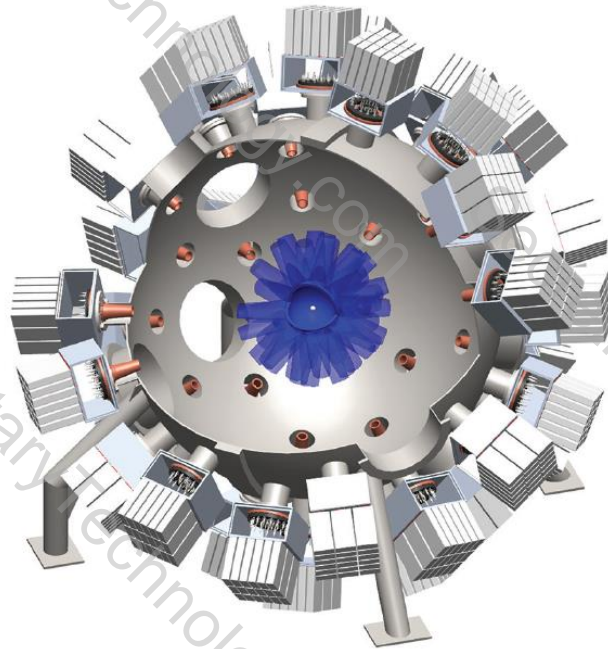


Figure 6: Illustration of the planned Plasma Liner Experiment (PLX) set-up, which will ultimately have ≥ 36 coaxial plasma guns mounted around a 2.74-m vacuum chamber. Image from Scientia February 2017.

If fully spherical plasma liners can be formed successfully, the key initial experiments would aim to characterize the peak ram-pressure scaling of the imploding plasma liner, as this is a key metric for the liner as a compression driver for MIF. Beyond that, the next priorities would be to (i) control and optimize the liner uniformity, (ii) initiate a program of PJMIF-compatible target formation, and (iii) compress the target using a plasma liner to show heating. An assessment of (ii) and (iii) are provided in [53]. In addition to the experimental work, the team has pursued modeling with team members University of Alabama in Huntsville and Brookhaven National Laboratory on the PLX experiments, and with Tech-X on plasma-liner compression of a magnetized target, with the objective on setting bounds on the minimum performance/uniformity of a liner and of target temperature and magnetization [54].

NumerEx. Stabilized Liner Compressor For Low-Cost Fusion

MIF covers a wide range of parameter space in ion density and magnetic fields in target plasmas, and the requirements in implosion velocity and pressure for a driver may vary greatly depending upon the the plasma parameters. The NumerEx team sought to develop a liquid metal liner implosion system for stabilized and repeatable compression at >1 km/s for magnetically confined plasmas at the lower end of ion density in the MIF regime. The driver concept is termed the “Stabilized Liner Compressor” (SLC), and it builds upon the “LINUS” approach developed at the Naval Research Laboratory in the

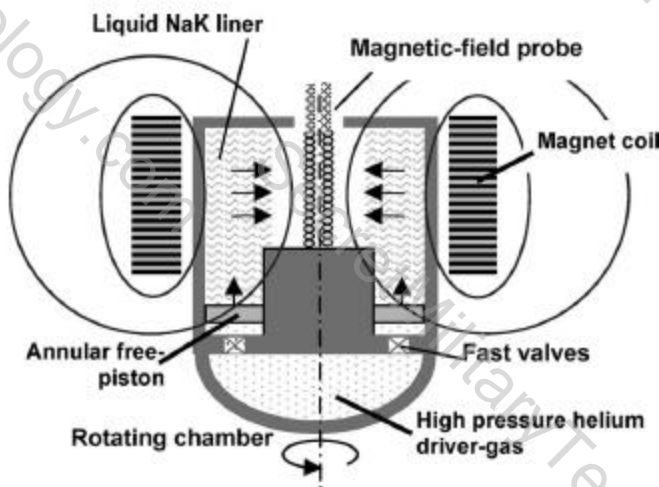


Figure 7. Schematic of a stabilized liquid liner compressor. Image reproduced from *IEEE Trans. Plasma Sci.*, vol. 36, no. 1, pp. 52–61, 2008.

1970s[55][56]. The lower implosion velocity for the SLC as compared to MagLIF or PJMIF reflects the intended parameter space for liquid liner compression, which is designed for lower density magnetically confined plasmas, such as an FRC. (Where MagLIF or PJMIF might be considered as “ICF with greatly relaxed implosion velocities” due to reduced thermal losses with magnetic fields, the liquid liner approach might be considered as pulsed “MCF with a smaller reactor size” due to greatly increased ion density from pulsed compression). The SLC uses a rotating chamber in which liquid metal is formed into a hollow cylinder.[57] During compression the liquid will be pushed by pistons driven by high-pressure gas, collapsing the inner surface around a target on the axis. The rotation of the liquid liner maintains a smooth inner surface, and is intended to mitigate against Rayleigh-Taylor instabilities that would otherwise occur near peak compression of the plasma. During the ALPHA project, the NumerEx team made progress on the simulation and design of the SLC, with MACH2 results able to replicate experimental data from the prior LINUS system at NRL[9]. MACH2 also helped to establish a design basis for a 1 km/s implosion system with 5 cm bore diameter, NaK as the liquid metal, high pressure helium driving free annular pistons, and rotation about a central bearing[58]. The point design was for proof-of-concept on the SLC itself, compressing on an axial magnetic field in vacuum (and not pairing with a target plasma during the ALPHA project). In addition to the MACH2 simulations for implosion dynamics and magnetic compression, the design was qualified for safety margins and performance in ANSYS with partner ARA. The critical components in the design were a fast valve for $<400\text{-}\mu\text{s}$ release of the $>10\text{-kpsi}$ He plenum, and a triggering mechanism for reliable, synchronized firing of the pistons. The team was able to experimentally demonstrate a suitable fast valve design, but was not able to reach a qualified engineering design for triggering within the budget for the project, and it was determined to not yet proceed to build the proof of concept SLC demonstrator. With additional engineering and development for the triggering mechanism, a SLC system can be completed and demonstrated. In addition to the SLC design work, the NumerEx team also applied MACH2 for preliminary modeling of FRC injection and compression in the SLC system. Based upon FRC parameters similar to those achieved in the AFRL

FRCHX Experiment, the NumerEx projections for the SLC show a maximum temperature of 2.4 keV <600- μ s after compression begins, and a density of ~ 300 x the initial density of a merged FRC target[59].

iii. Applied Science of MIF

Sandia National Lab/University of Rochester Laboratory for Laser Energetics: Magnetization and Heating Tools for Low-Cost Fusion

Sandia National Laboratories partnered with the Laboratory for Laser Energetics (LLE) at the University of Rochester to explore the behavior of magnetized plasmas under fusion conditions in the MIF regime, building upon the early successes of the MagLIF experiments at Sandia and seeking to collect more data, benchmark simulation codes, and establish a better understanding of MIF plasmas. A key challenge for MagLIF has been the low shot rate and limited diagnostic access on the Z Machine. To address this challenge, the Sandia/Rochester team collaborated in ALPHA to field the MagLIF concept on the University of Rochester LLE OMEGA facility to provide higher experimental throughput and diagnostic access to more rapidly explore the parameter space for MagLIF (and MIF more broadly). With some reconfiguration to deliver laser energy along an imploding cylindrical shell, the OMEGA facility is capable of conducting pre-heating, magnetization, and compression experiments that are similar to those possible on the Z-machine, though smaller in scale[60]. The Sandia/LLE team also collaborated to improve the performance of laser preheating in MagLIF, and thereby improve understanding of the initial conditions for the MagLIF

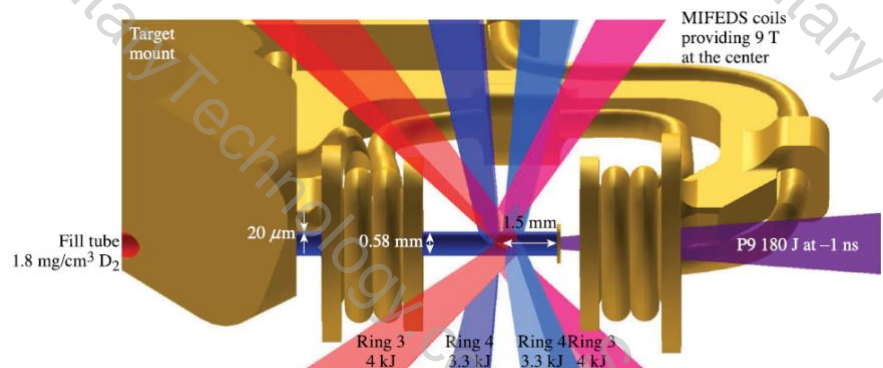


Figure 8: Drawing of the OMEGA laser-driven MagLIF set-up, with only 8 out of 40 beams shown for clarity. Rings 3 and 4 are used for compression. Figure adapted from Phys. Plasmas 26, 022706 (2019)

experiments. The team was able to achieve both major goals for the project. In completing multiple rounds of integrated “mini-MagLIF” shots on OMEGA, the team was able to leverage an upgraded “MIFEDS” magnetization system (funded by DOE Office of Fusion Energy Sciences) to access magnetic fields of > 10 T (prior to implosion)[61]. While the smaller length scale of the mini-MagLIF experiment cannot match all of the conditions for the full scale MagLIF (for example, confinement of alphas and secondary tritium ions are significantly reduced in the smaller mini-MagLIF), the OMEGA experiments

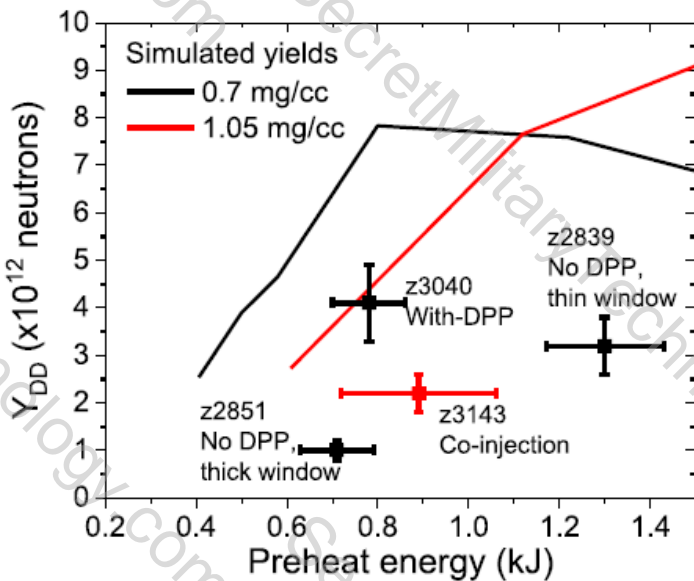


Figure 9: Simulated curves of neutron yield vs. preheat energy, from 2D LASNEX simulations, compared to experimental result to determine the effect of a distributed phase plate (DPP) on yield. Plot reproduced from *Phys. Plasmas* 26, 032707 (2019).

were able to confirm projections from LASNEX on fusion performance trends in the MagLIF configuration.[18] The team was also able to improve the uniformity and minimize the mix from the laser preheat in the ALPHA work, and fielded the improved preheat protocol in NNSA-funded MagLIF shots on the Z Machine. These new shots achieved a yield of $5e12$, a 2x improvement in fusion yield over the prior record of $2e12$ (DD neutrons) for MagLIF shots[11][18]. Future publications from the MagLIF team are anticipated to report another increase in DD yield, an improvement attributable, at least in part, to a laser pulse and experimental configuration (i.e. target density, preheat protocol) developed in ALPHA.

California Institute of Technology/Los Alamos National Lab: Heating and Compression Mechanisms for Fusion

As the ALPHA program sought to advance the science of magneto-inertial fusion with a limited budget, the use of low-cost experiments to develop an understanding of scaling in MIF plasmas was a critical focus. To this end, the California Institute of Technology (Caltech), in coordination with Los Alamos National Laboratory (LANL), investigated the scaling of adiabatic heating of plasma by propelling magnetized plasma jets into stationary heavy gas clouds to provide experimental data to investigate adiabatic compression. By moving to the liners rest frame, the Caltech/LANL team was able to investigate the jet-target collision using many experiments with a wide range of parameters to determine the equation of state relating compression, change in magnetic field, and temperature increase. The experimental work was supplemented with advanced computer models[62].

When a plasma is heated during compression the plasma density and temperature are expected to

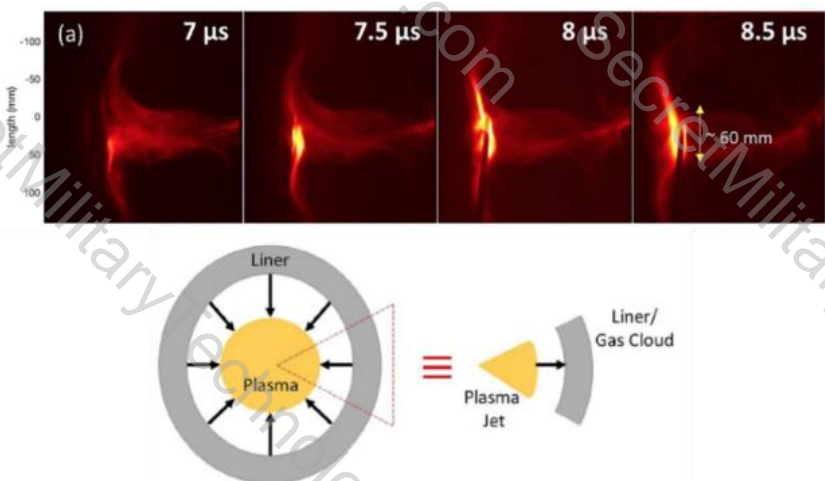


Figure 10: Top: Image from a fast framing camera, showing time evolution of a collision between a plasma jet and a gas target. Bottom Left: compression process for a generic MTF geometry. Bottom right: the same process in a reversed reference frame. Figure adapted from *Phys. Plasmas* 25, 112703 (2018)

increase as $P \sim n^\gamma$ and $\sim n^{\gamma-1}$. Gamma is the adiabatic constant, where $\gamma = (N + 2)/N$ and N is the number of degrees of freedom in the plasma. Here N is the degrees of freedom of a plasma ion, not the dimensionality of compression (which can take place in 1D, 2D, or 3D). If, for example, a plasma is sufficiently collisional when it is compressed in one or two dimensions N will still be 3 because the collisional plasma leads to an equipartition of energy among each degree of freedom. For less collisional plasmas, even under a 3D compression N may be less than 3. This project sought to determine γ for the scaling of plasma heating during compression, via a shifted frame-of-reference experiment. The team found that density and magnetic field increased and jet velocity decreased during the compression. Interestingly, electron temperature featured a very complicated time dependence—temperature increased initially, and then dropped < 1 μ s later (a time much shorter than the total compression time). The Caltech team attributed this to radiative loss due to three-body recombination in the plasma that results in hydrogen formation. The team found that a γ of 5/3 (i.e. $N=3$, three degrees of freedom) was found to be a good fit for scaling this adiabatic compression in 1D based on collisionality, with the necessity of correcting for electron radiative losses. Key results are summarized in [63]. Also notable, was that in order to make the density measurements that were needed to verify the scaling relationship, the team had to develop and deploy a spatially translatable fiber-coupled interferometer, which is described in [64]. Finally, it is worth noting that the Caltech experiment is in a regime where three-body recombination is important, however magneto-inertial fusion experiments will not be, and thus more work needs to be done at higher densities to investigate adiabatic scaling at MIF-relevant conditions.

iv. Exploratory Concepts

Lawrence Berkeley National Laboratory/Cornell University: MEMS Based Drivers For Fusion

In this project the Lawrence Berkeley National Laboratory teamed with Cornell University to develop an ion beam technology that can be manufactured with low-cost, scalable methods. Ion beams have potential uses across the full range of fusion approaches, from ICF (with heavy or light ion fusion), MCF (with neutral beam heating), and MIF (with the “phi target” driven by ion beams) [65] [66][4]. However, currently available ion beam technology cannot practically or economically scale to the current densities and beam energies required in most fusion concepts (particularly those that demand the ion beam as the primary energy input). LBNL and Cornell developed a new ion beam architecture based on microelectromechanical systems (MEMS) technology that utilizes an array of “beamlets” — which will be scalable up to hundreds or thousands of beamlets per 4 to 12 inch wafer, and enabling very high system-level current density as the array of parallel beamlets deliver high ion flux even as no individual beamlet approaches space charge limits. The design is based upon the MEQALAQ

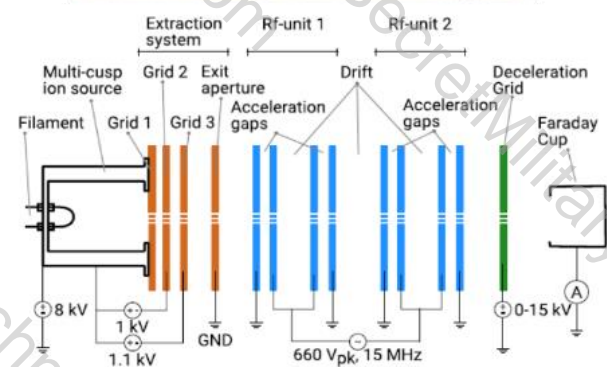
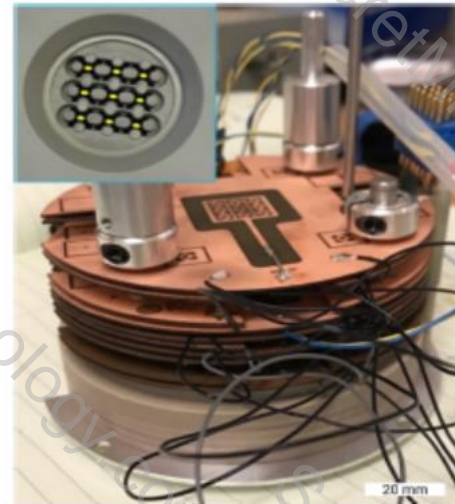


Figure 11: Top: Photo of the final assembly, showing a downstream matching quadrupole (inset). Bottom: Experimental set-up for a filament driven ion source to create a 3 x 3 array of beamlets. Figure adapted from Rev. Sci. Instrum. 89, 053302 (2018) and Rev. Sci. Instrum. 88, 063304 (2017).

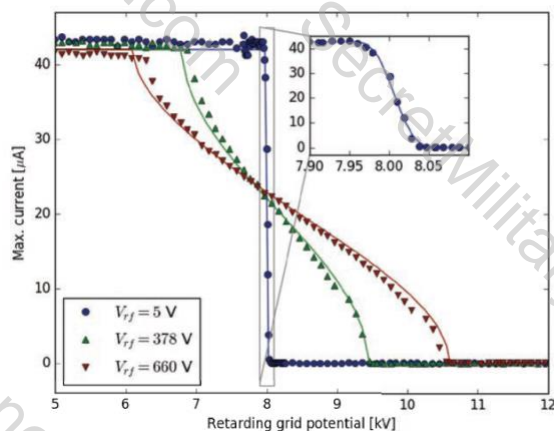


Figure 12. Retarding-grid voltage scan with two RF units for low, medium and high RF voltages (markers) compared to simulations (solid lines). Inset is a scan with the RF signal generator at its lowest setting. Figure reproduced from Physics Procedia 90 (2017) 136 – 142.

accelerator design developed at Brookhaven National Lab in the 1980's, but with the addition of MEMS technology offers a path to mass manufacturability, and simplicity and scalability in the integration of RF with MEMS wafers[67]. The team was able to demonstrate proof of concept for the MEMS accelerator with a prototype compact accelerator fabricated from PCB board. The prototype demonstrated injection and transport of a 5-10 uA beam in a 3x3 beam array, and achieved ion acceleration of 0.5 kV/gap, for a gradient of about 0.3 MV/m[68], [69]. Building on these results, the team has used a compact, near-board RF driver to achieve up to 2.6 kV per gap[70]. While the performance of the prototype was relatively modest, the critical elements for the scalable MEMS design were

established: a parallel array of beamlets, enabling high system-level current density, and the modular “stacking” of MEMS acceleration stages to enable high beam energy. The team has taken the first important steps to demonstrate that these elements can be “stacked” by demonstrating an acceleration of 125 V/gap at 22.7 MHz, and an increase of 250 V ion kinetic energy was observed in a two stage acceleration setup.[71] There is significant work remaining to mature and harden the design to develop practical accelerators, and the team is continuing to make progress on this front through continued ion beam development for the purposes of testing and characterization of materials for nuclear reactors and other potential applications in materials processing.[72]

Swarthmore College: Plasma Accelerator on the SSX

This project sought to explore the properties of a fully relaxed parcel of magnetized plasma, known as a Taylor state. Taylor states are elongated structures with helical magnetic field lines resembling a rope. These Taylor states exhibit interesting and potentially very beneficial properties upon compression, and their long lifetimes may make them suitable as a fusion target if they are able to maintain their temperatures and stability long enough to be compressed to fusion conditions. The goal of Swarthmore was to explore whether the helical Taylor state could become a suitable target for compression. Under this project, the team sought to measure the equations of state for a Taylor state by carrying out compression and heating experiments by creating a parcel of magnetized plasma, compressing it against the end wall of a chamber, and measuring plasma density, temperature, and magnetic field during compression[73], [74]. The team conducted their experiments on the existing Swarthmore Spheromak Experiment device (SSX), which has an advanced diagnostic suite and the capability to perform 100 experiments per day, which enabled rapid progress in understanding the behavior of these plasma plumes and illuminating their potential for use as new targets in the pursuit of fusion reactors. By studying nearly 200 compression events the team was able to determine which equation of state best described the behavior of the Taylor states. At higher, MIF-relevant densities with higher collisionality, parallel and perpendicular equations of

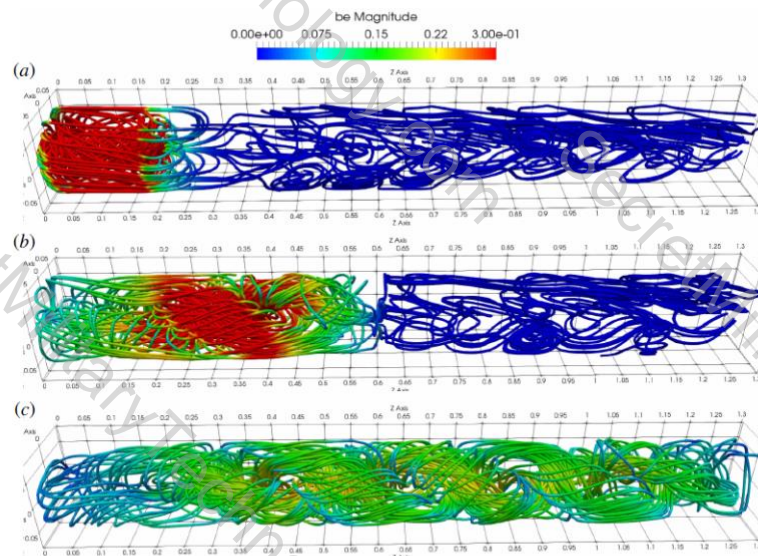


Figure 13: Taylor State formation sequence. Top: spheromak formed at left. Middle: at 2 μ s the spheromak tilts and begins to relax. Bottom: At 6.4 μ s a relaxed, twisted Taylor state has formed. Reproduced from J. Plasma Phys. (2018), vol. 84, 905840614.

state may morph into the same. In this work the team found that the parallel component of the Chew, Goldberger, and Low (CGL) equation of state was the best fit for the behavior of the Taylor state.[73] As a result, our understanding of the state of the art for Taylor state compression was advanced. The Swarthmore team observed that Taylor states have very different flux loss behavior than other targets, like field-reversed configurations, which may lead to significant flux decay when translating a Taylor State through a series of coils[75]. This likely indicates that Taylor states may face significant challenges if considered as a “drop-in” replacement for FRCs in fusion systems. It remains inconclusive whether they can be a fusion target for other systems and more study is likely required. Beyond studying the behavior of a single Taylor state, work is ongoing to merge two helical Taylor-state plasmas to increase the density to values of interest (e.g., $>5e^{16}/cc$) for subsequent liner compression.

Technology Transition

ARPA-E programs are focused in scope and limited in time, and are by definition not built into an existing roadmap within government or industry R&D. As a result, navigating technology transition along an uncertain path is an important consideration for all ARPA-E programs from inception through project selection, launch, and execution. As part of the model, ARPA-E mandates that a modest fraction of awarded funding be spent working towards the successful transition of technologies developed under ARPA-E programs. All of these aspects of the ARPA-E model applied to the ALPHA program, but the high technical risks and long time horizons for fusion development raise unique questions and challenges for how to pursue technology transition for a fusion program. In addition to the technology transition planning and execution by each of the ALPHA teams for their respective projects, ARPA-E led a technology transition campaign encompassing the ALPHA program and aimed both internally and externally. This section describes some of the internal and external efforts intended to help build and sustain momentum for the low-cost fusion energy concepts pursued in ALPHA.

A common theme in technology transition is to think from the end backwards. At program launch, each ALPHA team was asked to prepare a technology transition plan that described how their concept could eventually help make possible a more rapid and more affordable path to commercial fusion energy. These transition plans helped ARPA-E also set end-of-project internal goals and expectations tailored to each specific project. Having these long-term goals established early helped provide guide posts for the tech transition efforts over the course of the roughly 3-year program.

Early in the program, ARPA-E provided awardees with an overview of intellectual property (IP) considerations as well as the results of a commissioned fusion energy patent landscape.[76] From a cursory review of global patents in fusion energy, one can recognize that magnetic and inertial confinement approaches dominate the IP landscape; thus, perhaps magneto-inertial fusion is an area ripe for the creation of new IP. That said, more than half of the fusion energy IP assets have expired, primarily due to non-payment of fees, so one should be judicious about the timing of filing given the 20 years of patent protection granted relative to the anticipated timeline to commercialization.

The program-wide technology transition efforts also included outreach to and engagement with a broad group of stakeholders cultivated from fusion developers beyond the ALPHA program set, other government offices with interest in fusion, several flavors of private investment such as philanthropic,

mission-focused, strategic, and traditional venture, as well as representatives from the electric power and power plant industries. When experts with such diverse backgrounds come together, it can often be challenging just to find the common language that allows for a fruitful conversation. Thus, part of our external campaign was geared towards generating “conversation starters” written in a language common across the stakeholders. The first such conversation piece was an initial capital cost study led by Bechtel National with support from Woodruff Scientific and Decysive Systems[77]. The team assessed four conceptual fusion power plant designs, arrived at cost estimates according to models developed for current nuclear power plant technologies, and, most importantly, performed a sensitivity analysis to look for key levers effecting the capital cost estimates. Beyond the actual content of the cost study, the impact of the report was, in part, the conversations it enabled—fusion technologists and potential investors had shared interest in the content and approach and could discuss the findings, limitations, and future plans.

Another commissioned piece was an independent assessment of the prospects for low-cost fusion development performed by the advisory group known as the JASONS in the Summer of 2018. The findings and recommendations can be found in the complete report[38], but again there is significant value beyond those specifics in helping engage with other government offices and any others with an interest in the technical feasibility of these approaches to fusion development. Finally, as part of outreach to the technical community, the ALPHA teams organized a miniconference in 2018 on magneto-inertial fusion concepts and progress at the U.S.’s largest annual gathering of plasma physicists, the meeting of the American Physical Society’s Division of Plasma Physics[78].

In summary, the technology transition for ALPHA most certainly included tangible, specific steps to move through the development stages that remain until we achieve commercial fusion power, but the campaign also emphasized the early and continuous cultivation of tech transition partners from across a community that included fusion technologists in academia, national labs, and industry, private investors from various flavors of venture capital, and a variety of government and industry representatives. Only through the combined efforts of such a broad set of stakeholders can we expect to see continued progress, for directional shifts or landmark decisions in any large, complex endeavor often come about only through the unified effect of many little independent pockets of momentum.

After ALPHA

ALPHA was launched as a targeted exploration of a promising and underexplored space, with the particular goals of establishing new approaches that could be explored at lower costs (and correspondingly faster timelines) that could be compatible with private development. The results from the program show promise that intermediate-density approaches such as MIF and stabilized Z-pinches can produce thermonuclear plasmas of significant fusion yield in relatively small and inexpensive machines. However, the performance of these systems – in both Lawson triple product and fusion yield – remains several orders of magnitude below the best performance of high performance tokamaks or of NIF. The rapid progress for a modest investment in ALPHA is promising, but a great deal more development is required before any of these concepts can be established as viable candidates for fusion energy. In particular, the stabilized Z pinch is showing strong experimental evidence of achieving plasmas with both T_e and T_i exceeding 500 eV, which hopefully will be confirmed soon by direct

diagnostic measurements[28]. In the sixty-plus years of controlled fusion research, only a very small handful of fusion configurations have exceeded this metric, typically at much greater investments.

These approaches do not represent the entirety of “non-traditional” fusion approaches that may offer attractive features for simplified reactor design and development. Many efforts outside of the ALPHA program, including TAE, General Fusion, and Tokamak Energy, referenced above, plus new entrants such as Commonwealth Fusion Systems all have significantly-funded efforts towards compact or simplified reactor designs. ARPA-E supported work under the 2018 OPEN solicitation [79] to explore new concepts using novel RF heating for high performance, compact FRCs by Princeton Fusion Systems [80]; and imposed dynamo current drive sustainment of a spheromak plasma by CT Fusion[81]. University of Washington spinout Zap Energy also received an OPEN 2018 award to continue increasing the electrical current and performance for the stabilized Z pinch.

Significant progress in leveraging private industry for fusion development has also been made above and beyond the ALPHA program. Notably, between 2015 and 2018, the publicly disclosed private dollars invested in fusion doubled to over \$1B. More than 10 private fusion development companies have garnered over \$1M of private financing with more than half of these companies having raised over \$10M. In addition, the Fusion Industry Association (FIA) was established in 2018 and today consists of over nineteen companies with additional associated affiliates[82]. The private companies recognize that fusion approaches with reduced cost, size, complexity, and eventual nameplate generation capacity are needed to both accelerate development and, eventually, allow for market penetration. This view was encapsulated in the recent U.S. National Academies report *A Strategic Plan for U.S. Burning Plasma Research* in the second of its two main recommendations: “the U.S. should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.” [83]

Building on the ALPHA program and synergies with the FIA and the second recommendation of the National Academies report, ARPA-E is exploring opportunities for a potential new fusion program that is broader in scope than ALPHA while pursuing the same vision as ALPHA: catalyze R&D pathways to lower the cost and accelerate the development time scale for commercially viable fusion energy. In addition, the potential new program may place emphasis on achieving tech-to-market (T2M) outcomes that can help provide ARPA-E fusion awardees, private fusion ventures, and the larger fusion-energy R&D community a smoother and more sustainable development pathway toward commercially viable fusion energy that includes public, private, and philanthropic support and engagement.

The potential new program may seek to support efforts that:

- Advance the performance of innovative, lower-cost fusion concepts that have a plausible path toward timely, commercially viable fusion energy
- Catalyze development of enabling technologies for fusion power plants with reduced size and nameplate generation capacity [84], leveraging the expertise and experience of R&D communities both within and beyond mainstream fusion
- Explore programmatic mechanisms to incentivize more cooperation between the public and private sectors, and maximize cost-effectiveness of fusion development, e.g., diagnostic resource teams[85]

- Pursue T2M and/or TEA (techno-economic analysis) activities that will help build the runway for fusion-energy development; examples could include (but are not limited to) conducting market analysis, serving as a technical resource for eventual regulatory decision-making, and educating/engaging the full energy ecosystem in appropriate ways (especially private investors, philanthropic foundations, and public-interest advocacy groups).

Acknowledgements

We acknowledge the ALPHA teams for their tremendous efforts in pursuit of lower-cost pathways to fusion energy.

References

- [1] "ARPA-E ALPHA." [Online]. Available: <https://arpa-e.energy.gov/?q=arpa-e-programs/alpha>.
- [2] S. O. Dean, *Search for the Ultimate Energy Source – A History of the U.S. Fusion Energy Program*. Springer US, 2013.
- [3] D. Clery, *A piece of the sun : the quest for fusion energy*. Harry N. Abrams, 2013.
- [4] I. R. Lindemuth and R. C. Kirkpatrick, "Parameter space for magnetized fuel targets in inertial confinement fusion," *Nucl. Fusion*, vol. 23, no. 3, pp. 263–284, 1983.
- [5] I. R. Lindemuth *et al.*, "Target plasma formation for magnetic compression/magnetized target fusion," *Phys. Rev. Lett.*, vol. 75, no. 10, pp. 1953–1956, 1995.
- [6] G. A. Wurden *et al.*, "Magneto-Inertial Fusion," *J. Fusion Energy*, vol. 35, no. 1, pp. 69–77, Feb. 2016.
- [7] National Academies of Sciences, National Academy of Engineering, and the Insistitue of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. Washington, DC: The National Academies Press, 2007.
- [8] I. R. Lindemuth and R. E. Siemon, "The fundamental parameter space of controlled thermonuclear fusion," *Am. J. Phys.*, vol. 77, no. 5, pp. 407–416, 2009.
- [9] P. J. Turchi, S. D. Frese, and M. H. Frese, "Stabilized Liner Compressor For Low-Cost Controlled Fusion: Progress And Issues," *IEEE Trans. Plasma Sci.*, vol. 45, no. 10, pp. 2800–2809, 2017.
- [10] M. Hohenberger *et al.*, "Inertial confinement fusion implosions with imposed magnetic field compression using the OMEGA Laser," *Phys. Plasmas*, vol. 19, no. 5, p. 056306, May 2012.
- [11] M. R. Gomez *et al.*, "Experimental demonstration of fusion-relevant conditions in magnetized liner inertial fusion," *Phys. Rev. Lett.*, vol. 113, no. 15, pp. 1–5, 2014.
- [12] L. Grossman, "Inside the Quest for Fusion, Clean Energy's Holy Grail," *Time Magazine*, Oct-2015.
- [13] M. M. Waldrop, "Plasma physics: The fusion upstarts," *Nature*, vol. 511, no. 7510, pp. 398–400, Jul. 2014.
- [14] J. D. Lawson, "Some Criteria for a Power Producing Thermonuclear Reactor BY J. D. LAWSON,"

- Proc. Phys. Soc. Sect. B*, vol. 6, no. November, pp. 6–10, 1956.
- [15] S. Le Pape *et al.*, “Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility,” *Phys. Rev. Lett.*, vol. 120, no. 24, p. 245003, Jun. 2018.
- [16] J. Slough, B. Campbell, D. Kirtley, R. Milroy, C. Pihl, and G. Votroubek, “Staged Magnetic Compression of FRC Targets to Fusion Conditions,” *ALPHA Annual Review*, 2016. [Online]. Available: https://arpa-e.energy.gov/sites/default/files/ALPHA_SLOUGH.pdf. [Accessed: 29-May-2019].
- [17] S. A. Slutz *et al.*, “Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field,” *Phys. Plasmas*, vol. 17, p. 056303, 2010.
- [18] S. A. Slutz *et al.*, “Enhancing performance of magnetized liner inertial fusion at the Z facility,” *Phys. Plasmas*, vol. 25, no. 11, 2018.
- [19] Lawrence Livermore National Laboratory, “National Ignition Facility & Photon Science.” [Online]. Available: https://lasers.llnl.gov/about/faqs#nif_cost. [Accessed: 06-Jun-2019].
- [20] ARPA-E, “STRATEGIES FOR WIDE-BANDGAP, INEXPENSIVE TRANSISTORS FOR CONTROLLING HIGH EFFICIENCY SYSTEMS (SWITCHES), Funding Opportunity No. DE-FOA-0000942.” 2013.
- [21] H. A. Mantooth, M. D. Glover, and P. Shepherd, “Wide Bandgap Technologies and Their Implications on Miniaturizing Power Electronic Systems,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 3, pp. 374–385, 2014.
- [22] I. C. Kizilyalli, Y. Xu, E. Carlson, J. Manser, and D. W. Cunningham, “Current and future directions in power electronic devices and circuits based on wide band-gap semiconductors,” in *2017 IEEE 5th Workshop on Wide Bandgap Power Devices and Applications, WiPDA 2017*, 2017, vol. 2017–Decem, pp. 417–425.
- [23] M. Mazarakis and C. L. Olson, “A New High Current Fast 100ns LTD Based Driver for Z-pinch IFE at Sandia,” in *21st IEEE/NPS Symposium on Fusion Engineering SOFE 05*, 2005, pp. 1–4.
- [24] W. A. Stygar *et al.*, “Conceptual designs of two petawatt-class pulsed-power accelerators for high-energy-density-physics experiments,” *Phys. Rev. Spec. Top. - Accel. Beams*, vol. 18, no. 11, pp. 1–30, 2015.
- [25] U. Shumlak and C. W. Hartman, “Sheared Flow Stabilization of the $m = 1$ Kink Mode in Z Pinches,” *Phys. Rev. Lett.*, vol. 75, no. 18, pp. 3285–3288, 1995.
- [26] U. Shumlak, R. P. Golingo, B. A. Nelson, and D. J. Den Hartog, “Evidence of stabilization in the Z-pinch,” *Phys. Rev. Lett.*, vol. 87, no. 20, pp. 205005-1-205005-4, 2001.
- [27] U. Shumlak *et al.*, “Increasing plasma parameters using sheared flow stabilization of a Z-pinch,” *Phys. Plasmas*, vol. 24, no. 5, p. 055702, May 2017.
- [28] Y. Zhang *et al.*, “Sustained Neutron Production from a Sheared-Flow Stabilized Z Pinch,” *Phys. Rev. Lett.*, vol. 122, no. 13, p. 135001, 2019.
- [29] K. Tummel *et al.*, “Kinetic simulations of sheared flow stabilization in high-temperature Z-pinch plasmas,” *Phys. Plasmas*, vol. 26, no. 6, p. 062506, 2019.
- [30] U. Shumlak *et al.*, “Results from the Sheared-Flow Stabilized Z-Pinch and Scaling to Fusion

- Conditions," in IAEA, 2018, vol. EX, pp. 1–8.
- [31] R. P. Golingo, U. Shumlak, and B. A. Nelson, "Formation of a sheared flow Z pinch," *Phys. Plasmas*, vol. 12, p. 062505, 2005.
- [32] ARPA-E, "Department of Energy Announces \$98 Million for 40 Transformative Energy Technology Projects." ARPA-E, 2018.
- [33] J. Slough, S. Andreason, H. Gota, C. Pihl, and G. Votroubek, "The Pulsed High Density Experiment : Concept , Design , and Initial Results," *J. Fusion Energy*, vol. 26, no. 1/2, pp. 199–205, 2007.
- [34] J. T. Slough, A. L. Hoffman, R. D. Milroy, R. Maqueda, and L. C. Steinhauer, "Transport, energy balance, and stability of a large field-reversed configuration," *Phys. Plasmas*, vol. 2, no. 6, pp. 2286–2291, 1995.
- [35] G. Votroubek, J. Slough, S. Andreason, and C. Pihl, "Formation of a Stable Field Reversed Configuration through Merging," *J. Fusion Energy*, vol. 27, no. 1–2, pp. 123–127, Jun. 2008.
- [36] J. T. Slough *et al.*, "Confinement and stability of plasmas in a field-reversed configuration," *Phys. Rev. Lett.*, vol. 69, no. 15, pp. 2212–2215, Oct. 1992.
- [37] J. Slough, G. Votroubek, and C. Pihl, "Creation of a high-temperature plasma through merging and compression of supersonic field reversed configuration plasmoids," *Nucl. Fusion*, vol. 51, p. 53008, 2011.
- [38] (JASON) and G. Long, "Prospects for Low Cost Fusion Development," vol. JSR-18-011, no. November, 2018.
- [39] P. Wessel, F.J.; Rahman, H.U.; Rostroker, R.; Ney, "STAGED Z - PINCH FOR THE PRODUCTION OF HIGH - FLUX NEUTRONS AND NET ENERGY," 2017.
- [40] H. U. Rahman, F. J. Wessel, P. Ney, R. Presura, R. Ellahi, and P. K. Shukla, "Shock waves in a Z-pinch and the formation of high energy density plasma," *Phys. Plasmas*, vol. 19, no. 12, p. 122701, Dec. 2012.
- [41] H. U. Rahman *et al.*, "Ar and Kr on deuterium gas-puff staged Z-pinch implosions on a 1-MA driver: Experiment and simulation," *Phys. Plasmas*, vol. 26, no. 5, p. 052706, 2019.
- [42] J. Narkis *et al.*, "A semi-analytic model of gas-puff liner-on-target magneto-inertial fusion," *Phys. Plasmas*, vol. 26, no. 3, p. 032708, Mar. 2019.
- [43] "Nevada Terawatt Facility: Zebra." [Online]. Available: <https://www.unr.edu/physics/ntf/facility/zebra>. [Accessed: 30-May-2019].
- [44] F. Conti *et al.*, "Characterization of a Liner-on-Target Gas Injector for Staged Z-Pinch Experiments," *IEEE Trans. Plasma Sci.*, vol. 46, no. 11, pp. 3855–3863, 2019.
- [45] I. R. Lindemuth, M. R. Weis, and W. L. Atchison, "The staged z-pinch as a potential high gain fusion energy source: An independent review, a negative conclusion," *Phys. Plasmas*, vol. 25, no. 10, p. 102707, Oct. 2018.
- [46] "Dr Scott Hsu and Dr F. Douglas Witherspoon - Plasma guns fire into the race for fusion • scientia.global," *Scientia*, no. February 23, 2017.
- [47] Y. C. F. Thio *et al.*, "Plasma-Jet-Driven Magneto-Inertial Fusion," *Fusion Sci. Technol.*, pp. 1–18,

May 2019.

- [48] S. C. Hsu *et al.*, "Spherically Imploding Plasma Liners as a Standoff Driver for Magnetoinertial Fusion," vol. 40, no. 5, pp. 1287–1298, 2012.
- [49] S. C. Hsu *et al.*, "Experiment to Form and Characterize a Section of a Spherically Imploding Plasma Liner," *IEEE Trans. Plasma Sci.*, vol. 46, no. 6, pp. 1951–1961, Jun. 2018.
- [50] S. J. Langendorf and S. C. Hsu, "Semi-analytic model of plasma-jet-driven magneto-inertial fusion," *Phys. Plasmas*, vol. 24, no. 3, p. 032704, Mar. 2017.
- [51] S. J. Langendorf, K. C. Yates, S. C. Hsu, C. Thoma, and M. Gilmore, "Experimental Measurements of Ion Heating in Collisional Plasma Shocks and Interpenetrating Supersonic Plasma Flows," *Phys. Rev. Lett.*, vol. 121, no. 18, p. 185001, 2018.
- [52] W. Shih, R. Samulyak, S. C. Hsu, S. J. Langendorf, K. C. Yates, and Y. C. F. Thio, "Simulation study of the influence of experimental variations on the structure and quality of plasma liners," *Phys. Plasmas*, vol. 26, no. 3, 2019.
- [53] S. C. Hsu and S. J. Langendorf, "Magnetized Plasma Target for Plasma-Jet-Driven Magneto-Inertial Fusion," *J. Fusion Energy*, vol. 38, no. 1, pp. 182–198, 2019.
- [54] P. Stoltz, S. Hsu, S. Langendorf, and T. Byvank, "Estimates of Fusion Gain of Plasma Jet Driven Magneto-Inertial Fusion," *APS Div. Plasma Phys. Meet.*, vol. abstract i, 2018.
- [55] D. C. Quimby, A. L. Hoffman, and G. C. Vlases, "LINUS CYCLE CALCULATIONS INCLUDING PLASMA TRANSPORT," *Nucl. Fusion*, vol. 21, no. 5, pp. 553–570, 1981.
- [56] D. L. Book, D. A. Hammer, and P. J. Turchi, "THEORETICAL STUDIES OF THE FORMATION AND ADIABATIC COMPRESSION OF REVERSED-FIELD CONFIGURATIONS IN IMPLODING LINERS," *Nucl. Fusion*, vol. 18, no. 2, pp. 159–170, 1978.
- [57] P. J. Turchi, "Imploding Liner Compression of Plasma : Concepts and Issues," *IEEE Trans. Plasma Sci.*, vol. 36, no. 1, pp. 52–61, 2008.
- [58] S. D. Frese, M. H. Frese, and P. J. Turchi, "Stabilized Liner Compressor: 2D/2-D multiphysics simulations," in *43rd IEEE International Conference on Plasma Science (ICOPS)*, 2016, pp. 1–1.
- [59] M. H. Frese and S. D. Frese, "Formation, Translation, Capture, Merging and Compression of FRCs in an Imploding Rotationally Stabilized Line," in *The 45th IEEE International Conference on Plasma Science (ICOPS 2018)*, 2018.
- [60] J. R. Davies *et al.*, "Laser-driven magnetized liner inertial fusion," *Phys. Plasmas*, vol. 24, no. 6, p. 062701, Jun. 2017.
- [61] J. R. Davies *et al.*, "Inferring fuel areal density from secondary neutron yields in laser-driven magnetized liner inertial fusion," *Phys. Plasmas*, vol. 26, no. 2, 2019.
- [62] X. Zhai, H. Li, P. M. Bellan, and S. Li, "Three-dimensional MHD simulation of the Caltech plasma jet experiment: First results," *Astrophys. J.*, vol. 791, no. 1, 2014.
- [63] B. Seo and P. M. Bellan, "Experimental investigation of the compression and heating of an MHD-driven jet impacting a target cloud," *Phys. Plasmas*, vol. 25, no. 11, 2018.
- [64] B. Seo and P. M. Bellan, "Spatially translatable optical fiber-coupled heterodyne interferometer,"

- Rev. Sci. Instrum.*, vol. 88, no. 12, 2017.
- [65] *An Assessment of the Prospects for Inertial Fusion Energy*. National Academies Press, 2015.
 - [66] National Research Council, *Assessment of Inertial Confinement Fusion Targets*. Washington, DC: The National Academies Press, 2015.
 - [67] A. W. Maschke, "Space-Charge Limits for Linear Accelerators," 1979.
 - [68] A. Persaud *et al.*, "A compact linear accelerator based on a scalable microelectromechanical-system RF-structure," *Rev. Sci. Instrum.*, vol. 88, no. 6, 2017.
 - [69] P. A. Seidl *et al.*, "Source-to-accelerator quadrupole matching section for a compact linear accelerator," *Rev. Sci. Instrum.*, vol. 89, no. 5, 2018.
 - [70] P. A. Seidl *et al.*, "Multi-beam RF accelerators for ion implantation," Sep. 2018.
 - [71] K. B. Vinayakumar *et al.*, "Demonstration of waferscale voltage amplifier and electrostatic quadrupole focusing array for compact linear accelerators," *J. Appl. Phys.*, vol. 125, no. 19, p. 194901, May 2019.
 - [72] ARPA-E, "OPEN + Materials for Advanced Nuclear Energy," pp. 1–2.
 - [73] M. Kaur *et al.*, "Measuring the equations of state in a relaxed magnetohydrodynamic plasma," *Phys. Rev. E*, vol. 97, no. 1, pp. 1–4, 2018.
 - [74] M. Kaur *et al.*, "Magnetothermodynamics: measurements of the thermodynamic properties in a relaxed magnetohydrodynamic plasma," *J. Plasma Phys.*, vol. 84, no. 1, pp. 1–20, 2018.
 - [75] M. Kaur, K. Gelber, A. Light, and M. Brown, "Temperature and Lifetime Measurements in the SSX Wind Tunnel," *Plasma*, vol. 1, no. 2, pp. 229–241, 2018.
 - [76] iRunway, "Nuclear Fusion Global IP Landscape," 2016.
 - [77] Bechtel National Inc Woodruff Scientific Inc and Decysive Systems, "Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program," 2017.
 - [78] APS DPP, "60th Annual Meeting of the APS Division of Plasma Physics," *Epitome*, vol. 63, no. 11. Portland, OR, 2018.
 - [79] ARPA-E, "OPEN 2018, Funding Opportunity No. DE-FOA- 0001858." 2018.
 - [80] S. A. Cohen *et al.*, "Formation of collisionless high- β plasmas by odd-parity rotating magnetic fields," *Phys. Rev. Lett.*, vol. 98, no. 14, pp. 10–13, 2007.
 - [81] D. A. Sutherland *et al.*, "The dynamak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies," *Fusion Eng. Des.*, vol. 89, no. 4, pp. 412–425, 2014.
 - [82] Fusion Industry Association, "ABOUT FUSION." [Online]. Available: <https://www.fusionindustryassociation.org/impact>. [Accessed: 31-May-2019].
 - [83] E. and M. National Academies of Sciences, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*. Washington, D.C.: National Academies Press, 2018.
 - [84] ARPA-E, "Request for Information (RFI) DE-FOA-0002131 on Enabling Technologies for a

Commercially Viable Fusion Power Plant,” pp. 1–7, 2019.

- [85] ARPA-E, “SOLICITATION ON TOPICS INFORMING NEW PROGRAM AREAS Modification 01 Funding Opportunity No. DE-FOA-0001953 Topic D: Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion- Energy Concepts,” 2019. [Online]. Available: <https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=2a90b153-50f4-4a8e-b7da-fb9b912dc7a7>. [Accessed: 26-Jun-2019].