ICRF Plasma Production in TORE SUPRA: Analysis of Antenna Coupling and Plasma Properties

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1. *Introduction and motivation for RF plasma experiments*

Wall conditioning techniques in the presence of high permanent magnetic field will certainly be required in the next generation superconducting fusion devices to minimize tritium retention and/or control of the impurity content in the vacuum vessel. For present and future tokamaks, RF plasma production in the ion cyclotron range of frequencies (ICRF) is mainly envisaged as an effective tool because of its high potential and large efficiency for wall conditioning in the presence of magnetic field [1-4]. An asset of the RF technique is the ability of conventional ICRH antennas with Faraday shield (FS) to produce reliably target plasma (10^{16} m^{-3} < $\bar{n}_{e0}$ < 10^{19} m^{-3}) in tokamaks without any changes in the hardware [5]. According to the theory of ICRF plasma production, the $\tilde{E}_z$-component of the antenna near RF field (along the total magnetic field) is responsible for neutral gas breakdown and initial plasma build-up [5,6]. This field is induced by the RF voltage difference between the antenna strap and box (side limiters) and by the RF voltage generated between the tilted rods of the FS [5]. Recent numerical modeling showed that the $\tilde{E}_z$-field near the antenna may extend further out in the toroidal direction due to the presence of poloidal bumpers [7].

Conventional ICRH antennas of the loop-type may have low coupling in the regime of RF discharges. The antenna-plasma coupling efficiency will be characterized by the ratio $\eta = R_{pl} / (R_{pl}+R_v)$, where R_v is the antenna vacuum resistance and R_{pl} is the resistance due to plasma loading.

Several ideas have been proposed how to improve coupling of the ICRH poloidal antennas in that particular case. The first one is to reduce the width of the evanescent layer at the edge. For fast wave (FW) propagation in a non-uniform plasma with parabolic density profile, the width of this layer • r may be given in the form:

$$\bullet r/a \quad \bullet \quad (1-N_Z^2) \quad (\Omega \quad -1) \quad / \quad 2 \quad N_A^2(0), \qquad (1)$$

where a is the plasma radius, $N_Z = k_Z c/\omega < 1$, $\Omega = \omega/\omega_{ci} > 1$, $N_A(0) = \omega_{pi}(0)/\omega_{ci}(0)$ is the Alfvén refractive index in the plasma core. It is clear from (1) that • r becomes smaller at larger plasma density or lower toroidal magnetic field B_T (high harmonic FW regime (HHFW)). The dependence of R_{pl} on the two last parameters was studied in the RF plasma experiments on TEXTOR-94 [5] and was found in qualitatively good agreement with the wave vector k_r and • r behavior predicted by a 1-D dispersion code [8].

Antenna coupling may also be improved in the regime of slow wave (SW) propagation ($n_e \geq 3\times10^{13}$ m^{-3} for f=47.9 MHz) by tilting poloidal antenna strap along the B_T-direction [9]. Tilting at small angles (~1-2°) may be achieved by so-called "antenna magnetic rotation" as a result of superimposing the vertical magnetic field B_V on the toroidal one B_T [9].

A study of RF plasma production in the frequency range $\omega \bullet 2\omega_{ci}$ has been undertaken on TORE SUPRA taking into account antenna coupling predictions of theory and the TEXTOR-94 database [5]. Two scenarios for RF discharges have been tested (fixed frequency of the RF generator): (i) operation with pure toroidal magnetic field, at standard and lower B_T and (ii) operation in the magnetic configuration with a small vertical (B_V) field superimposed on B_T ($B_V << B_T$).

2. *Effect of B_T variation on antenna coupling and RF plasma parameters*

In this set of experiments, helium RF discharges were performed in the toroidal magnetic field range B_T = 2.43 T - 3.85 T. One double loop antenna (Q5) was used. Figure 1 shows a scenario of such RF discharges. Continuous He-flow into the vessel provided a pressure in the range $p_{He} \bullet$ 0.02-0.1 Pa. A total RF power of 50-200 kW was applied to the antenna straps from two independent RF generators driven in phase at the frequency f=47.9 MHz in the multi-pulse mode of operation ($\tau_{RF} \bullet$ 50 ms). Prompt and reliable RF plasma production is clearly seen (signal from central channel of the interferometer). Despite of He gas injection, H_α-signal of high enough amplitude was also registered from all chords used for observation. It indicates the presence of large amounts of hydrogen isotopes in RF discharge due to desorption from the wall [2]. Both, R_{pl} and $\bar{n}_e$ were roughly proportional to P_{RF}. The latter dependence is typical for weakly ionized plasmas. B_T scanning showed that RF plasmas with the central line averaged density up to $\bar{n}_{e0} \bullet 7\text{x}10^{17}$ m^{-3} were reliably produced in the mentioned range (Fig.2). An increase in antenna coupling of up to 23% (depending on P_{RF} and gas pressure) was obtained by decreasing B_T, in close agreement with the TEXTOR results [5]. However, no concomitant increase in line averaged density (like for small B_T decrease in TEXTOR) was also observed. The line averaged density profile was centrally flat at B_T =3.09 T and strongly shifted toward low magnetic field side (LFS) at lower B_T (Fig.3). To understand the results, a numerical analysis of dispersion curves for the TORE SUPRA RF plasma case has been undertaken using a 1-D dispersion code [8]. The code solves the dispersion relation $D(\boldsymbol{k}, \boldsymbol{r})=0$ for Maxwellian plasmas, fully accounting for finite temperature effects. Taking into account very low temperature (T_e <10 eV) and ionization degree (~10%) in RF plasmas [2], the following ion species and its concentrations have been used in the calculations: (70-85)%He^+ + (5-10)%He^{++} + (5-10)%H^+ + (5-10)%D^+. The obtained dispersion diagrams show a presence of an ion-ion hybrid resonance (IIHR) due to conversion of FW into SW near the plasma core for high magnetic field (B_T = 3.09 T - 3.85 T, n_{e0} = (3-6)x10^{17} m^{-3}, k_z ~ $1/R_0$). On decreasing the B_T-field, this resonance shifts to the high magnetic field side (HFS) and at B_T = 2.43 T, the IIHR disappears and the FW is evanescent between HFS and r/a < -0.7 (RF plasma radius was assumed to be $a \bullet$ 0.83 m). This could reasonably explain the shapes of the RF plasma density profiles in the tested range of B_T.

At even lower magnetic field (B_T =1.7 T), FW and ion Bernstein waves (IBW) are propagative over the whole plasma cross-section. However, RF plasma production in TORE SUPRA did not succeed at B_T < 2.43 T, contrasting with the TEXTOR database and the code predictions. A possible explanation of this phenomenon is the observed monotonic increase of the reflected power (>30%) with decreasing B_T, indicating a matching problem in the lower B_T range.

3. *Influence of B_V-field ($B_V << B_T$) on antenna-plasma properties*

In the second scenario ($B_V \bullet 0$), helium RF discharges were performed in a magnetic configuration with the magnetic field lines tilted by 1-2 degrees with respect to the horizontal. The applied vertical field was $|B_V|$ = (6-12)x10^{-2} T as compared to B_T =3.09 T or B_T =3.85 T. Figure 4 shows that RF voltage at the antenna V_{ant} slightly decreased and loading resistance R_{ant} increased in the presence of B_V for the given transmitted RF power P_{tr}. This behavior of the antenna parameters follows from the relation between antenna voltage and radiation resistance:

$$P_{ant} \bullet V^2_{ant} (R_{pl}+R_v) / 2X^2_{ant} \bullet P_{tr}, \qquad (2)$$

where $X_{ant} \bullet \omega L_{ant} >> (R_{pl}+R_v)$. The first experiments demonstrated a slight improvement in antenna coupling (up to 15%) at larger $|B_v|$ and a dependence on the sign of B_v (Fig.5). Here $R_n=R_{pl}$ at $B_v \bullet 0$ and $R_0=R_{pl}$ at $B_v=0$, respectively. The observed asymmetry in the relative change of R_{pl} versus the sign of B_v may be reasonably explained by asymmetry in the FS geometry: the FS rods are tilted at fixed angle ~ +7°.

ICRF plasma production in pure toroidal magnetic field is usually accompanied by the generation of intensive flux of energetic CX neutrals (which may play an essential role in the wall conditioning process) [2,3,5]. The fast hydrogen and deuterium atoms, registered by NPA so far, result from ion cyclotron acceleration ($\omega=2\omega_{CD}=\omega_{CH}$). The power absorption in helium RF plasmas with multi-ion species was estimated using 1-D full wave kinetic code "VICE" [10,11] and the relation to the location of the ion cyclotron layer position was confirmed experimentally [5].

The preliminary analysis of the fast CX hydrogen and deuterium atoms escaping RF plasma showed a tendency to get higher perpendicular equivalent temperature of the fast ions and the presence of energetic CX neutrals in toroidal direction for the case with $B_v \neq 0$ (Fig.6). In this case, the intensity of the toroidal flux of neutrals was comparable with that one in perpendicular direction. In ICRF discharges in pure toroidal magnetic field ($B_v=0$), fast neutrals in the toroidal direction were not registered. One should note that superimposing B_v over B_T may improve not only antenna coupling, but plasma confinement properties as well. Particle and energy losses along the resulting magnetic field lines will be dominant in this magnetic configuration [6]. Better antenna coupling and/or changes in the magnetic confinement configuration resulting from the presence of B_v-component may modify the fast particle trajectories. The distribution function of fast ions was observed to be more isotropic in this configuration. This might improve ICRF-wall conditioning efficiency compared with the results in pure toroidal magnetic field [4].

4. *Conclusions*

Two scenarios expected to lead to antenna coupling improvement have been successfully tested during RF plasma production experiments on TORE SUPRA using a standard ICRH antenna. At fixed transmitted power, antenna-plasma coupling efficiency was improved:

- up to 23% by operation at toroidal magnetic field values lower than the standard one (fixed frequency of the RF generator, *f*=47.9 MHz);
- up to 15% by superimposing vertical magnetic field B_V on toroidal one B_T ($B_V << B_T$).

The distribution function of fast ions resulting from ion cyclotron acceleration in ICRF plasmas was more isotropic in the presence of B_V ($B_V << B_T$).

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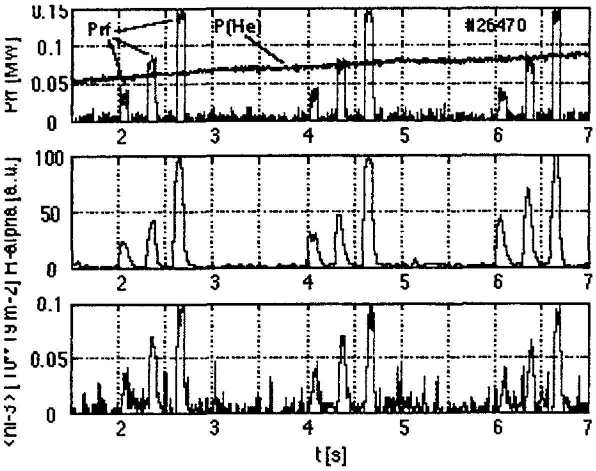

Fig.1. ICRF plasma production in helium: Q5-antenna in 0-phasing, P_{RF}=40-150 kW, $\tau_{RF}\approx$40-50 ms, f=47.9 MHz, B_T=3.09 T.

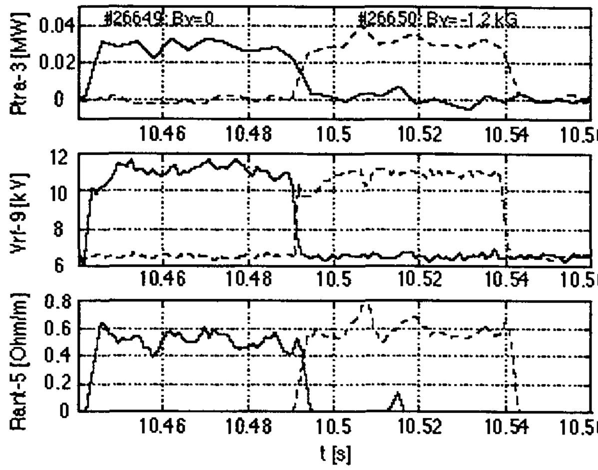

Fig.4. Influence of the B_V-field (B_V=-1.2 kG) on the antenna RF voltage and plasma loading resistance during RF plasma production at B_T=3.85 T: (Q5 antenna left strap, vacuum losses in the strap R_v=0.15 Ohm/m are included).

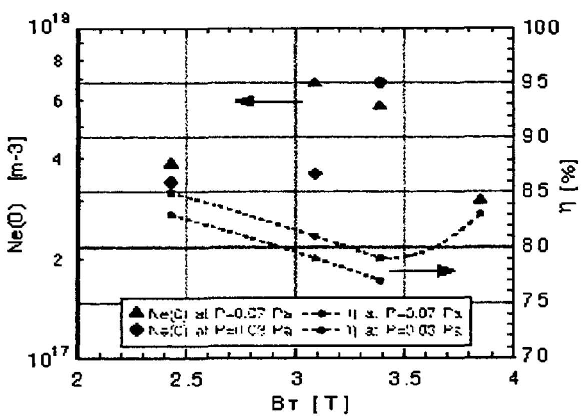

Fig.2. Central line-averaged RF plasma density n_{e0} and antenna-plasma coupling efficiency η versus toroidal magnetic field B_T: ($P_{RF}\approx$150 kW, other

parameters are mentioned in Fig.1).

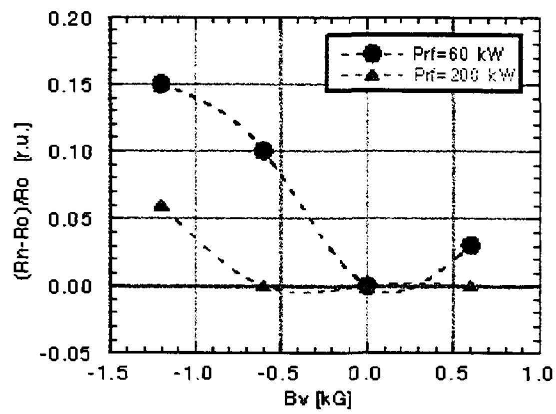

Fig.5. Relative changes in the Q5 antenna-plasma loading resistance in helium RF discharge at different sign and amplitude of the vertical magnetic

field B_V: (B_{T1}=3.09 T and B_{T2}=3.85 T).

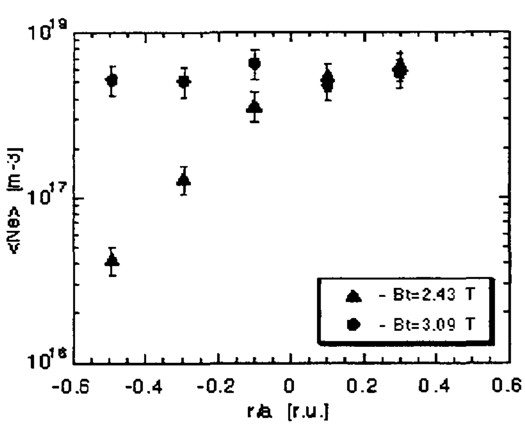

Fig.3. Modification of the line-averaged RF plasma density profile by variation of B_T: ($P_{RF}\approx$150 kW, other parameters are mentioned in Fig.1).

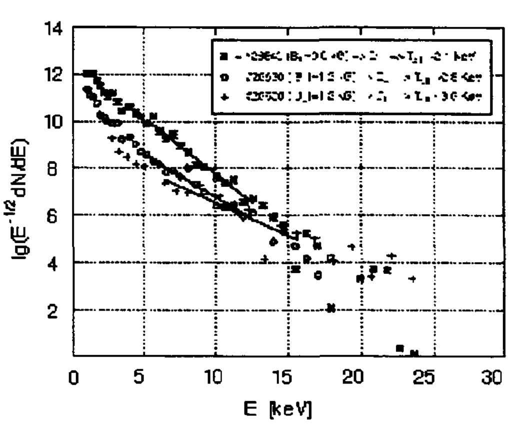

Fig.6. Energy distribution of the fast CX deuterium atoms escaping from ICRF plasma as a function of B_V superimposed on B_T (B_V =-1.2 kG, B_T =3.85 T).