MAXIMUM CONTROLLABLE DISPLACEMENT: RESULTS FROM NSTX

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NSTX

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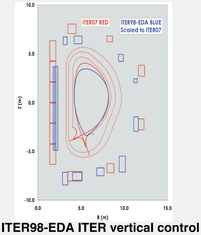
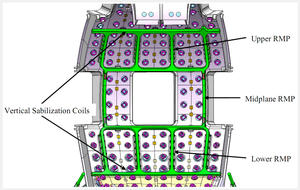
Motivation: ITER PF Design



ITER07 & ITER98-EDA ITER vertical control system comparison (D. Humphreys ITER STAC talk)



Proposed change in design of in-vessel coils for vertical stabilization and ELM control.

- ITER07 has degraded vertical control margins relative to ITER98-EDA:
  - Size and number of coils were reduced for cost reduction.
  - Plasma elongation is increased for performance recovery.
  - PF coils are moved farther away from plasma as fraction of minor radius.
  - Compensation through power supply and coil operating points is not sufficient.
- κ_{max}, ΔZ_{max} major design criteria.
- Vertical instability is damaging to the ITER structure (unlike NSTX).
- Identify range of safe operation is very important.

Experiment: Method of Obtaining ΔZ_{max}

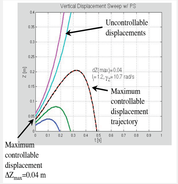
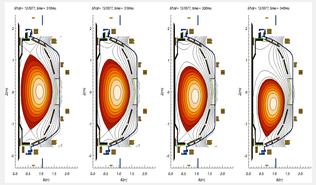


Illustration of experimental method defining ΔZ_{max}. Simulation corresponds to ITER end-of-rampup state with ΔZmax.~ 4 cm, ΔZmax /a ~ 2%.



Time evolution of an example ΔZ_{max} experiment shot from NSTX. The elongated plasma vertically drifts before the vertical control is turned back on.

- ΔZ_{max} is the maximum displacement beyond which VDE cannot be reversed.
- Using targets near κ_{max}, freeze coil commands to disable vertical control for period.
- Let plasma drift a vertical displacement of ΔZ.
- Apply maximum control command to the coils; vary the period to determine ΔZ_{max}
- At the same time apply constant shape circuit voltages which would keep constant shaping current.
- Gives the region of attraction, controllability region.
- Nondimensional parameter ΔZ_{max}/a can be used to compare different machines.

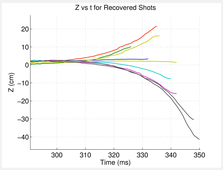
Experiment: Setup and Steps

- In the experiment (shot # 1207064 - 127087) we used helium plasma to keep the density constant, enabling reproducible results. Other parameters are:
  Ohmic discharge. 600 kA current. B_T ~ 5 kG. I_i ~ 1.4 Lower, upper gap ~ 45 cm

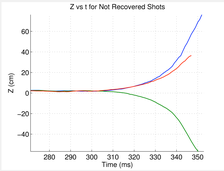
1. **Measured κ_{max}** – maximum controllability threshold in elongation.
   - We increased the elongation starting from 1.8 and determined maximum robustly controllable growth rate.
   - Scanned κ values showed that for κ > 1.9 the plasma is not controllable.

2. **Measure ΔZ_{max}** – maximum controllable displacement.
   - Set elongation below κ_{max} to κ=1.9.
   - Coil commands frozen to disable vertical control for a period to allow VDE.
   - Let the plasma drift for a specific period starting with 20 ms for the first experiment.
   - Restored the coil control command.
   - The control was turned back on with maximum available voltage (slew rate limited).
   - Repeated the experiment with increased drift periods [20, 30, 35, 40, 45, 50] ms.

Results: ΔZ and ΔZ_{max} Measurements

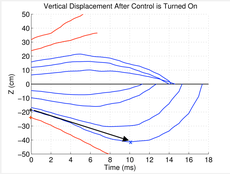


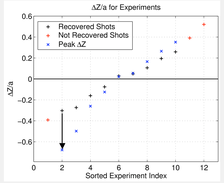
Vertical displacement for controllable shots (Cut off at the point of return)



Vertical displacement for uncontrollable shots

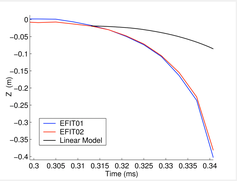
- At 300 ms, we turned the controller off and let the plasma drift.
- When we turned the control on some of the shots recovered while others did not.
- Standard deviation in ΔZ measurement signal noise is 0.7 cm





- Red lines show the shots were the vertical displacement was uncontrollable while the blue lines the controllable ones.
- NSTX is (mostly) up/down symmetric (mirror symmetry).
- ΔZ_{max} ~ **[18 - 24]** cm and ΔZ_{max}/a ~ **[%30 - %39]**.

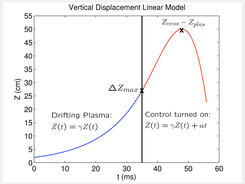
Analysis: TokSys Model Comparison



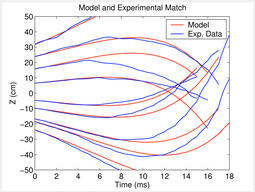
Example of a mismatch between TokSys numerical plasma model and the experimental data. Depending on how the model is used plasma or te coil model.

- ΔZ_{max} calculated for this equilibrium and control configuration using a linear TokSys model developed in a collaboration between DIII-D and NSTX is found to be ~ 40 cm, or ΔZ/a ~ 65%. The magnitude of this discrepancy is far greater than any observed sources of noise, and so is unlikely to be explained by such effects.
- We are assuming that the problem is with the 2-D structure of the model. A contributor to the discrepancy is inaccuracy in modeling the complex non-axisymmetric (3-D) passive structures of NSTX. Understanding the effect of complex non-axisymmetric conducting structures could be an important effect for determining vertical stability on ITER. As future work, we will look at VALEN, 3-D structure model that couples to plasma instability model.

Analysis: Simple Linear Vertical Displacement Model



Simple Linear Vertical Displacement Model



Data fit for α parameter

- For uncontrolled drifting plasma, the exponential growth is the dominant effect on Z and the ODE defining the motion can be written as:

$$\dot{Z}(t) = \gamma Z(t)$$

- Where γ =75s^{-1}. The first order effect of the coils on the vertical motion is assumed to be:

$$\frac{d\dot{Z}(t)}{dt} \approx \beta I = \alpha t$$

  i.e. the current changes the velocity of the rigidly moving plasma. Also during the ramp up *I* is proportional to *t*. Combining these two effects, we can find an approximation for the dynamics of the vertical motion after the control is turned on as:

$$\ddot{Z}(t) = \gamma \dot{Z}(t) + \alpha t$$

- α is found by data fitting as 4.5e5. Assuming that the plasma breaks when the edge of the rigidly moving plasma touches the vessel. We can find the ΔZ_{max} by the following BVP

$$Z_0 = \Delta Z_{max} \qquad Z_f = Z_{vess} - Z_{plas}$$
$$\dot{Z}_0 = \gamma\, \Delta Z_{max} \qquad \dot{Z}_f = 0$$

- Solving we get ΔZ_{max} ~ 27 cm. The good match with experimental data and ΔZ_{max} measurements suggests that the vertical dynamics is coupled linearly with the coil current.