Journal of Fusion Energy (2023) 42:17
https://doi.org/10.1007/s10894-023-00349-9

REVIEW

HB11—Understanding Hydrogen-Boron Fusion as a New Clean Energy Source

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Accepted: 31 March 2023 /

Abstract

HB11 Energy's mission is to realize large-scale electricity generation from the fusion of hydrogen with boron-11 (the HB11, or "proton-boron", reaction) without the environmental problems normally associated with nuclear energy. A non-thermal approach is taken in the initiation of the reaction using high-peak-power lasers, which was the pursuit of HB11 Energy founder Prof. Heinrich Hora's career as a theoretical physicist. In the 1980s, the invention of Chirped Pulse Amplification (CPA) of laser pulses by Donna Strickland and Gerard Mourou (Nobel Prize 2018) enabled the possibility of experimentally validating the earlier theoretical predictions. Several experimental demonstrations of the HB11 reaction using CPA lasers inspired the establishment of HB11 Energy and with it, the possibility of realizing an aneutronic nuclear energy source with easily accessible and safe fuel resources that could last thousands of years. Like all quests for fusion energy, there are significant scientific challenges remaining. HB11 Energy Holdings Pty Ltd, an Australian company, was established as the best vehicle to co-ordinate a global collaborative research effort to address these challenges and build capacity to host large-scale public private partnerships, such as those now recommended by the US National Academies of Science, Engineering and Medicine (NASEM) (US National Academies of Sciences, Engineering and Medicine in Bringing Fusion to the U.S. Grid,: National Academies Press, Washington, D.C, 2021). If net-energy-gain can be achieved through HB11 Energy's concepts, there are many engineering benefits over traditional DT fusion that will see a dramatically simpler and safer reactor being produced. A technoeconomic assessment of such a reactor is also discussed which presents many engineering challenges that will need to be met before commercial HB11 fusion can be deployed on a large-scale.

Keywords HB11 · Hydrogen boron fusion · Nuclear reactions · High-intensity lasers · Energy production · Non-thermal fusion

Introduction

The hydrogen-boron 11 (HB11), also known as proton-boron, fusion reaction is a most promising candidate for large-scale energy production in a bid to curb the future use of climate-impacting fossil fuels. As a nuclear process, it presents an energy density approximately seven orders of magnitude higher than chemical reactions and with an aneutronic primary reaction, it does not induce activation in materials, leading to negligible radioactive waste. In this reaction, three alpha-particles and 8.7 MeV of energy are produced.

$$^{1}p + {}^{11}B \rightarrow 3{}^{4}He^{+} + 8.7MeV$$

In principle, this enables the direct conversion of the kinetic energy of such charged particles into electricity, rather than through a thermal cycle. Furthermore, the primary fuel, boron, is abundant in nature with the world's largest known mine estimated to contain $\sim$ 1.2 billion metric tons of boron, of which 80% is the required isotope (boron-11).

As compared to classical deuterium–tritium (DT) fuel, boron targets have the advantage of being in a solid state at

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Extended author information available on the last page of the article room temperature, removing the need for cryogenics. This would be an important point for inertial confinement fusion (ICF) schemes, especially when moving to high repetition rate operations. Also, the cost of the targets is likely to be much less since they do not involve the presence of a radioactive isotope such as tritium, which must be produced (“*tritium breeding*”) and recovered (burn-up fractions in DT fusion reactor concepts range for a few percent to $\sim$ 30%), is hazardous, and cannot be stored for long periods of time.

Despite these advantages, relatively little attention has been given to the study of hydrogen-boron fusion. The reason for this lies in the reactivity of HB11 fuel, which indicates that the temperatures required to achieve a fusion burn are of an order of magnitude higher than for DT fuel and far exceed 100 MK (10 keV) [1]. Radiative losses are also larger compared with DT reactions, due to the higher charge (atomic number of 5). Accordingly, the authors of earlier work held a rather pessimistic evaluation of the prospects of this fuel for energy generation [1–5].

Significantly, this difficulty was addressed through the extensive study and development of non-thermal methods for hydrogen-boron fusion [6–8]. Such non-thermal approaches, coupled with the continuing improvement in ultra-high intensity lasers and the recent experimental results (detailed below), inspired the establishment of HB11 Energy Holdings. The enterprise is focused on accelerating scientific and engineering development in laser boron fusion towards net-energy gain. The final aim is to realize the urgent demand for a new large-scale energy source in the face of climate change. If the quest to achieve HB11 net-energy-gain is realized, it will present a promising and attractive prospect for a new clean-energy source.

This paper outlines some of the early history of HB11 fusion, including the basic history of Prof. Hora’s theoretical work and the initial target concept that inspired the establishment of HB11 Energy. The subsequent sections cover more recent experimental demonstrations of proton boron fusion, and the approaches presently under investigation to increase reaction rates towards net-energy-gain. Finally, a high-level summary of HB11 Energy’s techno-economic model is provided outlining key implications in reactor design on the type and final cost-of energy that it produces, and key engineering milestones required for the large-scale deployment of hydrogen-boron fusion.

History and Recent Results

The hydrogen-boron fusion reaction was discovered by Oliphant and Rutherford in 1933 [9]. Shortly after the discovery and early development of the laser in 1960s, hydrogen-boron has been considered as a fuel for laser fusion. [10].

The application of lasers to drive hydrogen-boron fusion was pursued by Prof. Hora from the 1970s [11–13]. An outcome of this work was that conditions required to meet the triple product threshold for proton-boron fusion were too extreme to be practical by thermal means.

During this decade some of the earliest hydrodynamic computer calculations for plasmas were performed [15, p. 182]. A simulation in 1978 suggested that the acceleration of a plasma front against the direction of a short ($100ps$) laser pulse could reach an extremely high value, $10^{12} cms^{-2}$. Accordingly, “plasma-block acceleration” was considered as a possible key to accelerating ions to the energies required for fusion—a non-thermal alternative to achieve fusion. Decades later, experimental results obtained by Sauerbrey (1996) [14] seemed to confirm such high accelerations in the plasma by measuring doppler-shifted spectral lines.

Over the same decade (1990s), the developments in chirped pulse laser amplification (CPA), including the first companies making such systems commercially available, led many labs around the world to pursue experimental research programs bringing to a deeper understanding of laser-ion acceleration mechanisms. The ability to accelerate particles, including protons, to energies more than 10 MeV– not possible with thermal mechanisms—became commonplace. A more complete summary of this history and these developments are given in a book [15].

These developments led to the first experimental demonstrations of non-thermal hydrogen-boron fusion, the first of which was performed by Belyaev et al., in 2005 [16], followed by many others [17]. The progression of obtained experimental results was summarized in [18] and given in Fig. 1.

Remarkably, so called “pitcher-catcher” concept [19] was introduced and studied experimentally. In this concept protons were accelerated in thin foil targets (“pitchers”) through the mechanism known as TNSA (Target Normal Sheath Acceleration) [20–24]. The protons from the pitcher were then impinging a secondary boron (or more commonly boron nitride) target (“catcher”) to produce energetic α-particles. This non-thermal fusion is also known as “beam fusion” because of its similarity with what takes place when an energetic proton beam (produced by a particle accelerator) is directed onto a solid boron target. The difference in acceleration mechanism results in protons with a larger energy spectrum in TNSA compared with direct proton beam irradiation. As for conversion efficiency between laser energy and proton generation this is typically around 10% [25].

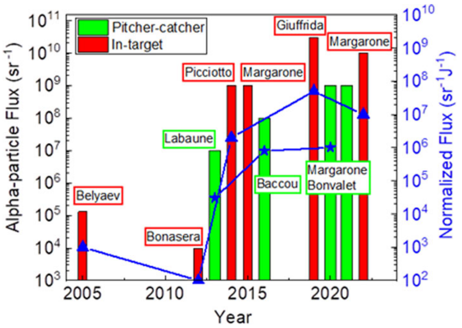

Fig. 1 Progress of experimental results on laser-driven proton-boron fusion. Over two decades the flux of alpha-particles achieved from proton-boron reactions increased 5 orders of magnitude for in-target configuration, which all show better performance than pitcher-catcher approach [18]

Other experiments used a different approach, directly irradiating the boron target (eventually enriched in hydrogen) with the laser. In this “in-target” scheme, protons are accelerated by different mechanisms including hole boring and radiation pressure acceleration [26, 27].

The number of fusion reactions achieved through this approach has been impressively high, with the highest reported α particle flux on the order of $10^{11}[sr^{-1}]$ from two key results. The first was from [28] using a nanosecond laser PALS at ELI Beamlines, Prague. The second was a high-energy high-intensity picosecond laser pulse produced by the LFEX system at Osaka University in Japan [18]. With an average energy of $\sim$ 3 MeV, an α particle flux of 10^{11} corresponds to a total energy of about $0.1J$. Since LFEX delivered an energy on target of the order of $1kJ$, the fusion-to-laser energy efficiency is about 0.01%, 4 orders of magnitude below “breakeven”, the point at which the energy produced by fusion reactions equals the driver energy (the input energy from the laser pulse). While this difference is significant, the history of fusion shows how progress of many orders of magnitude is possible with a focused research program.

Pathways to Increase Fusion Gain

The current record in α particle generation using short-pulse lasers ($\approx 10^{11}$ α particles per shot) has been obtained at the LFEX kJ laser in an experiment supported by HB11. The “breakeven” threshold corresponds to 2.15×10^{15} α particles per kJ of laser energy, corroborating the four orders of magnitude deficit from breakeven. This is indeed a challenge considering only 10 experimental demonstrations of hydrogen-boron fusion using lasers have been made. This leaves many opportunities to increase fusion reaction rates in the quest towards net-energy-gain, as is discussed in the following subsections.

The application of magnetic fields This option permits the possibility for spatial confinement of the plasma, the accelerated protons and the generated alpha particles. In this approach, the second laser of ns or ps duration irradiates a specifically designed conducting capacitor-coil target. The laser pulse ejects hot electrons from one part of the capacitor charging the second part. The potential difference drives an electric current in the U-turn-shape coil creating a sub-kT magnetic field inside the loop, lasting for several nanoseconds [29]. Then, a cylindrical target could be used, with its axis parallel to the direction of the magnetic field which will create a flux of protons and α-particles through the cylinder, as shown in Fig. 2. Therefore, instead of being dispersed in space, the flux of protons and bulk plasma containing boron will be confined, increasing the reaction rate but also producing more localized heating of the sample. This is the basis of HB11 Energy’s initial reactor concept where laser 1 accelerates ions through the cylindrical target (purple) to initiate the non-thermal fusion reaction while laser 2 applies a magnetic field pulse through the capacitive coil (yellow) [29–31].

Quantitatively, the desired laser parameters, and corresponding anticipated B-field strength, proton beam energy and flux were estimated in [32]. Considering the maximum cross section is found to be above 600 keV the required proton number of 10^{11} is estimated. It is shown that a 1 ps laser pulse of 30 kJ (30 PW) energy focused into a 200 µm spot and delivering 10^{20} W/cm^2 optical field intensity will be required for direct drive ignition. The ignition is predicted to occur in a HB11 cylinder of 1 cm length and 2 mm diameter being thermally isolated and confined by a 10 kT magnetic field generated by the capacitor-coil target irradiated with 3 kJ ns laser pulse.

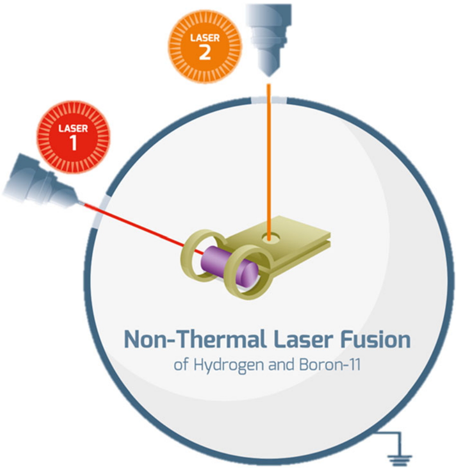

Fig. 2 HB11 Energy’s original concept considering two lasers—to generate fast proton and alpha-particle flux, and to confine the flux by means of a strong magnetic field initiated in a laser-irradiated conductive coil. Several target designs are being developed by HB11 Energy [31]

Reducing the Radiation Losses due to bremsstrahlung emission is another key challenge to increase reaction rates. Due to the high Z-number (Z = 5) of boron, such losses are more severe than in the case of DT fusion. A simple way to reduce such losses would be to use a material which contains more hydrogen than boron, as proposed by Belloni [33]. Such a material composition is more favorable also in view of triggering a chain reaction because it would increase the probability that the generated α-particle collides with a light proton as compared to a heavy boron, which cannot be effectively accelerated to energies capable of triggering further fusion reactions. Also, in the context of laser-driven proton-boron fusion, target designs with layers that trap radiation to reduce losses are being considered (c.f. Dewald [34]).

Non-Equilibrium Plasma where the electron temperature T_e is different from the ion temperature ($T_e < T_i$) may offer an avenue to increase reaction gains by minimizing electron collisions and radiative losses while increasing the ion reaction rates [10]. The more recent work by Wurzel & Hsu [35] states that bremsstrahlung power density always exceed the power density generated by fusion reaction when $T_e \geq T_i/3$ suggesting that $p - {}^{11}B$ ignition may require a non-equilibrium burn.

Degenerate Plasmas Another important issue concerns the effect of elastic collisions of suprathermal protons in the target. Such collisions are much more probable than nuclear collisions which leads to the protons losing most of their energy to electrons before having a chance to initiate a fusion reaction. Hence, we'd like to reduce the electron density in the plasma creating a non-neutral plasma. Techniques exist to address this for low plasma densities (namely by using Penning Malmberg traps), but the low density implies a very small number of fusion reactions. A more promising approach for fusion energy applications considers plasma degeneracy as an effective way to inhibit energy losses due to elastic collisions in high density plasmas. In degenerate matter, electrons occupy all available energy levels up to the Fermi energy. This inhibits all collisions characterized by an energy exchange below the Fermi level. To receive such energy, electrons would need to move up to an energy level which is already occupied by other electrons, which is prevented by Pauli's exclusion principle.

Degenerate plasmas are already typical of today's implosion experiments using DT cryogenic targets which result in the production of a classical plasma hot-spot surrounded by a dense degenerate fuel. However, the extent to which the degeneracy of the material can be used to moderate elastic scattering is a complex point demanding active research. HB11 Energy is developing studies on degeneracy effects extending the theoretical considerations in [33].

Target Geometry Another approach concerns the geometry of the targets which can be optimized to improve the efficiency of the laser interaction. Strategies range from micro- and nano-structured targets increasing laser absorption, to near-surface density profile, such as has been described in [36].

*Novel Target Material*s Most of today's experiments have been realized using boron-nitride targets, in which hydrogen was contained only as impurities, estimated less than 1% of the target composition. HB11 Energy is exploring novel target materials containing significantly more hydrogen than traditional boron-nitride targets by utilizing novel micro and nano structures. Candidates include the two-dimensional material "white graphene", with surface modifications allowing their use as a hydrogen-storage material, and another two-dimensional material borophene, which contains only hydrogen and boron [37]. Beyond composition, these materials allow target fabrication using solution-based methods that are amenable to large-scale manufacturing. A paper including the first demonstrations of proton-boron fusion using white graphene is in preparation.

The *"Avalanche Mechanism"* describes the process whereby the generated energetic α-particles undergo elastic collisions with bound protons, accelerating them and promoting further proton-boron fusion reactions. It was first proposed as an explanation for the unusually high reaction rates seen in experiments [38, 39]. While it has been the subject of debate [40] it has also been considered as one the most promising single approaches to significantly increase gain and was the subject of the first proposed scheme of a laser-driven HB11 reactor [30, 38].

To optimize a target concept to exploit gains from the avalanche process a deeper theoretical understanding is being explored by HB11 Energy. Points being addressed include an extension of the work by Belloni [33] to higher ion temperatures, to degenerate plasmas, and towards more refined kinetic approaches, for example via the Boltzmann-Fokker–Planck equation. It is also important to calculate the so-called *energy multiplication factor* [10] for laser-accelerated proton-streams in fast-ignition type approaches, taking into account both in-flight fusion reactions and suprathermal multiplication of the fusion products. Concerning the latter effect, the kinematic boost induced on the α-particles by the impinging protons is particularly relevant. The recent result from LFEX [18] also showed that α-particles with much larger energies than produced from the fusion reaction were generated and detected due to the direct energy transfer from accelerated protons to fusion products. This suggests yet another possibility to increase particle energies that could enhance the avalanche mechanism.

Hybrid Burn A fast-ignition-like approach is being investigated by HB11 Energy to increase fusion reaction rates by combining non-thermal mechanisms listed above with a traditional thermonuclear burn [41, 42]. While this approach would represent a considerably more capital-intensive investment, the prospects for further increases in gain may provide the economic justification for its pursuit.

Thermonuclear fusion reaction rates scale with the square of the ion density, so conventional ICF schemes require significant compression to minimize the energy required to ignite the fuel. Current laser-driven proton-boron experiments have all used uncompressed targets.

The "Hybrid burn" approach combines an inertial confinement scheme including elements of thermonuclear burn and of proton-driven fast ignition. Fast ignition decouples the implosion from the generation of the initiating spark, thereby relaxing some of the requirements on implosion symmetry. Here, the idea is to implode a hydrogen-boron target and around the stagnation time inject a beam of energetic protons generated by using a short-pulse high-intensity laser as in proton-driven fast-ignition [43]. The key difference is that in proton-driven fast-ignition the laser-accelerated protons serve only to produce local heating of the fuel to the temperatures needed to trigger DT fusion reactions. Here, instead, not only do the protons contribute to fuel heating, but they *directly* induce fusion reactions. HB11 is investigating a target concept where these effects can locally heat a section of the target into the "Hybrid" temperature range indicated in Fig. 3, where the average of the cross section of the fusion reaction over the assumed Maxwellian velocity distribution of protons and boron at the given kinetic temperature is shown [44].

3.1 Research Challenges

Relative to DT the field of laser-driven proton-boron fusion is young. Consequently, there are several research challenges to be addressed by the research that will be instrumental in accelerating progress in the field.

Material Properties One basic element which is still not precisely known, despite the discovery of HB11 fusion almost 90 years ago, is the precise behavior of proton boron fusion cross-section. Classical data on the proton-boron cross section by Nevins & Swain [4] has been more recently revisited by Sikora and Weller [45] who found higher cross sections in the range of $10MeV$. Still, the exact shape of the cross section at energies below a few hundred keV and for energies $> 3MeV$ is not known. Presently, several experiments are being planned to fill these gaps the results of which will be critical to developing the models used to simulate laser-driven proton-boron fusion experiments. Similarly, an understanding of the equation of state and opacities of boron under extreme conditions will be another critical requirement for accurate simulations, particularly under compression as proposed for the "Hybrid Burn".

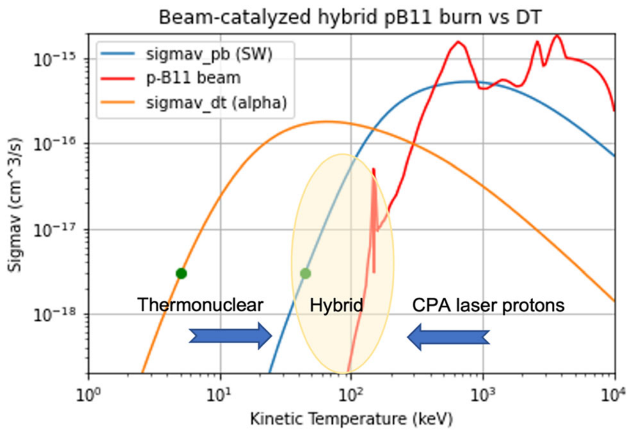

Fig. 3 Maxwellian-averaged fusion reactivity for thermonuclear deuterium–tritium (orange) and proton-boron (blue), as well as beam-driven proton-boron (red), as reported in [44]. Cross-section data is taken from [45]. The label "Hybrid" refers to the region of reactivity burn space within the yellow oval. In this region heating from CPA-laser-produced proton deposition and inflight fusion reactions can create a non-equilibrium component of burn that enhances the thermonuclear burn that would be produced in equilibrium. The green dot on the DT reactivity denotes the ideal ignition temperature and the green dot on the p-B11 curve indicates the temperature for equivalent reactivities

Simulations Many experiments in the field have focused on pitcher-catcher target configurations and demonstrated quite advanced results. Experimental results have been simulated through a chain of different codes: (1) Hydrodynamic codes [46] to simulate the effects induced by the laser pre-pulse and predict the extension of the pre-plasma. (2) PIC [47] and QED-PIC [48] codes to simulate the interaction of the laser beam with the pitcher and the generation of the beams of energetic protons. (3) Monte Carlo codes (e.g. GEANT4 [49], FLUKA [50, 51]) to simulate the interaction of the protons beams with the boron target and predict proton propagation, collisions, fusion reactions, propagation of reaction products etc.

Our understanding of direct irradiation experiments is far less advanced. Energetic protons are produced on the target front side by complex non-linear mechanisms such as hole boring [52]. In principle these can be simulated by using PIC codes, however they usually do not include fusion reactions (especially $p -^{11} B$ fusion reactions). Additionally performing 3D simulations including collisions, with realistic plasma densities and with realistic space and time scale presents severe limitations on accuracy and computation time. When a thick target is used, it becomes practically impossible to do a complete simulation using PIC codes.

One possible approach to address these challenges is to realize a close coupling of PIC to Monte Carlo codes, using PIC codes for a description of the source and the MC code to describe the propagation of hot electrons and energetic ions. However, we need to introduce the cross sections for the fusion reactions in the PIC codes and include a description of the plasma state in the MC code [53]. In parallel, the HB11 team is collaborating with Voss scientific to use the Chicago simulation code whose hybrid binary and Fokker–Planck collision operators enables a realistic model of the fusion plasma [54]. The charged particle interactions are modeled with an accurate binary fusion algorithm [55]. The details of the $p - ^{11}B$ reaction including fusion product distributions are currently available in Chicago. They have also recently been implemented in versions of the open-source PIC code SMILEI [56].

Beyond these efforts, there is a more general need for accurate simulations of proton-boron fusion experiments, combining all aspects of laser interactions, plasmas and nuclear reactions. These simulations will be an indispensable tool to access non-measured data, complete our understanding of experiments, and optimize target designs that will maximize gain.

Diagnostics Improvements in diagnostics are needed to obtain more effective and efficient data collection from experiments. Current experiments are mainly based on CR39 track detectors, which is extremely time-consuming and for which the interpretation of experimental results is always difficult (α-particles being a minor component with respect to laser-accelerated protons and ions). Thomson parabolas are used to measure protons and ions, however it's difficult to detect α-particles. Time-of-flight (TOF) measurements, using several types of detectors particularly adapted to detecting α-particles have also been used. The drawbacks come from the fact that TOF schemes give no discrimination on particles but only on their velocities, and on the small solid angle covered. Thus, it is essential to develop methods based on the indirect estimation of the $p - ^{11}B$ reaction by detecting products of different simultaneous reactions. HB11 Energy has developed one technique based on positron decay that has been detected from ^{11}C produced in the $^{11}B(p,n)^{11}C$ reaction [57]. The development of additional diagnostics, including detecting several signals simultaneously, will be required to limit doubts in data interpretation and to validate models and simulations.

Commercialisation: Technoeconomic Model and Engineering Challenges

The United States National Academy of Engineering has identified "providing energy from fusion" as one of the 14 top grand challenges of engineering [58]. While the realization of net-energy-gain is the primary goal from any fusion efforts, another recommendation from the National Academies of Science Engineering and Medicine (NASEM) [59] was that engineering efforts of an economical reactor should be pursued in parallel to scientific programs in order to compress the timeframe in which fusion energy can be realized and integrated into the grid.

HB11 Energy has developed a Technoeconomic model to assess the engineering requirements of a reactor. Given the prospects of direct conversion of the reaction products into electricity, the markets for which the model has been tested against are electricity for the grid and for electrolysis.

In theory, the direct conversion to electrical energy offers the highest efficiency being arbitrarily close to 100%. In practice, the question is complex, also because there are several "direct conversion" approaches. Consideration of the initial conversion of the ion energy to photon energy returns the estimate of 45% efficiency, while direct electrodynamic (DEC) conversion predicts up to 50% [60]. One of the recent concepts proposes to combine plasma magneto-hydrodynamics processes with Rankine steam cycle to achieve of 64% percent efficiency [61].

While much of the focus of other fusion efforts have been on grid electricity [62], electrolysis for hydrogen production has also been considered as a key market. Not included is the application of process heat, which can also be used for hydrogen production. Hydrogen has been forecast to be a larger market than grid electricity with the potential to replace CO_2 emissions from coal, oil and gas across many industries including transport and steel production [63]. These forecasts have led to significant hydrogen infrastructure investments around the world. Figure 4 shows a simple power loop for a laser-driven IFE powerplant that has been used as the basis for HB11 Energy's technoeconomic model.

A key feature of IFE fusion, which is reflected in this diagram, is that the system functions as a power amplifier and not as a power source. That is, fusion power available for conversion into electricity is proportional to the power on target multiplied by the target gain, G. In turn the power delivered to the target is the product of the laser power and efficiency η. The electrical power is determined by the generator conversion efficiency ε. The power available to the grid is the generated power minus the power for the laser. The following relations are useful in evaluating the

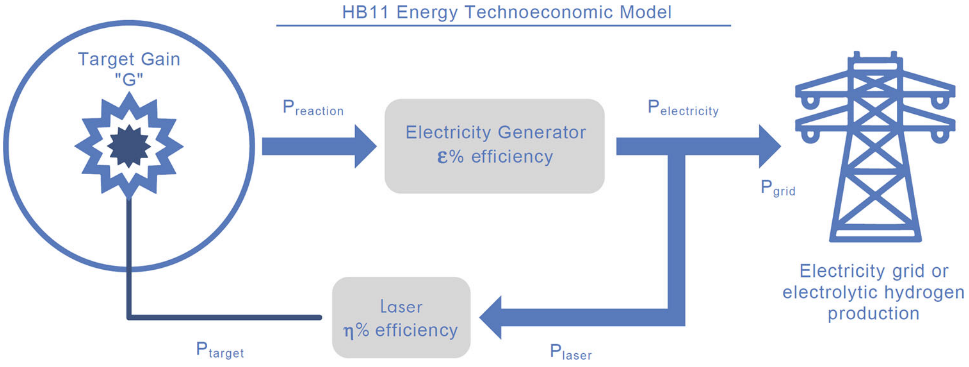

Fig. 4 Power loop for laser-driven IFE, where the reactor serves as a power amplifier rather than a power source. To increase the efficiency the recirculating power fraction should be minimized

key parameters of this model. The recirculating power fraction is given by $f = 1/\varepsilon\eta G$. Engineering breakeven is defined as $f = 1$, where the powerplant produces just enough power to operate. A recirculating power fraction $f = 0.25$ has been suggested as a starting point for nuclear fusion, and $f \leq 0.1$ is typical of nuclear fission reactors. The minimum target gain for operating at a given recirculating power fraction is given by $G = 1/\varepsilon\eta f$. This relation leads to the simple rule of thumb, $\eta G > 10$. Assuming $\varepsilon \in [36 - 40\%]$ corresponds to a recirculating power fraction of $\sim 25\%$, while $\eta G = 20$ drops that fraction to $\sim 10\%$, which is desirable for achieving the lowest cost of electricity from a plant.

The market constraints used as a boundary condition in this model that reflect economic viability are the levelized cost of electricity of \$35 per MWh (\$350 upper limit), and hydrogen \$1.5 per Kg H_2 (\$2.6 upper limit). While a detailed appraisal and sensitivity analysis of the technoeconomic model is beyond the scope of this paper, the range of the target gain required to achieve such economic viability varies between 100 and 300 when assuming a laser efficiency of 20%. Gains higher than this will both relax the engineering requirements and open the possibility for electricity generation at a cost lower than is currently paid. It may also make other energy intensive industries, such as carbon capture and storage, economically viable.

Several assumptions that have been embedded into this model represent key challenges beyond the scientific endeavors to increase gain and should be the subject or further research and engineering.

As the fusion system operates as an "amplifier" of the laser power, the efficiency of the laser system is critical, which we have estimated at 20%. This value can only be achieved using a diode-pumped solid state laser driver. It also sets a challenge for future laser system designs that enable average high-power and high repetition rates. Assuming a recirculating power fraction of 10%, a $500MW$ power plant would require $50MW$ to drive the laser system that would produce an average laser power output of $10MW$ (ignoring energy usage by the other subsystems).

The cost of replacement of the diodes is another critical cost driver. We have assumed a lifetime for diodes of 2.2 billion shots, with a replacement cost of \$1/W. Increasing the lifetime and reducing the replacement cost through improvements in diode manufacturing will materially address the economics of a laser-based fusion system.

The cost of the fuel may be another major cost driver. DT fusion cost analyses have assumed the material cost of the fuel is insignificant [64], however, in the "hybrid-burn" scenario, manufacturing requirements associated with the more complex targets; conducive to compression and similar to traditional direct-drive ICF, will add to this cost. Our modelling of the "Hybrid burn" suggests that a target cost of several dollars per target is acceptable if a target gain of 200 can be achieved. This represents a reasonable challenge, particularly given the ease of handling the earth-abundant boron-11 isotope relative to tritium in DT ICF systems.

Significant operational costs of DT systems are primarily associated with the replacement of the activated reactor components exposed to high neutron fluxes [64]. For the HB11 system, these costs are reduced for several reasons including that there will be no need for tritium breeding, storage, handling, extraction or atmospheric recovery, or a radioactive waste treatment facility. Subject to the specific target design that is chosen, the HB11 system may not rely on a thermal conversion system. Electricity can be captured via a direct electricity conversion system. While it is anticipated that heat will be generated, this could be used as process heat e.g. to complement hydrogen or electrolysis production.

The reactor lifetime is also assumed not to be limited by neutron irradiation as the reaction is aneutronic. There is a possibility for neutronic reactions in the proton-boron chain (11B + alpha → 14N + n, and 11B + p → 11 C + n), but at the level of $\sim 0.1\%$, and it is not expected to be a concern. The number of neutrons produced per MW of electrical power would be 2 orders of magnitude lower than in conventional uranium fission reactor. Accordingly, for the purpose of this model, the lifetime is anticipated to be 25 years which we consider to be conservative. In practice, producing energy from proton-boron fusion does create energetic particles e.g. from the $p - ^{10}B$ reaction. Although these are many orders of magnitude less than for DT reactions, their effect on safety and costing will need to be considered against the cost of production of isotopically pure ^{11}B in the fuel to ensure a truly aneutronic reaction. In the final design of the reactor, materials research will also be needed to understand the effect of α-particle damage to the materials and components of the reactor to bring more certainty to reactor lifetime estimates.

Based on HB11 Energy's technoeconomic model, some of the key goals that will enable fusion energy generation is a target design that can reach gain of > 100; a highly efficient, high-power, high repetition rate laser system driven by cost-effective diodes; and the manufacture of fuel targets for less than dollars / shot.

To evaluate boron abundance to supply future proton-boron energetics, let us compare it with uranium market. U annual consumption is around 10^5 tons per annum, primary for energy generation. Assuming every uranium nuclei fission delivers 20 times more energy than the boron reaction, and in the same time every B nuclei being about 20 times lighter than U, the boron supply needs for proton-boron energetics can be roughly estimated similar in tonnage, i.e. below 10^6 tons per year. This is 1000 times less than confirmed global boron reserves of $\sim 10^9$ tons, and several times less than current B consumption for other needs.

While the end-goal of these efforts is clean, safe and virtually unlimited fusion energy, a large prize, the scientific risk and potentially long timelines cannot be ignored as they will underpin investment decisions in both the public and private sectors. A challenge for all private fusion companies will be to embrace economies of scope in their business models to mitigate some of the investment risk, which will undoubtedly open new opportunities for multi-billion-dollar industries during the pursuit of these goals.

Conclusion

Proton-boron fusion has many attractive features as a potential source of clean, safe, and abundant energy, which inspired the career of Prof. Heinrich Hora as a theoretical physicist. Several experimental demonstrations of non-thermal HB11 fusion using lasers gave promise that it could become a practical reality, and HB11 Energy was founded to pursue this mission.

Relative to DT, the field of proton-boron fusion is young and there are considerable challenges that need to be addressed. Scientific challenges span areas of theory, modelling, material properties and experimental techniques are critical to the many gain-increasing strategies that we might leverage to maximise net-energy-gain in our target concepts.

While reaching net-energy-gain is the primary initial challenge, achieving this with the non-thermal laser fusion approach being pursued by HB11 presents a significantly simpler engineering path than for DT. Nonetheless, there remains significant engineering challenges to generate grid electricity or electrolytic hydrogen economically using hydrogen-boron fusion. Within the context of HB11's technoeconomic model, key challenges are identified in the areas of laser engineering, target fabrication and reactor engineering.

The magnitude of these challenges cannot be understated—it will not be possible for any one company, university, or national laboratory to achieve this mission in isolation and large collaborative partnerships involving private fusion companies and academia will be essential as will significant investment from both the public and private sector. Research groups around the world who can address the challenges outlined in this paper are encouraged to pursue them.

Author Contributions All authors contributed to and reviewed the manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Declarations

Competing interests The authors declare no competing interests.

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