Heating Bulk Ions in DEMO with ICRF waves

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Abstract-*Ion cyclotron resonance frequency heating (ICRF) is one of the auxiliary heating schemes presently envisaged for ITER and DEMO. In this paper we analyse the potential of ICRF waves to heat the fuel ions in DEMO. Our analysis is carried out for the EU DEMO design[1] (B = 6.8 T, I = 18.6 MA, R = 9.25 m, a = 2.64 m) optimized for a maximum pulse length of 2.3 hrs using the ICRF modelling codes PION and TORIC [2, 3] . We focus on second harmonic heating for tritium and fundamental minority heating of ^{3}He with a few percent of ^{3}He in a 50%:50% D-T plasma. The dependence of the ICRF characteristics and the ICRF-accelerated ions on the ICRF and plasma parameters is investigated, giving special attention to the DEMO design point at a plasma temperature of 30 keV and an electron density of $1.2 \cdot 10^{20}$ m^{-3}.*

I. INTRODUCTION

The plasma is a gas made of electrons and ions and, therefore, is a really good conductor. When plasma is heated at a temperature of the order of 10 keV - 100.000.000 ºC fusion reactions begin to occur delivering an important quantity of energy. In order to produce fusion reactions, plasma needs to be confined inside special devices. For the magnetic confinement method this is achieved via the application of a magnetic field that restricts the trajectory of the plasma particles due to the Lorentz force. The most successful device so far is the tokamak.

A. Ion Cyclotron Resonance Frequency (ICRF) Heating

For a tokamak, heating fuel ions to thermonuclear temperatures is of vital importance. Ion cyclotron resonance frequency (ICRF) heating is an auxiliary mechanism for heating the plasma in a tokamak. ICRF is based on launching electromagnetic waves from the low-field side. Wave-particle resonance occurs when the parallel Doppler shifted frequency of the wave is equal to an exact harmonic of the cyclotron frequency of the particle, i.e. $\omega = k_{||}v_{||}+n\omega_{ci}$, where ω is the wave frequency, $\omega_{ci} = q_i B(r)/(A_i m_p)$ (q_i is the charge, $B(r)$ the background magnetic field, A_i the mass number and m_p the proton mass) is the ion cyclotron frequency and $n = 1$ for the fundamental and $n > 2$ for higher harmonics. When resonance occurs, ions start damping the wave by absorbing its energy. This effect modifies the distribution function of ions which develops a tail in the high energy region. The fast ions produced by the energy absorption from the electromagnetic waves play an important role in heating the bulk plasma. Therefore, it is crucial to know how the energy of the wave is distributed among ions and electrons, and how the fast ions produced deliver their energy to the other particles, ions and electrons. The critical energy is the energy at which ions transfer energy equally to background electrons and ions, for energies larger than E_c collisions with background electrons predominate while for energies lower than E_c bulk ion heating is obtained.

$$E_c = 14.8 A T_e \left[\sum_j \frac{n_j Z_j^2}{n_e A_j} \right]^{\frac{2}{3}} \qquad (1)$$

II. DEMONSTRATION POWER PLANT (DEMO)

The DEMOnstration power plant is a proposed nuclear fusion power plant that is expected to be built after the experimental reactor ITER. ITER's main purpose is to confirm the feasibility of nuclear fusion as a source of net electrical energy while DEMO will be the first fusion reactor to produce electrical energy (Table I).

TABLE I
DEMO, ITER, AND JET PARAMETERS

Parameter	DEMO[1]	ITER	JET
Major radius R_o (m)	9.25	6.2	2.96
Minor radius r (m)	2.64	2	1.25-2.10
Tor. Magnetic field B (T)	6.8	5.3	3.45
Plasma current I_p (MA)	18.6	15	4.8
Safety fac. $q0$ and $q95$	1.1, 3	1.0, 3.5	1.0, 5.0
Elongation κ	1.52	1.7	1.68
Triangularity δ	0.33	0.33	0.4

The Joint European Torus (JET) is the fusion reactor located in Culham, UK. It is presently the biggest operating fusion reactor in the world.

III. ANALYSIS OF BULK ION HEATING IN DEMO

We concentrate our studies on the second harmonic ($n=2$) ICRF heating of tritium with and without ^{3}He in a 50%:50% D-T plasma.

A. ICRF scenario

The scenario is for a standard midplane launch with thermal plasma and the toroidal mode number $N = Rk_{||}$ is fixed. The basic ICRF parameters are shown in the following table (Table II).

[1]*We are grateful to Dr. T. Franke and Dr. R. Wenninger (PPPT, Garching) for DEMO parameters. They are for the EU DEMO design optimised for a maximum pulse length of 2.3 hrs (with CD 2.7hrs).*

Although there are many cases studied, there are two of them that are analyzed deeper, they correspond to $T = 30\ keV$ and for densities $n_e = 10^{20}$ and $n_e = 1.2 \cdot 10^{20}$. The case with $n_e = 1.2 \cdot 10^{20}$ and $T = 30\ keV$ is the DEMO design point.

TABLE II
ICRF PARAMETERS AT DEMO

Parameter	DEMO
Toroidal magnetic field *B* (T)	ICRF frequency (MHz)
ICRF frequency *f* (MHz)	66, 70, 74
Resonance location (r_{res}/a)	0.2 (LFS), -0.05, -0.2 (HFS)
ICRF Power (MW)	100
Toroidal mode number	50

B. Minority heating with ³He

In minority heating typically the plasma contains a few percent in concentration of an ion species which interacts with the ICRF waves. In this case, the frequency of the wave has been set at the fundamental harmonic of ³He, $\omega = \omega_{^3He} = 2\omega_T$.

The analysis has been carried out for a scan in the concentration of ³He (see Fig. 1), the total electron density n_e, temperature T, and wave frequencies (central and off-axis).

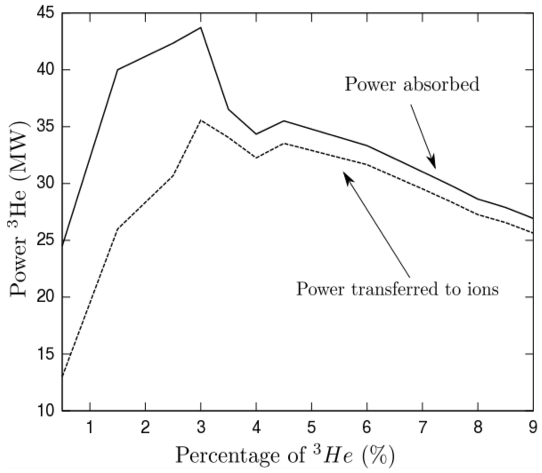

Fig. 1. *Power absorbed by ³He and transferred to bulk ions (MW) for each percentage of ³He. ICRF: N = 50, f = 70 MHz, T = 30 keV, P = 100 MW.*

For increasing concentration of ³He until 3-5% the power absorbed by ³He increases substantially while after a concentration of 5% the polarization of the wave starts to become less favorable and, therefore, the absorption power decreases, the power not absorbed by ³He goes directly to the electrons. In this case, for the DEMO design point, the power that is transferred to the bulk ions population is almost the same between 3-5%.

C. Second harmonic tritium heating scenario

The second harmonic tritium heating scenario is a 50%:50% D-T plasma heated by ICRF waves with a frequency equal to the second harmonic of T, i.e. $\omega = 2\omega_T$. In this case fast ions become more energetic than in the minority heating and the critical energy E_c is easier to be reached by fast ions. The results achieved are presented in Table III. Here the efficiency (η) stands for the ratio between the power transferred to bulk ions over the power absorbed by ³He and T respectively. Different frequencies produce different locations for the resonance region (c.f. resonance locations in Table II).

TABLE III
EFFICIENCY FOR DIFFERENT SCENARIOS WITH AN ICRF OUTPUT POWER OF 100 MW AT THE DEMO DESIGN POINT

Composition	66 MHz	70 MHz	74 MHz
³He 3%	55.84	35.56	26.65
³He 4%	54.80	32.25	24.37
³He 5%	48.10	31.90	23.50
³He 6%	45.20	31.76	22.54
T	43.00	26.65	15.51

IV. CONCLUSION

We have simulated ICRF heating for DEMO plasmas. Simulations show that for minority heating a concentration of 3-5% of ³He matches the highest efficiency while by placing the resonance region slightly off-axis (at 0.2a) ICRF heating is considerably enhanced in both scenarios avoiding a substantial fraction of direct electron damping. Notice that although minority heating shows a better efficiency the plasma dilution decreases the fusion reaction yield (Fig. 2).

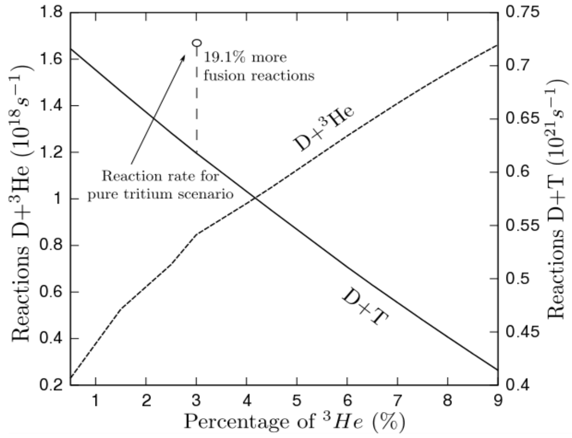

Fig. 2. Comparison of fusion reaction rate between ³He and T scenarios.

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