Physics basis of a Collective Thomson Scattering diagnostic for DEMO

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1. Introduction. Knowledge gained from burning-plasma operation with ITER should allow robust extrapolation of key operational parameters and plasma confinement properties to the case of DEMO. However, in case DEMO fusion performance does not meet these expectations, it may be relevant to assess confined bulk-ion plasma properties in DEMO for improved burn control. The harsh environment around the DEMO plasma, along with the need to maximize the first-wall area used for tritium breeding, place limitations on the number and type of diagnostics to be installed. The robustness and versatility [1] of a microwave-based Collective Thomson Scattering (CTS) diagnostic make it worthwhile to investigate the potential of a DEMO CTS diagnostic for thermal- and fast-ion measurements. Here we describe the first results of a feasibility study for a CTS diagnostic for DEMO, being performed under EUROfusion WPDC 2021–2025. This builds in part on the development of the – now finalized – design of the ITER CTS system, which will primarily focus on measurements of fusion-born α particles [2, 3]. For a DEMO CTS diagnostic, a wider range of plasma measurements are being considered, including bulk-ion temperature T_{i}, plasma toroidal rotation velocity v_{tor}, core fuel-ion ratio $n_{\mathrm{T}}/n_{\mathrm{D}}$, impurity content such as He ash, and fast α density to identify anomalous losses.

2. Utilizing the DEMO ECRH infrastructure. CTS relies on injecting a powerful probe beam into the plasma and collecting some of the resulting radiation scattered off microscopic ion-driven fluctuations [1]. To ease the integration and minimize the impact on the DEMO design, the original aim was to use one of the planned 170 GHz electron cyclotron (EC) resonance heating (ECRH) beams as the CTS probe beam, with the receiving quasi-optical system being a dedicated CTS setup making using of existing ECRH mirrors and transmission lines (TLs).

DEMO will feature two vertically staggered launchers for ECRH bulk heating, each supplied by a bundle of eight gyrotron TLs [4], see Fig. 1(a). As a first step, we investigated which sets of TLs from these two bundles could be used for an 170 GHz O-mode CTS diagnostic. For each of the $8 \times 8 = 64$ TL combinations, we performed raytracing using *Warmray* [5], based on the DEMO 2019 baseline plasma scenario [6] with central electron density $n_{\mathrm{e},0} \approx 1.2 \times 10^{20}$ m^{-3} and electron and ion temperatures $T_{\mathrm{e},0} \approx 41$ keV and $T_{\mathrm{i},0} \approx 32$ keV. TL combinations were ranked based on a figure-of-merit incorporating the resulting CTS overlap factor O_b (proportional to the CTS signal [3]), the EC radiation temperature seen by the CTS receiver (propor-

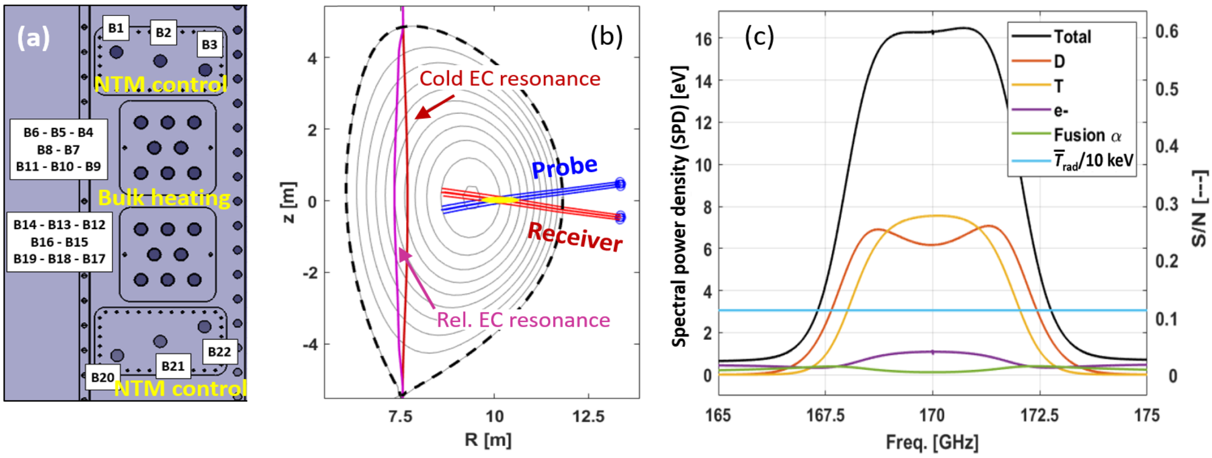

Figure 1: *(a) Location and labelling of the DEMO TLs as seen from the port plug closure plate towards the plasma. (b) Raytracing results for the optimal choice of 170 GHz ECRH TLs for the CTS probing radiation (blue; TL B6) and receiver beam (red; TL B19), shown in a poloidal cross section of DEMO. The scattering volume is shown in yellow. Dashed black line shows the last closed flux surface, and curves mark the cold and relativistic fundamental EC resonances as labelled. (b) Associated CTS spectral power density, mean radiation temperature* $\overline{T}_{\mathrm{rad}}$*, and the resulting signal-to-noise ratio assuming a 2 MW probe beam, integration time* $\Delta t = 100$ *ms, and* $\Delta f = 50$ *MHz frequency resolution. Top black curve shows the total CTS spectrum, remaining curves the contribution from individual particle species.*

tional to the diagnostic background noise), and the radial extent ΔR and location of the scattering volume relative to the magnetic axis. The scattering geometry and raytracing results for the best-case configuration are shown in a poloidal cross section of DEMO in Fig. 1(b), along with the associated spectral power density and diagnostic signal-to-noise ratio in Fig. 1(c).

Even in this optimal case, the radial resolution is large, $\Delta R \approx 1.0$ m, and the signal-to-noise ratio clearly insufficient to allow useful measurements. The latter issue is related to the high radiation temperature predicted for the CTS receiver view, due to a large toroidal viewing angle of $\beta \approx 18^\circ$ and associated Doppler broadening of the optically thick high-T_{e} EC resonance close to the scattering volume (Fig. 1b). Attempts to overcome this by toroidally displacing the probe or receiver beam to other diagnostic ports were unsuccessful. Consequently, a 170 GHz ECRH-based CTS diagnostic will not be viable at DEMO for any realistic mirror geometry.

Inspired by the ITER CTS design, which will employ a dedicated gyrotron operating at 60 GHz [2], well below the fundamental EC resonance, we considered whether a similar subharmonic system would be possible at DEMO. The aim was again to utilize the existing bulk-heating TLs, noting that the diamond window that forms the vacuum barrier in these TLs has optimal transmission at frequencies $f \approx 34n$ GHz, with $n = 1,2,3\ldots$. When factoring in EC resonance locations and the presence of an O-mode cutoff at the plasma edge, this restricts such a

Figure 2: *Raytracing results for an independent 60 GHz X-mode diagnostic, with* Δt *as for Fig. 1. (a) Predicted CTS spectrum with no toroidal plasma rotation. (b) Change in spectral power density in the downshifted spectral wing resulting from varying the assumed* v_{tor} *or* T_i *relative to the reference case in panel (a). (c) Downshifted part of the predicted spectrum for a fuel-ion scattering geometry with a 1:1 D/T core mixture. (d) Impact of different D/T core mixtures relative to the reference case in panel (c).*

setup to operation at 68 GHz in X-mode. Raytracing results for the most favourable case in this configuration indicate enhanced CTS signal-to-noise ratios by a factor of ~ 10 compared to the case of Fig. 1. Although a significant improvement, this is still insufficient and is furthermore accompanied by poor spatial resolution ($\Delta R \approx 2.0$ m) due to increased refraction.

3. An independent sub-harmonic setup. An entirely separate CTS system would allow independent diagnostic optimization and avoid potential latency in case all available ECRH power is needed for plasma control. Assuming full freedom regarding operating frequency and TL locations, we find that a system operating at 60 GHz (as on ITER) represents the best compromise between reduced background and increased sensitivity to refraction. Furthermore, the probe and receiver beams should ideally be further vertically spaced than the bulk-heating launchers in order to minimize ΔR. A promising option is a probe launcher located at the position of TL B1 in Fig. 1(a), albeit with a different injection geometry than for the planned NTM launcher, and a receiver view located either around B22 (with $\beta = +6^\circ$, giving a measurement angle of $\phi \approx 76^\circ$ to the magnetic field) or around B20 (with $\beta = +1^\circ$, giving $\phi \approx 88^\circ$). These configurations yield $\Delta R \approx 0.5$–0.6 m at $\rho_p \leq 0.1$, useful O_b factors of ≈ 5 m^{-1}, and sub-keV background.

For the scattering geometry with $\phi \approx 76^\circ$, Fig. 2(a) shows the resulting CTS spectrum and