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Real-time control applications of JET heterodyne radiometer electron temperature profiles using ICRH

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Abstract: The Real Time ECE data processing has been recently implemented at JET, by using a cross calibration between the Martin-Puplett interferometer (also known as Michelson) measurements and the Heterodyne faster data. The applicability of RT control with ICRH has been discussed in recent works. In particular, in case of a hollow electron temperature profile, central ICRF heating could be applied to restore temperature peaking. In this work a study about the possibility of controlling the electron temperature profile by using ICRH as an actuator, with inputs from ECE measurements, is described. The ICRH is here used for the optimization of the plasma ramp-down, in order to correct the end of the discharge and avoid the plasma disruption, though a similar approach could also be proposed to improve the plasma performances during the flat top. Preliminary results have been obtained on the physical and logical feasibility of using ICRH in a real-time control loop. A database of good pulses in identifiable conditions has been compiled and validated by covering the main experiments both in the baseline and hybrid scenarios. Such scenarios have been simulated, for a selected numbers of discharges, using the full-wave propagation solver TORIC-SSQLFP, in order to establish the ICRH power deposition profiles to be used to locally restore a peaked electron temperature profile.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging; Nuclear instruments and methods for hot plasma diagnostics

[1]See the author list of J. Mailloux et al., *Overview of JET results for optimising ITER operation*, Nucl. Fusion **62** (2022) 042026.

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2023 JINST 18 C05014

Contents

2023 JINST 18 C05014

1 Introduction

The Electron Cyclotron Emission (ECE) [1, 2] data processing with Real-Time (RT) capabilities has been recently implemented at JET (the Joint European Torus), the world's largest and most advanced tokamak, by using a cross calibration between the Martin-Puplett interferometer (also known as Michelson) measurements and the Heterodyne Radiometer faster data [3–7]. The capability of Ion Cyclotron Resonant Heating (ICRF) systems to reliably couple large amounts of power to ELMy H-mode plasmas has been demonstrated in different tokamak experiments [8]. The applicability of ICRH to RT control has been discussed in recent works [9–14] in case of a hollow electron temperature T_e profile: central ICRF heating has been recognized as a possible approach to restore temperature peaking. In particular, ICRH is proposed to correct the termination to reduce the risk of developing tearing modes leading to disruption. A similar approach could also be proposed to improve the plasma performances during the flat top (i.e. not only in the termination phase).

In particular, tearing modes possibly leading to a disruption are sometimes observed in the termination phase of pulses with hollow T_e-profiles due to core accumulation of high-Z impurities [8]. It should be remembered that the hollowing effects occur either through power deposited off-axis (deliberately or not) or by central impurity accumulation, which confirms the use of central ICRH. An attempt to correct the termination avoiding the development of these modes is possible, e.g. providing central additional heating to counteract the inward transport of high-Z impurities and re-establishing temperature profiles peaked [14]. As a result, central ICRF heating can be considered as a viable solution to restore temperature peaking, and it is here proposed for the optimization of the plasma ramp-down, in order to correct the termination so as to reduce the disruption probability.

In this paper the possibility of controlling the electron temperature profile by using ICRH as actuator, with inputs coming from ECE measurements, will be discussed. This can be achieved in the framework of a wider project whose first two steps are:

- First step: develop an automatic, robust, causal scheme for processing passive radiometer signals to provide real-time electron temperature profiles.
- Second step: evaluate the physical and logical feasibility of using ICRH in a real-time control loop (in order to define timing and pacing of using RF actuators in real-time control loops).

In section 2, a description of the JET heterodyne radiometer is given to be used for the measurement of the electron temperature profiles, while in section 3 the use of ICRH in a RT control loop is explained. Section 4 show the results obtained by simulating the application of ICRH power to selected plasma JET discharges.

2 JET heterodyne radiometer

A robust, causal scheme for processing ECE radiometer signals (see figure 1) to provide real-time electron temperature profiles has been developed since 2017 [5].

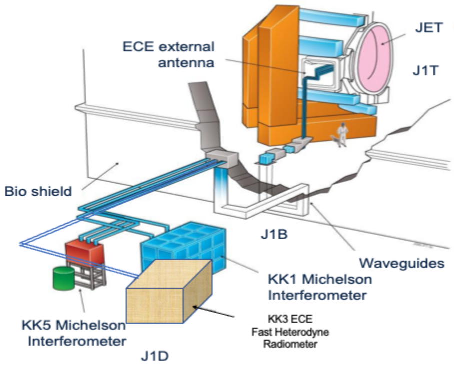


Figure 1. Overview of JET ECE diagnostics on Octant 7 main horizontal port. The Fourier Transform Spectrometers and the Heterodyne Radiometer are indicated. The picture is an indicative display of the ECE diagnostics to be intended only as a pictorial view.

Multiple electron temperature (T_e) diagnostics are routinely employed in the RT control systems of high-temperature plasma experiments. In particular, two typical approaches include ECE radiometers and Thomson scattering (TS) spectrometers. ECE radiometers can provide measurements with high temporal resolution (>100 kHz), particularly useful for analysis of MHD modes inside the plasma. TS diagnostics, instead, are often used to robustly monitor temperature and density profiles with lower temporal resolution (<100 Hz) but independently from the plasma equilibrium reconstruction and without the risk of reaching cut-off conditions in high density or low magnetic field pulses. At JET the temperature measurements through a heterodyne radiometer [15, 16] using ECE from the plasma has been successfully used for the real-time control of internal transport barriers [17]. Recently, the first RT applications of the JET extraordinary mode (X-mode) ECE interferometer has been presented [7], which can provide T_e profiles with moderate time resolution (60 Hz) and present an absolute calibration over a wide range of frequencies (70–500 GHz), independently from other diagnostics.

It should be noted that RT applications from heterodyne measurements vary from detecting impurity accumulation or influx, sawtooth and other MHD phenomena management and plasma heating optimization. For our purpose, the interferometer (called KK1) [5] is used to give reference data (i.e. calibrated data) to the heterodyne radiometer (called KK3), which is intended to be used in the RT loop thanks to its better resolution performance. In fact, KK1 has a lower resolution (about 16 ms), but it can offer absolute calibrated data. On the other hand, KK3's resolution is up to 2 ms, but it needs to be calibrated against the interferometer at each pulse. By combining the two diagnostics, it is possible to obtain an optimized closed-loop control system. The approach used to

2023 JINST 18 C05014

obtain RT electron temperature profiles is then providing an off-line cross calibration scheme of the heterodyne versus the interferometer diagnostics in order to avoid the need of a calibration pulse, like the previous heterodyne RT scheme.

3 Feasibility of using ICRH in a RT control loop

A database of good pulses in identifiable conditions to be used as benchmark has been compiled and validated by covering the main experiments both in the baseline and hybrid scenarios, with the objective of realizing a closed-loop feedback scheme like in figure 2. The real-time measurements from the available real-time diagnostics are, after cross-calibration, used to be compared with the reference values. Mismatches between measured and expected values are used as an input to the control algorithm, which in turn generate the real-time model parameters to be used by the ICRH actuator to restore the expected temperature profile.

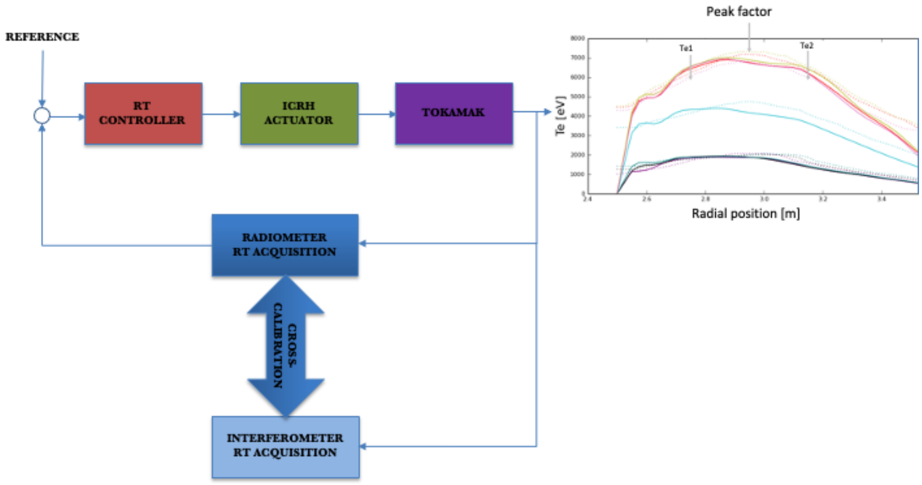


Figure 2. RT closed-loop feedback scheme with ICRH. The diagram illustrates the overall simplified phases of a possible tokamak real-time control scheme. After cross-calibration, the real-time measurements from the available real-time diagnostics are used to be compared with the reference values, thus producing a control signal for the ICRH actuator to restore the expected temperature profile. The graph on the right of the diagram is for illustrative purposes only and serves to indicate the expected peak profile.

The available ICRH resonant frequencies at JET are in the range of 23–57 MHz, and an ion minority heating scheme at the fundamental or a first harmonic heating related to the majority ion species has been considered for our goal. The minority heating has the advantage that a large fraction of power absorbed by the minority could be transferred, at the collisional time scale, directly to the bulk electrons. In particular, the transfer of power occurs in the central zone of the plasma where the fundamental resonance of the minority is located.

Before looking for the RT controller, a feasibility study on using the ICRH as an actuator to restore hollowed temperature profiles is required in order to optimize its application to the considered discharge. It is then required to evaluate different scenarios where the application of ICRH could be beneficial. Such scenarios have then been simulated, for a selected numbers of discharges, using the full-wave propagation solver TORIC-SSQLFP [19, 20], in order to establish the ICRH power deposition profiles [21], and as a further step whether the power deposited locally on ions and electrons could be able to restore the temperature profile.

TORIC is a numerical tool that solves the Maxwell-Vlasov integro-differential equation in 2D flux-surface geometry for Ion Cyclotron Resonance plasma heating. The inputs are the plasma kinetic profiles and the antenna geometry and frequency, while the output is the ICRH power deposition profiles versus the normalized plasma radius.

The simulation results give a complete and realistic description of the physics inside the plasma and account for antenna-plasma coupling.

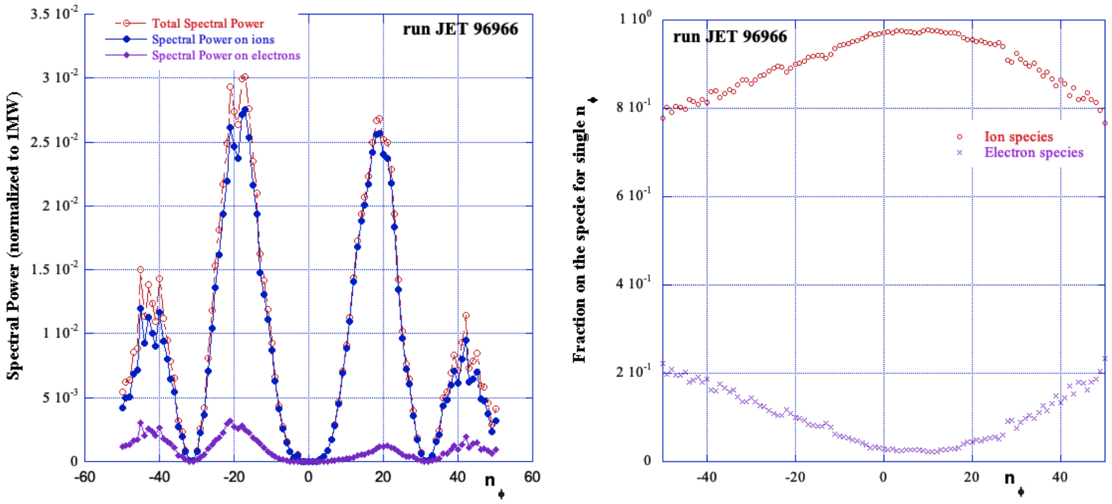
4 Simulation results

In order to simulate the capability of the ICRH in restoring the electron temperature profiles that precedes the plasma disruption the plasma parameters and profiles of the JET discharge number 96996 (studied in details in [9]) have been chosen, at the time ($t = 56.3$ s) when there is the inversion of the peaking in the electron temperature profile (see figure 1 and figure 2 in [9]). The frequency choice is $f = 42$ MHz that resonates at the first harmonic of the deuterium (majority species) near the plasma center ($\omega = 2\Omega_{CD}$, where Ω_{CD} is the deuterium cyclotron resonance frequency). In other words, TORIC-SSFPQL is run to calculate the ICRH power deposition profiles at the first harmonic when the ion plasma species is pure deuterium (without minority). The results can be summarized in figures 3 and 4 that report, respectively:

- The power spectrum radiated by the JET ICRH antenna and the spectral absorption on the various species (electron and deuterium ions);
- The power deposition profiles obtained for a single representative toroidal wavenumber n_ϕ (the peak of the spectrum) for the species under consideration (electrons and deuterium ions).

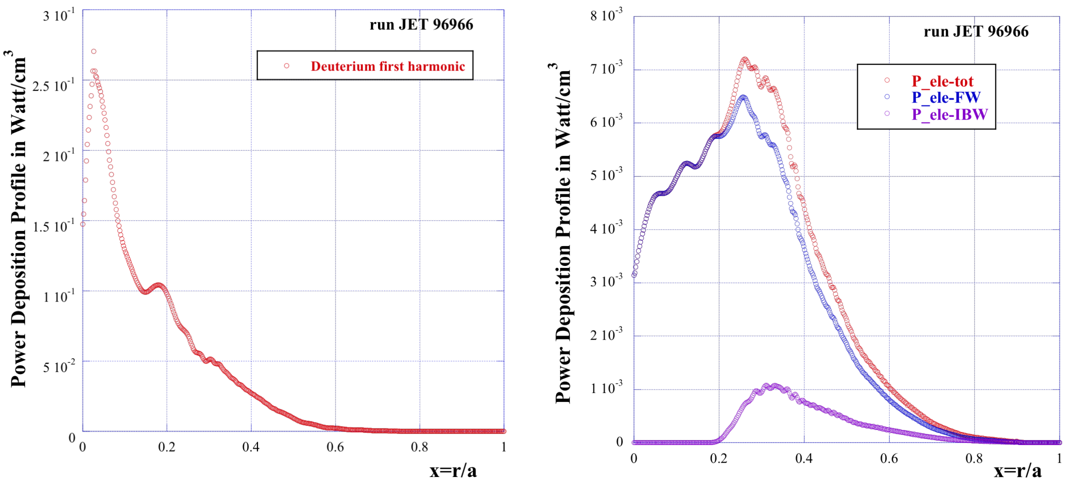
Figures 3a and 3b show the power spectrum (normalized to 1 MW) radiated by the JET A2 antenna. In particular figure 3a (on the left) shows the total power spectrum radiated by the antenna (red circles) and the spectral power absorbed by electrons and ions (magenta square and blue bullets, respectively). This plot shows that there is a peak in the spectrum for $n_\phi \approx \pm 20$ where most of the antenna power is delivered to the plasma. From the plot it is possible to see that the RF power is mainly absorbed by the ion species at the first harmonic of deuterium, while a small fraction is going on the electron species. This behavior is clearer in figure 3b (on the right) where the fraction of power radiated by the ICRH antenna from $-45 < n_\phi < +45$ and absorbed by electron and ion species is plotted vs n_ϕ. It can be observed that the power absorbed by the electrons tends to vanish for $n_\phi \approx 0$ due to the negligible Landau Damping effect when the parallel wavenumber is too low. In this zone of the spectrum the power (although small, see figure 3a) will be mainly absorbed by the deuterium ions. In general the power absorption on the ions is greater than 80% of all the power absorbed by the plasma, while less than 20% is absorbed by the electrons. However, it is expected that the heated deuterium would give the gained power to the bulk electron by collisions, so as to restore the electron temperature profile.

Figure 4 shows how the power is spatially distributed as a function of the normalized minor radius. In particular, figure 4a (on the left) shows the power deposition profile on the ion species (deuterium first harmonic), while the figure 4b (on the right) shows the power deposition profiles of the electron species for different deposition channels: Fast Wave Absorption (FWA) (blue circles),



(a) (b)

Figure 3. Power spectrum radiated by the JET antenna. Left: total power spectrum radiated by the antenna (red circles) and the spectral power absorbed by electrons and ions (magenta square and blue bullets, respectively). Right: fraction of power radiated by the ICRH antenna from $-45 < n_\phi < +45$ and absorbed by electron and ion species.



(a) (b)

Figure 4. Power Deposition Profiles. Left: power deposition profile on the ion species (deuterium first harmonic). Right: power deposition profiles of the electron species for different deposition channels: Fast Wave Absorption (FWA) (blue circles), Ion Bernstein Waves (IBW) (magenta circles) and Total Electron Absorption (TEA) (red circles). It should be observed that $x = 0$ corresponds to the plasma center, $x = 1$ to the plasma edge.

Ion Bernstein Waves (IBW) (magenta circles) and Total Electron Absorption (TEA) (red circles). This deposition has been obtained for a single n_ϕ representative of the spectrum: $n_\phi = 20$ (peak of the power spectrum, see figure 3a).

2023 JINST 18 C05014

A more complete analysis that includes the presence, in the plasma mixture, of an unavoidable hydrogen minority is under consideration. The Hydrogen minority resonates at the fundamental harmonic ($\omega = \Omega_{cH}$) at the same location of the first harmonic of deuterium and could absorb a relevant fraction of ICRH power. Owing to the lightness of the hydrogen ions, they can be accelerated up to very high energy levels, much higher than the critical energy, and during the slowing down are able to transfer their energy to the electron species. To this end, and in order to quantify the level of power transferred from the hydrogen ions to the electrons, a quasi-linear analysis is underway. Moreover on the basis of the power deposition profiles (obtained in the aftermath of the quasi-linear evaluation) a transport analysis would allow the evolution of the temperature profiles.

5 Conclusive remarks

In order to restore the electron temperature profile and reduce the risk of tearing modes possibly leading to a disruption, ICRH power is envisaged to heat the plasma center at the moment of the inversion of electron temperature peaking. In this preliminary simulation ICRH power at $f = 42$ MHz that resonates at the first harmonic of deuterium has been applied to the JET plasma discharge 96996. TORIC confirms the expected power deposition profile: most of the power delivered by the antenna is absorbed by the deuterium, while a fraction ($\approx 20\%$) is directly absorbed by the electrons via Landau damping. It is expected that the heated deuterium would give the gained power to the bulk electron by collisions, so that the electron temperature could be restored. In order for a correct evaluation of the electron temperature increase in the heated plasma zone, the use of transport models is required together with the ICRH power deposition profile at the end of the collisional time process. Further studies are ongoing to quantitatively evaluate the power required for the profile correction in presence of minorities (e.g. hydrogen) through new JET experimental data and by applying a similar approach to next step machines.

Acknowledgments

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2023 JINST 18 C05014