CONFERENCE PRE-PRINT

PROGRESS OF PROTON-BORON RESEARCH FOR FUSION ENERGY IN CHINA

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Abstract

Proton-boron (p-^{11}B) fusion represents one of the most promising pathways towards clean, aneutronic energy generation. The reaction utilizes abundant, non-radioactive fuel and yields three alpha particles, enabling the potential for direct electricity conversion. However, achieving net energy gain in p-^{11}B plasma presents formidable challenges due to the significantly high ion temperature and stringent confinement requirements. This paper reviews the multifaceted p-^{11}B fusion research program in China, which adopts a dual strategy combining fundamental beam-target experiments with advanced magnetic confinement devices. Key progress includes high-precision measurements of the reaction cross-section, theoretical work relaxing the conventional Lawson criterion through the active maintenance of non-thermal ion distributions, and experimental verification of reaction rate enhancements. Furthermore, systematic studies utilizing Spherical Torus platforms demonstrate superior alpha particle confinement and provide a concrete roadmap toward a commercial demonstration. The ongoing research is systematically addressing the fundamental physics, technological breakthroughs, and complex plasma challenges inherent to harnessing this advanced fuel cycle.

1. INTRODUCTION

Proton-boron fusion, (p-^{11}B→3α + 8.7MeV) ,among diverse fusion fuel cycles, has been considered to be an ideal fusion fuel for future clean energy the perspective of abundance in supply, intrinsic safety, its aneutronic nature with low radiation waste, and potential for direct energy conversion[1]. However, it is also known to be extremely difficult. The fundamental challenge is rooted in its low reaction cross-section, which determines a plasma regime different from D-T fusion and requires significantly higher plasma temperature and confinement conditions.

In contrast to conventional deuterium-tritium fusion, where the primary challenges lie in engineering, such as tritium breeding and neutron shielding, p-^{11}B fusion shifts the difficulty toward fundamental plasma physics. Due to its low cross-section, achieving sufficient reactivity requires high ion temperatures to enhance the fusion rate. Moreover, employing non-Maxwellian plasma distributions emerges as a crucial approach to further boost reactivity. Additionally, a high ratio of ion to electron temperature (Ti/Te) is essential to mitigate radiation losses, such as those from bremsstrahlung [2]. In magnetic fusion configurations, maintaining high beta is also critical to reduce radiation effects and ensure strong confinement.

A strategy for p-^{11}B fusion research, in Fig. 1, which is pursued through two parallel approaches: High-Energy-Density Physics (using laser and particle beam platforms) and Magnetic Fusion (using spherical torus, tokamak, and stellarator platforms). The research focuses on fundamental mechanisms like fusion cross-sections, fuel optimization, and nonlinear processes, as well as hydrogen-boron plasma properties such as equilibrium, stability, and confinement. A significant part of the R&D is dedicated to exploring the physics of spherical torus (ST) devices for achieving hydrogen boron plasma, reaction, burn, and ultimately, a clean fusion DEMO. The strategy concludes with an invitation for collaborations.

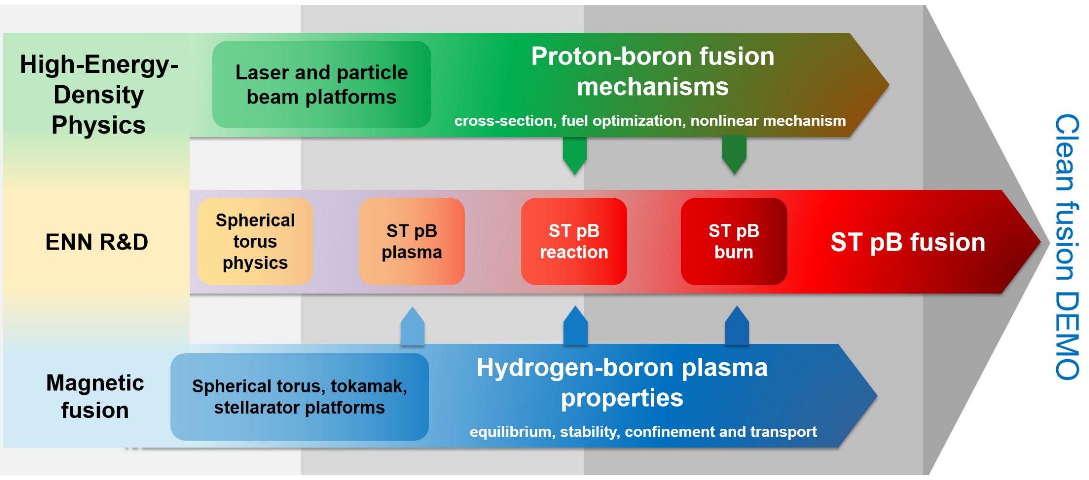


Fig. 1, Strategy of p-11B research towards energy commercialization

This overview builds on this strategic framework, systematically exploring three interconnected pillars of p-^{11}B fusion research: the fundamental physics of the p-^{11}B reaction, technologies for enhancing fusion rates, and advances in magnetic confinement devices. By synthesizing key findings from Chinese research teams, it aims to contextualize the current state of p-^{11}B fusion, identify remaining challenges, and outline pathways to commercialization.

2. FUNDAMENTAL LIMITATIONS OF PROTON-BORON FUSION REVISITED

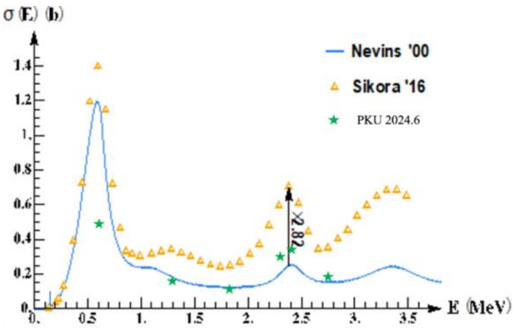
2.1 p-11B cross-section measurements and decay process

The measurement of the ^{11}B(p,α)αα reaction can be traced back to the 1930s [3]. However, after nearly a century of research, significant discrepancies remain in the cross-section data and excitation functions of this reaction[4,5]. These uncertainties play a decisive role in evaluating the ignition conditions for p-^{11}B fusion and are mainly caused by limitations in experimental techniques and the incompleteness of nuclear reaction theories. Early measurement methods, for example, limited solid-angle coverage of detectors, resulted in low detection efficiency; some experiments lacked particle identification and low-energy threshold optimization, and assumptions had to be made regarding reaction dynamics and emission mechanisms. These factors led to uncertainties in the final cross-section data as high as 30%, with discrepancies of about 50% between different results. Moreover, existing experimental data are concentrated around a few resonance peaks, leaving other energy regions insufficiently covered.

The Peking University nuclear physics team has conducted advanced measurements of the critical aneutronic fusion reaction ^{11}B(p,α)αα, using a 2×1.7 MV tandem electrostatic accelerator over the proton energy range of 0.675–3.0 MeV. Their experimental setup featured a custom detection system incorporating double-sided silicon strip detectors (DSSD) , enabling high-resolution measurement of α particles [6].

Key outcomes include precise differential and total cross-section data for both the α_0 (direct decay via ^{8}Be ground state) and α_1 (sequential decay via ^{8}Be excited state) channels, in Fig. 2. The development of innovative low-noise preamplifiers and a multi-channel data acquisition system facilitated high-statistics 3α coincidence measurements. The new cross-section results (0.5-3 MeV) align closely with earlier findings by Nevins and represent advanced levels of measurement accuracy.

Applying the Statistical Theory of Light Nucleus (STLN) to proton-boron fusion reveals significant challenges in modeling the reaction, in Fig. 3. The α_1 channel, whose cross-section is an order of magnitude larger than the α_0 channel, is critical yet poorly described. Current experimental data for α_1 is plagued by proton contamination and an inability to distinguish primary from secondary alpha particles, and it lacks self-consistent cross-section and angular distribution measurements [7]. These deficiencies hinder crucial model improvements, underscoring an urgent need for more precise α_1 measurements to advance the theoretical understanding of this aneutronic fusion reaction.



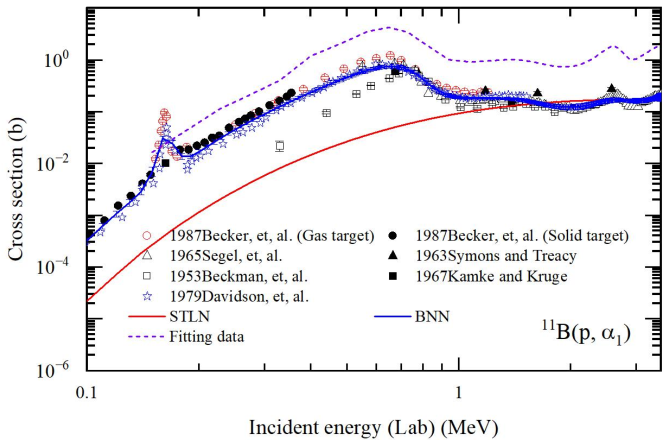
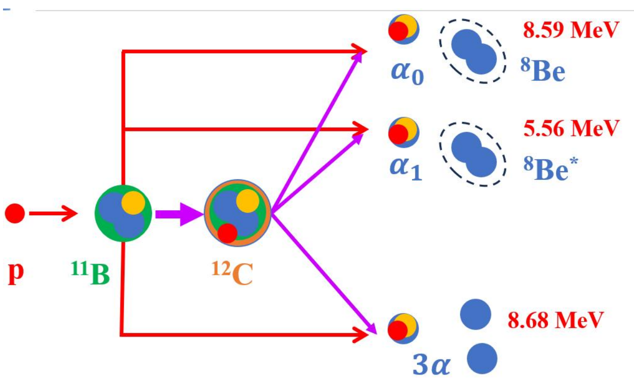


Fig.2, p-11B Cross-section data of new measurements and previous measurements.

Fig. 3, STLN analysis of experimental data.

A direct reaction theory study of the 11B(p,α)8Be reaction was conducted by Pang Danyang (BUAA)[8]. The research employed the Direct Reaction Model and the Distorted Wave Born Approximation (DWBA), treating the process as a two-body reaction. Key methodological choices included the use of Koning-Delaroche optical model potentials (OMPs) for the p-^{11}B system and the substitution of alpha-9Be data to approximate the alpha-8Be interaction. With spectroscopic factors set to unity, the study systematically compared calculated cross-sections across different OMPs, incident energies, and boron nuclear states. Future work will focus on refining the OMPs, incorporating realistic spectroscopic factors, and integrating both statistical and three-body breakup models for a more comprehensive description.



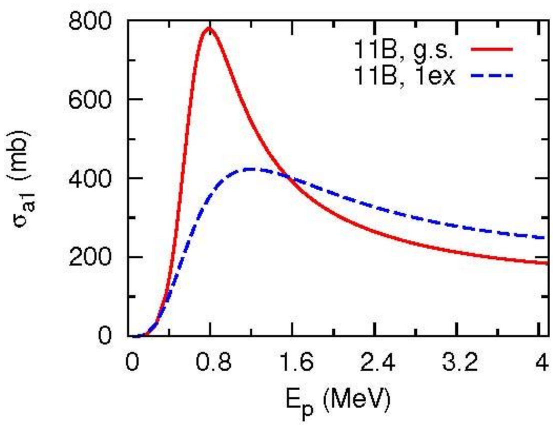


Fig. 4, Possible channels for p 11B reaction where the purple lines represents the compound nuclei model ans the red lines corresponding to the direct reaction progress.

Fig. 5, A comparison of the cross sections for the initial boron in its ground state and first excited

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2.2 Fundamental limitations of non-equilibrium plasma revisited

Plasma collisions naturally drive the system towards thermodynamic equilibrium. To maintain a non-equilibrium plasma, whether characterized by non-Maxwellian velocity distributions, anisotropic particle motion, or different temperatures between species, a continuous input of "recirculating power" is essential. This power directly counteracts the effects of collisional relaxation, which constantly attempts to restore equilibrium. The challenges posed by ion behavior and plasma thermalization lead directly to the concept of the "Rider Constraint,"[9] which highlights the fundamental energetic limitations of operating fusion systems substantially out of thermodynamic equilibrium. This constraint arises from the significant power required to counteract natural collisional processes and radiation losses.

The "Rider Constraint" articulates a fundamental challenge for aneutronic fusion, highlighting the severe energetic limitations imposed by ion behavior and radiation losses in systems operating far from thermodynamic equilibrium. However, recent research has revisited this constraint, revealing potential pathways to mitigate its stringency. Studies employing 0D Fokker-Planck models suggest that maintaining a non-thermal proton distribution can reduce the required energy confinement time by an order of magnitude, thereby lowering the engineering barriers for a p-^{11}B reactor. In a significant update[10], incorporated doubled fusion cross-section data and identified a critical "net energy gain window", see Fig.5. They determined that an electron temperature of ~140 keV and a tightly constrained ion-to-electron temperature ratio (Ti/Te) between 1.8 and 2.5 are optimal, see Fig.6. This specific regime balances fusion power against radiation and energy transfer losses, minimizing the Lawson confinement parameter and offering a more optimistic, though still demanding, outlook for p-^{11}B fusion energy gain.

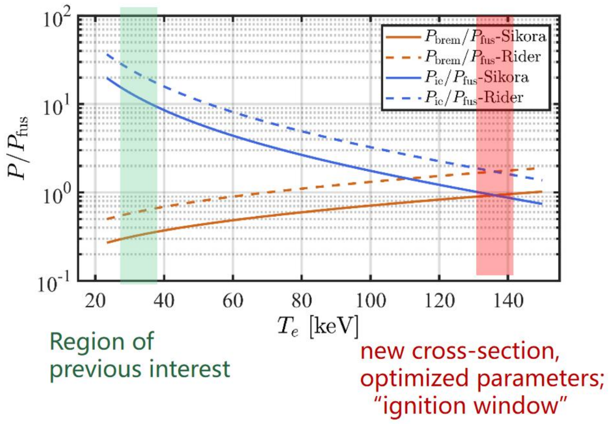

Fig. 5, (a) The ratio P/P_{fus} as a function of electron temperature. (b) the required recycled efficiency of the recirculating power as a function of electron temperature.

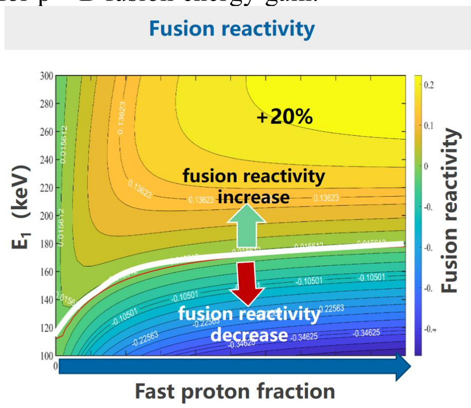

Fig. 6, 20% enhancement in reactor-scale proton-boron fusion reaction rates is achievable considering recirculating power constraints for burning plasma.

3. KEY ISSUES TO BREAKTHROUGH: REACTION RATE ENHANCEMENT, BRUNMSTRUNLUG REDUCTION

3.1 Enhancement of Fusion Reactivity under Non-Thermal Equilibrium Conditions

Significant work has been dedicated to establishing robust and efficient methods for calculating ⟨ σv⟩ for various non-Maxwellian plasmas [11]. Researchers have developed a simple and fast Monte Carlo approach that can compute the six-dimensional integral for arbitrary ion velocity distributions with high accuracy, serving as a powerful tool for kinetic simulations and analysis. Furthermore, analytical and unified expressions have been derived, notably simplifying the calculation of reactivity for two drift bi-Maxwellian reactants with different drift velocities, temperatures, and anisotropies, which is highly relevant for magnetized plasmas.

These computational tools have been applied to quantify reactivity enhancement for various non-thermal proton distributions in p-^{11}B fusion. Specifically, studies focusing on drift-ring-beam, slowing-down, and kappa super-thermal distributions confirm that within the key ion temperature range of 100–500 keV, p-^{11}B fusion reactivity can be significantly enhanced compared to the purely Maxwellian case, all while keeping the total plasma kinetic energy constant[12]. Furthermore, a key theoretical investigation established the upper bound of non-thermal fusion reactivity for a reactant coexisting with a thermal background: for p-^{11}B, the maximum achievable reactivity can surpass the conventional Maxwellian-Maxwellian case by a substantial margin (typically 50% to 300%)[13]. These maximal enhancements are tied to highly distinctive non-thermal distributions, usually featuring one or multiple mono-energetic beam-like components, providing a clear theoretical target for experimental efforts to optimize non-thermal fusion performance.

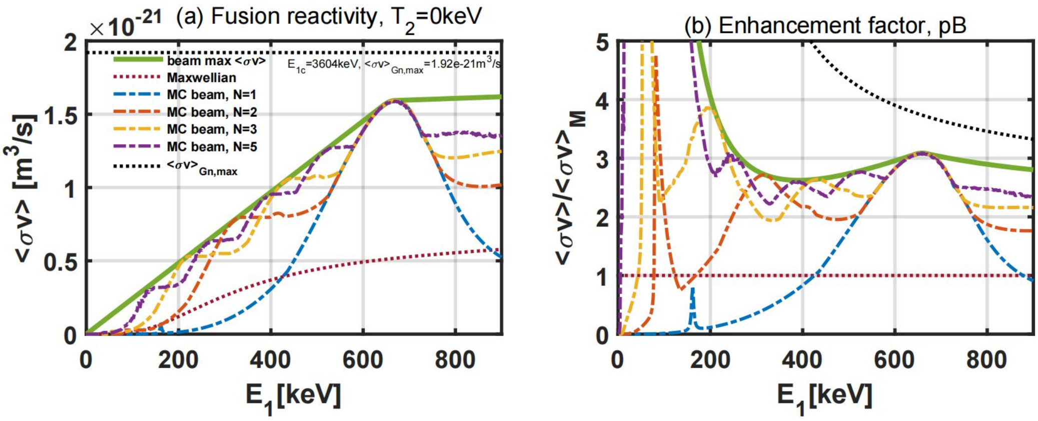

Fig. 7, Quantifying the maximum possible enhancement of the fusion reaction rate (⟨ σv⟩) by actively shaping the ion distribution function.

A practical implications of enhanced reactivity for reactor feasibility, specifically, the concept (examined for magnetized toroidal plasma conditions) that a velocity differential (or drift) between protons and boron ions can boost the p−^{11}B fusion reaction rate enough to ease the standard Lawson criterion [14]. This theoretical study further explores how such velocity differentials in magnetized toroidal plasmas could substantially reduce the Lawson ignition criterion for p-^{11}B fusion: by maintaining a relative velocity comparable to the plasma sound speed (Mach 1–2 at ~100 keV), the reaction rate increases from ~1×10^{-22} m³/s to ~6×10^{-22} m³/s, lowering the required triple product ($n_i\tau\_E\ T_i$) to ~10^{23} $m^{-3}\cdot s\cdot keV$, only one order of magnitude above ITER's D-T target.

Active generation of non-thermal ions. Achieving a high fusion rate in non-thermal plasmas requires a viable mechanism to actively generate and sustain favorable non-Maxwellian distributions. To address this, a collaborative team from ENN and Shanghai Jiao Tong University (SJTU) has explored active heating methods using kinetic simulations, with numerical studies via the LAPINS and EPOCH codes validating the underlying ion acceleration mechanisms. These simulations model the injection of a 100 keV hydrogen beam into a magnetized hydrogen-boron plasma, observing the excitation of ion Bernstein waves (IBWs) and the formation of high-energy ion tails, Fig. 8 [15].

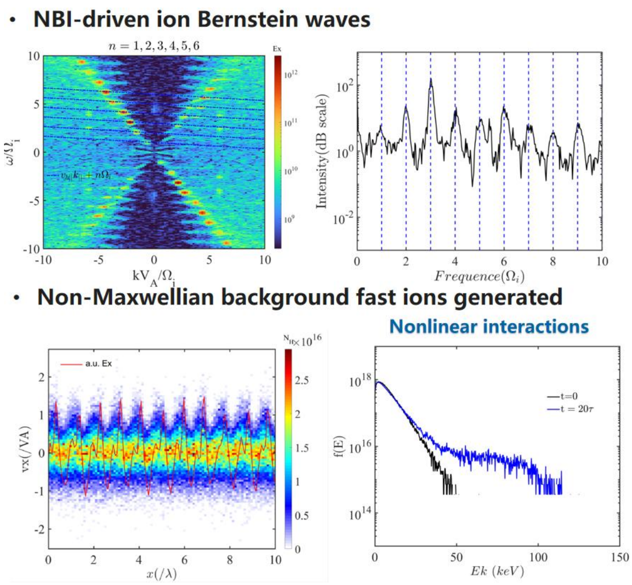

Fig. 8, 100 keV H beam perpendicular magnetic field injection into HB (9:1) magnetized plasma

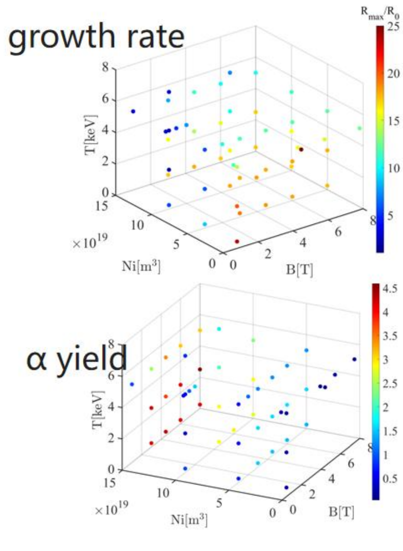

Fig. 9, Exploring parameters controlling reaction gain

Parameter scans further reveal key trends: a combination of high magnetic field, high density, and low temperature boosts alpha-particle yield, while a high magnetic field paired with lower density or temperature enhances the growth rate of the instability that drives ion acceleration, see Fig. 9.

This nonlinear wave-particle interaction mechanism is critical: it preferentially transfers neutral beam injection (NBI) energy to lighter hydrogen ions, forming a non-Maxwellian tail that significantly boosts p-^{11}B fusion yield. Under optimal simulated conditions (low temperature and high density), this active non-Maxwellian generation mechanism notably increased the fusion reaction rate offering a clear pathway for the practical application of non-thermal fusion schemes.

3.2 Enhancing p-11B cross-section

The fundamental challenge of p-^{11}B fusion stems from its low reaction cross-section. Finding a way to enhance the effective fusion cross-section would resolve this core issue and the associated challenges. A potential key solution to this very issue is the use of spin-polarized fuels, which is under consideration at ENN. Theoretical quantum analysis, considering angular momentum conservation, indicates that fully parallel polarized p-^{11}B fuel can enhance the reaction cross-section by up to ~60%, with even partial polarization yielding a significant 20% increase. While these findings align with established theoretical work, experimental validation is crucial to resolve discrepancies in the literature. The primary challenge for practical application lies in mitigating depolarization effects within magnetic confinement, driven mainly by magnetic fluctuations and wall collisions.

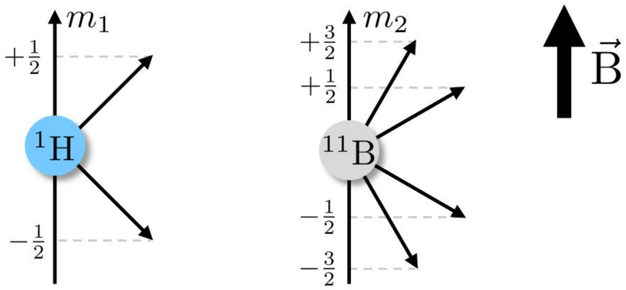

Fig. 10, schematic of spin-polarization for hydrogen and boron.

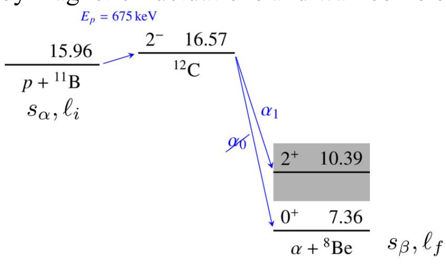

Fig. 11, Exploring parameters controlling reaction gain

Research by Liu Jie's team (China Academy of Engineering Physics) theorizes that intense laser fields can enhance the p-^{11}B fusion cross-section[16]. Among three models tested, semiclassical simulation and the Kramers-Henneberger (KH) transformation both predicted an increase, while a Volkov-state (VSA) approach failed due to the omission of Coulomb effects. The KH transformation, though effective, demands laser parameters exceeding current limits, defining the key challenge for practical application.

3.2 Beam-target experiments to explore the mechanisms to enhancement reactivity

A team led by Zhao Yongtao at Xi'an Jiaotong University (XJTU) has demonstrated a novel intense beam-driven scheme for p-^{11}B fusion at the XG-III laser facility[17]. Their approach used a picosecond laser to generate a proton beam via TNSA, which then interacted with a preheated, homogeneous boron-doped TAC foam plasma. This setup produced an α-particle yield of up to 10^{10} per steradian per shot, the highest value normalized to laser energy reported to date. The results significantly exceeded classical beam-target expectations by four orders of magnitude, achieving a 12% proton-to-α energy conversion efficiency and a maximum fusion probability of 2.3×10^{-2}. The enhancement is attributed to strong electric fields, non-equilibrium reactions, and the unique foam plasma structure, establishing a promising new pathway for aneutronic fusion.

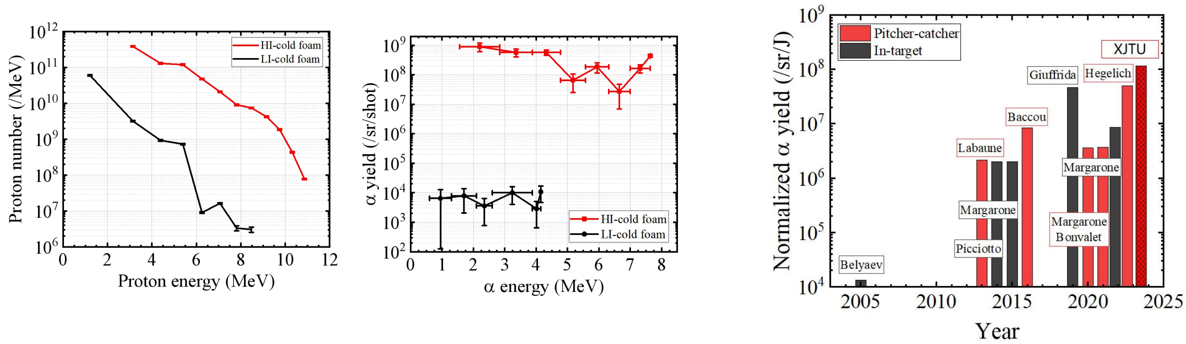

Fig. 12, Beam density effect: 2-3 orders of magnitude enhancement of proton beam intensity will induce ~4-5 orders enhancement of the α particles yield.

Fig. 13, Maximum alpha particle yield by year for various lasers for both pitcher-catcher and in-target irradiation geometries..

Further theoretical work [18] by Wu Dong (SJTU) identifies a preformed boron plasma as the key to enhancing alpha yield. The gain is driven by two effects: degeneracy, which reduces proton energy loss (~40% yield increase); and suppressed collective EM effects due to lower plasma resistivity, which enables deep proton penetration and boosts yields by 1~2 orders of magnitude. This confirms plasma pre-formation as the underlying mechanism for the dramatic efficiency gain.

The ENN-IMP collaboration conducted p-^{11}B reaction experiments on the 320 kV high-voltage platform at IMP [19]. Employing solid hydrogen-doped boron (HB) targets with approximately 25 at.% H, see Fig14, experiments observed an average enhancement of about 30% in the alpha-particle yield compared to pure boron targets, across the center-of-mass energy range of 110-240 keV, see Fig 15. This result provides conclusive evidence that engineering the fuel composition can substantially improve reactivity in the low-energy regime. However, the physical origin of this enhancement is not yet fully understood and remains under active investigation.Ongoing research efforts are now focused on quantifying the influence of plasma conditions and applied magnetic fields on the p-^{11}B fusion reactivity.

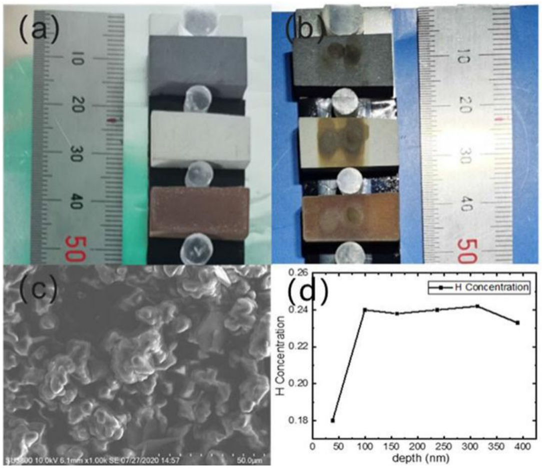

Fig. 14, Beam density effect: 2-3 orders of magnitude enhancement of proton beam intensity will induce ~4-5 orders enhancement of the α particles yield.

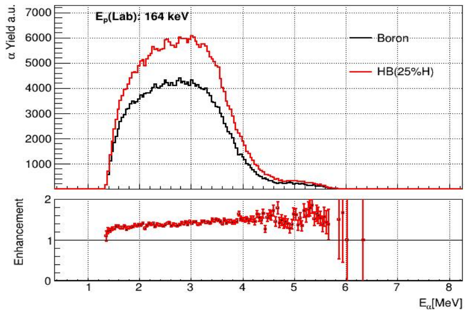

Fig. 15, A typical α spectrum at E_{lab} = 164 keV, comparing the boron (black) and HB (red) targets.

Interestingly, it has also been found the α_0/α_1 branching ratio near the 160 keV resonance shows a strong dependence on proton energy, see Fig. 16. This relationship directly determines the energy spectrum of emitted alpha particles, which is crucial for designing p-^{11}B diagnostics and NBI heating systems. It also explains the absence of the α_0 peak in earlier LHD experiments [20].

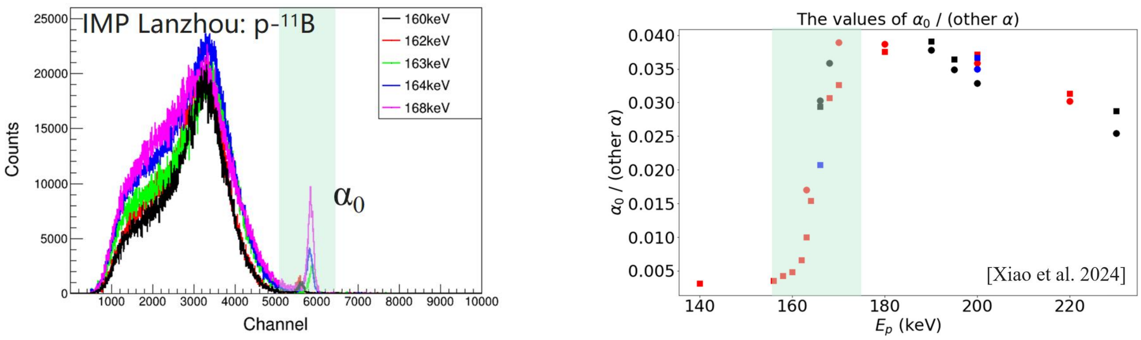

Fig. 16, Observation of α particle spectrum near 160 keV resonance, and α_0/α_1 branching ratio variation with reaction energy.

4. NEW SCHEME AND STRATEGY TOWARDS PROTON-BORON FUSION ENERGY

4.1 ST + p-^{11}B boost the potential of clean fusion energy

The integration of the Spherical Torus (ST) configuration [21] with p-^{11}B fusion fuel presents a powerful synergy that addresses the core challenges of both systems, shown in Fig. 17.

The ST offers a high plasma beta, enabling good confinement at a relatively low toroidal magnetic field. This characteristic is critically advantageous for p-^{11}B fusion. At the high operational temperatures p-^{11}B requires, energy loss through cyclotron radiation, which intensifies with magnetic field strength—becomes a severe issue. The ST's ability to achieve high performance at lower fields directly helps mitigate these dominant radiative losses.

Conversely, p-^{11}B fusion provides a solution to the ST's primary engineering limitation: the constrained space for a central solenoid. A traditional D-T ST reactor would require this limited space to house both a large solenoid and a bulky breeding blanket. The aneutronic nature of p-^{11}B eliminates the need for a breeding blanket, freeing up the central column to be optimized solely for magnetic field generation.

In essence, the ST's high-beta, low-field physics perfectly complements the needs of p-^{11}B, while p-^{11}B's aneutronic property alleviates the ST's key engineering constraint. This mutual enhancement allows the ST to leverage its strengths while circumventing its weakness, unlocking a more viable path to clean p-^{11}B fusion energy.

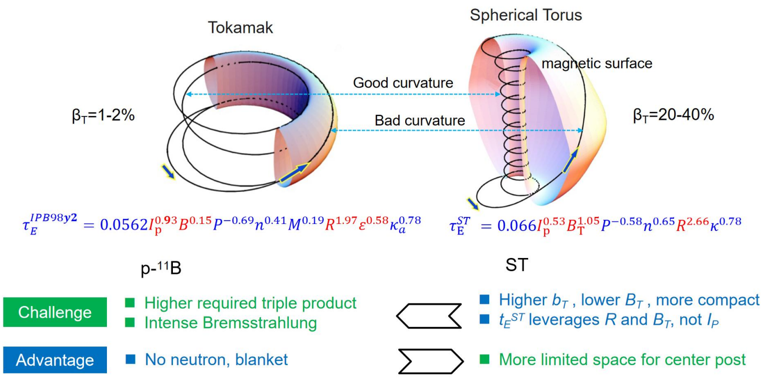

Fig. 17, ST + p-11B boost the potential of clean fusion energy.

In addition, recent theoretical study demonstrates that a magnetic well in a high-beta tokamak significantly improves plasma confinement by squeezing trapped particle orbits and suppressing turbulence. This results in a strongly favorable ion energy confinement scaling ($\tau_E \propto T_i^2$), markedly enhancing the feasibility of igniting aneutronic fusion in compact reactors.[22]

ENN has outlined a detailed roadmap for p-^{11}B fusion in a ST, a combination that leverages the fuel's clean nature and the ST's favorable confinement[23]. System code results demonstrate the feasibility of a high-gain (Q>10) reactor with key parameters like 6 T field and hot-ion mode. The strategy evolves from current devices to next-generation STs, aiming for a demonstration by ~2035 driven by critical advances in technology and plasma physics.

A comprehensive simulation of p-^{11}B fusion in the EHL-2 [24] spherical torus establishes that thermal reactions become dominant at ion temperatures above 26 keV, validating its high-temperature design strategy. Under EHL-2 parameters (200 keV H-beam at 1 MW), simulations predict a total α power of ~0.95 kW, with superior α confinement (98% retention). Parameter scans further identify an optimal boron concentration of ~14%, providing key physics basis for future aneutronic fusion devices, shown in Fig 18 [25]. The experimental demonstration of a p-^{11}B fusion reaction driven by combined ICRF and NBI heating is now underway on the EXL-50U [26].

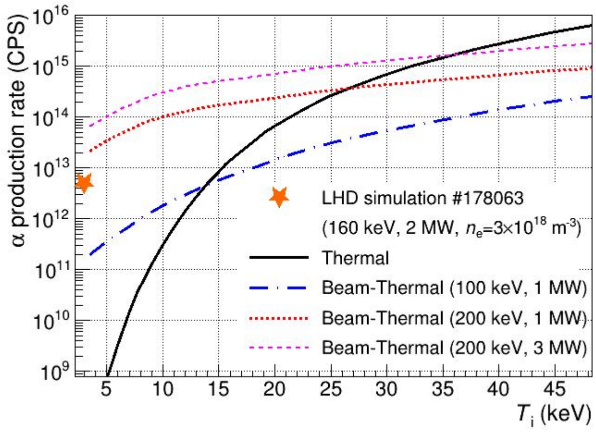

Fig. 18, Comparison of reactivities between thermal-thermal and beam-thermal reactions in EHL-2.

4.2 p-^{11}B fusion with laser-driven novel targets at high energy density

Two complementary strategies, nanowire-enhanced Z-pinch compression and nano-high-energy-density matter (Nano-HEDM) demonstrate significant potential in enabling viable p-^{11}B fusion conditions.

Guoqiang Zhang's team (CAS Shanghai) explored femtosecond laser-irradiated nanowire arrays[27]; PIC simulations show these targets drive a Z-pinch mechanism, creating extreme conditions (~10^{16}A/cm² current density, ~10^6T magnetic fields) for fusion. The simulations predict D-T neutron yields one oder of magnitute higher than D-D in deuterium-doped setups and notable alpha-particle production for p-^{11}B reactions. Experiments on deuterium-doped nanowires confirm neutron generation and record alpha-particle yields up to 1.5×10^7 per shot, proving this platform a viable path to p-^{11}B fusion in high-energy-density plasmas.

Nano-HEDM for Particle Acceleration and Fusion Plasmas[28]. Wenjun Ma's group (Peking University) utilizes Nano-HEDM structured nanomaterials irradiated by femtosecond PW lasers to drive Coulomb explosions, accelerating protons to 150 MeV and generating near-solid-density plasmas. This approach offers a compact alternative to conventional accelerators and converts ~10% of laser energy into fast ions. However, despite achieving high densities and temperatures, Nano-HEDM systems fall short of the Lawson criterion due to picosecond-scale confinement times. Enhancing fusion viability thus requires innovative methods to significantly improve plasma confinement.

4.3 Laser driven proton source for application in magnetic fusion

In recent years, laser ion acceleration has advanced rapidly and is widely applied in p-^{11}B reaction research. While the frontier of laser acceleration prioritizes high cutoff energy, directionality, and monoenergeticity, magnetic confinement scenarios have distinct requirements: high efficiency, a large quantity of fast protons (not extremely high energy, 300-1000 keV), and relatively low demands for directionality and monoenergeticity (overly high-energy protons are hard to confine). Specific proton demands, based on preliminary rough estimates, stand at 10^{13} for EXL-50U and 10^{17} for EHL-2.

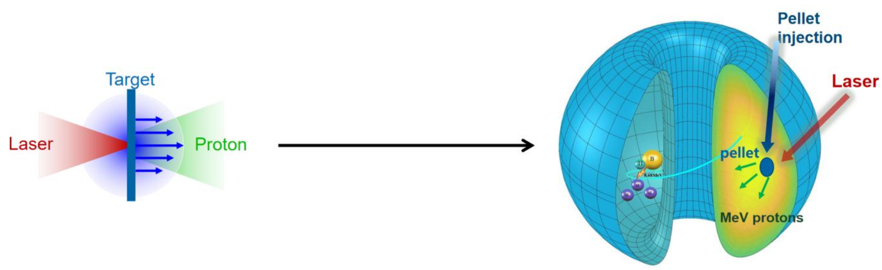

Fig. 19. Schematic of a laser-driven proton source for magnetic confinement fusion.

For integration with magnetic confinement, the most promising approach is combining with pellet injection technology: ultrashort and ultraintense lasers irradiate pellets that have entered plasma but not disintegrated, generating electron-ion separation electric fields to accelerate protons. This avoids magnetic shielding issues, enabling in-device proton production to boost reactions, while other methods such as powder injection also hold potential for future exploration.

Collaborative work with teams from XJTU and PKU has progressed to experimental verification on a laser platform. Through PIC simulations and preliminary tests, we have evaluated key parameters including laser selection, acceleration conditions, and proton beam characteristics[29].

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