Proof of principle of Electron Cyclotron Emission as a complementary diagnostic for the plasma position

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***Abstract*—Today's tokamaks use magnetic diagnostics to control the plasma position. In future fusion reactors (e.g. DEMO) the performance of magnetic diagnostics will be compromised by integrator drifts over long pulses and by radiation. Microwave diagnostics are good alternatives, as they are expected to be robust to the harsh radiation environment. Reflectometry has shown its potential to measure the density profile and hence to derive the separatrix position. This submission demonstrates how Electron Cyclotron Emission (ECE) can do the same via the electron temperature (T_e) profile.**

It will be shown that T_e at the separatrix can be calculated as a function of several well-diagnosed plasma parameters for a wide range of scenarios. From ECE measurements, the T_e profile can be derived, taking into account problematic effects such as shinethrough and corrupt measurement channels. Trivially, finding the position where the profile matches the separatrix temperature gives the separatrix position.

In a proof-of-principle experiment on ASDEX Upgrade, the radial plasma position was controlled using the separatrix position derived from ECE measurements. After initial success, problems with cutoff and latency led to a loss of control. An outline is given on how to remedy these issues and develop this proop-of-principle into a viable diagnostic for fusion reactors.

I. INTRODUCTION

If DEMO reaches its target of producing significant fusion power, then it will unavoidably produce high levels of neutron radiation. The radiation presents a challenge to many conventional diagnostics, in particular magnetic coils [1]–[3] which are typically the main diagnostic used for plasma position control. Coils can be shielded, but then their dynamic response becomes slow. Magnetic diagnostics are also subject to drift, so will need correcting over long pulses [4]. Developing accurate and reliable diagnostics is extremely important since position control actuators in DEMO are challenged even in simulations with ideal diagnostics [5] and loss of control would lead to a disruption, which must be avoided at all costs.

One option is to use radiation-hard Hall probes, which can be placed close to the plasma [6]. Another is reflectometry, which estimates the separatrix position based on the density profile [7]. This paper presents a new possibility; using Electron Cyclotron Emission (ECE) to measure the electron temperature (T_e) profile and estimate the separatrix position, analagous to reflectometry. Since ECE, like reflectometry, uses microwaves, it belongs to the small group of diagnostics which are expected to be feasible in the DEMO environment [1].

II. METHOD

To convert raw ECE measurements into a T_e profile, artefacts such as corrupt channels and shinethrough [8] must be detected and removed. Artefacts from cutoff are more complicated and not treated at this stage. Channels are marked as corrupt if the measurement is outside the range $-10 < T_e < 10^5\,\mathrm{eV}$ or if T_e is more-than-double/less-than-half or more than 100eV higher/lower than *both* neighbouring channels. Channels with radial position R<1.85m are ignored since they are far away from the separatrix. The shinethrough is detected as a local minimum with $T_e < 1\,\mathrm{keV}$, where the depth of the dip is at least 100eV. Measurements from a radial location outside this minimum are ignored. Finally, a spatial low pass filter is used to smooth the profile. A comparison of raw data and the sanitised profile can be seen in fig 1.

Analysing data from a large number of shots, it was found that the temperature at the separatrix $T_{e,sep}$ could be well described by a function of the stored energy (W_{MHD}), heating power ($P_{NBI} + P_{IC} + P_{EC} + P_{ohm} = P_{tot}$), edge density ($n_{e,edge}$) and radiating impurities (N_2):

$$
\begin{aligned}
T_{e,sep} = 26{+}4e^{-4}W_{MHD}{+}8e^{-8}(log_{10}(W_{MHD}^{\frac{1}{4}}))^{50}{+}100\frac{P_{NBI}}{P_{tot}} \\
-80\left(\frac{P_{NBI}}{P_{tot}}\right)^2 + 10\frac{P_{EC}}{P_{tot}} + 50\left(\frac{P_{EC}}{P_{tot}}\right)^2 - 200\frac{P_{IC}}{P_{tot}} \\
+300\left(\frac{P_{IC}}{P_{tot}}\right)^2 - 1e^{-5}P_{tot} - 4e^{-19}n_{e,edge} - 1e^{-2}N_2 \qquad (1)
\end{aligned}
$$

Coefficients were fitted after removing outliers caused by pellets, impurity events, cutoff or fast transients such as beam blips. Other parameters such as plasma current, toroidal magnetic field, and core radiation were found to have an insignificant effect. The effect of error fields from magnetic perturbation coils was observed but not yet included in the fit.

To demonstrate the validity of the method, fig. 2 compares the estimate of the separatrix position $R_{sep,ECE}$ with the magnetic separatrix $R_{sep,mag}$ for two very different scenarios. Both the absolute values and the dynamics match - even down to the resolution of individual ELMs. Since $R_{sep,ECE}$ has larger high-frequency components than $R_{sep,mag}$, a temporal low pass filter was added. Note that equation (1) performs much better than the other two methods for estimating $T_{e,sep}$.

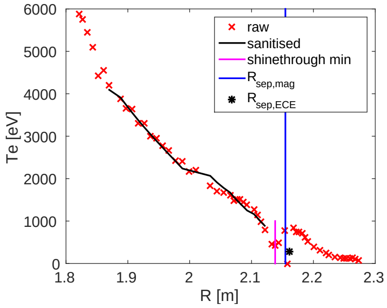

Fig. 1. A sanitised profile (-) is extracted from raw ECE data (x). Note the corrupt channel measuring 0eV and the unrealistically high Te measured around R=2.17m due to shinethrough.

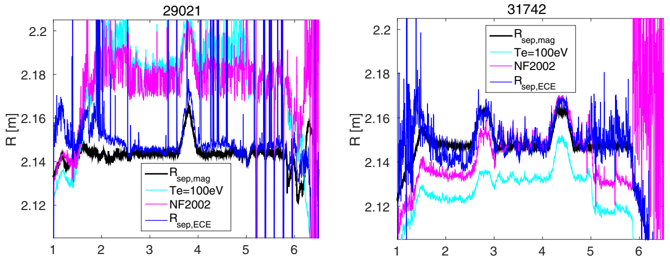

Fig. 2. Comparison of $R_{sep,ECE}$ with $R_{sep,mag}$. Also plotted are a naive estimate using $T_{e,sep} = 100\,\text{eV}$ and a simple model for SOL transport given in ref. [9]. Pellets are launched in #29021 from t=5s onwards, and the gas supply fluctuates with 4Hz in #31742.

III. EXPERIMENTAL RESULTS

Due to unscheduled changes at the end of the AUG campaign, the experiment was run in an upper single null (USN) configuration, and during the changeover to hydrogen gas. The routine was shown to be surprisingly robust to running in USN, however uncertainty in the amount of hydrogen to puff led to higher-than-expected density and the ECE was in cutoff from t=2.3s. As noted before, the routine does not detect cutoff, so from this point on $R_{sep,ECE}$ deviated from $R_{sep,mag}$ until the discharge disrupted, as shown in fig. 3. Until t=2.3s however, there is much that can be learned. The transition from the magnetic to the ECE controller at t=1.8s was successful, and a disturbance shortly after was rejected. Oscillations appear from t=2.1s that may be due to the high density, or to the latency of the ECE measurements.

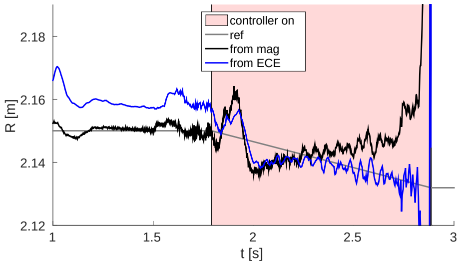

Fig. 3. ASDEX Upgrade shot using $R_{sep,mag}$ to control the radial plasma position until t=1.8s, and then switching to $R_{sep,ECE}$. The reference trajectory is shown in grey.

IV. FUTURE WORK

A trivial improvement will be to reduce the latency from 6ms to 2ms for real-time ECE measurements. This upgrade is already planned for sawtooth control experiments. It would be advantageous to use an observer with a forward model and a transport model to estimate the T_e profile. The forward model will be especially critical in DEMO [10]. Cutoff should be detected, perhaps using ray-tracing. Indirect dependencies on magnetic measurements (W_{MHD} and $n_{e,edge}$) should be assessed to see if non-magnetic replacements can be found.

So far, only R_{sep} has been considered, but it is equally possible to detect and control the vertical plasma position with ECE. If one assumes that the core is up-down symmetric, then an array of ECE lines of sight can localise the plasma centre. In AUG, this could be emulated using a soft X-ray camera.

Looking towards the future, the empirical function used here to calculate $T_{e,sep}$ should be reformulated from physics principles, such that it can be extrapolated to DEMO. The feasibility of this method in a pellet fuelled scenario should be assessed, since DEMO forsees pellet fuelling. Finally, a Bayesian framework should be developed to combine estimates of the plasma position from all DEMO diagnostics - conventional magnetic coils, Hall probes, reflectometry, ECE and any new concepts that may arise between now and then.

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