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Book of Abstracts

4th International Workshop on Proton-Boron Fusion

September 30th to October 3rd, 2024

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Igniting H-^{11}B fusion fuel

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Abstract

Proton-boron fusion is experiencing a renewed interest as a possible energy source. The reaction ($p + {}^{11}B \rightarrow 3\alpha + 8.6$ MeV) is aneutronic and does not involve radioactive or rare isotopes. Ignition and burn of H-^{11}B fuel, however, remain extremely challenging at present, because of severe physics and technology limitations [1-3]. Ideal ignition has been demonstrated only lately (and marginally) [4], thanks to recent cross section data [5] and the inclusion of suprathermal fusion reactions.

We have revisited the findings on ideal ignition [6], in the light of the latest available reactivity [7], an alternative self-consistent calculation of the electron temperature, an increased extent of the suprathermal effects and the impact of plasma density. At high density, we find that the ideal ignition temperature is appreciably relaxed (e.g. $T_i \simeq 150\,\mathrm{keV}$ for $n_i \sim 10^{26}\,\mathrm{cm}^{-3}$ and an optimal ^{11}B/H concentration $\varepsilon = 0.15$) and burn becomes substantial.

We then report analytic results on central hot-spot ignition in both isobaric and isochoric inertial confinement configurations. Although implosion-driven ignition appears to be unfeasible, the isochoric self-heating conditions foster favourable preliminary conclusions on the utilization of proton fast ignition. In the isochoric case, we find a broad minimum in the ignition energy at $\rho R \simeq 8.5\,\mathrm{g/cm^2}$ and $220 \lesssim T_i \lesssim 340\,\mathrm{keV}$ ($80 \lesssim T_e \lesssim 95\,\mathrm{keV}$), for $\varepsilon = 0.15$. In addition, we briefly present laser driver requirements for the target implosion and the proton ignitor. Finally, we outline target design requirements.

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Proton-Boron Tests With FF-2B Dense Plasma Focus

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Abstract

Experiments with deuterium fill gas have demonstrated that ion energies >200 keV, relevant to pB11 fusion, can be obtained in a dense plasma focus (DPF) device. These observations have motivated LPPFusion's preparations, starting in 2023, for tests of isotopically pure decaborane (B10H14) as a fill gas in the FF-2B DPF. In preparing for the decaborane tests, we redesigned the spark gap switches on the device, reducing their inductance and increasing peak current by over 50% to nearly 2 MA. Tests with deuterium and the new switches demonstrated the need to redesign the beryllium electrodes in order to improve the durability of the anode and to reduce the number of filaments in the current sheath. This reduction in the number of filaments was needed to increase the current in each filament to allow the filaments to survive to the end of the rundown. This is expected to greatly increase the density of plasma in the plasmoid formed by the pinch forces in the device. In addition, we have optimized the preionization system to ensure a symmetrical breakdown and compression. We report here on the initial tests of these improvements with decaborane as the fill gas.

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The FUSION (FUsion StudIes of prOton boron Neutron-less reaction in laser-generated plasma) project

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Abstract

The FUSION (**FU**sion **S**tudIes of pr**O**ton boron **N**eutronless reaction in laser-generated plasma) project was initiated in 2022 by researchers from INFN (Istituto Nazionale di Fisica Nucleare, Italy) and ENEA (*Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile*) with the objectives of developing a new generation of solid targets (WP3) to enhance the p(11B, α)2α reaction rates (WP1), designing innovative diagnostic approaches (WP4) for the measurement of reaction products, and, finally, determining the stopping powers of alpha particles and protons in a plasma environment (WP2). Two experimental campaigns focused on studying the p(11B, α)2α reaction in plasma using the developed targets and advanced diagnostic methods are planned at the Prague Asterix Laser System (PALS) facility with the Asterix laser. The first campaign, incorporating the targets and diagnostic techniques developed as part of the FUSION project, concluded in March 2024. Experiments on the stopping power of protons and alpha particles in plasma will be conducted by generating a plasma with a nanosecond laser pulse and studying the interaction of a conventional proton/alpha beam with it. The protons and alpha particles will be produced using a Singletron accelerator available at the University of Catania. The FUSION project involves the participation of ten INFN sections and three external scientific partners, including ELI-beamlines, HILASE, and PALS in the Czech Republic.

The primary objectives of the FUSION project are to gain a deeper understanding of the p(11B) reaction and to optimize it for maximum alpha yield, particularly with the new generation of high-repetition-rate laser systems. This work will present and discuss the current status of the FUSION project and its main achievements from the experimental campaigns.

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p-B^{11} heating requirements to initiate propagating burn

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Abstract

We present the latest results from our studies of the proton-boron burn space for ICF in an attempt to identify regions where sufficient gain could be achieved to enable a practical power reactor. A fundamental principle of ICF is to limit the size of the driver by heating a limited amount of fuel such that it ignites and propagates the burn into adjacent cold fuel that is highly compressed on a low adiabat. Results from 0-D power balance studies have identified ignition regions for isobaric and isochoric pB^{11} plasma configurations having high initial values of density, temperature, and ρR [1]. We are also developing more advanced 0-D burn models, as well as performing 1-D simulations using the HELIOS radiation hydrodynamics code [2]. The main topic of this talk is a preliminary analysis of the energy and power that are required to heat the regions used as initial conditions in the 0-D and 1-D models. We use the measured parameters from NIF shot N210808 (near ignition) as a benchmark for comparing the requirements for a burning plasma DT vs pB^{11}. As found in the 0-D scaling, pB^{11} ignition requires compressing to >1000X solid density and heating the plasma to 100-300 keV, which is impossible via hot-spot ignition. We present an initial analysis of the beam parameters required to achieve these conditions via proton fast ignition from analytic estimates, hybrid-kinetic simulations using CHICAGO, and preliminary 1-D HELIOS simulations of beam-target interactions. The results from preliminary simulations of burn propagation using the hybrid TriForce Code are discussed in a companion talk at this meeting [3].

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Modelling pB^{11} burn propagation for inertial confinement fusion

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Abstract

We present a generalised 0D model for studying the hotspot evolution of a pre-compressed and pre-heated ICF fuel target. It is assumed that the spherical hotspot is surrounded by cold, dense fuel in an initially isobaric configuration. Following the methodology developed by Atzeni and Caruso [1], this model simulates the initial deflagration stage of burn propagation, driven by alpha deposition and electron conduction into the shocked region. The ion and electron power balance equations account for relativistic effects in the bremsstrahlung energy loss [2] and ion-electron energy exchange terms [3]. Fusion alphas are assumed to deposit their energy instantaneously, and the energy deposition fractions to hotspot ions, hotspot electrons and shocked fuel are calculated with consideration of both the target geometry and stopping power. For this we use the latest parameterisation of the Li-Petrasso charged particle stopping power theory [4]. Reaction kinetics and suprathermal effects are also accounted for when simulating the hotspot. This model has been validated in the context of DT and correctly predicts the critical ignition conditions. Simulations of pB^{11} show evidence of evanescent burn, but not self-sustaining burn propagation. Even at conditions for ion self-heating, the ion-electron exchange term quickly increases the electron temperature so that bremsstrahlung losses dominate. A fuel gain exceeding unity has been demonstrated with boron-to-proton ratio $\varepsilon = 0.2$, hotspot temperature $T_h > 200$ keV and areal density $\rho R > 3$ g/cm^2. However, a target design with a commercially relevant gain that considers engineering losses remains elusive.

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Flexible experimental platform to study laser-plasma interaction and particle acceleration at the ELI-NP 10 PW laser

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Abstract

Nanostructured targets are capable of efficient energy absorption of ultra-intense laser radiation, resulting in high laser energy conversion into high-ion kinetic energy. This aspect makes them an attractive option for the implementation of a laser-driven fusion concept using a fuel mix of pB and DT. As a potential realization of targets, Marvel Fusion envisions arrays of high-aspect-ratio aligned nanowires capable of efficiently generating high fluxes of fast ions with a tunable spectrum in the MeV range, a concept referred to as Nano Accelerator (NA) [1]. Ultra-intense ($I > 10^{20}$ W/cm^2) and high temporal contrast ($< 10^{-10}$) lasers are essential to provide high laser energy deposition and prevent early-stage ionization of nanostructured targets. The Extreme Light Infrastructure for Nuclear Physics (ELI-NP) hosts one of the most powerful lasers worldwide, capable of delivering 10 PW laser pulses, and with inherent ultra-high laser contrast, characteristics that make it the ideal facility for testing and developing the NA concept.

Within a collaboration with ELI-NP and Thales, Marvel Fusion has recently started a series of experimental campaigns for the Operation of a Direct drive high Intensity Nano accelerator (ODIN) at 10-PW-level at ELI-NP. Here we present the experimental platform deployed in the E6 chamber at ELI-NP and the results obtained. The platform consists of a core system capable of flexibly hosting various kinds of targets at different laser incidence angles. A high-power diagnostic has been implemented to characterize the on-shot 10 PW focus and target transmission. Combined with the evaluation of target specular reflection, these measurements are essential to determine the total energy absorbed by the targets. Moreover, a set of particle diagnostics, including 4x Thomson Parabolas, 4x electron spectrometers, an ion time-of-flight detector, and several filtered CR-39s, were deployed at different angles to characterize the particle spectral distributions, showing efficient energy transfer from the laser to the ions in our NA.

The ODIN platform allows for a full characterization of the coupling between the 10 PW laser pulse and the NA target at 10-shot rate per vacuum cycle, enabling us to evaluate the performances of such targets in the prospect of fusion generation.

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Operation of a direct-drive Nano Accelerator for efficient generation of MeV-energy ions

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Abstract

The interaction of high-intensity laser pulses with near-critical-density materials enables efficient absorption of laser energy, which consequently leads to its conversion to high-energy particles and radiation. However, scaling this process to laser powers of multi-PW and beyond requires careful consideration of the laser propagation in the material, as local electron-density inhomogeneities can lead to uncontrolled laser modulations that prevent sustaining an efficient conversion process within larger volumes. A solution to this problem is to use ordered nanostructured arrays with sub-wavelength features; a system dubbed as a Nano Accelerator[1]. In such targets, a homogeneous electron density is maintained across the target while avoiding destructive laser modulations throughout the absorption process in the interaction volume. This consequently leads to an efficient absorption of the laser energy and its conversion to high-current ionic beams in a controlled manner. In the future, this technology may allow scaling the process to exawatt-class lasers to produce high ion currents for fusion-energy power plants and other applications.

In this contribution we will present the first demonstration of the Nano Accelerator driven by 10 PW laser pulses. Experiments were conducted with the HPLS laser at the Extreme Light Infrastructure for Nuclear Physics (ELI-NP), which was operated at approximately 200 J of energy on target at a pulse duration of 23 fs. The original focusing geometry was modified from F/60 to F/20 leading to intensities of approximately 5×10^{20} W/cm^2. For this initial demonstration, structured, high-aspect-ratio (length vs. diameter), nanowire arrays of various geometries were investigated, including arrays with wire diameters down to 50 nm and lengths beyond 20 µm. With an inter-wire spacing of 800 nm and above, the average relativistic electron density was kept to near-critical values. By monitoring the specularly reflected laser light and capturing the ion spectra via Thomson Parabola & CR-39 spectrometers we demonstrate an efficient conversion of laser energy to high-energy ions. In addition, we show the possibility of controlling the emitted ion spectra by varying the nanostructure parameters. Finally, we will discuss prospects of using the Nano Accelerator towards driving targets containing mixed fusion fuels for energy production

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Properties of non-cryogenic DTs and their relevance for fusion

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Abstract

In inertial confinement fusion, pure deuterium-tritium (DT) is usually used as a fusion fuel. However, as pure DT is a gas at room temperature, this requires cryogenic technology with significant associated costs. In their paper [1], Guskov et al. suggest using low-Z compounds that contain DT and are non-cryogenic at room temperature. They showed that these fuels (here called non-cryogenic DT) can be ignited for ρDTR ≥ 0.3 g cm−2 and kTe ≥ 14 keV, i.e., parameters which are about threefold higher but still in the same order of magnitude as those for DT. In deriving these results the authors in [1] assume that ionic and electronic temperatures are equal and consider only electronic stopping power. Here show that at temperatures greater than 10 keV, ionic stopping power is not negligible compared to the electronic one. We demonstrate that this necessarily leads to higher ionic than electronic temperatures. Both factors facilitate ignition compared to the model used in [1] showing that non-cryogenic DT compounds are more versatile than previously known. In addition, we find that heavy beryllium borohydride ignites more easily than BeDT. Our results are based on an analytical model that incorporates a detailed stopping power analysis, as well as on numerical simulations using a version of the community hydro code MULTI-IFE. Simulating a kicked tamper scenario consisting of high-Z material radially compressing the fuel, we furthermore show that non-cryogenic DT fuels are capable of producing high gain at external energy levels much lower than those predicted in [1]. Alleviating the constraints and costs of cryogenic technology and the fact that non-cryogenic DT fuels are solids at room temperature opens up new design options for fusion targets and thus contributes to the larger goal of making inertial fusion energy an economically viable source of clean energy. In addition, the discussion presented here generalizes the analysis of fuel mixes for energy production.

Numerical investigations of the conditions related to (Pfus/PBrems) > 1 in low-density proton -Boron fusion plasma

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Abstract

The neutron-free p11B fusion reaction generates three (3) iso-energetic alpha particles with 8.7 MeV total energy, that can be converted into electricity without passing through a thermodynamic cycle [1, 2]. However, the up today alpha particle measurements from non-thermal p11B fusion experiments [3, 4, 5, 6], with a record of $\approx$ 1011 alpha particles per laser shot [7], haven't demonstrated break-even ignition$\{Q = (Pfus / PBrems) = 1\}$. In this context and according to the theoretical and numerical works of [8, 9, 10], a self-sustained p11B fusion ignition ($Q > 1$) may be attributed to the chain reactions effect and the related avalanche alpha heating effect. The latter effects concern the heating of the fusion medium and the generation of an alpha particles avalanche, through the rise of the p, 11B species temperatures, within the optimal reactivity region ($300 \text{ keV} < T \leq 700 \text{ keV}$) [8, 9, 10]. A self-consistent multi-fluid global particle and energy balance code [10, 11], with collisions between all medium species and Bremsstrahlung radiation losses, enables the temporal description of the fusion medium physical parameters. Bremsstrahlung losses are optimized, considering density ratios between the p, 11B species ($\varepsilon = np / nB > 1$) [1, 10, 12, 13, 14]. According to our previous work [15], a low – density, fully ionized p11B medium $\{n = 1020 \text{ m } -3 , (np / nB) > 1\}$, may be ignited ($1 \leq Q \leq 1.25$) in the initial temperature range of $130 \text{ keV} \leq Tin \leq 400 \text{ keV}$ [10], as a consequence of the avalanche effect manifestation at a lower bound of alpha particle production. The present numerical study uses the same model with [10, 11] and investigates the potentiality of the obtainment of enhanced low-density ignition conditions ($Q > 1.25$), below $Tin < 100$ keV. For this purpose, two (2) medium configurations are considered, referring to the injection of energetic protons ($100 \text{ keV} \leq Ep,0 \leq 700 \text{ keV}$) in a p11B or a 11B medium with density ratios: $(np / nB) > 1$ and initial temperature in the range of: $1 \text{ keV} \leq Tin \leq 400 \text{ keV}$. The proposed configurations could be classified as "hybrid", similar to those presented in [16]. The numerical results show ignition below $Tin < 100$ keV and optimum ignition conditions up to $Q \sim 1.4$, as a direct consequence of the triggering of the avalanche alpha heating effect, by the energetic protons. The proposed initial plasma temperature conditions and the generation of energetic protons are feasible to be achieved with the currently existing laser-based technologies [e.g. PW laser of ELI - Romanian pillar].

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Kinetic simulations of proton-boron fusion burn waves

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Abstract

Fast ignition by laser-driven ion beams [1] of proton–boron plasmas offers a possible path towards clean fusion energy. This process consists of two primary stages: first, an isochoric high-density plasma is assembled by spherical compression; then, an ion beam strikes the target increasing the temperature of the compressed plasma to fusion relevant conditions. In this presentation, we investigate the conditions that must be achieved in the second stage of a fast-ignition experiment to ignite the target using a particle-in-cell code with Monte Carlo collisions (PIC-MCC) [2]. The PIC-MCC approach allows us to study the kinetic physics present in the release of the fusion hot-spot such as non-local transport and non-thermal velocity distributions. In addition to simulating Coulomb collisions and fusion reactions, we model bremsstrahlung emission and inverse bremsstrahlung absorption. Radiation is particularly important to include in studying these systems because radiation emission increases with atomic number, density, and temperature as $(Zn)^2T^{1/2}$. For a configuration with an ion ratio n_B/n_p=0.2, an initial density of 1000 g/cc, a hot-spot temperature of 200 keV, and surrounding plasma of 10 eV, the model predicts that the radiation emitted by the hot-spot is re-absorbed by the surrounding fuel heating it up to 30 keV within 20 ps. This reduces the amount of work that the expanding hot spot must do on the plasma to heat it to ignition conditions.

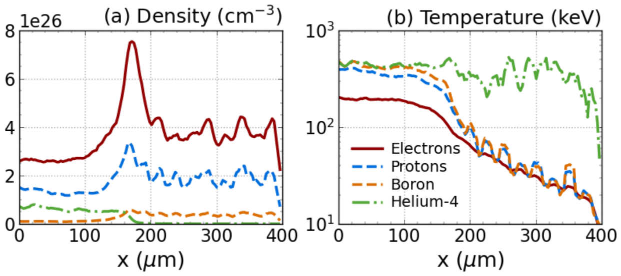

Figure 1. Density and temperature profiles at 15 ps of a 200 keV hot-spot expanding into an initially 10 eV plasma at 1000 g/cc. The ion temperature has increased by a factor of two in the hot region by fusion heating and by a factor of 1000 in the cold region by inverse bremsstrahlung absorption.

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Low temperature fusion ignition of p11B medium by D-T energetic alphas

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Abstract

Our previous numerical results for a low density p11B fusion medium (n ~ 1020 m -3) show ignition: 1 ≤ (Pfus / PBrems) ≤ 1.3, in the relatively high initial temperature range: 150 keV ≤ Tin ≤ 350 keV [1, 2, 3, 4, 5], as a consequence of Bremsstrahlung losses optimization {(np / nB) > 1}, and the avalanche alpha heating effect [6, 7, 8, 9]. The important fusion species temperature rise occurs in time, when the produced alpha particle density is approximately two (~2) orders of magnitude lower, than the total initial medium density. Configurations based on the injection of energetic protons or alpha particles [3, 4, 10] in a low - density p11B medium enable enhanced fusion ignition below Tin ≤ 100 keV. The main challenges in low - density fusion - oriented configurations are: (1) The p11B medium maximum volume for the obtainment of a significant output power, (2) The density of the injected energetic species (protons or alphas) and (3) The ignition of the medium at the lowest possible initial temperature (~1 -10 keV). Laser beams are capable to produce high energy species with relatively low densities, to be used in big fusion volumes. In the current work, we investigate through numerical simulations, a new low - density p11B plasma configuration, that may enable fusion ignition from a relatively low initial temperature (~10 keV), compared to the high initial medium temperatures of [11, 12, 13, 1]. In the proposed configuration, the low - density fuel mixture (n ~ 1020 m-3) is composed by p11B and D-T or (D3He), with appropriate density ratios. The nuclear fuels of D-T and D3He require relatively lower energies for fusion ignition, compared to the p11B nuclear fuel and produce energetic particles, that may transfer their energy to the low - temperature (p, 11B) fusion species. Thus, the main idea is to ignite a low - temperature [(p11B) – (D-T)] medium and achieve high p, 11B fusion species temperatures, through the energetic alpha heating from D-T in the whole medium volume. This means that, D-T (or D3He) will work as a booster, just for the first step of ignition of the low - temperature p11B medium (Tin ~ 10 keV). Continuous injection of low temperature p - 11B species will allow the sustainment of the fusion burn. The results are obtained by a multi-fluid code, including collisions between all the species and Bremsstrahlung losses [14, 1]. The simulations show that, for the initial fuel mixture temperature of Tin ~ 10 keV, the maximum D-T reactivity appears, before the observation time of the maximum p,11B fusion species temperatures. Thus, the high – density D-T fusion generated energetic alphas (Eα,0 = 3. 5 MeV), transfer their energy to the p, 11B fusion species, increasing their temperature, within the optimum p11B reactivity region (). At the time of the maximum fusion species (p, 11B) temperatures, the D-T fuel is depleted and the remaining high - temperature fluids (p, 11B and alphas) have the capability to burn the refueled low - temperature p11B medium. Similar numerical results are obtained, using D3He in the fuel mixture, with the advantage of no - neutron generation (neglecting the low neutron production from the secondary DD reaction).

[*] Acknowledgement: This work has been carried out within the framework of the COST Action CA21128- PROBONO "PROton BOron Nuclear fusion: from energy production to medical applications", supported by COST (European Cooperation in Science and Technology - www.cost.eu).

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Hydrogen- and boron-rich materials, with special focus on ammonia borane NH_3BH_3

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Abstract

In the early 2000s, sodium borohydride $NaBH_4$ (with 10.8% wt% H) was rediscovered for its potential to store and produce hydrogen on demand [1]. This marked the beginning of a renewed interest in hydrogen- and boron-rich materials, especially as hydrogen carriers. By the mid-2000s, ammonia borane NH_3BH_3 (AB), perhaps the most well-known example, was rediscovered [2]. Isoelectronic to ethane, it is solid at room temperature due to the presence of dihydrogen bonds and contains 19.6% hydrogen by mass. This was followed by the emergence of metal amidoboranes, hydrazine borane and its derivatives, mono- and bi-metallic borohydrides, and polyboranes (or boron clusters) [3]. These materials have had varying degrees of success in the field of hydrogen storage, and the less promising candidates have been investigated for other applications, such as liquid fuel for fuel cells or solid electrolytes for metal-ion batteries.

Since 2007, our research activities have been focused on this area. We have studied all of these materials, and more recently, we have directed our efforts towards amine boranes with carbon chains RNH_2BH_3 ($R = C_xH_y$) with two objectives in mind [4]. The first concerns their use as surfactants for the nanostructuring of AB (Figure 1), and the second aims to use them as precursors for porous boron carbonitride ceramics [5]. The targeted applications remain hydrogen storage, but also the storage of gases such as carbon dioxide or ammonia, with the ultimate goal of developing gas purification membranes.

The 4th International Workshop on Proton Boron Fusion is therefore a great opportunity to present an overview of our research activities focused on hydrogen- and boron-rich materials, with AB and our recent work on its nanostructuring as the central theme.

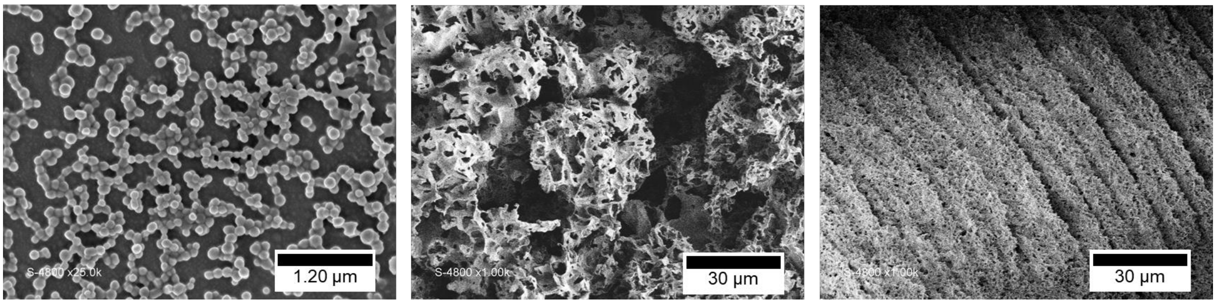

Figure 1. Towards the nanostructuration of AB (unpublished data for the SEM images in the center and on the right).

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Ammonia Borane (AB) and Heavy AB Laser-driven Nuclear Fusion Fuels for Proposed Ion and Neutron Sources

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Abstract

Boranes in general, and in particular Ammonia Borane (AB), H3BNH3, have been proposed [1] as nuclear-fusion fuel-material for laser-targets for direct, or 'in target' laser-driven Proton-Boron (P-B) [2] fusion reactions: 1 1H + 11 5B = 3 x 4 2He + 8.7 MeV/fusion reaction. This is because solid AB contains both fusion nuclei: Boron and Hydrogen, while storing even higher H concentration than liquid Hydrogen. First experiments with laser-driven AB fusion [3] have already generated a normalized Alpha-particle flux equalling record fluxes obtained with other types of target materials [2]. Ref. [1] has proposed to use laserdriven AB-targets to generate tabletop Ion Sources (Alpha and Proton) for applications such as isotope fabrication. AB as well as Diborane, B2H6, fusion fuels could also be considered for fuelling future ProtonBoron Fusion Energy Reactors [1]. Heavy- AB, see below, was already considered a potential fuel for Deuterium-Tritium Fusion Energy Reactors [4], and we also propose Heavy-Diborane as future DT or DD fusion fuel. Indeed, the number density of DT is over two times higher in solid Heavy-AB at normal temperature than in solid cryogenic DT fusion fuel. We now propose to extend our studies of AB nuclear-fusion fuel-materials for laser-targets to 'Heavy AB' in which the Hydrogen atoms are replaced by Deuterium (D) or even Tritium (T): D3BND3 for DD fusion (2 1D + 2 1D = 3 1T + 1 0p + 4 MeV/fusion or 2 1D + 2 1D = 3 2He + 1 0n + 3.3 MeV/fusion) or even D3BNT3 for DT fusion (2 1D + 3 1T = 4 2He + 1 0n +17.6 MeV/fusion). We would like to compare the ion fluxes emitted AB and Heavy-AB identical targets when irradiated by laser in identical conditions. We expect even higher nuclear-fusion-yield from

laser-irradiated Heavy-Hydrogen-AB than from AB because the fusioncrossections are higher at same kinetic energies of fusing particles. Heavy-Hydrogen fusion generates neutrons which escape the fusion-target and can be measured exactly, unlike Alpha particles from ProtonBoron fusion. Therefore, one could better characterise experimentally, the laser-plasma conditions (leading 2 to the Heavy-Hydrogen fusion) in Heavy-AB targets compared to AB targets. Since the targets and irradiation conditions are identical one could use the particle emission from Heavy-AB targets to better understand the P-B fusion conditions in AB targets by comparing the respective fusion particle fluxes, and fusion crossections, for example. Heavy-AB can be synthesized by using Deuterated [5] or Tritiated precursors to AB formation. Using both AB and Heavy AB fusion-fuels would extend the range of laser-driven Ion Sources to: Proton (3MeV and higher), Alpha (1-8MeV), 3He (0.8MeV), Tritium (1MeV and higher), Deuterium (several MeV), and even Neutron Sources with 2.45MeV or 14.06MeV neutron energies. This increase in the Source type of particles will also extend their applications. For isotope generation we proposed the target-nucleus for isotope production could be included in the AB molecule for efficient nuclear interaction [1]: let us call this the "in-molecule isotope-target nucleus' concept. A good example is the isotope production for Positron Emission Tomography (PET) using the accelerated Proton or the fusion generated Alpha-particle interacting with the Nitrogen nucleus in the AB [1] or Heavy AB fusion fuel: 14N (p, α) 11C (half-life = 20.4min) or 14N (α, γ) 18F (half-life = 109.8min). We propose to extend this concept to more borohydride molecules like, for example Al (BH4)3 laser-target materials to generated 30P (half-life = 2.5min) PET from:27Al (α, n) 30P. Add the large variety of metal borohydrides like: Na (BH4) , Ca(BH4)2 , In(BH4)3 , NaSc(BH4)4 [6], etc., and indeed the class of metal derivatives of BNH materials like Na(NH2BH3) or Ca (NH2BH3)2 . Proposed AB [1] and Heavy AB fusion fuel targets for such laser-driven Ion Sources could be either solid micro- or nano- crystals, single crystals, pressed in pellets or coated on tapes as well as high repetition liquid (molten) borane droplet targets. The high repetition laser and targets will increase the time-average Flux of the Ion source [1]. Examples of AB micro- or nano- crystals fabrication aro also shown in [7] and [8]

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Potential Boron Materials for Proton-Boron Fusion

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Abstract

Proton-Boron (pB) fusion is an advanced nuclear fusion reaction offering a cleaner alternative to traditional fusion methods. pB fusion has great potential to be used in high-tech application from medicine to energy production. Since Boron-11 will be used for pB fusion reaction, Boron based substances could be accepted as fuel for pB fusion technique. Recent studies showed that Boron nitride (BN) and Ammonium borane (NH_3BH_3) come to the fore from the other Boron containing candidates. In this study, physical, mechanical and chemical properties of BN and NH_3BH_3 were investigated for being usage potential pB fusion applications (1). BN offers several advantages for proton-boron fusion reactors, including high thermal stability, chemical inertness, excellent thermal conductivity, and effective neutron absorption, making it ideal for plasma-facing components and thermal management systems (2). Additionally, BN's properties as an electrical insulator and its resistance to radiation and mechanical stress enhance the safety and longevity of fusion reactor components (3). Despite its advantages, BN can be expensive to produce and process, which might increase the overall cost of fusion reactor construction. In addition, BN's brittleness can be a limitation, as it may be prone to cracking under mechanical stress, potentially affecting the durability of reactor components (4). Borane compounds were next interesting materials for proton Boron fusion applications. The most studied borane compound was NH_3BH_3 due to its high hydrogen density, chemical stability, ease of decomposition at relatively low temperatures, and low toxicity, making it an efficient and safer hydrogen source (5). Moreover, its versatility in fuel preparation allows for flexible application in various fusion reactor designs. NH_3BH_3 can be challenging to handle due to its sensitivity to moisture and potential for rapid decomposition under certain conditions, posing storage and stability issues. Furthermore, its production and processing can be complex and costly, potentially increasing the overall expenses for fusion reactor operations. Other borane compounds that could be used as laser-target materials for proton-boron fusion include Ammonia-Borane (BNH_6 or H_3BNH_3) and Lithium-dodeco-closo-dodecaborate ($Li_2B_{12}H$). Hydrogenated boron materials increase hydrogen content, enhance stability, and improve neutron absorption, making them useful for fusion reactions. However, their complex and expensive synthesis, along with storage and handling challenges and the risk of premature hydrogen release, pose significant drawbacks (6). Borophene holds significant potential for use in proton-boron fusion reactors due to its high thermal conductivity, mechanical strength, flexibility, and unique electronic properties. These attributes could improve the efficiency, stability, and durability of fusion reactor components, contributing to the advancement and feasibility of proton-boron fusion as a sustainable energy source. However, further research and development are necessary to fully understand and optimize Borophene's application in this context (7). Current developments are promising, but there is a need to develop high-tech materials for the future.

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Boron Hydrides: A Fuel of Choice for p-B Fusion?

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Abstract

The search for an optimal pB fuel remains in its infancy and yet it is a key aspect for the ultimate success of useful pB fusion. Hitherto, all tested pB fusion targets comprised compounds of boron with heteroelements such as nitrogen, silicon, or carbon-rich polymer films, offering only sparse boron content and multi-element contamination that interferes with the pB fusion process by diverting energy from the system. It is, therefore, of interest to investigate the potential of a group of compounds containing only atoms of hydrogen and boron - the boron hydrides (commonly referred to as the boranes) as fuels for the pB fusion process. The boranes are a broad family of spherically-aromatic molecules with polyhedral cluster geometries of atoms of boron surrounded by a sheath of hydrogen atoms. They do not occur naturally, but are readily synthesized in specialised laboratories (like our own) from abundantly available natural materials, where multi-gram and kilogram scale production is feasible.

Within this contribution, we present the first demonstration[1] of the use of solid boranes as a pB fuel (within an "in-target" geometry) and show, for first time, that the solid boron hydride, octadecaborane - *anti*-$B_{18}H_{22}$, produces a relatively high yield of alpha particles of about 10^9 per steradian using a sub-nanosecond, low-contrast laser pulse (PALS) with a typical intensity of 10^{16} Wcm^{-2}.[1] We also provide an overall perspective of boron hydride materials as targets for laser-driven pB fusion.

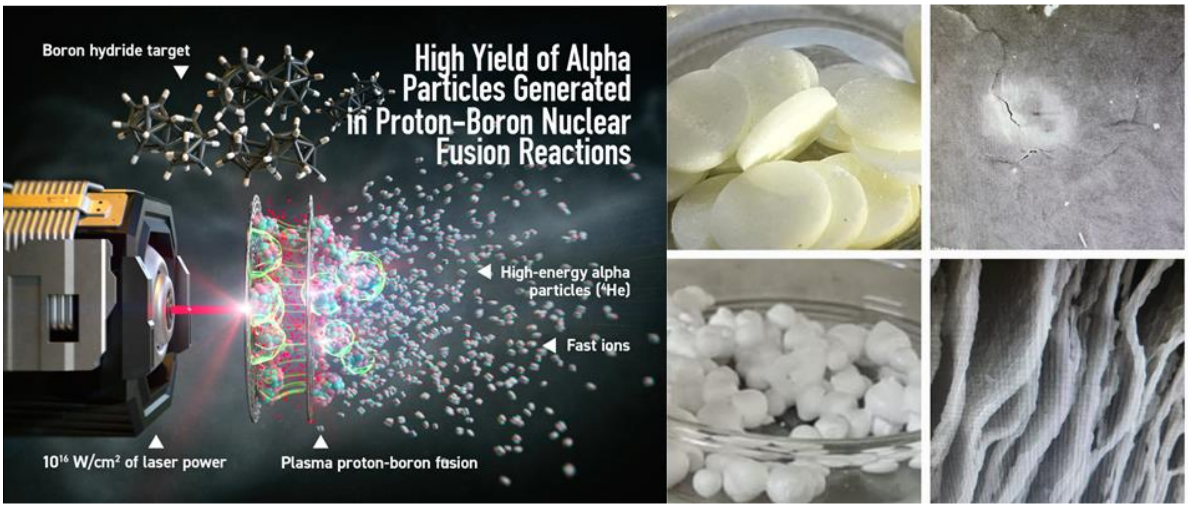

Figure 1. pB fusion from $B_{18}H_{22}$ targets - compressed discs and porous foams.

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Commercially Attractive Fusion Energy-Challenges and Opportunities

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Abstract

The past several years have witnessed significant progress in the science of laboratory fusion. Of particular note, is the demonstration of fusion scientific gain, Q_{sci}, the ratio of fusion energy output to the incident energy to heat and confine the plasma, greater than one at the National Ignition Facility (NIF) with deuterium-tritium (DT) fuel. This achievement is the first time that Q_{sci} was achieved for ANY fusion concept. It is also important to recognize that NIF was designed and built with technology available in the 1990's and with science, rather than energy, as its mission and motivation.

The Q_{sci} achieved on NIF, with the most explored and easiest fuel to achieve gain (DT) is far less than that required for commercially attractive fusion energy. This presentation will focus on the requirements and challenges that must be met for commercially viable fusion energy, with an emphasis on laser driven Inertial Fusion (ICF) including the use of proton -boron fuel.

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Radioisotopes production using lasers: from basic science to applications.

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Abstract

Laser technologies have advanced significantly with the understanding of Chirped Pulse Amplification (CPA), which allows energetic laser beams to be compressed to tens of femtoseconds (fs) pulse durations and focused to a few micrometers (μm). Protons with energies of tens of MeV can be accelerated using methods such as Target Normal Sheath Acceleration (TNSA) and focused on secondary targets. Under these conditions, nuclear reactions can occur, producing radioisotopes relevant for medical purposes. High repetition lasers can produce sufficient isotopes for medical applications, making this approach competitive with conventional methods that rely on accelerators. The production of the ^{67}Cu, ^{63}Zn, ^{18}F, and ^{11}C were investigated [1] at the 1-petawatt (PW) laser facility at Vega III in Salamanca, Spain. These radionuclides are used in positron emission tomography (PET) and other applications. The reactions ^{10}B(p,α)^{7}Be and ^{70}Zn(p,4n)^{67}Ga were also measured to further constrain proton distributions at different angles. The nuclear reaction products were investigated using the pitcher-catcher method, with protons produced by an aluminum target and impinging on various targets in both the forward and backward directions relative to the laser. Angular distributions of radioisotopes were measured using a High Purity Germanium Detector (HPGE). Our results, presented in detail in Rodrigues et al. [1], are reasonably reproduced by numerical estimates following the approach of Kimura et al. [2]. Preliminary results from radioisotopes production tests performed at ELI Beamlines Facility, Czech Republic, will be also presented. Laser technologies are mature enough to compete with accelerators for medical radioisotope production. While costs for construction, space, maintenance, etc., may attest to their competitiveness, the results suggest that this may be a more advantageous technology.

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Production of ^{11}C for PET imaging using a HRR laser-driven proton source

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Abstract

In recent years, there has been a growing interest in laser-driven ion accelerators as a potential alternative to conventional accelerators [1]. A particularly promising application is the production of radionuclides relevant for medical diagnosis, such as ^{11}C for PET imaging. Typically, the production of these nuclides is centralised at cyclotrons, reducing the number of facilities required, but limiting the range of usable radionuclides to those with longer lifetimes [2]. In this context, compact laser-driven accelerators appear as an appealing option for the in-situ generation of short-lived isotopes. Albeit the activities required for PET imaging (>MBq) are well above those achievable from a single laser irradiation (~kBq), the advent of high-power, high-repetition-rate laser systems opens the path to demonstrating relevant activities through the continuous irradiation, provided a suitable target system is developed. A target assembly based on a rotating wheel and automatic alignment procedure for laser-driven proton acceleration at multi-Hertz rates has been developed and commissioned [3]. The assembly, capable of hosting >5000 targets and ensuring continuous replenishment of the target with micron-level precision, has been demonstrated to achieve stable and continuous MeV proton acceleration at rates of up to 10 Hz using our in-house 45 TW laser system [3].

The continuous production of ^{11}C via the proton-boron fusion [^{11}B(p,n)^{11}C] reaction has been recently demonstrated from our target assembly using the 1 Hz, 1 PW VEGA-3 system (CLPU, Spain) [4]. In an initial campaign, an activity of ~12 kBq/shot was measured, with a peak activity of 234 kBq achieved through accumulation of 20 consecutive shots [4]. Furthermore, results of a more recent campaign will be presented, where activation levels in excess of 4 MBq where achieved, as measured through using coincidence detectors, and supported by online measurements of high-flux neutron generation. We demonstrate that the degradation of the laser-driven ion beam due to heating of optics is currently the only bottleneck preventing the production of pre-clinical (~10MBq) PET activities with current laser systems. The scalability to next-generation laser systems will be explored to study the potential for production of clinical (~200MBq) activities.

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Medical-use radioisotopes production using a high-repetition-rate laser system

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Abstract

Radionuclides are used worldwide for medicine for example in diagnostics and therapeutic procedures such as positron emission tomography (PET) imaging and targeted radionuclide therapy once incorporated into a radiopharmaceutical.

Most of the radionuclides require a cyclotron or a nuclear reactor to be produced. We aim to produce them using lasers, for they are more compact and cheaper to both run and maintain, thus bringing radionuclides use into more hospitals.

We performed an experiment using the high-repetition rate petawatt laser VEGA III at the CLPU facility (Salamanca, Spain). This pitcher-catcher type experiment involved several types of catcher target materials, all interacting with the laser-driven TNSA proton beam: calcium-based targets to produce ^{44}Sc (β^+ emitter) and ^{47}Sc (β^- emitter), boron-based targets to produce α particles and ^{11}C and lithium-based targets to produce neutrons.

Results from high purity germanium detector gamma spectrometer show the effective production of scandium radioisotopes from calcium silicate targets ($1\text{x}10^5$ nuclei/shot for ^{44}Sc and $2.5\text{x}10^3$ nuclei/shot for ^{47}Sc), which yields to several patient doses if a high-repetition-rate installation is used and proportionality assumed. We also measure $1.7\text{x}10^7$ neutrons/shot production with LiF targets and thick BN targets allow us to measure $5\text{x}10^6$ α/shot (from the interaction of protons with ^{10}B alone) and $1.6\text{x}10^7$ ^{11}C/shot.

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Laser-Accelerated Proton Beams from Optically Shaped Gasous Targets for Pitcher–Catcher pB Fusion Scheme

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Abstract

Proton-Boron (pB) fusion is currently being explored as a promising alternative for neutron-less, laser-ignited fusion [1]. Two primary experimental approaches under consideration are in-target irradiation and the pitcher-catcher schemes. In this work, we propose investigating a novel pitcher for the pitcher-catcher fusion scheme [2-4]. Specifically, the Boron target (catcher) will be irradiated using proton beams that are accelerated by optically shaped gaseous target profiles (pitcher) in the near-critical density (NCR) plasma regime.

High pressure NCR gaseous targets are considered a promising alternative to solid targets, that can support High Repetition Rate (HRR) debris-free proton sources. Here we present a novel, gaseous profile optical shaping method, capable of generating NCR profiles via multiple laser induced, blastwaves (BWs) [5]. The counterpropagating BWs compress the target upon their shock front collision, achieving steep density gradient plasma slabs of a few microns width. The optical shaping is studied using 3D MagnetoHydroDynamic (MHD) simulations while 3D Particle-In-Cell (PIC) models, are used to simulate the 45 TW fs Zeus laser plasma interaction to demonstrate the efficiency of proton acceleration. Notably, the Magnetic Vortex Acceleration (MVA) mechanism [5] shows high efficiency in coupling laser energy into the target, producing a proton beam energy spectrum well-suited for the realization of the proposed scheme, as confirmed by PIC simulations.

Finally, we present preliminary experimental findings of the shaping of the gas-jet targets, implemented at the experimental chamber of the 45 TW, Ti:sapphire, Zeus laser system, hosted at the Institute of Plasma Physics & Lasers (IPPL) of the Hellenic Mediterranean University [6].

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Generation of alpha particles by laser-driven p+^{11}B fusion reactions at high-repetition-rate

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Abstract

Driving the nuclear fusion reaction p+11B→ 3α + 8.7 MeV in laboratory conditions, by interaction between high-power laser pulses and matter, has become a popular field of research, due to numerous applications that it can potentially allow: a potential alternative to deuterium-tritium (DT) for fusion energy production [1,2], astrophysics [3] and alpha-particle generation for medical treatments [4]. Possible schemes for laser-driven p+11B reactions are to directly irradiate a borated target with energetic laser pulses at high intensity or, alternatively, direct a beam of laser-accelerated protons onto a boron sample (the so-called "pitcher-catcher" scheme). These techniques were successfully implemented, so far, with energetic lasers yielding hundreds to thousands of joules per shot [5-7]. This is possible on a few large installations and for a limited number of shots. Instead, we present here a complementary approach, exploiting the high-repetition rate of the VEGA III petawatt laser at CLPU (Spain), aiming at accumulating results from many interactions at lower energy (20 J in about 50 fs at maximum compression, leading to about 7 J conveyed on target), and at moderate intensity (about 1019 W/cm2), for a better control of the parameters and statistics of the measurements.

In this work, we aim at providing a detailed insight of the effectiveness of the laser-driven p+11B fusion in the pitcher-catcher scheme, at high-repetition rate. Despite a moderate energy per pulse, our experiment allowed exploring the laser-driven fusion process with tens (up to hundreds) of laser shots, leading to an improved optimization of the diagnostic techniques and an enhanced statistics of the obtained results. We will discuss the challenges of implementing this experimental scheme and

highlight its critical aspects, in terms of detection of fusion products and assessment of its performance.

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Experimental and computational evaluation of Alpha particle production from Laser-driven proton-boron nuclear reaction in hole-boring scheme.

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Abstract

The majority of studies on laser-driven proton-boron nuclear reaction is based on the measurement of α-particles with Solid-state nuclear tracks detector (Cr39). However, Cr39's interpretation is difficult due to the presence of several other accelerated particles which can biase the analysis. Furthermore, in some laser irradiation geometries, cross-checking measurements are almost impossible. In this case, numerical simulations can play a very important role in supporting the experimental analysis. In our work, we exploited different laser irradiation schemes (pitcher-catcher and direct irradiation) during a same experimental campaign, and we performed numerical analysis, allowing to obtain conclusive results on laser-driven proton-boron reactions. A direct comparison of the two laser irradiation schemes, using the same laser parameters is presented.

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High-Repetition-Rate experiments of laser-triggered nuclear fusion reactions at ELI-Beamlines

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Abstract

Deuterium-tritium (DT) is the well-known best candidate fuel for future nuclear fusion reactors, because it provides larger fusion cross section at lower energies, with respect to other proposed fuels. But supply and management of radioactive tritium give several serious problems for a future reactor. For these reasons, advanced schemes employing other fuels are now under study. The most promising is $p+{}^{11}B \rightarrow 3\alpha + 8.7$ MeV, where reactants are not radioactive and abundant in nature, but which requires much higher energies than DT for showing cross-sections somehow comparable. Thus, there are today several studies performed on this reaction for future energy purposes (both for magnetic confinement fusion and inertial confinement fusion approaches [1,2]) but also for other reasons: astrophysics [3], alpha-particle generation for medical treatments [4], ... These experimental studies were successfully implemented, so far, with energetic lasers yielding hundreds to thousands of joules per shot [5-7]. This is possible on a few large installations and for a limited number of shots.

Instead, we proposed a complementary approach, with much lower pulse energy but exploiting high-repetition rate laser-systems at PW-power scale [8,9], implementing the 'pitcher-catcher' scheme for $p+{}^{11}B$ reaction with laser intensities about 10^{19} W/cm^2 in VEGA III PW laser. In this work we describe the experiments recently performed with the same scheme at L3 laser facility at ELI-Beamlines with much higher intensity: about 10^{21} W/cm^2. Moreover, we exploited the potential of the in-target scheme for the same laser but this time with deuterated targets to trigger DD nuclear reactions. Both the two schemes were successfully implemented and triggered the related reactions and, in this presentation, we are going to give details of them and of the preliminary results achieved.

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Angular distribution of TNSA-accelerated protons towards pitcher-catcher scheme optimization in p-^{11}B experiments

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Abstract

In laser-plasma interaction, for experiments aiming at optimizing proton-Boron reaction, it is crucial to identify possible sources of instabilities that can affect the reproducibility of sequential shots and so alpha particle emission. Due to the necessity of attaining a good statistics, employment of high repetition rate lasers is gaining more and more interest, also linked to the significative ongoing improvements of the laser technology. These kind of lasers are specially suited for testing laser-driven beam acceleration schemes, as for example in Extreme Light Infrastructure facilities. Despite the fact that these infrastructures are now widespread and widely used, a critical point to address is the level of reproducibility that can be obtained in nominally identical shots and, how the stochastic variations of the interaction can affect the spectra of the accelerated ions at different angles. We present experimental results of proton spectra achieved with both TOF diamond detectors and Thomson spectrometry arranged at different angles with respect to the target normal in the framework of an experimental campaign, at the VEGA III laser at CLPU (Salamanca). The interaction regime is based on pulses having duration in the order of 220fs, laser intensities up to 10^{20}W cm^{-2} and about 25J

energy on solid targets. We show results obtained considering a statistical analysis of a significant number of similar shots.

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First comprehensive study of the 11B-p fusion reaction using a sub nanosecond laser in both in-target and pitcher-catcher schemes

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The ^{11}B (p,α)2α reaction, involving the fusion of low-energy protons (p) with a ^{11}B nucleus to produce three alpha particles (α), has emerged as a promising alternative or complementary approach for clean and efficient energy generation. In this study, the nuclear fusion channel of the p-^{11}B reaction was initiated by a sub-nanosecond laser pulse focused onto 10 µm thick boron-doped thin targets, with intensities around 10^{16} W/cm². The experiment was conducted at the Prague Asterix Laser System (PALS) facility using the Asterix laser, which operates at a fundamental wavelength of 1315.2 nm and delivers an average energy of 600 J within a 300 ps (FWHM) pulse duration on target. Two acceleration schemes were examined: the *in-target* and the *pitcher-catcher* configurations.

In the *in-target* scheme, the longitudinal ponderomotive force generated by the intense laser pulse creates an electrostatic field that accelerates protons from the front surface of the target, prompting direct interactions with boron ions within the same target. Conversely, in the *pitcher-catcher* scheme, the first target is employed to produce energetic protons, which subsequently collide with a second target composed of ^{11}B.

A thorough characterization of the alpha particle flux and angular distribution was achieved using multiple diagnostic tools, including Silicon Carbide and Diamond detectors in a Time of Flight (TOF) configuration, CR39 track detectors, and Thomson Parabola Spectrometers (TPS). These diagnostics facilitated the measurement of key characteristics of particles generated in both the backward (target front side) and forward (target rear side) directions, as well as from the secondary target. The concurrent analysis of the two acceleration schemes yielded significant insights into the p-^{11}B reaction. Alpha particles with energies up to 8 MeV were observed in the *in-target* configuration, surpassing those in the pitcher-catcher setup. Furthermore, the deployment of various diagnostics led to the development and validation of a precise method to distinguish alpha particles from the proton background. The use of multiple complementary diagnostics was crucial in determining the proton energy cut-off, as well as the angular and energy distribution of the emitted particles. A total of 10^{12} alpha particles per solid angle were detected, with a clear dependence on the angle of emission. On the other hand, the *pitcher-catcher* scheme demonstrated an alpha particle distribution that perfectly aligns with the classical cross-section emission, as expected. Owing to the encouraging and remarkable results achieved during the aforementioned experimental campaign, a project has recently been funded by the INFN (Istituto Nazionale di Fisica Nucleare) on this topic. The international initiative, entitled FUSION (FUsion StudIes of prOton boron Neutronless reaction in laser-generated plasma), aims to enhance the fusion reactions and investigate the mechanisms of interaction to optimize the production of alpha particles in the p-^{11}B field.

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Advancement of Alpha Particles Detection and Visualization using CR39 detectors in Proton- Boron Fusion

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Abstract

The objectives of this research are to present preliminary results on dependency of alpha particle generation efficiency on different compositions of primary targets comparing both the "pitcher-catcher" and “in plasma” schemes. This will allow a comparison to be made between the quantity and characteristics of generated alpha particles in proton-boron fusion. In this study specific targets and irradiation schemes designed to optimise alpha yield and fusion rates. Furthermore, sophisticated diagnostic systems are employed to reconstruct the alpha angular distribution and discriminate between emitted charged particles. This Experiment is performed at the Prague Asterix Laser System (PALS) facility in Prague. Concurrent measurements are taken for "in plasma" and "pitcher-catcher" combinations. The fusion reactions are initiated in a plasma generated by long-pulse laser (600 ps) that interact with primary target which consists of various types of boron-based materials (polymer-boron and polymer-boric acid mixtures prepared with different compositions by varying the weight ratio between polymer and boron or boric acid) with a thickness of about 3 mm and a boron/polymer ratio of 10-20-50% and reference (acrylic resin alone) not containing any boron content. The protons in the generated plasma accelerated from the primary target surface to a maximum energy of around 1.5 MeV, they were directed onto a secondary target composed of 200 micron-thick neutral boron that was positioned perpendicular to the primary targets normal. The detecting system has a variety of diagnostic instruments to measure the charged particles that are produced by both primary and secondary targets. The CR39 detectors have been widely used and equipped with aluminium filters of varying thicknesses to block heavier ions and differentiate particles based on their Linear Energy Transfer (LET). This procedure facilitates the estimation of different energy contributions and reconstruction of the alpha-particle spectrum. CR39 detectors are precisely positioned forward and backward relative to the laser propagation axis. Time of Flight (ToF) silicon carbide (SiC) and diamond detectors have been placed next to the CR39 detectors at similar detection angles to the primary and secondary targets for energy distribution measurements and identification of plasma ions and alpha particles. To undertake an accurate analysis, two Thomson Parabola (TP) spectrometers are employed. The location of one TP spectrometer is positioned approximately 0° with respect to the primary target's normal, which is anticipated to have the maximum number of protons. The second TP spectrometer is in the backward direction.

Our results show that increasing the alpha particle rate can be accomplished with an optimised target containing a high concentration of ^{11}B. This can lead to improvements in fusion efficiency as well as insightful understanding of the processes underlying alpha particle generation.

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Diamond Array Detector and Monte Carlo code for p11B reaction products discrimination

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Abstract

In order to improve, investigate and explain the p11B fusion reaction in plasmas, the FUSION project aims to bring novelty in several aspects thanks to a synergy of different branches. Besides optimizing the reaction scheme using various laser systems, new targets, and the most advanced simulation tools, optimizing and enhancing diagnostic techniques for plasma and the resulting reaction products is crucial. Diagnostics such as Time-of-Flight (ToF) detectors results of paramount importance to obtain useful information about the experiment.

Thanks to the excellent physical properties of diamond, such as its wide band-gap, fast response time, and radiation hardness, diamond detectors are among the alternative diagnostic tools for next-generation fusion machines. In view of this, a prototype diamonds array device was built at University of Rome 'Tor Vergata' and tested at the PALS laser facility (Prague) for the FUSION experiment.

Six diamond radiation detectors with a sandwich structure, incorporating metal, intrinsic diamond and metal again were realized and calibrated. The fabrication includes a high-purity intrinsic diamond layer deposited through Microwave Plasma Enhanced Chemical Vapor Deposition (MP-CVD) into a low-cost substrate of High-Pressure-High-Temperature (HPHT) diamond. Each diamond was microwire bonded in a PCB and an appropriate aluminum housing was constructed for shielding the EMP noise and for allocating two passive CR39 detectors. On the same side, six circular pinholes were created above the corresponding six diamond unit, to which aluminum filters of different thicknesses are applied to allow efficient discrimination of the particles impinging through their stopping power.

A code written in Python, integrated with the SRIM/TRIM simulation code, was developed. The aim of the code is to process particle distribution (dN/dE) given as input to retrieve the ToF signal that this distribution generates on the diamond array (or in a ToF detector, in general). This can lead to have an hybrid predictive scenario where simulation results are merged with real data in order not only to obtain speculative outcomes on the origin of the signal, but also a robust method of comparison and compatibility of results with other diagnostics, such as the CR39, included in the device, or Thomson Parabola. This code aims at developing a signal prediction tool based on experimental conditions, to provide precise design and optimization guidelines for the diamond detector unit and its electronics.

This work has been carried out within the framework of the COST Action CA21128-PROBONO “PROton BOron Nuclear fusion: from energy production to medical applications”, supported by COST (European Cooperation in Science and Technology -www.cost.eu).

FUSION Experiment and measurement of ion stopping power in plasmas

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Abstract

The FUSION project (FUsion Studies of prOton boron Neutronless reaction in laser-generated plasma) aims at enhancing the efficiency of p-11B fusion reaction in plasma; the applications of this process are very interesting, from massive energy production to laser-driven ion acceleration. One of the fundamental aspects for the development of this technology is the energy loss of involved ions in plasmas. While ion stopping power in cold matter is now relatively well known and has been characterized with the help of a large set of experimental data and renowned studies (starting from the work conducted by Bethe almost a century ago [1, 2]), a lot of open questions remain when it comes to ions stopping in ionized matter, i.e. in a plasma, especially in the energy range where projectile ion velocity approaches the one of free plasma electrons. Theoretical and semiempirical simulations are thus essential to ensure appropriate experimental designs and interpretation of results. However, in the aforementioned energy domain there is a lack of experimental constraints, needed to tune-up the simulations; in particular, data reported in literature are few and in poor agreement with prediction of existing models. The main aim of this work is a systematic and careful measurement of stopping power for several ions versus plasma parameters, especially in the region of thermal velocities, where the energy deposition should depend strongly on plasma temperature, density and ionization fraction. This contribution will provide an overview of the proposed techniques, and the results obtained during first tests for the characterization of experimental apparatus.

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4th International Workshop on Proton-Boron Fusion
30th September – 3rd October 2024
FRASCATI, ITALY

Compact Ion Beam System for Studying D-D and p-B11 Fusion Reactions

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Abstract

We demonstrate a compact ion beam device capable of accelerating $H+$ and $D+$ ions up to 75 keV energy, on to a solid target, with sufficient beam current to study fusion reactions. The ion beam system uses a microwave driven plasma source to generate ions that are accelerated to high energy with a DC acceleration structure. The plasma source is driven by pulsed microwaves from a solid-state RF amplifier, which is impedance matched to the plasma source chamber at the ISM band frequency (2.4 - 2.5 GHz). The plasma chamber is held at high positive DC potential and is isolated from the impedance matching structure (at ground potential) by a dielectric-filled gap. To facilitate the use of high-energy-particle detectors near the target, the plasma chamber is biased to a high positive voltage, while the target remains grounded. A target loaded with deuterium is used to study $D-D$ fusion and a $B4C$ or $LaB6$ target is used to study $p-11B$ fusion. Detectors include solid-state charged particle detector and a scintillation fast neutron detector. The complete ion beam system can fit on a laboratory table and is a useful tool for teaching undergraduate and graduate students about the physics of fusion.

Laser-driven generation of high-flux and energetic alpha particles through novel target schemes

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Abstract

High-intensity lasers can accelerate ions to MeV energies capable of driving proton-boron (pb) fusion reactions and generating multi-MeV alpha particles [1]. For applications (e.g., radioisotope production), improving laser-to-alpha conversion efficiency, energy spectrum, and angular distribution of the alpha particle beam is beneficial. We present experimental and numerical investigations demonstrating the generation of up to 5x10^7 alphas/sr/J (see Figure 1) from novel target geometries with moderate laser parameters (~10J, 800 fs, 10^{19} W/cm^2) through the implementation of several low-density depositions which improve laser-energy absorption into protons [2], thus enhancing the pb fusion reaction yield. This is comparable to the highest reported yields achieved with kJ-class[3] and ultra-high-intensity laser systems[4]. In addition, we show the results of a numerical study based on a novel laser-target interaction scheme capable of generating highly energetic (>20 MeV) beamed alpha particle streams desirable for medical radioisotope [5] production.

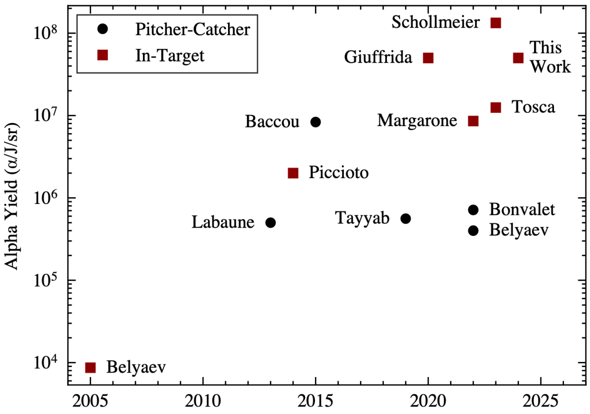

Figure 1. Summary of alpha-particle yield, normalized by laser energy from recent laser-driven pb fusion experiments.

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Experimental Study of p-11B fusion in the 50-240keV Range

Di Luo

Abstract

The proton-boron fusion ($11B + p \rightarrow 3\alpha + 8.7$ MeV) has a lower cross-section compared to the deuterium-tritium reaction, but it has the advantages of abundant fuel and a reaction process that does not directly produce high-energy neutrons. We utilized the accelerator in the Institute of Modern Physics to carry out experimental research on the proton-boron fusion for the range 50 to 240keV.Through experiments of the proton beam interacting with solid boron targets/hydrogen-boron targets/carbon-hydrogen-boron targets, we measured the alpha particles and characteristic gamma spectral lines. We found that the yield of alpha particles for the hydrogen-boron target is higher than the boron target at the same proton energy; the ratio of $\alpha0$ to $\alpha1$ reaction channel increases rapidly around 170keV; if a high-intensity beam is used on the carbon-hydrogen-boron target, an increase in the yield ratio is observed. The characteristic spectral lines of 4.4MeV and 11.7MeV generated by the gamma channel ($11B + p \rightarrow 12C + 16.1$ MeV) were measured and the ratio of gamma to alpha was obtained.

Application of cavity-type target geometry in proton-boron fusion reactions driven by high-power, nanosecond laser pulses

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Abstract

The rapid growth of interest in laser induced proton-boron reaction resulted in numerous experiments, majority of which utilized short-pulse, high-intensity laser systems. However, no reports of employing laser pulses exceeding sub-nanosecond range are found in literature. The results of numerical simulations presented in this work prove that it is possible to obtain thermodynamical parameters of the plasma which are sufficient to drive deuterium-deuterium fusion reactions by employing the cavity-type geometry (Cavity Pressure Acceleration mechanism[1]) with high-power, nanosecond-long laser pulses. Radiation-hydrodynamics simulations performed using the FLASH code[2] show that up to fourfold increase in electron temperature, while maintaining higher density and pressure of the plasma, can be obtained in this scenario compared to irradiating a flat target of the same material. This approach, previously tested using ps-class laser system[3,4], in principle allows to generate multi-MeV proton beams via one of the thermonuclear D-D reaction channel rather than Target Normal Sheath Acceleration mechanism, which is a widely used technique for ion acceleration with short pulse laser system. Such target geometry, tailored specifically for L4n beamline at ELI-Beamlines (Czech Republic), for the first time will be applied in pitcher-catcher configuration of proton-boron fusion related experiment in the near future.

Acknowledgements

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Equation of State of Shock Compressed BN in the Megabar Pressure Range

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Abstract

The interest in the behavior of boron nitride (BN) in extreme conditions is largely justified by recent renaissance in hydrogen boron fusion studies and by the perspective of application of this material as ablator in ICF in alternative to diamond (high density carbon, HDC). In particular, hydro simulations related to hydrogen boron fusion will need information on the Equation of State of boron and boron compounds.

The database of experimental Equation of State (EoS) points for BN is very limited. Only a few points are available on boron nitride in extreme conditions between 12 and 27 Mbars [1] while for pure boron there is one point at 56 Mbars [2].

Therefore, we have conducted studies of the BN EoS at the PALS installation in Prague, Czech Republic. High compression of BN (up to 15 Mbar) was achieved with the PALS laser operating at 3ω (438 nm) with pulse length of $\tau_L \sim 350$ ps delivering energy up to 200 J. A flat-top intensity profile within the focal spot of ~400 μm diameter was assured by using a phase plate.

The experimental points were obtained using Streaked Optical Pyrometry (SOP), Velocity Interferometer System for Any Reflector (VISAR) and Photonic Doppler Velocimeter (PDV) diagnostics. The VISAR system was constructed during experimental campaigns although, for the moment, only worked as a reflectivity diagnostic. PDV was used for timing measurements.

In the experiment, we used multilayer stepped targets produced at Scitech Precision, UK, with either aluminum or quartz as reference material. We then simultaneously measured the shock velocities in the reference material and in BN, and we used the impedance mismatch technique to obtain the experimental points on the equation of state (EoS) of BN, which were in fair agreement with the available theoretical models.

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Laser-Driven pB Fusion at ELI Beamlines and at the Charles University

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Abstract

High-intensity laser pulses interacting with materials rich in hydrogen and boron, when properly configured, can initiate the proton-boron (pB) fusion reaction, resulting in the generation of three energetic alpha particles (p+11B → 3He + 8.7 MeV). These alpha particles are of considerable interest in emerging applications such as green energy production and non-invasive cancer treatments.

One potential approach to increasing alpha particle yield is to explore various target configurations, modifying the concentrations of the elements involved in the reaction or enhancing laser absorption by the target.

In our study, we first conducted an experiment aimed at boosting the volumetric laser absorption within the target by using boron nitride nanotube (BNNT) targets, which possess an average density of 1/5th that of solid density and compared the results with a standard flat Polyester (PS) target [1]. The comparison showed a 1.5-fold increase in proton cutoff energy and a 2.5-fold increase in the N4+ / C4+ ion cutoff energy.

Additionally, we employed thin films of plasma polymers ppC:H evaporated on BN substrates with varying densities. These ppC:H films were used as hydrogen sources when their properties were optimally matched with the laser parameters [2-3]. Currently, to combine the benefits of target morphology and low density with the hydrogen content of the target, we have prepared plasma polymerized hexane nanoparticles (ppC:H NPs) within a gas aggregation cluster source (GAS) as advanced targets for laser-driven pB fusion. The mean size of NPs can be tuned between 600 nm and 120 nm, depending on the discharge power. We examined the porosity of the NP deposits by measuring BET isotherms, while RBS/ERDA measurements were used to assess the elemental content, including the hydrogen concentration. Furthermore, we prepared hybrid nanostructures by r.f. magnetron sputtering of 100-nm boron thin films over the multilayers of 120 and 600-nm ppC:H NPs. The penetration of boron into the voids between the NPs was characterized by Nuclear Depth Profiling. These targets have successfully triggered the pB fusion reaction using a short pulse high energy laser TARANIS (8J in 900fs) and the results showed that ppC:H NPs combined with B-rich materials enhance the laser-driven pB fusion.

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Synthesis, characterization and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

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Abstract

The investigation of laser-driven ^{11}B(p,α)2α fusion reaction has attracted growing research interest in the recent years thanks to the latest advancements in high-power laser technology [1]. Several applications have been considered, ranging from fusion energy production to bright alpha particle sources [2] and medical applications [3]. In this context, the design and fabrication of optimized targets crucial to improve the fusion yield and meet the application requirements.
In this contribution we report on the synthesis, characterization and testing of a novel class of targets for laser-driven proton-boron fusion experiments, namely boron-based nanofoams produced by means of the femtosecond Pulsed Laser Deposition (fs-PLD) technique. By exploiting the versatility of the fs-PLD [4], nanostructured boron foams with controlled density (20-100 mg/cm^3), thickness (up to 100 µm) and hydrogen content (from no hydrogen up to 1:1 boron/ atomic ratio by co-deposition of boron and high density polyethylene) are produced.
Experimental tests performed with the Taranis laser system at Queen's University Belfast (8 J, 800 fs, 10^{19} W/cm2) have shown a significant alpha yield (above 5×10^{8} sr-1) using hydrogenated boron nanofoam targets, marking a ~50-fold increase with respect to the pure boron foam on a polypropylene substrate. The ongoing analysis of the experimental data indicates a strong contribution of in-target fusion reactions occurring within the nanofoam layer. These results underscore the potential of nano-engineered targets in laser-driven proton-boron fusion experiments. Future work will focus on further refining target properties and exploring different laser parameters to maximize fusion efficiency and better understand the underlying mechanisms driving in-target fusion reactions in nanostructured materials.

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High-power laser interaction with Carbon nano-foams

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Abstract

Porous materials, or *foams*, of light elements have numerous applications in laser-matter interaction, being able to increase the coupling of the laser with the target, thus maximizing the energy stored in the plasma. Plastic foams have been employed for decades in this sense, but it is important to investigate alternative chemical compositions and morphologies for new regimes of interaction.

In this work we report about the experimental study of nano-structured foams made of pure Carbon under high-power laser irradiation. The foams were produced by the Pulsed Laser Deposition (PLD) technique at the Micro- and Nano-structured Materials Laboratory (NanoLab) of the Politecnico di Milano and they have been irradiated at the ABC laser facility at ENEA Centro Ricerche Frascati, with an intensity on target of more than 10^{14} W/cm^2. A thorough characterization of the plasma produced during the interaction has been achieved by the large number of diverse diagnostics fielded in the experiment. An increased ablation loading has been found for a specific set of foam parameters, which can be useful for proton-Boron fusion in the in-target scheme. Doping these foams with hydrogen and Boron may lead to an increased yield in fusion products compared to solid homogeneous materials. Further theoretical and experimental developments of this work will be discussed.

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Laser-driven intense particle beam generation and the applications in proton-boron nuclear reaction study

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Abstract

Compared with DT thermal nuclear fusion scheme, proton-boron fusion attract less attention because it requires higher temperature for the maximum cross section and it is difficult to realize the energy gain over the bremsstrahlung loss. However, high power lasers open the path to fusion under non-equilibrium condition like fast ignition scenario but the fuel is boron. In this way, the protons will not only serve as the heating source but directly induce nuclear reaction. In this talk, we will introduce our recent results concerning the intense particle beam generation as well as beam-target nuclear reaction study based on high power lasers as follows.

1) We experimentally generated brilliant electron beams and gamma rays through picosecond-laser-NCD (near critical density) plasma interactions. With the same laser, the electron beam energy and temperature are enhanced by one order compared with foil case. The gamma rays are enhanced by two orders if a high-Z converter are used.

2) We experimentally studied the $p^{11}B$ nuclear reactions in CHOB plasma circumstance initiated by laser-accelerated intense proton beams. The time of flight (TOF) technique based on plastic scintillator are developed for the alpha particle detection. Compared with CHO case, once the target is boron doped, the TOF signal is greatly enhanced due to the fact that proton boron reaction happens. The reaction product yield are enhanced in plasmas compared with cold matter. The yield increases with beam intensity non-linearly and exceeds the beam-target interaction predictions

3) We conducted $^{12}C(e/\gamma, p)^{11}B$ reaction measurement to discriminate the mechanism for the $p^{11}B$ nuclear reaction enhancement. The electrons and gamma rays, that are usually generated simultaneously with protons, induced very little proton and boron element in the target, and had negligible influence on the proton boron nuclear reaction enhancement.

4th International Workshop on Proton-Boron Fusion
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Challenge and Prospect of Spherical Torus (ST) p-^{11}B Fusion Energy

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Abstract

To overcome the database gap and reach the goal of p-^{11}B plasma burn in the EHL-3A device [1], major areas of R&D can be delineated as follows: (see, Figure)

1) Measure and model accurately the double differential p-^{11}B fusion cross-sections and utilize the non-thermal enhancement of the observed fusion reaction rates [2];
2) Reduce and contain electron Bremsstrahlung and synchrotron radiation losses, and metal impurities via a super-X divertor configuration allowed by demountable toroidal field magnets;
3) Raise the efficiency of ion heating including the superthermal components, via nonlinear or stochastic mechanisms; and
4) Study the unique advantages of ST p-B plasmas, such as high beta, improved energy confinement via boronized CFC wall tiles, high current drive efficiency by electromagnetic waves at multiple harmonics [3], suppressed ion turbulence transport via strong plasma flow shear and substantial boron "impurity", tearing mode stability via positive gradients of parallel current densities, and enhanced containment of superthermal electrons and ions by increasing the space between the LCFS and the outboard plasma facing components.

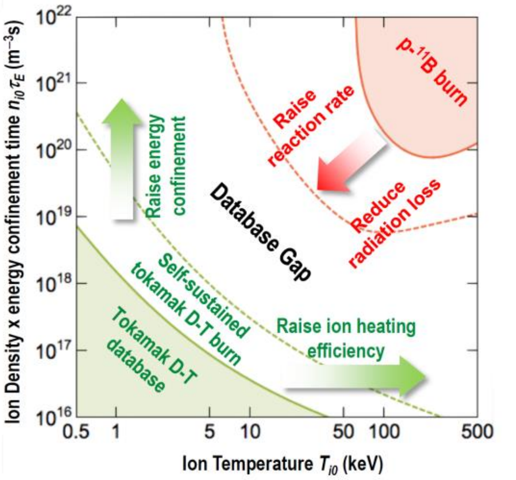

Figure. Database gap in self-sustained p-^{11}B burn and directions of R&D.

Data from EXL-50 [3] and EXL-50U have revealed plasma confinement transitions from turbulent to quiescent states under strong boron fueling and moderate ECRH power. Recent collisionless plasma data from MAST, NSTX, Globus-M2, and ST40 suggested a stronger leverage of B_T and R and a weaker leverage on I_p in τ_E scaling. As a result, designs of compact next-step ST experiments have been suggested [1] (see, Table). The benefits of substantial boron fueling in D or D-T plasmas can help bridge the database gap of p-^{11}B plasmas. In view of the possibility of testing fusion α physics without significant neutrons and the progression of MAST-U and EHL-2, EHL-3A and STEP goals, extensive tests of p-B plasma properties in wide parameter ranges are therefore encouraged.

Acknowledgements

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*Table. Parameter goals for present and future ST **DT** or **p-^{11}B** fusion devices*

	EXL-50U	MAST-U	EHL-2	EHL-3A	STEP
$T_{i0}n_{i0}\tau_E$ (10^{20}keVm^{-3}s)	0.05	0.5	15	400	40
Major radius R (m)	0.6-0.8	0.7	1.05	2	3.6
Minor radius a (m)	0.4-0.5	0.41	0.57	1.1	2
Toroidal field B_T (T)	1.2-0.9	0.9	3	4	3.2
Plasma current I_p (MA)	0.5-0.7	2	3	10	23
Flat-top time @ B_{TMAX} (s)	2	6	3	∞	∞
Fusion power P_{DT}/P_{pB} (MW)	–	–	~0.002	~0.28	~1500

Demonstration of aneutronic p-^{11}B reaction in a magnetic confinement device

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Abstract

Aneutronic fusion using commonly available fuels such as proton (p) and boron 11 (^{11}B) is one of the most attractive potential energy sources. The development of techniques to realize its potential is desirable for the experimental capability to produce p-^{11}B fusion in the magnetically confined fusion device using hydrogen beam injections. We performed experiments of p-^{11}B fusion in the magnetic confinement fusion device Large Helical Device under the collaboration between the National Institute for Fusion Science (NIFS) in Japan, and TAE Technologies in the USA [1, 2]. The experiments were conducted with the support of intense negative-ion-source-based hydrogen beams (N-NBs) [3], and an impurity powder dropper (IPD) [4] co-developed under the collaboration between NIFS and Princeton Plasma Physics Laboratory, USA. In p-^{11}B experiments, intense N-NBs whose acceleration energy were of up to 163 keV were injected into a plasma with natural boron grain injection by the IPD. Significant quantities of signal pulses resulting from p-^{11}B fusion-born alpha particles were measured using a custom-designed alpha particle detector based on a passivated implanted planar silicon detector. The time trend of the alpha particle counting rate obtained with the alpha particle detector was in good agreement with the global p-^{11}B alpha emission rate calculated based on classical confinement of the energetic proton using experimentally obtained plasma parameters. We will present the detail of experimental results and comparison with the numerical calculation.

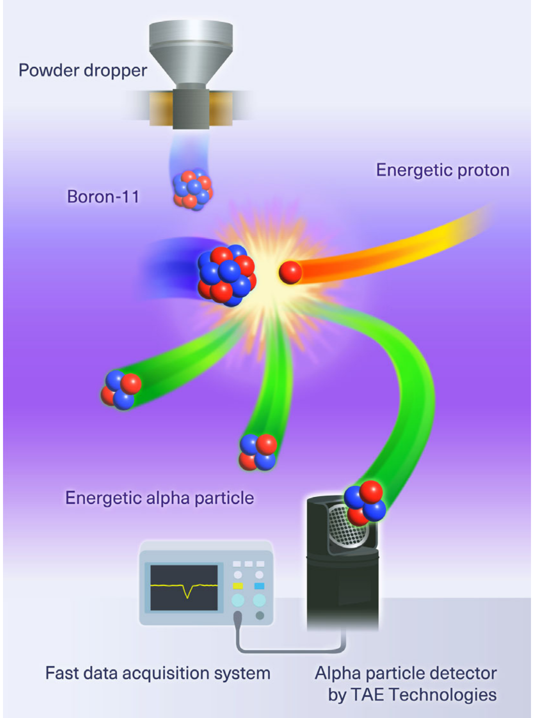

Figure 1. Experiment for p-^{11}B demonstration performed in Large Helical Device.

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Evaluation of Multiple Channels of p-11B Fusion Reaction in Magnetically Confined Plasma

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Abstract

We plan to carry out p-11B plasma experiments in an upcoming spherical torus (ST) EHL-2 [1] to measure the reaction rates covering the resonances at the 675keV and the 162keV [2]. Neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) will be used to heat the plasma and generate superthermal ion components and increase the reaction rate. Both thermonuclear and superthermal reactions will be measured and analyzed.

We calculated the anticipated alpha and gamma emissions in thermal-thermal, beam-thermal (target) [3], and superthermal-thermal [4] p-11B reactions in EHL-2 and EXL-50U [1]. EHL-2's parameter goals include n_e0=1.3×〖10〗^20 m^(-3), T_i0=30keV, I_p=3MA and B_T=3T at R=1.05m. Assuming n_B=0.07n_i, 〖1.5×10〗^15 and 〖5×10〗^14 alpha particles per second can be produced by p-11B thermal-thermal reactions and beam-thermal fusion (200keV, 1MW NBI), respectively (Figure 1). Gamma emissions are also estimated and considered as an auxiliary detection approach. In the case of EXL-50U, the ICRH-NBI synergy may drive superthermal-thermal p-11B reactions and produces approximately 〖5×10〗^6 alpha particle particles per second (20keV, 3MW NBI + 1.5 MW ICRH).

These results are found to be sensitive to the details of p-11B reaction model, which at present is unreliable [5,6]. New measurements to its double differential cross section are therefore planned to improve the understanding of reaction mechanism. The status of this R&D will be reported at the workshop.

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SULF laser-driven proton acceleration

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Abstract

Laser-driven ion acceleration is attracting widespread interests because of the prospects of realizing compact and desktop ultrafast ion sources, which has potential applications in many fields, such as cancer therapy, proton-boron fusion, proton imaging etc. This report will introduce the recent progress on laser-driven proton acceleration carried out in the Shanghai Superintense Ultrafast Laser Facility (SULF).

SULF is the first 10 PW-class laser facility in China, located in Shanghai Pudong New District, which was proposed and constructed by the Shanghai Institute of Optics and Fine Mechanics in 2016. In 2017, the SULF-10 PW beamline has realized output peak power up to 10.3 PW with 339 J output pulse energy compressed to 21 fs pulse duration. This peak power was further increased to 12.9 PW in 2019.

In the commissioning phase of SULF-10 PW laser beamline, the laser energy of 72±9 J is directed to a focal spot of ~6 μm diameter (FWHM) in 30 fs pulse duration, yielding a focused peak intensity around 2.0×10^{21} W/cm^2. As shown in Fig.1, high-energy proton beams with maximum cut-off energy up to 62.5 MeV are achieved using flat copper foils at the optimum target thickness of 4 μm via target normal sheath acceleration (TNSA) mechanism. [1]

Meanwhile, we also apply the 3D-printed microwire array structure to enhance the proton acceleration. [2] After optimizing the laser contrast of SULF-10 PW laser beamline with the single plasma mirror, by using the 1.7 PW laser interacting with microwire array targets, the 62.8 MeV proton beams are obtained at the optimal structure period, which is significantly enhanced compared with flat foils.

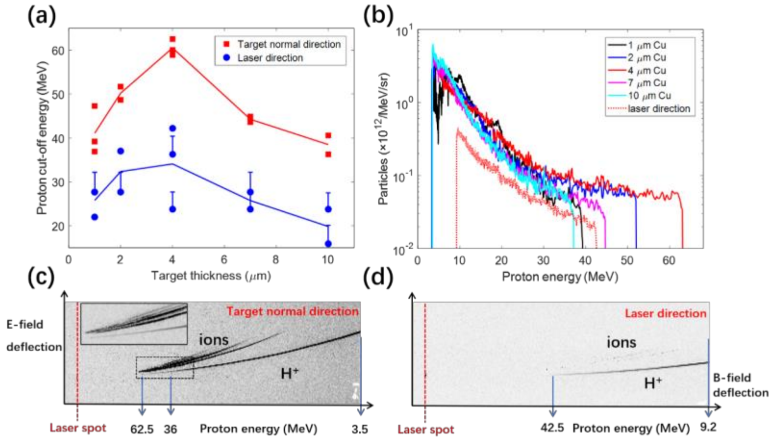

Figure 1. The proton cut-off energy as a function of the target thickness of the plain Cu foils measured in the target normal direction (red squares) and in the laser propagation direction (blue circles). (b) Typical proton spectra for five target thicknesses. (c)-(d) The raw IP data in the target normal direction and laser direction for the best result of proton acceleration from a shot on a 4-μm Cu foil, where the inset in (c) is a magnified image of the ion trace in the high-energy region.

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Plasma diagnostics for detection of alpha particles

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Abstract

With the development of high-intensity, high-repetition-rate laser systems, it has become critical to be able to detect and characterize in real time the laser-generated plasma parameters such as gamma rays, electrons, high-energy protons, and heavier ions. In the case of a laser-driven proton boron fusion experiment, the particular interest is in detecting and characterizing the resulting alpha particle beam. CR-39 nuclear tracker detectors (sensitive to each individual particle with nearly 100 % efficiency) are often used to detect alpha particles. However, they are more useful for determining the total delivered dose rather than for determining the beam properties for each individual shot.

Set of standard ion diagnostics optimized for a real-time feedback such as ion collectors, single-crystal diamond and silicon carbide detectors and Thomson parabola spectrometer can be used as complementary diagnostics. The use of absorbers placed in front of the time-of-flight detectors might help in the discrimination of proton and alpha particles energy spectra and ensures no heavier ions (carbon, boron etc) contributes to the total signal, while the TPS can be used to check the maximum energies for different ion species.

Analysis of data acquired during our experimental campaign, summary of the optimal conditions for detection of laser-driven alpha particles and key results will be presented and discussed.

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Preliminary study of ion-plasma interaction within the Geant4 toolkit in the framework of the p-11B Fusion reaction in plasma for energy applications

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Abstract

We present a preliminary study of simulating ion-plasma interactions within the Geant4 toolkit, with a specific focus on the proton-boron (p-11B) fusion reaction in plasma. The p + 11B → 3 alpha reaction, known for its potential in aneutronic energy production, Our main goal is examined the hydrodynamical model in perspective, to use Geant4 as a toolkit, and the outcomes of hydrodynamical model which we are using in geant4 toolkit has been taken by our other colleagues. If we achive our goal, than it will be serves as a foundational step toward future integration into the Geant4 toolkit to replicate the conditions of a laser-induced plasma, where ionization, recombination, and nuclear fusion processes occur, relevant to inertial confinement fusion (ICF) and alpha particle source development.

Key outcomes of this study include the development of a robust simulation platform for p-11B fusion, providing insights into optimising the reaction for energy production. This research also lays the groundwork for future experimental validation, offering a pathway towards more efficient and controlled p-11B fusion processes.

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Proton Boron fusion via Micro Bubble Implosion: a preliminary study

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Abstract

The development of ultra-high-intensity lasers (UHIL) facilities, thanks to the Chirp-Pulse-Amplification (CPA), allows thinking about many new applications.
Micro-Bubble-Implosion is a concept introduced in [1], which consists of the possibility of having an implosion of a spherical cavity target due to the redistribution of the electrons due to the interaction of the target with a UHIL ($10^{18} - 10^{22} W/cm^2$). Due to the interaction, the target is completely ionized, and the electrons, due to their much lower mass compared to the ions, will reach an equilibrium condition. This charge separation may lead to the generation of a very intense electric field, which will lead to the implosion of the ions. By considering very light ions, i.e., hydrogen and eventually its isotopes, numerical and analytical models show that when the ions are fully compressed, they can reach densities in the order of about 10^5 times the ordinary solid state, i.e. like in a white-dwarf, leading to an electric field which can be as high as two order of magnitude lower than the so-called Schwinger limit ($10^{18}\ V/m$).
The main applications are related to ions acceleration up to the relativistic regime and ultra-intense coulomb field generation [1,2].
In this work, we will show a preliminary study related to the application of MBI to nuclear fusion. We carried out a numerical analysis employing a 1D code. We considered a submicrometric target constituted by an external gold layer and two internal layers made of boron and hydrogen. We simulated the evolution in time of these layers, and consequently, we defined a procedure to evaluate the reactivity $< \sigma v >$.
Thanks to this, we consider several theoretical scenarios coherent with the MBI phenomenon that may lead, under the proper assumption, to the breakeven point. For example, Figure 1 shows the reactivity vs the Energy of particles [3] for suitable geometric parameters of the bubble. In the full paper, more geometric cases and figures of merit will be shown.

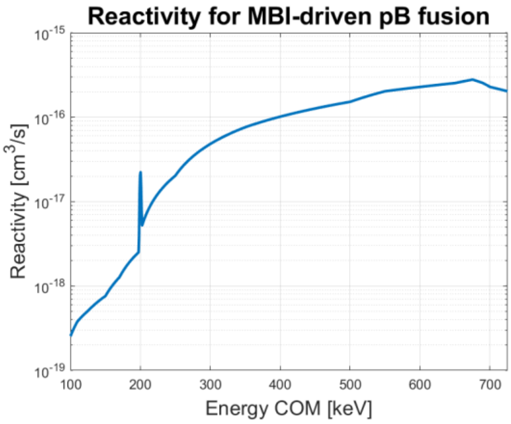

Figure 1. $< \sigma v >$ vs COM energy.

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Short-pulse laser-driven hydrodynamics and its relevance to proton-boron fusion experiments

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Abstract

Many approaches to proton-boron fusion rely upon the interaction of intense lasers with pulse lengths in the 10s fs to few ps range, with solid targets. These targets may be thin, to optimise acceleration mechanisms such as TNSA and RPA, or have nano-structured surfaces, to enhance laser coupling. Such micron or nano-scale structures are susceptible to disruption by hydrodynamic motion, which may compromise the intended functioning of the target. In the field of laser-plasma interactions, we commonly associate hydrodynamics with experiments driven by nanosecond laser pulses. However, hydrodynamic motion can also be initiated by the interaction of a short-pulse laser with a solid target and produce significant effects on picosecond timescales [1-12]. This motion is usually not well represented by PIC simulations and nor is it commonly diagnosed in experiments. In this presentation we will consider some experiments where picosecond and sub-picosecond hydrodynamic evolution is diagnosed, driven by both picosecond [1,2,7] and 10s femtosecond laser systems [4-6, 8-12] interacting with both solid and CH foam targets. These experiments have all been comprehensively modelled using PIC, hydrodynamic and radiation-hydrodynamics simulation codes, run in series, in both 1- and 2-D. In addition, we will consider a purely simulation-based study to investigate the regimes in which hydrodynamics is important [3].

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Progress and challenges in laser developments for Fusion at Amplitude Laser

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Abstract

Amplitude Laser has a long experience in developing and providing high intensity lasers to facilities interested in exploring and exploiting compact particle acceleration. While Petawatt lasers were until recently used to explore the acceleration of electrons up to 5GeV energy in as short as 10cm length, or production of protons up to 60MeV energy, facilities now aim at providing dedicated beamlines, and improving the flux by increasing the repetition rate of the lasers and targets in the range between 10Hz and 100Hz.

This trend requires ultrafast laser companies to develop the corresponding pump lasers. Indeed, for a 2PW laser to be operated at 10Hz operation, Amplitude has developed a dedicated pump laser delivering up to 70J at 10Hz @1µm in the nanosecond regime. This laser development constitutes a significant improvement in Amplitude laser portfolio, induced innovative solutions to manage heat load in high energy lasers, and opened a path towards high energy lasers dedicated to shock compression studies.

Since the recent achievements at NIF on net gain with inertial confinement fusion, several national and private initiatives require kJ class laser technologies both for compression or ignition, both at few shots per minute but also at 10Hz operation.

We propose to present Amplitude roadmap for the development of such kJ class lasers, our technical progress on relevant technological bricks, and the corresponding challenges.

For example, proton generation require usually very high temporal contrast, be it with 30fs or 500fs pulse durations, and we will present our recent progress on high contrast seeders based on OPCPA, either operable at 800nm or 1µm.

Additionally, the use of several laser beams to be focused on a target require precise timing synchronization of the different beams, we will present our solutions to control the time-of-arrival of several laser pulses with a sub-ps precision.

We will also present our ability to provide temporally shaped pulses at 100J energy in the nanosecond regime, of particular interest for optimized compression of targets.

Finally, we will present our progress on kJ-class laser heads development, supported by the Thrill European project.

Interestingly, we can also anticipate attractive perspectives for other applications that could benefit from the laser developments dedicated to inertial confinement fusion.

Silicon Detectors Adapted to Neutron Detection: Prospects, Challenges and Road Map

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Abstract

Semiconductor-based neutron detectors are characterized by small size, high energy resolution, good spatial resolution and stable response at the depletion voltage. Consequently, these neutron-detectors are important for the fields of nuclear proliferation prevention, monitoring neutron-scattering experiments, cancer treatment and fusion experiments. However, there are some problems such as low neutron detection and limited resistance to radiation; therefore, critical improvements are needed to enable sufficiently effective neutron detection.

Since neutrons are not charged particles, they cannot be detected by ionization directly using silicon detectors. However, if a semiconductor detector incorporates a neutron reactive material it can be used as a neutron detector. For this, if neutrons are fast, they need to be moderated with compounds rich in hydrogen. If neutrons are slow, only converter layers are required. Through the reactions caused inside these layers, charged particles are produced as reaction products, which are then detected by the silicon detectors. Planar and 3D detectors filled with the converter materials will be considered. Prospects, issues and mitigation strategies, including a brief insight into a new fabrication batch aiming for a new technology at CNM which will try to mitigate the current issues and optimize the parameters will be discussed. Geant4 will be used to simulate the behaviour of conversation layer. In conclusion we will briefly compare SiC to Si based neutron detectors for nuclear fusion experiments.

Acknowledgement

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FRASCATI, ITALY

The Quest of Proton Boron Fusion and Related Topics

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Abstract

Recent progress in inertial fusion as well as magnetic confinement experiments have initiated new research efforts for Fusion Energy. The main path is based on the Deuterium Tritium Reaction. While many research groups in start-ups and national institutions are addressing basic physics issues, technological problems associated with Tritium breeding and the material problems due to the high neutron flux are not yet addressed with the necessary intensity to achieve the goal of Fusion Energy within a couple of decades. Therefore, it is timely to investigate the potential of neutron free fusion reactions like the (_5^11)B (p,α)2α reaction using conventional accelerator beams and intense laser generated proton beams. We performed experiments at the 320 kV high voltage platform at the Institute of modern Physics in Lanzhou and the Laser Fusion Research Center at Mianyang. There are different reaction channels, but in no case three alpha particles are emitted with each 2.7MeV energy. In the experiments at IMP-Lanzhou we also used hydrogen doped boron targets and the alpha yield in this case is increased by approximately 30%. In experiments with intense proton beams at the Laser Fusion Research Center in Mianyang we observed up to 1010/sr/ alpha particles per laser-shot. This presently constitutes the highest yield normalized to the laser energy on target.

Posters

Characterization of Ion Beams Produced in a Small Dense Plasma Focus Device

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Abstract

The Dense Plasma Focus (DPF) device stands out as a promising approach for fusion energy generation, particularly using hydrogen-boron (pB11) fuel [1, 2]. Its potential advantages over other fusion technologies stem from its compact size, simplicity, and unique approach to plasma confinement. The DPF is extremely compact, with electrodes typically measuring just a few centimeters in diameter. The entire apparatus can fit within a small room, making it much smaller than other fusion devices. It doesn't require external magnets or lasers like other fusion devices, reducing the complexity and potential cost of the system. The DPF generates a high-density plasma requiring ion confinement less demanding than the millions of orbits required in tokamaks or other fusion devices. Finaly and most important, unlike other fusion approaches that focus on maintaining plasma stability, the DPF leverages the natural filamentation instabilities of the plasma to concentrate its energy. This unique feature potentially simplifies the challenge of achieving the necessary conditions for fusion, as it doesn't rely on combating instabilities but rather harnesses them.

The present work focuses on measuring the kinetic energy of deuterium ion and neutron beams emitted by a small Dense Plasma Focus (DPF) device. A Faraday Cup diagnostic is developed to characterize the ion beam produced by the DPF device. Utilizing the time-of-flight (TOF) method, the kinetic energy of the deuterium ions is determined. The Faraday Cup captures the ions, allowing for the precise measurement of their current, while the TOF method is used to calculate the ions' velocity and, subsequently, their kinetic energy. A specially designed differential gas pumping system is employed to enhance the accuracy of the measurements. This system helps maintain a controlled environment, ensuring that the ion beam's characteristics are less affected by external gas interactions, thus improving the reliability of the data collected. In addition to the electrical signals recorded, a diagnostic setup consisting of a scintillator and a photomultiplier tube records both the hard X-rays and neutrons produced by the DPF. An attempt is made to correlate the recorded data.

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Laser-Plasma method of obtaining nanosystems and its use for H-B11 films preparation

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Abstract

Recent progress in nanosystems development has generated significant enthusiasm for the creation of high-aspect-ratio 2D nanostructures - the elementary blocks of different type and size materials preparation [1,2].

Most of the research has primarily focused on two-dimensional 2D planar nanostructures where the film thickness is significantly smaller than the planar dimensions. With advances in nanofabrication techniques and the increasing demand in the field, it is possible to exploit the effect of film thickness towards synthesis of 3D diluted compounds.

On the basis of our previous investigations, we are developing and using the Laser-Plasma method which enables preparation of nanostructured layers with fine and perfect structures of high purity and even different isotope content [3,4]. The usage of resonance light heat creates the opportunity to energize the selected atoms as well as their groups (assembles) and to produce plasma with the necessary properties relevant to structures which must be prepared. This technique was successfully used by the authors to study the conditions for obtaining diamond-like films, as well as thin 2D layers of B4C and SiC, the both homogeneously doped GaAs:Mn layers and two-dimensional structures, including a δ-doped GaAs:Mn layer and a InxGa1 – xAs quantum well separated by a GaAs spacer [3].

In this study, we showcase the fabrication of nanostructures by laser plasma method reaching thicknesses of up to 500 nm, accomplished through the creation of nano trenches in the different substrates including monocrystalline silicon, pure natural boron and boron enriched by isotope B11. Subsequently, the evolution of structural and geometrical properties as a function of parameters of laser plasma process have been presented as well as possibility of introducing hydrogen atoms into the boron structure.

The results are substantiated with computing simulations. Our works open horizons in the utilization of the third dimension for diluted and enriched materials useful for preparation of different structures including targets for potential applications in future laser technologies.

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Thermal Stability of Neutron-Irradiated Defects in Transparent Polycrystalline α-Al_2O_3

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Abstract

α-Al_2O_3, or corundum, is known for its exceptional hardness, stability at high temperatures, and optical properties. This makes it suitable for use in harsh environments such as nuclear reactors and high-power lasers.

While nuclear fusion is considered a "clean" energy source, it produces high-energy neutrons that can interact with the materials in fusion reactors. These interactions can cause structural defects in the reactor materials and lead to nuclear activation, which converts stable isotopes into radioactive ones, creating secondary radioactive waste.

This study examines how fast neutron irradiation affects the stability of point defects in transparent polycrystalline α-Al_2O_3 ceramics. The defects are optically active, meaning they absorb and emit light, which can be observed as specific luminescence bands in photoluminescence (PL) spectra. Electron paramagnetic resonance (EPR) spectroscopy is used to identify defects such as trapped hole centers and electron-type F+ centers, while PL spectroscopy confirms the presence of F- and F2-type centers.

Key findings include:

- F+ Centers: Higher neutron flux results in a greater number of F+ centers, which are electron-type defects associated with oxygen vacancies.
- Hole-Trapped Centers: The study also identifies hole-trapped centers that contribute to the average EPR signal around the "$g \approx 2$" value.
- Thermal Annealing: The material shows the fastest thermal annealing of radiation-induced paramagnetic defects at temperatures between 600 and 750 K.

In conclusion, increased neutron flux leads to more F+ centers, and the most effective thermal annealing of these defects occurs between 600 and 750 K.

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This work has been carried out within the framework of the COST Action CA21128- PROBONO “PROton BOron Nuclear fusion: from energy production to medical applications”, supported by COST (European Cooperation in Science and Technology - www.cost.eu)."

Production of α particles sources through p-^{11}B nuclear reactions initiated by relativistic lasers

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The landscape of attainable radio-isotopes with medical cyclotrons is limited due to the low energy of accelerated particles. A few radio-isotopes are produced with low energy protons at hospitals. In France, only the ARRONAX cyclotron in Nantes is able to produce several isotopes with energetic protons but also alpha particles, for a broad range of medical applications. A new way of producing those radio-isotopes has been studied, that is, using secondary alpha particles sources as a way to generate those relevant isotopes. Proton-Boron nuclear reactions have been actively studied these last few years as a possible way of producing secondary alpha particles sources. Proton acceleration by interaction of ultra-high intense lasers with hydrogenated targets is the preferred way to initiate those type of reactions. [1] The versability of such laser systems is the preferred way to complement conventionally used medical cyclotrons.The two main mechanisms of proton acceleration studied for this nuclear scheme are the Target Normal Sheath Acceleration (TNSA) and the Hole-Boring (HB) process. In the first case, protons are accelerated at the rear side of the target via the electrostatic field induced by laser driven electrons escaping from the target. The exponential shape of the proton energy spectrum induces a great number of nuclear reactions throughout a Boron secondary target despite a decrease of the cross-section above the main resonance at 675 keV. For the Hole-Boring process, protons are accelerated at the front side thanks to the electric field induced by the electrons pushed by the radiation pressure of these high laser intensities. Accelerated protons interact directly with boron atoms contained within the same target [2]. Different types of targets have been studied both numerically and experimentally for Hole-Boring based alpha production. Particle-in-Cell (PIC) and Monte-Carlo (FLUKA) simulations have been conducted to better understand experimental campaigns done on the VEGA-III laser at CLPU, Salamanca, Spain in november 2022 and march 2023. This laser is characterized by a short pulse duration, 30fs and a high-repetition rate of 1Hz. The two proton acceleration schemes have been studied numerically to better understand the experimental data and to deepen the analysis. PIC simulations for TNSA protons could directly be compared with experimental diagnostics and gave confidence for Hole-Boring protons results. Monte-Carlo simulations for both schemes were then directly compared to experimental data and confirmed the results. Simulations for scattered ions also gave confidence in the interpretation of the diagnostic and helped discriminate particles obtained on the detectors.

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Measurement methods in a non-conventional nuclear fusion reactor

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Abstract

Alpha Ring fusion reactor development focuses on producing nuclear fusion under plasma conditions much less extreme in density and temperature than traditional methods. The approach is to leverage collective correlated dynamics of local charges. Experimental measurements in the fusion reactor are primarily two-fold: (1) evaluating power gain by heat out (calorimetry) divided by electrical power in, and (2) measuring high-energy fusion products. Analysis of systematic and statistical errors is key to evaluating the potential of this non-traditional approach to fusion

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Electrospun polymer fibers for potential new generation of solid targets in $p^{11}B$ fusion

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Abstract

Nuclear reaction between a proton and a ^{11}B nucleus ($p^{11}B$ fusion) constitutes today an attractive route to avoid the well known challenges featuring conventional methods for power generation based on nuclear fusion. Handling of tritium, radiation damage and radioactivity are issues under consideration of the scientific communities. In this respect, the yielding three energetic α-particles is very attractive, as it only involves abundant and stable isotopes in the reactants and no neutrons in the reaction products. The chance to optimize the $p^{11}B$ reaction producing intense α-particles streams in compact, and potentially economic way, open the way for the realization of a new generation of solid targets sustaining not only the efficient $p^{11}B$ fusion but also the need for economic procedures. In this concern, developing low cost, efficient, low time- and material-consuming production methods, with high throughput and reproducibility is a challenging issue. Within the project FUSION we are studying the potential of a fabrication method based on the production of polymer fibers by means of electrospinning (ES), as a potential alternative to the ones already tested. This technique allows to obtain tape or mat of dense fibers (on a gram scale) having on demand diameter (from submicron to tens of microns), composition (polymers, hybrid organics/inorganics), arrangement (aligned or random oriented, see Figure 1), extension (up to several cm^2), thickness (from micrometric monolayers to hundred of microns)[1-2]. The obtained material can be either free standing or deposited on different substrates. Therefore, if on one hand ES offers the undoubted advantages of versatility, cheapness and high production rate, on the other hand it presents new technological challenges. The need for precise thicknesses and material densities required by the nuclear experiments of FUSION questions the ES about its real performance limits. However, plastic fibers

made by Poly(methyl methacrylate) (PMMA) or Polystyrene (PS) constitute natural proton sources and allow to embed inorganic Boron (with demanded density) into the polymers, thus making electrospun fibers good candidates for alternative solid targets suited in efficient $p^{11}B$ fusion. In this contribution, we show the first studies on the optimization procedure to produce compact aligned and randomly oriented fibers with the potential for a new generation of targets for FUSION project. In particular the control of the geometries and the layer distributions are tackled and the first optimization results are shown. The here presented fibers are promising building blocks for future targets in FUSION experiment.

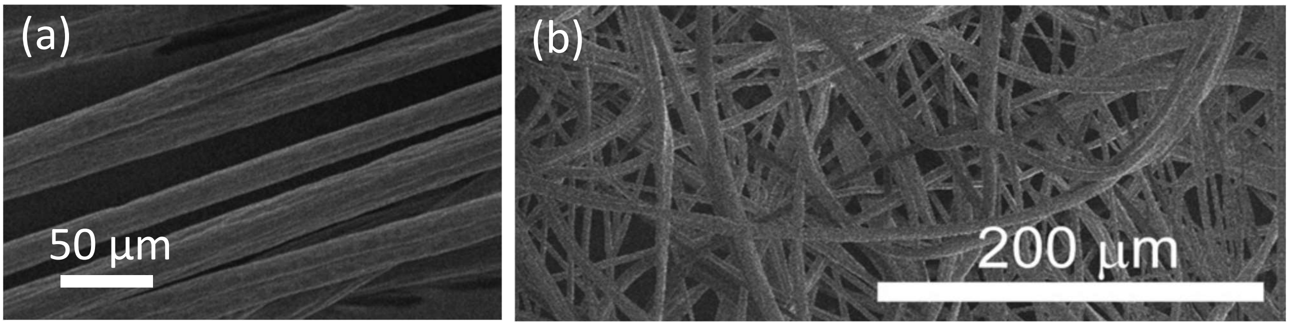

Figure 1. PMMA electrospun fibers. (a) Aligned fiber showing optimal uniformity and absence of defects. (b) Random oriented fibers.

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Measurement of the modification of α yields and proton stopping powers in boron plasma

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Abstract

The stopping power of light ions in solids has been extensively studied for decades, with both theoretical and experimental success. The same cannot be said for a plasma environment, where collective effects may modify the interaction. Experimental characterization of this phenomena, and understanding its underlaying plasma dynamics is important for e.g. plasma charge strippers in accelerators, and for stellar energy transport in astrophysics.

Studying the interaction of protons with boron plasma specifically may have implications for fusion reactor design, where the effect of electronic screening on boron-proton fusion becomes important through changes to the stopping power of the incoming protons and the outgoing α particles which contribute to heating the plasma.

To perform these experiments, we employ our high contrast 20 TW laser to generate a high repetition rate TNSA proton beams. Using an auxiliary laser pulse, we tailor the pre-formed boron plasma plume target. The proton beams are characterized using a Thompson parabola ion spectrometer, and boron-proton fusion products are detected by CR39 detectors and are later analyzed using AI-based software.

I will present preliminary results on irradiation of solid boron, and present the planned experimental campaign.

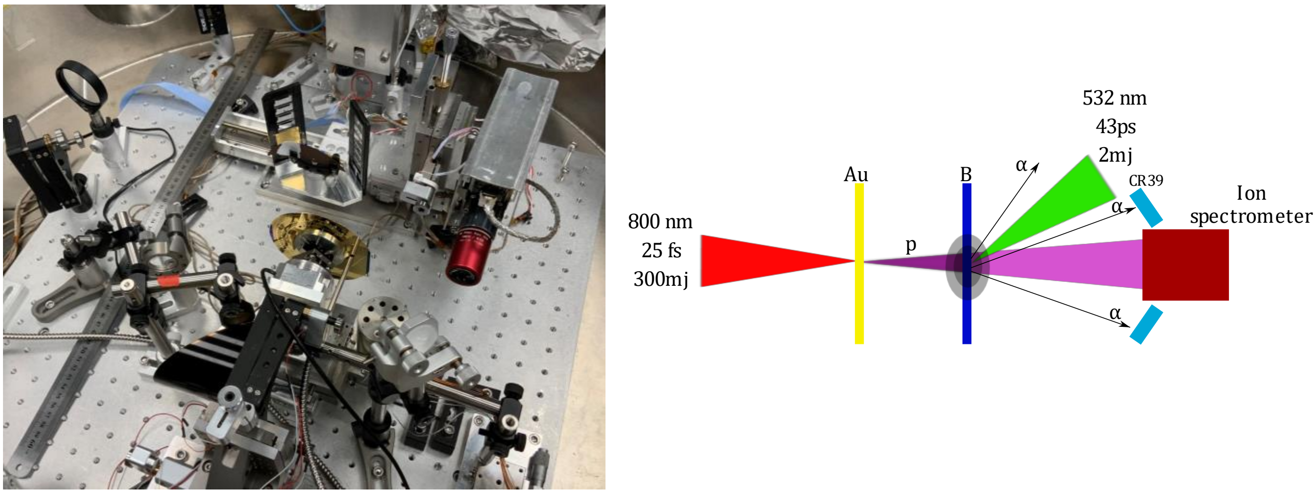

Figure 1.The experimental system: (Left) Image of the experimental chamber. (Right) Schematic view of the planed full system.

Characterization of Ion Beams Produced in a Small Dense Plasma Focus Device

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Abstract

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The present work focuses on measuring the kinetic energy of deuterium ion and neutron beams emitted by a small Dense Plasma Focus (DPF) device. A Faraday Cup diagnostic is developed to characterize the ion beam produced by the DPF device. Utilizing the time-of-flight (TOF) method, the kinetic energy of the deuterium ions is determined. The Faraday Cup captures the ions, allowing for the precise measurement of their current, while the TOF method is used to calculate the ions' velocity and, subsequently, their kinetic energy. A specially designed differential gas pumping system is employed to enhance the accuracy of the measurements. This system helps maintain a controlled environment, ensuring that the ion beam's characteristics are less affected by external gas interactions, thus improving the reliability of the data collected. In addition to the electrical signals recorded, a diagnostic setup consisting of a scintillator and a photomultiplier tube records both the hard X-rays and neutrons produced by the DPF. An attempt is made to correlate the recorded data.

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Development and optimization of Thomson spectrometry for laser-driven low-rate fusion reactions experiments

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Abstract

The interaction of high-power lasers with matter can be exploited for driving low-rate fusion reactions in laboratory conditions. Such experiments have gained significant interest, due to the numerous applications that laser-driven fusion reactions potentially allow, including research on fuels for fusion energy production [1,2], astrophysics [3] and alpha-particle generation for medical treatments [4]. However, the detection of the nuclear fusion reactants and the typical ionic products of the low-rate fusion processes, is a challenging issue, due to their low flux and the necessity of differentiating them from the various ion species that are accelerated during the laser-matter interaction. One of the diagnostic devices that can be implemented in laser-driven fusion experiments, is a Thomson spectrometer (TS), which is capable to detect and discriminate ions according to their mass-to-charge ratio (m/q). In this work we report about the results obtained with a TS, which was designed, developed and upgraded throughout the last years at the ENEA research center in Frascati (Italy), in the context of different laser-driven fusion experiments [6,7]. This device has been successfully

implemented in schemes for p+11B fusion reactions (with both in-target and pitcher-catcher configurations), aiming at detecting the generated alpha particles. With an adequate filtering system [8], we also implemented the TS in an experiment of laser-driven D-D fusion reactions, where it showed promising results in differentiating the accelerated deuterium form the other ion species. Finally, we will show the design of a novel, improved prototype of TS that is currently under development.

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Selective ablation and laser induced periodical surface structures (LIPSS) produced on (Ni/Ti) nano layer thin film with fs laser pulses.

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Abstract

Nickel-titanium (Ni/Ti) nanolayer thin film (NLTF) is a class of composite material made of alternating nanometer-scale Ni and Ti layers. Multilayer thin films of Ni/Ti are found in applications in neutron and soft x-ray optics due to their excellent contrast factor, in reactive films for micro-joining solutions, and many others. The interaction of fs laser pulses with Ni/Ti thin film is presented. The experimental sample, composed of ten alternating Ni and Ti layers, was deposited on a silicon substrate by ion-sputtering [1]. Single and multi-pulse irradiation was done in the air with focused and linearly polarized fs laser pulses (pulse duration 170 s, wavelength 1026 nm). For achieving selective ablation of one or more layers, without reaching the Si substrate, the single pulse energy gradually increased from the ablation threshold to a level that completely removed the NLTF [2]. Photomechanical spallation is considered the most important process for the realization of selective ablation [3]. We also studied multi-pulse irradiation and the production of laser-induced periodic surface structures (LIPSSs) on the NLTF [4]. We used optical and scanning electron microscopy (SEM&EDS) in the experiment. A non-contact optical profilometer was used to prove the selective ablation of a particular nano-layer from the rest of the NLTF. From the results, we found optimal conditions to achieve selective ablation and LIPSS formation on the Ni/Ti thin film (Fig1.).

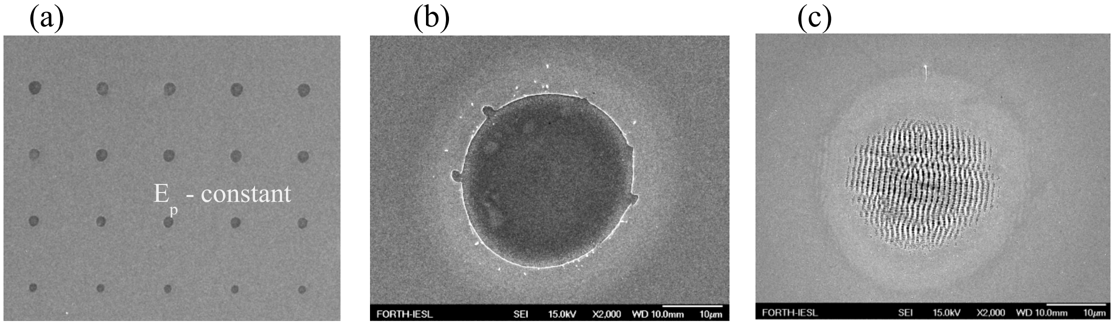

Figure 1. SEM micrographs of (Ni/Ti) surface: (a) scheme of irradiation, (b) single pulse selective ablation (c) LIPSS with 10 laser pulses irradiations (pulse duration τ=170 fs; wavelength 1026 nm).

References

[1] S. Petrovic, et al., *Intermetallics* **25**, 27-33 (2012)
[2] B. Gakovic, et al., *Journal Of Applied Physics* **122**, 223106 (2017)
[3] L. V. Zhigilei, Z. Lin, and D. S. Ivanov, *J. Phys. Chem.* **113**, 11892–11906 (2009)
[4] J. Tsibidis, et al., *Nanomaterials* **11**, 316 (2021)

TIMETABLE

		Monday 30 September			**Tuesday** 1 October			**Wednesday** 2 October			**Thursday** 3 October
	08:15	**Registration**									
	08:45	**Welcome**	**S3**	**09:00**	**I - Rodrigues**	**S5**	**09:00**	**I - Molloy**	**S6**	**09:00**	**I - Peng**
S1	**09:00**	**I - Belloni**		**09:30**	O - Alejo		**09:30**	O - Luo		**09:30**	**I - Ogawa**
	09:30	**I - Lerner**		**09:50**	O - Larreur		**09:50**	O - Tchórz		**10:00**	O - Li
	10:00	O - Cirrone		**10:10**	O - Tazes		**10:10**	O - Batani		**10:20**	O - Zhang
	10:20	**Coffee Break**		**10:30**	**Coffee Break**		**10:30**	**Coffee Break**		**10:40**	**Coffee Break**
	11:00	**I - Mehlhorn**		**11:00**	**I - Scisciò**		**11:00**	**I - Tosca**		**11:00**	O - Velyhan
	11:30	O - Borscz		**11:30**	O - Huault		**11:30**	O - Maffini		**11:20**	O - Hassan
	11:50	O - Fazzini		**11:50**	O - Consoli		**11:50**	O - Cipriani		**11:40**	O - Ciardiello
	12:10	O - Rivas		**12:10**	O - Alonzo		**12:10**	O - Ren		**12:00**	O - Pasley
	12:30	**Lunch**		**12:30**	**Lunch**		**12:30**	**Lunch**		**12:20**	**Lunch**
S2	**14:00**	**I - Ruhl**	**S4**	**14:00**	**I - Petringa**		**14:00**	**FACILITY TOUR**	**S7**	**14:00**	O - Courjaud
	14:30	O - Daponta		**14:30**	O - Abubaker					**14:20**	O - Lastovicka-Medin
	14:50	O - Lavell		**14:50**	O - Raso					**14:40**	O - Hoffmann
	15:10	O - Moustaizis		**15:10**	O - Altana					**15:00**	**Concluding remarks**
	15:30	**Coffee Break**		**15:30**	O - Chen		**16:00**				
	16:00	**I - Demirci**		**15:50**	**Coffee Break**			**FREE TIME**			
	16:30	O - Turcu		**16:15**	**POSTER**						
	16:50	O - Kamislioglu									
	17:10	O - Londesborough									
	17:30	O - Campbell		**17:45**			**19:30**	**SOCIAL DINNER**			

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