

Fusion Burning Waves in Degenerate Plasmas

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Degenerate plasmas present very interesting features for fusion burning waves ignition and propagation. However, the outcome of fusion burning waves in non-degenerate plasmas is limited by the strength of ion-electron Coulomb collisions and subsequent energy loss mechanisms as electron heat conduction and radiation emission (bremsstrahlung.)

In this paper, an analysis is presented on the **degeneracy effects** in the stopping power of suprathermal charged particles, in the energy transmitted from ions to electrons by Coulomb collisions and in the bremsstrahlung radiation emission from electrons. If the energy transmitted from ions to electrons can be minimized, the loss of energy by bremsstrahlung radiation from the plasma is also minimized, so the ion in the plasma can reach much higher temperatures, while electrons remains at lower temperatures, due to degeneracy effects.

Main results of this analysis is that very powerful fusion burning waves could be launched into previously compressed degenerate plasmas. This can be specially suitable for proton-boron fusion, which needs ion temperatures above 200 keV, but it is also applicable to any type of fusion reaction, where ignition can be triggered by an incoming ion beam or another external source of energy deposited in a small fraction of the compressed plasma (fast ignition).

1.- Non-degenerate Proton-Boron Plasma Analysis.

For classical Plasmas, the suprathermal alpha particles born as a result of the fusion reactions of Proton- Boron¹¹ plasmas gives their 8.7 MeV energy (three alpha particles of 2.9 MeV) to electrons and ions in the fusion wave region (see figure 1.) Proton Boron reactions need a high temperature of ions (more than 200 keV) to have a non negligible reaction rate $\langle \sigma v \rangle$ [5]. Initially, almost all the energy of the high energy alpha particles coming form fusion goes to electrons, since in non-degenerate plasmas (this is not the case for degenerated ones) the stopping power of high energy particles is much more efficient with low energy electrons. But in the case of burning plasmas, where the electrons increase their energy, the stopping power is much more efficient with ions. The problem arise when part of the energy

of the ions goes to electrons by electron-ion coulomb collision mechanisms, cooling down the ion temperature. In the electron fluid it can be found three different ways to lose their energy: by Bremsstrahlung emission, by Inverse Compton Scattering when the electron temperature is higher than the effective radiation temperature (T_r), and by Heat Conduction mechanisms.

From previous analysis, and taking into account new reaction rates data[5], the development of a fusion wave in a non-degenerate Proton-Boron¹¹ plasma is not possible, since the energy coming from fusion reactions is not enough to heat up ions to 200 keV temperature. The results, in a zero-dimensional analysis[3][4] is shown in figure 3. It can be shown that the energy transferred from ions to electrons is high, so ions are cooled down and the energy is lost by radiation emission and electron conduction. As a conclusion, in a Proton-Boron¹¹ classical or non degenerate plasma, it is not possible to launch a Fusion Wave.

2.- Degenerate plasmas.

The situation changes dramatically in a degenerate plasma, where bremsstrahlung emission, stopping of charged particles by electrons, and other Coulomb collision processes are inhibited by the fact that no additional electrons can be transferred into the fully occupied states of a degenerate plasma. On the contrary, electron thermal conduction is not inhibited at all, but this process remains negligible provided the electron temperature in the plasma is kept at low values and without significant gradients. The test for degeneracy is usually expressed as

$$n_e > 1.4 \times 10^{23} \left(\frac{kT}{10} \right)^{3/2} \quad (1)$$

where n_e is measured in electrons per cubic centimeter and kT must be expressed in eV. For a plasma at 100 eV, the electron density has to be larger than $44 \times 10^{23} \text{ cm}^{-3}$ for being degenerate. This is about 100 times as high as the electron density of solid stoichiometric DT. In experiments reported in reference [1], densities 600 times as high as the density of solid DT were reached. In that case, the temperature must be below 350 eV to have a degenerate plasma. According to the charged-particle leakage as compared to neutron leakage in those experiments, the temperature was of this order of magnitude or slightly above. It is worth pointing out that the experiment was not totally optimized for isentropic compression. This means that lower temperatures could be produced in suitably tailored implosions, in order to create a compressed degenerate plasma.

Figure 1.- Relevant Mechanisms in the Development of a Nuclear Fusion Wave.

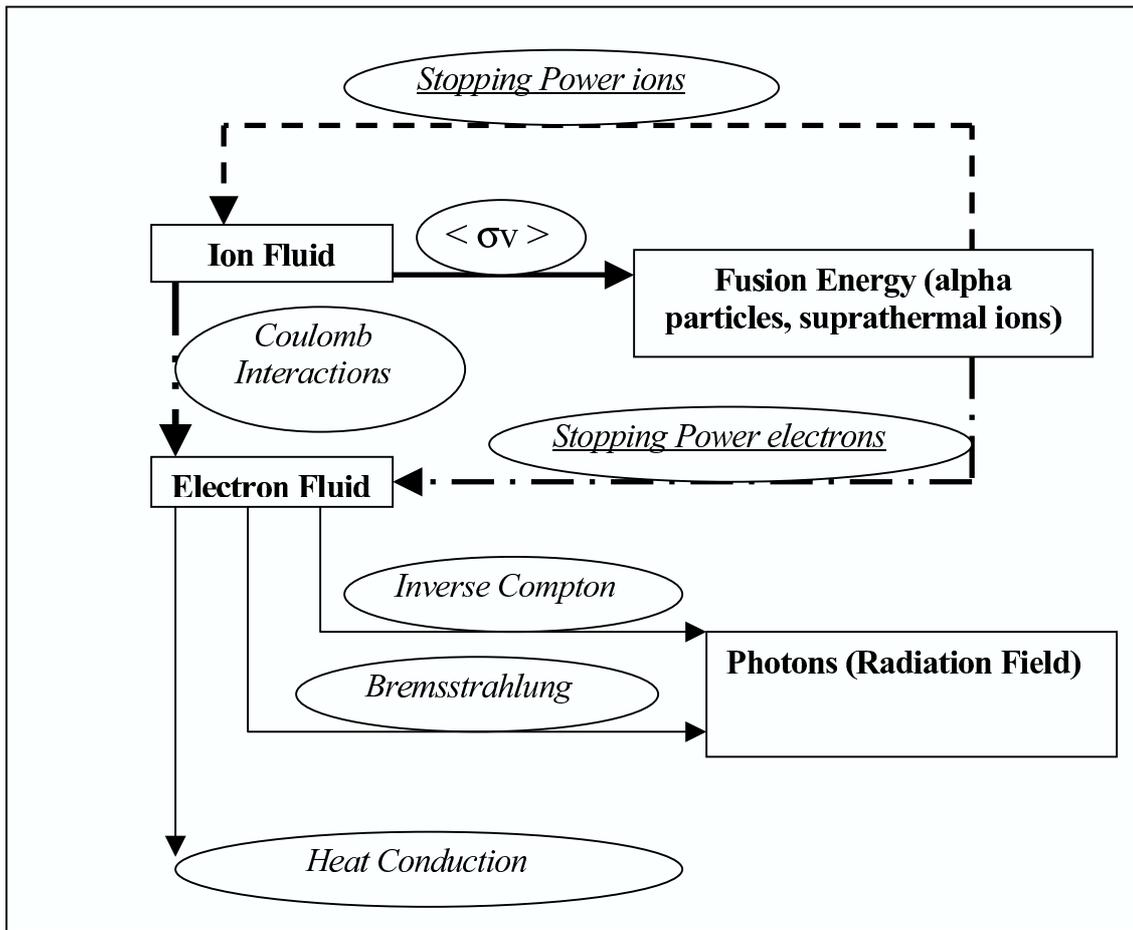
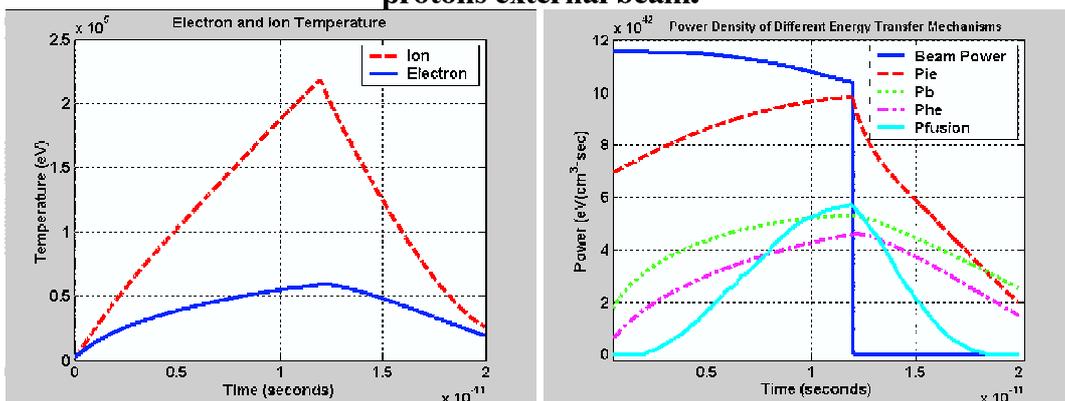


Figure 3.- Temperature and Power Density of Beam Power, Power from ions to electrons (P_{ie}), Power of Bremmstrahlung (P_b), Power of heat Conduction (P_{he}) and Power of Fusion (P_f) for the ignitor in a classical plasma of 700 gr/cm^3 and 5 MeV protons external beam.



In a degenerate plasma, the relative importance of the mechanisms shown in figure 1 changes dramatically. To begin with, ions from an igniting beam would mainly be stopped by the target ions. As a result of this type of interaction, the electron fluid would remain much colder than the ion fluid. At the same time, as the *ion-electron Coulomb collision term* would be largely inhibited because of Pauli's exclusion principle, the difference $T_i - T_e$ would

remain very high for a time long enough for the fusion burning wave to develop. Once the fusion burning wave is launched, it is important that the time of confinement (which is defined by the sound velocity of the plasma at a given density) is larger than the time of fusion. For degenerate plasmas, and using the Quotidian EOS for the plasma (which takes into account degenerate effects), sound velocity for different degenerate plasmas densities has been calculated, and the results shows that the time of fusion is well below the time of confinement. Also it is important that after the isentropic compression, the plasma temperature has to be well below the degenerate one. The limits are 358 eV for 100 gr/cm³, 1.66 keV for 1000 gr/cm³, and 7.7 keV for 10000 gr/cm³.)

3.- Conclusions

In the case of a degenerate plasma, fusion-born charged-particles will travel across a transparent electron fluid and will suffer strong Coulomb repulsions with the ions. Knock-on ions will move in a similar way, and both suprathermal and thermal fusion reaction would be possible. After a suitable isentropic compression (different that the one used for the hot spark model), where electrons will be degenerate, an external ultrapowerful beam impinging on the already compressed target will heat up the ions in the ignitor region[2], while electrons remain degenerate. After the external pulse, the alpha particles will heat up ions in the plasma (not electrons, since they are degenerate.) This means that the lose of energy term in the ion equation will be much lower, so the temperature finally reached can be higher than the 200 keV threshold, and a fusion wave can be launched. Further studies on stopping power in degenerate plasmas (to be included in the energy equations and a study of the isentropic compression with a maximum density and a minimum temperature to obtain a well degenerate plasma are already being developed.

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