Coherent MHD Behaviour
in a Shallow Magnetic Well Configuration in Heliotron J

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This article presents the first experimental results from a novel configuration in Heliotron J, which features a shallow magnetic well in the core of the plasma. A broadband coherent fluctuation of approximately 10 kHz is observed in a low-β electron cyclotron heated (ECH) plasma at rotational transform $\iota/2\pi = 0.55$ in this configuration, while no mode appears in a deep magnetic well configuration. An electron cyclotron emission measurement shows the mode is excited in the core region where the magnetic well is shallow. This indicates Heliotron J is able to sustain viable plasmas with an edge-hill, although these can be destabilised even at low density and pressure.

In designing and optimising the magnetic field of stellarator/heliotron (S/H) devices, rotational transform and magnetic well depth are key properties that determine magnetohydrodynamic (MHD) stability. Generally, a magnetic well has a stabilising effect on MHD modes, whereas a magnetic hill has a destabilising effect [1], for instance appearing in the Mercier stability criterion of ideal interchange modes [2]. Interchange modes have been observed previously in Heliotron J [3], and previous experiments show that interchange modes can significantly reduce the achieved central β in S/H devices [4]. Such modes may be destabilised even in the Mercier-stable region in some operating regimes [5]. This indicates the importance of further research on how magnetic configuration parameters influence the stability of MHD modes. However, once a S/H fusion device is designed with specific magnetic configuration parameters, it is difficult to change them widely. In this paper, we present experimental results on MHD stability by changing the magnetic well depth in Heliotron J.

The Heliotron J device is a medium-sized helical-axis stellarator/heliotron, with a minor radius a = 0.1–0.2 m, and a major radius R = 1.2 m [6]. In its standard configuration, Heliotron J features a deep magnetic well across the entire plasma, that is expected to stabilise pressure-driven MHD modes for $\beta = 2\mu_0 p/B^2$ up to 3% [7]. However, the five configurable coils of the Heliotron J device allow one to reconfigure the device into a shallow-well configuration, that features a shallower well in the core region, and a magnetic hill in the
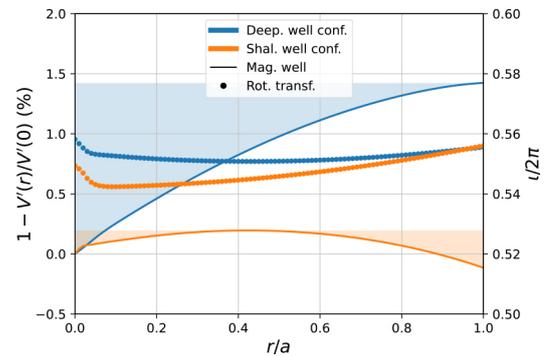

Fig. 1. Profiles of rotational transform and magnetic well for shallow and deep magnetic well configurations.

edge region. The profiles of magnetic well and rotational transform in the two configurations are shown in Fig. 1, as calculated by the VMEC equilibrium code [8, 9]. A normalised magnetic well depth w is used, defined as $w = 1 - V'(r)/V'(0)$, where V denotes the volume enclosed by a flux surface of minor radius r and the derivative is with respect to the toroidal flux. In the deep magnetic well (standard) configuration, a strong increase in w is seen going to larger minor radii, indicating a deep magnetic well. The shallow-well configuration, on the other hand, has a shallow well from the core to $r/a = 0.4$, and a magnetic hill from $r/a = 0.4$ to the plasma edge. Both configurations have low shear, with the shear being marginally larger in the shallow-well configuration. We now present results from two plasma shots (#88206 and #88212) in the shallow-well configuration. A plasma

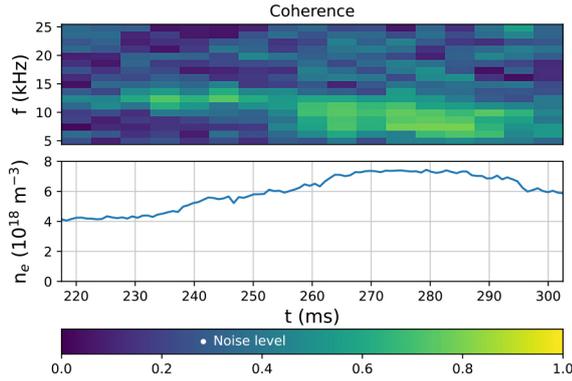*Corresponding author's e-mail: s.p.reinhoudt@student.tue.nl*

Fig. 2. Time evolution of the magnetic probe coherence spectrum and electron density and in shot 88206 (sh.-well).
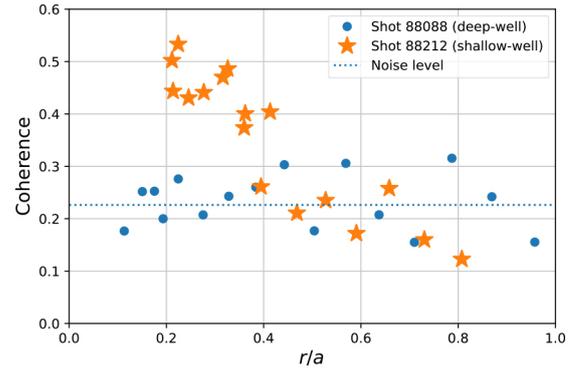

Fig. 3. Coherence between ECE power and the magnetic probe at the #2.5 port ($\phi = 33.3$ deg) from $t = 260$ to 270 ms as function of minor radius of ECE resonance.

was produced and sustained using 70 GHz second harmonic X-mode electron cyclotron heating (ECH) only. The ECH system was engaged at a constant power of 209 kW, with the resonance location placed near the magnetic axis. The line-averaged electron density was 0.6×10^{19} m^{-3}, and the average β is as low as 0.1%. The parallel refractive index $N_\parallel$ was set to be 0.1 according to the raytracing code TRAVIS [10], to minimise magnetic distortions due to the driven current. The total plasma current was measured to be constant at approximately 1 kA using a Rogowski coil, making significant changes in magnetic configuration due to current implausible. Magnetic probes that measure fluctuations in the poloidal magnetic field are used to detect coherent modes. Figure 2 shows the time evolution of the line-averaged electron density along a line of sight grazing the core plasma, ($r_{min}/a \approx 0.25$), and the coherence between the signals from two magnetic probes separated by a toroidal angle of 90 deg. A broadband patch of coherence is visible around 10 kHz, from $t = 260$ to 295 ms. This matches the peaking of the electron density, corroborating that this is a pressure-driven mode. The mode frequency appears to marginally decrease as time progresses. The toroidal mode number estimated from the toroidal magnetic probe array is $n = 1$. The poloidal mode number is not available due to low signal-to-noise ratio of the poloidal probes. Such a patch of coherence at 10 kHz was not observed in shots in the deep-well configuration with identical heating settings. This therefore provides evidence of a broadband magnetic mode in the shallow-well configuration that is absent in the deep-well configuration.

Next, the influence of the mode on temperature fluctuations is investigated. If the mode causes temperature fluctuations, these fluctuations are expected to be coherent with the magnetic fluctuations. To this end, the electron cyclotron emission (ECE) was measured using a radiometer equipped with a high-sampling digital storage oscilloscope (DSO) for intermediate frequency (2–18 GHz) signals. The temporal evolution of the spectral power distribution of this ECE waveform was then determined, giving a measure of the temporal temperature evolution at various ECE frequency resonance locations. The ECE resonance locations were determined using TRAVIS. It should be noted that the optical thickness

of the plasma in the ECE frequency range was typically around 1.0, indicating an optically grey plasma. Multi-reflected ECE may therefore distort the ideal correspondence of ECE signal strength to electron temperature. Figure 3 shows the radial profile of coherence between ECE power and a magnetic probe signal in the plasma from $t = 260$ to 270 ms. These coherences are averaged over the mode frequency band, from 7 to 13 kHz. For reference, a shot with identical heating settings in the deep-well configuration (#88088) is also included in this figure. In the shallow-well configuration, the coherence is clearly higher than the noise level at $r/a < 0.4$. The electron temperature thus fluctuates coherently with magnetic fluctuations in the core of the device, evidencing that the mode is excited in the core plasma. There are no low-order rational surfaces that might locally destabilize the mode in the core, and the magnetic shear is expected to be too low to stabilize the mode anywhere. The excitation in the core rather than the edge can therefore likely be attributed to the pressure, which is higher in the core than in the edge plasma. In the low-β plasmas considered, the magnetic well in the deep-well configuration is then sufficiently deep to stabilise the mode, explaining the lack of observed coherence in this configuration. Conversely, the absence of such a deep well allows the mode to be excited in the plasma core in the shallow-well configuration.

This research presents the first results from the Heliotron configuration featuring a shallow magnetic well. A mode is observed at low density in this configuration, whereas no interchange-type MHD instabilities are typically observed in the deep-well configuration up to the cut-off density (3×10^{19} m^{-3}) in ECH plasmas. It is required to further scan experimental conditions such as the electron density, ECH power and magnetic configuration to investigate the observed mode properties.

[1] M. Drevlak *et al.*, Nucl. Fusion **59**, 016010 (2019).

[2] C. Mercier, Nucl. Fusion **4**, 213 (1964).
[3] S. Yamamoto *et al.*, Fusion Sci. Technol. **51**, 92 (2007).
[4] S. Sakakibara *et al.*, Nucl. Fusion **55**, 083020 (2015).
[5] O. Motojima *et al.*, Nucl. Fusion **43**, 1674 (2003).
[6] T. Obiki *et al.*, Nucl. Fusion **41**, 833 (2001).
[7] M. Wakatani *et al.*, Nucl. Fusion **40**, 569 (2000).
[8] S.P. Hirshman and J.C. Whitson, Phys. Fluids **26**, 3553 (1983).
[9] S.P. Hirshman *et al.*, Comput. Phys. Commun. **43**, 143 (1986).
[10] N.B. Marushchenko *et al.*, Comput. Phys. Commun. **185**, 165 (2014).