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1. INTRODUCTION

Ion Cyclotron Range of Frequency (ICRF) waves are candidates for heating (ICRH), current drive, and possible flow drive in ITER and future tokamaks. There are considerable challenges developing the technology of ICRF systems and the tools for assessing effects on plasma performance. These tools are important both for guiding present experiments and for indicating efforts for future research. This paper addresses some of the tools for simulating ICRH.

The TORIC ICRF full-wave code [1] solves the kinetic wave equation in 2D axisymmetric equilibria. TORIC solves Maxwell's Equations for a fixed wave frequency with a linear plasma response in a mixed spectral-finite element basis. The antenna is modelled as a sheet current. A kinetic model for the plasma dielectric response is derived using an Eikonal ansatz.

2. METHODS

TORIC has been coupled into the TRANSP code using a compact portable namelist and ascii data files that allow input data from any time slice to be captured and later studied in greater detail using standalone runs. TRANSP-TORIC is being used for timedependent analysis of ICRH experiments in various tokamaks, and for predictions of ITER performance [2].

A recent improvement has enabled TRANSP to compute the renormalization of the antenna vacuum spectrum $V(n_\phi)$ with n_ϕ the toroidal wave number. by the coupling with the plasma. The Poynting flux of power from the antenna $P(n_\phi)$ is returned by TORIC for each n_ϕ. The renormalized spectrum $R(n_\phi)$ is given by $V(n_\phi)\times P(n_\phi)$ normalized so that the sum over n_ϕ of $R(n_\phi)$ gives the total antenna power. Another recent improvement is parallelization of the standalone TORIC [3]. Features being worked on include parallelization of TORIC in TRANSP, and adding the relativistic Collisional/QuasiLinear 3D code CQL3D [4] for improving the accuracy of the coupling of minority ions to the plasma and other fast ions. The first is important since high resolution time-dependent runs are very CPU intensive. The second is important to improve the accuracy the ICRH calculations. TRANSP-TORIC is being used to analyze ICRH in numerous JET plasmas using the standard A2 antenna [5] as well as the new ITER-Like ILA antenna [6] with H or ^{3}He fundamental cyclotron resonance heating in D plasmas. The ILA has eight current straps in four rows $\times$ two columns.

Special attention is given here to cases with H-minority at relatively low n_H/n_e fractions to calculate electric field components and power deposition accurately without requiring a very large number of poloidal mesh points. TRANSP-TORIC runs have produces time-dependent simulations approximating $V(n_\phi)$ with up to 20 values of n_ϕ and using 323 radial mesh points and either 64, 128, or 512 poloidal mesh points. Runs with one n_ϕ value and 512 poloidal mesh points require many hundred CPU hours on a single processor to simulate the full time evolution.

3. RESULTS

We concentrate on several plasmas having record amounts of ICRH power coupled via the ILA antenna. The first pulse (Pulse No: 75000, see Table 1) was performed in L-mode with 4.3MW of ICRF power coupled from the ILA antenna. The full ILA was used with dipole phasing. Effects of the renormalization of $V(n_\phi)$ by plasma coupling from a run with eight n_ϕ values are shown in Fig.1.

The effective spectrum $R(n_\phi)$ is shifted to lower values of n_ϕ due to the stronger absorption of power near the magnetic axis at lower n_ϕ. Less total power is absorbed by electrons and more by thermal ions. The relative absorption for n_ϕ = 22, 32, and 42 is 0.067, 0.027, and 0.009 respectively. Contour plots of Re(Eζ) (parallel to B_{tor}) at n_ϕ = 22 and 42, also in Fig.1, show stronger focus and thus more absorption at lower n_ϕ. This shift to lower n_ϕ could have important implications for ICRF current drive since large n_ϕ would be more effective.

Plasmas with ^{3}He minority and the Ion Cyclotron Wave (ICW) have been shown to give rise to ICRF-driven toroidal rotation in C-MOD [7]. However, the ICW mode responsible for this rotation had not yet been identified numerically in bigger machines and others plasma compositions. In this paper, we demonstrate for the first time the excitation of the ICW by the fast wave in a (H)-D JET plasma. Figure 2, showing the contour lines of R_e(Eζ) for the same shot depicted in Fig.1 but using 1024 poloidalmesh points, reveals thismode's short wavelength structure. The ICWis seen just inside the ion-ion resonance layer, and its amplitude is amplified in the direction traveling from high to lower B_{tor} and against the direction of B_{pol}, causing an up / down asymmetry with respect to the midplane. The direction of B_{pol} is counter-clockwise in Figure 2. The wave intensity is stronger by a factor of ten above the midplane.We confirmed this ICW phenomena by numerically reversing B_{pol}, which caused a reverse of the asymmetry.

The shot with record coupling from the ILA to an H-mode plasma was Pulse No: 78070 (using only the upper half). It had 1.9MW coupled via the ILA and another 6MW coupled via the A2. This shot also had 16MW neutral beam absorbed power allowing charge-exchange measurements. Results are summarized in Table 1. Waveforms for a very similar Pulse No: (78034) are shown in Fig.3.

We have also modeled cases with higher minority fractions ($n_{minority}/n_e \simeq$ C5−10%) and have used up to 256 poloidal mesh points in the time-dependent TRANSP-TORIC runs, and 512 poloidal mesh points for TORIC-standalone, single time-step runs for finer analysis. Results for one of these (Pulse No: 69393) are compared with those from a prediction for ITER [2] in Table 1. The ITER heating has larger fractions of direct electron heating and of the minority ion-thermal ion heating.

It is important to verify the numerical solutions, and to test the applicability of the modelling. One test of the accuracy of the analysis is to compare the neutron emission rate and the stored energy. EFIT provides measurement of the perpendicular stored energy $W_\perp$. TRANSP computes this as the sum of the thermal (isotropic) energy W_{th} and $W_\perp$ of the fast ions. These are compared in Fig.4. Fair agreement (generally within ≃ 20%) is achieved, indicating the accuracy of the TRANSP-TORIC analysis. Approximate agreement with the simulated and measured neutron emission rate indicates general accuracy of the TRANSP modelling and that the ICRH is not significantly effecting the beam ions (as shown in Table 1).

SUMMARY AND FURTHER WORK

TRANSP-TORIC is being used to model ICRH in JET plasmas. Approximate agreement with the diamagnetic energy is achieved in ICRH with Hminority. The shift of the vacuum n_ϕ spectrum is computed, taking account of the plasma absorption of ICRH power. The computed shift is toward lower n_ϕ.We identified for the first time the ICWmode in JET plasmas. Future work is being undertaken to parallelize TRANSP-TORIC and to include CQL3D. Benchmarking with other codes such as AORSA [8] are planned.

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Pulse No: Time (s)	JET 75500 14.0	JET 78070 15.0	JET 69393 5.8	ITER 20100P07 250.0
Regime	L-mode	H-mode	ITB	H-mode
Heating	ICRH	ICRH, NB	ICRH, NB	ICRH, NBI, ECRH
Antenna	ILA	A2 and ILA	A2	dipole phasing
ICRF frequency (MHz)	42	42	32	53
peak vacuum n_ϕ	32	32	27	27
equivalent $k_\parallel$ (/m)	10.1	10.5	8.6	4.2
minority	H	H	^3He	^3He
n_{min}/n_e (%)	5	5	10	2
$T_e(0)$ (keV)	7.0	5.4	7.0	23.0
RF $\rightarrow$ Thermal D	9 (harmonic)	9 (harmonic)	0	1 (fund)
RF $\rightarrow$ Thermal T	-	-	-	12 (harmonic)
RF $\rightarrow$ Impurity	0	0	1 (fund)	0
RF $\rightarrow$ NB	0	1 (fund)	4 (fund)	0
RF $\rightarrow$ minority	81 (fund)	67 (fund)	89 (fund)	50 (fund)
electrons-Landau damping	10	23	7	37
electrons-IBW	1	0	0	0
minority $\rightarrow$ thermal ion heating	40	34	59	78
minority $\rightarrow$ electron heating	60	66	61	22

Table 1: Comparisons of conditions and heating fractions (%) for ICRH in JET and in ITER predictions. Quoted results for JET Pulse No: 78070 are for the ILA. The A2 antenna has similar fractions. The ITER heating scheme was 2nd harmonic cyclotron T heating in 50-50 DT plasma ^3He.

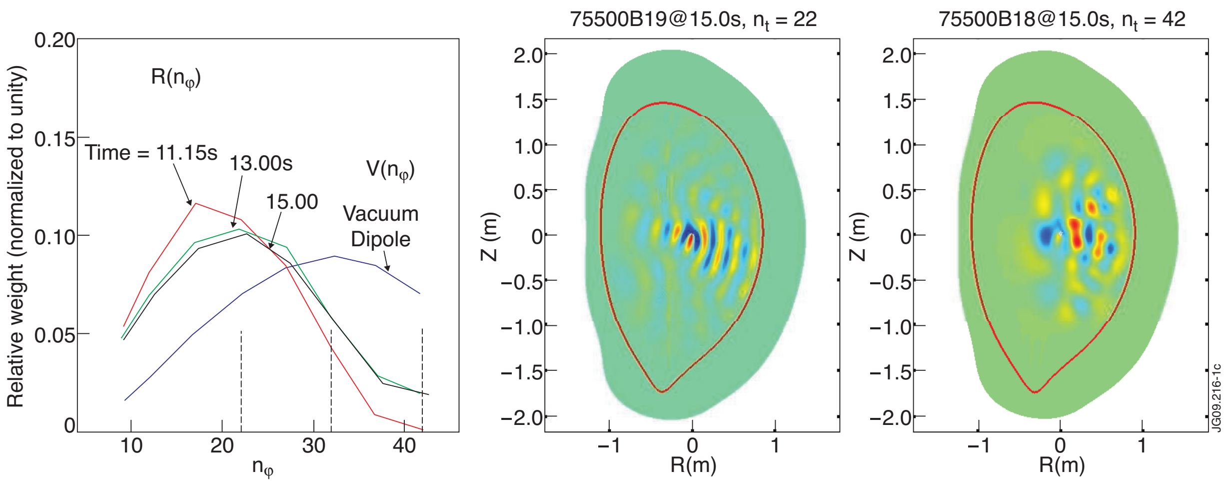

Figure 1: Results for the L-mode plasma heated by the ILA. Left panel: shift of V(n_ϕ) by plasma coupling; Right panels: contours of Re(Eζ) at n_ϕ = 22 (below the peak at 32), and n_ϕ = 42 above the peak. These runs used 14, 512, and 512 poloidal mesh points, respectively.

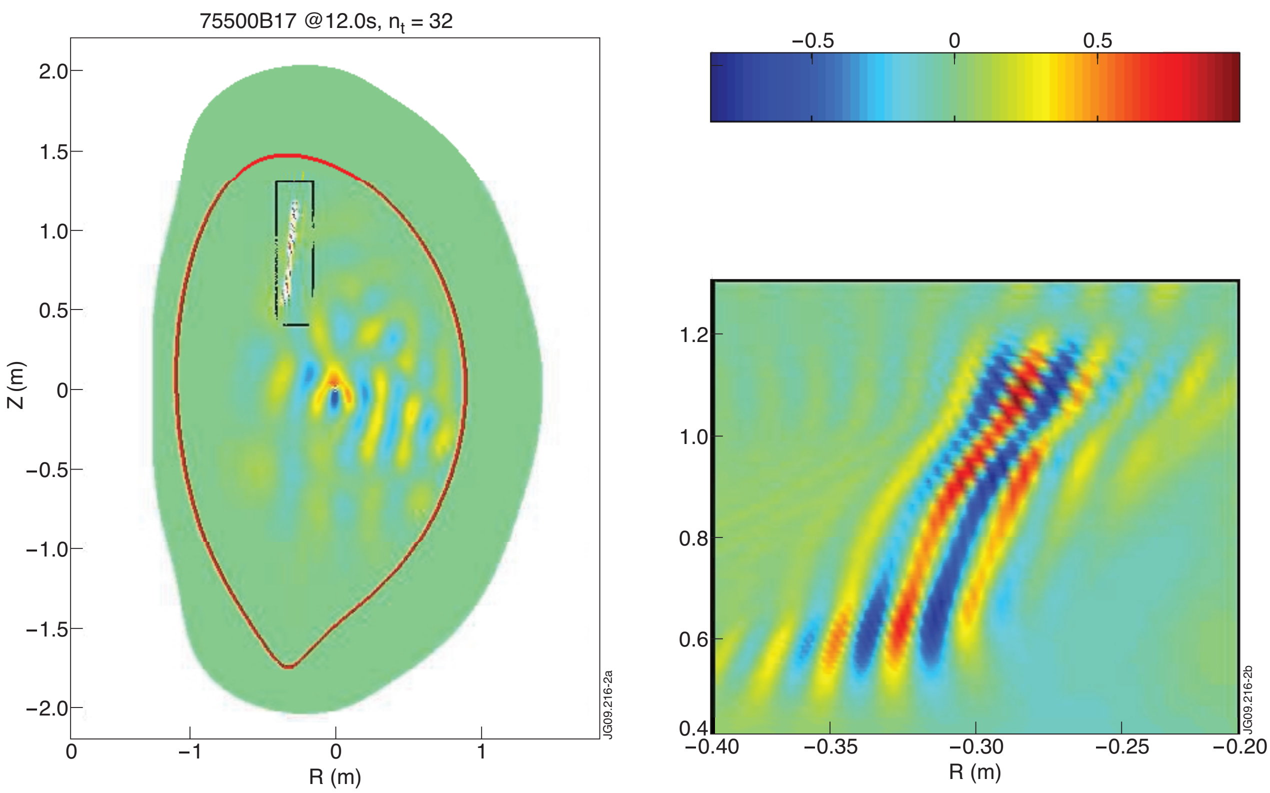

Figure 2: Contours of Re(Eζ) at n_ϕ = 32 computed for L-mode plasma (Pulse No: 75500) computed on two processors using 1024 poloidal mesh points. The region in the small rectangle on the left is magnified on the right and shows the signature of Ion Cyclotron Wave mode conversion. This mode is barely discernible with 256 mesh points, and gets progressively clearer as the number is increased to 512, and then 1024. The units of the color scale are V/m/MW_{abs}.

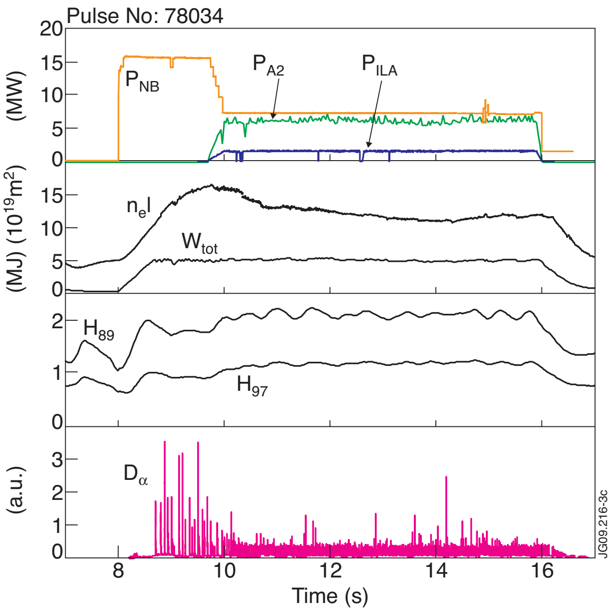

Figure 3: High performance H-mode plasma (Pulse No's: 78034, similar to 78070 in Table 1) with Type I ELMS heated by beams, the upper-half of the ILA, and the four A2 antennas.

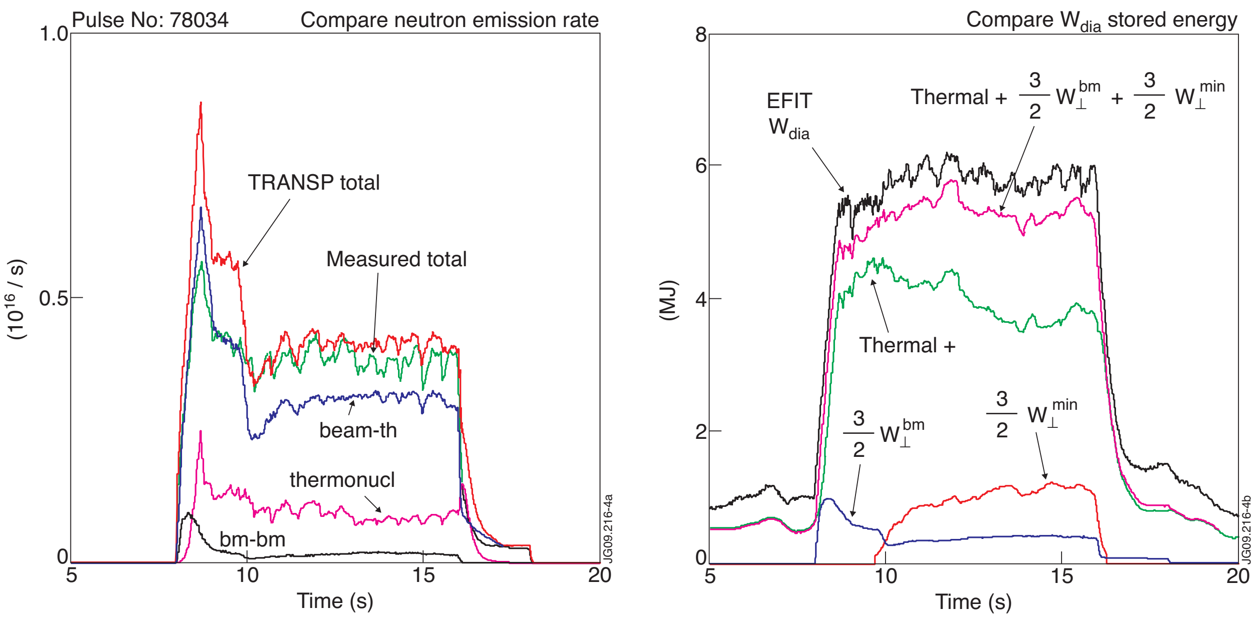

Figure 4: . Comparison of the neutron emission rate and the stored energy computed by TRANSP and EFIT for the H-mode plasma shown in Figure 4 showing agreement.