Verification and Optimization of the VDE in the HL-3 Tokamak

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Introduction

Vertical displacement events (VDEs) [1] are one of the main causes of major disruption that could damage plasma facing components (PFCs), especially in reactor-size tokamaks. For example, only two major disruptions are allowed throughout all stages of ITER operation. Elongated plasma, an effective approach to enable high plasma confinement, is inherently vertically unstable. Additionally, perturbations in other parameters, such as poloidal beta β_p, internal inductance l_i and toroidal current density j_φ, can also increase the vertical growth rate of VDEs, making it very difficult to precisely control the plasma vertical position. Therefore, it is a high priority to evaluate VDEs in closed-loop simulation with high-fidelity models.

Integrated workflow to simulate the VDE

An integrated workflow (in Fig.1) is developed to verify and optimize the VDE predictions in the HL-3 tokamak. The workflow is divided into two parts, i.e. plasma control and the non-linear plasma model. The plasma model is designed to replace the evolution of plasma parameters when there is no discharge commissioning, while the plasma control loop remains the same as the one embedded in the PCS. The objective of feedback (FB) control is R, Z and Ip, with the control strategy based on coil voltages. Notably, coil currents are not explicitly involved in the FB loop [2]. The reference trajectories for R, Z, I_p and coil voltages (V_{PF}) in feedforward (FF) settings are determined through model-based optimizations or trial and error by pilots. The gains in the PID controller are also aligned with the PCS. At the core of the workflow is a non-linear plasma mode, which is numerically coupled using the free-boundary equilibrium code FEEQS.M [3] and the fast transport code METIS [4]. In FEEQS.M, the circuit equations for the PF coil system are coupled with the G-S equation to compute the evolution of (R, Z), elongation (κ) and (δ), using the input $V_{PF}^{FF}+V_{PF}^{FB}$ from the plasma control loop. The developed

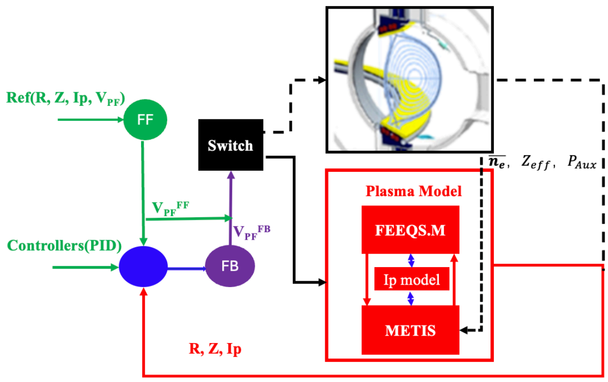
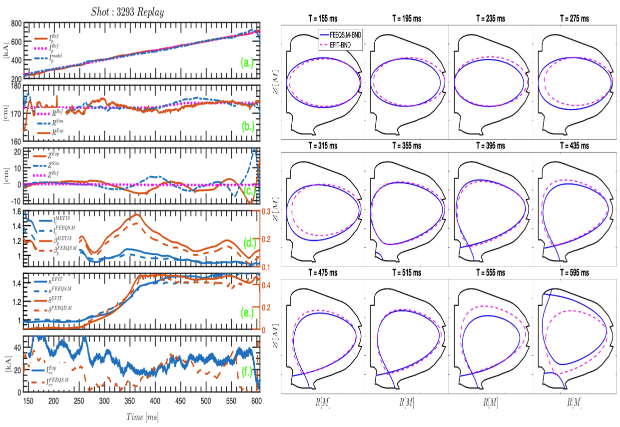


Fig. 1 Scheme of integrated workflow. Black dashed lines represent for on-line plasma operations.

workflow is deployed to virtually replay a dedicated shot, i.e. #3293, which terminates with a VDE-induced disruption during I_p ramp-up phase. The objective of #3293 is to achieve a nominal diverted plasma shape with $I_p \sim 1.5\ MA$, $\kappa \sim 1.5$ and $\delta \sim 0.5$. However, due to the limited flux swing capacity provided by CS and PF coils to sustain such a high I_p, the plasma shape must transition quickly from limiter to divertor shape to reduce Ohmic consumption. This requires κ to increase from 1.0 to 1.5 during the ramp-up phase. Such a dynamic scenario introduces significant oscillations, e.g., j_φ evolves drastically in response to variations in β_p and l_i. These rapid changes are accompanied by fast modifications in R, Z and I_p, driving the FF + FB control loop into an intensive working state with V_{PFs} as the only available actuators. Ultimately, this highly dynamic shot terminates with a VDE-induced disruption.

The coupled workflow is first applied to replay the nominal shot with the same control strategy, i.e. FF and FB, consistent with their applications in PCS. By analyzing the simulation results, an optimization with modified FF settings, in terms of a new reference trajectory, is then deployed to reliably avoid the VDE during the continued increase of I_p.

Verification of VDE by the developed workflow



Plasma parameters between simulation and experiment match well before VDE occurs around 600 ms (left). However, Z matches well while the plasma shape remains in the limiter phase (before 300 ms), but deviates after transitioning to the divertor configuration, responding more rapidly than in the experiment during the VDE disruption.

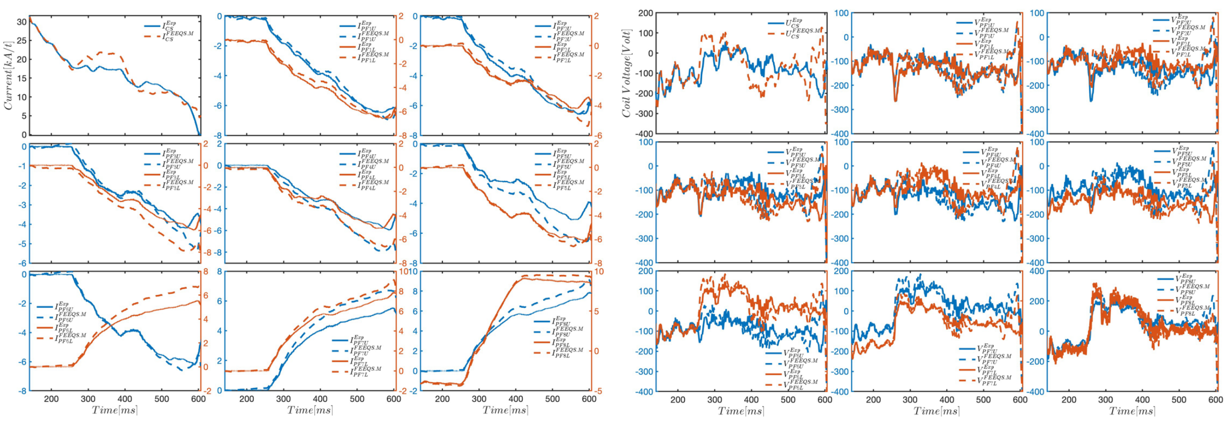
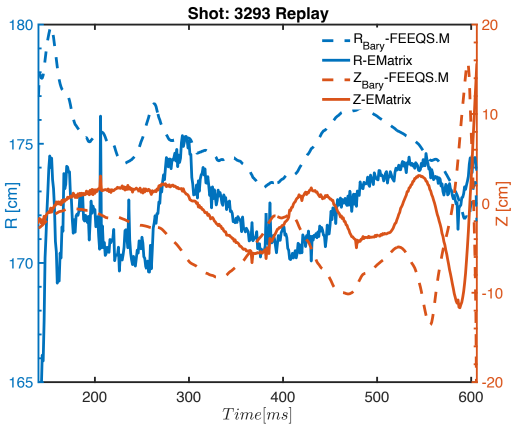


Fig. 2 Comparisons of IPFs and VPFs between FEEQ.S simulation (dashed line) and experiment (plain line) for #3292.

Analysis of the VDE disruption



It is obviously found, shown in the left figure, that R-EMartix is smaller than R_{Bary}-FEEQS.M, whereas Z-EMartix is similar to Z_{Bary}-FEEQS.M, except that Z_{Bary}-FEEQS.M responds more quickly than Z-EMartix. A noticeable bump appears in R-EMartix between 250 ms and 350 ms, during plasma shape transition from limiter to divertor. A possible explanation for this bump is the modification of jφ, i.e. the oscillation in βp shown in (d.) of Fig in 1. Variations in jφ alter the magnetic field in magnetic, which in turn affect the estimation of R, Z. It should be noted that the exact causes, e.g., modification of plasma internal profiles and potential micro- or macro-MHD instabilities, leading to the VDE-induced disruption are complex and very difficult to identify conclusively.

Optimization of VDE by the developed workflow

With an optimized increased R^{Ref}, the simulation remains stable and shows no indication of a VDE, even though the j_φ parameters, in terms of β_p and l_i, are preserved as the experiment. The simulation is terminated at 635 ms, corresponding to the end of pulse #3293.

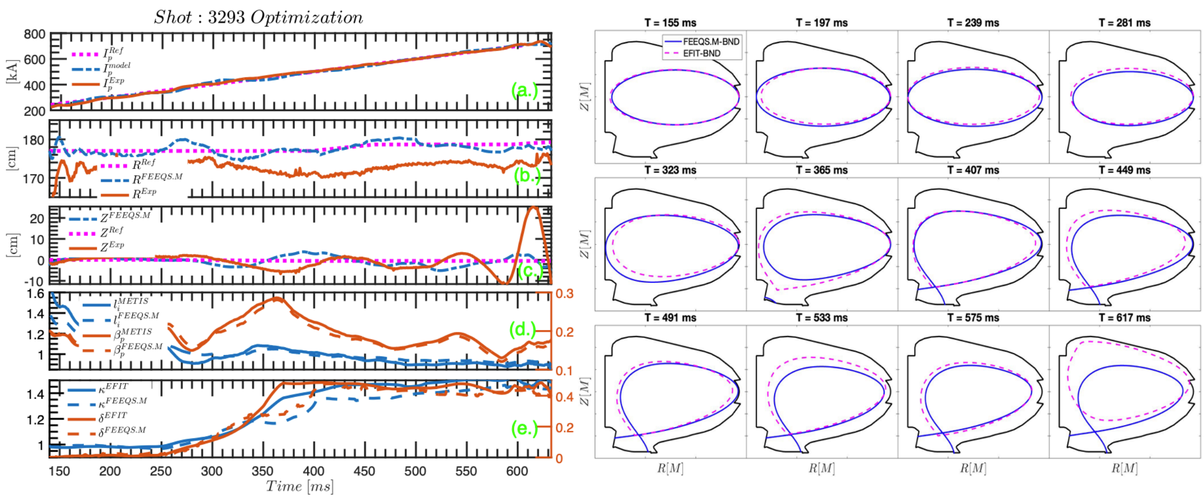


Fig. 3 Left: comparison between simulation and experiment for #3293, (a) Ip, (b) radial position R, (c) vertical position Z, (d) β_p and l_i, (e) κ and σ, (f) I_{vv}. Right: plasma boundary between magnetics-constrained EFIT and FEEQS.M.

It is found that in Fig.3 at the beginning, when the plasma shape is in the limiter phase, all CS and PF coil currents closely match the experimental values, even though R^{Ref} has been increased by *5 cm*. After the onset of the limiter to divertor transition, starting at 250 ms, the PF coil currents begin to deviate from the experimental values. Nevertheless, the observation of VDE-induced disruption is completely avoided in the optimized simulation, although coil currents in PF5 and PF6 are much higher than those measured in the experiment, as it presented in Fig.4.

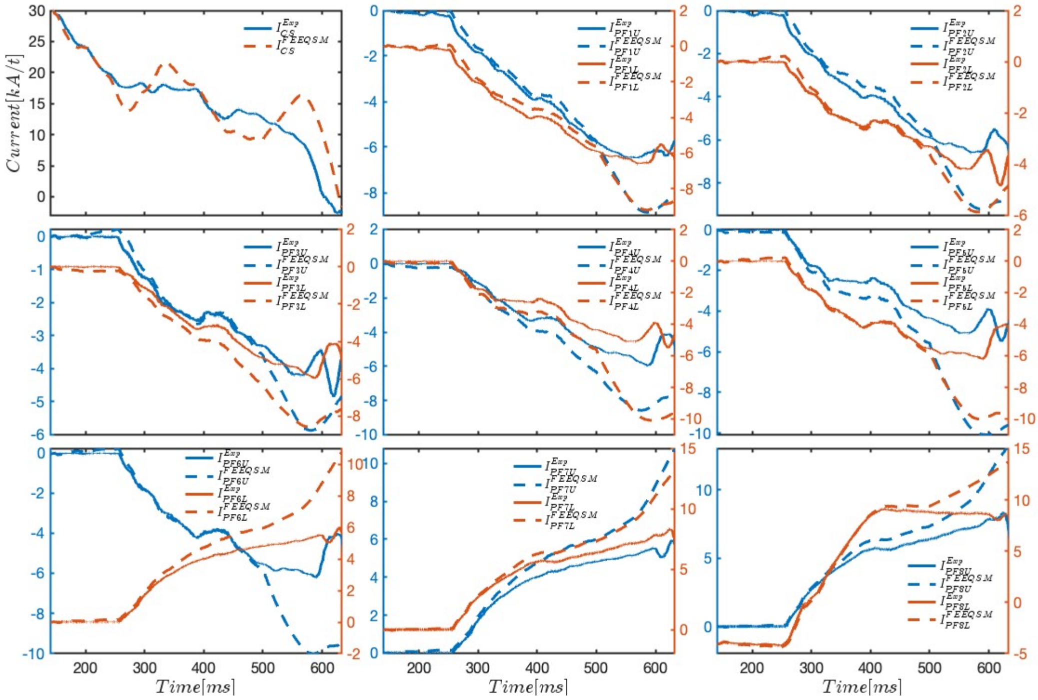


Fig. 4 Comparison of I_{PFs} and between FEEQ.S simulation (dashed line) and experiment (plain line) for #3292 .

Conclusion and future work

In this work, a sophisticated workflow by coupling the FEEQS.M and METIS codes with FB control strategy, is developed to verify and optimize the VDE predictions in the HL-3 tokamak. The evolution of I_p is constructed based on scaling law with experimental data. The FB control loop remains the same as the "real" application in the PCS. The workflow is first validated by replaying a VDE shot of 3293, and later optimized to a VDE-avoidance scenario through adding the R^{Ref} by 5 cm. Future work will focus on high performance plasma explorations with various H&CDs, neural network techniques to expedite simulations.

Acknowledgment

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