Magnetically-Driven High-Energy-Density Physics: A Case Study in Collaborative Success

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***Abstract*—High-energy-density physics research has focused on examining new frontiers of plasma behavior in the extreme conditions found in fusion plasmas and astrophysical systems, amongst others. This has increasingly necessitated the use of large-scale experimental facilities to achieve such conditions, which are typically located at national laboratories. During a highly productive couple of decades, significant advances have been made in inertial fusion performance, including achieving ignition at NIF, powerful x-ray sources for astrophysics studies, and contributions to basic science issues. A great deal of this progress has been based on physics scaling studies, novel experimental and numerical research, and diagnostic development carried out at a university scale. In this article, we will focus on pulsed power high-energy-density research and highlight how university-scale programs have been a fundamental part of progress. Contributions have comprised those from both large collaboratives, such as the NNSA Centers of Excellence, and innovative single PI programs, and training in both physics and pulsed power engineering remains a focus.**

***Index Terms*—High-energy-density physics, inertial confinement fusion, laboratory astrophysics, pulsed power.**

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I. Introduction

In THE 1990 s, load configurations for the SATURN driver at Sandia National Laboratories included "wire arrays"; several fine metallic wires strung between two electrodes to form a cylinder of some 20–40-mm diameter. The 8 MA, 100-ns current pulse on SATURN turned these wires rapidly into plasma, accelerated them radially inward to ~100 km/s, and finally compressed them onto the cylinder's central axis. Kinetic and compressional magnetic energies were converted to internal energy in the plasma, and a hot, dense Z-pinch column radiated this energy away in the form of X-rays. Optimizing this configuration led to a dramatic increase in the soft X-ray power that could be generated, from a few TW initially [1] to 50 TW on SATURN [2], [3], and then to 1.8-MJ yield at 280 TW on Z in 1998 [4], [5].

These successes opened up a range of possibilities for research, both in wire-array systems directly and in applications of the radiation and plasmas that could be generated [6], [7]. Pulsed power drivers from 10 s of kiloamperes to a few mega-amperes housed on university campuses provide flexible platforms for a wide range of "hands-on" studies. These experimental programs typically have extensive diagnostic access, and data are readily combined with well-benchmarked simulations to work on specific issues, which then contribute to the larger national picture. They allow students to test, fail, and then improve and advance in their studies. This complemented the systems at Sandia, which could drive far higher energy densities but typically had limited diagnostic access at that time. The ability to image, measure, and probe plasmas more thoroughly and much more frequently than on Z has proven invaluable for understanding plasma performance across the parameter space, as well as to train students.

We discuss here one example of a collaboration of university research programs that has been particularly successful in this role. In 2002, Profs. David Hammer and Bruce Kusse at Cornell University founded the "Center for High Energy Density Physics in Pulsed Power," supported by the National Nuclear Security Administration Stewardship Science Academic Alliances (NNSA SSAAs) program. The collaboration included Cornell University, Imperial College London; the University of Nevada, Reno; the University of Rochester, the Weizmann Institute of Science, Israel; and the P. N. Lebedev Institute, Russia. The "Center" remained under the leadership of Prof. David Hammer and Prof. Bruce

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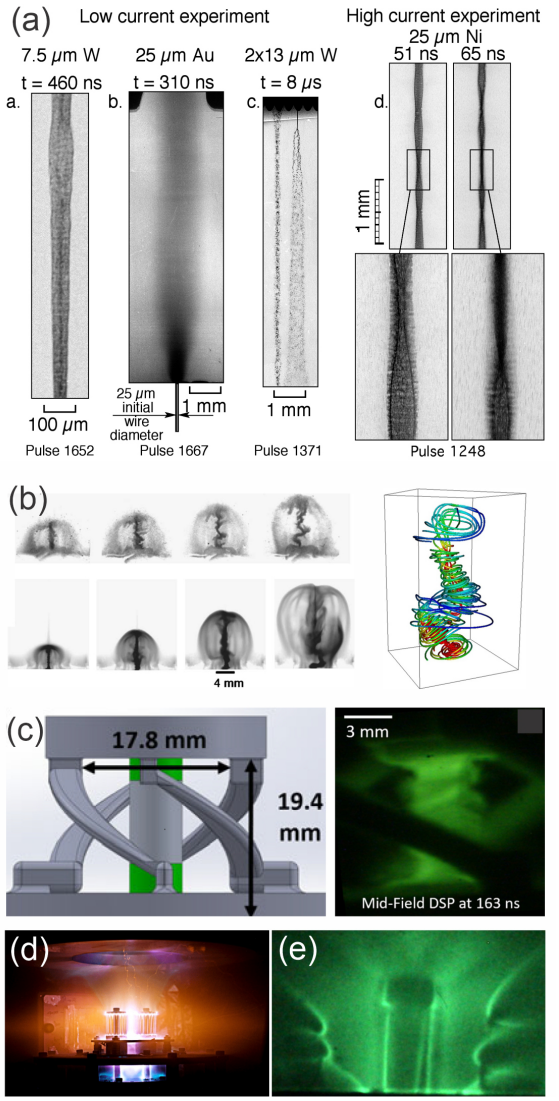


Fig. 1. (a) X-ray radiography demonstrating the complex behavior of exploding wires, (b) experimental and simulated images of magnetic tower jets [72], (c) self-magnetizing liner experiment termed the dynamic screw pinch [62], (d) dual wire array arrangement for studying magnetic reconnection [85], and (e) inverse wire array experiment generating multiple interacting bow shocks [92].

Kusse until 2022, when it passed to the present PI, Prof. Ryan McBride, at the University of Michigan. This new incarnation, called the Center for Magnetic Acceleration Compression, and Heating (C-MACH), has a term running to 2028. C-MACH directly continues and develops the HED physics programs developed under the original center. In addition, new institutions were invited to join, and new focus areas, including power flow and magnetic turbulence, were added to broaden center participation and reach. The continued NNSA support for a collaboration in pulsed power plasma science and technology has led to a wide range of innovations and significant contributions on national and international scales.

II. Driving Innovation in Z-Pinch Physics

Many of the performance trends for different wire array configurations were noted in the Sandia work optimizing peak X-ray powers, but a more complete physics explanation was desirable, and the center played a key role here. The original center (2003–2007 DE-FC03-02NA00057) was built on seminal contributions by the founding directors and co-PIs. Optical and X-ray imaging of exploding wires uncovered the complex nature of the energy delivery in single wires [8], [9], [10], [11], [12], [13], [14] [Fig. 1(a)] and led to the development of the X-pinch as a high-density plasma and a radiography source [15], [16], as well as the analytical description of mass ablation in wire arrays led by Prof. Sergey Lebedev [17], [18]. These advancements led to a more quantitative understanding of behavior and also to the ability to design wire array variants, including the establishment of Z-pinches as a valuable tool in the then-nascent field of laboratory astrophysics [19], [20] [Fig. 1(b)]. The study of cylindrical wire array systems for high X-ray power provided a focus, and the 1-MA COBRA generator [21] was constructed at Cornell to drive these alongside the 1.4-MA MAGPIE generator [22] at Imperial College London. Experimental and diagnostic development by all Center partners was complemented by magnetohydrodynamics (MHD) simulations of single wires in various magnetic geometries led by Prof. Jeremy Chittenden at Imperial College using the MH2D code [23].

Subsequent center iterations (2008–2012, 2012–2017, and 2017–2022) were all funded under the NNSA Stewardship Sciences Academic Program and dramatically expanded the development of Z-pinch plasmas to a wide range of applications and research areas. Support of the inertial confinement fusion program at Sandia remained a central theme, with wire arrays, gas puff, and metal liner loads receiving considerable study. Wire array studies encompassed single and nested system for ablation [24], [25], [26], [27], [28], [29], [30] and implosion stability studies [31], [32], [33], [34], [35], [36], [37], [38], while novel coiled [39], [40], etched [41], [42], and spherical arrays [43] allowed a detailed study of magnetically driven ablation physics. Gas puff system generated extensive studies of MHD instability during implosion [44], [45], [46], [47], [48], and more recently, studies of turbulence [49].

Liner work primarily supports the development of the MagLIF concept for ICF and IFE [50], [51], [52]. While a university-scale driver cannot implode full-scale MagLIF liners, scaled and focused physics experiments can access important aspects of the design. Thin foil liner implosions [52] examined the acceleration phase, gas-filled foil liners examined shock propagation into the fuel [54], and over-massed liner loads allowed breakdown and current distribution to be examined [55], [56], [57], [58], [59]. With an axial B-field, the formation of helical instabilities noted at Sandia was reproduced and studied [60], [61]. Novel approaches to address fuel magnetization were developed, including the use of twisted return-current paths (Dynamic Screw Pinch [62] [Fig. 1(c)]) and field-reversed configuration plasmas (FRCs) [63].

Astrophysically relevant studies expanded to include the interaction of hydrodynamic jets with target plasmas [64], [65], [66], magnetically launched jets and episodic jets [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], rotation in jets [79], and in accretion-disk type flows [80], [81], [82], [83], [84].In addition, Center partners have also developed novel experimental platforms for magnetic reconnection [85], [86], [87] [Fig. 1(d)] and radiative shocks [88], [89], [90], [91], [92] [Fig. 1(e)] at a range of current levels.

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Both diagnostic development [93], [94], [95], [96], [97], [98], [99], [100], [101] and pulsed power technology are an important part of the center's core activity. Optical Thomson scattering has been deployed at several sites, including for examination of flow conditions, shocks, and turbulent plasmas [49], [102], [103], [104], [105], [106], [107]. Novel developments in emission spectroscopy along multiple lines of sight have unraveled the complex distribution of current and magnetic field in Z-pinches and Bremsstrahlung diodes [108], [109], [110], [111], [112], [113], [114], and revealed the turbulence at stagnation [115], [116], [117], [118], [119], [120] and the plasma rotation [121], [122], [123] in Z-pinches and in magnetized-plasma compression. Novel diagnostics for turbulence [124], [125], compact magnetic probes [126], HV switch trigger technologies [127], [128], and portable X-ray sources [99] have all been designed and developed by students, faculty, and researchers under the center.

The center also accelerated the application of MHD codes in high-resolution 3-D to simulate full wire array systems. The "Gorgon" code [129], [130], [131], [132], [133] employed novel magnetic solver schemes to allow the massively parallel operation required for high-resolution calculations, as well as simulated diagnostic output for direct comparison to experiments (e.g., [31], [70], [134]). The PERSEUS code [135], [136], [137], [138] was also developed to encompass extended MHD effects, including hall physics. Both codes are now employed at several national laboratories following development through the center. MHD work is further supported by plasma theory concerning the compression of magnetized and turbulent plasmas [139], [140], [141], [142], [143], [144], [145], [146], [147].

The center has proven to be both an engine of scientific productivity and a highly effective workforce supply chain in HED science. During the recently concluded five-year period (2017–2022), the Cornell-led Center published 102 peer-reviewed journal papers, and ten PhD students were placed at National Laboratories (three at SNL, five at LLNL, and two at LANL). The center has maintained this performance for its full 23-year tenure, annually producing >20 papers and placing multiple graduate students at national laboratories." Many center graduates now occupy national leadership roles. The NNSA SSAA program has continuously provided vital foundational support for a wide range of HED science and pulsed power activities, including both mission focused and blue-skies research, which has enabled this success.

III. Continued Expansion of the Center

In its most recent renewal phase (2023–2028 DE-NA-0004148), the center has expanded its collaboration to include new partners, institutions, and capabilities. Presently, there are nine PI sites (see Table I).

Wire arrays and gas puffs are now utilized in X-ray-driven ablation experiments, enabling comparisons of magnetized and unmagnetized flows, and strategically important radiation effects testing. Many of these ideas have been developed in the center and fielded on Z as part of the academic access program.

IV. Conclusion

Academic programs remain a vital part of the HEDP, plasma science, and broader scientific research ecosystems, and maintaining their vitality is crucial for the national program in all areas of science. The NNSA's consistent support of the Cornell- and Michigan-led Center of Excellence has provided foundational support for pulsed power programs, which have proven highly successful and productive over the last two decades. The center continues to expand its capabilities and novel contributions to science. This center acts as a steward of pulsed power-driven plasma systems, developing workforce talent, physics programs, pulsed power drivers, simulation codes, and diagnostics.

TABLE I
MACH Center Partners and Capabilities

INSTITUTION	DRIVER or SPECIALIZATION
Univ. Michigan (McBride PI, Jordan)	MAIZE, 1 MA, 200ns [149]
	BLUE, 0.2 MA, 100ns [150]
Cornell University (Kusse, Hammer, Hare, Lavine)	COBRA, 1.1 MA, 100/200ns [21]
	XP, 0.5 MA, 50ns [151]
	PUFFIN, 0.7 MA, 1500ns
	PERSEUS, X-MHD code [136]
	Thomson Scattering [49]
Imperial College (Bland, Lebedev, Chittenden)	MAGPIE, 1.4 MA, 240ns [22]
	Mach, 1.5 MA, 400ns [152]
	Dry x-pinches 130-250kA, 300ns
	Gorgon, MHD code [130] Thomson Scattering [102-107]
Weizmann Institute (Maron)	Spectroscopic methods, experiments, analysis development [108-123]
Princeton Univ. (Fisch)	Plasma Theory [140-148]
UC San Diego (Bott-Suzuki, Valdivia)	Bertha, 0.20 MA, 1100ns [107]
	Rama, 0.75 MA, 1300ns [153]
U. Rochester (Gourdain)	HADES, 1 MA, 300ns [154]
U. Washington (Srinivasan)	Kinetic and multi-fluid plasma Simulations [155-156]
Univ. New Mexico (Portillo)	Lobo (300 kA, 80 ns rise) [157]

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T. Shelkovenko, photograph and biography not available at the time of publication.

S. Pikuz, photograph and biography not available at the time of publication.

B. Srinivasan, photograph and biography not available at the time of publication.

P. Gourdain, photograph and biography not available at the time of publication.

S. Portillo, photograph and biography not available at the time of publication.

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