# Proton-Boron-Fusion for Enhanced Alpha-Particle Emission from Laser-Plasma Heating of Novel, Hydrogen-and-Boron-Rich, Borane, Microstructured, Solid Targets

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# New Concept Proposed: Proton-Boron Fusion Alpha-Source with Borane Micro/Nano-Structure Targets Driven by PW Lasers

Borane: New Material for Laser Target: Hydrogen rich: H/B ≥ 100% , e.g. $B_{10}H_{14}$, $H_6BN$

→

Alpha Source with: Borane Micro- Nano-structure driven by high intensity laser I~$10^{20}$W/cm$^2$

←

High Power PW, Laser Driver: I~$10^{20}$ W/cm$^2$ is efficiently Absorbed ~100% in Micro-Nano-Structures

↓

Enhanced Number of Proton-Boron Fusion Reactions
Enhance Alpha Flux

Info: 11B + p → 3α + 8.7 MeV (1.4 pJ/PB reaction)
Proton-Boron-Fusion, some basic data: Max crossection σ ~1Barn=$10^{-24}$ cm$^2$ at Energy ~ 600keV

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# New Material: Borane Crystals/Powders are very rich in Hydrogen: H/B ≥ 100% - 600% . Boranes are Natural Materials for Proton-Boron Laser-Fusion Targets

Examples of Boranes: $B_{10}H_{14}$ [H/B=140%], $BNH_6$ [H/B=600%, but Nitrogen], $Li_2B_{12}H_{12}$ [H/B=100%]

New materials for Hydrogen storage: $BNH_6$ is comparable to liquid Hydrogen in H storage per unit volume .

Densities ~ 1g/cm$^3$

Melting temperature ~100C.

Soluble in solvents: most Boranes.

Very little physical and chemical data available. Because they are 'novel materials'. Research needed.

Material: Usually Crystaline Powders: Micro- or even Nano-crystals. Flakes and solid chunks also available.

**BC2723 Ammonia Borane (CAS: 13774-81-7)**

| | |
|---|---|
| Catalog No. | BC2723 |
| Molecular Formula | BH6N |
| CAS Number | 13774-81-7 |
| Appearance | Beige crystalline solid |
| Purity | 99%~99.999% |


Suppliers, e.g. Stanford Advanced Materials. Typical R&D price ~USD500/5grams. Can be bought in bulk.

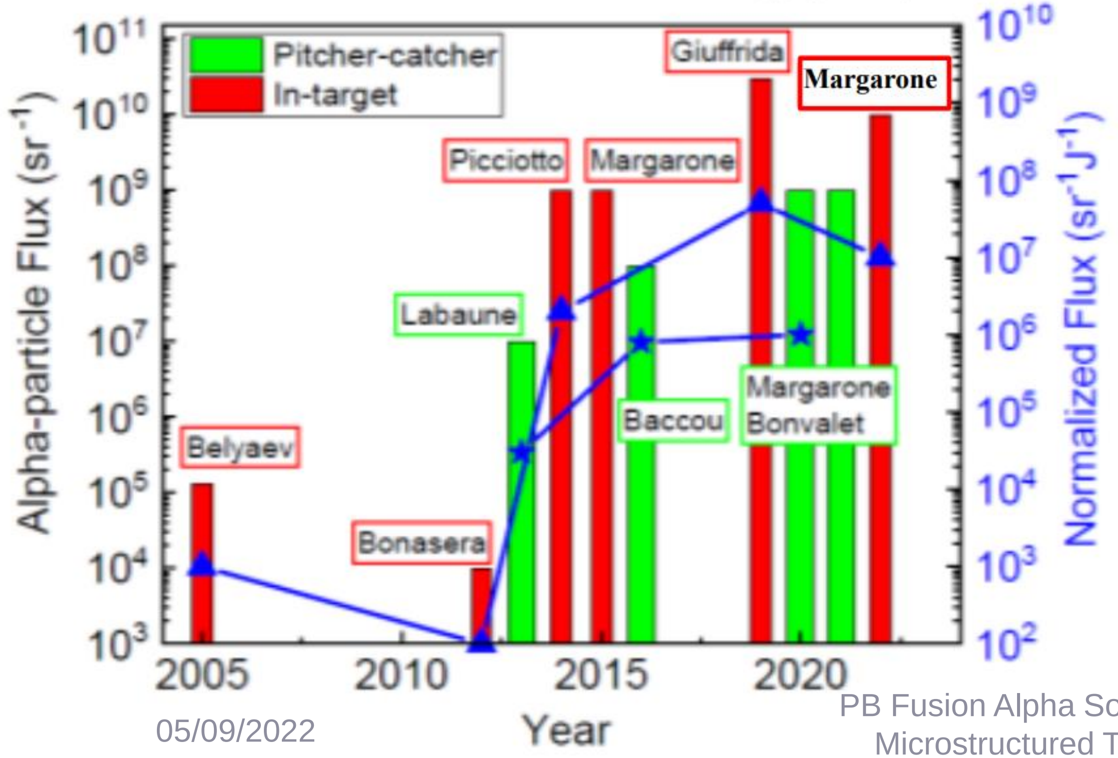
Safety: many boranes are toxic and flammable.

But for Ammonia-Borane=(AB)=Borazane ($BNH_6$).

[Sigma Aldrich]: No toxicity and No flashpoint, dust protection needed. [American Elements]: NONH for all transport

# In-Target Proton-Boron Fusion Alpha Alpha-Source with Hydrogenated Boron-Nitride flat targets. Margarone et al., Appl Sci (2022) and Giuffrida et al., Phys Rev (2020)

1. Record Alpha flux with >x$10^{10}$ alphas/sr/pulse Targets (FBK, Italy): Boron Nitride (BN), solid, BN contains hydrogen ~ few% incorporated during its manufacture: Boron nitride is obtained by reacting trioxide ($B_2O_3$) or boric acid ($H_3BO_3$) with ammonia ($NH_3$) or urea ($CO(NH_2)_2$) in a nitrogen atmosphere [Ref. 1, 2 and 5]. FBK also produces hydrogen-doped boron targets for PB alpha sources.
2. LFEX Laser: E-laser=1400J, T-laser = 2.2ps, I-laser ~ 3x$10^{19}$ W/$cm^2$ (Maragarone (2022)
3. PALS Laser: E-laser=600J, T-laser = 300ps, I-laser ~ 3x$10^{16}$ W/$cm^2$ (Giuffrida(2020)



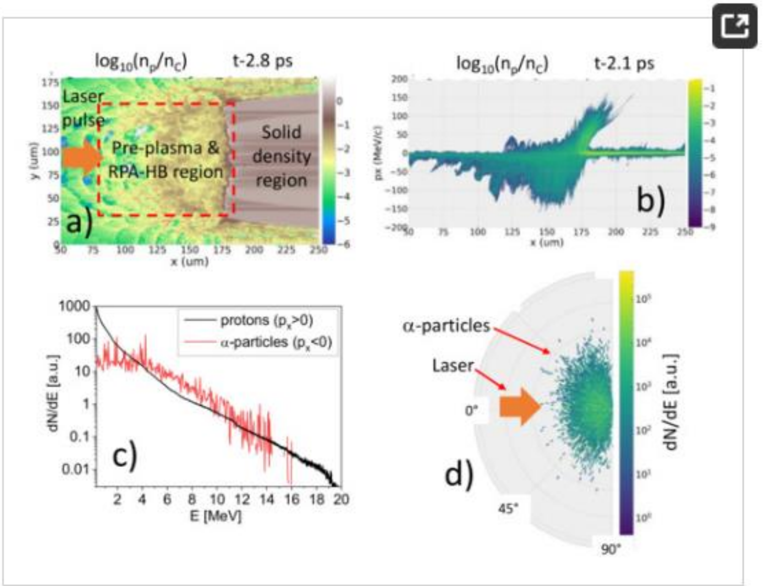




**Figure 4.** (**a**) The proton density map that was calculated by 2D PIC simulations at t = 2.8 ps (i.e., 1.2 ps after the highest intensity peak entered the highest density part of the target); (**b**) the proton phase space plot at t = 2.1 ps (the proton density is shown in units of plasma critical density); (**c**) the proton energy distribution ($p_X$ > 0) and α-particle energy distribution at the target's front side from PIC and Monte Carlo simulations, respectively; and (**d**) the α-particle angular distribution from the same simulation run.

# High Laser Absorption in Micro-cone targets at high intensities: $2x10^{20}$ W/cm$^2$ T. Ebert et al., PoP (2020)

Problem: Need high laser intensity for ~MeV particle acceleration.
But Low Laser absorption in 'flat' solid targets at I >$10^{18}$ W/cm$^2$
Solution: Micro- Nano-Structured Target Surfaces !!!

Example: Silicon micro-cones: 15μm height, 5μm diameter - Ebert(2020)
Laser absorption ~100% at I=$2x10^{20}$ W/cm$^2$
E-Laser = 160J, T-laser = 1ps; Laser Intensity = $2x10^{20}$ W/cm$^2$ ;
Focus diameter = 10μm
Electron 'temperature' =4.6MeV; Proton 'temp' =2.4 MeV

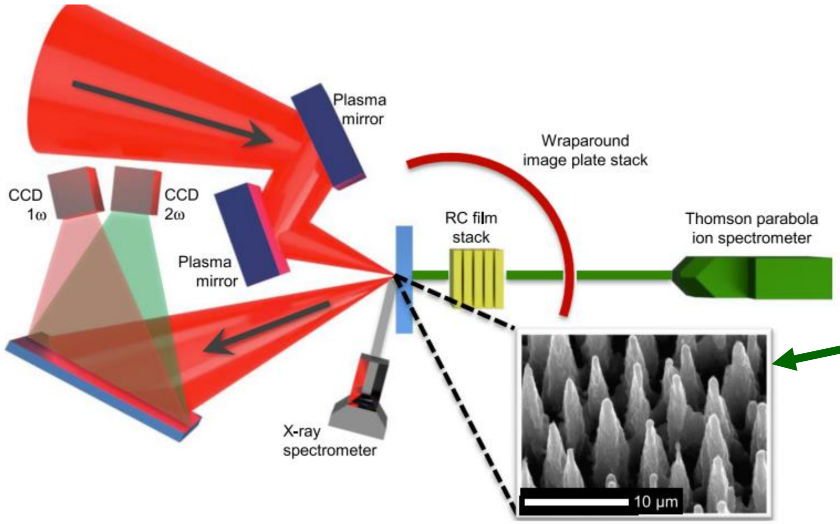



FIG. 1. Schematic illustration of the experimental setup. The experiment was performed using the Vulcan Petawatt Laser (Central Laser Facility, UK). The temporal laser contrast was increased to $10^{11}$ by using a double plasma mirror system. The incident angle between the laser and the target with respect to target normal is 20°. Reflected and emitted light from the target front surface is collected via a ground glass scattering screen by two cameras for fundamental and second harmonic radiation. In addition, a conical KAP (potassium acid phthalate) x-ray spectrometer is aligned to the target front. On the target back side, a radiochromic film (RCF) stack and a Thomson parabola ion spectrometer, as well as a wraparound image plate stack for measuring the electron emission, are positioned. Inset: Scanning electron microscopy recording of the front surface of a microstructured silicon target, as used within the experimental campaign.


Phys. Plasmas 27, 043106 (2020); doi: 10.1063/1.5125775
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27, 043106-2


| | Reflection 1053 nm (%) | Reflection 527 nm (arb. units) | X-ray intensity (keV sr$^{-1}$, $\times10^{10}$) | $K_\alpha$ intensity (keV sr$^{-1}$, $\times10^{10}$) | No. of electrons (PSL J$^{-1}$) | Electron temp. (MeV) | No. of protons ($\times10^{11}$) | Proton temp. (MeV) | Proton conversion efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|
| Flat | 20 ± 3 | 1.0 ± 0.5 | 0.54 ± 0.10 | 0.11 ± 0.01 | 21 ± 10 | 4 ± 1 | 4.3 ± 0.5 | 2.5 ± 0.1 | 0.27 |
| Struct. | 6 ± 1 | 0.10 ± 0.05 | 5.43 ± 1.30 | 1.3 ± 0.13 | 65 ± 22 | 4.6 ± 0.4 | 19 ± 1 | 2.36 ± 0.04 | 1.01 |
| Ratio | 0.3× | 0.1× | 7.3× | 12× | 3.1× | 1.2× | 4.4× | 1.0× | 3.7× |


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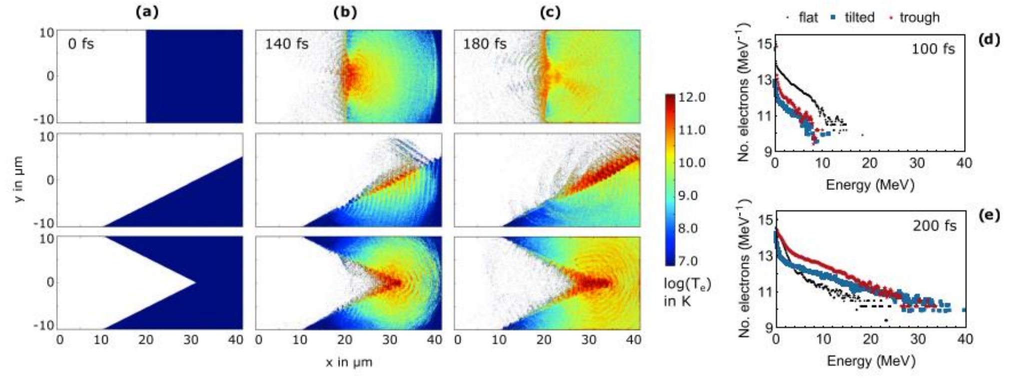


FIG. 4. Simulated electron temperatures $T_e$ for three different target geometries at (a) 0 fs, (b) 140 fs, and (c) 180 fs after simulation start. At the top, a flat reference target is shown. The middle row depicts a tilted target, while the bottom row corresponds to the surface geometry of a trough between two microstructures. For the latter, the heated region is much longer existent, and the electrons show a wider opening angle. The color bar denotes $\log(T_e)$ in K. The electron spectrum is shown in the subfigure (d) at 100 fs and (e) 200 fs. While the electron number and cut-off energy of the flat target are higher at early times, the tilted and trough geometry dominate at later stages. At both snapshots, the trough performs better than the tilted target.

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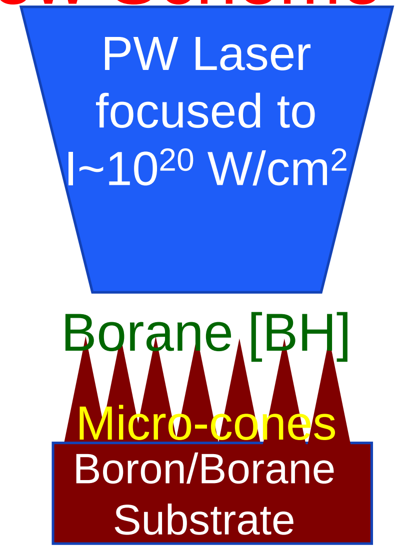
# New Hydrogen-Rich, Borane, Micro-structure Target and PW-Laser Driver for In-Target Proton-Boron Fusion Alpha-Source : Proposed New Scheme




- **Record Alpha flux** >$10^{10}$ alphas/sr/pulse in-target reactions [Slide # 5]

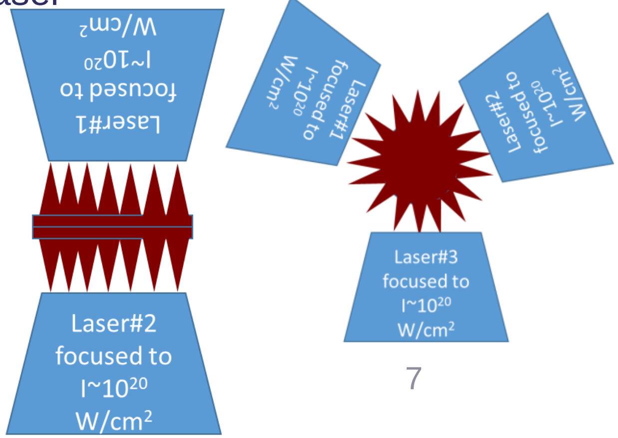
Target: solid Boron Nitride with traces of hydrogen ~ few%

Lasers I=3x$10^{19}$ W/cm$^2$ LFEX, Margarone(2022) and 3x$10^{16}$ W/cm$^2$ PALS, Giuffrida(2020)

- **Proposed New Scheme:** Borane micro-structure target with PW laser driver, I>$10^{20}$ W/cm$^2$. Expected enhanced Alpha particle yield because of **higher Hydrogen density** and **higher laser intensity:**

1. New, Borane, hydrogen rich, H/B = 100% target compared to hydrogenated BN target. The higher target Hydrogen content would increase the number of PB reactions In-Target.
2. Micro-Structure targets can be driven with Higher Laser Intensities I ≥ $10^{20}$ W/cm$^2$
3. Example of other available Lasers:
    1. ELI-NP [Romania], 2x1PW with ~22J/22fs and 2x10PW with 220J/22fs. The PW beamline has just become available for experiments.
    2. Vulcan and Orion [UK] PW lasers with ~1kJ/1ps.
    3. Omega-EP [US], 2x1kJ laser, 10picosecond, with focal spot, e.g. Dfocus~ 450µm. [Note that 10ps pulse duration would be maximum if Microstructure spacing ~10µm. Otherwise microstructures may disintegrate during laser pulse]
4. Expand scheme to 2D and 3D :further increase the number of PB reactions.
5. Additional neutron and gamma-ray diagnostics are needed for measuring the In-target Alpha emission: $\alpha$( 11B, 14N)n and/or p(11B, 11C)n, p(11B,12C)$\gamma$ .

New Scheme for PB fusion alpha source: PW Laser incident on Microstructure Borane Target (above). 2D and 3D extension of scheme (below)

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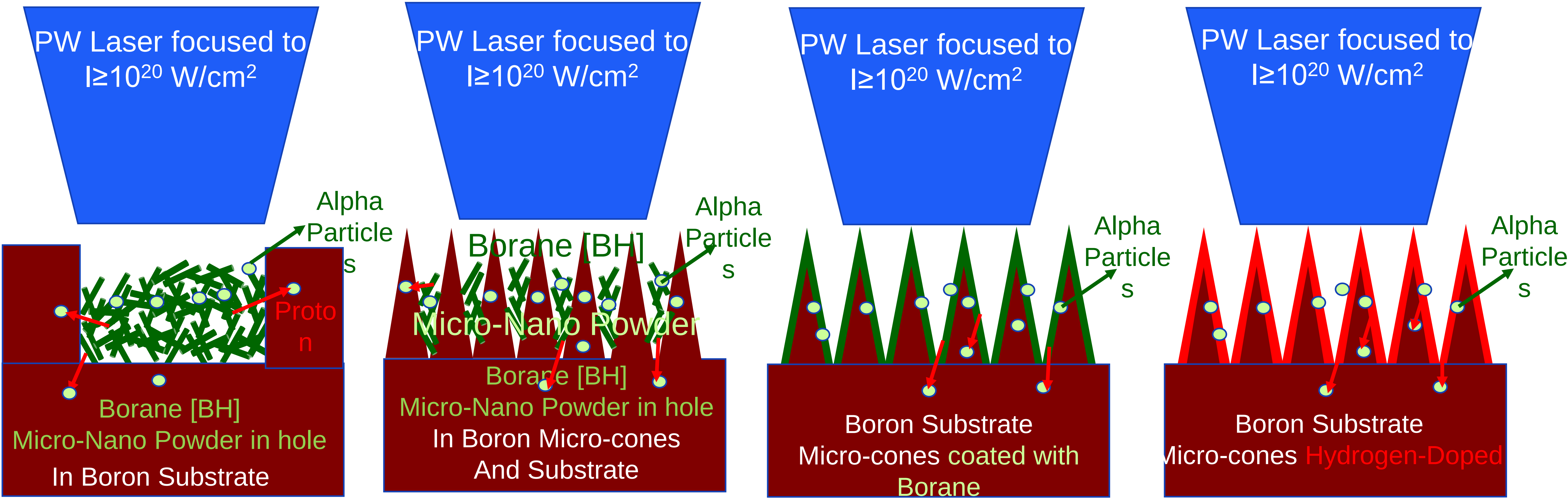
# New Proposed Geometries for Borane Micro-structured targets for PW Laser driven PB fusion

Alpha-sources : PB fusion in Borane crystals and in Boron substrate from energetic protons:




(1) Borane Micro-Nano-Crystals Powder.
Contained in large 20-100μm 'holes' in Boron substrate

(2) Borane Micro-Nano-Crystals Powder.
Contained between the Boron Micro-structure: cones or holes.

(3) Borane coating of Boron Micro-structure: cones or holes.
1-Method, melt and solidify Borane Powder covering microstructure.
2-Method: pour Borane solution on microstructure. Obtain coated microstructure after coating evaporates.

(4) Hydrogen-Doped Boron Micro-structure on Boron substrate.
Method: Ion implantation.

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# Micro-scale DD fusion in dense relativistic nanowire array plasmas: A. Curtis et al., Nature Communications (2018)

NATURE COMMUNICATIONS | DOI: 10.1038/s41467-018-03445-z

Nanowires irradiated with femtosecond high intensity lasers $10^{19}$ W $cm^{-2}$, produce Dense and Hot Plasma Nano-pinches. [V Kymak et al., PRL (2018), Ref.5]

Deuterium-Deuterium (DD) Fusion has been demonstrated in femtosecond laser irradiated ($10^{19}$ W $cm^{-2}$ ) targets of Deuterated polyethylene (CD2) Nanowires on CD2 substrate. [A. Curtis et al., Nat Comms (2018), Ref.6]

A Neutron Flux of **$2 \times 10^6$ fusion neutrons per joule,** is emitted by the nanowires. Simulation: "….At intensities >$1 \times 10^{21}$ W $cm^{-2}$, the majority of the fusion reactions will occur in the substrate layer…"

Target: arrays of aligned CD2 nanowires either 0.2 – 0.4 μm diameter and ~5 μm in length. The average density of the arrays corresponded to 16 and 19% solid density, respectively.

Laser: energy up to 1.65 J, pulse duration 60 fs with ultra-high contrast (>$10^{12}$) – needed for nano-wires, and wavelength of λ = 400 nm.

| | | | |
|---|---|---|---|
| (2i) | ${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T$ ( 1.01 MeV ) + $p^{+}$ ( 3.02 MeV ) | | 50% |
| (2ii) | $\rightarrow {}^{3}_{2}He$ ( 0.82 MeV ) + $n^{0}$ ( 2.45 MeV ) | | 50% |

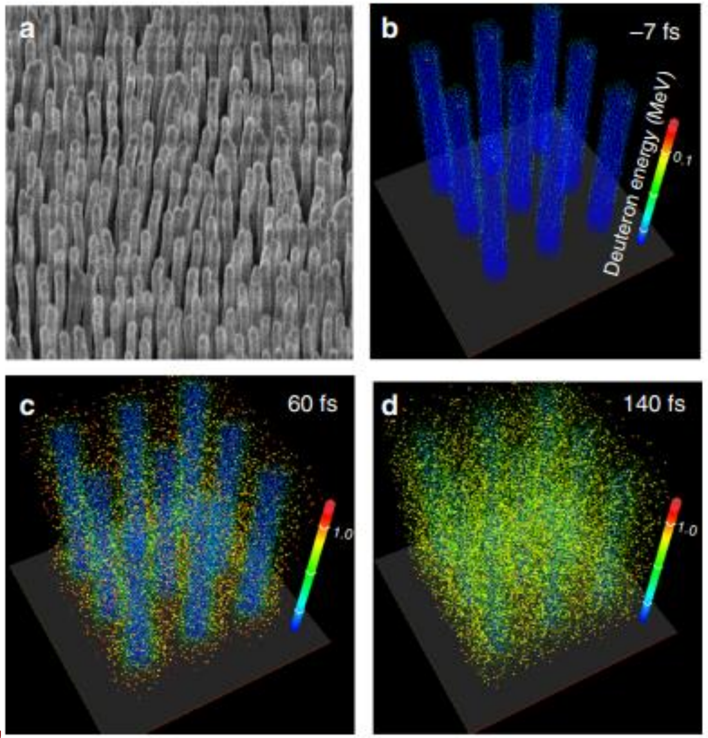


**Fig. 1** SEM image and 3D PIC simulation of energy distribution of deuterons. **a** SEM image of an array of 200 nm diameter $CD_2$ nanowires. **b**-**d** Three-dimensional particle-in-cell (PIC) simulation of the evolution of the energy distribution of deuterons in an array of 400 nm diameter $CD_2$ nanowires irradiated at an intensity of $8 \times 10^{19}$ W $cm^{-2}$ by an ultra-high contrast $\lambda$ = 400 nm laser pulse of 60 fs FWHM duration. The laser pulses penetrate deep into the array where they rapidly heat the nanowires to extreme temperatures, causing the nanowires to explode (Fig. 1c, d). Deuterons are rapidly accelerated into the voids up to MeV energies, producing D-D fusion reactions and characteristic 2.45 MeV neutrons. Times are measured with respect to the peak of the laser pulse. The average density of the nanowire array corresponds to 16% solid density

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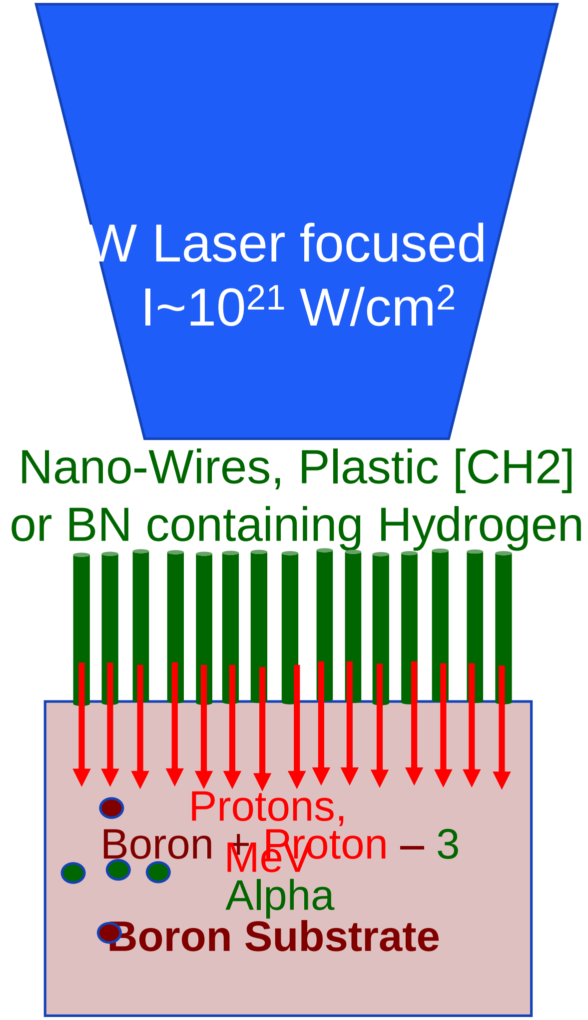
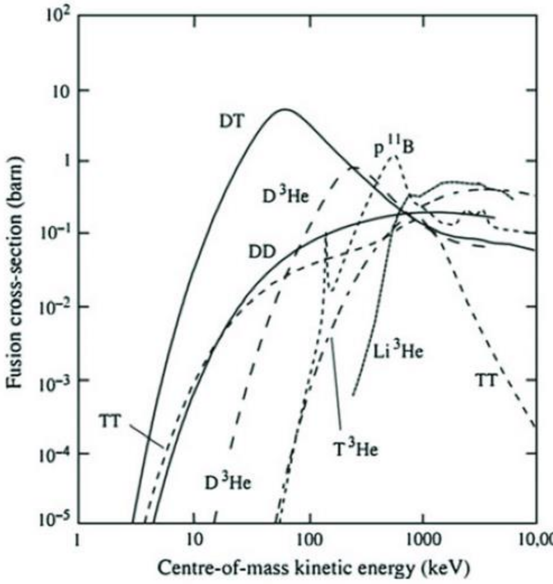
# New: Nano-Wire Targets with Boron substrate driven by PW, Femtosecond Laser generating P-B Fusion Alpha-Sources : Proposed New Scheme.




Schematic of the new PB Fusion Alpha Source Scheme with laser-targets of CH2-Nanowire-Array on Boron-Substrate irradiated with Femtosecond, Pettawat Laser Focused to I~$10^{21}$ W/cm$^2$ . Nanowire material could also be Borane if achievable, or hydrogenated BN.

1. MeV protons are accelerated in the Nanowire-Z-pinch and injected into the Boron substrate similar to Deuterium ions in Curtis(2018) previous slide. The ~MeV Protons + Boron – 3 Alphas
2. [Curtis (2018)]: I= $10^{19}$ W cm$^{-2}$ : 2 × $10^6$ neutrons/joule ~4x$10^6$ DD reactions/J
3. Assume that at I~$10^{21}$ W/cm$^2$ Number of PB reactions in Boron substrate > Number of DD reactions in CD2 nano-wires at I= $10^{19}$ W cm$^{-2}$ , which is 4 × $10^6$ DD reactions/J. (Paper: I~$10^{21}$ W/cm$^2$ most DD reactions will be in CD2 substrate and will exceed the reactions in nanowires)
4. Scaling to ELI-NP PW, 22J/pulse, 22fs, I~$10^{21}$ W/cm$^2$ , Flux of PB reactions in Boron substrate > 8.8 × $10^7$ PB reactions/pulse or > 2.6x$10^8$ alphas/pulse.
5. Scaling to ELI-NP 10PW, 220J/pulse, 22fs, I~$10^{21}$ W/cm$^2$ Flux > 2.6x$10^9$ alphas/pulse




Fusion crossections [DOI: 10.1088/1742-6596/1003/1/012076]
Note:
DD and PB crossections at energies ~1MeV

# Conclusions

1. New Concept: Alpha Source with Borane Micro-Nano-Structure Targets irradiated by PW Lasers at High Intensities ≥ $10^{20}$ W/cm$^2$
2. New Borane, hydrogen rich HB11 solid targets for PB Alpha Sources.
3. New Borane Microstructure irradiated by PW Lasers at ~$10^{20}$ W/cm$^2$. Enhancement of PB fusion alpha yield.
4. New Nanostructured PW- FS-laser-targets for PB Fusion Alpha Source.

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ICET thanks Prof KA Tanaka for suggesting the interesting new papers on femtosecond laser nano-wire heating by A Pukhov and co-authors, as well as organizing discussions on this subject with ICET, P Ghenuche and JF Ong at ELI-NP in Bucharest.

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# Thank you!
# Grazie!
# Ciao!

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