Preface/Editorial for PoP Special Issue

"Private Fusion Research: Opportunities and Challenges in Plasma Science"

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I. Introduction and Motivation

Recent years have seen a dramatic growth in privately funded fusion activities, which, in the US, are now at a scale comparable to the government sponsored program. Work in the private sector has been built on solid foundations laid down by years of publicly funded research but offers the potential to expand the field into new directions with a sharper focus on energy applications. And while the two funding streams that support fusion research share the same underlying scientific principles, it is natural that the private and public sectors will have different perspectives on the challenges and opportunities in plasma science moving forward. This special topic collection explores future directions for our science in light of the expanded research base. The papers in the collection are of the type "Perspectives" which are intended to provide the author's unique views on where the field is headed and promising strategies for progress. We believe that this set of papers can make a significant contribution to an ongoing dialog in the field and will help us take maximum advantage of the opportunities that this new circumstance offers.

II. Scope, Subjects and Themes

Privately financed organizations, which are working toward commercial fusion energy, must address a wide range of scientific, technical, economic and societal issues. In this collection we asked contributors to focus on the subset of those issues most closely aligned with the interests of readers of Physics of Plasmas. These subjects overlap in many ways with major elements of current research programs, though with a notable emphasis on the energy mission. In the request for papers, listed topics included: 1) Validated theory and predictive models with an emphasis on practical tools which can be used for machine design and operation. 2) Experimental research that reduces uncertainties on the path toward commercialization and which guides design and operation of fusion power plants. 3) Measurement systems and control strategies that can be deployed in the high-radiation, high heat flux environment of a fusion power plant. 4) Systems for plasma heating and, if needed for steady-state or high average power devices - current drive, along with fusion compatible antennas or launching structures. 5) Development of mature strategies for prediction, avoidance and mitigation of off-normal events consistent with the

requirements of high reliability and high availability. 6) Development of fusion-compatible materials for device structure and for the plasma-material interface. A succinct summary of plasma research needs can be found in a quote from the 2007 FESAC report [1] "*The state of knowledge must be sufficient for the construction, with high confidence, of a device that permits the creation of sustained plasmas that meet simultaneously, all the conditions required for practical production of fusion energy"*. We note that suggestions and plans for future research which were outlined by contributors to this special topic were consistent with the details of this report and other more recent community planning activities [2,3].

A number of themes emerge from the contributed manuscripts. Perhaps the most significant is the question of which scientific questions and what technology developments are best addressed by privately funded entities and which should be funded by government agencies. Sorting out capabilities, priorities and resource allocation will have a profound impact on the development of the field. Shared use of scientific codes or experimental facilities is an obvious win-win, but will require appropriate "rules of engagement" that protect the interests of private investors and U.S. taxpayers. Another important issue concerns changes in research emphasis driven by the sharper focus and increased urgency for the fusion energy mission. This will require sorting out appropriate roles and areas of emphasis for private and public plasma physics research including the relative influence of a "pull" from industry compared to the scientific and technological push from traditional research institutions. Government agencies will need to revisit policy decisions on funding priorities while considering how these might be best coordinated with private efforts to accelerate overall progress. We can anticipate evolution of those roles as industry efforts mature toward deployment of commercial fusion systems. Related to research opportunities, papers in this Special Topic ask how private fusion efforts can best support the critical areas of student training and workforce development. The entrance of well-funded private fusion companies can be expected to impact the entire fusion ecosystem, including national laboratories and universities. Finally, the papers address, either directly or indirectly, the role of peer review, peer evaluation and scientific journals in a program with both private and public researchers.

III. Brief Summary of contributions

III.A. Opportunities for expanded plasma and fusion science research

III.A.1 Tokamaks

Research on tokamak configurations has been extensive and has achieved plasma conditions close to what is required for commercial exploitation. The tokamak program has benefitted from a broadly based, long-term program with more than 160 experiments built and operated at a wide range of sizes/costs over the last six decades. This diversity of effort allowed new ideas to be developed and tested quickly and cheaply before migrating toward larger facilities. The advent of a large privately funded program offers the possibility of maintaining this approach – with

multiple approaches for device architecture, component design, research focus and organizational approach already evident.

Important scientific questions remain open and have been identified and discussed extensively via coordinated community efforts which included proposals for addressing and closing these issues [1,2,3,4]. Contributors to this special topic have summarized these studies [5,6,7], pointing out that the largest gaps are related to fusion technology and plasma engineering, which have increased salience in a program more strongly directed toward fusion energy. It is worth noting that while, to date, the program has emphasized plasma science, it has not been unaware of the requirements presented by fusion as a practical energy source – considering for example, cost, reliability, safety and regulation. These have often been implicit in the topics chosen for study – looking ahead to solutions that will be practical for future fusion energy systems. However, the entrance of private players is sharpening the focus for ongoing and planned research.

Critical questions and proposed research for plasma science identified by contributors included:

1. Burning plasma physics [5,6,8]: This entails the ability to predict the nonlinear, self-consistent equilibrium state where the main source of heat is from thermalization of fusion alphas and includes the calculation of power sources, classical and anomalous fast-particle losses, MHD stability and mode amplitude driven by superthermal particle populations, along with any effects on underlying micro-turbulence and thermal energy transport [9]. Full modeling of this physics is at or beyond our current capabilities but is crucial for a fusion power source. Early work on TFTR and JET [10,11] along with extensive theory and modeling provide reason for optimism but the matter won't be settled until solid experimental data is available [12]. Tokamak experiments proposed or under construction by the private sector should provide this data [5,8] and inform later experiments on ITER.

2. The interface between the extremely hot plasma and ordinary matter [5,6]: In a fusion power device, much of the critical engineering focuses around issues of thermal management. The most challenging of these issues exists at the boundary between the plasma and the first wall. The goal is to find configurational and operational scenarios that keep damage to the first wall sufficiently low and consistent with an economically viable maintenance schedule and which simultaneously allow a burning core plasma (including sufficient removal of helium ash and other impurities). This area should benefit from public-private collaboration where continued progress in modeling along with ongoing research and exploration on existing devices should complement experiments on high-power burning plasma devices, which will operate in the required regimes.

3. Prediction, avoidance and mitigation of plasma transients [5,6]: The plasma current, which provides the confining magnetic fields in a tokamak, also provides a source of free energy for MHD instabilities and can lead to potentially destructive global disruptions. A great deal of research is focused on predicting the occurrence of these disruptions and

developing strategies to avoid or mitigate their effects [5,6]. At the plasma edge, an analogous mechanism can lead to periodic large Edge Localized Modes (ELMs), which can present unacceptable transient heat loads on the first wall. The search for regimes and operational approaches that combine adequate core energy confinement without large ELMs is also a major research topic and a prime target for public-private collaboration.

4. Plasma control in a diagnostic-poor, high-radiation environment [6]: Progress in the tokamak experimental program has been paced by the development of ever more capable plasma measurement systems. However, because of port access limitations along with the high radiation environment and high thermal loads, many of these diagnostic systems cannot be made compatible with the environment of an operating fusion plasma power plant. Strategies for providing adequate plasma control using only diagnostics that can be fielded on a fusion device need to be developed.

5. Optimization of the tokamak configuration [8,13]: Within the overall configurational envelope that defines a tokamak, options remain. Two of these options are subjects for significant current study – the plasma aspect ratio [14] and the plasma triangularity. Since a fusion power system with enough flexibility to explore the full range of options is not possible, experiments at smaller scale along with comparisons of experiments at fusion scale will be required.

6. Clarification of options for steady-state vs high-averaged-power versions of a tokamak power plant [6]: “Standard” tokamak operation derives its plasma current through the transformer action of external coils. This makes such configurations intrinsically pulsed. Future fusion power systems could operate in a pulsed, high-average power mode if the number of thermal/mechanical cycles can be small enough to be consistent with engineering requirements [15]. Options for steady-state operation are under intense study, requiring plasma regimes that optimize the bootstrap current and an assist from external current drive. The physics, integrated operational challenges and overall impact on energy costs of these two options needs to be evaluated to assess the best path for fusion energy.

7. Development of theory and computational models accurate enough and fast enough to be used in the fusion plant design process: Through development of theory, improvements in algorithms and deployment of larger computers, progress in plasma modeling over recent decades has been impressive. However, a gap has opened up between the most complete models, which can take weeks or months to run and the requirements for fast turn-around required for device design. Approaches employing machine learning and artificial intelligence have begun to emerge which may close this gap [16].

III.A.2 Stellarators

Stellarator research, which dates back to the field's earliest days, is in the midst of a renaissance with the discovery and experimental exploitation of configuration optimization techniques that provide significantly improved confinement and stability [17,18,19]. These techniques attempt, in various ways, to overcome the challenge inherent in a non-axisymmetric magnetic confinement scheme, compared to the tokamak, whose axisymmetry guarantees good confinement via conservation of canonical angular momentum. The various techniques for stellarator optimization specify 3D coils that implement a quasi-symmetry which can theoretically recover the plasma performance required for fusion power. And since the stellarator derives its confining poloidal field via external coils rather than a plasma current, the configuration is intrinsically steady-state and resistant to major disruptions. In overall performance, breadth of experimental research and proximity to commercialization, stellarators are generally viewed as second only to the tokamak. Unsurprisingly, a number of private stellarator fusion companies have been formed with the aim of accelerating commercialization of fusion energy [20].

To achieve this goal, a number of critical scientific and technological issues will need to be addressed. As in the case for tokamaks and some proposed IFE schemes, the existence of a large public research program raises the question about which issues will be addressed by public programs, which by private industry and how partnerships between the two might be structured. Of particular salience for stellarator research is the enormous range of configurations afforded by 3D geometry. This offers an opportunity for further optimization but will also require difficult decisions since the number of potential options if far too large to winnow through trial and error.

Critical plasma science issues include:

1. Collisional particle transport – especially for fusion alphas [21]: The original schemes for stellarator optimization were motivated by the lack of confined orbits in non-optimized designs [17]. While these ideas have been generally successful, it is not possible to achieve complete particle confinement at all radii at once and it is challenging to extend the effects to the ion energies associated with fusion alphas. Theoretical and computational work in this area continues, and needs to be validated against experiments operating in relevant plasma regimes with the appropriate magnetic configuration.
2. MHD driven fast particle transport: As in the tokamak, strongly non-thermal fusion alpha populations that will be present in burning plasmas can drive MHD instabilities, which in turn can expel the fast particles from the plasma. While this issue is being actively studied computationally, the self-consistent nonlinear physics is extraordinarily challenging. Experimental tests will require plasma operating at fusion-power levels of performance.
3. Turbulent transport optimization: An exciting avenue of research for stellarators concerns the pursuit of optimized configurations, which not only confine single particle orbits, but also minimize the level of plasma turbulence [22]. New devices have been proposed to

take advantage of this class of optimization [23]. Experiments in this area have also been recently proposed for W7-X device [24].

4. Heat and particle exhaust including helium ash [21]: All fusion power producing devices will need solutions to the challenge of interfacing ordinary materials to an extremely hot plasma. The 3D geometry of a stellarator presents both challenges and opportunities in this area. A large number of concepts have been proposed [21,25] and experiments on the W7-X device have already begun [26].

Engineering science & technology issues facing the stellarator are generally similar to those for the tokamak and other magnetic confinement devices. However, a few are unique and are worth noting.

1. Coil complexity [21]: To achieve the promise of the optimized stellarator, 3D coils must be fabricated and assembled with significant precision. This challenge has driven the cost and schedule for recent experiments, so efforts are underway to include "simplicity" and "manufacturability" as criteria in the overall optimization schemes. To help control costs by increasing fusion power density, private industry is looking at employing higher field HTS coils in their proposed designs.
2. Coil Shielding [21]: The stellarator magnetic field configuration is composed of high-order multi-poles which fall off rapidly from the 3D coils. As a result, designs may require relatively short distances between the coils and the plasma which imposes a challenge on shielding the superconductors from fusion neutrons and induced gamma rays.
3. Heating systems [21]: Electron cyclotron heating provides an elegant solution for today's generation of experiments. However, many proposed fusion power systems would be built to operate at higher magnetic field in order to increase the power density and lower costs. For that application, a new generation of very high frequency gyrotrons would be required for heating.

III.A.3 Alternate magnetic confinement concepts

Over the years, alternative magnetic confinement fusion (MCF) approaches have been referred to by various names, such as alternates and innovative confinement concepts. This category encompasses fusion approaches outside the mainstream MCF approaches, namely, tokamaks and stellarators. Alternative MCF concepts often offer the potential for lower cost, engineering simplicity, compact design, and other advantages. While having been scientifically pursued for many years, funding levels have remained comparatively lower than mainstream MCF approaches, so that alternative MCF concepts generally have a less mature physics basis compared to the tokamak. Interest increased dramatically over the last decade with the initiation of a series of ARPA-E programs [27], which initially supported concepts with a plasma density

intermediate between mainstream MCF and ICF concepts. Issues identified by contributors included:

1. Importance of numerical modeling for understanding, design, and scaling [29,33]: Whole device simulations are essential for any fusion research. Such modeling becomes even more important as plasma parameters and fusion reaction rates increase, and diagnostic measurements become more difficult. Validated simulation results provide scientific insights and confidence for extrapolating current experimental devices to higher performance. Kinetic plasma models support conclusions about thermal fusion, contributions from non-thermal effects, and ultimately alpha heating.
2. Parallel developments of ancillary technologies needed for an integrated power plant and building an industrial ecosystem [29,30]: A fusion power plant will need many ancillary technologies that are best developed in parallel, so they can be integrated into a unified system. Many of these technologies are common to all fusion schemes. Specific technology gaps mentioned by contributors included high-repetition-rate pulsed power and high-duty-cycle electrodes. Furthermore, viable fusion power needs a strong industrial ecosystem including key component suppliers and utility partners.
3. Possibility of using advanced fusion reactions, e.g. P-B11 [28]: While reducing neutron production compared to hydrogen, the larger effective charge of boron plasmas leads to increased radiative losses in addition to reduced fusion cross sections, which poses challenges to thermal fusion concepts using P-B11. High magnetic fields are suggested as a mechanism to maintain $T_i > T_e$ in some high-beta MCF approaches.
4. Capital cost savings for power plants based on intermediate density, high-beta MCF concepts [28,29]: High-beta MCF concepts offer strong scaling with total current and require smaller plasma volumes, which translate to lower capital costs of an eventual fusion power plant. Costs can be further reduced by emphasizing aneutronic fusion reactions such as P-B11 [28].
5. Critical need for rapid progress towards a viable fusion concept [28,29]: Due to the urgency of anthropogenic climate change, fusion energy must be developed on a timescale relevant to address global concerns by applying industrialized scientific methods to resolve outstanding challenges. Consideration must also be given to determine which approach can achieve a transition to a fusion-based economy fastest and with the least expenditure of resources.

III.A.4 Inertial fusion

Research on inertial confinement fusion (ICF) has been active since the publication by Nuckolls et al. [31] and has continued with significant international investment producing high-quality scientific research. While ICF platforms have contributed to many areas of science, their fusion

application has been primarily directed towards achieving a burning plasma for model validation associated with stockpile stewardship. Nevertheless, energy applications, inertial fusion energy (IFE), have also been pursued. Continued performance increases and the recent demonstration of scientific breakeven on the NIF (National Ignition Facility) [32] have accelerated interest in the possibilities.

Critical topics for plasma science and fusion energy identified by contributors included:

1. Leveraging the scientific breakeven demonstration on the NIF [33]: The experimental demonstration of ignition and gain validated the ICF approach and has catalyzed private and public IFE research, and indeed all fusion research efforts. Challenges remain for target design and fabrication and cost-effective delivery of sufficient energy to the target. Novel laser architectures based on KrF excimer amplifiers may provide a solution by using direct drive to compress targets and requiring lower convergence ratios.
2. Exploiting separation between the fusion plasma and the driver [33]: A key advantage of many ICF concepts is the standoff distance [31] offered by using laser drivers to compress the fusion plasma. The separation offers engineering simplicity of the components of an energy system, for example, first wall, blanket, and shielding, and improves maintainability. Note that similar advantages exist for pulsed power driven alternative MCF concepts, which have a linear plasma geometry and no magnetic field coils.
3. Advanced fusion reactions in IFE [33]: Techniques have been developed for IFE concepts to achieve radiation trapping, thereby mitigating the radiative losses in P-B11 plasmas. Furthermore, the up-scattering of protons by energetic alphas could create a non-thermal energy distribution and a corresponding enhanced fusion reactivity.
4. Developments of ancillary technologies needed for an integrated power plant and building an industrial ecosystem [33]: These technology gaps include energy-efficient lasers and target fabrication. It was noted that both ICF and MCF might benefit from deploying devices with liquid walls as has long been proposed for fusion designs [34,35].

III.A.5 Fusion Technology

While the focus of this special topic concerns the impact of emerging private fusion efforts on the direction of plasma science, many of the contributors took the opportunity to summarize challenges and opportunities in the area of fusion technology. These issues have also been thoroughly catalogued and discussed in community planning reports [1,2,3,4]. To summarize briefly, the issue include:

1. Fuel cycle [7,21,30,33]: A variety of fusion blanket designs have been proposed and studied computationally, however almost no experimental experience or data is yet available. The blanket must serve three crucial functions a) tritium breeding, allowing self-sufficiency of fusion fuel with enough excess to allow rapid deployment of new power plants b) shielding from the intense fusion neutron and gamma radiation of the device's life-time components and c) heat exchange to keep the fusion core within allowable limits while providing power for external use. The designs must be engineered for high reliability, availability and maintainability, must minimize radioactive waste and must not interact unfavorably with the magnetic fields used for plasma containment.

2. First wall design and materials [5,6,21,29,30,33]: The materials and components in direct contact with the plasma need to remove the intense heating and energetic particle bombardment which that entails. Material selection and joining techniques are particularly critical. This area of research concerns not only divertors and limiter structures, which are typically described as "armor" to protect the device's vacuum barrier, but also more complicated launching structures for RF heating and/or current drive. In addition to heat directly from the plasma, these structures must simultaneously withstand severe radiation fluences and must not trap significant quantities of tritium fuel.

3. Structural materials [7,33,36]: All structural materials inside the shielding blankets will be subject to intense radiation. The choice of materials affects the overall design of the plant and has first order impacts on its reliability and availability. A strategy for developing and testing increasingly capable materials will be a key requirement for any significant deployment of fusion power.

4. Magnets [5,8,21,37]: Magnets are a key enabling technology for all magnetic confinement configurations, particularly for tokamaks and stellarators where the magnetic coils are a significant cost and performance driver.

III.A.6 Emerging opportunities for public-private collaboration

With common technical issues as summarized above and the incentives for sharing expertise and other resources, public and private organizations are already starting to work together. Anecdotally, we find that working level scientists express strong interest in these collaborations and actively seek out opportunities – just as they have been accustomed to in the previous era of all-public funding. Several contributors discussed their openness to cooperative work and possible approaches to carrying it out [5,6,8]. Some ongoing work is funded directly by the private fusion companies, who bring on outside experts as consultants or collaborators. It is clear however, that systematic mechanisms for funding this research will be crucial if it is to realize its full potential. A US-DOE program, INFUSE (Innovation Network for Fusion Energy) began a pilot program in 2019, which provided funding for researchers working at US national labs to work in

support of requesting private companies [38]. The companies were required to cost share 20% of the funding in the form of cash, equipment or other in-kind contribution. Recently the program has been opened up for participation by U.S. universities. To help cement this approach in the U.S., the White House convened a summit in March 2022, which focused on "Developing a Bold Decadal Vision for Commercial Fusion Energy" and highlighted the role of the private sector. Most recently, a DOE/SC sponsored workshop on February 29, 2024 was carried out with the aim of developing rules of engagement and plans for regular federal funding opportunities [39]. In the UK, the STEP program [7] will be the nexus for funding and planning for the public activities in partnerships with private industry. Planning for STEP is advancing quite rapidly and is actively building the industrial partnerships that will be required. The pace of such initiatives is increasing. In April, 2023, the Japanese government announced a national strategy for fusion energy industrialization [40] In September 2023, the government of Germany announced plans for an augmented fusion energy program that includes a strong role for the private sector. While these different countries have somewhat different visions for the role and timing of private sector fusion research, it is clear that the corresponding portion of plasma science research will also be impacted by these developments.

III.B Changes anticipated in the fusion ecosystem

All contributors to this special topic agree that science and technology issues remain to be solved and will require sustained and ongoing research in parallel as commercialization proceeds. Examples from other fields and industries were cited as examples that could help guide planning for fusion [36]. The aircraft and rocket industry, for example maintain a keen interest in the science of aerodynamics and propulsion. The same case can be made for fission energy, which gave rise to and continues to motivate a host of nuclear energy departments at research universities.

The roles and responsibilities for the different categories of institutions – private companies, national labs, universities and government agencies will need to be clarified and explored [6,7,36]. Different authors have stressed different models for defining these roles with the U.S. industry favoring a "pull" from industry [5] while the UK [7], Japan and Germany envision a "push" from government labs and agencies. There is general but not universal agreement about the relative strengths that different entities bring to the table – the labs and universities currently being the chief repositories of technical expertise in the underlying science with industry having leading capabilities in engineering, technical-economic analysis and supply chains. But otherwise, there are diverse opinions about where leadership will lie in the future. Outcomes of ongoing work should illuminate and clarify these questions in the next few years. There is also strong agreement on the fundamental need for public-private partnership over the crucial question of regulation. Fortunately, progress is being made in this area in the U.S. [41] and U.K. [7] and frameworks are in discussion under the aegis of the UN IAEA. The role of universities seems likely to evolve as well, with a focus that goes beyond the historical focus on plasma science [36]. In

addition to their role in developing the future workforce, academic expertise in various fields of engineering, finance and economics will likely broaden contributions from that sector. Universities provide a pipeline for new ideas and venture creation. It was noted that almost 60% of the fusion start-ups have their roots in academia compared to less than 20% from national labs [36]. A growing fusion industry should provide strong incentives and new opportunities for employment of university graduates. Overall, the fusion program should look toward adjacent fields for models on how a discipline can respond to the creation of a new industry.

The entrance of significant, privately funded efforts raises a number of issues about how policies and processes will need to adapt to the new ecosystem. Sharing of experimental facilities, supercomputers, data and codes will require "rules of engagement" that protect the interest of taxpayer-funded agencies as well as private fusion investors. We can also expect private fusion companies to act as traditional vendors in supplying public research programs with key components of advanced design. This would allow technology, developed by the private sector, to be shared while protecting intellectual property.

Executing on this vision of a shared research ecosystem raises a number of critical questions. The development of mutually agreeable ground rules, as noted above, will need to precede any large-scale program of collaboration. In the past, with all work funded by governments, the basis for collaborations was bilateral or multilateral agreements. While that may serve as a model, details of such agreements will likely need to significant alteration before they are acceptable for defining private-public partnerships. Key issues include how costs are to be shared and how priorities are to be set. Priority setting would include decisions on the focus of scientific and technical issues, runtime on public and private facilities, upgrades and on new facility starts. One step in this direction has been the initiation of a significant milestone based, "cost share" program between the U.S. Government and private industry. Negotiations on terms for this program were lengthy, but should serve as a model for similar activities in the future.

III.C Approach to publication and other dissemination of research results

It was gratifying to see an agreement from various authors on the need to continue the practice of sharing scientific results through the traditional mechanisms of peered-review publication [6,7,8,42] While protection of IP will be critical to private investors and thus to the health of the nascent fusion industry, historic progress in fusion science has been based on broad sharing of research results since the "great declassification" of 1957. It is important to note that an open stance on publication is essential to provide attractive career paths for early career scientists and engineers. Views differ on the time scale for commercialization, but all parties agree that fusion is an exceptionally hard problem and will require broad and deep efforts. The tension between the need to protect IP while publishing scientific results is perhaps not as intractable as some might have thought. IP and patents apply to human inventions, while scientific research focuses on discovery of underlying natural laws. So, while we can expect some hurdles as the various

institutions try to navigate this space, the current attitudes expressed suggest that there is a strong intention to reach a productive solution. Private companies are already thinking about how to implement a policy that "defaults to openness" [42].

IV. Conclusions

Contributors to this special topic have different views (sometimes dramatically different) on which fusion concepts to pursue and on the readiness and timeline for commercialization. However, all agree that the goal of practical fusion power is compelling and should be a priority for public funding and private investment. The ecosystem that is emerging is feeling its way toward an optimum organizational paradigm with different countries likely to follow different paths. The entrance of the private sector in a serious way, should provide significant opportunities for enhanced plasma science and fusion science research with a long-reaching impact on the entire field.

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