Evaluation of LPPFusion Dense Plasma Focus Research

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Abstract

LPPFusion has made an impressive effort to address DPF physics and engineering issues given the limited number of personnel involved. One point that became clear to the committee was that the LPPFusion program is vastly underfunded and merits a much higher funding level, if it is to make significant progress in the near future.

A distinct feature of the devices is scalability. Smaller and larger devices appear to have similar dynamic characteristics. Nevertheless, relatively few experimental parameters are available for optimizing the configuration and its operation.

Pursuit of the $p^{11}B$ fusion fuel cycle is highly desirable, because that cycle does not directly emit neutrons, which greatly complicate concepts based on other fusion fuel cycles. However, it is well known that the $p^{11}B$ cycle involves extremely difficult plasma physics. In principle the DPF has a number of attractive aspects as a fusion reactor. Included are relative simplicity and small size. However, the margins for error in each aspect are relatively small. The attractiveness of a low power, low capital cost, and a "clean" fusion power reactor system is worthy of continuing the research at a much higher funding level. If greatly expanded funding can be found, significant improvements in diagnostics would be important. Also, a number of other devices could be brought into being to test various parameters, including scaling to net energy

Introduction

At the request of Eric Lerner, LPPFusion President and Chief Scientist, a committee of plasma physicists and fusion technology personnel was assembled to evaluate the LPPFusion program. This review follows a 2013 review by most of the same committee members. Before a formal session with LPPFusion personnel, committee members read and/or reread the LPPFusion patent and peer reviewed journal articles on the Dense Plasma Focus (DPF), the central LPPFusion program. On June 14, 2021 the committee met via Zoom with LPPFusion personnel, heard formal presentations and asked copious questions.

The primary responder was Eric Lerner, who was very knowledgeable and who did not hesitate to acknowledge topics about which he could not properly address. LPPFusion has made an impressive effort to address DPF physics and engineering issues given the limited number of personnel involved. One point that became clear to the committee was that the LPPFusion program is vastly underfunded and in order to make significant progress in the near future, a much higher funding level is required.

The Dense Plasma Focus (DPF) Concept

The LPPFusion approach utilizes the DPF concept to attempt the first laboratory test of $p^{11}B$ ignition. The DPF is a form of plasma pinch in which a capacitor-driven high-voltage pulse is discharged into a low-pressure gas between coaxial cylinders, generating a short duration, hot, high-density, and very high magnetic field plasma. The ease with which DPF devices can be constructed led to numerous experiments driven by capacitors with varying energy.

A distinct feature of the devices is scalability. Smaller and larger devices appear to have similar dynamic characteristics. Analysis of X-ray emissions show internal structure of the plasma with well-defined filamentary structures with electron skin-depth size and intensely radiating small entities. Numerous experiments have been performed using deuterium or a deuterium/nitrogen mixture as a working gas. It was found that the yield of DD fusion neutrons per shot scaled approximately as $Y_n \propto W^2$ with capacitor energy W, but the scaling deteriorated for capacitor energies approaching 1 MJ. It should be noted that values associated with the final plasma, which LPPFusion calls a plasmoid, appear to have densities $\approx 10^{20}$ cm^{-3}, giga gauss (GG) magnetic fields, and ion temperatures ≈150-200 keV.

The DPF approach is characterized by a relatively simple configuration compared to many magnetic fusion energy (MFE) or inertial fusion energy (IFE) concepts. This is somewhat counterbalanced by a relatively few experimental parameters for optimizing the configuration and its operation.

DPF Physics

The physics of the DPF is extremely complicated. While LPPFusion has done an admirable, first-cut analysis of the related physics, much remains to be done to develop a good understanding of the physics and to advance to the point where the physics understanding is fully capable of being a useful predictable vehicle.

The road to ignition using DPF devices involves four steps whose detailed description and related physics can be found in the literature. Briefly, in the first step the current sheath moving through the plasma between electrodes breaks up into an array of filaments. The filamentary current sheath driven by the interaction of its own currents and magnetic field, travels to the end of the anode, where the filaments converge to a single central pinch region. In the second step, this pinch retains the filamentary structure. Each filament has its own kinky shape and evolves in a twisted fashion until it is transformed into a hot spot or plasmoid. In the third step, the hot spot collapses, reaching large values of density and magnetic field. In the fourth step, large axial electric fields are generated at the expense of the energy stored in the plasmoid, resulting in emission of charged particle beams.

Theoretically and diagnostically challenging physics effects play important roles in the DPF: (i) self-organization of the plasma and magnetic field; (ii) very high beta (plasma pressure / magnetic field pressure); and (iii) fusion product effects. The formation of the

DPF final plasmoid proceeds through a series of instabilities within a short time (<10 ns), which makes both diagnosis and external control difficult.

The lack of an advanced theoretical or computational framework, especially for self-organization and beta~1, is not a showstopper, but it does complicate various calculations—including energy transfer, instabilities, and scaling, for example. To the committee's knowledge, no existing plasma physics theoretical or computational tools are capable of definitive analysis of such effects for DPF. However, no other fusion concept can be said to be completely understood either.

Pursuit of the $p^{11}B$ fusion fuel cycle is highly desirable, because that cycle does not directly emit neutrons, which greatly complicate concepts based on other fusion fuel cycles. However, it is well known that the $p^{11}B$ cycle involves extremely difficult plasma physics. We know of only one other U.S. organization pursuing that fuel cycle.

The plasma physics of all fusion concepts is difficult and incomplete. Having said that, the physics understanding of other concepts is far more extensive than for the DPF because many orders of magnitude more effort has been devoted to those concepts.

LPPFusion believes the Quantum Magnetic Field (QMF) effect is important in the DPF. In classical plasmas both fusion power and radiation losses scale as the square of the density, and the power balance depends only on the temperature and the ratio of the fuel concentration making ignition nearly impossible for a plasma in thermal equilibrium. This is because the $p^{11}B$ fusion cross section is appreciable only for temperatures higher than 200 keV. At such temperatures and thermal equilibrium ($T_e=T_i$) the bremsstrahlung losses approximately equal the power generated by fusion. Apart from the apparent insurmountable task of recycling or reflecting the power losses, the only way to overcome this difficulty would be if the plasma was not isothermal and the fuel is burned at high ion and low electron temperature ($T_i>>T_e$). Achieving this "hot ion" mode requires that fusion by-products (alpha particles) dissipate their energy primarily on ions and not on electrons and that ion-electron transfer does not occur too quickly.

An attractive and innovative aspect of the DPF aneutronic fusion is the realization that the electron wavelength is of the order of its gyro-radius, so quantum mechanical effects are important. The angular momentum of the electrons is quantized and can only have discreet levels, known as Landau levels. For the ions with temperature of 300 keV the required magnetic field B must be B>14 GG for protons, B>3 GG for alphas and B>1.3 GG for ^{11}B. The large magnetic fields also affect the Coulomb logarithm reducing the ion-electron collision frequency. The QMF effect has been studied extensively in the case of neutron stars and has been incorporated in their numerical codes. In the DPF, fusion involves reduction of energy transfer from ions to electrons, reduction of bremsstrahlung radiation and preferential heating of ions by the fusion products. In a zero-dimensional model simulation of the $p^{11}B$ fusion, the fusion power exceeded the bremsstrahlung emission by a factor of two, allowing ignition and 80% burn-up of the fuel.

To achieve $p^{11}B$ ignition requires ion temperatures between 300-500 keV. LPPFusion relies on the QMF effect to suppress electron heating and reduce on the bremsstrahlung losses that for isothermal plasmas exceed fusion power at T=200 keV. In addition to suppressing bremsstrahlung, LPPFusion must also eliminate cyclotron radiation by screening it. Given that the value of the magnetic field comes from the QMF requirement, the screening condition will determine the lower value of the density.

These topics may be elucidated by replacing DD fuel with D^3He fuel that, for similar densities and energies to the DD experiments, provides more total fusion energy and 80% of that energy as fusion-product protons with twice the gyroradius of $p^{11}B$, DT, or D^3He fusion-product alpha particles.

Accomplishments Since the 2013 Review

1) With monolithic tungsten electrodes, LPPFusion has increased the confined mean ion energy from 150 keV to over 250 keV. This is currently the highest confined ion energy of any fusion device.

2) Operating with a deuterium-nitrogen mixture in their two experimental devices, LPPFusion has increased the fusion yield per shot peak to 0.25 J with the same input energy of 60 kJ. This is an important demonstration that DPF operates more efficiently with heavy elements.

3) Using beryllium electrodes, LPPFusion achieved the highest purity plasma reported in any fusion experiment.

4) In their upgraded device, LPPFusion produced regularly spaced tight filaments at the start of the pulse. Their failure to reach high density and I^4 scaling was attributed to current oscillations that increased when changing from tungsten to beryllium electrodes. The committee was told that circuit changes to minimize this problem are to be tested soon.

DPF As a Fusion Reactor

In principle the DPF has a number of attractive aspects as a fusion reactor. Included are relative simplicity and small size. However, as Lerner recognized many years ago in his patent, the margins for error in each aspect of the DPF are relatively small. Lerner calls for direct energy conversion of particle streams, for which techniques have been studied previously and may be thought of as reasonable. However, a significant output from the plasmoid will be in the form of x-ray bremsstrahlung, which Lerner postulates might be efficiently converted to electric power in an innovate converter. To our knowledge, no serious analysis or related experiments have been performed on this important concept.

Because the $p^{11}B$ fusion cycle emits three alpha particles per reaction, in-vessel components near the plasmoid will be subjected to immense fluxes of energetic helium ions. It has been shown that surface damage from such bombardment will be severe and could limit the lifetime of such components to short operational times. LPPFusion will not be able to solve those problems without very large related funding, so it may be advantageous to collaborate with ORNL, who will be addressing those problems for divertors in toroidal systems.

Effort will be needed to address the unique technology issues to be faced with a $p^{11}B$ fusion fuel in a pulsed system. Fatigue lifetimes for in-vessel components must be addressed to show that reasonable capacity values (>80-90%) could be achieved in power plants. This is an area that may require collaboration with the fusion community at large.

Conclusions & Recommendations

The attractiveness of a low power, low capital cost, and “clean” fusion power reactor system is worthy of continuing the research at a much higher funding level.

LPPFusion might examine fusion fuels other than $p^{11}B$ for demonstrating net energy yield, particularly DT fuel. Getting $p^{11}B$ fuel to an acceptable value of fusion Q (total fusion energy / total input energy) requires that the electron temperature be much less than the ion temperature (Te << Ti). This hinges on a quantum magnetic field (QMF) effect that is used in astrophysics but has not been verified in the laboratory.

Direct electrostatic energy conversion of a directed beam of ions was demonstrated at LLNL in the 1970s at high efficiencies, but fusion products will be born isotopically and thus in the DPF will have a large fraction of their energy transverse to the beam, which will appear on the direct converter electrodes as heat, rather than the desired conversion of directed kinetic energy into the electronic circuit. The inductive electric field associated with the decay of the plasmoid when the synchrotron frequency exceeds twice the plasma frequency might convert the isotropically generated fusion products to directed beams. While such beams have been observed in DPF the timing and efficiency of acceleration has not been demonstrated in LPPFusion experiments.

Bremsstrahlung radiation x-rays will have an energy spectrum up to the energy of the electrons creating it. LPPFusion has put forth a novel, multi-layer, solid-state direct conversion concept that should be tested experimentally. The market for such a conversion concept could be significant beyond the DPF application.

If greatly expanded funding can be found, significant improvements in diagnostics would be important. Also, a number of other devices could be brought into being to test various parameters, including scaling to net energy.

It is essential that at some point electrodes must be tested to determine if they will have economically viable lifetimes. A repetition rate of 200 Hz equates to ~6 x 10^9 cycles per year, so frequent changeout will probably be required.

LPPFusion might want to consider the DOE INFUSE program of industry/national lab cooperation for providing help with diagnostics for LPPFusion PDF devices. Considerable pulsed-power diagnostic expertise and instrumentation exists at LANL, SNL, and LLNL. National Lab budgets cover the Lab part of the research. Industry must provide 20% matching effort.

A small effort might be directed toward addressing non-electric applications to gain some credibility with investors and DOE. Both “spin off” and non-electricity producing applications might be explored.

Finally for greater or better clarity in presentations, LPPFusion might create figures illustrating the geometry and key aspects of the physics for the evolution of the plasmoid inside the apparatus, especially the details of the final state, would help explain some features of the analysis.

Brief bios of the Review Committee Members

Dr. Robert L. Hirsch, Committee Chairman

- Senior Energy Advisor, Management Information Services, Inc. (MISI) and consultant in energy technologies, 2007-present.
- Consultant in chemical analysis automation and world oil production, 1995-2007
- VP Electric Power Research Institute, 1991-1994.
- VP for Exploration and Production Research, ARCO, 1980-1991
- General Manager, Exxon Research and Engineering, 1977-1984.
- Director fusion research, USAEC & ERDA, 1972-1976

Dr. John Santarius

- Associate Director for Alternate Applications and Concepts, Fusion Technology Institute, University of Wisconsin-Madison, 2005-present.
- Research Professor, Engineering Physics Department, University of Wisconsin-Madison, 2004-2016; Emeritus, Aug 2016-present. (Asst., Assoc., Senior) Scientist, University of Wisconsin-Madison, 1979-2003.I
- EEE Fusion Technology Standing Committee, 2000-2011.
- Excellence in Fusion Engineering award, Fusion Power Associates, 1991.
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Dr. Gerald L. Kulcinski

- Grainger Professor of Nuclear Engineering-Emeritus. He was the Director of the Fusion Technology Institute at the University of Wisconsin-Madison 1973-2014, and Associate Dean of Research for the College of Engineering from 2001 to 2014.
- Member of the National Academy of Engineering and served as a chair, co-chair, or member of six Academy study committees.
- Awards include the NASA Public Service Medal, the NASA Exceptional Public Service Medal, and fellowship in the American Nuclear Society.
- Served on the NASA Advisory Council from 2005-2009 and the Advisory Committee for the Department of Commerce on Emerging Technology from 2008-2018.

Prof. Dennis Papadopoulos

- Professor Emeritus, Department of Physics, University of Maryland
- Research Professor, Department of Astronomy, University of Maryland, College Park – 2020-present
- Co-Director East-West Space Science Center, University of Maryland, College Park
- Senior scientist and division consultant, Plasma Physics Division, Naval Research Laboratory - 1969-1979
- Science Advisor, Applied Physics Division, Office of Fusion Energy, DOE, 1978.
- Fellow of American Physical Society (1975) & of The Washington Academy of Science (1978)