EUROfusion

EUROFUSION CP(15)03/22

D. Gallart et al.

Modelling of ICRF Heating in DEMO with Special Emphasis on Bulk Ion Heating

(27th April 2015 – 29th April 2015)
Lake Arrowhead, California, USA

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Modelling of ICRF Heating in DEMO with Special Emphasis on Bulk Ion Heating

Dani Gallart*, Mervi Mantsinen†,* and Yevgen Kazakov**

*Barcelona Supercomputing Center, Barcelona, Spain
†Catalan Institution for Research and Advanced Studies, Barcelona, Spain
**Laboratory for Plasma Physics LPP-ERM/KMS, Brussels, Belgium

Abstract. Ion cyclotron resonance frequency (ICRF) heating 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 DEMO1 Reference Scenario from October 2013 ($B = 6.8\ T$, $I = 18.6\ MA$, $R = 9.25\ m$, $a = 2.64\ m$) optimized for a maximum pulse length of 2.3 hrs using the ICRF modelling codes PION and TORIC. We focus on second harmonic heating of tritium and fundamental minority heating of ^{3}He ions (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 core plasma temperature of 30 keV and an electron density of $1.2 \cdot 10^{20}\ m^{-3}$.

Keywords: DEMO, ICRF, PION, bulk ion heating
PACS: 52.50.Qt

INTRODUCTION

Heating fuel ions to thermonuclear temperatures is of vital importance for energetic confinement fusion. Ion cyclotron resonance frequency (ICRF) heating is an auxiliary mechanism for heating the plasma in a fusion device. ICRF is based on launching electromagnetic waves from the low-field side (outer side of the tokamak). 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. $\omega = k_\parallel v_\parallel + l\omega_{ci}$, where ω is the wave frequency, $\omega_{ci} = \frac{q_i B(R)}{A_i m_p}$ (q_i is the charge, A_i the mass number of the resonant ions and m_p the proton mass) is the ion cyclotron frequency and $l = 1$ for the fundamental and $l \geq 2$ 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 wave energy is distributed among ions and electrons, and how the fast ions produced transfer their energy to the other particles, bulk ions and electrons. The critical energy

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

is the energy at which ions transfer it equally to background electrons and ions. For energies larger than E_c collisions with background electrons predominate while for fast ion energies lower than E_c dominant bulk ion heating is obtained. Here A is the mass number of the fast ion species, T_e is the electron temperature, the sum goes through the ion species, n_j, A_j and Z_j are the density, mass number and charge number of the j-ith ion species respectively and n_e is the electron density.

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. While ITER's main purpose is to confirm the feasibility of nuclear fusion as an energy source, DEMO is planned as the first fusion reactor to produce net electrical energy. In Table 1a, the main parameters of DEMO and ITER are compared. For DEMO, we consider the DEMO1 Reference Scenario from October 2013 ($B = 6.8\ T$, $I = 18.6\ MA$, $R_0 = 9.25\ m$, $a = 2.64\ m$) optimized for a maximum pulse length of 2.3 hrs.

TABLE 1. (a) DEMO and ITER parameters. (b) ICRF parameters for DEMO.

(a)

Parameter	DEMO	ITER
Major radius R_0 (m)	9.25	6.2
Minor radius a (m)	2.64	2
Tor. magnetic field B (T)	6.8	5.3
Plasma current I_p (MA)	18.6	15
Safety fac. q_0 and q_{95}	1.1, 3	1.0, 3.5
Elongation κ	1.52	1.7
Triangularity δ	0.33	0.33
Plasma volume (m^3)	2009	831
Fusion power (MW)	2119	400-500
Electric output power	500	-

(b)

Parameter	DEMO
Toroidal magnetic field B (T)	6.8
ICRF frequency (MHz)	66, 70, 74
Resonance location ($\frac{r_{res}}{a}$)	0.2, -0.05, -0.2
ICRF Power (MW)	100
Toroidal mode number N_ϕ	50

ANALYSIS OF BULK ION HEATING IN DEMO

We concentrate our studies on the second harmonic ($l = 2$) ICRF heating of tritium with and without ^{3}He in a 50%:50% D-T plasma in DEMO. The scenarios are modeled with PION [1] and TORIC [2] codes for a standard low-field side (LFS) midplane launch with thermal plasma (there is no ICRF+NBI interaction) and a fixed toroidal mode number $N_\phi \simeq Rk_\parallel$ ($k_\parallel$ is the wave number along the magnetic field). $P_{ICRF} = 100\ MW$ has been considered as a baseline value of the coupled ICRF power. The basic parameters of ICRF system are summarized in Table 1b. The analysis has been carried out for a scan in the central electron density and the electron temperature T_e which has been kept equal to the ion temperature $T_e = T_i$. The frequency of the wave f has been varied in order to place the resonance either on axis or on the high field side (HFS) or LFS. Two cases are analyzed in more detail: (i) $T_e = 30\ keV$ and $n_e = 10^{20}\ m^{-3}$, (ii) $T_e = 30\ keV$ and $n_e = 1.2 \cdot 10^{20}\ m^{-3}$. The latter corresponds to the DEMO design point.

^{3}He minority heating

Typically, in minority heating, 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 equal to the fundamental harmonic of ^{3}He, $\omega = \omega_{^3He} = 2\omega_T$. We have analyzed the behavior of the bulk ion heating by varying the concentration of ^{3}He and the plasma and ICRF parameters mentioned above.

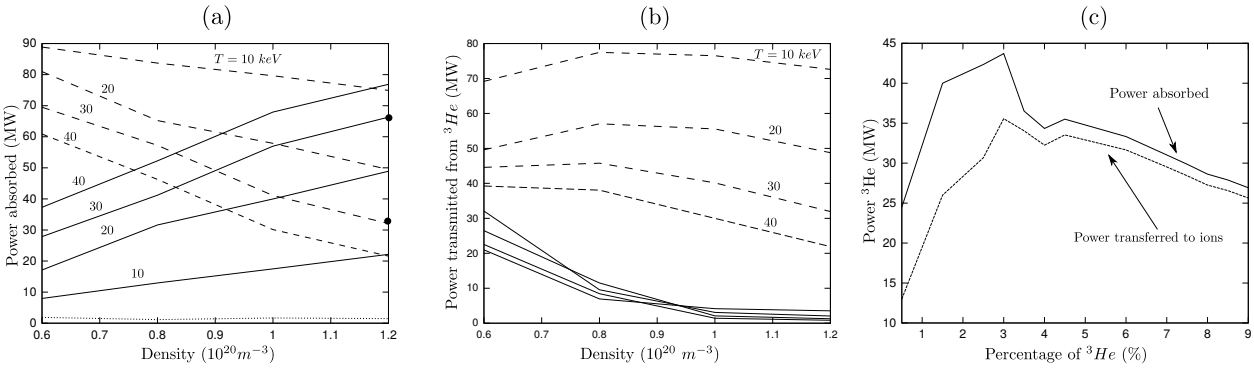

FIGURE 1. ^{3}He minority heating with 5% of ^{3}He as given by PION ($f = 70\ MHz$, $N_\phi = 50$, $P = 100MW$). (a) Scan in n_e and T_e of the power directly absorbed by ^{3}He (dashed line), electron damping (solid line) and tritium ions (dotted line), black dots represent the DEMO design point. (b) Scan in n_e and T_e of the power transferred collisionally from fast ^{3}He ions to bulk ions (dashed line) and to electrons (solid line). (c) Scan in ^{3}He concentration of the power absorbed by ^{3}He and transferred to bulk ions for the DEMO design point.

The analysis of bulk ion heating for a scan on plasma temperature T_e and plasma density n_e with a fixed ^{3}He concentration of 5% is presented in Fig. 1a and b. Figure 1a shows the power absorbed by ^{3}He and direct electron

damping for $f = 70\ MHz$ (central resonance). Increasing T_e and n_e results in a lower power directly absorbed by ^{3}He ions and higher efficiency at direct electron damping. Collisional redistribution of the absorbed power is shown in Fig. 1b. The power transferred to bulk ions shows a slightly decreasing behavior with n_e. At highest densities it matches the power absorbed by ^{3}He, since the power transferred to the electrons decreases substantially with the electron density. As the electron density increases, the power absorbed by ^{3}He decreases (Fig. 1a) and the average energy of the fast ions decreases. This is the reason why the power transferred to electrons decreases. In fact, for $n_e = 1.2 \cdot 10^{20}\ m^{-3}$ almost all the power absorbed is transferred to bulk ions. Notice that the power transferred to bulk ions decreases with the increasing plasma temperature. The power transferred to bulk ions by ^{3}He for the DEMO design point is 31.9 MW.

The dependence of bulk ion heating on the ^{3}He concentration for the DEMO design point is shown in Fig. 1c. It shows two different regions, one region in which the power absorbed grows with the percentage of ^{3}He until the maximum is reached at 3% and then a region of negative slope in which the power absorbed decreases. For increasing concentration of ^{3}He until $3-5\%$ the power absorbed increases substantially while after a concentration of 5% the polarization of the wave starts to become less favorable and, therefore, the absorption power decreases. In this case, the power that actually remains in the bulk ion population is almost the same between $3-5\%$. For concentrations lower than 3% the difference between the power absorbed and the power transferred to the bulk ions is quite big, of the order of 10 MW. The relatively large electron heating fraction at lowest ^{3}He concentration are due to the increase of the average fast ion energy content from 131 keV to 500 keV when ^{3}He concentration is decreased from 5% to 0.5%. Note that the change in E_c is due to the change in ^{3}He concentration. For 5% and 0.5% of ^{3}He, E_c equals 794 keV and 765 keV, respectively. For concentrations larger than 3% of ^{3}He, the power is mainly transferred to the bulk ions population which means that the average energy of fast ions is significantly lower than E_c.

Second harmonic tritium scenario

We have alse carried out simulations of the second harmonic tritium ($\omega = 2\omega_T$) scenario for a 50:50 D-T plasma. As before, the frequency is set to 70 MHz so the resonance is located at the center of the plasma. This scenario has two main advantages in comparison with ^{3}He minority heating. Firstly, that no ^{3}He is required and secondly, there is no dilution by ^{3}He. As we can see from Fig. 2a the D+T reaction rate for second harmonic tritium scenario is 19% greater than ^{3}He minority scenario at 3% concentration.

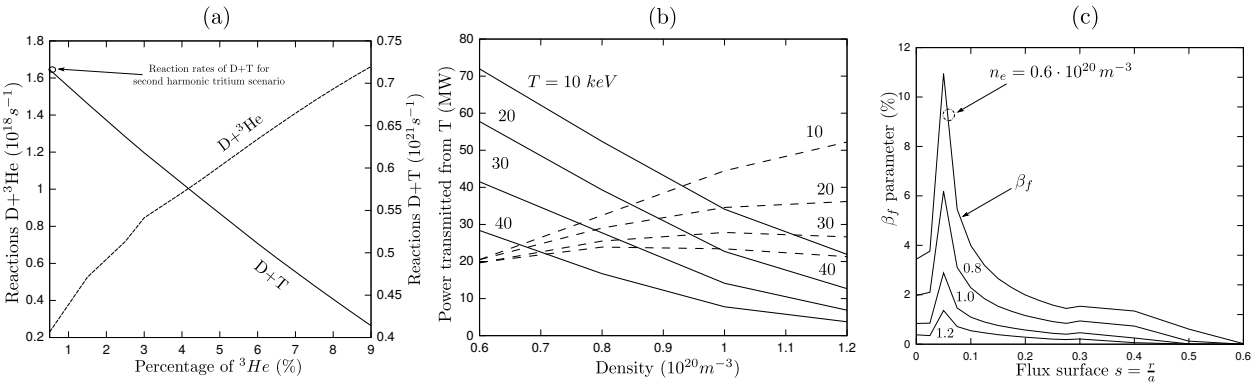

FIGURE 2. Second harmonic tritium scenario as given by PION ($f = 70\ MHz$, $N_\phi = 50$, $P = 100\ MW$). (a) D-T and D-^{3}He fusion reaction rates as a function of ^{3}He concentration. (b) Scan in n_e and T_e of the power transferred from fast T ions to bulk ions (dashed line) and power transferred to electrons (solid line). (c) β_f parameter profile as function of flux surface s for different electron densities n_e at $T = 30\ keV$.

The power absorbed by T ions and direct electron damping follows a similar trend with the electron density n_e and T_e as seen in the ^{3}He scenario shown in Fig. 1a. In particular, as the temperature T_e and n_e increases the power absorbed by T ions decreases. The main difference between the second harmonic T and ^{3}He minority scenarios is that the energy of fast ions for the second harmonic tritium heating scenario is greater than that of the minority heating scenario as more energetic ions tend to absorb the energy for $l \geq 2$ [3]. This is the reason why the power transfer to bulk ions behaves so differently for the two scenarios (Fig. 1b and Fig. 2b). For second harmonic tritium scenario for low densities the power transfer to electrons is much more important than the transfer to bulk ions as $\langle E_f \rangle > E_c$. Only

for high electron densities $n_e \sim 10^{20}\ m^{-3}$ all the cases have $\langle E_f \rangle \leq E_c$. This scenario achieves 26.7 MW of power transfer to bulk ions at the DEMO design point which is lower than the ^{3}He minority scenario studied above.

Figure 2c shows the value of $\beta_f = 2\mu_0 p_f / B$ for different electron densities n_e for second harmonic tritium scenario. Here p_f is the fast ion pressure which is proportional to E_f. In agreement with the analysis of the power transferred to bulk ions, as the electron density is increased, the β_f parameter and p_f decrease, i.e. the average energy of fast ions $\langle E_f \rangle$ decreases (which implies that power transfer to electrons will decrease). The β_f value reaches maximum of 11% at the resonance. In comparison, the maximum β_f value for the ^{3}He minority scenario is 3% at a ^{3}He concentration of 5%.

The results shown above are computed for a frequency of 70 MHz, which places the resonance in the center of the plasma. We have also carried out simulations with the off-axis resonance locations, $r/a = 0.2$ and -0.2, corresponding to a wave frequency of 66 MHz and 74 MHz, respectively. These simulations have been carried out with PION but they have been compared with TORIC which showed good agreement. According to the results presented in Table 2 the bulk ion heating fraction by ICRF can be maximized in DEMO by placing the ICRF resonance slightly off-axis on the low-field side to minimize the competing direct electron damping (Table 2).

TABLE 2. The fraction of bulk ion heating for different scenarios with an ICRF output power of 100 MW at the DEMO design point.

Composition	66 MHz	70 MHz	74 MHz
^{3}He 3%	55.8	35.6	26.7
^{3}He 4%	54.8	32.3	24.4
^{3}He 5%	48.1	31.9	23.5
^{3}He 6%	45.2	31.8	22.5
T	43.0	26.7	15.5

As follows from Table 2, LFS off-axis heating at 66 MHz ($r/a = 0.2$) is the most effective case in terms of bulk ion heating. In this case direct electron damping is weaker than for the other two cases ($f = 70$ MHz and $f = 74$ MHz) as the wave reaches the ion cyclotron resonance before reaching the plasma center where strong electron damping occurs. The ^{3}He 3% case shows the best efficiency with 55.8% while the second harmonic tritium scenario shows an efficiency of 43% but without the drawback of plasma dilution.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

We are grateful to Dr. R. Wenninger and Dipl.-Ing T. Franke (PPPT, Garching) for DEMO parameters. They are for the DEMO1 Reference Scenario from October 2013 optimised for a maximum pulse length of 2.3 hrs (with CD 2.7hrs)

REFERENCES

1. L.-G. Eriksson, T. Hellsten, and U. Willén, *Nuclear Fusion* **33**, 1037 (1993).
2. M. Brambilla, and R. Bilato, *Nuclear Fusion* **46**, S387 (2006).
3. L.-G. Eriksson, and P. Helander, *Physics of Plasmas* **1**, 308 (1994).