Muon Catalyzed fusion

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Based on our previous work:

"New scheme to trigger fusion in a compact magnetic fusion device by combining muon catalysis and alpha heating effects"
High power Laser Science And Engineering, Vol.4, e42, 7 pages (2016)

Main idea
Two (2) steps operation for fusion ignition

$$\mathrm{D} + \mathrm{T} \rightarrow \boxed{\alpha(3.5\ \mathrm{MeV})} + n(14.1\ \mathrm{MeV})$$

Step 1: Use muons to Trigger fusion effects in low temperature (< 100 eV) D-T fuel and generate **energetic alpha** (and neutrons)

Step 2: **alpha energy transfer** Ignite fusion in a volume of D-T plasma with 300 eV – 800 eV initial temperature

See also S. Eliezer and Z. Henis,
"Muon-catalyzed fusion-an energy production perspective",
Fusion Technology, 26(1), August 1994

☆ Potential application for p-^{11}B fusion ignition

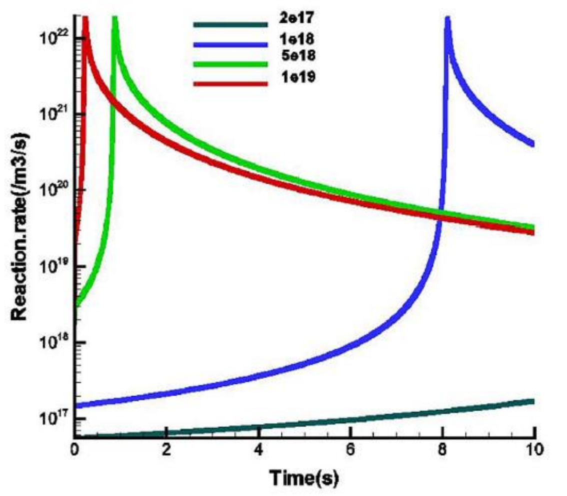


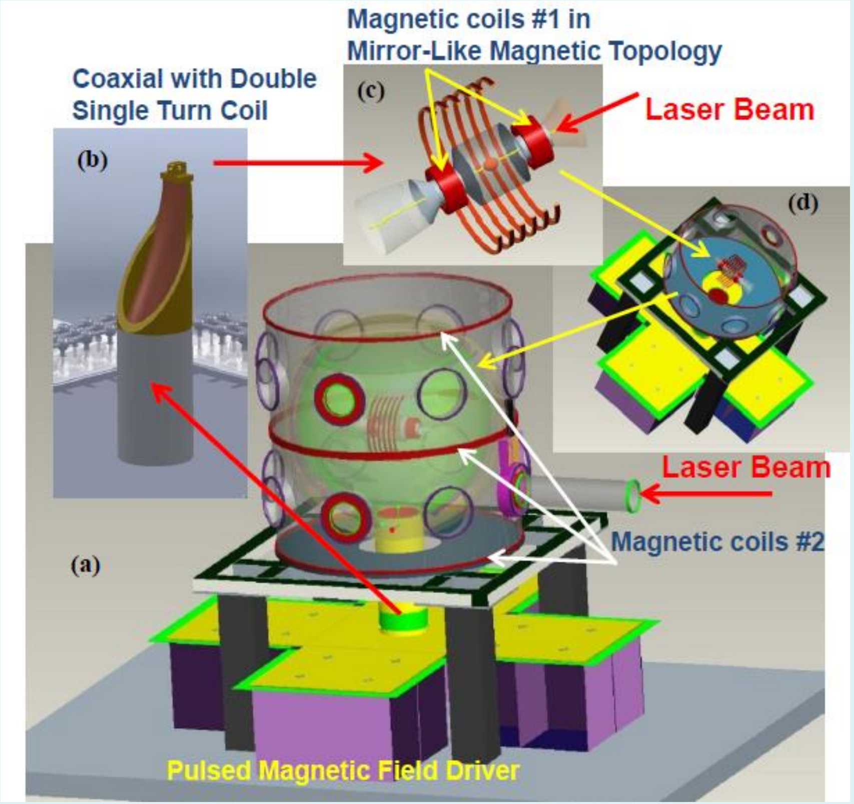
Figure 5. Temporal evolution of the reaction rate. The curves correspond to different initial values of the alpha particles produced by the μCF in the spark part of the device: (a) red 10^{19} m^{-3}, green 5×10^{18} m^{-3}, blue 10^{18} m^{-3} and deep green 2×10^{17} m^{-3}.

Step 1 → **spark part**

TUC SOREQ Soreq Nuclear Research Center FORTH

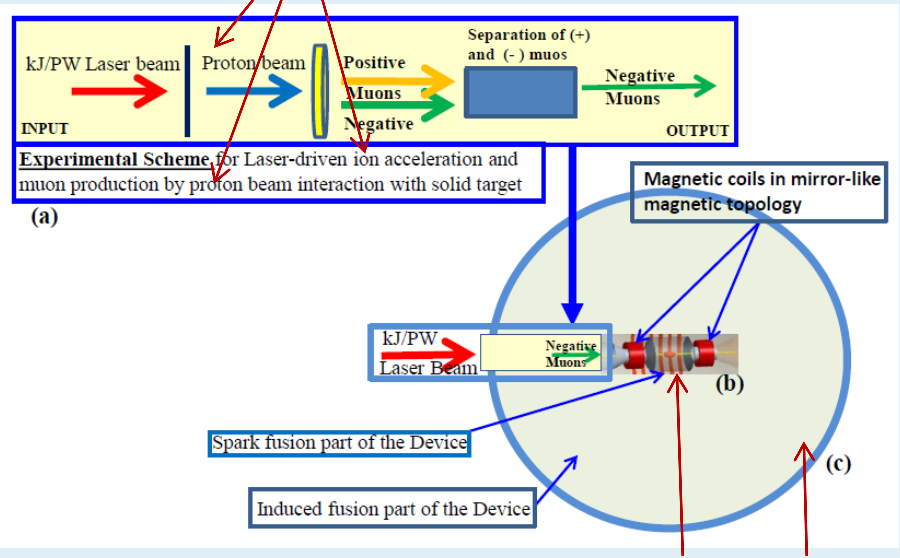
Potential Experimental Configuration for Muon Catalyzed Fusion

[*] Preliminary designs (not in scale)



Initial proposed effort [Step #1]:
Study and Develop the Spark fusion part

e- beam [or protons]



(b) ~ 1 cm^3 [10^{-6} m^3] (c) ~ 10^{-4} m^3 or 10^{-3} m^3

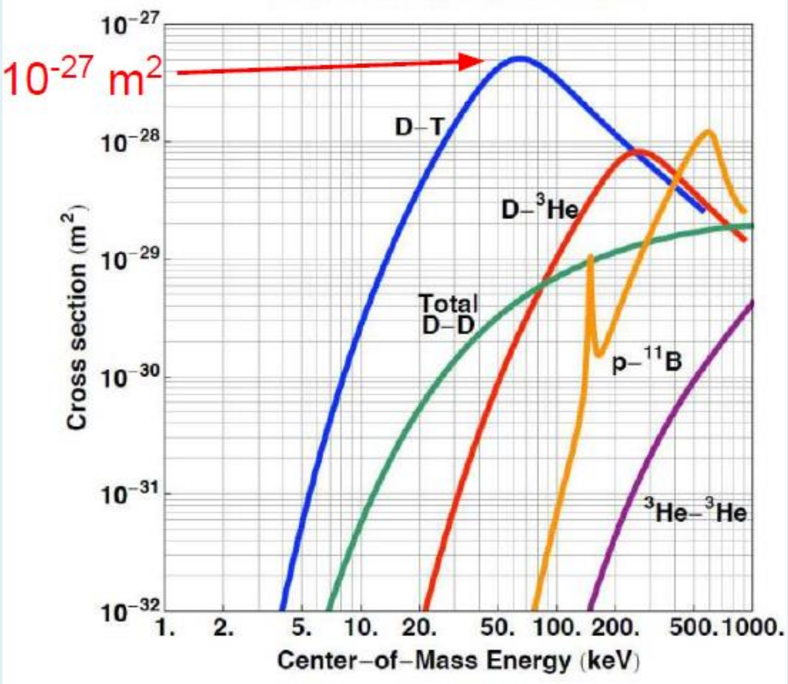
Fusion Reactions

Thermonuclear Fusion

Tin (D-T) ~ 5 keV Pf > PBremss σ (D-T)~ 1 barn

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV}) \quad 50\%$$
$$\rightarrow {}^3\mathrm{He}(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV}) \quad 50\%$$
$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \alpha(3.6\ \mathrm{MeV}) + p(14.7\ \mathrm{MeV})$$

★ $p + {}^{11}\mathrm{B} \rightarrow 3\alpha + 8.7\ \mathrm{MeV}$

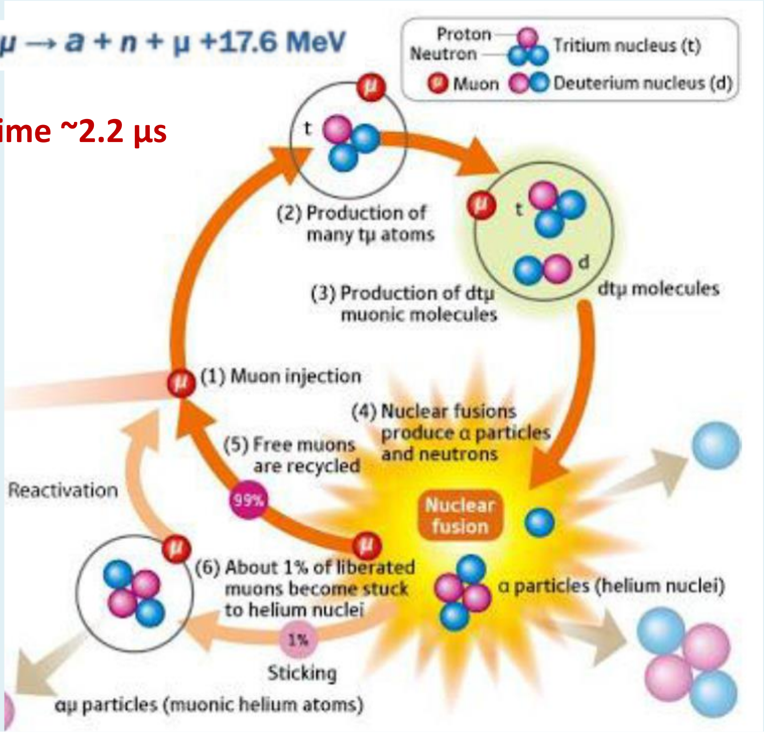


μ-Catalyzed fusion

Tin (dtμ) ~ 1 eV – 10 eV -100 eV σ (dtμ)~ 100 -1000 barns

dtμ → a + n + μ +17.6 MeV

μ lifetime ~2.2 μs

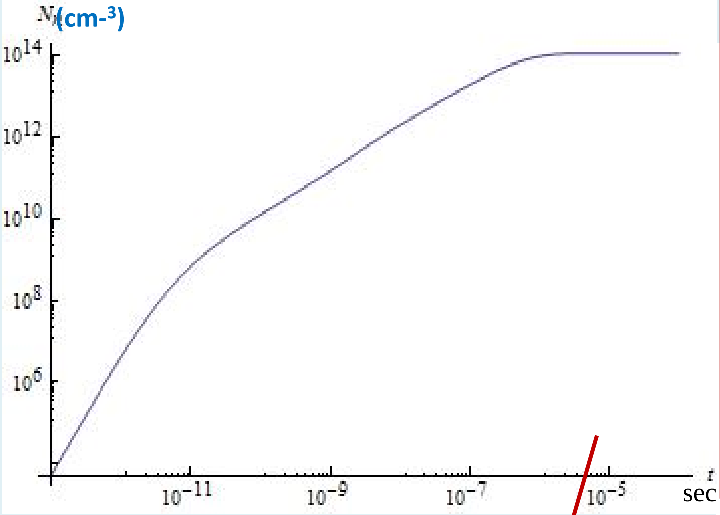


stages dμ formation (10^{-11} sec) → muon transfer ($<10^{-8}$ sec) → dtμ molecule formation ($<10^{-8}$ sec) → nuclear fusion → release muon

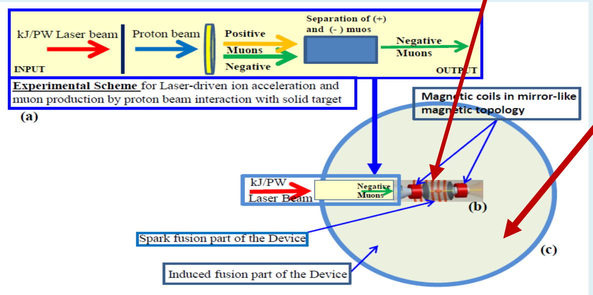
Calculations for dtμ fusion cycle in the spark-part using the different coefficients of the previous model

$\mu = (10^{11} - 10^{12})$ / shot

Tin ~ 10 eV   N (d,t) = 10^{20} cm^{-3} - 10^{21} cm^{-3}



Temporal evolution of the produced alpha or neutrons



Simulations using a multi-fluid code describing the temporal evolution of the D-T medium Tin = 300 eV or 800 eV including different densities of additional energetic alphas from the spark-part

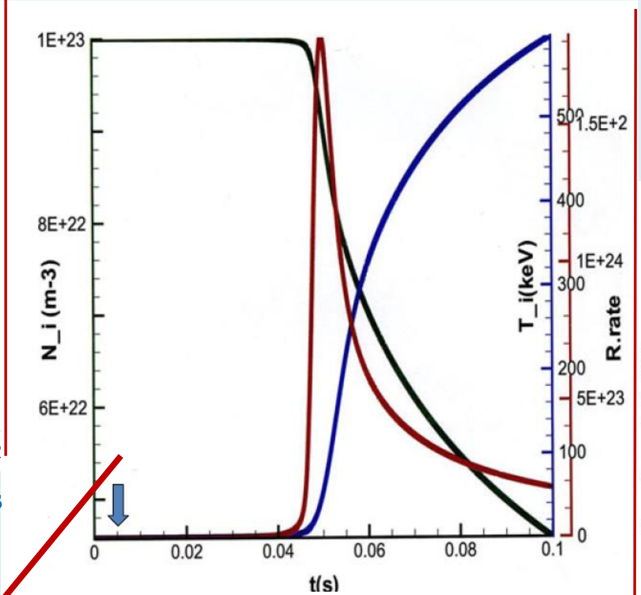


Figure 3. Temporal evolution of the reaction rate, plasma ion density and plasma ion temperature. The blue arrow indicates the end of operation of the μCF in the spark fusion part of the device which correspond to 1 μs.

For a volume of 10^{-3} m^3 or 10^{-4} m^3

Alpha or Neutrons ~ 10^{18}

n (D,T) = 10^{16} cm^{-3} – 10^{17} cm^{-3}

Reaction Rate = alpha/m³/sec

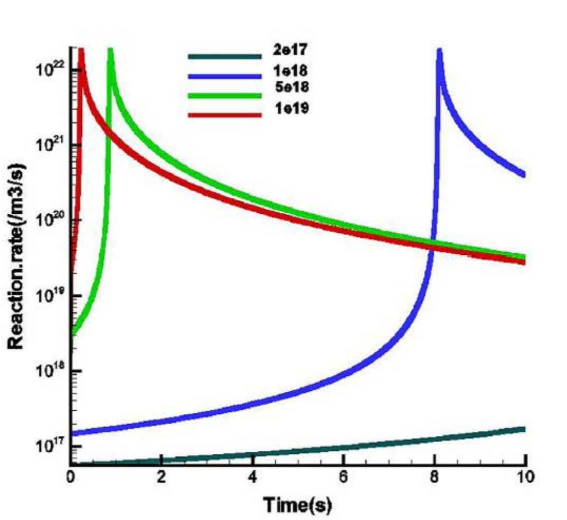


Figure 5. Temporal evolution of the reaction rate. The curves correspond to different initial values of the alpha particles produced by the μCF in the spark part of the device: (a) red 10^{19} m^{-3}, green 5×10^{18} m^{-3}, blue 10^{18} m^{-3} and deep green 2×10^{17} m^{-3}.

Discussion on p-^{11}B fusion activities using muon catalyzed techniques

p-^{11}B nuclear fusion is <u>aneutronic</u> and produces three (3) alpha particles with 8.7 MeV total energy.

☆ Main difficulties for p-B fusion ignition ($Q = P_{fus}/P_{Brems} \geq 1$) are Bremsstrahlung losses and cross section which is important at higher than 250 keV medium temperature

☆ Direct "fusion process" from "muonic-molecules" with $Z > 1$ like pBμ is feasible.[*] But with VERY low efficiency compared to dtμ fusion.

→ we need NEW experimental investigations

☆ Therefore we explore the previous described approach: the two part configuration.
Two schemes are proposed for the two part configuration

☆ **First scheme**

$\mathrm{D} + \mathrm{T} \to \alpha(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$ **! !**

Use in the spark part **the dtμ** catalyzed fusion reaction to generate **energetic alphas**

☆ **Second scheme**

$\mathrm{D} + \mathrm{D} \to \mathrm{T}(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV})$ **? ?**

use in the spark part **the ddμ** catalyzed fusion reaction to generate **energetic protons**
(ddμ << dtμ but there is not problem with tritium employment and generate lower energy neutrons)

☆ A special configuration for non-thermal neutral or non-neutral p-^{11}B medium can also be explored.

N. Nissim, Z. Henis, S. Eliezer, Y. Schweitzer, C. Daponta, and S. D. Moustaizis, "Boosting of fusion reactions initiated by laser accelerated proton beam in a non-thermal neutral and non-neutral proton-boron plasma", *Frontiers in Physics*, vol. 12, **DOI**: 10.3389/fphy.2024.1428608, 2024.

[*] <u>See</u> **S. Eliezer,** *"Muon Catalyzed Nuclear Fusion" Laser and Particle Beams vol.* 6, *part* 1, *pp.* 63-81, 1988,
S. Eliezer and Z. Henis, *"Muon-catalyzed fusion-an energy production perspective"*, Fusion Technology, 26(1),

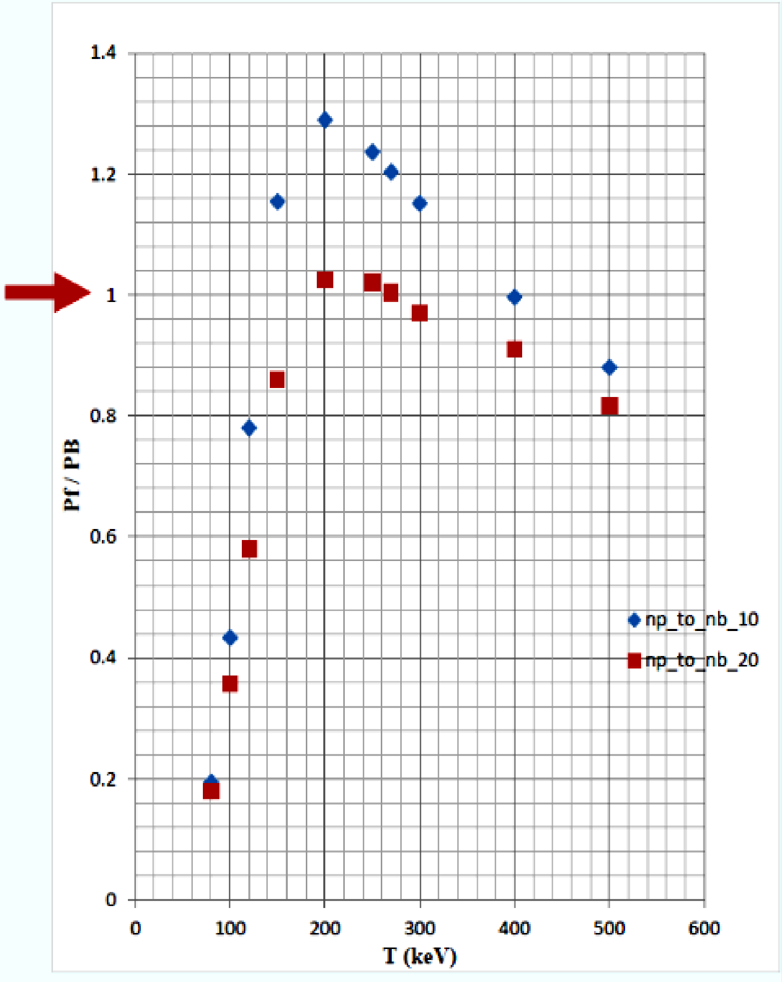
Numerical investigation of ignition conditions in low density ($n_p = 10^{20}$ m^{-3}) p-^{11}B medium with $n_p / n_B = 10$ or $n_p / n_B = 20$

Three main Critical points for the achievement of fusion ignition conditions: $Q = P_{fus}/P_{Brems} > 1$

1) $n_p / n_B > 1$ (*),

2) The manifestation of avalanche effect, when the produced alpha particle density is ~ 2 orders of magnitude lower than the initial ^{11}B medium density. The code could be used for the investigation of experimental setups and proposals preparation. (*)

3) $T_i \geq 2\ T_e$ (*)

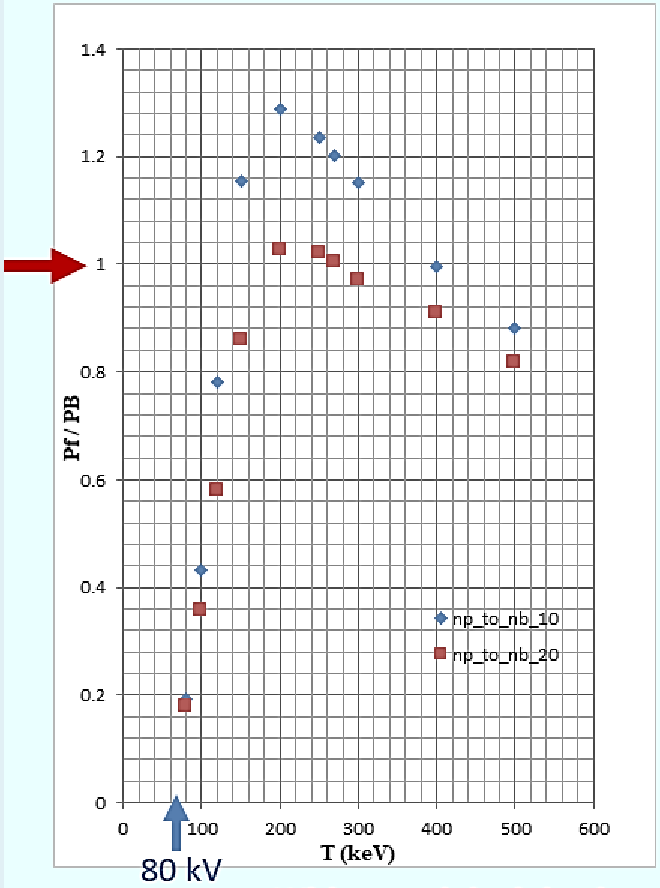


(*)

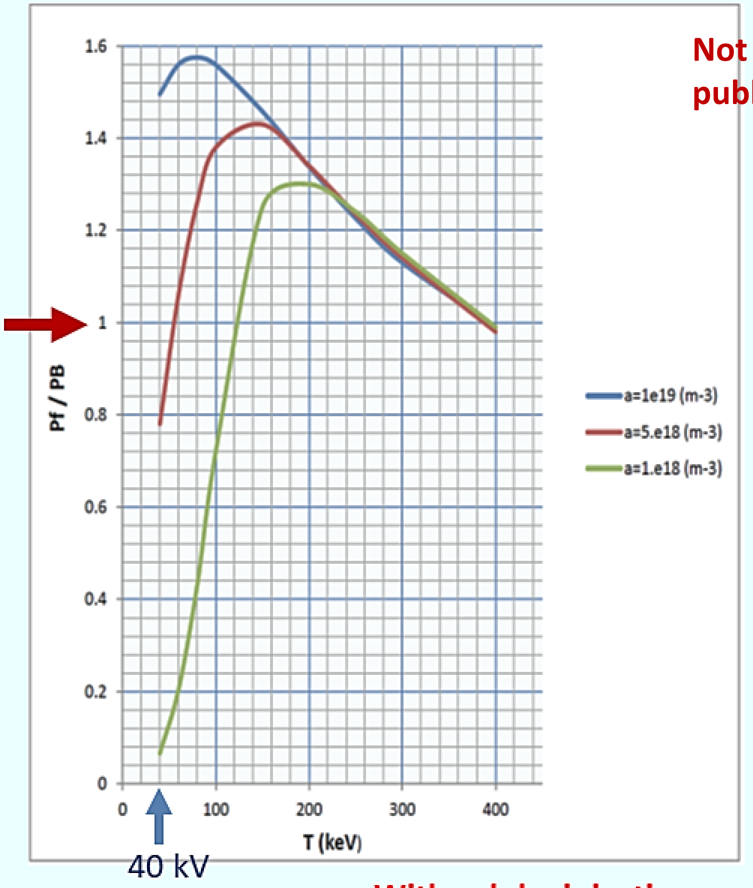
[3]_**S. D. Moustaizis**, C. Daponta, S. Eliezer, Z. Henis, P. Lalousis, N. Nissim, and Y. Schweitzer, "Alpha heating and avalanche effect simulations for low density proton-boron fusion plasma", *Journal of Instrumentation*, vol. 19, **DOI:** 10.1088/1748-0221/19/01/C01015, 2024.

Numerical investigation of ignition conditions in low density (n_p= 10 ^{20} m^{-3}) p-^{11}B medium with n_p/ n_B = 10 or n_p / n_B = 20 and 40 keV ≤ T_{in} = T_p = T_B ≤ 500 keV

First scheme
Including
Energetic alphas



Without alpha injection



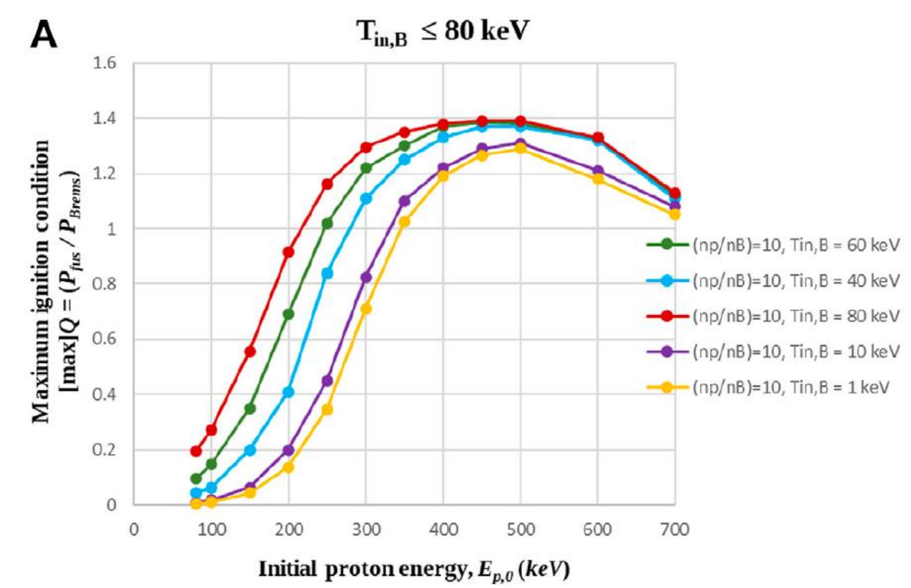
Not yet published

With alpha injection

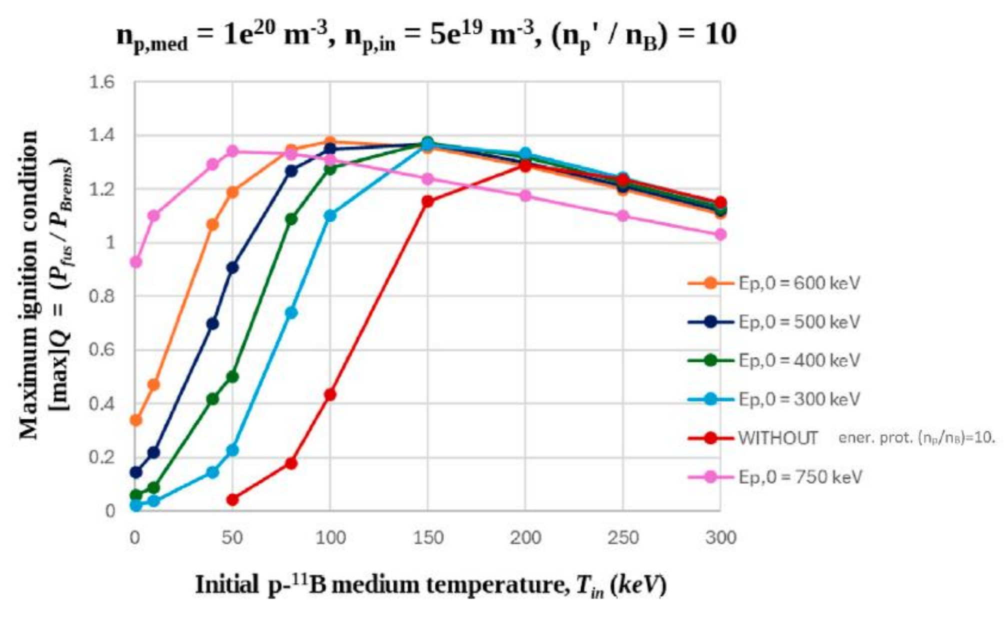
Second Scheme

Including Energetic Protons in Boron OR p-^{11}B medium of different initial temperatures (T_{in})

Boron medium : $n_p / n_B = 10$, $n_B = 10^{19}$ m^{-3}



p-^{11}B medium



See yellow color curve : T_{inB} = 1 keV
with energetic protons of 500 keV

See violet color curve : energetic protons of 750 keV
Tin p-^{11}B ~ 20 keV

[1]_C. Daponta, **S. D. Moustaizis**, S. Eliezer, Z. Henis, P. Lalousis, N. Nissim, and Y. Schweitzer, "Towards p-^{11}B configurations with high (P_{fus} / P_{Brems}) ratio", *Frontiers in Physics*,vol.12, **DOI:** 10.3389/fphy.2024.1425963, 2024.

Comments

☆ Laser- driven muon production by energetic electrons [good production efficiency]

☆ Laser-induced muon catalyzed fusion, feasibility [experimental] studies: μ up to ~ **10^{11}/shot** [*]

☆ **Requested number** of muons for fusion applications **10^{12}/shot or higher**

☆ Energy of muons: From the initial high energy the μ slows down to a few keV (e.g ~2.5 keV), to form a muonic atom (μd, μt) in the fusion medium.

☆ Source of high alpha and neutron fluxes

☆ Potential use of muon catalyzed fusion, as a new diagnostic for muon detection, due to specific energy spectrum of the produced alphas and neutrons

☆ Potential Application in aneutronic p-^{11}B fusion ignition
Preliminary results from numerical simulations on the subject

[*] see the numerical simulations : High power Laser Science And Engineering, Vol.4, e42, 7 pages (2016)

S. Eliezer and Z. Henis, *"Muon-catalyzed fusion-an energy production perspective"*, Fusion Technology, 26(1), August 1994

THANK YOU for Your Attention