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Editorial

Advances in the Study of Laser-Driven Proton-Boron Fusion

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The topic of proton-boron fusion has recently attracted considerable interest in the scientific community, both for its future perspectives for energy production and for nearer-term possibilities to realize high-brightness α-particle sources. Very interesting experimental results have been obtained, in particular in laser-driven experiments but also using other experimental approaches. The goal of this special issue is to collect the most recent developments in experiments, theory, advanced targetry, diagnostics, and numerical simulation codes.

Fusion energy represents the most promising scientific and technology option for a long-term sustainable energy solution for mankind. It will also help meet the decarbonization targets for the second half of the century. The conventional route to fusion for power generation is based on the deuterium-tritium (DT) reaction, which yields one α-particle and one neutron and releases a total energy of 17.6 MeV. Worldwide research focuses on magnetic or inertial confinement of DT fuel. These approaches show the highest potential to demonstrate net energy gain, due also to the fact that DT fuel has the highest thermal reactivity among all possible fusion fuels at relatively low temperatures. Significant progress continues being made in both magnetic and inertial DT fusion. In August 2021, 1.3 MJ of fusion energy was obtained at the National Ignition Facility in the U.S. by irradiating a DT capsule with 1.8 MJ of laser energy, a result very close to breakeven [1–3]. Later, in December 2022, the laser energy was increased to 2.1 MJ allowing to obtain 3 MJ of fusion energy [4]. This corresponds to a gain of 1.5: the first result in history beyond breakeven and the first to demonstrate net energy gain. On the side of magnetic confinement fusion, in December 2021, a total fusion energy of 59 MJ was obtained at the tokamak JET (Joint European Torus) based in Culham, UK, more than doubling JET's 1997 record [5].

While DT fusion appears to be the most scientifically mature approach to build a fusion power plant by mid-century [6], it also faces severe physics and engineering challenges which are very likely to increase costs, complicate regulations, and hinder public acceptance and economic viability. We recall, here, tritium's initial availability (production), breeding, and on-site management, as well as the radiation damage and activation induced by the high-energy neutrons in reactor materials. These challenges motivate the continued pursuit of alternative approaches which may simplify the pathway to commercial fusion energy.

Proton-boron (pB) fusion has long been seen as the holy grail of fusion energy [7]. Indeed, the reaction ($p + {}^{11}B \longrightarrow 3\alpha + 8.7$ Mev) does not produce neutrons. Although some neutrons are produced by secondary reactions, the total neutron yield remains negligible with respect to future fusion reactors based on DT reaction or to power plants using nuclear fission of uranium. This implies little activation of materials and hence a very low amount of radioactive waste. In addition, the reaction involves only abundant and stable isotopes in the reactants, avoiding breeding, radiation protection, and security issues related to tritium. This makes pB fusion a clean and environmentally acceptable technology. Furthermore, the reaction produces only charged particles (3α-particles per fusion event), with the potential advantage of allowing direct energy conversion, without passing through a thermodynamic cycle. This might dramatically enhance the efficiency of electricity generation.

However, the hydrogen-boron fusion plasma requires unpractical temperatures to be thermodynamically ignited and sustained in the laboratory, which explains why pB fusion has been left, from a historical perspective, as a future step after the achievement of DT fusion.

Following the discovery of the laser in the 1960s, Heinrich Hora, now Emeritus Professor at the University of New South Wales, pursued an alternative means to realize the proton-boron fusion reaction from the 1970s [8].

Hora's work included computer hydrodynamic simulations applied to plasmas [7] which suggested that the acceleration of a plasma front irradiated by a short-pulse (100 ps) laser pulse could reach extremely high values, potentially enough to achieve energies required for fusion. This finding was practically simultaneous to the discovery of chirped pulse laser amplification and the modern understanding of laser ion acceleration mechanisms. A more complete summary of this history is given in [10].

In the last decade, several experiments demonstrated high yields in α-particle production [11–14], thus reviving the interest in pB fusion amongst many research groups and also bringing to the creation of private companies working on the topic, as it is the case of the company HB11 Energy Holdings (Sydney, Australia) founded by Prof Hora himself [15].

These experiments used high-energy short-pulse lasers and produced up to 10^{11} α-particles per shot [16, 17] and additionally provided the evidence of a few-MeV boost in their kinetic energy, an effect allowed by the kinematics of the fusion reaction [18]. Indeed, these lasers can produce highly energetic protons that can directly transfer part of their energy to the reaction products. This opens the possibility of inducing reactions which are useful, for instance, to produce radioisotopes for medical therapeutics or imaging.

Although interesting, all current results remain far from energy breakeven, which corresponds to about $2 \times 10^{15}\alpha$-particles generated per shot per kJ laser energy. Achieving breakeven and gain might rely on the possibility of departing from the thermal equilibrium of classical inertial confinement schemes and initiating a fusion avalanche (or chain) reaction [19].

Following these latest developments, this special issue aims at collating original research and review articles with a focus on the mechanism of pB fusion in laser-produced plasmas, the possible implications for future energy production, and the possibility of developing high-brightness α-particle sources for applications such as the production of medical radioisotopes. The special issue is composed of a balanced selection of articles, encompassing a broad spectrum of topics, including in particular

(i) Recent results in laser-driven proton-boron fusion experiments

(ii) The onset of avalanche processes in H-^{11}B fuel and the quest for breakeven

(iii) Measurements of cross section of the proton-boron fusion reaction

(iv) Developments in diagnostics for proton-boron fusion experiments

(v) Hybrid approaches (thermal/nonthermal) to proton-boron fusion for energy production

(vi) Proton-boron fusion in nonlaser systems (e.g., vacuum discharges)

(vii) Advanced targetry for laser-driven proton-boron experiments.

It is worth noticing how wide is the geographical distribution of the contributors to this special issue (Europe, US, China, Australia, and Russia), which shows how nowadays pB fusion is an active research topic spreading worldwide.

This special issue was inspired by a series of on-line seminars (2021-2022) [20] promoted by HB11 energy to map the state of the art of pB fusion research. Some of the articles refer to work presented in that series of seminars.

We shall emphasize that the results reported in the special issue and elsewhere in the last two decades are not part of a coordinated research program. Unlike fusion studies based on DT, pB fusion research remains the initiative of single research groups mainly based in university and academia. We hope that our editorial initiative will establish a foundation for the systematic investigation of possible ignition schemes by consolidating research efforts in laser-driven pB fusion to date. We also hope that it will help building and strengthening the cooperation in the field as it evolves.

Looking forward, a European Union COST program has been granted to support the development of the community studying proton-boron fusion: PROBONO (CA21128-proton-boron nuclear fusion: from energy production to medical applications) [21]. This program represents the first attempt to coordinate the research effort across European countries (and several extra-European partners) on pB research. We also call for additional and more systematic support in terms of funding opportunities (both public and private) and policy recognition in order to further develop this research field and the related international cooperation in the near future.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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