p-B^{11} ignition via ps & ns lasers: burn physics, target design, & experimental validation

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Executive Summary

The p-B11 advanced fusion fuel cycle is an attractive alternative to D-T fusion in that the fuel is stable (non-radioactive) and the primary fusion products are aneutronic charged particles, enabling the possibility of higher efficiency direct energy conversion. However, the fusion cross section is lower and peaks at higher ion temperatures, making the associated Lawson criterion for thermonuclear burn significantly higher. Since 2005, "pitcher-catcher" experiments in Russia, France, the Czech Republic, Japan, and the US have shown substantial alpha yields from p-B11 reaction driven by short pulse CPA lasers irradiating uncompressed targets. However, these alphas have been generated by beam fusion reactions, which do not scale to ignition and gain. We propose to investigate the possibility of achieving ignition and gain via a hybrid approach to p-B11 fusion that combines thermonuclear burn elements of fast ignition ICF with inflight fusion reactions by CPA laser accelerated protons. Analytic calculations, hydrodynamic simulations, and hybrid fluid-PIC simulations can be used to develop a baseline target design, which could be validated in scaled experiments on OMEGA-60 & EP.

The p-B11 advanced fusion fuel cycle is an attractive alternative to D-T fusion in that the fuel is stable (non-radioactive) and the primary fusion products are aneutronic charged particles, enabling the possibility of higher efficiency direct energy conversion. In addition, for an ICF approach, the fuel is initially in the solid state and does not required cryogenic handling. However, the fusion cross section is lower and peaks at higher ion temperatures (shown by Fig. 1), making the associated Lawson criterion for thermonuclear burn significantly higher, as noted in a draft ARPA-E sponsored article[2]. However, as noted, a recent work[3] reports finding higher reactivity (~30%) using an updated cross section[4], as well as accounting for kinetic effects of reaction products on the proton spectrum. The authors conclude that ignition may be theoretically possible in the magnetic confinement device that they considered. We propose to study the impact of these factors on a p-B11 ICF target concept.

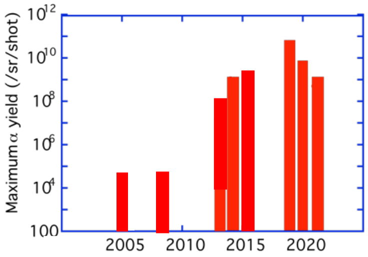

Fig 2 pB-reaction yield versus year - "pitcher-catcher" expts.

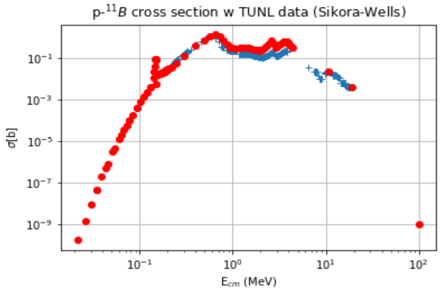

Fig 1 p-B cross-sections - new TUNL data (red) [3].

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[2] Wurzel & Hsu (ARPA-E), Progress toward Fusion Energy Breakeven and Gain as Measured against the Lawson Criterion, arXiv:2105.10954v1

[3] S. V. Putvinski, D. D. Ryutov, and P. N. Yushmanov, "Fusion reactivity of the pB11 plasma revisited," *Nuclear Fusion,* vol. 59, no. 7, p. 076018, 2019.

[4] M. H. Sikora and H. R. Weller, "A New Evaluation of the 11B(p,α)αα Reaction Rates," *Journal of Fusion Energy,* vol. 35, no. 3, pp. 538-543, 2016/06/01 2016, doi: 10.1007/s10894-016-0069-y.

Since 2005, “pitcher-catcher” experiments in Russia, France, the Czech Republic, Japan, and the US have shown substantial alpha yields from p-B11 reaction driven by short pulse CPA lasers (see Fig. 2). Our analysis of these experiments shows that the magnitude of the alpha particle yield is consistent with their generation via beam fusion reactions by laser accelerated protons slowing down and reacting with boron nuclei of the “catcher” target. Further, when the boron plasmas are sufficiently hot to decrease the proton stopping power, the fusion yields have been increased by up to an order of magnitude. Moreover, we have found that the surprisingly high yields obtained in these experiments appear to be explained by several factors including the new cross section, which has significantly higher values (~30% more) in the few MeV range, in some cases by an increase in proton range in heated plasmas, and finally by kinetic effects that are related to those described by Putvinski. However, our recent analyses have confirmed what has been previously published; beam fusion reactions alone do not scale to net gain and energy production. Further, as seen in Fig 3, a power plant analysis of a conceptual laser-driven p-B11 system shows that the required target gain will be of the order of 200, which is the same as a DT system. Given that the p-B11 reactivity is lower, this will be a formidable challenge, which starts with developing an integrated target design.

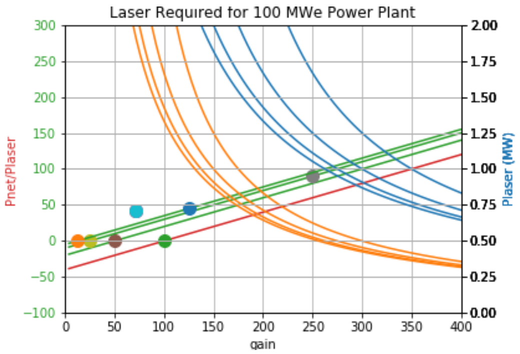

Figure 3 Power Plant Analysis showing target gain of ~200 are required for pB11

We have begun to develop an updated generalized Lawson criteria analysis for p-B11 that incorporates the new cross section data, as well as any other effects that indicate that it could be a viable fusion fuel cycle. Figure 4 displays a preliminary result from our analysis of the Maxwellian-averaged reactivity of D-T and p-B11 (using the latest Sikora-Wells or SW cross section), as well as the reactivity of high energy beam protons. A recently published a paper on aneutronic fusion[5] references a 1973 report from LLNL (Weaver, Zimmerman, & Wood, “Exotic CTR Fuels: Non-Thermal Effects and Laser Fusion Applications”) that contains a highly relevant discussion of the physics of p-B11 fusion. They developed a computer code (FOKN) that follows the energy distributions of nuclear reactants and products, under the assumption of an infinite medium. They discuss various strategies for non-steady operation including control of radiation and driving a strong detonation shock wave through extremely compressed fuel. We see that it will be necessary to pursue a modern revisit of this type of

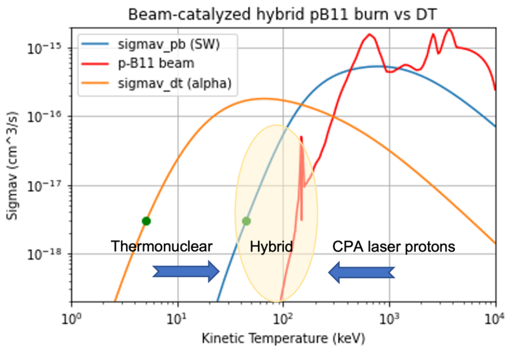

Figure 4 DT & P-B11 thermal reactivity & beam fusion

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[5] M. L. Shmatov, "Analysis of assumption about the possibility of the highly effective scenario of in-flight muon catalyzed fusion," *Physics of Plasmas,* vol. 28, no. 12, p. 124501, 2021, doi: 10.1063/5.0075500.

kinetic burn model for p-B11 using hybrid codes, such as Voss' Chicago. Hybrid kinetic-fluid simulations will play a key role in the further development of this updated generalized Lawson criteria analysis by accounting for the fusion reactivity of the thermal and beam components of the proton distribution function that properly accounts for elastic and inelastic processes as a function of fuel isotopic composition, density, and temperature, as well as accounting for the impact of kinetic energy exchange between the plasma distribution functions on the fusion reactivity.

Thermonuclear fusion reactivity scales with the square of the ion density, so all ICF schemes require significant compression to minimize the energy required for igniting the fuel. The USPL-driven p-B11 experiments reported thus far have all used uncompressed targets. We propose to investigate the possibility of achieving ignition and gain via a hybrid approach to p-B11 fusion (see Fig. 4) that combines thermonuclear burn elements of fast ignition ICF with inflight fusion reactions by CPA laser accelerated protons. The main line approaches to ICF, supported by the NNSA, are pursuing hot spot ignition, which requires that the compression be accomplished while avoiding the growth of hydrodynamic instabilities that create mix that precludes the generation of a sufficiently robust fusion spark. Traditional fast ignition decouples the implosion from the generation of the initiating spark, thereby relaxing some of the requirements on implosion symmetry. We see that the isochoric scaling published by Dan Clark in 2007[6] is a good starting point for studying the implosion of pb fuel to high densities. The requirements on the deposition of CPA laser-generated fast electron energy to achieve ignition in DT have been widely studied and published. Ions, notably protons and perhaps carbon, have also been proposed as an alternative ignition trigger because of their superior transport and focusing properties. We propose to develop a parallel set of criteria for the fast ignition of compressed p-B11 fuel, and then to study options for igniting the fuel by a combination of proton energy deposition and inflight thermonuclear reactions. This will extend the successful "pitcher-catcher" concept described above to targets at significantly higher densities and regimes of density and temperature where proton ranges can be extended by both electron heating and degeneracy effects.

Our study of proton-boron fast ignition ICF driven by short pulse lasers will use the latest cross sections, as well as a hybrid kinetic-fluid approach to calculating the implosion, burn, and expansion physics of an IFE target. As noted by Putvinski, the peak of the cross section lies in the suprathermal tail of the proton distribution function, and this critical population can be increased via up-scattering ("lift") by collisions with fast alpha particles. We propose to study what we term a "hybrid burn" scenario where protons generated by CPA laser acceleration add an energetic population to the proton distribution function, as well as providing additional fast alpha particles that will both heat the fuel and provide additional up-scattering events. This will require us to develop a kinetic algorithm for tracking the proton distribution function across the broad energy range encompassed by the bulk thermonuclear component from below and the slowing-down, beam-fusion component from above. We will quantify the possibility of ignition and burn in these fast ignition-like configurations, accounting for the power balance between heating, thermonuclear and inflight fusion reactions, charged particle deposition, Bremsstrahlung,

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[6] D. S. Clark and M. Tabak, "A self-similar isochoric implosion for fast ignition," *Nuclear Fusion,* vol. 47, no. 9, pp. 1147-1156, 2007/08/22 2007, doi: 10.1088/0029-5515/47/9/011.

thermal conduction, and hydrodynamic expansion via isochoric models and rad-hydro simulations. We will use models that include the effects of density and temperature on the interaction of charged particles in the plasma, including both slowing down and up scattering terms. We will also identify H:B isotopic ratios that maximize fusion yield and minimize Bremsstrahlung production, as well as consider designs that include radiation trapping layers to reduce losses (c.f. Dewald 2019[7]). Our goal is to identify whether there is a regime where the hybrid burn concept can take advantage of the higher p-B11 reactivity in the ≥200 keV energy regime associated with the Sikora-Weller cross section, leading to ignition and gain.

It will be important to accurately model the time dependence of all processes in this pulsed ICF scenario, especially the slowing-down and interaction times of energetic species, to arrive at a self-consistent design. Further, the CPA laser interaction time scale must be consistent with the hydrodynamic time history. The fast ignition laser pulse must deliver the necessary energy and proton flux to the target prior to expansion of the imploded fuel. Laser acceleration generally generates bi-Maxwellian proton distributions, dependent on the laser intensity through the normalized vector potential: $a_0 = 0.855\,\lambda_L(\mu m)\sqrt{I_{18}\ (w/cm^2\,)}$, where I_{18} is the laser intensity in units of 10^{18} (w/cm^2). The size of the target, the total laser energy, and laser pulse duration will set the laser intensity, which will in turn set the peak proton energy and associated distribution function. The hydrodynamic and laser acceleration calculations will need to be iterated until the range of the laser generated protons is an appropriate match to the target ρr and the resulting fusion reactions give sufficient burn-up fraction prior to hydrodynamic disassembly.

While we can begin to study the p-B11 burn physics through 0-D energetic models, detailed designs will require 1-D, 2-D, and eventually 3-D simulations. Pursuing these simulations will require that we first build the necessary computational capabilities for rigorous p-B11 studies, including an accurate EOS table, opacity, stopping-power, and fusion reactivity models of pB-fuel from first-principles calculations and implementing them into rad-hydro codes, similar to what has been done for DT-ICF fusion studies[6-10]. Further, the hybrid burn model will require further development of using Chicago or LSP to provide the kinetic simulation tools required to track the proton distribution function and its interaction with other energetic particle species. LSP, or OSIRIS can be used to also model various laser acceleration scenarios for providing the energetic proton ignitor beam. We can then use these capabilities to examine design concepts for p-B11 targets and derive scaling laws for hybrid burn.

To make sure that these simulations are well grounded on scientifically accurate plasma and nuclear physics, we also propose to perform validation experiments on the Omega Facility (Omega-EP + Omega-60). Such experiments will be able to combine compression and proton acceleration to study hybrid burn for the most promising target designs.

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[7] E. L. Dewald *et al.*, "Pushered single shell implosions for mix and radiation trapping studies using high-Z layers on National Ignition Facility," *Physics of Plasmas,* vol. 26, no. 7, p. 072705, 2019, doi: 10.1063/1.5109426.

[6] S. X. Hu *et al.,* Phys. Rev. Lett. 104, 235003 (2010); Phys. Rev. B 84, 224109 (2011).

[7] S. X. Hu et al., Physical Review B 96, 144203 (2017); V. V. Karasiev and S. X. Hu, Phys. Rev. E 103, 033202 (2021).

[8] T. A. Mehlhorn, J. Appl. Phys. 52, 6522-6532 (1981).

[9] Y. H. Ding, A. White, S. X. Hu et al., Phys. Rev. Lett. 121, 145001 (2018).