Alpha heating and avalanche effect simulations for low density proton-boron fusion plasma

S. Moustaizis[1], C. Daponta, [1], S. Eliezer[2], Z. Henis[2], P. Lalousis[3], N. Nissim[2] and Y. Schweitzer[2]

1] Technical University of Crete [TUC], Lab of Matter Structure and Laser Physics, Chania, Crete, Greece
[2] Applied Physics, Soreq Nuclear Research Center, Yavne, Israel
[3] Institute of Electronic Structure and Laser FORTH, Heraklion, Greece

TUC

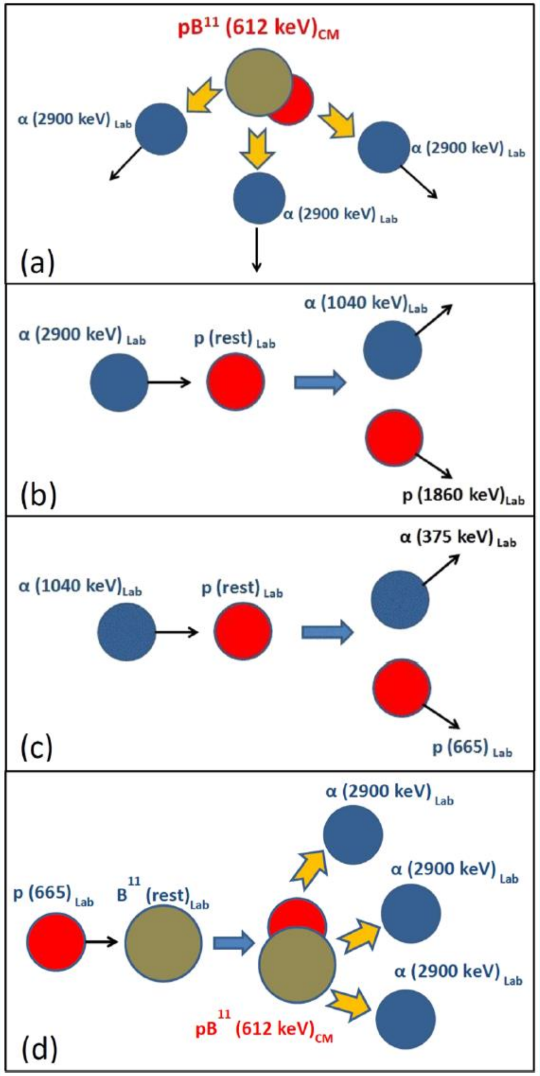
SOREQ
Soreq Nuclear Research Center

FORTH
FOUNDATION FOR RESEARCH AND TECHNOLOGY · HELLAS

2nd Workshop on p-B fusion, 5-8 September 2022, Catania, Italy

Investigate the effects of alphas in $H^{11}B$ Plasma

The $H^{11}B$ nuclear fusion reaction is attractive not only because it is aneutronic, but also because it has the advantage to produce three alphas with 8.7 MeV total energy.



The alpha heating AND the Avalanche effect mechanism

Increases the FUSION SPECIES Temperature

Improves the reaction rate

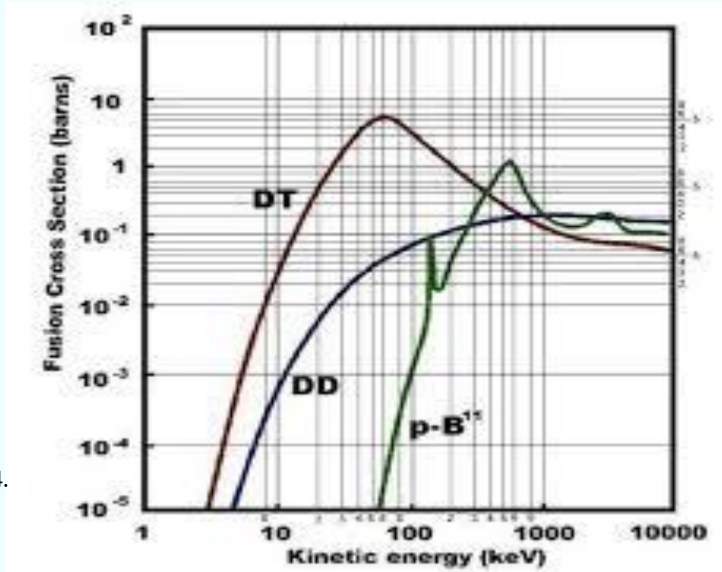
Allows the ignition of the fusion process at relatively low plasma temperatures T<< 250 keV

<u>Experimental results [1-7]</u>

Relevant experimental results on alpha production, by laser-driven proton beam interaction with ^{11}B target,

Chain reactions [no-nuclear] and Avalanche effect

<u>Eliezer et al.</u> PHYSICS OF PLASMAS 23, 050704 (2016)



[1] Labaune, C., S. Deprieraux, S. Goyon, C. Loisel, G. Yahia & J. Rafelski *Nature Communications* **4**, 2506 (2013).

[2] G. Korn, D. Margarone, A. Picciotto, Lecture at the IZEST conference, Paris, Romanian Embassy, 19 September 2014.

[3] A. Picciotto et al. *Physical Review X* **4**, 031030 (2014).

[4] Guifrida et al. (2020)

[5] Osaka 2020 experiment

[6] Experiment 2020 Texas PW, [7] Bonvalet J., Nicolai Ph., Raffestin D., et al., Physical Review E 103, 053202 (2021)

Numerical studies on the temporal evolution of the p-B medium parameters, temperature and density of the fusion species, alpha density and Reaction Rate (RR)

Using a zero dimension, multi-fluid, global particle and energy balance code, including collisions, adapted for $H^{11}B$ fusion plasma

Optimization of Bremsstrahlung losses

(1) Low electron density or (2)_ratio p/B > 1

Chain reactions [no-nuclear]

Alpha Heating and Avalanche effect

Alpha Heating effect

Transfer of energy from the alphas
to the fusion species (p, B)

Increases the Temperature of the fusion species

Improves the alpha density production, due to the increase of the nuclear reaction cross section and consequently, of the RR or reactivity

More and More transfer of energy to the fusion species

Avalanche effect

Increases the alpha density until a value, which is equal to one (1) order of magnitude lower than the initial fusion medium density

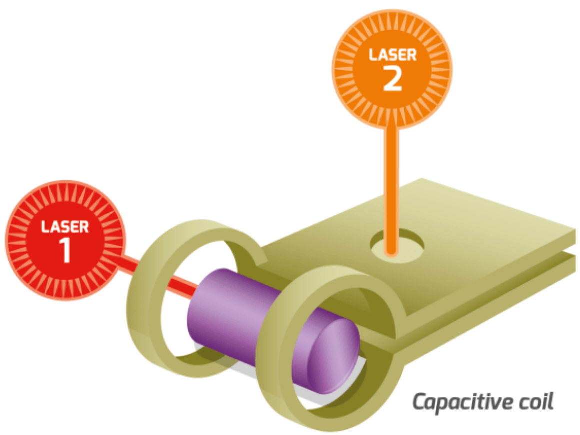
Important rise of the fusion species temperature

Fast enhancement of the fusion ignition, and the RR reach a Maximum value, corresponding to the optimum value of the p-B nuclear reaction cross section

80 keV initial temperature of fusion species, using one side interaction of solid density p-B target with short laser pulse (laser 1-ps or sub-ps) and high power (PW)

Magnetic confinement

Second laser and capacitive coil



Kilotesla magnetic field
by second laser and capacitive coil
increases reaction yield
in cylindrical shaped fuel

Demonstration of kilotesla field:
FUJIOKA, S. et al. *Nat. Sci. Rep.* 3, 1170-1176. (2013)

Simulation of higher reaction yield:
LALOUSIS, P., Hora H. et al. *J. Fusion Energy* 34, 62-67. (2015)

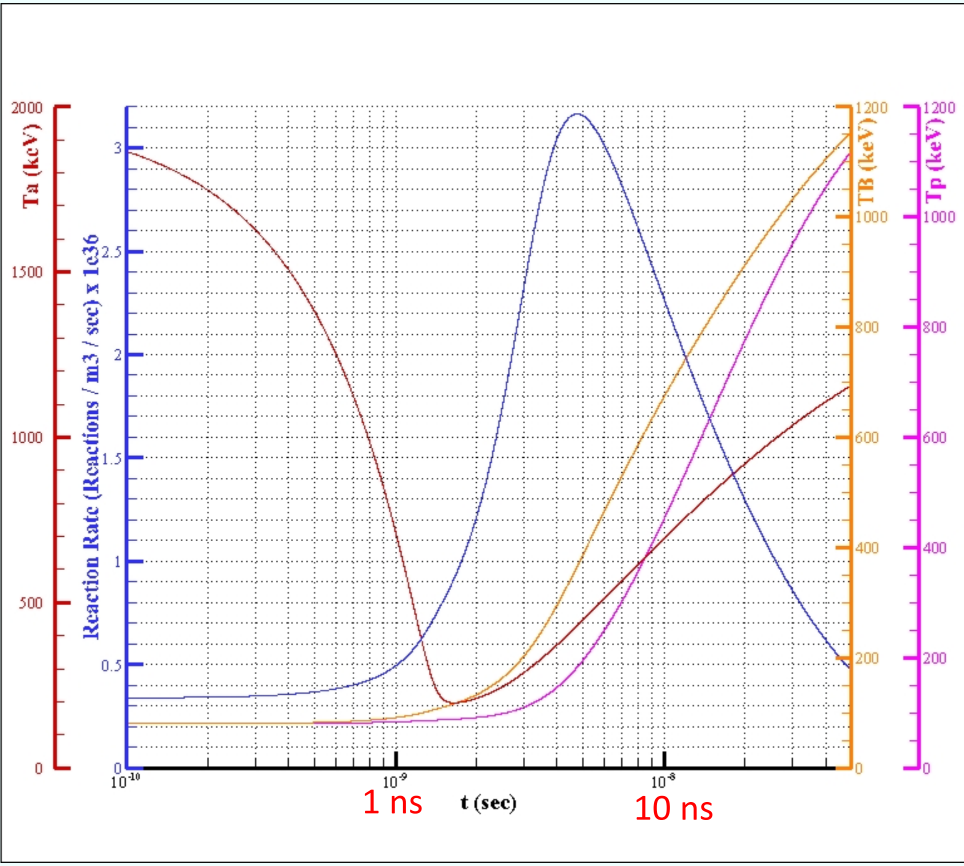
Bibliography on the description of the proposed by Prof. Hora scheme and the related Numerical Simulations
see Web page of:

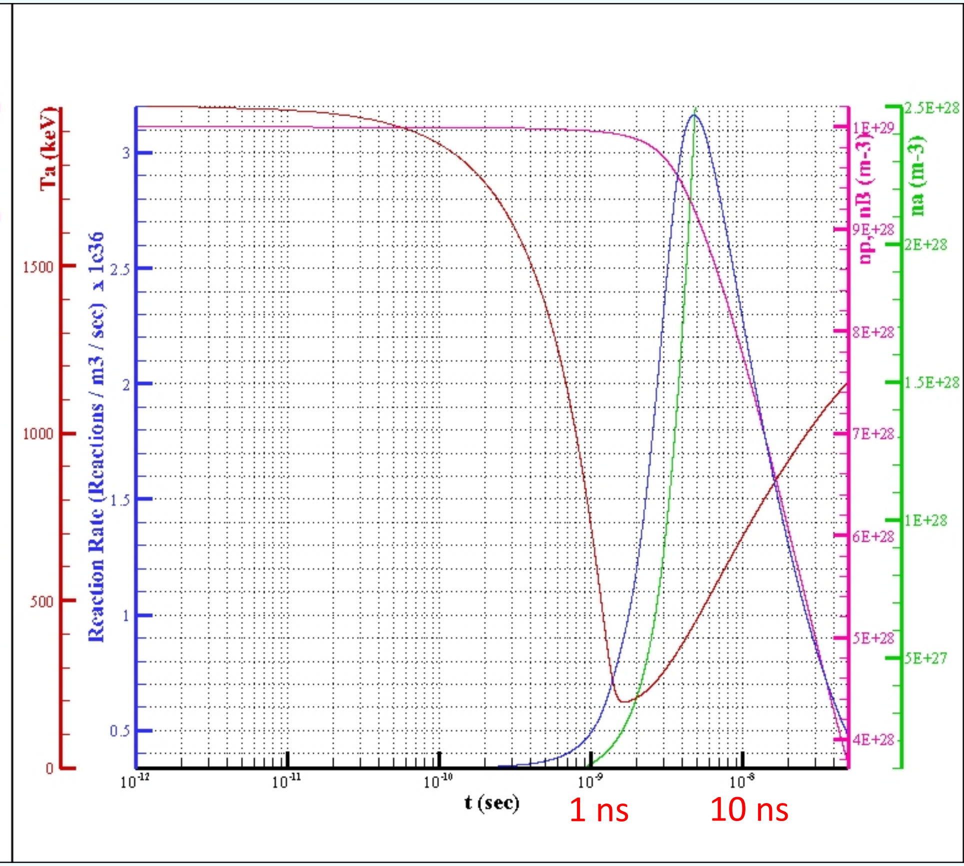
HB11 ENERGY
LASER BORON FUSION

Different from IC fusion scheme like NIF

Now, we work on a 1-D multi-fluid code with high magnetic field, including collisions between the medium species

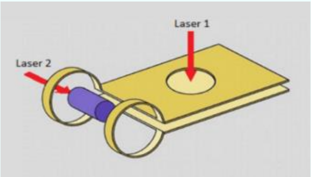
Non-Neutral, Solid State Density, T = 80 keV



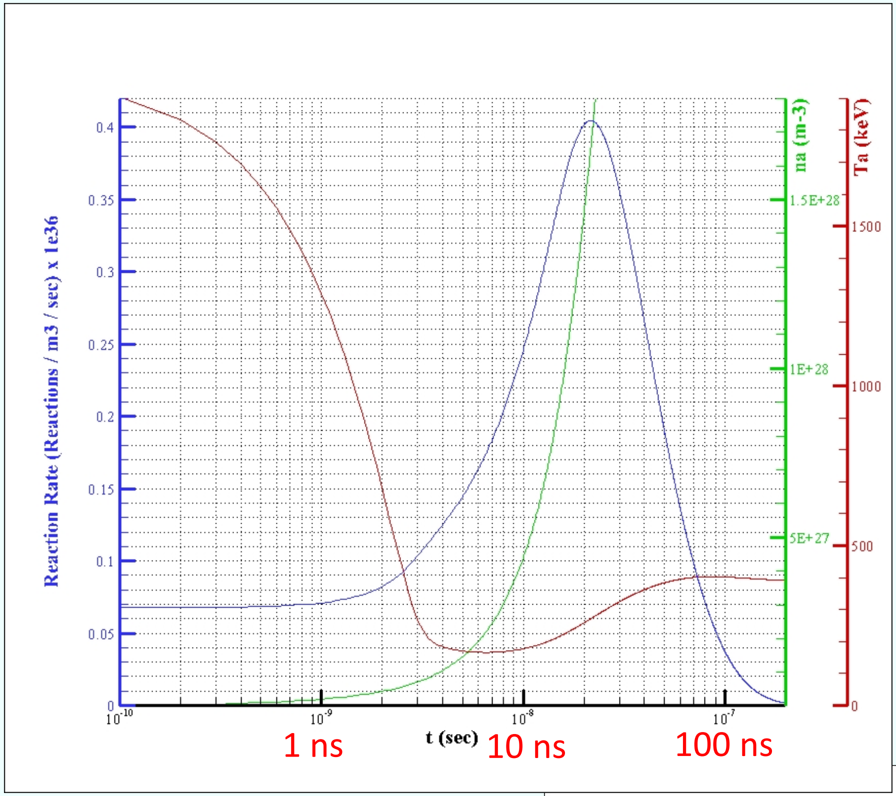


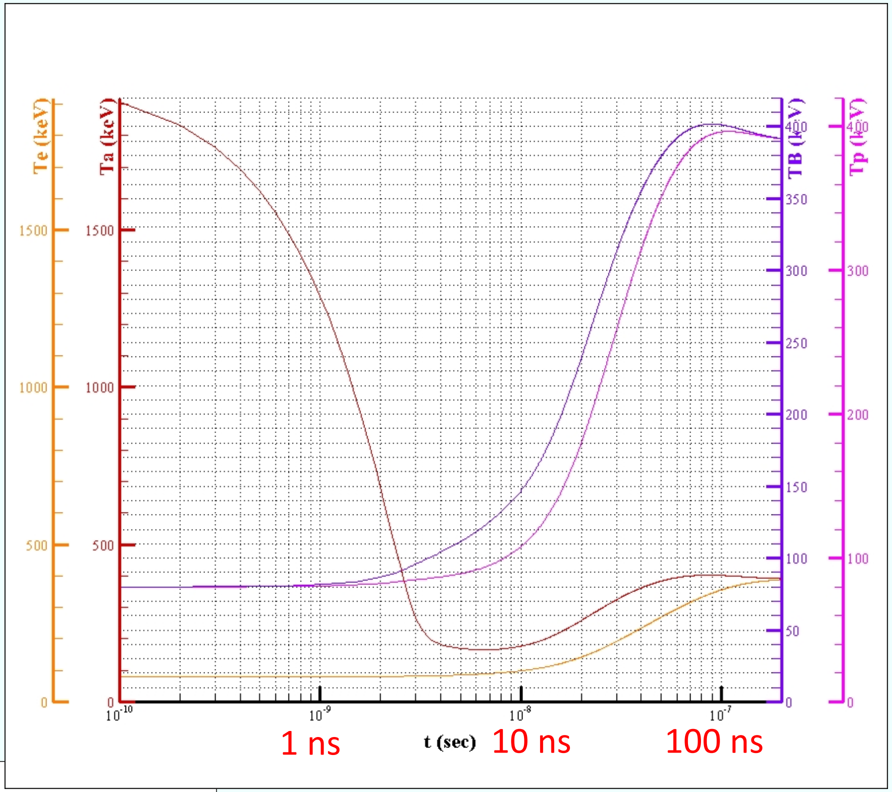
(Blue curve) : Reaction Rate,
(Orange curve) : Boron temperature,
(Pink curve) : Protons temperature,
(Red curve) : Alpha temperature

(Blue curve) : Reaction Rate,
(Light green curve) : Alpha density,
(Pink curve) : Protons and Boron density,
(Red curve) : Alpha temperature

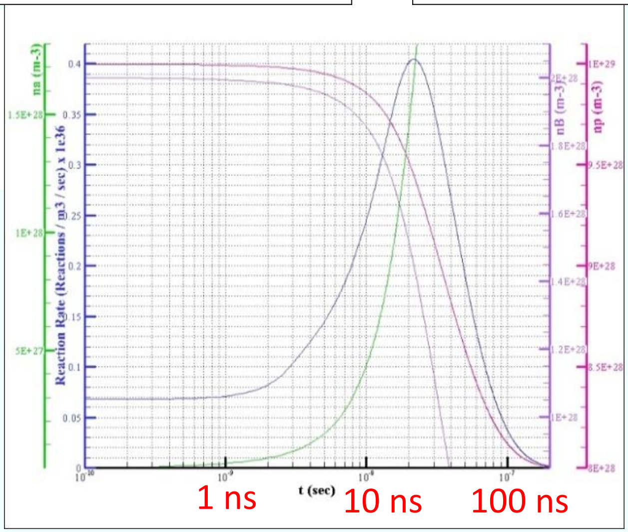


np/nB = 5, Neutral Solid State Density, T = 80 keV

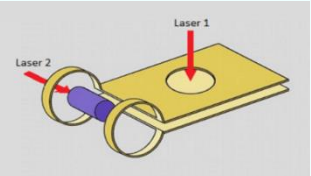




(Blue curve) : Reaction Rate,
(Red curve) : Alpha temperature
(Light green curve) : Alpha density



(Purple curve) : Boron temperature
(Pink curve) : Protons temperature
(Red curve) : Alpha temperature
(Orange curve) : Electron temperature



Fuel Depletion,
B consumed faster

The new fusion race

There is an increased interest to develop fusion devices or prototypes, based on the **H, ^{11}B** fuel.

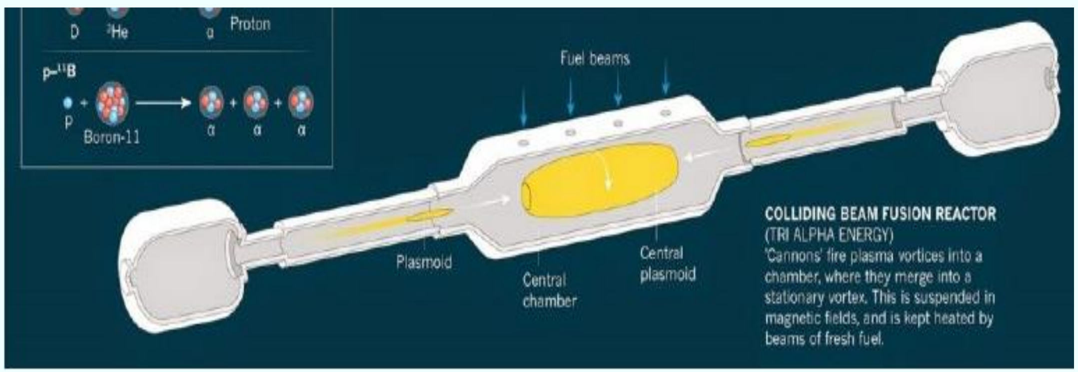
The main reasons are **[except for the fact that it is an aneutronic fusion reaction]**
- the dimensions, the cost and the potential applications of such devices.

The cost of these devices is at least a factor of **100** lower than the cost of the Tokamak or ICF machines.

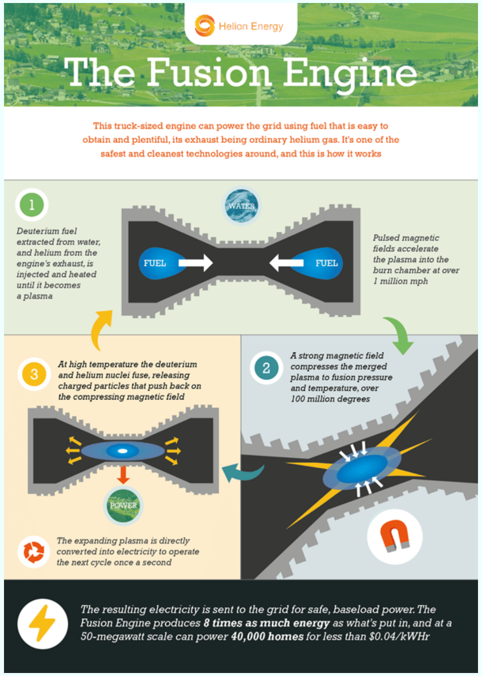
The success concerning the development of such prototypes and the involvement of important industrial partners, could allow to scale down the whole operation cost for applications, from billions to millions and from big scale operation with huge dimensions of installation to compact (transportable) power plants.

Without Laser

Hydrogen - Boron

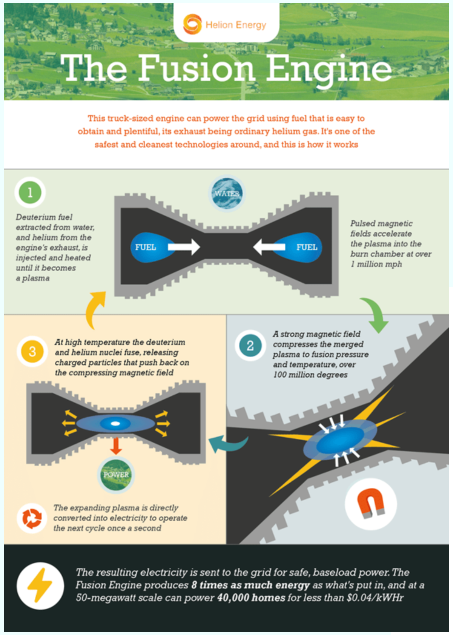


TRI-ALPHA ENERGY (TAE)

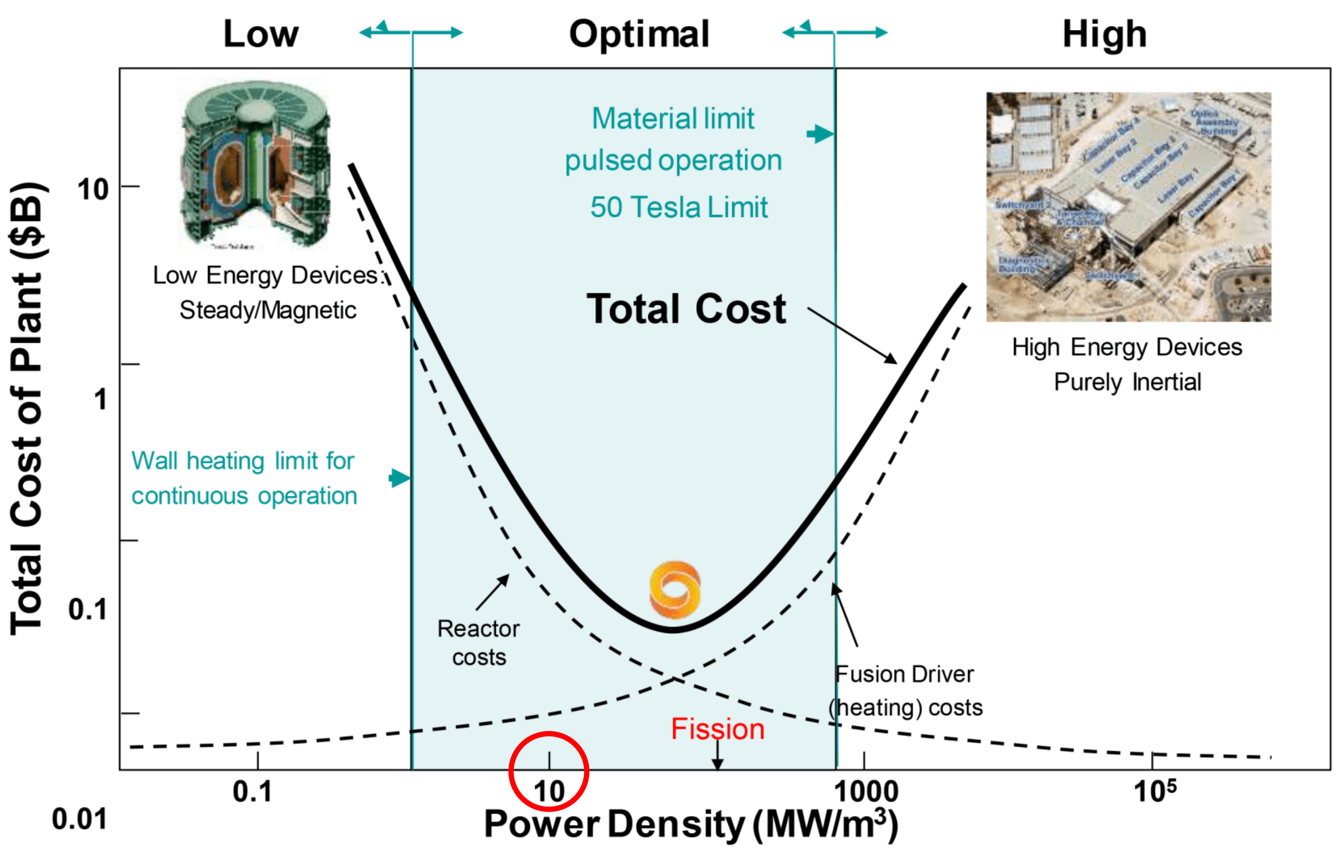


D - He3

HELION ENERGY



Energy Density



Helion Energy MSNW arpa·e

Numerical investigation of ignition and self-sustained conditions for low density ($n_p = n_B \sim 10^{20}$ m^{-3}) proton-boron fusion plasmas is an interesting study topic for application in compact magnetic fusion devices.

Initial Temperature of fusion species between 80 keV to 350 keV

Simulations using a multi-fluid code in the low temperature range, allow the determination of the necessary conditions, that correlate the temporal increase of the alpha density, the fast enhanced fusion ignition of the p-^{11}B fusion reaction rate (RR) and the temperature rise of the fusion species (p, B), with the proof of the avalanche effect.

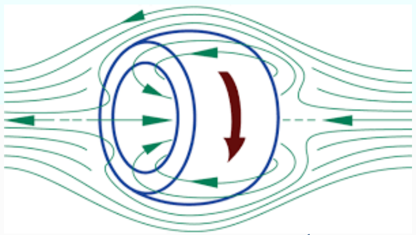
In the case of a high initial fusion medium temperature, the chain reactions alpha heating effect contributes to the maintenance and the rise of the temperature of the fusion species (p, B) to high values, for self-sustained fusion, until fuel depletion.

For this temperature range, the electron density is considered orders of magnitude lower than the initial ion density of the fusion species (p, B), for the optimization of Bremsstrahlung losses.

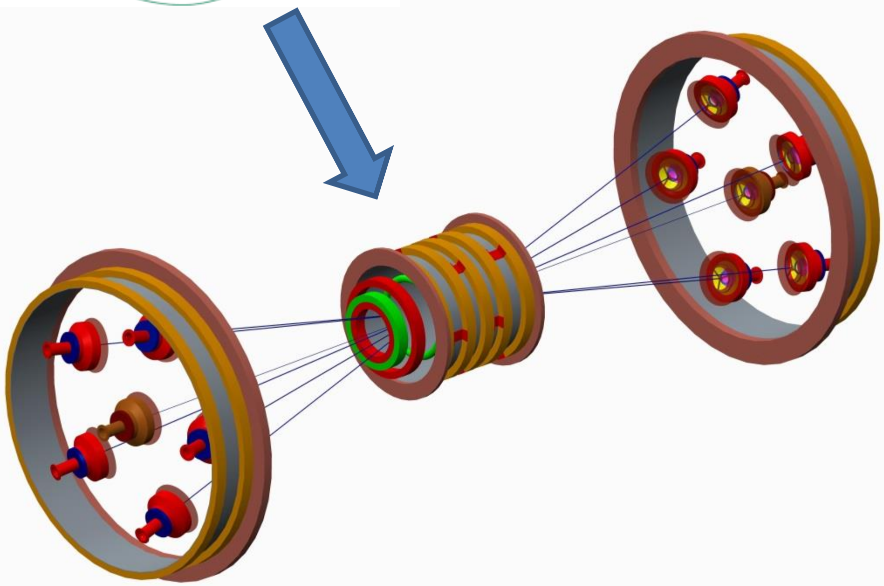
What is an important effect concerning the electron density besides the Bremsstrahlung losses

Fusion in Compact Magnetic Fusion Devices

International interest for the development of Compact Magnetic Fusion Devices, operating with plasma densities 10^{14} cm^{-3} – 10^{16} cm^{-3} [1, 2, 3]



Potential formation of a "Field Reversed Configuration" (FRC), using tangential high current ion beam for strong trapping



Plasma formation in the center part of the device, produced by a series of ion beams [p, B], using pulsed high current diodes

Put together existing technologies

High current Ion beam
Up to 17 – 20 kAmp

Ion beam energy

80 keV – 350 keV

Low current High current

Pulse Duration: 1 – 5 μs

Electron density control

Magnetic field
10-20 T
see MIT Tokomak superconductor magnets

[1] T. J. Mcguire, "*Active cooling of structures immersed in plasma*", US Patent 2014/0301517 (2014).

[2] T. J. Mcguire, "*Heating plasma for fusion power using magnetic field oscillation*", US Patent 2014/0301519 (2014).

[3] N. Rostoker, M. W. Binderbauer, H. J. Monkhorst, "*Colliding Beam Fusion Reactor*", SCIENCE, VOL. 278, p. 1119, (1997) and https://tae.com/research-library/.

Magnetic Fusion Device (MFD)

Using a multi-fluid zero dimension, global particle and energy balance code adapted for $H^{11}B$ fusion plasma, including collisions

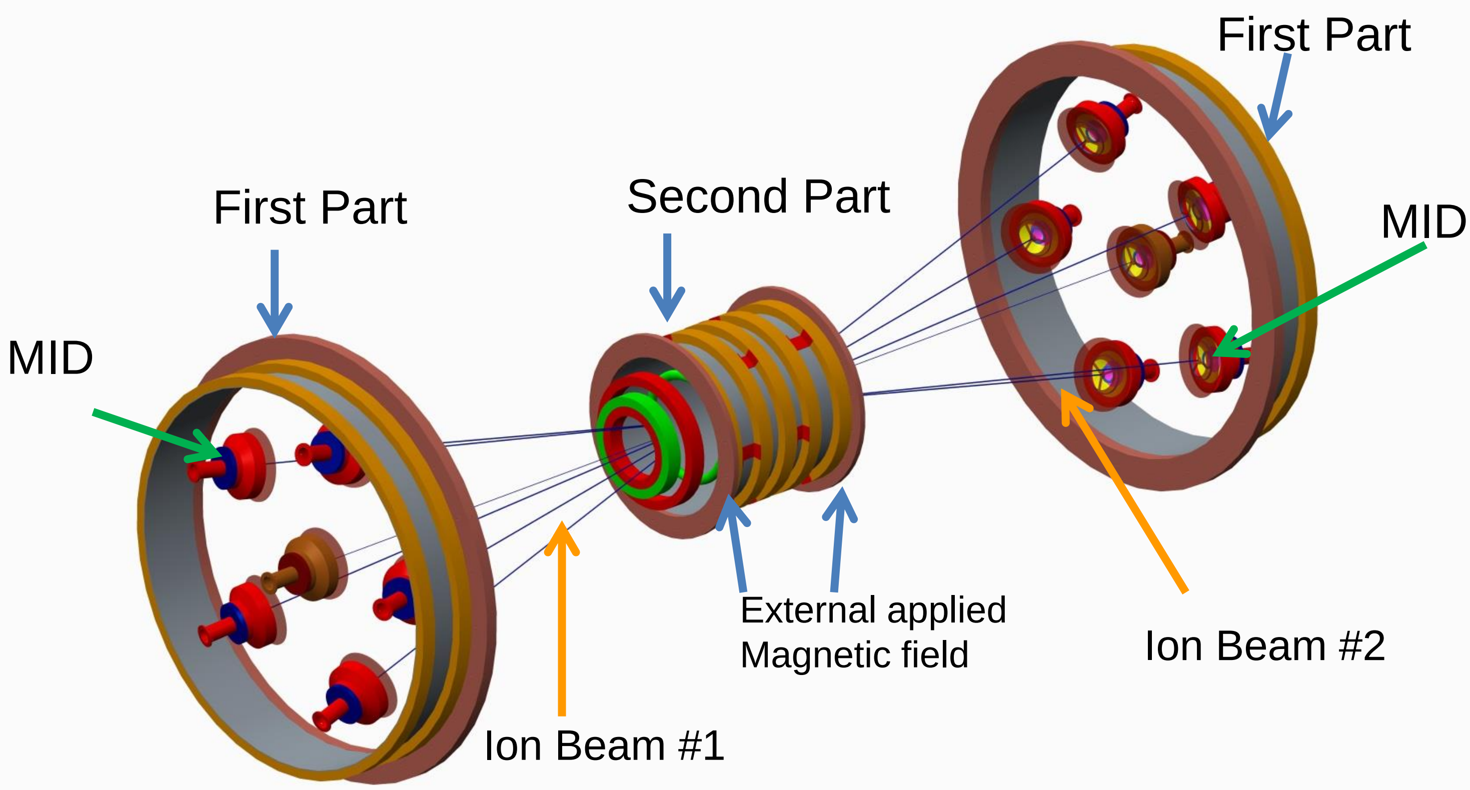
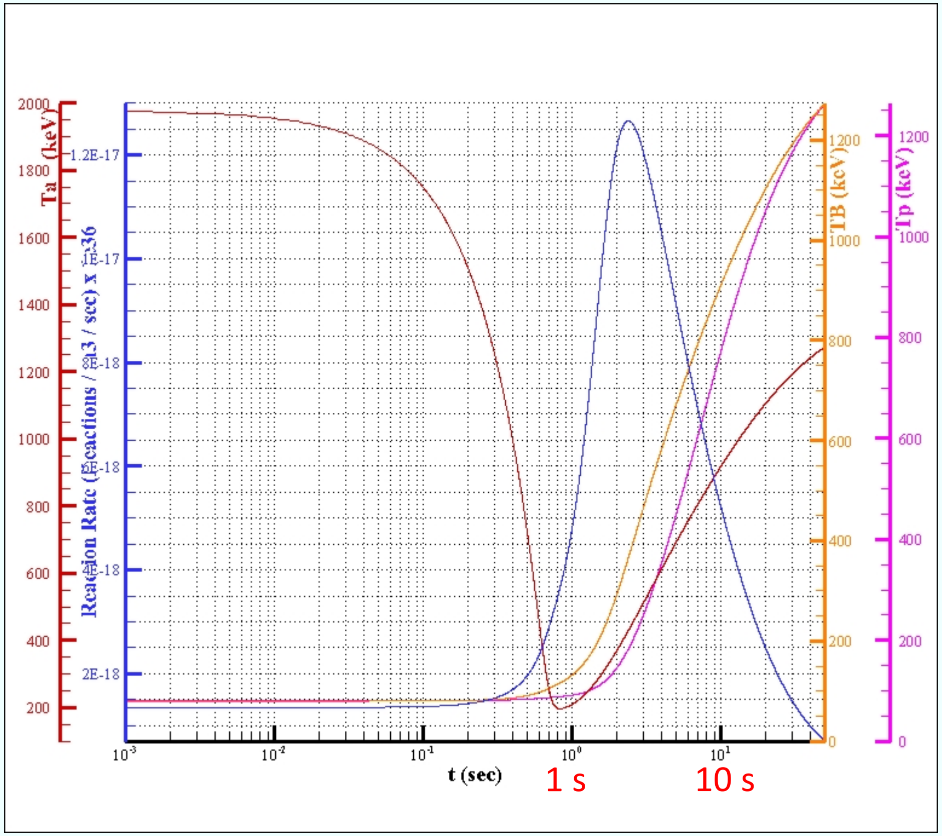


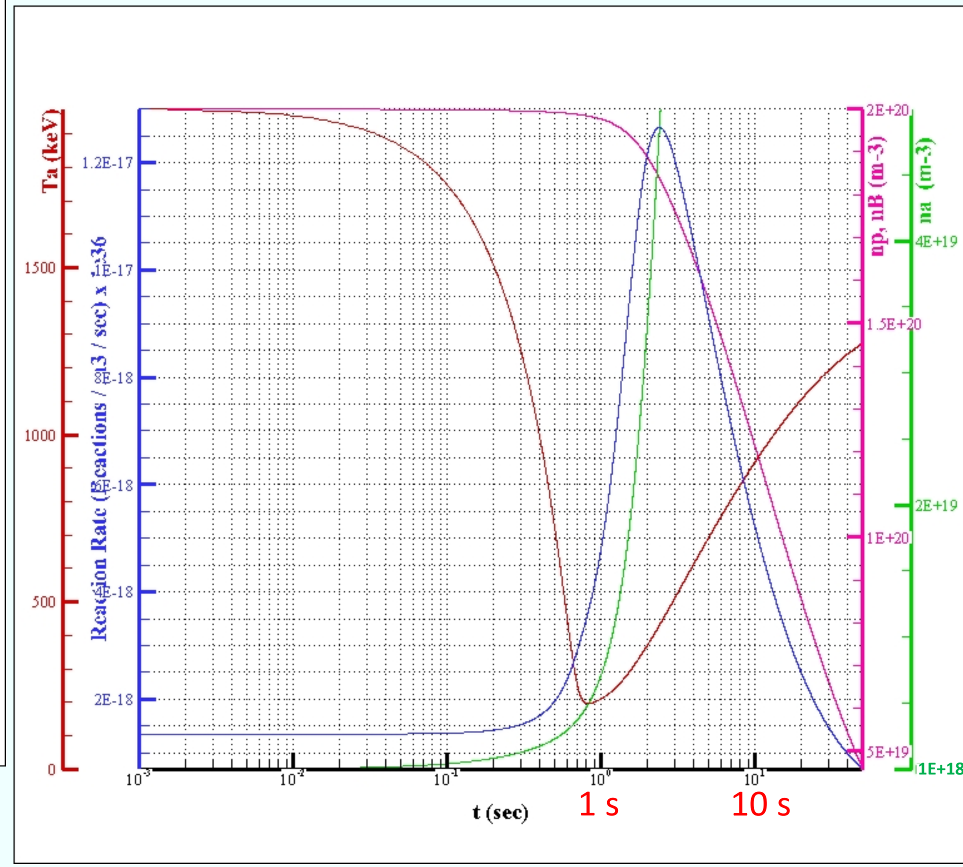
Fig.1 presents a section of the proposed Configuration, including the first part, the second part and the positions of the MID devices for the production, acceleration and extraction of high current and high energy ion beams of each species (protons IB#1 and Boron IB#2).
The hydrogen-Boron plasma is formed in the central configuration (second part) by the ion beams interaction and it is trapped, through the application of an external high magnetic field (~ 10T - 15T).

*Moustaizis et al., "*Numerical investigations on fusion ignition process in plasma formed by the interaction of energetic and high current ion beams:, *EPS 2018 paper*

Low initial medium density : np = nB ~ 10 ^{20} m^{-3}, T = 80 keV

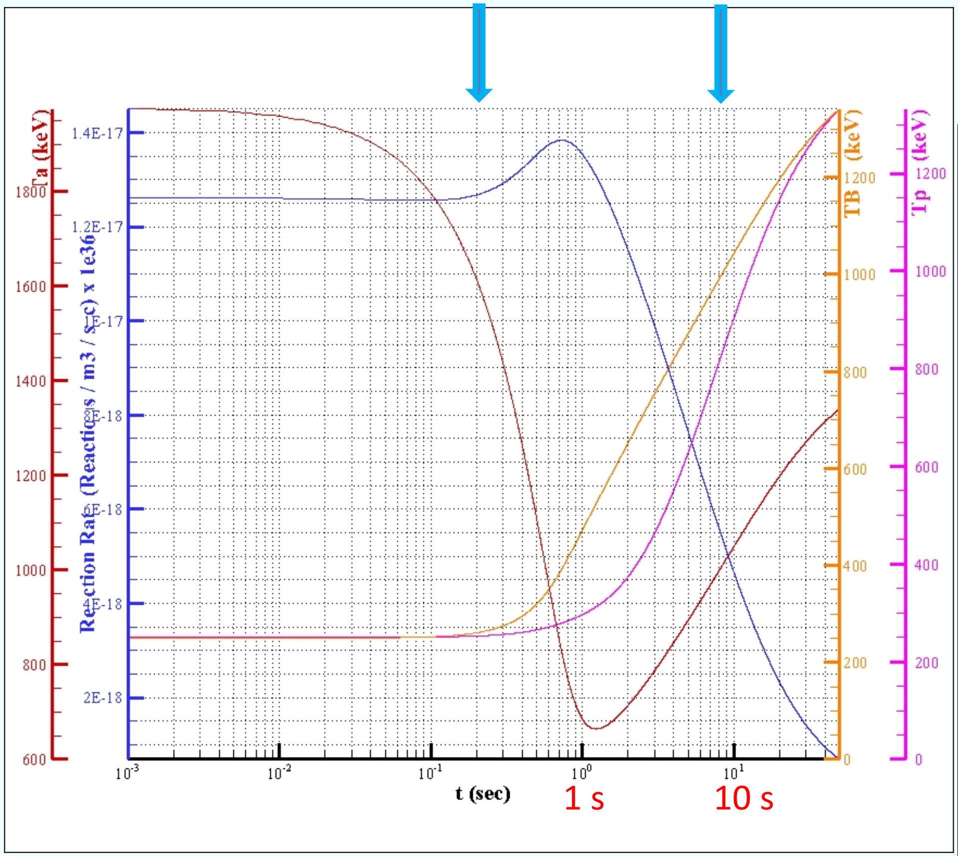


(Blue curve) : **Reaction Rate,**
(Orange curve) : **Boron temperature,**
(Pink curve) : **Protons temperature,**
(Red curve) : **Alpha temperature**

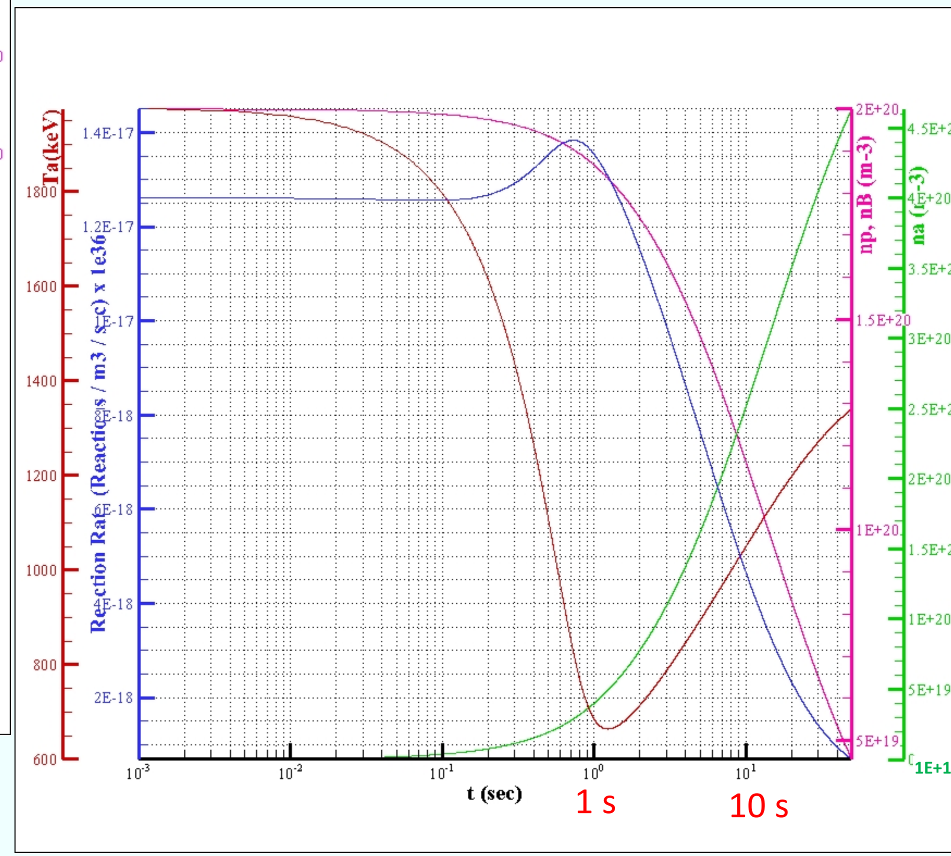


(Blue curve) : **Reaction Rate,**
(Light green curve) : **Alpha density,**
(Pink curve) : **Protons and Boron density,**
(Red curve) : **Alpha temperature**

Low initial medium density : np = nB ~ 10^{20} m^{-3}, T = 250 keV

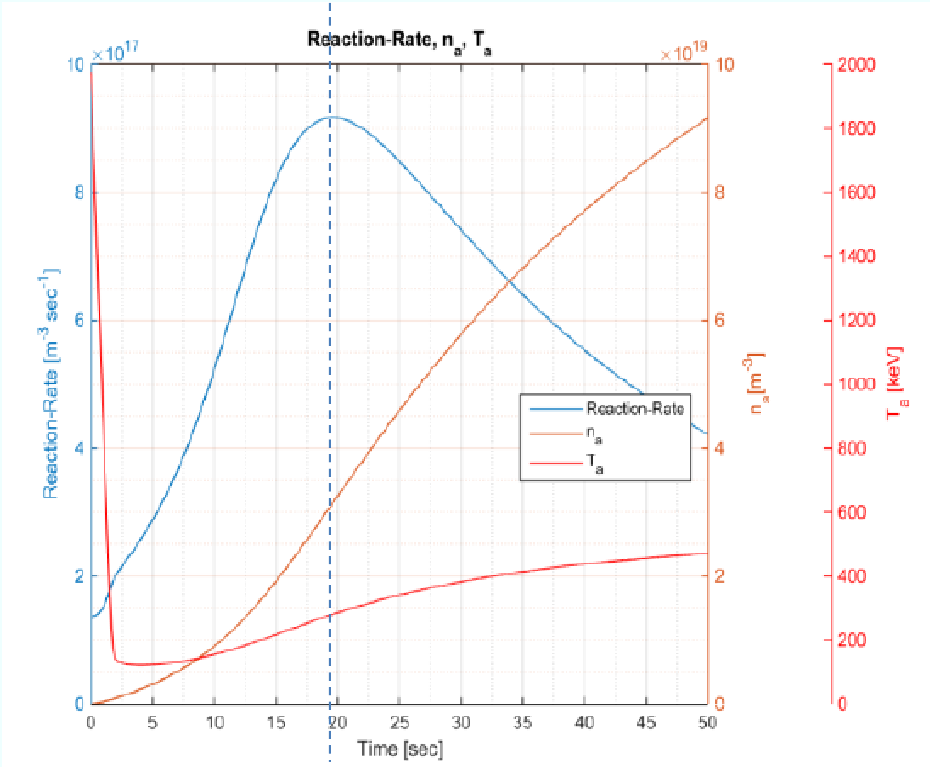


(Blue curve) : Reaction Rate,
(Orange curve) : Boron temperature,
(Pink curve) : Protons temperature,
(Red curve) : Alpha temperature

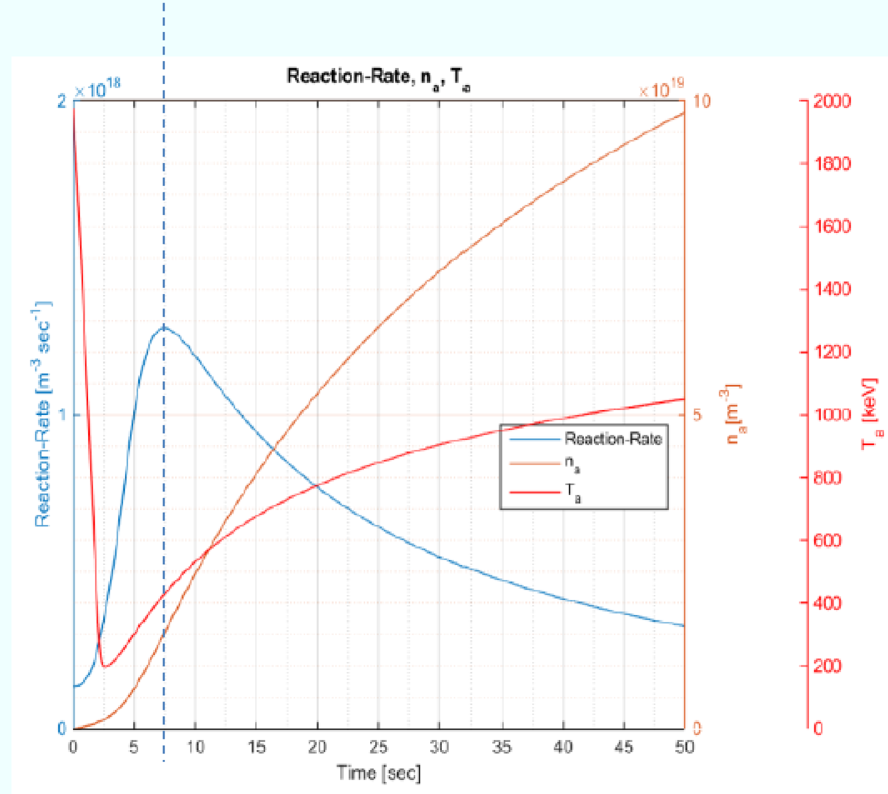


(Blue curve) : Reaction Rate,
(Light green curve) : Alpha density,
(Pink curve) : Protons and Boron density,
(Red curve) : Alpha temperature

Effect of the electron density on the time [T1] that the RR reaches its maximum value



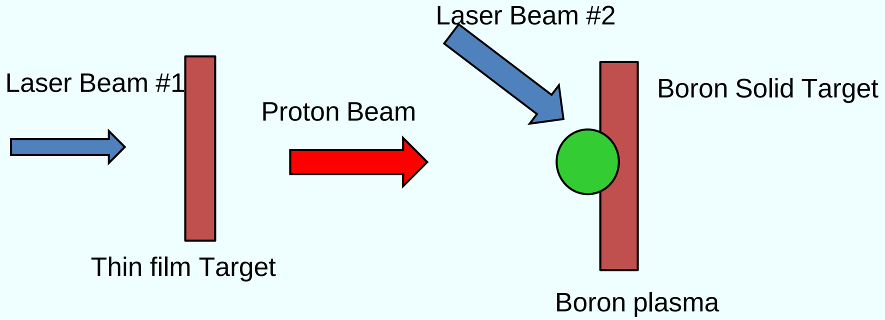
~ 25 sec



~ 7 sec

Five (5) orders of magnitude lower electron density

Figure presents the temporal evolution of the reaction rate, the alpha density, the alpha temperature (left side) and the temporal evolution of proton or Boron density, the electron temperature, the proton temperature and the Boron temperature (right side) with initial values of plasma density 6.3 x 10 ^{13} cm $^{-3}$ and initial temperature of 80 keV.

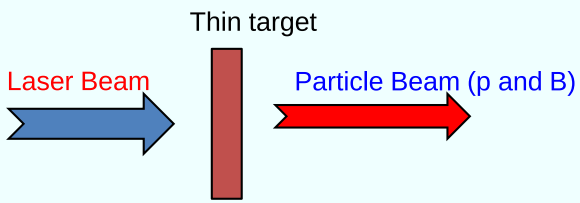


[1]

Very Nice Experimental Results

BUT

Not Fusion Oriented Experiments



Particle Beam Optimization

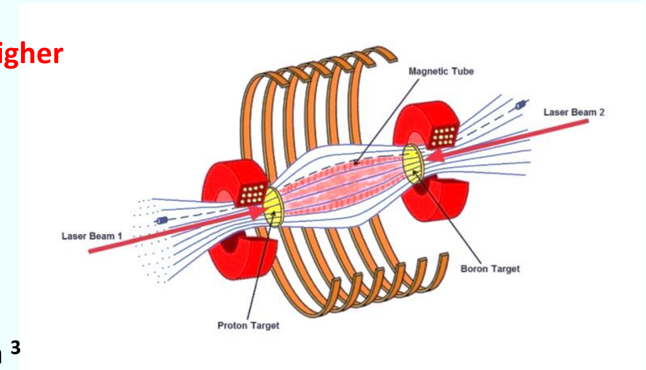
Number (density) and Energy [2]

Density of 10^{16} cm^{-3} or higher

Pulsed Magnetic Field

30 – 40 T

Total Volume ~ 5 - 10 cm^{3}



Investigation of the alpha heating effect

[3]

Plasma formation by beams Interaction (tuning beam energy)

electron density reduction

And

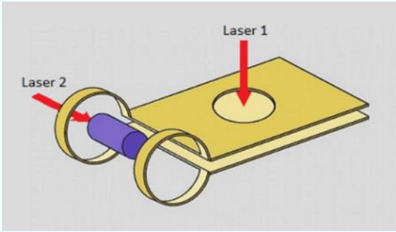
Select different p/B ratio in order to optimize Bremss losses

HB11 ENERGY LASER BORON FUSION

nsec scale

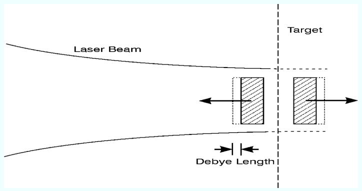
Laser Induced high magnetic Field

ps



Experimental verification of

The Plasma Block Acceleration



[4]

space charge neutral with ion current density

$j > 10^{13}$ $Amps/cm^2$

H. Hora, J. Badziak et al. Phys. Plasmas 14, 072701 (2007); H. Hora Laser and Particle Beams 27, 207 (2009)

Conclusions

During the fusion process of the proton-boron fuel, the temporal evolution of the medium species physical parameters, presents significant temporal correlations effects,
relating their temperature and density profiles with the density rise of the produced alphas.

These effects follow a sequence of time dependent events. The energy temporal profile of the produced alphas indicates significant decline, due to energy transfer to the fusion species (p, ^{11}B).

The temperature rise of the fusion species results in the density rise of the produced alphas, due to the higher corresponding value of the nuclear reaction cross-section. Consequently, more and more alpha particles are produced, increasing the amount of energy transfer to the fusion species and as a result, the fast enhanced fusion ignition effect of the RR.

The corresponding density of the produced alpha particles is 1 order of magnitude less than the initial p-B density

From the numerical simulations, the time t_c corresponding to the manifestation of the avalanche effect ,
allows the evaluation of the necessary energy deposition in the medium,
E = (density of alphas (t_c) x (energy of alphas (t_c)), which results to an important temperature rise of the p-^{11}B medium.
This E depends on the initial conditions of temperature and density of the p-^{11}B medium.

The density of the produced alphas continues to increase and the RR attains a maximum value at a time, for which the energy of the fusion species corresponds to an optimum or near to the maximum cross-section of their nuclear reaction. Then, the RR decreases, due to the fast depletion of the fusion fuel, but the alpha density continues to rise, due to the high values of the fusion species temperatures, that correspond to higher values of the nuclear reaction cross-section.

Conclusions

The rise of the RR, determines the time, which characterizes the manifestation of the avalanche effect.
The avalanche effect is the result of an accumulative process and as such it must be treated, because it is the result of the alpha density rise, due to the temperature rise of the fusion species (p, ^{11}B).
The decline of the alpha temperature, from the initial time of the fusion process, increases gradually the temperature of the fusion species, resulting in an accumulative process, which significantly increases the density of alphas up to a value, for which the fast enhanced fusion ignition effect of the RR occurs.

Another important numerical result, that supports the accumulative process and consequently the manifestation (appearance) of the avalanche effect, concerns the significant temporal evolution of the slope of the curve, describing the time depletion of the fusion fuel density.

The numerical simulations show an important change in the slope of the fusion species density (p, ^{11}B), followed by a fast decrease of the fuel density. This effect occurs for a time interval, corresponding to the alpha density rise, the fast enhanced fusion ignition effect of the RR (rise of the RR) and the temperature rise of the fusion species.
This “three point” effect confirms the manifestation (appearance) of the avalanche effect.

Also, the results of the simulations of the present work and the summary remarks prove that the fusion chain reactions alpha heating effect (avalanche effect) contributes essentially to a self-sustainable fusion process of the (p, ^{11}B) fuel, in agreement with theoretical works.

Proposal for p - B11 fusion oriented experiments

THANK YOU