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FUSION REACTION BURN IN A D-T MIXTURE PLASMA

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1D simulation has been carried out on fusion reaction detonation in Deuterium-Tritium mixture plasma. The fusion reaction is initiated in a small hot spot of the thermonuclear fuel in the end of the target implosion induced by an external source. The simulation is based on the numerical resolve of the fluids equations consisting of densities, momentums and heat equations. Ions density decreasing due to the fusion reaction is taken into account. Importance is given for the alpha energy deposition in the thermonuclear fuel. The energy losses due to bremsstrahlung emission and by heat conduction are computed. Dense plasma effect is discussed and considered.

Applications are presented for inertial confinement fusion (ICF). Namely, in the case of the cylindrical magnetized target implosion by heavy ions beam and in the case of the spherical target implosion by an intense laser pulse.

INTRODUCTION.

It is very important to well-known how the fusion burning propagates out of the heated region to the ignition temperature by an external source to the rest of the thermonuclear fuel.

Some physical effects are taken into account, in the present simulation, namely: the energy losses by bremsstrahlug radiation [2], the relativistic effect and the screening effect on the fusion reaction rate [3]. This work is organized as follow: in the sections 2, 3 and 4, we expose the physical effects considered in this simulation. In section 5, we present the model equations which are the continuity equation, the momentum equation and the energy one. Finally, we finish this work by a conclusion.

ALPHA ENERGY DEPOSITION.

We assume that the alpha energy is deposed in the thermonuclear fuel by dynamic friction mechanism [4]. The resolution of the individual alpha particle motion classical equation, allows to calculate the fraction of the energy deposed after it travel a distance s, so: $f_{\alpha s}(\vec{r}) = 2(s/l_\alpha) - (s/l_\alpha)^2$, where l_α is the mean free path of the alpha particle and $\vec{r}$ .is its birth position. The average rate of the energy deposed by all alpha particles in the ignition region is calculated by averaging $f_{\alpha s}(\vec{r})$:

$$f_\alpha = 2/(2\pi R^2)\int_0^R r dr \int \sin\theta d\theta \int f_{\alpha s}(\vec{r}) d\phi \qquad (1)$$

In the case of uniform sphere this integral can be evaluated analytically. But, for the cylindrical geometry, an approach formula is given for this integral, in the presence of an axial magnetic field:

$$f_\alpha = (x_\alpha + x_\alpha{}^2)/(1 + 13x_\alpha/9 + x_\alpha{}^2), \qquad (2)$$

where $x_{\alpha.} = (8/3)\left(\overline{R} + c^2/\sqrt{2c^2 + 1000}\right)$, $\overline{R} = R/l_\alpha$ and $c = R\omega_\alpha / v_{\alpha 0}$.

BREMSSTRAHLUNG LOSS OF ENERGY.

The bremsstrahlung specific radiation power is calculated in the Ref.[2] using a relativistic Maxwell-Boltzmann electrons distribution function. The following formula is obtained:

$$P_{br} = c_0 n_e{}^2 \sqrt{T_e/(m_e c^2)}(K^{e-e}(T_e) + K^{e-i}(T_e)), \qquad (3)$$

where $c_0 = (16/3)\sqrt{2\pi/3}\alpha r_e^2 m_e c^3$., α is the fine structure constant and r_e is the classical electron radius. On a width range of electrons temperature (1-500 keV), fits for corrections K^{e-e} and K^{e-i} ,are presented, so: $K^{e-i}(y) = 1.1 + 0.59y + 3.06y^2 - 2.56y^3 + 0.85y^4$ and $K^{e-e}(y) = 1.78y - 0.15y^2 + 0.58y^3$, where $y = T_e/m_e c^2$.

SCREENING FUSION REACTION RATE.

The most useful expression for the fusion reactivity is evaluated for Deuterium-Tritium mixture by Hively (1983) [3]:

$$<\sigma v_r> = 9.10\times 10^{-16}\exp(-0.572(\ln(T/64.2))^{2.13})cm^3/s, \qquad (4)$$

where $V_r = \left|\vec{V}_D - \vec{V}_T\right|$ is the relative velocity.

The expression (4) is corrected by mean of the electrons screened effect in the thermonuclear plasma. That the nucleuses electrostatic potential interaction to be reduced compared to the Coulomb potential, $\sim 1/r$:

$V(r)=\frac{e^2}{4\pi\varepsilon_0 r}\exp(-r/\lambda_D)\approx\frac{e^2}{4\pi\varepsilon_0 r}-\frac{e^2}{4\pi\varepsilon_0\lambda_D}=V_c(r)-E_s$, where E_s is the screening energy. Then:

$$<\sigma v_r>_s=<\sigma v_r>\left[1+\sqrt{3}\Gamma_e^{3/2}\right], \tag{5}$$

where $\Gamma_e=e^2/(4\pi\varepsilon_0 a_B T)$ and a_B is the Bohr radius. Then fusion reaction rate is given in our simulation by:

$$R_f=9.10\times10^{-16}n_D n_T\left[1+\sqrt{3}\Gamma_e^{3/2}\right]\exp(-0.572(\ln(T/64.2))^{2.13})cm^{-3}/s \quad (6)$$

MODEL FLUID EQUATIONS.

The present work is making in the frame of the fluid theory. The basic equations are respectively, the continuity equation, the momentum equation and the energy conservation equation.

CONTINUITY EQUATIONS.

The continuity equations can be presented, taking into account the diminution of n_D and n_T densities due to the fusion reaction, as:

$$\partial n_e/\partial t+\vec{\nabla}.(n_e\vec{V}_e)=0 \tag{7}$$

$$\partial n_{D,T}/\partial t+\vec{\nabla}.(n_{D,T}\vec{V}_{D,T})=-n_D n_T<\sigma\left|\vec{V}_D-\vec{V}_T\right|> \tag{8}$$

The second member in eq.(8) describes the decrease of the ions density due to the fusion reaction.

MOMENTUM EQUATIONS

The momentum equations can be represented for the electrons, Deuterium and Tritium ions as:

$$m_{e,D,T}\frac{d(n_{e,D,T}\vec{V}_{e,D,T})}{dt}=-\vec{\nabla}(n_{e,D,T}T)-en_{e,D,T}\vec{V}_{e,D,T}\times\vec{B}-n_e\nu_{e,D,T}\vec{V}_{e,D,T} \tag{9}$$

where, $d/dt=\partial/\partial t+\vec{V}.\vec{\nabla}$ and ν_j is the collisions frequency for the j kind.

ENERGY CONSERVATION EQUATION

The heat equation for isotherm plasma taking into account the heat flux, the bremsstrahlung losses and the alpha energy deposition can be presented as:

$$\frac{3}{2}\frac{d}{dt}\left[(n_e+n_D+n_T)T\right]+n_eT\vec{\nabla}.\vec{V}_e+n_eT\vec{\nabla}.\vec{V}_e+n_eT\vec{\nabla}.\vec{V}_e=$$

$$-\vec{\nabla}.(\vec{q}_e+\vec{q}_D+\vec{q}_T)-P_{br}+E_\alpha f_\alpha R_f, \tag{10}$$

This eq. (13) describes the spatio-temporal evolution of the plasma temperature taking into account the heat flux, $\vec{q}_j$, the bremsstrahlung energy loss and the alpha deposition energy. Eqs. (7-10) permit to well describe the burn of the fusion reaction in D-T mixture.

CONCLUSION

In this work, we have presented a system of coupled equations which can describe the detonation of reaction fusion in a deuterium-tritium plasma mixture. The ions density decrease due to the thermonuclear fusion reaction is considered. In this study some important physical effects are taken into account, especially the screening effect due to the dense plasma and the bremsstrahlung losses of plasma energy. The numerical resolution of these equations permits to well-known the spatio-temporal evolution of the fusion reaction.

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