Experimental Vertical Stability Studies for ITER Performance and Design Guidance

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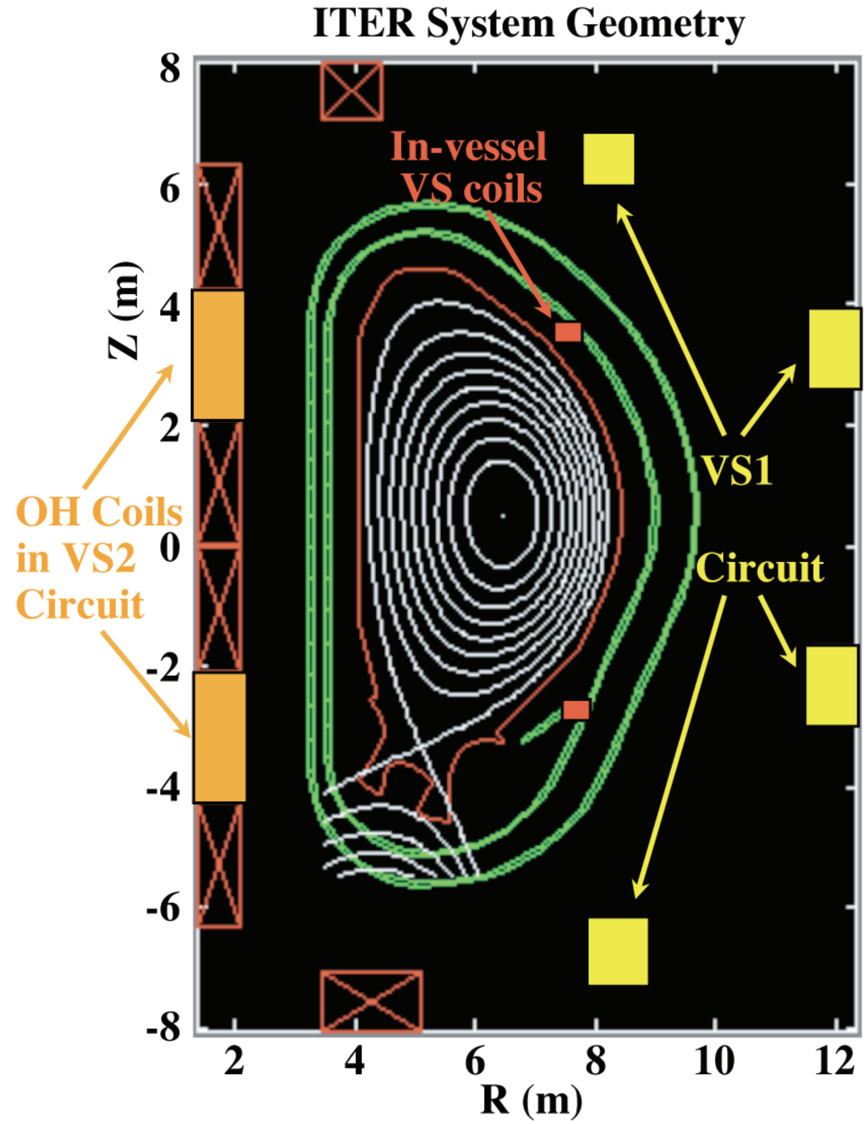

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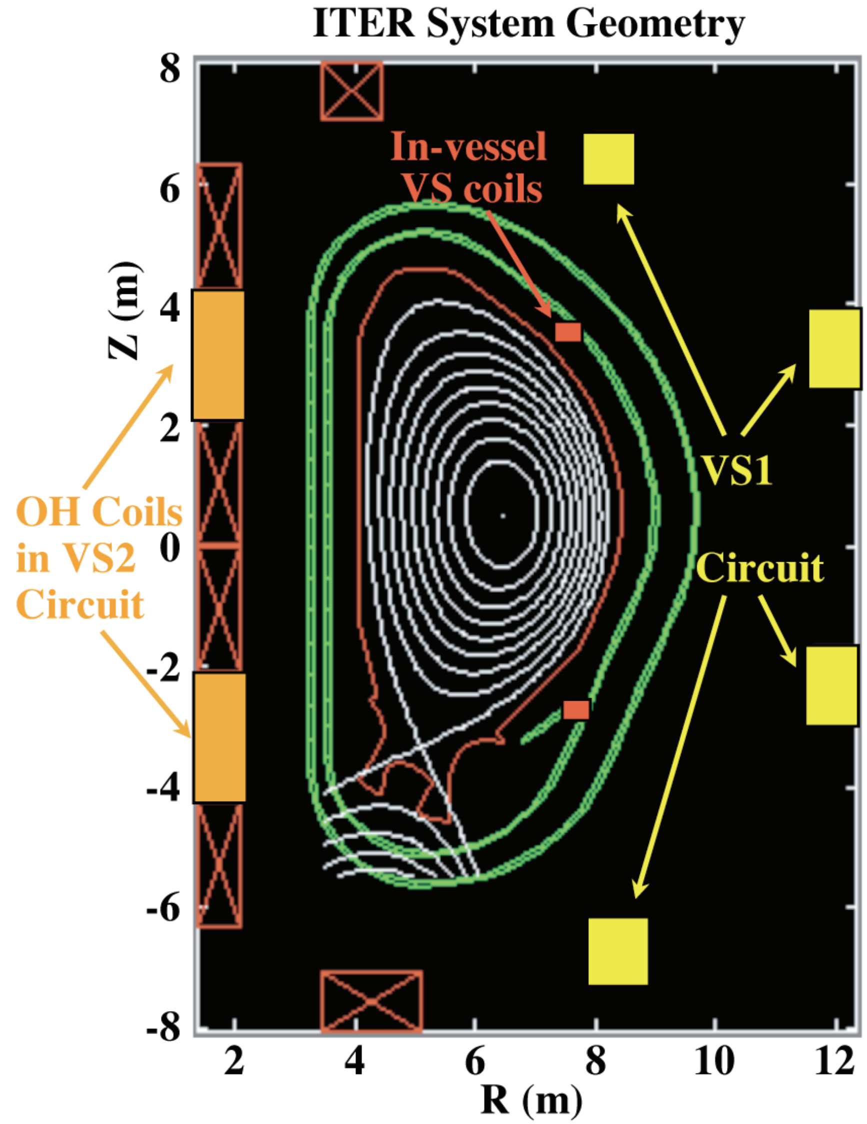
ITER Baseline System Uses Four Outboard Coils for Vertical stability Control

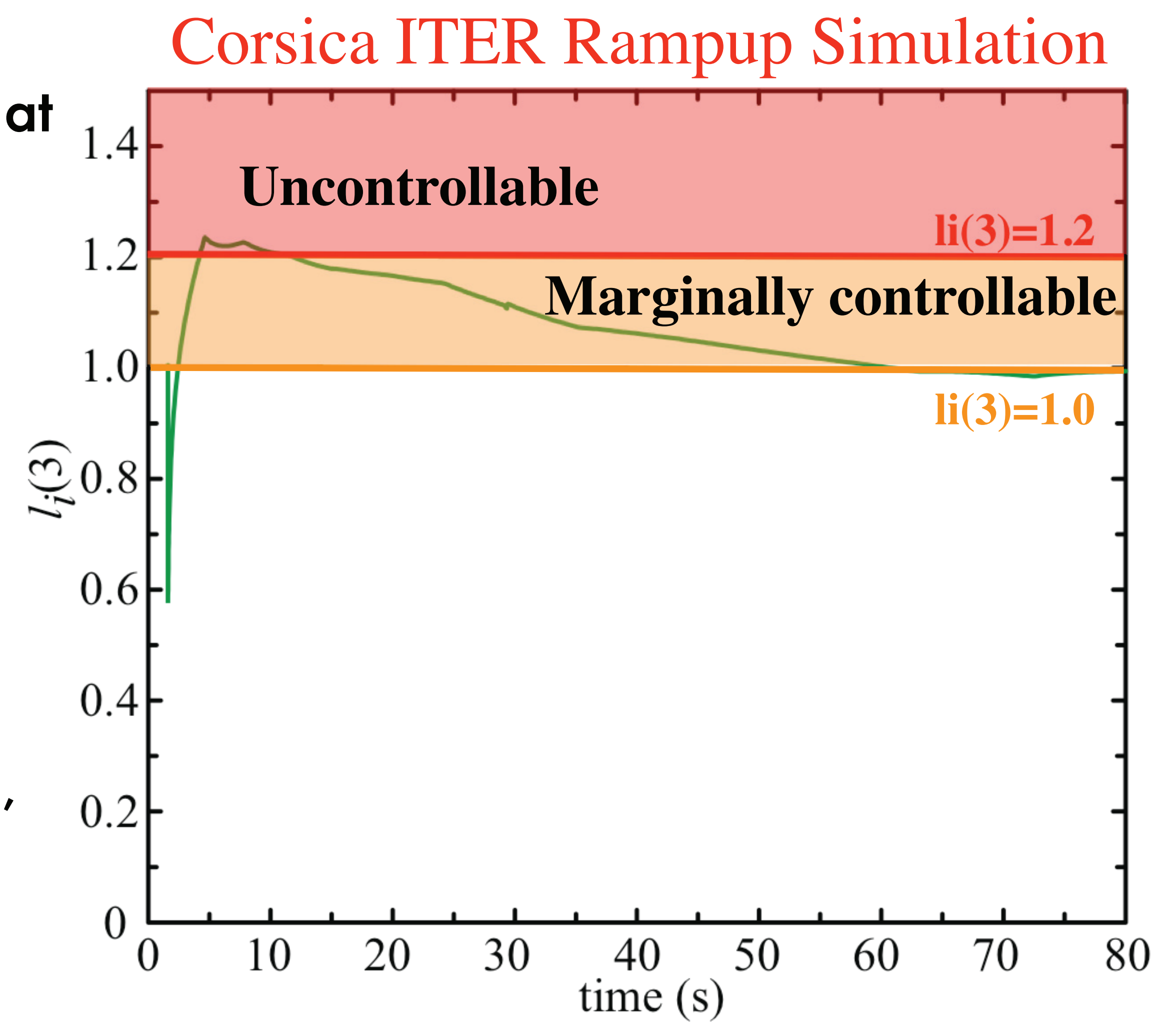
- Baseline system: "VS1" circuit = 4 outboard coils (PF2-5) with 6 kV operating voltage
- Proposals to enhance VS system include (from 2007-08 Design Review/STAC studies):
  - Use "VS2" circuit = 2 central solenoid coils (6 kV)
  - Add in-vessel VS coils mounted on vessel wall behind blanket modules



Baseline Scenarios Challenge Vertical Control Capability of Baseline Control System

- 1.0 < $\ell_i(3)$ < 1.2 during rampup at full elongation is marginally controllable by baseline VS1 system

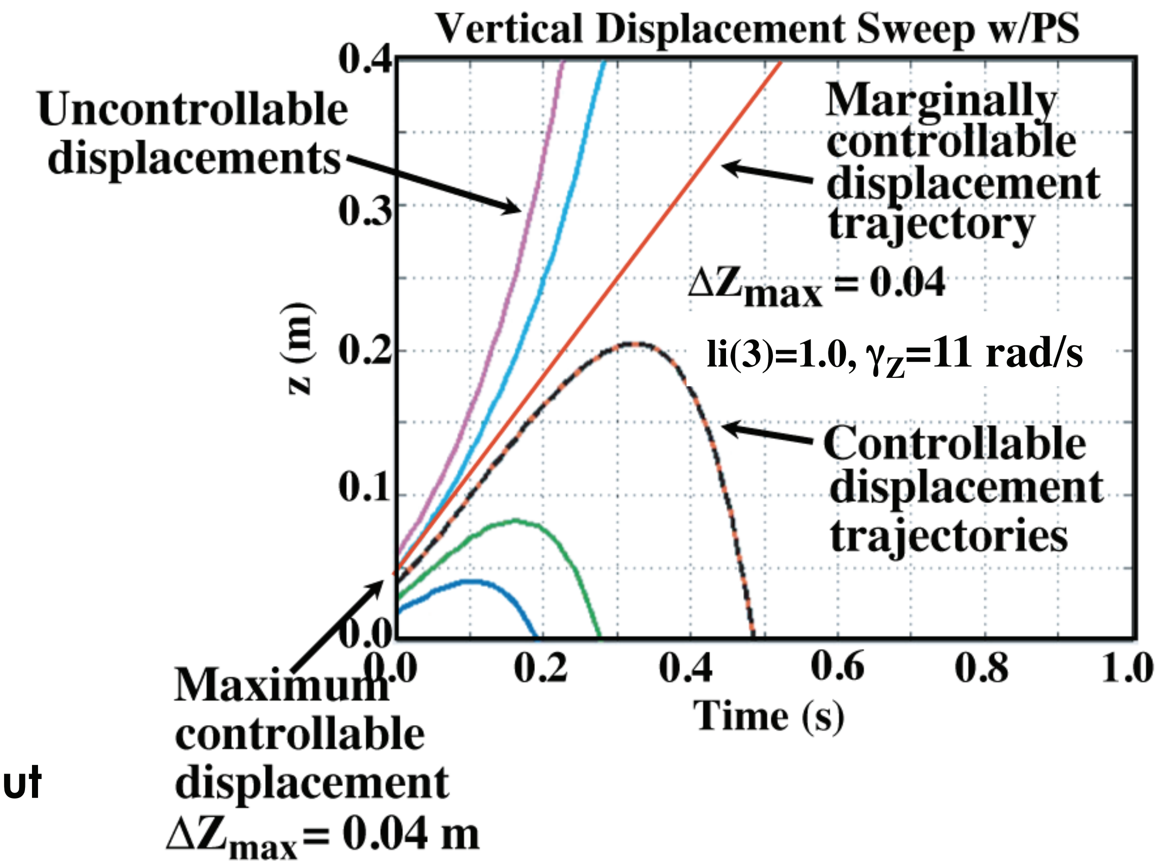
- Uncontrollable $\ell_i(3)$ > 1.2 can occur in baseline startup scenario, in high q_{95} operation, or in rampdown



Maximum Controllable Displacement Metric Addresses Consequences of Different Voltage, Current Limits

- Plasma allowed to drift distance ΔZ
- Apply fully saturated step voltage commands to power supplies:
  - Maximum and fastest possible radial field to oppose vertical motion
- ΔZ_{MAX} = maximum value of ΔZ beyond which vertical motion cannot be reversed
- NOT a true control demonstration, but a measure of "best possible"
- $\Delta Z_{MAX}/a$ is machine-independent metric for guidance in ITER design

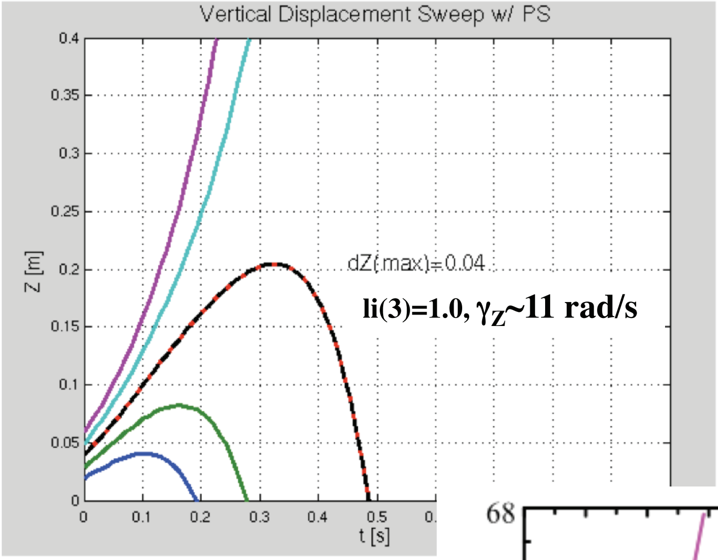
Example of Analysis and Gedanken Experiment to Calculate ΔZ_{max}



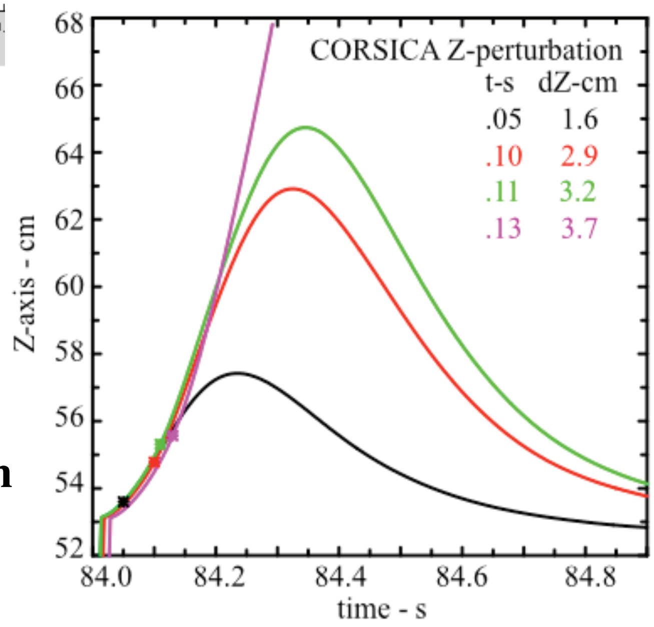
$$\Delta Z_{\max} = \frac{\partial z}{\partial I_V}\frac{M_{*VC}}{L_{*V}}\frac{V_{sat}}{L_C}\frac{1}{\gamma_z}\left(1-e^{-\frac{\Delta I_{\max} L_C \gamma_z}{V_{sat}}}\right)e^{-\gamma_z T_{PS}}$$

ITER Analyses Find $\Delta Z_{max}/a$~2% for Baseline VS1 System and End of Rampup Equilibrium

- **Linear rigid TokSys model:** $\Delta Z_{max}/a \sim 2.1\%$
- **Nonlinear nonrigid Corsica simulation:** $\Delta Z_{max}/a \sim 1.8\%$
- **Question: is this capability sufficient? Need experimental guidance…**

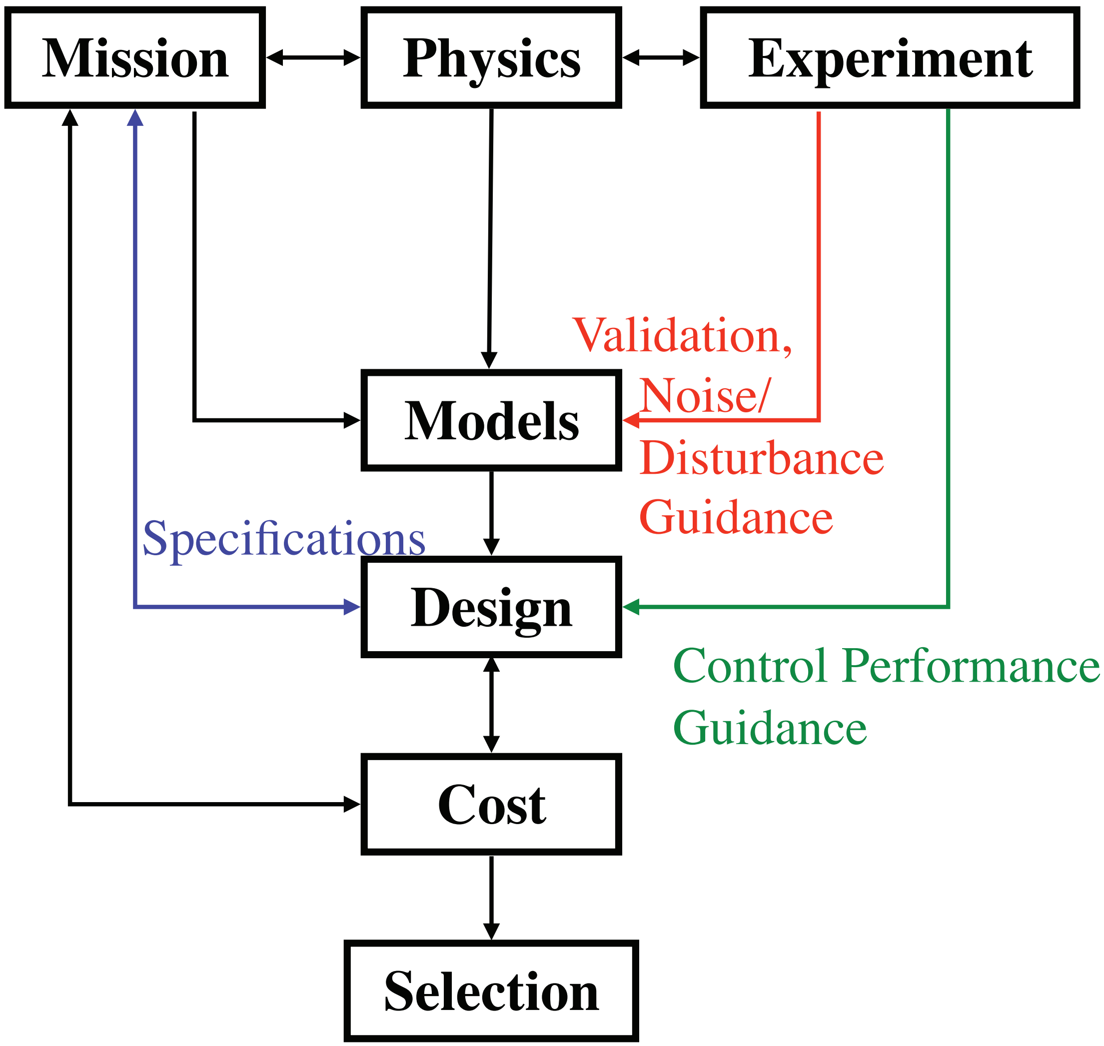


Rigid TokSys plasma model



Nonrigid Corsica plasma simulation

Experiments are Essential to Provide Guidance for Operational Robustness, Noise, Disturbances

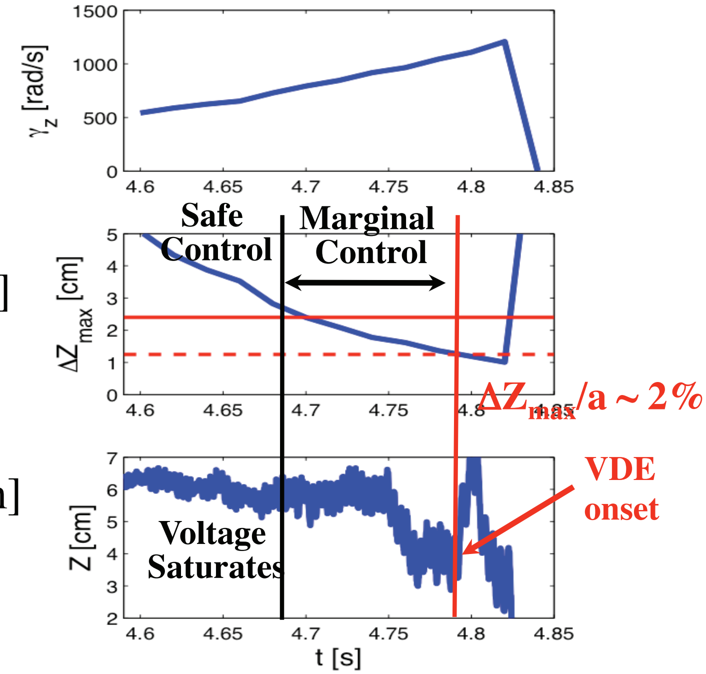


- There is **no fully predictive model of noise/ disturbance environment expected in ITER:**
  - ⇒ Experimental guidance necessary

Calculated $\Delta Z_{max}/a$ ~ 2% Guarantees Loss of Control, $\Delta Z_{max}/a$ ~ 4% Marginal in DIII-D and C-Mod

- Experiments performed in DIII-D and C-Mod changing elongation (growth rate) to find limit to vertical control
- $\Delta Z_{max}/a$ ~ 2% guarantees loss of vertical control
- Marginal ΔZ_{max} in both machines corresponds to $\Delta Z_{max}/a$ ~ 4%
- "Safe" operation in both machines corresponds to $\Delta Z_{max}/a$ > 5%
- Typical robust operation corresponds to $\Delta Z_{max}/a$ > 10%

DIII-D

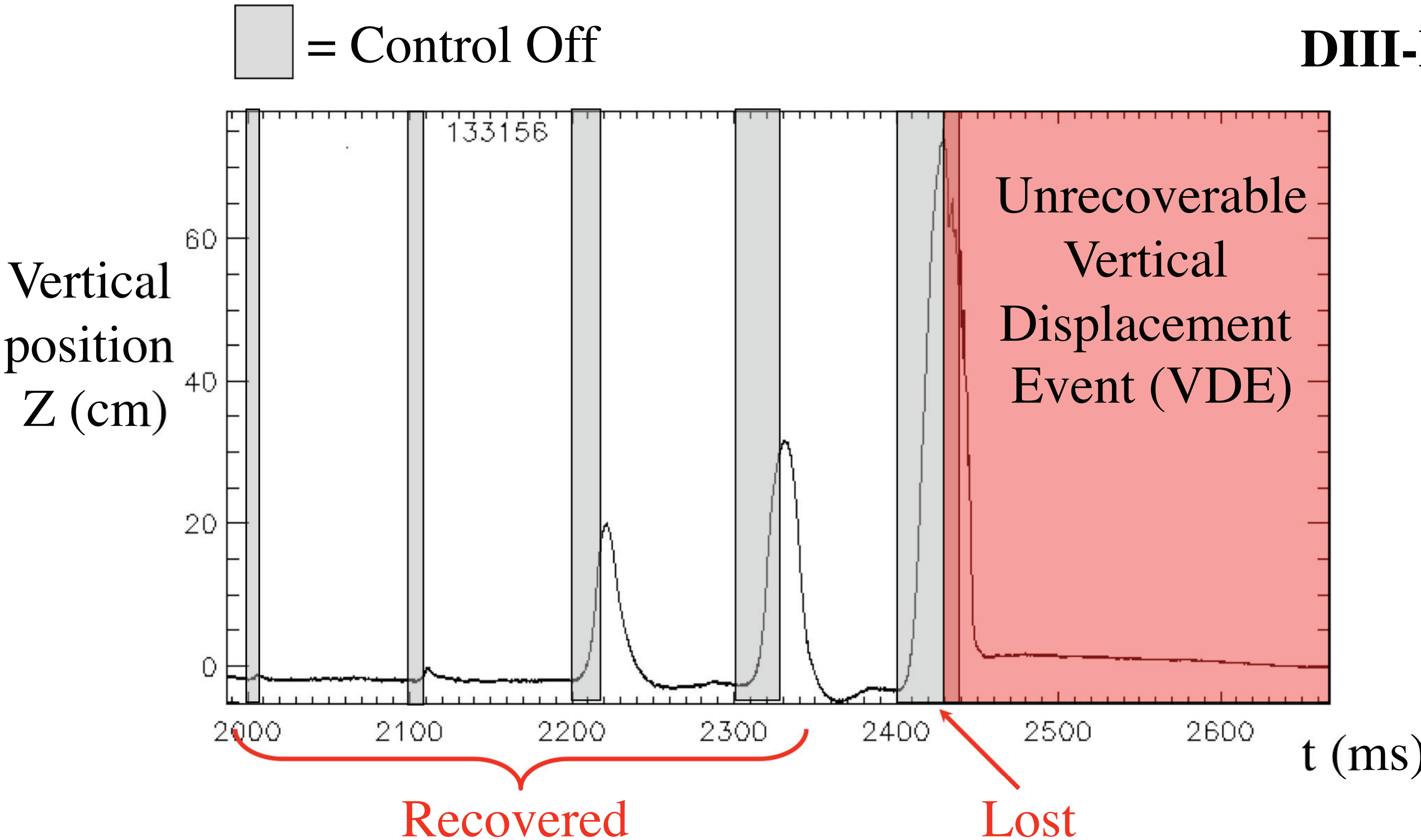


C-Mod

Case	γ_z (rad/s)	m_s	ΔZ_{max} (cm)	$\Delta Z_{max}/a$ (%)	$\Delta Z_{max}/\langle\Delta Z_{noise}\rangle$
1	210	0.41	2.8	13%	28
2	260	0.37	2.1	9.7%	21
3	310	0.33	1.5	6.9%	15
4	410	0.28	0.8	3.7%	8

Unsafe C-Mod operating point

Experiments Varying the Control Off Time and Vertical Displacement Search Large ΔZ Space in One Shot

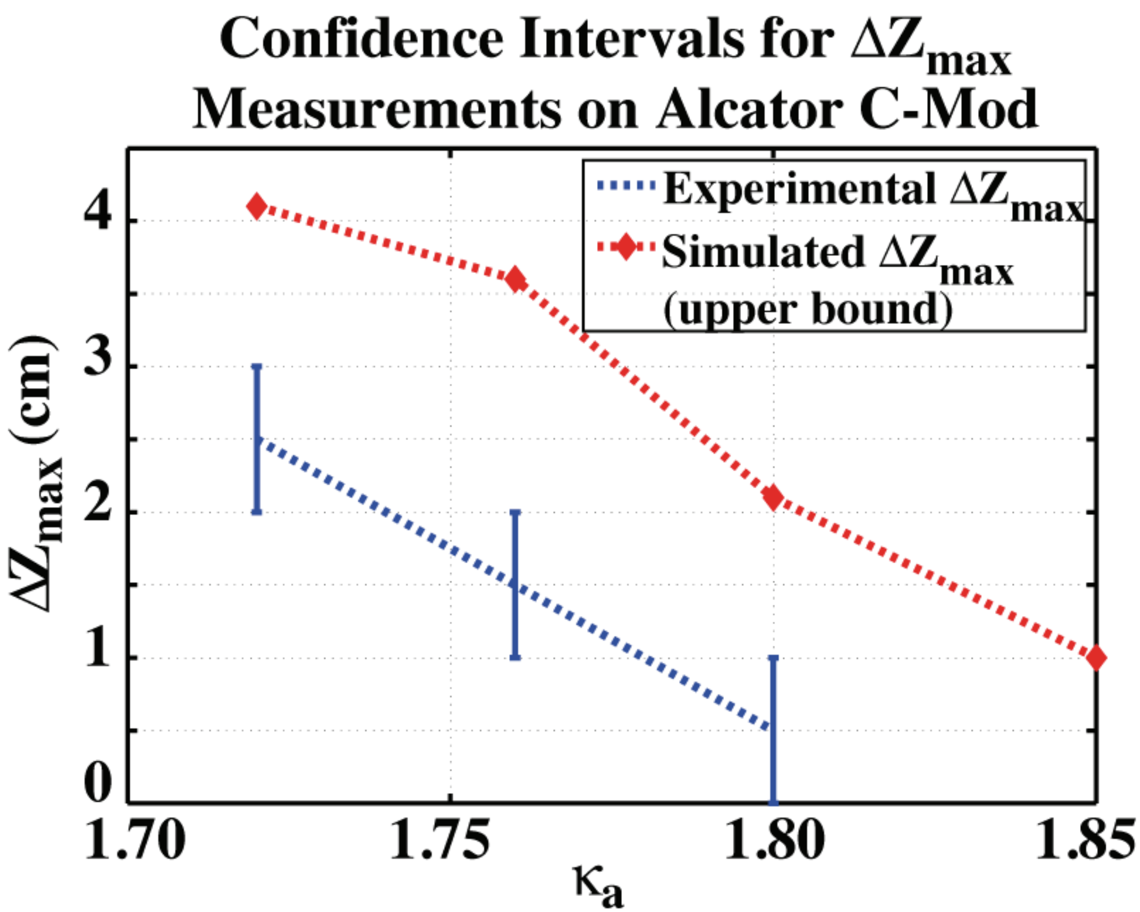


Alcator C-Mod ΔZ_{max} Experiment Shows Predicted Values Are About Twice Experimental Values

- Elongation κ_a varied, vertical control disabled for varying periods

- Calculated ΔZ_{MAX} ~ 30-50% above maximum experimental value for each κ_a

- Alcator C-Mod ΔZ_{max} determined by coil current limit, not voltage limit
  - Similar to proposed ITER in-vessel coils

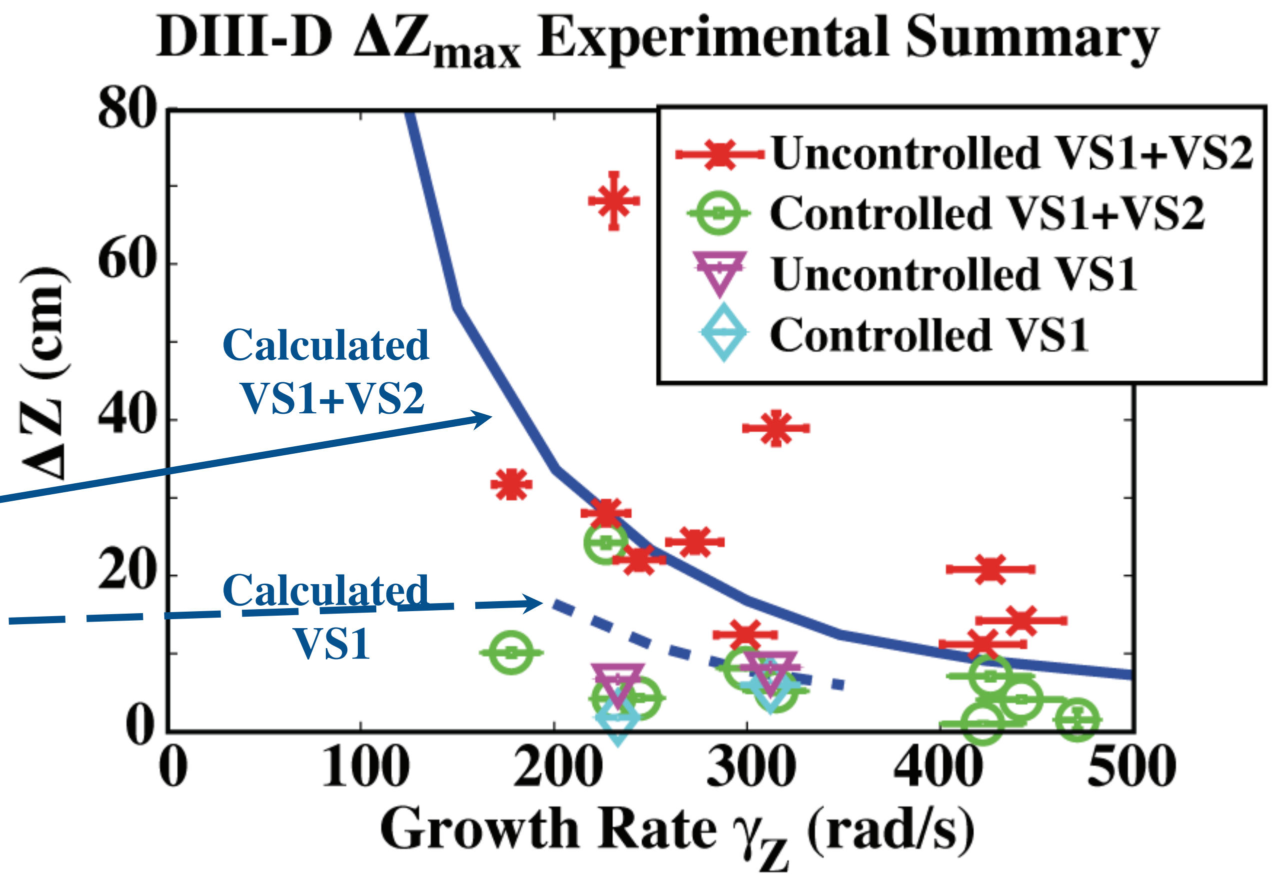


DIII-D ΔZ_{max} Experiment Shows Use of Inboard Coils Approximately Doubles Performance

- Elongation varied to vary growth rate in different discharges

- Use of inboard+outboard coils ~ doubles ΔZ_{max} of outboard-only

- Calculated ΔZ_{max} ~20-30% above experimental values

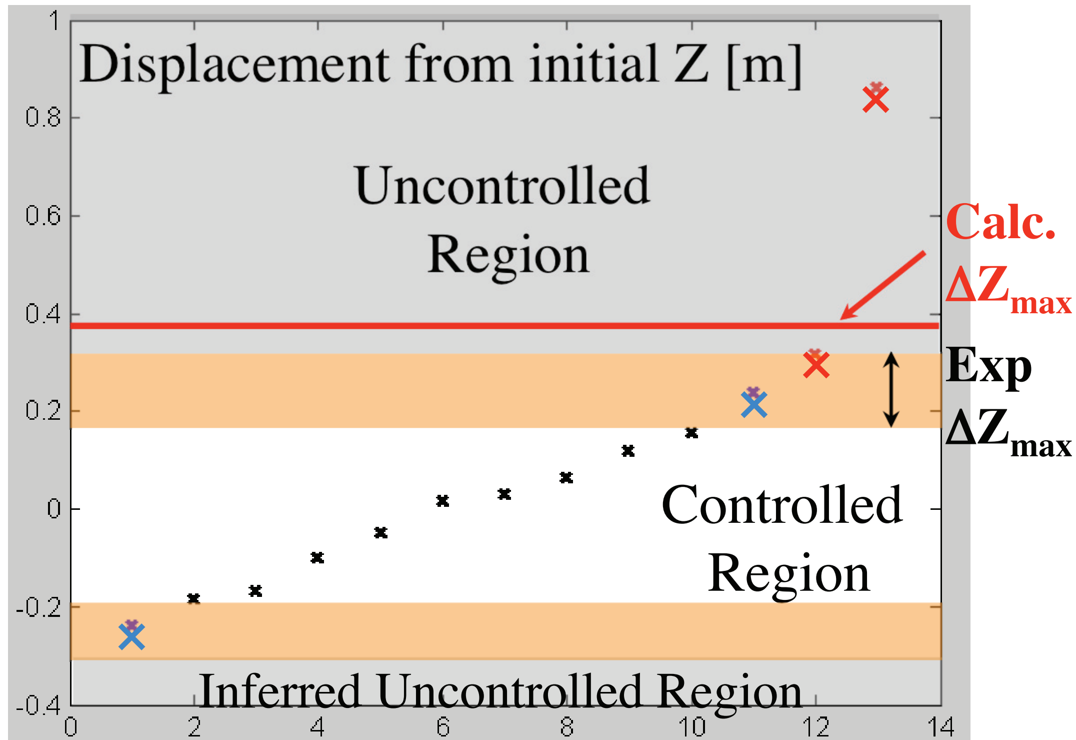


VS1 = outboard coilset

VS2 = inboard coilset

NSTX ΔZ_{max} Experiment Shows Predicted Value ~30% Greater than Experiment

- Single equilibrium target was studied with varying distances of vertical drift:
  - Single growth rate and ΔZ_{MAX} value
  - Finely resolved range of ΔZ cases
- Calculated value ΔZ_{MAX}~30% above experimental maximum
- Potential role of nonaxisymmetric conductors, nonlinear interaction with limiter
  - Suggests need for modeling 3D effects of ITER conductors



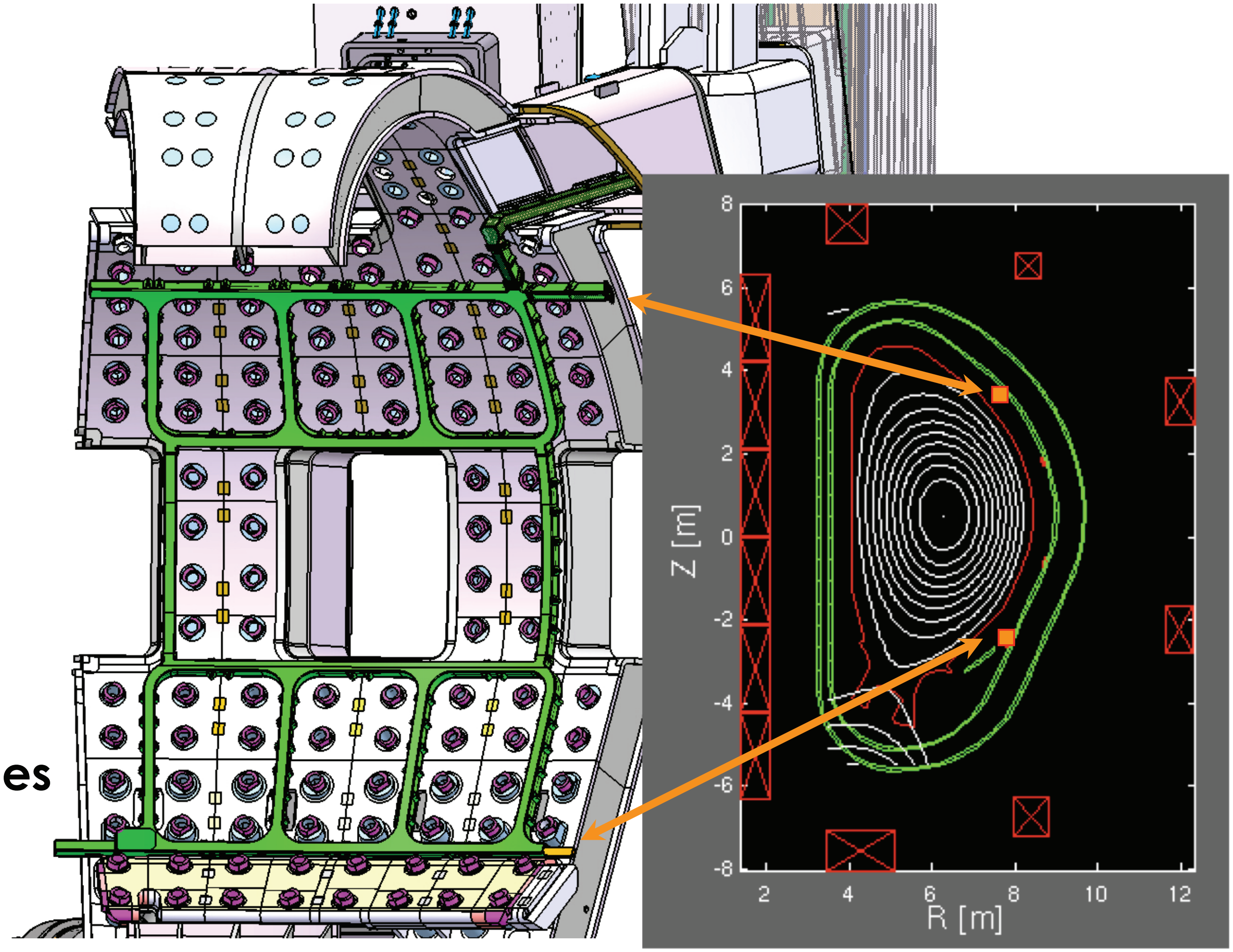
Sorted Experimental Shot Index

× = controlled
× = limiter interaction, restored
× = uncontrolled

ITER Design Now Incorporates In-Vessel Coils for Increased Vertical Control Capability

- In-vessel coils alone provide $\Delta Z_{max}/a \sim 5\%$ capability

- Pose significant engineering design, fabrication, and maintenance challenges



Summary and Conclusions

- **Multi-machine experiments for vertical control performance have:**
  - Quantified vertical control performance in present devices
  - Partially validated theoretical performance scalings
  - Translated performance data/analysis into metric specifications

- **Experiments/analysis have provided key motivation for improving ITER vertical control capability:**
  - $\Delta Z_{max}/a > 5\%$ required for robust control at edge of ITER operating space
  - $\Delta Z_{max}/a \sim 2\%$ is capability of ITER baseline system
  - ITER in-vessel coils being designed to provide $\Delta Z_{max}/a > 5\%$
  - Discrepancies between calculation and experiment emphasize need for margin in design

- **Work remains to carefully analyze physics of control limits:**
  - Details of noise-determined control limits
  - Types, magnitudes, detailed histories of disturbances to expect in ITER

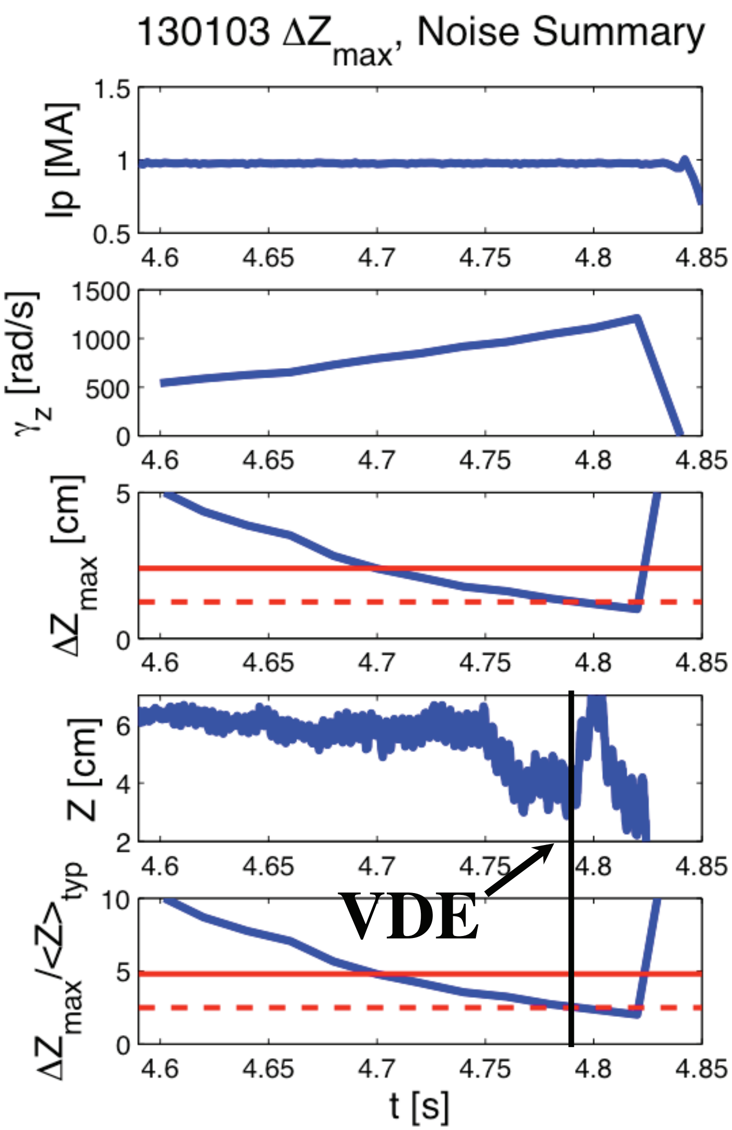
Multi-machine Noise Data Shows $\langle Z \rangle_{noise}/a \sim 0.5–1\%$

- Data represents all sources of noise in real-time vertical position estimator for each device ($\langle Z \rangle_{noise}$ = standard deviation in "typical" operation)
- Noise contributions include instrumentation, power supply pickup, discrete measurement reconstruction error, plasma instability-driven signals, etc.
- TCV underwent extensive noise-abatement process to reduce $\langle Z \rangle_{noise}$
- Implies $\Delta Z_{max}/a \sim 5\%$ corresponds to $\Delta Z_{max}/\langle Z \rangle_{noise} \sim 5–10$ in present experiments

Device	Typical $\langle Z \rangle_{rms}$ (cm)	Minor radius, a (cm)	$\langle Z \rangle/a$ (%)
Alcator C-Mod	0.10	21	0.5
DIII-D	0.4	60	0.7
JET	1.4	100	1.4
NSTX	0.7	63	1.1
TCV	0.05	25	0.2

Controllability Threshold Experiments in DIII-D Show $\Delta Z_{max}/\langle Z\rangle_{noise} \sim$ 2–3 Assures VDE

- **DIII-D: increasing elongation in single discharge to increase growth rate γ_Z until VDE**
- **Uncontrollable VDE occurs at $\Delta Z_{max}/\langle Z\rangle_{noise} \sim 2$–$3$**
- **Consistent with ΔZ_{max}, $\langle Z\rangle_{noise}$ controllability threshold data in DIII-D:**
  - VDE guaranteed at $\Delta Z_{max}/a \sim 2\%$
  - Typical $\langle Z\rangle_{noise}/a \sim 0.7\%$
  - $\Delta Z_{max}/\langle Z\rangle_{noise} \sim 3$ assures VDE
- **Marginal control in Alcator C-Mod and DIII-D corresponds to:**
  - $\Delta Z_{max}/a \sim 4\%$
  - $\Delta Z_{max}/\langle Z\rangle_{noise} \sim 5$–$8$



Disturbances Alone Will Require ITER to Have Sufficient $\Delta Z_{max}/a$ Capability

- **Noise sets typical control limits in DIII-D, Alcator C-Mod, JET, NSTX:**
  - → **Noise-driven $\langle Z \rangle_{RMS}/a \sim 0.5\text{-}1\%$ in these**

- **It is possible that ITER will have lower noise than US machines:**
  - → **CRPP-Lausanne has contract for magnetic diagnostics/noise reduction**
  - → **Noise reduction procedure demonstrated in TCV: $\langle Z \rangle_{RMS}/a < 0.2\%$**

- **Nevertheless, various plasma disturbances may set limit to control in ITER:**
  - → **DIII-D ITER demonstration discharges produce ELM-driven plasma perturbation $\Delta Z_{ELM}/a \sim 3\%$**