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INTRODUCTION

The JET tokamak has been turned into a fully metallic machine including a beryllium first wall and a tungsten divertor. Tungsten has low sputtering yield but very high radiation capability and therefore limiting the tungsten content is a crucial issue in order to maintain high temperatures and good fusion yield. Central electron heating has been shown to be efficient to reduce impurity radiation of the plasma core [1]. Ion cyclotron resonance heating (ICRH) has the disadvantage to enhance the tungsten source because RF sheath rectification occurs in the near-field of the antenna leading to DC potential exceeding 100V and subsequent sputtering [2]. On JET, experiments performed in L-mode [3-4] and H-Mode [4-5] with 3–4MW of ICRH power have shown a significant reduction of the core (r/a < 0.2) tungsten concentration when compared to NBI-only heated pulses. We report here experiments performed in H-mode with ICRH power up to 6MW. Optimization of the heating scenario (position of the IC resonance, H minority concentration) is also presented.

1. EXPERIMENTAL SCENARIO AND IMPROVEMENT OF THE ICRH POWER HANDLING CAPABILITY

The reported experiments were carried out in low triangularity with a magnetic field of 2.7T, a plasma current of 2.5MA and a NBI power in the 13–19MW range in order to be well above the L-H threshold transition. Sweeping of the strike points (DR ~ 12cm) was used to control the temperature of the divertor tiles. Central density was typically $7 \times 10^{19} m^{-3}$. The hydrogen minority ICRH scenario in dipole strap phasing (f = 42.5MHz) was used with a minority concentration X[H] of about 6% (unless specified) and the IC resonance layer slightly off-axis (DR~8cm on the high field side) with respect of the magnetic axis (unless specified).

The power handling capability of the 4-antenna ICRH system has been significantly improved by using D_2 gas injection from top or mid-plane valves instead of divertor valves. With a gas rate of 1×10^{22}el./s, the coupling resistance is enhanced by 50%, using a mid-plane valve close to the antenna, and the launched RF power output is increased accordingly for a given RF voltage [6]. Plasmas using gas injection from these locations have slightly lower impurity contamination when compared with standard injection from the divertor. Moreover the pedestal pressure is not affected and the H-factor of these discharges is even often slightly higher. At low gas rate (0.55×10^{22}el./s), 4.5MWwas coupled during 3s in H-mode plasmas with type-I ELMs, whereas the power could be pushed to 6MW with higher gas rate (1.2×10^{22}el./s).

2. EFFECT OF ICRH POWER ON THE CORE TUNGSTEN RADIATION

When a fraction of the NBI power is replaced by ICRH power (P_{ICRH}), the central electron temperature increases linearly with P_{ICRH} when exceeding 3MW (DT_e = 1.5keV with 6MW) and it results in an increased peaking of the electron temperature inside r/a < 0.3. At the same time a flattening of the density profile occurs with a peaking factor $n_e(0)/\langle n_e \rangle$ decreasing from 1.55 to 1.45 with P_{ICRH} = 5MW. For the NBI-only pulse, the central line-integrated soft X-ray radiation indicates tungsten accumulation and strong flushing of the impurity by the sawtooth crash whereas, when applying 6MW of ICRH, the radiation is more steady although the time-averaged value is slightly higher (Figure 1). After de-convolution of the light integrated along the soft X-ray channels, the strong decrease of core radiation (r/a < 0.2), averaged on 1 second, is confirmed with increasing ICRH power (decreased 3 time with 6MW) while the radiation at mid-radius and total bulk radiation (from bolometry) start to decrease from P_{ICRH} ~ 4MW (Figure 2). The nickel impurity content at mid-radius, measured by VUV spectrometer, also starts decreasing from this power level. This reduction of core radiation is beneficial for the global energy confinement and the thermal confinement time (and $H_{98,y}$ factor) increases by ~ 6 % with 6MW of ICRH power.

When increasing the ICRH power, both the enhanced peaking of T_e and the flattening of n_e contribute to make the convection evolving from inward to outward, consistently with the reduction of peaking of the radiated power $P_{rad}(r/a = 0)/P_{rad}(r/a = 0.3)$ (Figure 3). This suggests that neo-classical transport is the main cause for reduction of tungsten concentration in the core.

3. OPTIMIZATION OF THE ICRH SCENARIO

The minority concentration X[H] was varied between 2 and 22% in a series of pulses with constant power (P_{NBI} = 15MW, P_{ICRH} = 4.8MW) [8]. When reducing X[H], the electron temperature profile gets more peaked and the core radiation peaking estimated from $P_{rad}(r/a = 0)./ P_{rad}(r/a = 0.45)$ decreases strongly. However the central radiation, from SXR, does not vary by more than ~ 15% between X[H] = 2% and X[H] = 15% after 3s of ICRH. In the 2% case a 3.5s sawtooth-free period is obtained and very slow accumulation of tungsten in the core is observed. The H-factor increases from ~ 0.69 to ~ 0.75 and neutron yield by a factor ~ 2 when X[H] is reduced from 20% to 2%. This is related to the reduction of the RF heating efficiency at high X[H] [8].

When the position of the hydrogen IC resonance with respect of the magnetic is moved from –20cm (HFS) to +10cm (LFS) by varying the magnetic field, the central electron temperature increases by ~ 15% and the peak core radiation (r/a < 0.2) decreases by more than 50% (figure 4). At the same time the amplitude of the (1,1) mode, averaged on ~ 3 sawtooth periods (close circles), decreases very significantly. Frequency spectrum indicates the presence of fishbones when the resonance is on the low field side (B_t > 2.7T) which contribute to the removal of the tungsten from the core.

CONCLUSIONS

By extending the available ICRH power, mitigation of the core tungsten contamination of H-mode plasma core has been achieved on JET with the ITER-like wall. Low hydrogen minority concentration (X|H] < 5%) and central heating or off-axis on the low field side (inside q = 1 surface) are both beneficial for reducing the plasma core (r/a < 0.2) radiation. This is also beneficial for the global energy confinement and the total radiated power starts decreasing when the ICRH power exceeds 4MW. A 3.5s-long sawtooth-free discharge indicates very slow W accumulation which could be an issue for long pulse operation.

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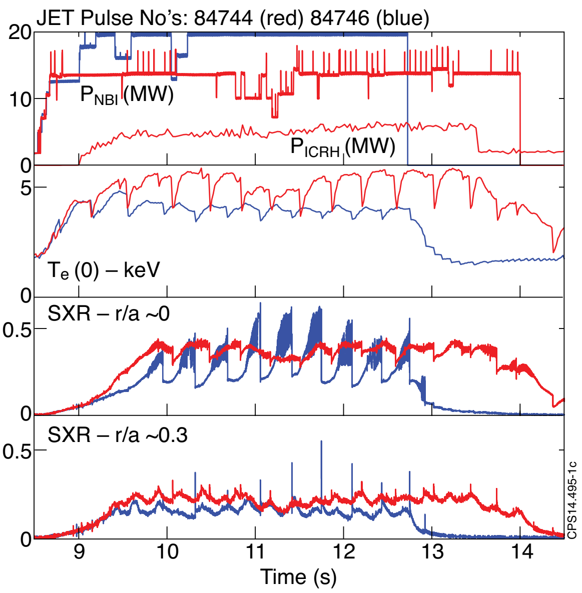

Figure 1: JET Pulse Nos: 84744 (with ICRH, red lines) and 84746 (no ICRH, blue lines). Ptot = 20MW, Gas rate = 1.2 × 10^{22}el./s.

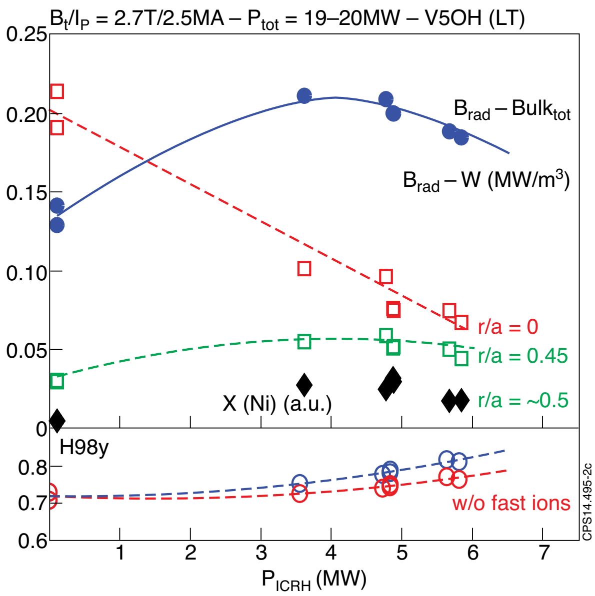

Figure 2: Fraction of radiated power in the plasma bulk, radiated power density and Ni concentrations. Gas rate = 0.9–1.2 × 10^{22}el./s.

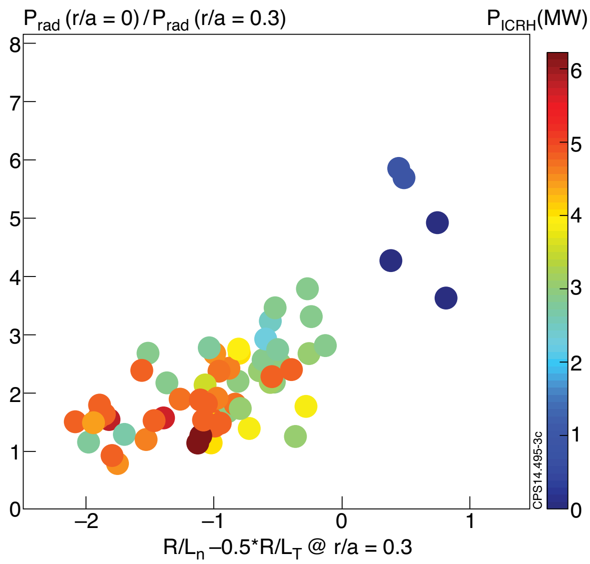

Figure 3. Peaking of the radiated power density vs. normalized gradient lengths.

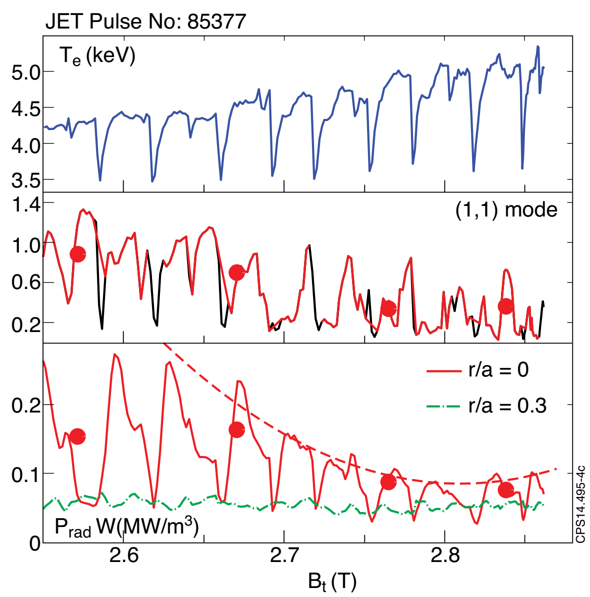

Figure 4. T_e, (1,1) mode amplitude, radiated power vs. magnetic field. (central IC resonance is for Bt = 2.78T)