

A Superthermal Nuclear Fusion Reactor

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The new concept of a superthermal DT fusion reactor, here discussed, is based on the observation that the cross section of the fusion reactions increases dramatically if the kinetic energy in the rest frame of the colliding nuclei increases from the order of 10 keV, typical for thermal fusion reactors, to the order of 100 keV. The DT reaction rate, for thermal D ions at 10 keV, and isotropic distribution of T ions, is a function of the kinetic energy of the tritons, given by the quantity

$$\langle \sigma v_r \rangle = \frac{1}{4\pi} \int d\Omega_T \int d^3v v_r \sigma f_M(v) \quad (1)$$

where σ is the cross section for DT fusion reactions, v_r is the DT relative velocity, $d\Omega_T$ is the differential of the solid angle in the T velocity space, f_M is the Maxwellian distribution for D ions, and the integrals are evaluated on the whole directions in T velocity space and on the whole space of D velocities. In the energy range 10 – 100 keV the DT reaction rate increases by two orders of magnitude, as shown in Fig. 1.

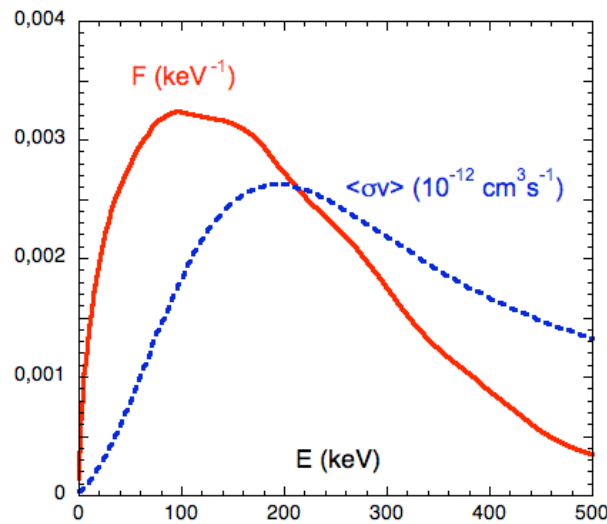


FIG. 1. The reaction rate for DT reactions (dashed line) for Maxwellian D at 10 keV temperature and isotropic T is plotted vs the kinetic energy of the tritons. The energy distribution function of the tritons corresponding to the peak power absorption for the RF heating scenario discussed here is also shown (continuous line).

The acceleration of a T minority at kinetic energies of the order of 100 keV will increase the fusion power by one order of magnitude with respect to the thermal distribution at 10 keV, even assuming that the concentration of the tritons is only 10%. It is worth to note that the record value of the fusion energy gain factor $Q \approx 0.22$ achieved at JET tokamak in near steady state conditions was obtained by ICRF heating of a 10% minority of D ions in T plasma, aimed at increasing the DT fusion rate by superthermal D ions [1]. However, a limitation of such scheme is that for higher minority concentrations a mode conversion (MC) regime can occur, with RF power absorption by plasma electrons. In recent years, a new ICRF ion heating scheme has been proposed [2]-[4], which could accelerate a robust ($> 20\%$) tritium minority at energies sufficient to significantly increase the DT fusion rate. In this scheme, fast magnetosonic waves (FMW) launched by ICRF antennas in a D-H (T) tokamak plasma, are mode converted in Ion Bernstein Waves (IBW) near the cut-off, located in the low field side. The IBW power is then absorbed partially by electron Landau damping and partially by ion cyclotron damping, which occurs near the plasma centre, where the first ion cyclotron harmonic resonance of T ions, $\omega \approx 2 \Omega_T$, is located. The MC process involves a competitive RF power flow either to IBW or to ICW (Ion Cyclotron Wave) branches [5], [6]. However, IBW dominates for high β plasmas and low poloidal field B_p [5], as occurs in the scenario discussed here. We consider a compact tokamak configuration with operating parameter listed in the Table I below.

R(m)	a (m)	B (T)	I (MA)	$T_o(\text{keV})$	$n_o(\text{m}^{-3})$	κ	δ	q_{95}	$\Delta_s(\text{cm})$
1.6	0.55	12	8	10	$5 \cdot 10^{20}$	1.9	0.4	3.5	6

TABLE I. Parameters of the tokamak configuration for tritium heating by IBW coupled by mode conversion of FMW in D-H(T) plasma with 40% D, 35% H and 25% T. The density and temperature profiles vs the normalized minor radius r are given, respectively, by $n_e = n_o(1-r^2)$ and $T = T_o(1-r^2)^2$.

A burning plasma could be obtained in such configuration by the injection of 20 MW ICRF power, coupled by four antennas, with radiating areas of 0.25 m^2 , at the operating frequency $f = 125 \text{ MW}$ and toroidal wave number $N_{||} = 4$.

This heating scenario has been analyzed by the code TORIC [7]. The total power absorption by electrons is about 50% and occurs near the FMW cut-off, at about 30 cm from the axis, in the low field side. The residual power is absorbed by the T ions near the first ion cyclotron harmonic

layer, which is located at about 6 cm from the axis, in the high field side. The deposition profiles, in terms of power density absorption per MW of RF coupled power vs the normalized minor radius, are shown in Fig. 2. Two dimensional plots of the power absorption are shown in Fig. 3.

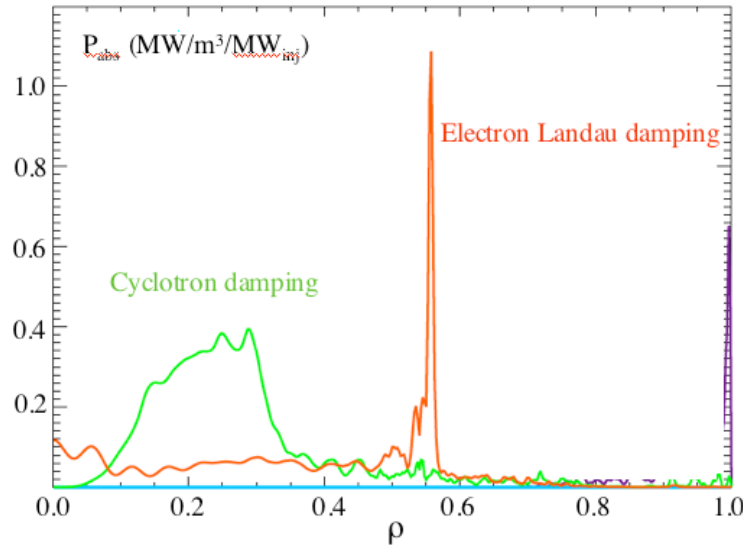


FIG. 2. Power deposition profiles vs the normalized minor radius obtained by the code TORIC.

The energy distribution $F(E)$ of the tritium minority, shown in Fig. 1 (red, continuous line) for $\rho = 0.3$, corresponding to the position of the maximum power absorption via cyclotron damping, has been evaluated with the 1D Fokker-Planck code of Ref. [8]. The peak value of the energy distribution function is at $E \approx 100$ keV, not far from the peak of the DT fusion rate $\langle \sigma v_r \rangle$. The cross section for DT fusion reactions has been evaluated by the parametric expression of Ref. [9]. As a result, the total fusion power density, given by the integral

$$P_f = n_D n_T \int dE \langle \sigma v_r \rangle(E) F(E) \quad (2)$$

has a radial profile corresponding to the radial profile of the power absorption by tritium ions (Fig. 2, green line) with a peak value of about 150 MW/m^3 . Therefore, the total fusion power expected for the proposed scenario is about 200 MW, corresponding to $Q \approx 10$. The code JETTO [10], based on a mixed Bohm-GyroBohm transport model, has been used to predict the plasma temperature. The global energy confinement time obtained by the model of thermal diffusivity used in JETTO to analyze this scenario is in agreement with the L-mode ITER89-P scaling laws. As a result of the JETTO predictive simulation, the expected central plasma temperature is about

10 keV, provided at least 50% of the fusion power carried by the particles is absorbed by the electrons in the plasma core.

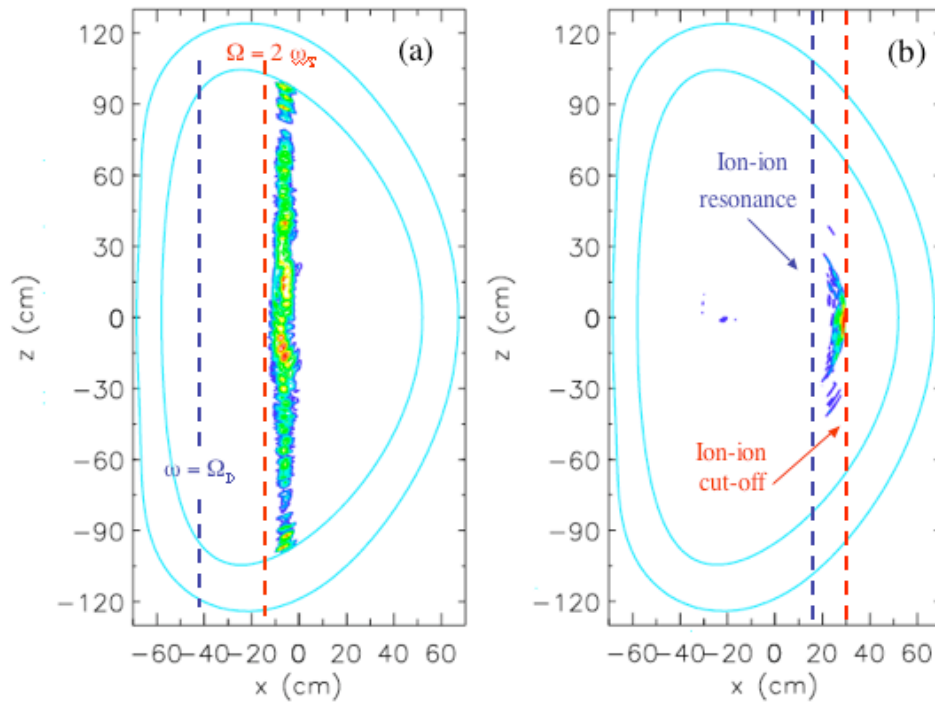


FIG. 3. Two dimensional plots of the power absorptions of the IBW by the ion cyclotron damping at $\omega = 2 \Omega_T$ (a) and by the electron Landau damping (b). The positions of the ion-cyclotron resonances $\omega = 2 \Omega_T$ and $\omega = \Omega_D$ (a) as well as the ion-ion resonance and cut-off (b) are also shown. The fundamental resonance of H is located outside the vessel, at $x = 71$ cm.

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