Detection of neoclassical tearing modes in ITER using electron cyclotron emission with inline configuration

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The control of Neoclassical Tearing Modes (NTMs) through localized current drive is the primary task of the Upper Launchers (UL) of ITER's 170 GHz Electron Cyclotron (EC) Heating and CD (H&CD) system [1]. NTMs detection and localization with Electron Cyclotron Emission (ECE) diagnostics close to the plasma mid-plane could be overly demanding in ITER, since the control of the EC launchers steering and the mapping of ECE signals to ECCD location must be fast and accurate enough to deposit ECCD inside an NTM island when it is only a few cm wide. An ECE diagnostic sharing the line of sight with the ECCD system can track NTM position with respect to the location of ECCD location without the need to know the exact mirror orientation or to rely on magnetic equilibrium reconstruction [2]. An analysis of a possible inline ECE configuration in the UL is presented here. Since sharing exactly the same line between EC wave injection at MW power level and ECE detection at nW power level might be technically challenging, and it is anyway unfeasible if multiple beams are used for ECCD, we have also considered the additional requirements and limitations of quasi-inline configurations, with toroidal or small poloidal offsets between ECE and ECCD lines. All the evaluations are based on the plasma parameters of the baseline 15 MA H-mode scenario [3] at the current flat-top.

First harmonic O-mode (OM1) emission is characterized here for two virtual beams, one for the Upper Steering Mirror (USM) and one for the Lower Steering Mirror (LSM), each representative of the row of four beams foreseen on the corresponding mirror by the UL design [1]. In the last revision of the UL design USM and LSM are located at $(R,z) = (7.006, 4.436)$ m and $(R,z) = (7.062, 4.233)$ m respectively, with an almost constant toroidal injection/detection angle $\beta \simeq 20^\circ$ along the steering range. Since the design of the optics has not been finalized yet, the beam parameters are taken from [4]. ECE has been modelled with the ray-tracing code SPECE [5] over a range of the steering angle $-9^\circ \leq \gamma \leq 9^\circ$, slightly larger than what is allowed by the steering mechanism. The analysis has been performed over the frequency range 150 GHz $\leq f \leq$ 190 GHz, sufficient to shift the emission location from the plasma low field side edge to the innermost reachable minor radius at any orientation of the steering mirrors. As a reference, second harmonic X-Mode (XM2) ECE, preferred over OM1 for optimum spatial resolution, has been modelled for an equatorial line of sight for 220 GHz $\leq f \leq$ 280 GHz, assuming an antenna with radial view located on the plasma mid-plane at $(R,z) = (9.00, 0.64)$ m.

The UL is optimized for localized ECCD, being the focussed beams almost tangent to the flux surfaces in the region of the EC resonance. This allows inline ECE to achieve a radial resolution comparable or slightly better than equatorial ECE diagnostics. Fig. 1 shows the full width at 1/e of the emission profile $\Delta\rho$ achievable by inline-ECE when the ECCD beam is aimed at the $q = 3/2$ or at the $q = 2$ surfaces, respectively located at $\rho_{3/2} = 0.780$ and $\rho_2 = 0.875$, being ρ the square root of the normalized poloidal flux. For a given orientation of the mirrors, different radial locations correspond to different ECE frequencies. In the region of interest for NTM detection the profile width for inline-ECE is $0.01 \leq \Delta\rho \leq 0.03$, comparable with the results of the equatorial line. On the other hand the dependence of the radial location ρ of emission with frequency is totally different between equatorial and inline ECE (Fig. 2 left). For the equatorial line $|\mathrm{d}\rho/\mathrm{d}f| \simeq 0.017$ GHz^{-1} is determined by the magnetic field variation along the line of sight, while the peculiar geometry of the inline configuration strongly affects the value of $|\mathrm{d}\rho/\mathrm{d}f|$: at the lower end of the frequency range (i.e. larger radii) it is already smaller than for the equatorial case, and it reduces further with increasing frequency, dropping to zero when emission occurs at the tangency point between the line of sight and the flux surface, typically at 180 GHz $\leq f \leq$ 185 GHz. The region inside the tangent surface can only be observed by changing the steering angle γ of the mirror. In order to achieve a sampling $\Delta\rho \simeq 0.01$ a spacing among ECE channels $\Delta f_s \lesssim 1$ GHz is required, while the sensitivity of ρ on γ at $f = 170$ GHz spans the range 0.015 deg$^{-1} \leq |\mathrm{d}\rho/\mathrm{d}\gamma| \leq 0.03$ deg^{-1} between the $q = 3/2$ and $q = 2$ surfaces, with slightly larger values for the USM (Fig. 2 right).

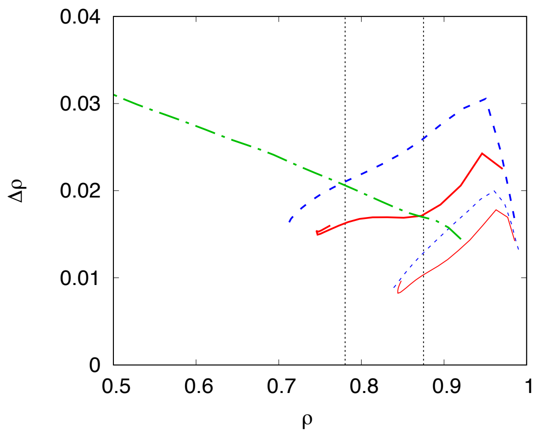

Figure 1: *Spatial resolution for equatorial (dash-dot) and inline ECE from LSM (solid) and USM (dashed), with steering mirrors oriented to center ECCD at the $q = 3/2$ (thick) and $q = 2$ surfaces (thin).*

These results can also be useful to evaluate the consequences of choosing a quasi-inline configuration, which for ITER's upper launchers can be obtained by considering ECE and ECCD respectively on: (i) corresponding lines in different ports; (ii) separate lines on the same steering mirror in the same port; (iii) different steering mirrors in the same port. In case (i) ECE and ECCD profiles overlap is limited mainly by the consistency between the mirrors' steering angles: Fig. 2 (right) shows that an accuracy of 0.3° is sufficient to limit the mismatch to $\delta\rho \leq 0.01$

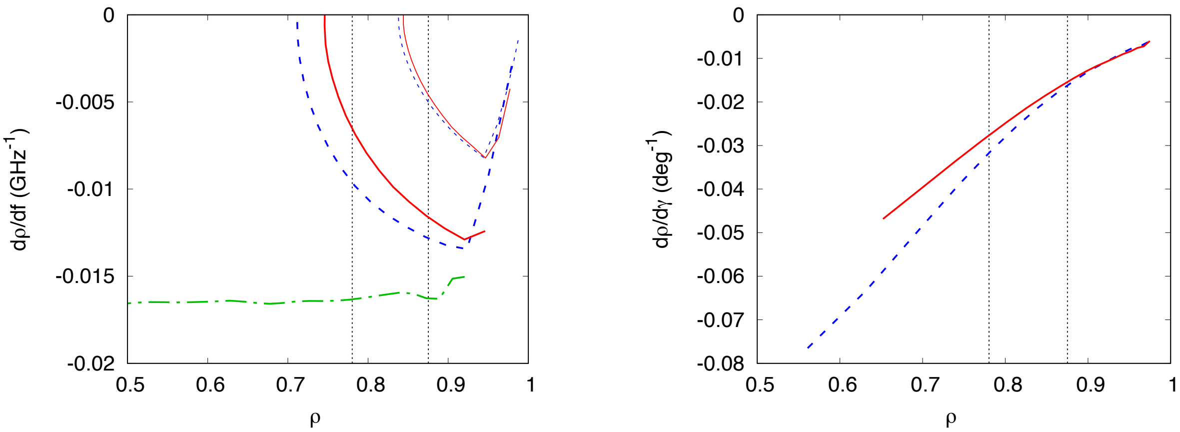

Figure 2: *Left: rate of change of the emission minor radius* ρ *with ECE frequency* f *for equatorial (dash-dot), and for LSM (solid) and USM (dashed) inline ECE, with steering mirrors oriented to have ECCD centered at the* $q = 3/2$ *surface (thick) and* $q = 2$ *(thin). Right: rate of change of the emission radius* ρ *with the steering angle* γ *for inline ECE at* $f = 170$ *GHz from LSM (solid) and USM (dashed).*

in the region of interest for NTM. In case (ii) the different trajectories of two beams sharing the same mirror result in a small offset $\delta\rho$ between ECE and ECCD, which can be compensated by adjusting the ECE frequency. Fig. 3 (left) reports the offset of each of the four beams on a mirror with respect to the corresponding virtual beam with the present UL design. The frequency offset $\Delta f = \delta\rho(\mathrm{d}\rho/\mathrm{d}f)^{-1}$ required to ECE to match ECCD location is estimated to be as high as $|\Delta f| \simeq 3$ GHz for the external beams of the USM when aiming at the $q = 3/2$ surface, and smaller in the other cases. This offset is expected to reduce when UL optics will be optimized for a better overlap among the beams sharing the same steering mirror. The ECE/ECCD mismatch arising in case (iii) can be compensated by adjusting the steering of one of the two mirrors (Fig. 3 right). Such an adjustment varies between $\rho_{3/2}$ and ρ_2 by $|\Delta\gamma_{3/2} - \Delta\gamma_2| \simeq 0.5°$ so that even a constant adjustment to an intermediate value $\Delta\gamma = -0.5°$ already allows to limit the residual offset to $\delta\rho_\gamma < 0.01$ at the two rational surfaces.

For a preliminary analysis on NTM detection capabilities, the approach used in [6] for an equatorial ECE diagnostic has been applied to inline ECE. The code SPECE, adapted to deal with helical electron temperature perturbations, has been used to compute the ECE signal expected at the UL in presence of NTMs at the $q = 3/2$ and $q = 2/1$ surfaces. When the beam is already aimed at the rational surface the detection algorithm of [7], developed for equatorial ECE, detects the island as soon as it grows large enough to induce a fluctuation in the ECE signal larger than the thermal noise. At the $q = 3/2$ surface thermal noise is estimated to be $\Delta T \simeq 20$ eV, and the island is detected when its width exceeds $\Delta\rho \simeq 0.015$.

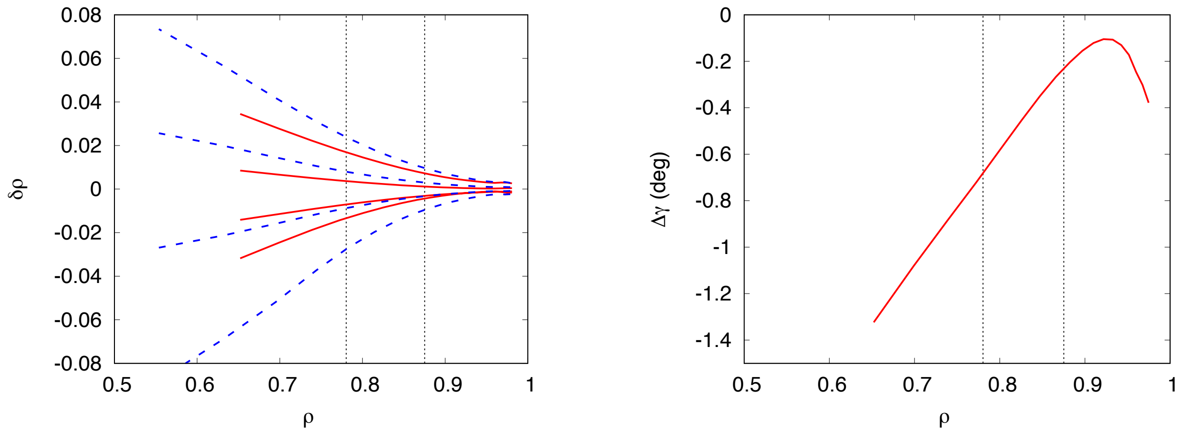

Figure 3: *Left: difference of ECE location* ρ *at* $f = 170$ *GHz between the USM beams (solid) or the LSM beams (dashed) and their respective virtual beam. Right: difference* $\Delta\gamma = \gamma_{USM} - \gamma_{LSM}$ *between the steering angles of USM and LSM required to have the virtual beams ECE at* $f = 170$ *GHz located at the same radius* ρ.

Conclusions

An inline-ECE diagnostic in ITER's EC UL has been characterized in terms of expected spatial resolution, which is comparable to that of an equatorial ECE diagnostic, frequency range and channels spacing, and mirrors steering accuracy required for NTM detection and localization at the $q = 3/2$ and $q = 2$ surfaces. The limitations due to the impossibility of sharing exactly the same line between ECE and the EC heating system have been analyzed, and they do not seem to degrade the inline ECE performance significantly, bringing to inaccuracies estimated to be smaller than the intrinsic ECE spatial resolution. The capability of detecting an NTM island growing just above ECE spatial resolution has been shown, but further analysis is required to assess the possibility of tracking NTM islands when the UL is not already aiming at the correct location.

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