Investigations of ICRF heating scenarios on EAST plasma

X.J. Zhang, Y.P. Zhao, C.Q. Qin, J.P. Qian

Institute of Plasma Physics, Chinese Academy of Sciences

(Received: 30 October 2009 / Accepted: 28 April 2010)

For designing scenarios with optimal ICRF performances in EAST tokamak plasma, the fast wave propagation and absorption should be first investigated. Here several possible Ion Cyclotron Resonance Heating (ICRH) scenarios have been explored are minority heating of hydrogen in a deuterium plasma and mode conversion heating of ^{3}He in a deuterium plasma. The TORIC code has been used to simulate the heating. TORIC solves the finite Larmor radius wave equations in the ion cyclotron frequency range in an arbitrary axisymmetric toroidal geometry. The fast wave propagation/absorption characteristics, power partitions among plasma species are analyzed.

Keywords: Minority Heating, Mode Conversion, EAST

1. Introduction

EAST tokamak [1] is to perform advanced tokamak research in a high performance regime and to explore methods for achieving steady-state operation for a tokamak fusion reactor. Heating and current driving using fast wave in the ion cyclotron range of frequencies is one of the main features in EAST tokamak. Different ICR heating modes are required to meet the requirements for the initial operation, including minority and second harmonic heating and mode conversion heating. Possible species mixed include dominantly D with H minority or D plasmas with ^{3}He minority for initial operation. In order to contribute to the development and understanding of the ICRH in EAST, we have been analyzing various options by using the TORIC full wave code. In this modeling study here, two physical scenarios are considered: (a) Fast Wave (FW) minority heating with H in D plasma at 36 MHz; (b) FW mode conversion electron heating with ^{3}He in D plasma (5%H fixed) at 32 MHz. An analysis of the numerical results is also presented in this paper.

2. The TORIC code

TORIC [2, 3, 4] solves the Maxwell wave equation given by

$$\nabla \times \nabla \times \vec{E} = \frac{\omega^2}{c^2}\left(\vec{E} + \frac{4\pi i}{\omega}\left(J_P + J_A\right)\right)$$

Where J_P is the plasma current and J_A the antenna current. In the Finite Larmor Radius (FLR) approximation, the plasma current can be approximated by

$$J_p = J^{(0)} + \sum_{Ions} J_i^{(2)} + J_e^{(2)}$$

Where $J^{(0)}$, $J_i^{(2)}$ and $J_e^{(2)}$ denote the zero Larmor radius current and the ion and electron FLR currents, respectively. The resulting wave equations describe damping by the ions at the fundamental ion cyclotron frequency and its first harmonic and Cerenkov damping by electrons. The wave equations solved by TORIC are derived from Vlasov equation by expanding the electro-magnetic fields in Fourier modes in the toroidal and poloidal angles. While for the FW an expansion to second order in the Larmor radius is adequate, large Larmor radius effects are taken into account to describe Ion Bernstein Wave (IBW) [5]. The TORIC code has been improved by the parallelization of solver [6].

TORIC has been coupled to the 2D Fokker-Planck code for ions, SSFPQL [7-9]. It solves the steady-state surface averaged quasi-linear Fokker-Planck equation for ions heated at the fundamental and the first cyclotron harmonics by using the output of TORIC to build the surface averaged quasi-linear diffusion coefficient. The code provides information on the radial profiles of the suprathermal populations generated by ion cyclotron heating, and on the collisional redistribution between these tails and the background ions and electrons. These are very crucial for the quasi-linear analysis.

3. Results of numerical modeling

We present an analysis of possible two ICRF heating scenarios for EAST. The results are for a single toroidal mode number, $n_\varphi = 12$ for 36MHz and $n_\varphi = 15$ for 32MHz.

The density and temperature are assumed to have profiles inside the separatrix:

$$n_e = \left(n_{e0} - n_{sep}\right)\left(1 - \left(r/a\right)^2\right) + n_{sep},$$

$$T_\alpha = \left(T_{\alpha 0} - T_{\alpha sep}\right)\left(1 - \left(r/a\right)^2\right) + T_{\alpha sep}$$

author's e-mail: xjzhang@ipp.ac.cn

$(\alpha = i \quad or \quad e)$

3.1 H/D Heating Scenarios

In this section, we mainly discuss the results of ICRF minority ion heating by using the TORIC code. The fast wave propagation and absorption characteristics, and power partitions among electrons and ions are investigated.

We have used the parameters of MHD equilibrium at t=3.6s in the shot of 9088 of EAST during 2008 campaign. The main parameters of MHD equilibrium are calculated by using EFIT code with data from experiments. The results are for the toroidal mode number, $n_{\varphi} = 12$ and 36 MHz

The main plasma parameters for study are as follows:

$n_{e0} = 3\times10^{13}(\text{cm}^{-3})$, $n_{sep} = 5\times10^{12}(\text{cm}^{-3})$,

$T_{e0} = 2\text{keV}$, $T_{i0} = 2\text{keV}$,

$T_{esep} = 0.2\text{keV}$, $T_{isep} = 0.2\text{keV}$, $f = 36\text{MHz}$

$I_P = 500\text{kA}, B_T = 2.5\text{T}$

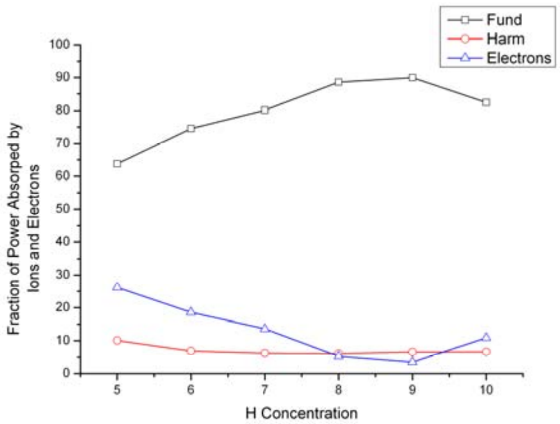

Fig.1 the power fraction coupled to various species vs the minority concentration: the meaning of Fund is power to Fundmental harmonic. The meaning of Harm is power to second harmonis. The meaning of Electrons is power to electrons,

In fig.1, the power fraction coupled to various species are plotted vs the H concentration at a fixed value of the toroidal mode number 12. The peak is centered on a minority concentration of 9%.

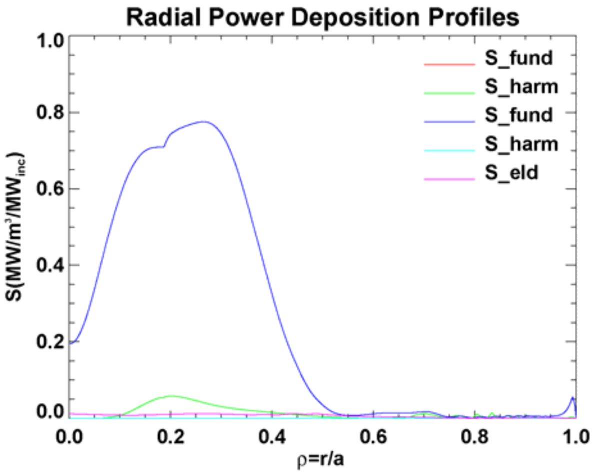

Fig.2 the radial power deposition profile: the meaning of blue line is power to H Fundamental harmonic. The meaning of green line is power to D second harmonic. The meaning of pink line is power to electrons. The meaning of red line is power to D Fundamental harmonic. The meaning of sky blue line is power to H second harmonic.

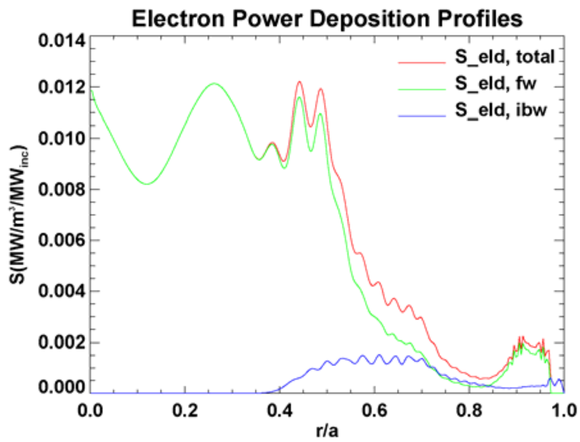

Fig.3 the electron power deposition profiles: the meaning of red line is total power to electrons. The meaning of green line is power to electrons due to fast wave. The meaning of blue line is power to electrons due to IBW.

Fig.2 and fig.3 display the corresponding power deposition profile of the plasma species. The location of fundamental resonance is at 7.365 cm on the low field side and ion-ion resonance is at 5.050cm on the high field side. Over 90% of total absorbed power is going to plasma ions through the fundamental cyclotron resonance of H and the second harmonic resonance of D with P_H=89.95% and P_D= 6.58%. The rest is absorbed by electrons with P_e =3.47% through Electron Landau Damping (ELD) and Transit-Time Magnetic Pamping (TTMP) or by mode-converted IBW. The fast wave excited from the low field side antenna propagates towards the magnetic axis. The waves encounter first the

H fundamental resonance and then the ion-ion evanescence layer, bounded by ion-ion resonance towards the high field side and by the cutoff towards the low field side. The rf power not absorbed neither by ion at cyclotron layer nor by the electrons is partially reflected and transmitted at ion-ion evanescence layer, and mode converted to shorter waves.

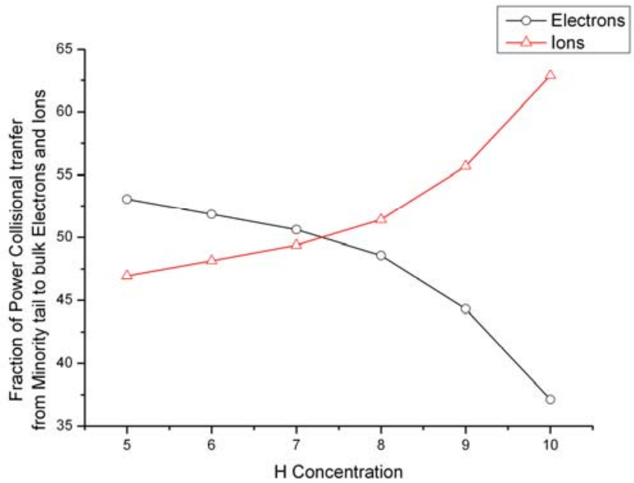

Fig.4 Fraction of power to bulk ions and electrons vs the minority concentration

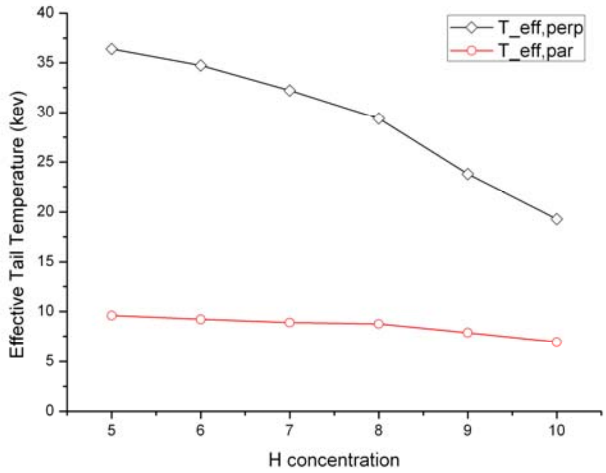

Fig.5 the effective temperature of the tail for different H concentrations

The quasi-linear calculations were performed with TORIC-SSQLFP package. The relevant plot is shown in fig.4 where the fraction of power on the bulk ions and electrons is shown vs the H concentration. No more than 65% of the coupled power can be transferred to the bulk ions. Increase the H concentration decrease the power transferred to bulk electrons. This is confirmed by the details of quasi-linear calculations, as shown in fig.5. Due to the high effective tail temperatures, most of absorbed power is thermalized on the electrons. Further preliminary calculations show that the fractions of power transfer to electron increase from 44.32% to 62.32% through increasing the ICRH power from 2MW to 5MW. The electron absorptions also increase when increasing the electron temperature.

3.2 ^{3}He/D Heating Scenarios

The main parameters for the study in this section are as follows.

$n_{e0} = 1\times10^{14}(\mathrm{cm}^{-3})$, $n_{sep} = 1\times10^{13}(\mathrm{cm}^{-3})$,

$T_{e0} = 2\mathrm{keV}$, $T_{i0} = 2\mathrm{keV}$,

$T_{esep} = 0.2\mathrm{keV}$, $T_{isep} = 0.2\mathrm{keV}$, $f = 32\mathrm{MHz}$

Here the TORIC uses simple analytic formulae for the description of equilibrium [4] with $I_P = 750\mathrm{kA}$ and $B_T = 3.5\mathrm{T}$

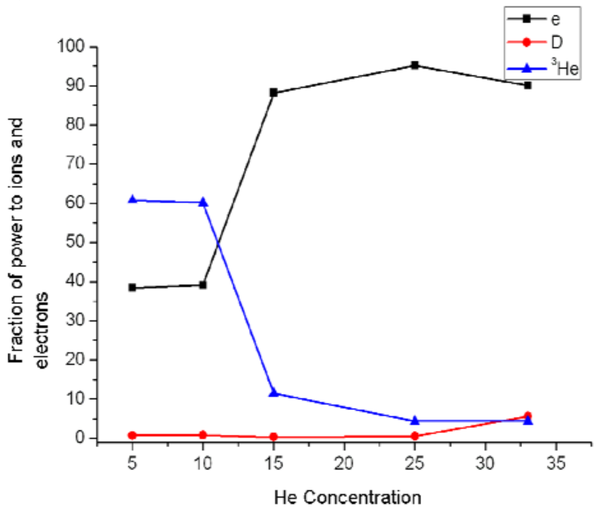

Fig.6 RF power distribution in D (^{3}He-H) plasma

For a given frequency and magnetic field, the location of the mode conversion layer and electron power deposition can be varied by changing the ^{3}He concentration. Fig. 6 shows the power distribution for the same parameters above. In D (^{3}He-H) scenarios, there is a clear transition to mode conversion dominant regimes around the ^{3}He of minority concentration greater than 10%. As ^{3}He increases, the fraction of rf power which can reach ^{3}He cyclotron resonance layer decreases rapidly.

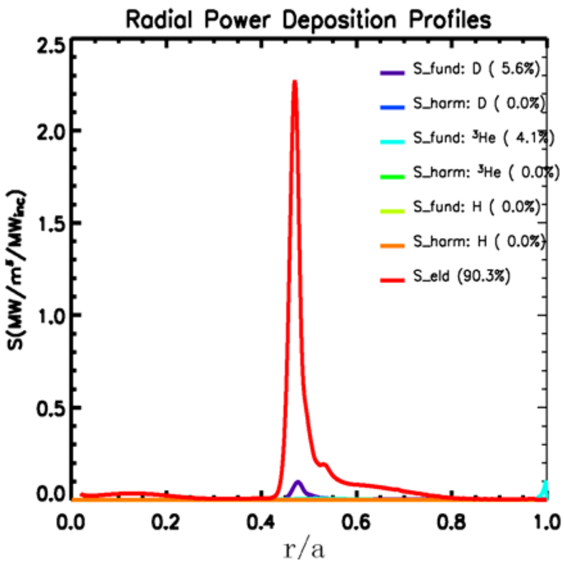

Fig.7 The radial power deposition profiles for the mode conversion case with mixture of D:^{3}He:H (29:33:5).

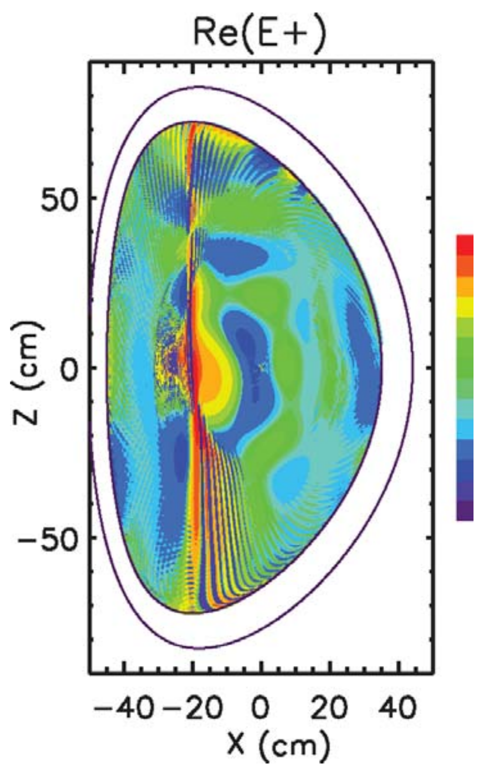

Fig. 8 The contour plot of fast wave field .Converged TORIC simulation of the mode conversion case with mixture of D-^{3}He-H.

According to the simulations for 33% ^{3}He with 5% H in D plasma in fig.7, the power partition among the absorbing species was as follows: the absorbed rf power due to FW and mode conversion electron heating is 90.3%. The FW power is absorbed via fundamental ^{3}He cyclotron damping is 4.1%. The remaining 5.6% of the power is absorbed via fundamental Deuterium cyclotron damping on the tokamak high field side. In mode conversion heating regime, FW are mode converted to short wavelength waves. These waves damp strongly on electrons, giving rise to electron heating on the shorter time scale of electron-electron collisions. As is shown in fig. 8, three waves—ICW, IBW and FW, are resolved at the mode conversion layer. IBW go the high field side. ICWs travel towards the low field side above and below the midplane.

4. Conclusions

The TORIC code has been used to simulate the heating. The fast wave propagation and absorption characteristics, power partitions among plasma species are analyzed. The minority heating in EAST tokamak is investigated by using TORIC package which takes into account the EAST magnetic field structure. ICRH power absorbed by minority ions is maximized for H concentration around 9%. Quasi-linear calculations show that no more than 65% of the coupled power can be transferred to the bulk ions. Increase the H concentration decrease the power transferred to bulk electrons. The electron absorptions also increase when increasing the electron temperature.Increase in effective temperature decreases the fractions of power transferred to the bulk ions. EAST reference scenarios with 32 MHz at B=3.5 T shows a clear transition to mode conversion dominant regimes in D (^{3}He-H) scenarios. In mode conversion regime, the electron absorbed almost all of the absorbed power.

5. References

[1] Jiangang Li, 1st EAST IAC Meeting, 2003
[2] M.Brambilla Nucl. Fusion 34 (1994) 1121
[3] M.Brambilla Plasma phys. Control.Fusion 31(1989) 723
[4] M. Brambilla Plasma phys. Control.Fusion 41 (1999) 1
[5] M.Brambilla 27th EPS Conf. on Controlled Fusion and Plasma Physics 2000
[6] J.C.Wright, P.D.Bonoli, et al. Comp.Phys.Comm. 164(2004) 330
[7] M.Brambilla and R.Bilato Nuclear. Fusion 46(2006)S387
[8] M.Brambilla, R.Bilato,J.C.Wright,P.Bonoli 33rd EPS Conference on Plasma Phys. 2006
[9] A.Cardinali,B.Esposito,F.Rimini,M.Brambilla,F.Crisanti,et al. 33rd EPS Conference on Plasma Phys. 2006