Alpha heating in magnetic and inertial confinement fusion

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In a magnetic fusion reactor the alpha particles are produced primarily from the reaction $D + T \rightarrow \alpha + n$, where the alpha is created with 3.5 MeV, and the neutron is released with 14.1MeV. Moreover in such a reactor the neutrons leaving the plasma will be used to breed tritium (by reacting with lithium) and also will heat the blanket to produce steam, hence electricity. The alpha particles will be confined by the magnetic field and through collisions will heat the plasma species. If this alpha heating rate is equal (or greater) than the plasma energy loss rate then the plasma will ignite, and the plasma burning process will be self-sustained.

A dynamical, zero-dimensional multi-fluid model of alpha heating, treating electrons, reacting $D-T$ ions and alpha particles as four separate fluids, applicable to both magnetically confined and inertially confined plasmas has been developed. The model computes the temporal evolution (a) of the densities of the electrons, the reacting ions, and the alphas produced by nuclear reactions, and (b) the internal energies of the electrons, ions, and alphas. The internal energies include temperature equilibration due to collisions between the various plasma species, and various sources and sinks due to the generation of alphas and depletion of the reacting ions. The model is applied to an ITER type discharge, and to p-^{11}B fusion reactions initiated by very powerful laser irradiation on solid fuel.

The global particle and energy balance 0th-spatial-order equations are as follows:

$$\frac{dn_e}{dt} = -\frac{n_e}{\tau_p} + S_f$$

$$\frac{dn_d}{dt} = -\frac{n_d}{\tau_p} - S_r + S_f$$

$$\frac{dn_t}{dt} = -\frac{n_t}{\tau_p} - S_r + S_f$$

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_p} + S_r$$

$$\frac{d\varepsilon_e}{dt} = -\frac{\varepsilon_e}{\tau_\varepsilon} + Q_{fe} + Q_{ep}$$

$$\frac{d\varepsilon_d}{dt} = -\frac{\varepsilon_d}{\tau_\varepsilon} - Q_{rd} + Q_{fd} + Q_{dp}$$

$$\frac{d\varepsilon_t}{dt} = -\frac{\varepsilon_t}{\tau_\varepsilon} - Q_{rt} + Q_{ft} + Q_{tp}$$

$$\frac{d\varepsilon_\alpha}{dt} = -\frac{\varepsilon_\alpha}{\tau_\varepsilon} + 3.5(\text{Mev})S_r + Q_{\alpha p}$$

Here, n_e, n_d, n_t, n_α are the electron, deuterium, tritium and alpha densities and $\varepsilon_e, \varepsilon_d, \varepsilon_t, \varepsilon_\alpha$, are the internal energies of electrons, deuterium, tritium, and alphas respectively; the energy and particle confinement times are τ_ε and τ_p. S_r is the reaction rate for D-T, $S_r = n_d n_t < \sigma(u) >$, with its reactivity based on the Bosch and

Halle[1] formulation; S_f is the fueling rate by cold particles; Q_{ep}, Q_{dp}, Q_{tp}, Q_{ap} are temperature-equilibration terms due to collisions between the various particles. For example, for electrons, $Q_{ep} = n_\alpha \nu^{\alpha/e}(T_\alpha - T_e) + n_e \nu^{e/d}(T_d - T_e) + n_e \nu^{e/t}(T_t - T_e)$. Here we consider Coulomb collisions between electrons and the reacting ions and the alphas, and also between the alphas and the reacting ions. The collision frequencies are taken from Callen[2]; Q_{fe}, Q_{fd}, Q_{ft} are energy source terms due to fueling; Q_{rd} and Q_{rt} are energy depletion terms due to reactions for deuterium and tritium respectively. It is noted that at present we do not include additional heating to the fuel, and also we do not include recycling and bremsstrahlung. We assume that initially the fuel is at certain temperature, and density, and use the above model to see if alpha heating will take place to self-sustain the reaction.

In the following scenario we take two parametric values of ITER, i.e. volume of 837m^3 and magnetic field of 5.3T. The beta is defined as the sum of the pressures of the electrons, reacting ions and alphas over the magnetic pressure. We take a 50%-50% mixture of D and T with an electron density of $4 \times 10^{19} m^{-3}$, and temperature of the electrons and the reacting ions, at time zero, of 10keV. We assume energy confinement time equal to the particle confinement time at the value of 7s. Also we assume the refueling rate by cold particles is equal to the rate of particlelosses n_e/τ_p.

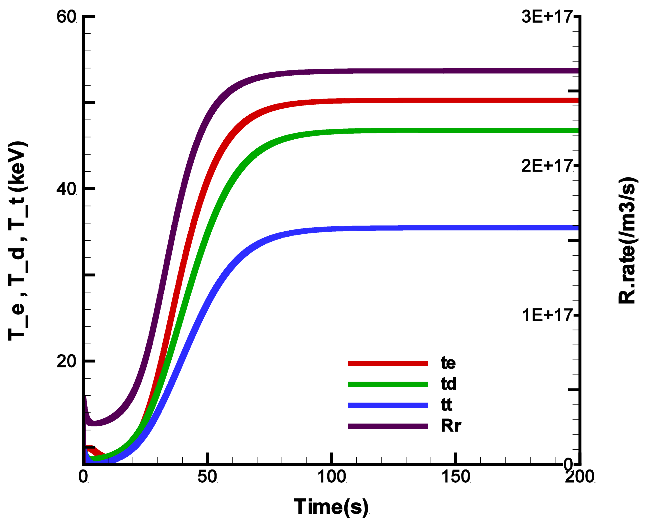

Figure 1: Plots of electron (red), deuterium (green) tritium (blue) temperatures and reaction rate (black)

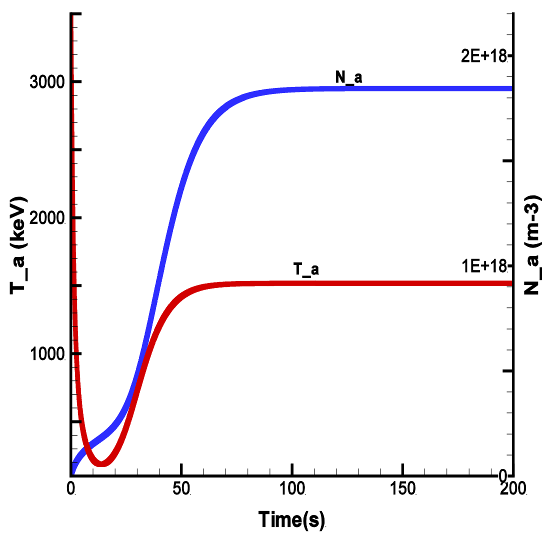

Figure 2: Plots of alpha temperature (red) and alpha density (blue)

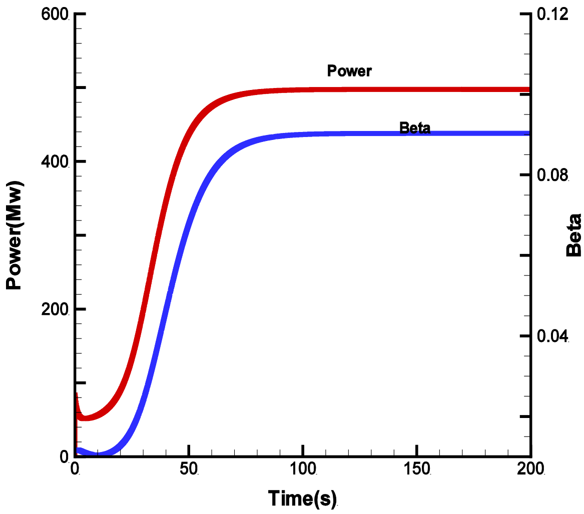

Figure 3: Plot of power output and beta.

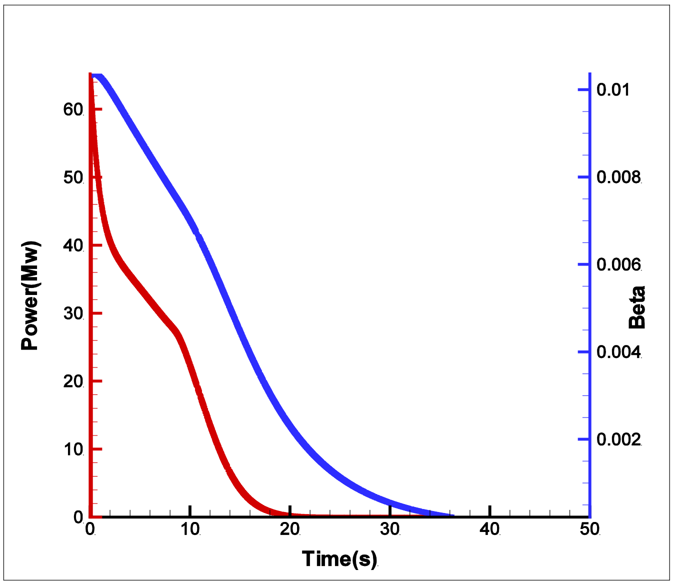

Figure 4: Plot of the power output (in Mw) and beta, for the Scenario where the initial temperature of the plasma is 9keV.

Figure 1 displays the temporal evolution of the electron and reacting ion temperatures, and the reaction rate. It is clearly shown that after 70s the temperatures and the reaction rate reach steady-state values. Figure 2 shows the temporal evolution and the alpha particle density and temperature. The temperature of the alphas goes to a steady value of about 1.5MeV and its density to $1.85 \times 10^{18} m^{-3}$. Figure 3 displays the power output, which is the volume of the device multiplied by the reaction rate times the energy of a neutron at birth, and beta. From the above Figures it is clearly shown that the heating of the fuel by the alphas approaches a steady state, and the burning process is self-sustained. Figure 4 displays the power output and beta for the scenario where the initial density of electrons is 4×10^{19} and the initial temperature of the electrons and the reacting ions is 9keV; the rest of the parameters are the same as in the scenario displayed by Figures1-3. It is clearly shown in Figure 4 that in this scenario the burning process is not self-sustained, because it has been extinguished. Improvements to this global particle and energy balance model applicable to tokamak reactors are possible. A complete study would require a workflow including equilibrium and transport codes.

This global particle and energy balance model, without particle and energy loses and without fueling, is also applied to inertial fusion. We consider the p-^{11}B reaction, at solid state density irradiated by a powerful laser, in which three alphas of 2.9MeV energy are generated. We assume initially that the p-^{11}B plasma is with temperature of 100keV, and solid state density of $1.27 \times 10^{29} m^{-3}$. Figure 5 displays the temporal evolution of the alpha particle density, the reaction rate and the temperature of the boron ions. We see that the reaction rate reaches a maximum at 18nanosecs, and then it starts to decrease. It is shown that alpha heating increases the temperature of the boron ions from 100keV to 600keV. The decrease of the reaction rate after 18nanosec is due to the depletion of the reacting fuel. Recently a theory[3] has been proposed to the avalanche of the alphas in the p-^{11}B reaction. This avalanche process will enhance the alpha heating in the p-^{11}B fusion.

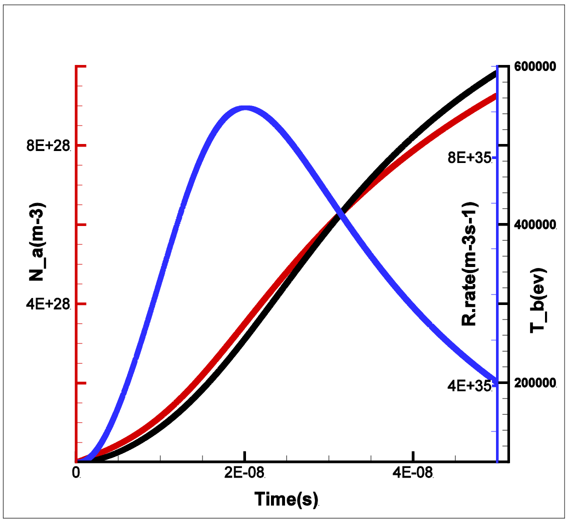

Figure 5: *Temporal evolution of alpha particle density (red), reaction rate (blue) and temperature of the boron ions (black) in eV.*

Summarizing, to study the dynamics of either a magnetically or an inetrially confined burning plasma we have developed a 0th-spatial-order code based on a multi-fluid model in the framework of which the electrons, reacting D-T (or H-B) ions and alpha particles are considered as four separate fluids. The code was exemplified for ITER-type discharges and p-^{11}B fusion reactions initiated by very powerful laser irradiation on solid fuel. Extensions of the model in realistic two dimensional geometry in connection with fusion confinement systems, as well as by taking into account reactivities with different D- and T-distribution-function temperatures, additional heating source terms, recycling and bremsstrahlung radiation are under way.

References

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