# Numerical investigations on fusion ignition process in plasma formed by the interaction of energetic and high current ion beams

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## Abstract

Numerical investigations on the interaction of two energetic and high current density ion beams trapped in a volume with external applied magnetic field enable to study nuclear fusion process for different ion species. The final plasma is formed by the interaction of the two beams and is composed by the two different ion species of the beams and by low density electrons. The configuration of the beams could be constituted in a first case by one proton beam and one $^{11}$B beam and in a second case by two deuterium beams. The proposed scheme for the high power ion beams production is based on both the Magnetically Insulated Diode (MID) and Pulsed Power (PP) techniques. These techniques allow generating high energy ion beams up to hundreds of keV with current density up to few tens of A/cm$^2$, with relatively low electron density. The application of this scheme for fusion overcomes the difficulty concerning the Hydrogen - $^{11}$B fuel for which the cross section for reactions is efficient for energies higher than 250 keV. The low electron density in the formed fusion plasma minimizes the bremsstrahlung radiation losses, especially for the case of the Hydrogen-$^{11}$B fusion plasma. The temporal evolution of the plasma parameters and especially the reaction rate was investigated using a multi-fluid, zero dimension, global particle and energy balance code. The code allows to estimate the alpha heating effect on the temporal evolution of the formed fusion plasma temperature and the maximum value of the reaction rate, especially for the Hydrogen-$^{11}$B fusion case, where each reaction produce three alphas with total energy of 8.7 MeV. The numerical study allows estimating the time interval to achieve the maximum of the reaction rate as a function of the initial conditions concerning the energy and the current density of the ion beams. The present work based on existing technologies (MID and PP) and will contribute on the design and potential development of Compact Magnetic Fusion Devices (CMFD) with output power of the order of 100 MW.

There is an increase interest concerning the development of Compact Magnetic Fusion Devices (CMFD) operating with plasma densities $10^{11}$ cm$^{-3}$ – $10^{16}$ cm$^{-3}$ [1-4]. These devices have the advantage to produce clean energy with relatively low coast and reduce occupation volume compared to Tokamak or ICF machines. The CMFD allow experimental investigation on (a)different fusion fuels, (b) alpha ($^4$He) heating effect in the fusion plasma and (c) develop energy production plans especial for aneutronic nuclear fusion reactions as is the case for hydrogen-$^{11}$B nuclear fusion reaction. The present work concerns numerical investigations on the temporal evolution of fusion plasma parameters formed by high current density and high energy beams [5-11] using a multi-fluid, zero dimension global particle and energy balance code (based on the code described in ref. [12]). In the first part of the paper we present a brief description of the CMFD and the plasma production using high current and high energy (100 keV-250 keV) colliding beams produced by using Magnetically Insulated Diodes (MID) configurations (magnetic insulation first described by Stinnett, see ref. [13]). The hydrogen-$^{11}$B fusion fuel is attractive for clean energy production because the corresponding nuclear fusion reaction is aneutronic, and the three produced alphas, with total energy up to 8.7 MeV, improve the alpha heating effect in the plasma [14]. The proposed CMFD is composed by two main parts (see fig. 1). The first part concerns the two conical configurations and the second part concern the central cylindrical configuration. Each conical configuration used for the production and the propagation of the high current density and high energy (200 keV or higher) ion beam and is connected respectively to the end of the cylindrical central configuration (second part) of the device (see fig. 1). The cylindrical central configuration is used for the magnetic (B~7T) trapping of the fusion plasma formed by the injection of the two high power ion beams from each conical configuration of the two first parts of the device.
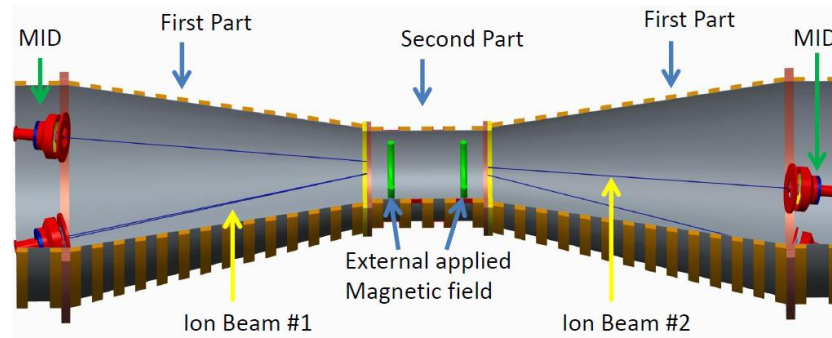
Fig. 1 presents a section of the proposed CMFD including the first part, the second part and the positions of the MID devices for the production of the high current and high energy ion beams of each species (Hydrogen IB#1 and Boron IB#2). The hydrogen-$^{11}$B plasma is formed in the central configuration (second part) by the interaction of the ion beams and it is trapped by applying an external high magnetic field (~7 T).

Pulsed MID device is a powerful candidate for the production of high energy and high current density ion beams up to 20 A/cm$^2$ -150 A/cm$^2$ [5, 6] with pulse duration from tens of ns to µs. MID was proposed for different applications including fusion and could work for positive and negative ion beam production [5-11] with beam energy up to 250 keV – 1.5 MeV. Our previous work using a multi-fluid, one dimensional (1-D) code enables to describe the spatio-temporal evolution of the acceleration and the extraction of high power negative ions beam (NI) of hydrogen from a MID for different initial geometrical and physical parameters [15-17]. This code allows both confirming the operation of experimental setups of the international bibliography on the NI hydrogen production from pulsed MID devices and designing new configurations. The advantage of negative ions is based on the possibility of neutralization of the beam by photo-detachment using laser beam techniques. In our previous work [17] there is extensive description of a proposed configuration on high power neutral beam production from a MID configuration including numerical results using the 1-D multi-fluid code [15, 16]. The photo-detachment process allows to propagate the high power beam from the source to the interaction volume avoiding space charge effects. Experimental results confirm that pulsed MID devices could be used for high current density positive ion beam production with values similar to these of NI beams [7-11]. The modification and the use of the same 1-D multifluid code [15, 16] confirms the extraction of high current density and high energy positive ion beam from a pulsed MID with values similar to these for NI beam production. Experiments confirm negative Boron formation [18, 19] in plasmas as well as the photo-detachment process for neutralization [19, 20]. But there is limited bibliographic information on Boron negative ion acceleration and extraction from high current MID device as is the case for hydrogen. The operation of MID is not the main subject of the present work and the brief previous description on MID devices is used to justify the possibility to achieve high current density of hydrogen and Boron ion beams with the appropriate energy in order to form a relatively high temperature fusion plasma, in the proposed CMFD and overcome the problem of the low cross section (or reactivity) of the hydrogen-$^{11}$B nuclear fusion reaction, for plasma temperatures lower than 200 keV [21]. We plan to describe the operation of the proposed CMFD including the ion beams production from MID devices in a future work. We want to emphasize that the operation of the proposed CMFD is based on two main characteristic operational times. The first concerns the operation of the MID and the acceleration and the extraction of the ion beams which will be of the order of few hundreds of nanoseconds to 1 µs. The second characteristic time concerns the temporal evolution and trapping of the formed fusion plasma in the central configuration of the device and it is of the order of tens of seconds depending on the initial plasma parameters (density of plasma ions and electrons, initial ion and electron temperatures). The use of the multi-fluid zero

dimension, global particle and energy balance code (see ref. [12]) allows to evaluate the temporal evolution of the plasma species parameters and especially the alpha production, the alpha density, the alpha temperature, the alpha heating effect and the reaction rate (R.R.). The code includes calculations concerning the collision energy transfer between the plasma species (fluids) such as electrons, protons, Boron and the produced alphas. The code evaluates the characteristic time interval necessary to achieve the maximum of the reaction rate as a function of the initial plasma parameters. We study two main different cases for the operation of the proposed CMFD. In the first case we present numerical results on the temporal evolution of the formed hydrogen-[11]B fusion plasma with initial ion density up to $6.3 \times 10^{19}$ m$^{-3}$ and initial temperature of 80 keV for all the species. The left side of the Fig.2 shows the temporal evolution of R. R, the alpha density, the alpha temperature and the right side of fig.2 shows the temporal evolution of the Boron (or proton) density and the temperature of the electrons and the ions of the plasma.  For this case the R.R. achieves a maximum value of $0.9 \times 10^{18}$ m$^{-3}$sec$^{-1}$ after 20 sec and the corresponding plasma ions temperatures is higher than 200keV confirming the increase of the initial plasma ions temperature due to alpha heating effect. The reactivity for the hydrogen-[11]B nuclear fusion reaction is relatively high for temperatures of 200 keV -300 keV [21] improving the R.R. The R.R decreases rapidly after 25 sec – 30 sec due to the depletion of the plasma ions density.
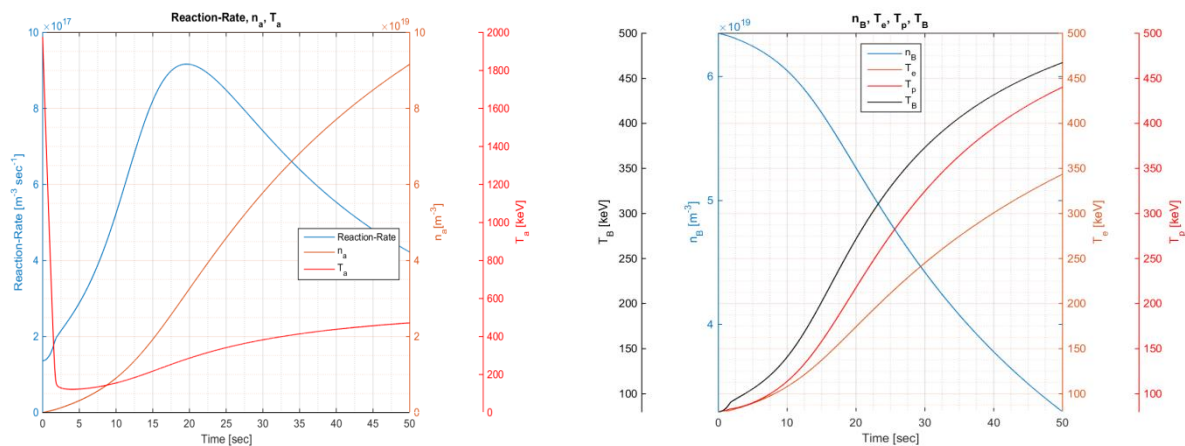


Fig.2 presents the temporal evolution of the reaction rate, the alpha density, the alpha temperature (left side)and the temporal evolution of proton or Boron density, the electron temperature, the proton  temperature and  the Boron  temperature (right side) with initial values of plasma ions (p and B) density $6.3 \times 10^{13}$ cm$^{-3}$ and initial temperature of 80  keV.

In the second case the numerical results concern the temporal evolution of the formed fusion plasma in the CMFD with the same initial ion density ($6.3 \times 10^{19}$ m$^{-3}$) and ion and electron temperatures (80keV) as it is for the first case but with five (5) orders of magnitude lower electron density. At this point we like to emphasize that the use of ion beams to form the fusion plasma allows controlling the electron density. The left side of fig.3 shows the temporal evolution of the R.R, the alpha density, the alpha temperature and the right side of fig.3 shows the temporal evolution of the Boron density and the temperature of the electrons and the plasma ions. A higher value of R. R up to $1.3 \times 10^{18}$ m$^{-3}$sec$^{-1}$ is achieved after a time interval of 10 sec, which is shorter by a factor of 2.5 than this of the first case. The first important result concerns the plasma ions temperatures which are very high compare to the first case confirming that low electron density is favorable for energy transfer to protons and Boron ions due to alpha heating effect. The second important result is that 20sec-25sec after the maximum value of the R. R. the alpha ion temperature is relatively high up to 0.9 MeV with an alpha density up to $6. \times 10^{19}$ m$^{-3}$, which is extremely important for continues operation of the proposed CMFD. In fact the high density and high temperature of alphas contribute to burn the fuel if the refueling process occurs few tens of seconds

after the maximum value of R.R. (see fig.3). Also the low electron density enables, to decrease the Bremsstrahlungand and cyclotron radiation losses of the plasma.
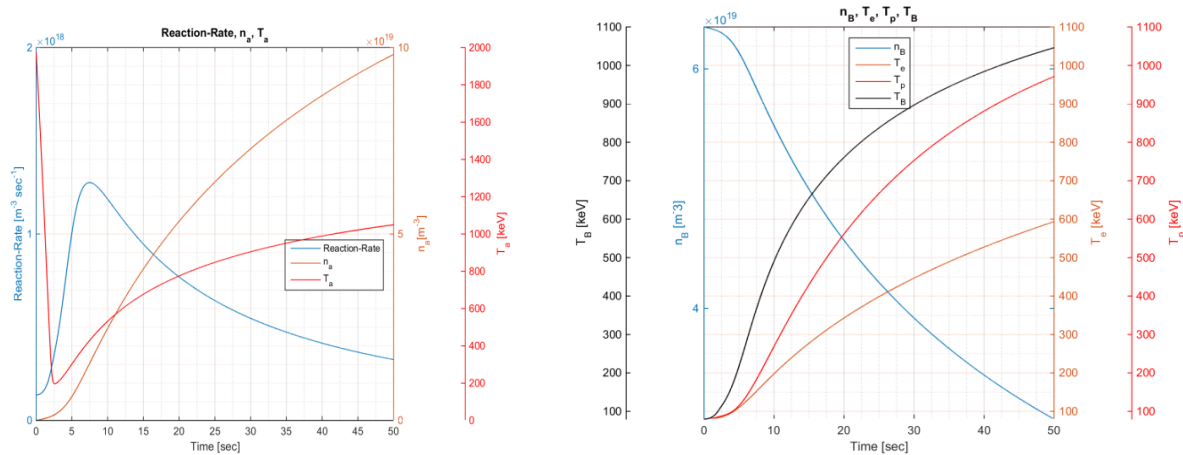


Fig.3  presents the temporal evolution of the reaction rate, the alpha density, the alpha temperature (left side.) and the temporal evolution of proton or Boron density, the electron temperature, the proton  temperature and  the Boron  temperature (right side) with initial values of plasma ions (p and B) density $6.3 \times 10^{13}$ cm$^{-3}$, five (5) orders of magnitude lower electron density and  initial temperature of 80 keV.

Summarizing, to study the temporal evolution of formed fusion plasma by the interaction of two high energy and high current density beams we have use a multi-fluid zero dimension, global particle and energy balance code including collisions between the plasma species, considered as four separate fluids (electrons, protons, Boron and alphas). The numerical results confirm that the alpha heating effect allows the reacting ions of the fusion plasma to reach high temperatures and consequently to improve the R.R values especially for the case for low electron density. The produced high density and high temperature alphas in the CMFD, enable continuous operation with an output power of tens of MW for a volume of about 2 m$^3$ of the formed fusion plasma, without including plasma losses.

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