Physics of Plasmas

RESEARCH ARTICLE | SEPTEMBER 29 2023

The academic research ecosystem required to support the development of fusion energy

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

D. G. Whyte ✉ ; C. Paz-Soldan ; B. Wirth

Phys. Plasmas 30, 090604 (2023)
https://doi.org/10.1063/5.0167369

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

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Cite as: Phys. Plasmas **30**, 090604 (2023); doi: 10.1063/5.0167369
Submitted: 12 July 2023 · Accepted: 29 August 2023 ·
Published Online: 29 September 2023

D. G. Whyte,[1,a)] C. Paz-Soldan,[2] and B. Wirth[3]

AFFILIATIONS

[1] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2] Columbia University, New York, New York 10027, USA
[3] University of Tennessee-Knoxville, Knoxville, Tennessee 37996, 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:** whyte@psfc.mit.edu

ABSTRACT

The advent of a fusion energy industry is being strongly supported by academics and universities, with the majority of fusion companies launching out of universities. Universities also play critical roles in technical innovation, workforce development, and independent arbiters of science and technology. The ability of the US academic landscape to support and grow the fusion energy sector is analyzed via a numerical distribution of full time faculty engaged in fusion and plasma. This data is compared to university support in two existing technology-driven industries: nuclear and aeronautics. This comparison clearly shows that the university system requires not only significant absolute growth but also a wider distribution of faculty at universities and across the required disciplines.

I. INTRODUCTION

The plasma and fusion landscape has changed dramatically in the last several years both in the US and internationally. A large number of companies have been formed whose stated goal is to develop commercial fusion power plants. These companies have been funded primarily by private sector capital. In parallel and in response to this development, several national government programs have been significantly modified: prominent examples being the UK STEP program[1] and US Fusion Pilot Plant (FPP).[2] In general, these government programs have two features: align themselves and leverage the private-sector fusion companies, and accelerate the timeline to fusion power on the grid to a decadal timescale.

These developments motivate an examination of the role of universities in developing and sustaining a fusion energy industry. The reason being that all existing high-tech industries reside on a three-legged support of companies, government, and academia, where each play critical roles and interact with each other. Examples of such industries are computing, aeronautics, nuclear fission, and biotechnology. In these examples not only is there a present thriving ecosystem, but they all underwent significant changes in the last two decades due to innovations or evolutions on the technical side (e.g., digital search, gene sequencing), commercialization side (e.g., private-sector orbital launch, mobile computing), and meeting new energy demands (e.g., solar, small modular reactors). These innovations either originated at universities[3] or universities have had to evolve their education structures around technology and societal demands regarding climate change for example at Stanford[4] or Columbia.[5] Fusion is highly similar to these examples. It has foundations in a challenging science discipline: plasma physics, yet further requires interdisciplinary integration of multiple engineering and science disciplines. As a new technology fusion will also require expertise in disciplines outside of the STEM fields, such as finance,[6] safety, licensing, and market analysis. Another similarity is that a successful fusion enterprise will have major geopolitical, societal and economic impact. Yet, fusion is not identical to these fields for several reasons: the fusion private sector is relatively nascent, the physics of fusion allows for an extremely diverse set of technologies and approaches, and technological readiness levels remain low in several key areas.

These observations motivate this study and discussion on the role of universities in the fusion ecosystem. The authors are senior academics at institutions substantially involved in plasma and fusion research, and who have participated in recent activities aligned with this topic, such as the FESAC strategic planning[7] and the NASEM report on Bringing Fusion to the US Grid.[2] However, the comments and observations made here are our own. It is noted that in the US, the national lab system has historically played a significant role in fusion science and technology and that will certainly be the case going forward. Tight integration and collaboration will be required between universities and national labs from the public-facing side of fusion's development, but they do not perform identical functions. As will be seen, there are specific challenges that face universities and so we focus on these.

Section II studies the role of universities in plasma science and technical innovation and in new venture creation. Section III discusses the role of universities in establishing the need for new user facilities and capabilities that broadly support fusion. Section IV comments on the need for academics in independent peer review and growing social acceptance. Section V studies the needs and challenges of supporting an expanding and multidisciplinary workforce. Section VI provides conclusions.

II. INNOVATION AND VENTURE CREATION

The root of fusion energy is the physics of plasma confinement and stability. This arises from the Lawson criterion (see Wurzel *et al.*[8] for a recent exposition), which sets minimum temperatures above 4 keV for the fusion fuel, thus assuring that the fuel is in the plasma state. However, the Lawson criterion only specifies the required product of density and confinement to meet a specific plasma energy gain factor or ignition. The consequence is that the plasma state can vary over enormous ranges, spanning from $\sim 10^{20}$ m^{-3} in magnetic confinement to $>10^{30}$ m^{-3} in inertial confinement, with the corresponding confinement times varying from ~ 1 s down to <1 ns. This fact alone means that fusion can be tackled by an extraordinary range of innovative plasma confinement methodologies. Moreover, plasma physics and applications are so broad that the field of fusion plasmas is effectively a sub-discipline. The difficulty of achieving the Lawson criterion simultaneously, thus, requires deep roots in the discipline of plasma physics, while simultaneously considering the associated technology requirements. In the examples above for example this required understanding of magnets in magnetic fusion energy (MFE), and lasers and optics in inertial fusion energy (IFE). Universities are certainly not the sole location of expertise in these topics, but the very nature of a university tends to collect and push together the multidisciplinary fields required for fusion energy, while maintaining an anchor in the plasma physics required for fusion science. Another feature of universities is unique in fostering innovation, namely, their graduate education mission. For graduate students, advanced degrees require not only classroom instruction but also original research in the form of theses. The constant refresh of talent and topics triggered by graduate education is a natural environment for encouraging discovery.

The critical role of universities in innovation and venture creation is supported by an assessment of the private sector fusion companies. The Fusion Industry Association[9] lists 37 companies as primary members. By examining publicly available documents for 36 of these companies (one company had no public information), we have ascertained the origin of the companies and assigned them as being from universities, national/government labs (US or international) and/or "other." This last category typically is a company origin solely from the private sector or nonpublic. A university origin is assigned if some of the founders or intellectual property came directly out of a university. Universities account for the majority of the fusion companies, with a total of 21 (or 58%). Twelve (or 33%) had private/other origins, and national labs accounted for 6 (or 17%). It is noted that in the latter case all the companies associated with national labs also shared origins with a university and so were counted in both categories. The first company established is TAE with its origins at UC-Irvine. The largest existing company in terms of capital raised is Commonwealth Fusion Systems with its origins at MIT. The companies from universities cover a wide range of plasma confinement approaches spanning "established" magnetic confinement (e.g., tokamaks, stellarators), "innovative" magnetic confinement (e.g., mirrors), magneto-inertial confinement (e.g., pinches), and inertial confinement. There is also diversity in the type of universities launching fusion companies: 2/3 of the universities are public and 1/3 are private. This analysis supports the assertion that universities are uniquely powerful incubators for fusion venture creation.

The assessment of the FIA primary members also reveals that universities will need to play a critical role in evolving and developing a more complete venture/commercial fusion ecosystem. 34 of the 36 companies are best described as "vertical integrators" for fusion energy systems, meaning that their role in the fusion industry is to hold and understand the holistic concept of the entire fusion power plant. This is a natural consequence of the highly diverse nature of the confinement approaches being taken. To use an analogy to a mature industry such as aeronautics, these companies seek to be a Boeing or Airbus that develop and hold the overall design of the commercial product, i.e., the jet airplane. Yet, these vertical integration companies rely on a range of other companies that produce the required components for the plane. Looking at the fission energy industry is no different: fission power plant commercial designs rely on a supply chain of specialized components. This is likely to be the case for fusion. However, only two of the 36 companies listed by FIA (Kyoto Fusioneering and Shine) are focused on supplying technologies. It seems evident that there will be substantial need and opportunity to supplement the existing supply chain for required components (vacuum vessels, balance of plant), supplemented by further venture creation in fusion that delivers first-of-kind component technologies that do not exist in the present supply chain. This could include specialized materials for the harsh fusion environment, testing capabilities for materials and components, neutronics calculations, blankets, fuel cycle technology, RF sources/transmission, cryogenics, optics, lasers, and power-switching. The inherent multi-disciplinary nature of these areas favor university innovation, incubation, and venture creation. While some of these capabilities may be supplied by existing companies, national labs, or the fusion companies themselves, the inherent "newness" of the fusion requirements, and the major role these will play in meeting economic viability make it likely that the university venture creation is, in fact, just starting.

III. SHARED CAPABILITIES/USER FACILITIES

Many technical and development challenges face the delivery of fully capable and reliable fusion energy systems. The technical and scientific challenges are well documented in numerous reports over the last decade (Greenwald report,[10] FESAC,[7] NASEM[2]), and these challenges largely remain. New capabilities/facilities are required to tackle these challenges spanning from plasma experiments, to materials development, up to integrated component testing.

The onset of the private-sector fusion effort has placed further stress on these challenges in three ways. First the diversity of approaches has increased; this naturally adds to the diversity of requirements in the new capabilities. Second, the timelines for obtaining critical information and solutions are shortened due to the aggressive private-sector timelines, and the accompanying government-based support programs. Third, the private sector component produces a tension between competitive advantages in accessing technology solutions across companies and the desire, particularly from publicly funded sources, that provide capabilities that are generic and open in nature.

We assert that universities will play a critical role in addressing these challenges. The diversity and accelerated timeline call for a wider range of small to mid-scale capabilities that have a natural landing place at universities. Universities provide cost-effectiveness and sharing due to institutional and philanthropic support. Universities also have intrinsic breadth in disciplines and, therefore, best practices from adjacent disciplines associated with thriving high-tech industries can be adapted. Universities require openness in their research, which avoids complexities around shared capabilities at national labs that may have dual-uses for research and national security uses. Universities as non-profits also intrinsically avoid competitive conflicts that occur when a commercial company is operating a shared user facility. Furthermore, the university host is an opportunity to improve access to these new capabilities to young scientists and students who in turn are being trained in critical science and technology capabilities that serve the fusion industry. Cross-institutional access has a relatively low barrier since academic exchanges of students and postdocs are commonplace at all universities. A further benefit of this model is that the congregation of young talent and access to new capabilities will be a further impetus for venture creation for fusion out of the universities.

While these are compelling arguments, there will also be shared capabilities/facilities whose scale will surpass the infrastructure capabilities of universities (or some subset thereof). In this case, national/government labs would be appropriate to provide that infrastructure. However, even in this case, universities should be heavily engaged, not only for purpose of access to student and postdocs but also realizing that academics are highly valuable in providing non-conflicted, merit-based science and technology guidance, and leadership to the facilities.

In addition to the growth of technical/scientific capabilities, universities should also be asked to provide other support mechanisms to the fusion energy eco-system. The management of intellectual property and improved practices around technology transfer are critical topics where universities must contribute. As the fusion industry matures, the demand for broad independent expert academic analysis of fusion will increase. Topics here would include energy market analysis, safety and licensing (including advice to regulatory bodies), customer and end-use adaptation, and societal impact/acceptance.

IV. INDEPENDENT REVIEW AND SOCIAL ACCEPTANCE

Plasma and fusion science and technology are difficult, frontier-pushing fields. As the diversity of private sector approaches to fusion grows, there will an increased requirement for independent, unconflicted review of science and technology pathways and claims. Senior, tenured academics play a key role on this issue since while they are experts in their respected fields, their academic position insulates them from pressures that might arise from companies seeking to validate their claims. This is common in mature technology industries where senior academics are used to provide unvarnished view. A particularly important example will be the vetting of technical milestone achievements private–public partnerships and cost-sharing programs.

However, conflicts of interest are not automatically relieved by using academics. Universities and faculty can be heavily involved in fusion venture creation and also engage in research support for companies. This provides a financial and programmatic link between academics and the fusion industry. Transparency in research and financial relationships will be necessary for academics to be trusted voices. Also having a distributed and well-populated academia with knowledge in fusion will provide better opportunities to avoid conflict of interest. This likely requires having a broader distribution of expertise at universities than we presently have in the US (see Sec. V).

Another public-facing role for academics is that through their local, community and global educational roles they are naturally involved in improving understanding of new technology. Furthermore, as a larger set of social-science disciplines become involved in fusion, they will play leading roles in establishing social acceptance. Here again a wide distribution of academics in various communities will be necessary to be effective, since local community involvement will be critical in this area.

V. WORKFORCE DEVELOPMENT

The skill-sets and timelines demanded by the fusion private sector will place severe demands on our educational programs. A growing and thriving fusion industry will require a new, extremely talented, and diverse workforce. A qualitative examination of the present plasma and fusion education channels indicate significant deficiencies.

The scale of academic participation required to meet the current private industry timelines is beyond the current ability of academia to provide. It should be noted that with success, the fusion industry could meet or surpass the nuclear fission industry, and even rival other large high-tech sectors, such as aeronautics. We have carried out an informal analysis of the size and scale of the academic network in the US by examining the number and size of faculty at universities engaged in fusion via their listing on the University Fusion Association website.[11] Data was gathered by internet searches for fusion and plasma research at these universities. Only active tenure-track or tenured faculty were counted. In addition, we have assessed the scale of faculty at nuclear engineering and aero/Astro departments by sampling the top ten programs as listed by US News and World Report of graduate programs.[12] The total number of universities active in plasma and fusion we identified is 57, which at first glance is healthy being comparable to total listed fission programs (40) and aero/astro (82) programs. However, the average number of faculty at each institution is three plasma/fusion, as compared to 19.5 for nuclear and 32 for aero/astro. Figure 1 provides a histogram of the fusion/plasma faculty at each university. This indicates a median value of 2 faculty per institution involved in fusion. This is compared to median values of 16.5 and 35 for the top ranked nuclear and aero/astro departments, respectively.

We have also approximated the percentage of faculty in the two broad fusion categories: the result is 85% with primary focus on plasma science and 15% with primary focus on materials and/or fusion technology.

This examination of faculty distribution illuminates key challenges for fusion industry and the universities in workforce development (albeit here focused on US).

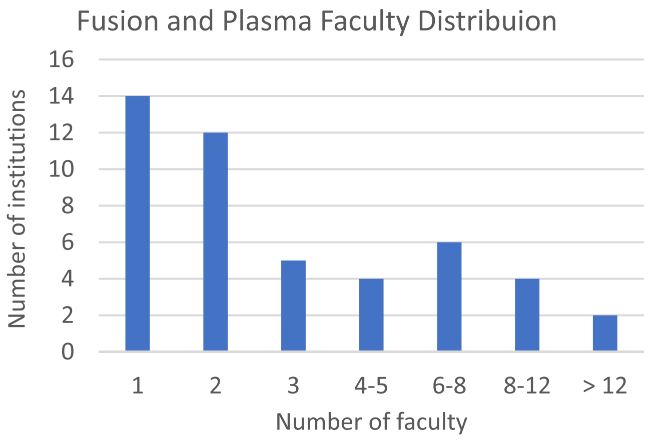

FIG. 1. Distribution of faculty size at US academic institutions. Includes active tenure-track and tenured professors, but not other categories such as researchers, instructors, adjuncts, and emeritus appointments.

- The market demand, as judged by the existence of 33 private-sector companies, not to mention existing workforce demand, such as national labs and plasma/fusion adjacent industries, will far exceed the teaching and supervisory capacity of universities active in fusion. It is difficult to precisely quantify this demand, but a recent survey of the four Seattle-area fusion companies indicated that their staff doubled to 224 from 2021 to 2022, and that would double again in the next year to over 500. Given this survey represents $<20\%$ of the fusion companies, the workforce demands are in the multiple 100s per year. The survey also indicated that the desired skill set was shifting from science to engineering.[13]
- Compounded to this scale problem is the lack of diversity required both in the wide-ranging plasma confinement approaches and in the plasma-technology balance.
- Furthermore, with a median number of instructors being 2 this makes it logistically impossible for such a small number of faculty at a given institution to diversify into the number of topics necessary to broadly cover fusion. This requirement is answered in fission and aero/Astro where >9–10 average faculty can cover the various disciplinary topics necessary for the students to be trained in areas critical to the industry. There are only five US academic institutions that presently are nine or greater, which would be an approximate minimum for establishing a dedicated fusion academic department.

These challenges call for an immediate discussion among the private-sector customers, the university work force developers and the public-sector/government, which is the majority source of financial support for education. This is a difficult problem due to the inherent long timescales in faculty recruitment/promotion and graduate study programs. Solutions can include

- Increased direct financial support of students from private sector participants.
- Commitments in faculty slot growth from educational institutions, which may include the endowment of faculty slots from private sector companies.
- Government-based broad programs that have sufficient timescale and scope, which allow universities to make the long-term commitment to increase tenure-track faculty positions to provide supervisory capability and student support.
- An intentional re-balancing of faculty expertise that reflects the shifting needs of plasma and technology expertise needed by the private sector, while maintaining the required broad approach to plasma research and education, given its wide range of science and industrial applications outside of fusion.
- An examination of the balance between masters and Ph.D. degrees granted. Our personal observation is that fusion presently is heavily skewed to Ph.D., yet master's degrees are very common targets for graduates who want to step directly into industry roles.
- Several mechanisms to increase master's enrollment should be explored. Direct government support for master's fellowships would increase the attractiveness of the master's path. Industry should partner with academia to couple relevant internships to existing master's programs. Universities should explore mechanisms to share instructional resources to broaden offerings beyond their existing specialties. Government could also directly support fusion traineeship programs in academia.
- Shared instructional resources across universities, particularly to support the immediate demands from the industry.
- The elevation of fusion within departments and/or the creation of dedicated plasma/fusion departments, which would provide a higher profile for early-stage entries of talent into fusion at undergraduate level, plus improve the prospects for diverse and sustainable faculty hiring/promotion. This option is likely only viable in the later stages of a larger and thriving private sector fusion effort. In the near-term, the creation of multi-disciplinary centers at universities focused on fusion will probably be needed.

VI. DISCUSSION AND CONCLUSIONS

A vigorous fusion energy industry will provide an expanded customer base for the product of universities: talent and ideas. Universities will play critical roles in venture creation, technology innovation, workforce development, improved diversity, independent assessment, and local/global social acceptance. A qualitative consideration of the present US university system indicates that it is insufficiently populated, diverse, and distributed to fully support the immense effort of standing up a new fusion energy workforce and industry. A relative but quantitative assessment of fusion to similar multi-disciplinary endeavors, such as nuclear engineering and aeronautics/astronautics in the US academy strongly reinforce this view.

This is a consequence of shifting from a program dominantly funded for decades by the government for science purposes, to a field where investment, and aligned public funds, is the primary driver to an industry built on applied science and technology. Since the UK, Canada and Europe are also experiencing this shift, their university systems face similar challenges. A particular challenge of this transition is its relative speed with the funding and number of fusion companies rapidly expanding in 3–4 years; a timescale faster than academia typically reacts.

An apt comparison to the academic landscape required to support the fusion energy ecosystem is the development of nuclear engineering as an academic discipline following World War II and the

Manhattan project to support the development of a civilian nuclear power industry.[14,15] Soon after the completion of World War II, the Atomic Energy Commission was created in the 1946 Atomic Energy Act, and numerous proposals were put forward for peaceful uses of nuclear energy, including submarines, aircraft, locomotives, ships, and power plants. In December 1953, President Eisenhower delivered his Atoms for Peace speech to the United Nations,[16] which was shortly followed by the successful demonstration and launch of the first nuclear submarine, the Nautilus, in 1954, and the 1954 Atomic Energy Act that set the stage for the private development of civilian nuclear power.[17] Academic departments began developing curriculum and training in nuclear engineering soon after the end of World War II, although it is important to point out that there were no faculty with degrees in nuclear engineering, a lack of textbooks and unclassified background materials, and a minimum of relevant equipment available at universities.[14] As well, it was strongly felt that a new academic discipline was required, since the field of nuclear engineering encompassed a wide scope of activities and could not simply exist as a subdiscipline within mechanical engineering, electrical engineering, mechanical engineering, physics or chemistry because graduates would need a broad background on many of these topics before embarking on study in the broader field of nuclear engineering. Indeed, Murphy noted that nuclear engineering departments initially started with graduate training before later adding undergraduate education,[14] this is akin to our recommendation to add Master's programs and likely also increasing undergraduate students.

According to the National Academies 1990 report, the first nuclear engineering programs heavily involved "physics, especially nuclear physics, and toward materials of special interest to nuclear weapons. Later, with the introduction of military and commercial nuclear reactors, nuclear engineering graduates were employed in the design and engineering of reactors and in reactor R&D in national laboratories."[15] As such, the nuclear engineering curriculum became more interdisciplinary and "evolved to cover more reactor engineering areas, such as heat transfer, reactor control, structural materials, radiation effects, and radiation shielding. Of concern were power generation and extraction of energy from the reactor core."[15] Subsequently, interest in radiation effects evolved into applications of radiation for both imaging and nuclear medicine as well. It is also important to point out that government support was instrumental in both developing curricula and providing needed equipment to universities. Early curriculum was influenced by the Oak Ridge School of Reactor Technology developed at ORNL, and the International School hosted at Argonne National Laboratory.[14] As well, the AEC provided financial support for development of textbooks in collaboration with the American Society for Engineering Education and provided funding for equipment and research reactors at universities, leading to the 1953 development of the North Carolina State research reactor, followed by many others. Support from the National Laboratories and the Atomic Energy Commission were coordinated with the leadership of Admiral Rickover, who understood the critical role of universities and enabled the establishment of NE programs and test reactors at many universities. He established the Center for Excellence in Education because "nurturing careers of excellence and leadership in science and technology in young scholars is an essential investment in the United States national and global future."[18] By the late 1950s, a little more than 10 years after the first nuclear engineering classes were taught, the American Nuclear Society, the AEAC and the ASEE came together to establish a committee to develop consistency across nuclear engineering departments and curricula, the Committee on Object Criteria in Nuclear Engineering Education.[14]

Thus, the comparison to the birth of nuclear engineering as an academic discipline reveals similar shared challenges in a broadening of nuclear technology into a geographically distributed civilian power generation capability, the transition from initially primarily "physics" focused to later broadening across a diverse set of engineering capability including radiation damage in materials, and strong support from the Federal government that requires close collaboration with the National Laboratories. This comparison clearly shows that the university system not only requires significant absolute growth, but also a wider distribution of faculty at universities and across the required disciplines.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Dennis G. Whyte: Formal analysis (equal); Writing – original draft (equal); Writing – review & editing (equal). **Carlos Paz-Soldan:** Writing – review & editing (equal). **Brian D. Wirth:** Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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[17] See https://www.nrc.gov/docs/ML1327/ML13274A489.pdf#page=23 for the Atomic Energy Act which sets the laws for use of nuclear energy in the US.

[18] See https://www.cee.org/about-us/history/history for a description of Admiral Rickover's vision of the needed educational excellence needed for the national and global future.