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Experiments on ICRF Coupling with Different Phasings

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High power density ICRF launchers will be needed for ITER and, after the end of the 2004 and 2005 campaigns on JET, an ITER-like ICRF launcher will be installed and tested in JET. The reference design coupling performance (dipole phasing) may be improved if the loss of heating efficiency for the launcher in toroidal monopole phasing is reduced. In older measurements of plasma energy content vs. input power at JET, practically no hydrogen minority heating was observed for monopole with the present A2 antennae [1], although the coupling resistance was better in monopole than in dipole. The unaccounted coupled power in monopole is likely deposited through parasitic absorption in the enhanced sheaths.

To further investigate the phasing dependence of heating efficiency with the JET A2 antennae, L-mode coupling experiments were conducted varying input power and its modulation, antenna-plasma distance, plasma configuration, number of active antennas, and phasing. Comparative monopole/dipole 42 MHz ICRF power ramp-up (< 8 MW) discharges at B=2.7T with a hydrogen minority scenario for two plasma currents I=2.8 MA (so called standard flux expansion SFE configuration) and I=2 MA (diagnostics optimized DOC configuration) are shown in Fig.1.

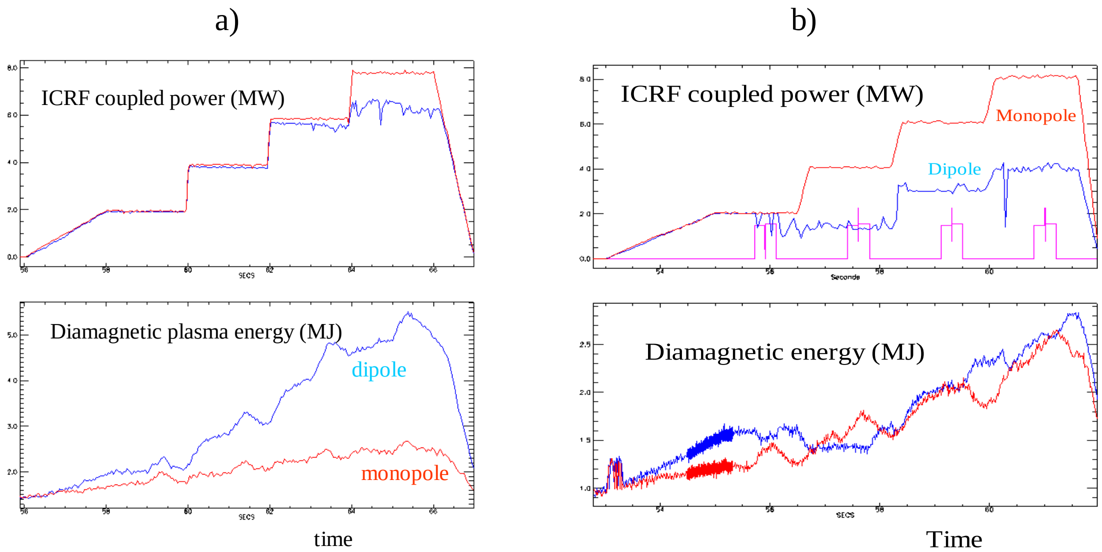

Fig.1 Evolution of coupled power and plasma energy for a) SFE 2.8 MA (#52672, #52670) and b) DOC-U 2 MA (#58944, #58949) configurations in a power ramp-up to 8 MW with steps of 2 MW.

In both cases in monopole the diamagnetic plasma energy grows significantly slower with power than in dipole. The heating efficiency is about one half of that found in dipole phasing (0pi0pi). The result was confirmed both by plasma energy content considerations and NPA analysis [2] of the minority fast ion tails, indicating that the poor heating in the plasma core was not due to increase of transport. In the SFE case, with dipole phasing the line-integrated proton distribution function is about 5 times larger than with monopole phasing throughout the NPA measurement range of 0.3-1.1 MeV. However, the characteristic tail temperatures of the line-integrated distribution functions are very similar, about 240-250 keV. The pitch-angle averaged Fokker-Planck ICRF code PION [3] is used to compare the calculated thermal and non-thermal contributions to the plasma diamagnetic energy content with the measured one. Depending on plasma temperature, density and injected power, different proportions end up in bulk plasma and to fast ions. The idea is to scale down the power seen by PION to influence the fast ion energy content and use this to match the diamagnetic energy calculated by PION to that of magnetic measurements.

$$W_{dia} = W_{th} + (3/2)W_{fast}$$

The amount of power that must be left out from the simulations to match W_{dia} is equal to the power not absorbed in the plasma. Constraining the calculations also with the measured proton tail temperature, the time evolution of the measured diamagnetic energy is qualitatively reproduced for the SFE case if the coupled ICRF power for monopole phasing in the simulation is reduced by a factor of 0.7 and central hydrogen concentration is assumed to be about twice the hydrogen concentration measured at the plasma edge. The ICRF power absorbed by protons for monopole phasing is about 50% of that for dipole phasing in this SFE case. Direct electron damping and damping at the second harmonic resonance of deuterium majority ions and carbon minority ions are, according to the PION code, small, and the electron temperature and neutron measurements do not suggest that these damping mechanisms would take more power for monopole than for dipole phasing. Furthermore, mode conversion, as estimated with the Budden model, is not strong enough to account for the difference.

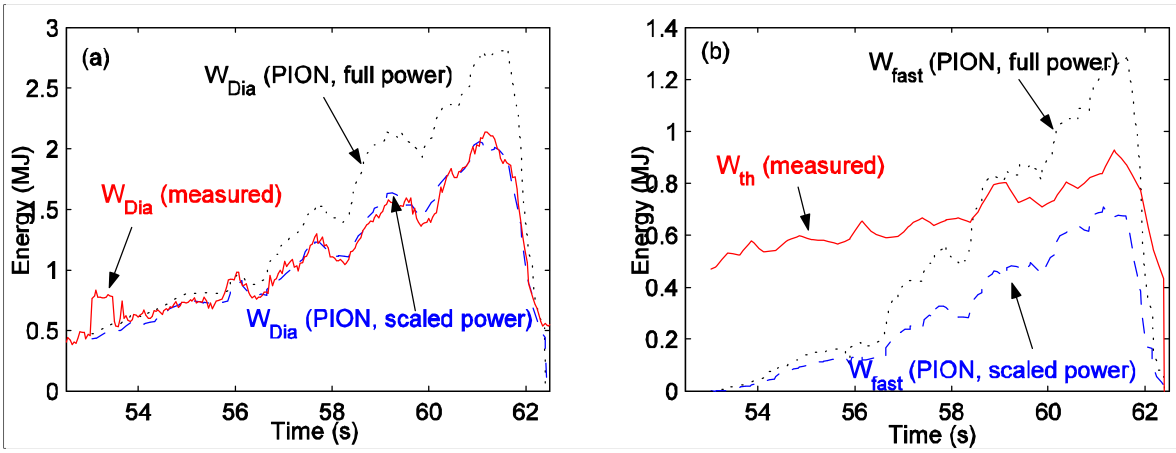

Fig.2 (a) Diamagnetic energy content from measurements (—) and from PION calculations with full power (···) and with optimally scaled power (---) to match the measured W_{dia}. (b) Thermal energy content (—), fast ion energy content calculated by PION using full injected power (···) and optimally scaled power (---).

Figure 2(a) shows for the DOC-U case the measured diamagnetic energy together with two PION calculations where the dotted black line corresponds to a simulation made taking into account the total injected power in the experiment whereas the dashed blue line is made with optimally scaled input power. At the highest power of 8 MW, PION calculations show that about 55% of the injected power is not absorbed into the core plasma. Thermal plasma energy content and fast ion energy contents for the corresponding simulations are plotted in Figure 2(b). For the DOC-U case, no NPA diagnostics was available.

In both SFE and DOC-U case, the reference antenna front – plasma distance (ROG) was 4 cm while the up-down asymmetry for this distance was larger for the DOC-U. No significant change in the difference in the monopole and dipole plasma core heating efficiencies was found when the ROG was varied from 4 cm to 8 cm and back with 6 MW of coupled power. Power and phase modulation (between dipole and monopole) within the same discharge produced similar results, too. The heating efficiency in 00pipi phasing was larger than in monopole but closer to that of monopole than dipole, while the 0pipi0 phasing resulted only 10% lower heating efficiency than the dipole. Interestingly, monopole antennae with only one (1.6 MW) or two straps (3.2 MW) active heated with a 1.5 times better efficiency than the standard antenna with 4 straps active (4 MW). In all the cases discussed above, the coupling resistance remained 1.5-2 times higher in monopole than in dipole throughout the discharge.

The above results indicate that the parallel wave number spectrum radiated by the antenna plays an important role in the plasma core heating efficiency. This may support the model of parasitic ICRF absorption by the near or far rf sheath voltage rectification [4]. This is further supported by the fact that the part of the ICRF coupled power which is not seen to be absorbed in the core is not detected in the measured radiation or divertor heat loss channels. Heating efficiency and the missing power (EIN-ERAD-ETC)/ERF in terms of the total injected power EIN, radiated power ERAD, heating power ETC at the divertor thermocouples and coupled rf power ERF are shown for various JET discharges with different ICRF phasings, power and configuration in Table I. In spite of large measurement inaccuracies the missing power seems to be systematically large for low ICRF heating efficiency and vice versa, in accordance with earlier findings from thermocouple measurements [5].

The problems in the antenna rf probe operation during the monopole heating prevent relating the lost power to the antenna sheath dissipation conclusively. As the plasma density or the flux of particles towards the antenna front is not known, one is not able to estimate the sheath power dissipation. Estimates of this power with reasonable guesses for the antenna plasma properties and standard rf sheath models do not give as large parasitic loss as seen in the present experiments. However, it is possible that sheaths far from the antenna can also dissipate significant amount of power and thus be responsible for the missing power [6]. In the present experiments, the absorbed ICRF power in the core plasma was of the same order of magnitude as the single pass absorption predicted for the ICRF waves. The monopole heating may thus be a viable option in heating scenarios of such devices where this single pass absorption is large, if significant parasitic absorption applies only to that part of the coupled wave power which is not absorbed during the single pass through the core or does not reach the core by wave propagation.

Shot (#)	phasing	Frequency (MHz)	B/I (T/MA)	Power (MW)	Rog/gap3/gap4	N (1019 m-2)	remarks	Heating efficiency	(EIN-ERAD-ETC)/ERF (“missing power”)
52670	**0000**	**42**	**2.7/2.8**	**8**	**4/7/8.4**	**6**	**SFE**	**0.5**	**0.7 ± 0.1**
52672	**0pi0pi**	**42**	**2.7/2.8**	**~8**	**4/7/8.4**	**6**		**~1**	**0 ± 0.1**
48868	**0000**	**42**	**2.7/2.7**	**5**	**3.7/5.5/9.5**	**6**		**0.3**	**0.5 ± 0.15**
48867	**0pi0pi**	**42**	**2.7/2.7**	**5.5**	**3.7/5.5/9.5**	**6**		**0.95**	**0 ± 0.2**
58944	**0000**	**42**	**2.7/2.0**	**8**	**4/7/11.5**	**5.7**	**DOC-U**	**0.35**	**0.5 ± 0.15**
58949	**0pi0pi**	**42**	**2.7/2.0**	**4**	**4/7/11.5**	**5.5**		**~1**	**0 ± 0.25**
58945	**0 0**	**42**	**2.7/2.0**	**3.5**	**4/7/11.5**	**5.6**	**2 straps**	**0.5**	**0.5 ± 0.25**
58956	**0**	**42**	**2.7/2.0**	**1.5**	**4/7/11.5**	**5.5**	**1 strap**	**0.5**	**0 ± 0.6**
52677	**0000**	**42**	**2.7/2.8**	**6**	**4/7/8.4**	**5.7**	**Rog scan**	**0.3**	**0.6 ± 0.1**
52676	**0pi?0pi**	**42**	**2.7/2.8**	**6**	**4/7/8.4**	**6.5**	**Rog scan**	**~1**	**0 ± 0.1**
58680	**90 deg**	**37**	**1.8/2.0**	**4**	**5/9.6/8.3**	**6**		**0.43**	**0.6 ± 0.15**
58682	**90 deg**	**51**	**3.4/2.0**	**4**	**5/9.6/8.3**	**5**	**12 MW NBI**	**0.95**	**0 ± 0.15**

Table I. Heating efficiency and power input and loss balance for various JET ICRF discharges.

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