Demonstration of vertical stability control based on non-inductive Faraday-effect polarimetry measurements on DIII-D

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Long-pulse or steady-state fusion reactors are envisioned to control vertical stability based on non-inductive measurements, i.e. that do not rely upon temporal change of magnetic field . For the first time, vertical stability control using Faraday-effect polarimetry has been demonstrated on DIII-D. A Faraday-effect polarimeter was developed to absolutely determine the vertical position of the plasma magnetic axis and is capable of microsecond resolution. A Faraday-based vertical stability controller was used to robustly stabilize elongated diverted plasmas against vertical displacement events with growth rates up to 300 s^{-1} in various plasma shapes. Initial tests show that the Faraday-based controller remains effective even when the plasma vertical position is outside of the desired measurement range. Initial tests also identify future research needs, such as mitigating undesired control oscillations, critical to implementing the controller in fusion reactors.

A non-inductive control-capable vertical position measurement was developed utilizing the Radial Interferometer-Polarimeter (RIP)[1] diagnostic. RIP consists of three radial chords, vertically-spaced (Z = 13.5 cm, 0 cm, and -13.5 cm relative to the vacuum vessel center) measuring of line-integrated density ($\int n_e dl$) and Faraday effect ($\int B_R n_e dl$.) For each point in time, a linear fit to the 3 measured points is performed, and the Z-intercept ($B_R = 0$) determines the plasma magnetic axis within the chord coverage[2] (Fig. 1). RIP is capable of time resolution up to 10 MHz, which is downsampled to 20 kHz (with 50 μs latency) for the initial plasma control system tests being performed on DIII-D.

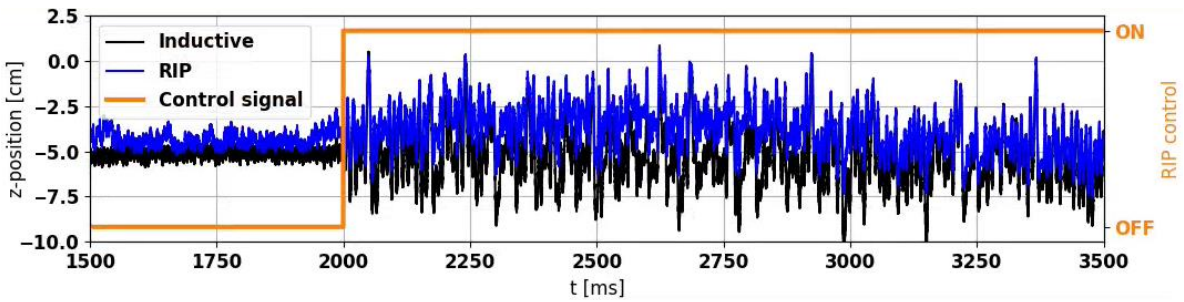

Figure 1: First demonstration of non-inductive vertical stability control on DIII-D. Control is transferred from the inductive controller to the RIP controller at 2000 ms (orange.) Magnetic axis Z-position as measured by RIP (blue) compared to the inductively-measured Z-position of the current centroid (black,) shows the plasma vertical position remains bounded (no VDEs occur) while under RIP control until the end of the discharge.

Initial tests using the Faraday-based controller successfully demonstrated vertical stability control in various plasma shapes. Vertical stability control using Faraday-effect polarimetry instead of inductive magnetic probes was maintained in both stationary (Fig. 1) and in vertically-translated (Fig 2) plasma discharges. Control of vertical instabilities with growth rates up to 300 s^{-1} was achieved in initial tests (compared to 800 s^{-1} achieved by the inductive controller[3],) with the maximum growth rate achieved by the RIP controller limited most likely by unfinished tuning of the proportional gain in the PID controller or by conflict between the RIP vertical stability controller and a plasma shape controller. Initial tests successfully demonstrated changeover from inductively-driven control to the new Faraday-effect-driven control in diverted elongated tokamak plasmas, in lower and upper single null plasmas with κ up to 1.8.

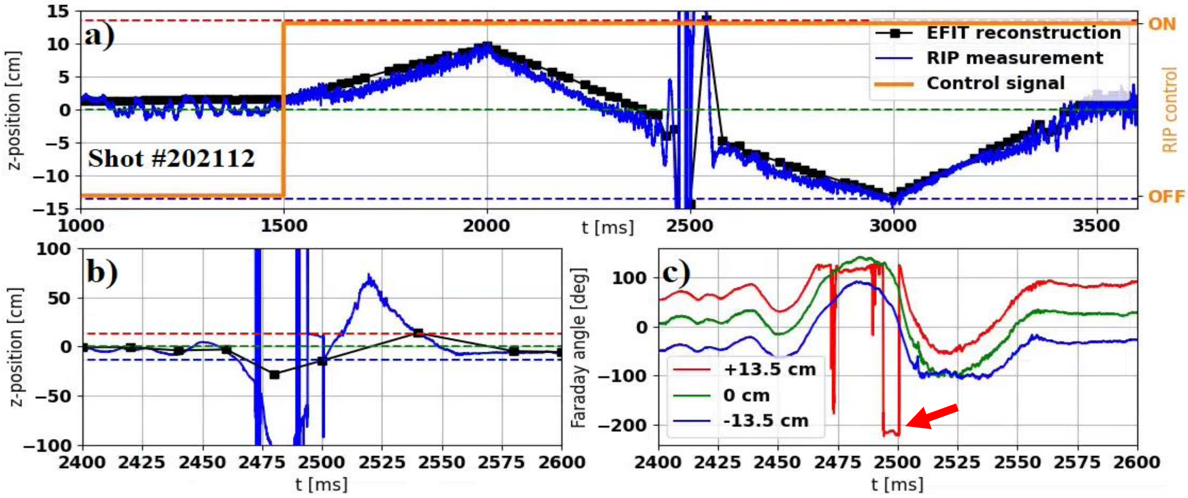

*Figure 2: **a)** Z-position of the magnetic axis during a triangle-wave scan controlled by RIP after t = 1500 ms (changeover from inductive to RIP control marked with vertical dotted orange line) as measured in real time by RIP (blue) and as calculated by the Grad-Shafranov equilibrium fitting code EFIT (black.) RIP chord positions are marked with horizontal dashed lines. **b)** Zoom-in in time and zoom-out in space of "a)" during temporary loss of control around 2500 ms. **c)** Faraday phase measured by the three RIP chords during "b)," showing phase jumps in the Z = 13.5 cm chord between 2470 and 2500 ms (red arrow.)*

Initial tests also show evidence of robustness of the Faraday-based controller against abnormal events. In Fig. 2, a brief loss of vertical stability control occurs during the triangle waveform scan ($t \approx 2500\ ms$,) likely due to conflict between the RIP-based vertical stability controller and a plasma shape controller. Recovery of control was demonstrated despite +/- 30 cm oscillations in Z taking the plasma far outside the range of RIP chord coverage (+/- 13.5 cm), where the assumption of linearity needed for accurate Z_0 measurement is not valid, resulting in exaggerated Z_0 magnitudes (Fig. 2b) which still induce directionally-correct control responses. The upper chord experienced brief phase jumps after the oscillations began (Fig. 2c) which are undesired but can be recovered from: a merit of polarimetric measurement.

Initial tests identify future research needs to implement the Faraday-based controller in fusion reactors. Stronger oscillations in Z-position (approximately 100 Hz and 2-5 cm in amplitude) were observed under RIP control than under magnetic control (Fig. 1), implying a need for a more balanced proportional gain for the PID controller than was achieved during this first experiment. Internal measurements of magnetic axis Z-position and external measurements of current centroid position showed the 100 Hz oscillations to be in-phase and at the same amplitude, implying rigid movement of the plasma rather than core-edge decoupling, and thus that these oscillations are not intrinsic to core-measuring vertical stability control. Further development and testing of the Faraday-based vertical stability control are planned to optimize performance and more fully utilize the RIP MHz bandwidth which offers the potential for feedback on the timescale of the plasma instability growth rate.

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[1] Chen, Jie, et al. *Review of Scientific Instruments* 87.11 (2016).
[2] Ding, W. X., et al. *Review of Scientific Instruments* 89.10 (2018).
[3] Barr, Jayson L., et al. *Nuclear Fusion* 61.12 (2021): 126019.