EX-S/#3058

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 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 I_p, 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.

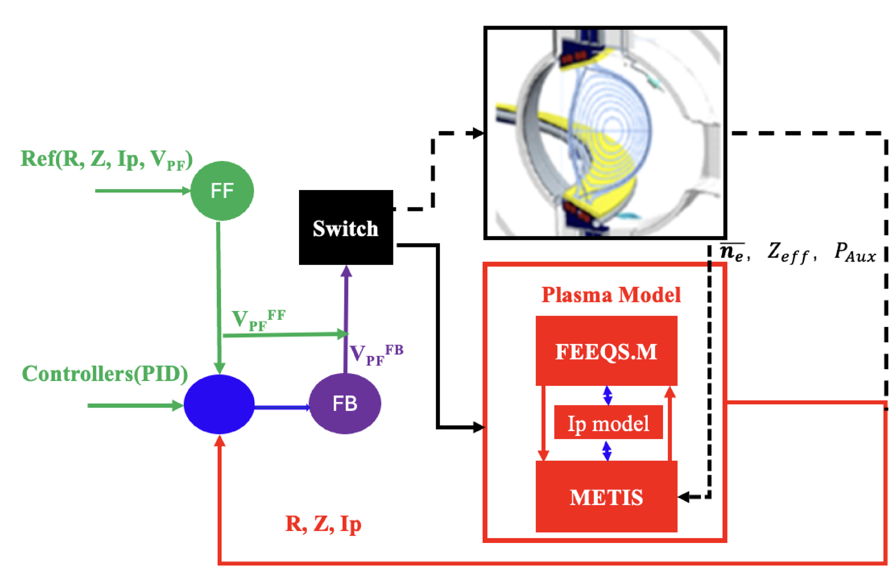


Fig. 1: Schematic of integrated workflow. Black dashed lines represent for on-line plasma operations

Feedback control strategy based on coil voltage

$$V_{PF}^{Total} = V_{PF}^{FF} + V_{PF}^{FB}$$
$$V_{PF}^{FB} = V_{PF,R}^{FB} + V_{PF,Z}^{FB} + V_{PF,I_p}^{FB}$$
$$V_{PF,R}^{FB} = \Delta R * PID * M_{matrix,R}\ ,\ \textit{Same methods w.r.t Z and } I_p,$$

Plasma current model

$$V_{loop} = R_p(I_p - I_p^{NI}) + L_p\frac{dI_p}{dt}$$
$$V_{loop} = -2\pi\frac{\partial\psi_{bnd}^{FEEQS.M}}{\partial t},\quad L_p = \mu_0 R_0\left(\ln(8\frac{R_0}{a}\sqrt{\frac{2}{1+\kappa^2}}) - 2 + \frac{l_i}{2}\right)$$

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.

Time evolution of (*R, Z*) through FEEQS

$$\Delta^*\psi(R,Z) = -\mu_0 R J_\phi(R,Z),$$
$$\Delta^* \equiv R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial}{\partial R}\right) + \frac{\partial^2}{\partial Z^2}.$$
$$J_\phi(R,\psi(R,Z,t),t) = \begin{cases} Rp'(\psi(R,Z,t)) + \frac{ff'(\psi(R,Z,t))}{\mu_0 R} & \text{in plasma area } \Omega_{pl}(\psi(R,Z,t)) \\ \frac{I_i}{S_i} & \text{in coil number } 1 \le i \le M \\ j_S = -\frac{\sigma}{R}\frac{\partial\psi(t)}{\partial t} & \text{in S (passive plates)} \\ 0 & \text{elsewhere} \end{cases}$$
$$\frac{I_i}{S_i} = \sum_{j=1}^{N} R_{ij}V_j(t) + \sum_{k=1}^{M} C_{ik}\int_{C_k}\frac{\partial\psi(t)}{\partial t}dRdZ\ ,\ 1\le i\le M,\ R_{ij} = \begin{cases} 0 & i\ne j \\ \frac{n_i}{R_i S_i} & i=j \end{cases}\ C_{ij} = \begin{cases} 0 \\ -\frac{2\pi n_i{}^2}{R_i S_i{}^2}. \end{cases}$$

Time evolution of plasma profiles (*ρ*) by METIS

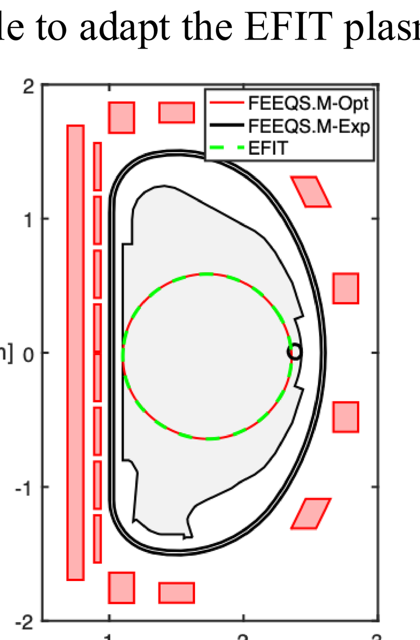
$$\frac{\partial\psi}{\partial t} = \frac{\eta(T_e)}{\mu_0\rho_b^2 F^2}\frac{1}{\hat\rho}\frac{\partial}{\partial\hat\rho}\left(\hat\rho FGH\frac{\partial\psi}{\partial\hat\rho}\right) + \frac{R_0 H\eta(T_e)}{B_0}\langle j_{NI}\cdot B\rangle$$
$$\textbf{B.C.}:\ \frac{\partial\psi}{\partial\hat\rho}\Big|_{\hat\rho=0} = 0;\ \frac{\partial\psi}{\partial\hat\rho}\Big|_{\hat\rho=1}^{t} = -\frac{\mu_0 R_0}{2\pi GH}I_p(t).$$
$$F = \frac{R_0 B_0}{f}\ ,\ G = \langle\frac{R_0^2|\nabla\rho|^2}{R^2}\rangle\ ,\ H = \frac{F}{\langle R_0^2/R^2\rangle}$$
$$n_e(\hat\rho,t) = n_e^{prof}\overline{n}_e(t),$$

The developed 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 ~1.5 *MA*, κ~1.5 and δ~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.

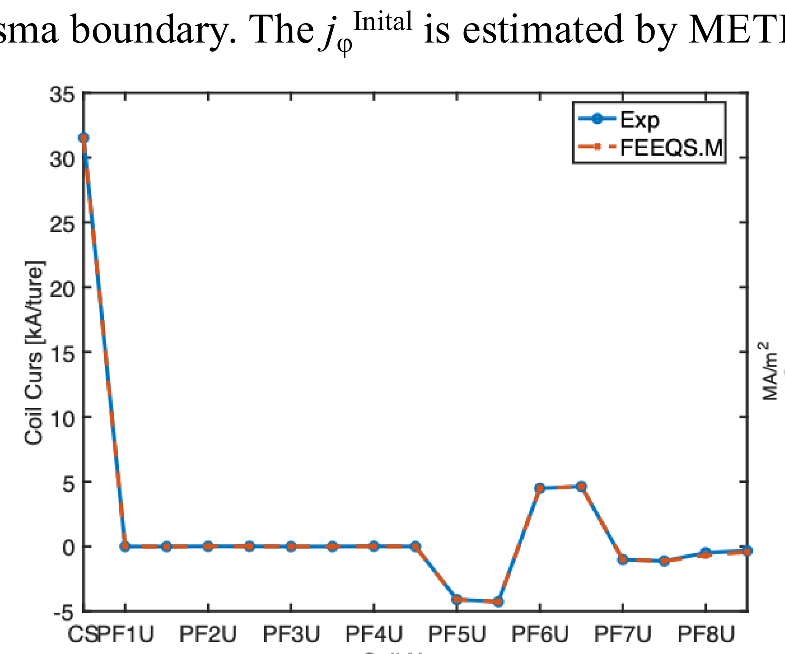
The coupled workflow is first applied to replay the nominal shot with the same control strategy, i.e. FF and FB, consistent with their applications in PCS. By analyzing the simulation results, an optimization with modified FF settings, in terms of a new reference trajectory, is then deployed to reliably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

Initial Equilibrium and Plasma Current Profile

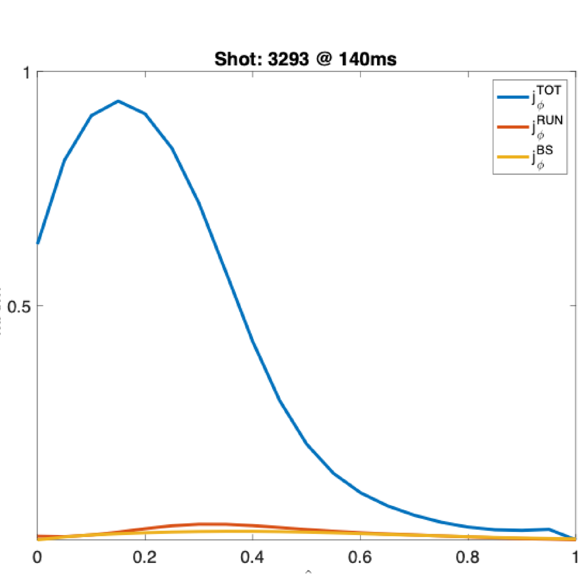
Initial equilibrium is calculated by FEEQS for 3293 at 140 *ms*, where PF8 coil currents are modified a little to adapt the EFIT plasma boundary. The j_φ^{Inital} is estimated by METIS with EFIT equilibrium data.



Plasma boundary comparison

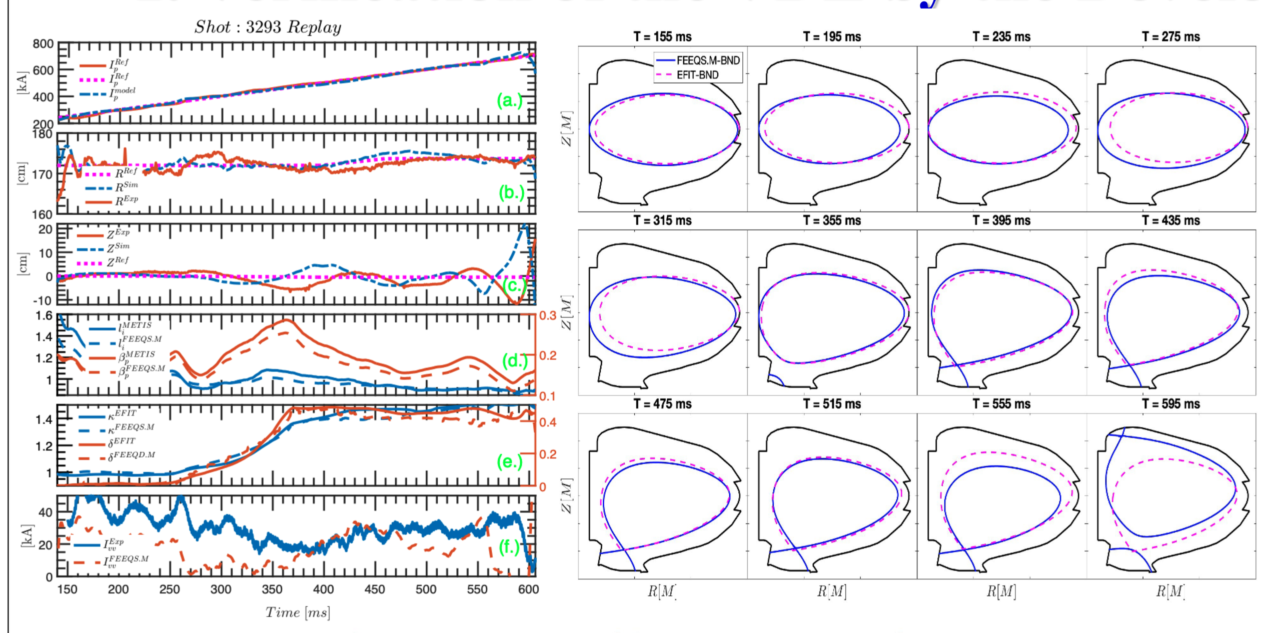


Coil currents for CS, PF1U, PF1L,…PF8L

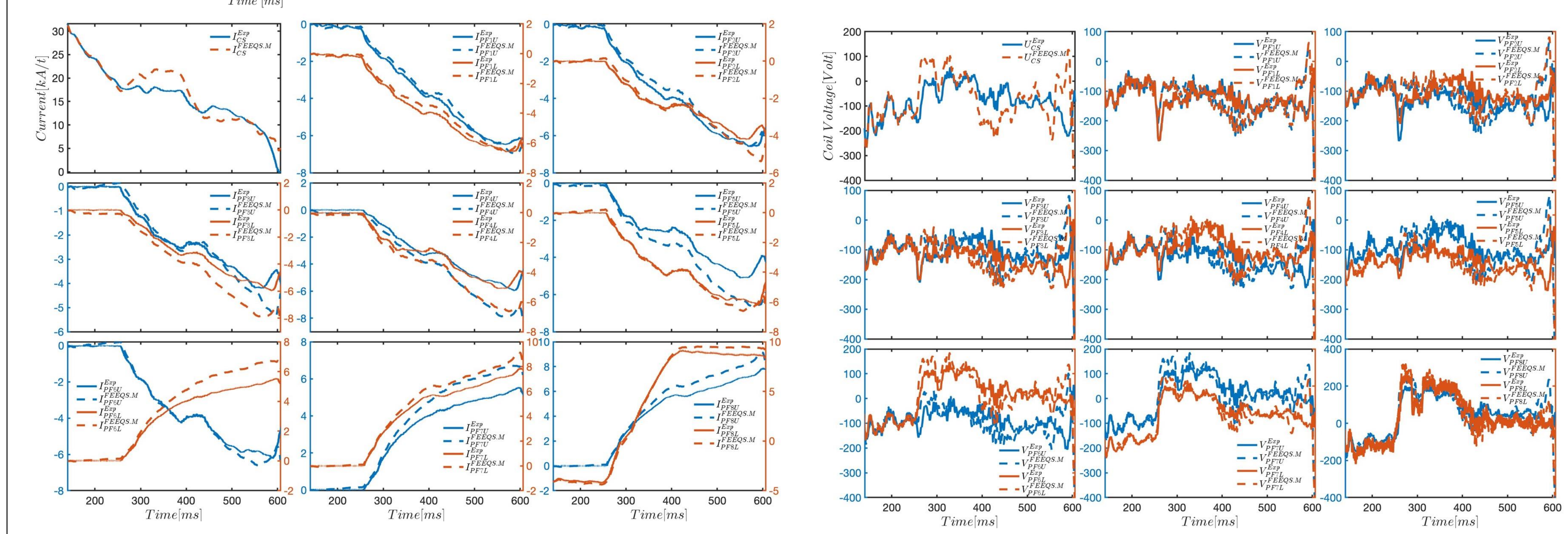


Plasma current profile

1. Verification of the VDE by the Developed Workflow

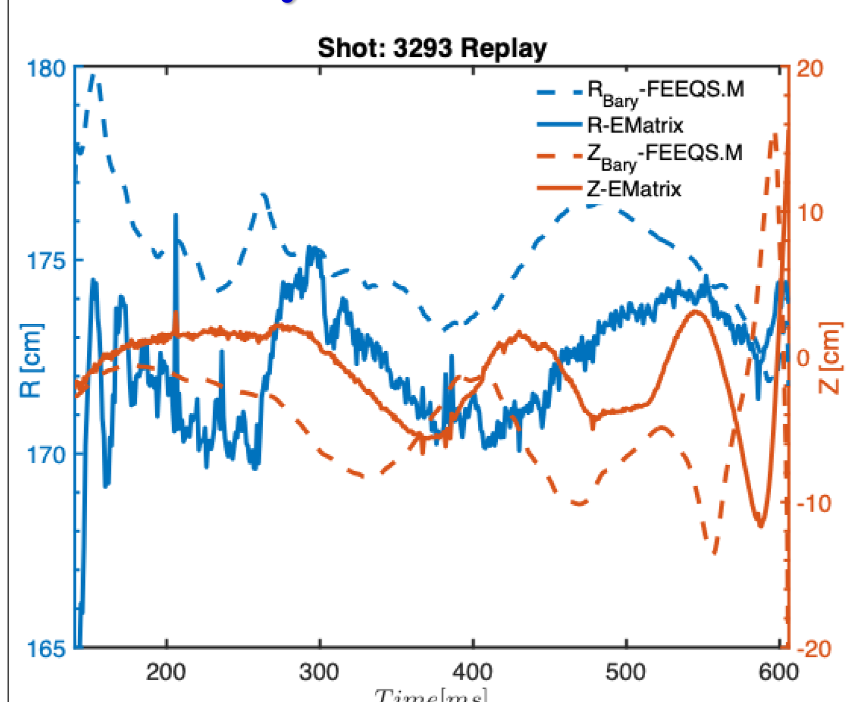


Plasma parameters between simulation and experiment match well before VDE occurs around 600ms. However, Z matches well while the plasma shape remains in the limiter phase (before 300 ms), but deviates after transitioning to the divertor configuration, responding more rapidly than in the experiment during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



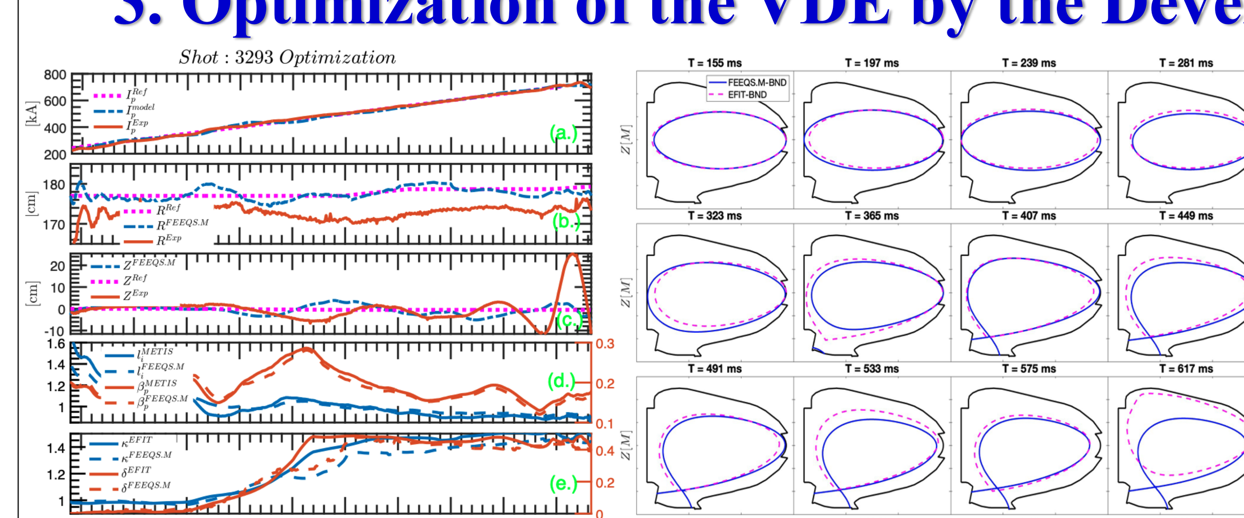
The higher I_{CS} observed in simulation between 300 ms and 400 ms indicates that R_p is underestimated by METIS. The good agreement of $I_{PF1,8}$ suggests R is consistent and well controller. The deviations in $I_{PF6,7}$ are aligned with the previously discussed difference in Z which is responding faster in simulation. The well-tracked coil voltages further confirm that the circuit equations embedded in FEEQS.M are valid.

2. Analysis of the VDE Disruption

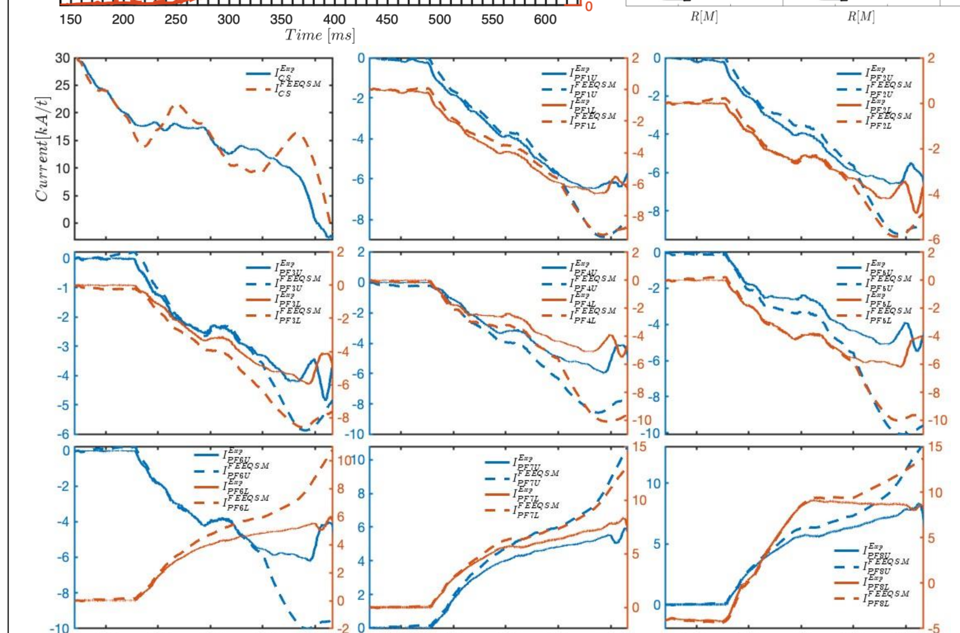


It is obviously found that *R-EMartix* is smaller than *R$_{Bary}$-FEEQS.M*, whereas *Z-EMartix* is similar to *Z$_{Bary}$-FEEQS.M*, except that *Z$_{Bary}$-FEEQS.M* responds more quickly than *Z-EMartix*. A noticeable bump appears in *R-EMartix* between 250 ms and 350 ms, during plasma shape transition from limiter to divertor. A possible explanation for this bump is the modification of j_φ, i.e. the oscillation in β_p shown in (d.) of Fig in 1. Variations in j_φ 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.

3. Optimization of the 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.



It is found that 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.

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.

Reference

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[3] J. Blum *et al* 2019 *J. Comp. Phys.* **394** 594.

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