Experimental Vertical Stability Studies for ITER Performance and Design Guidance

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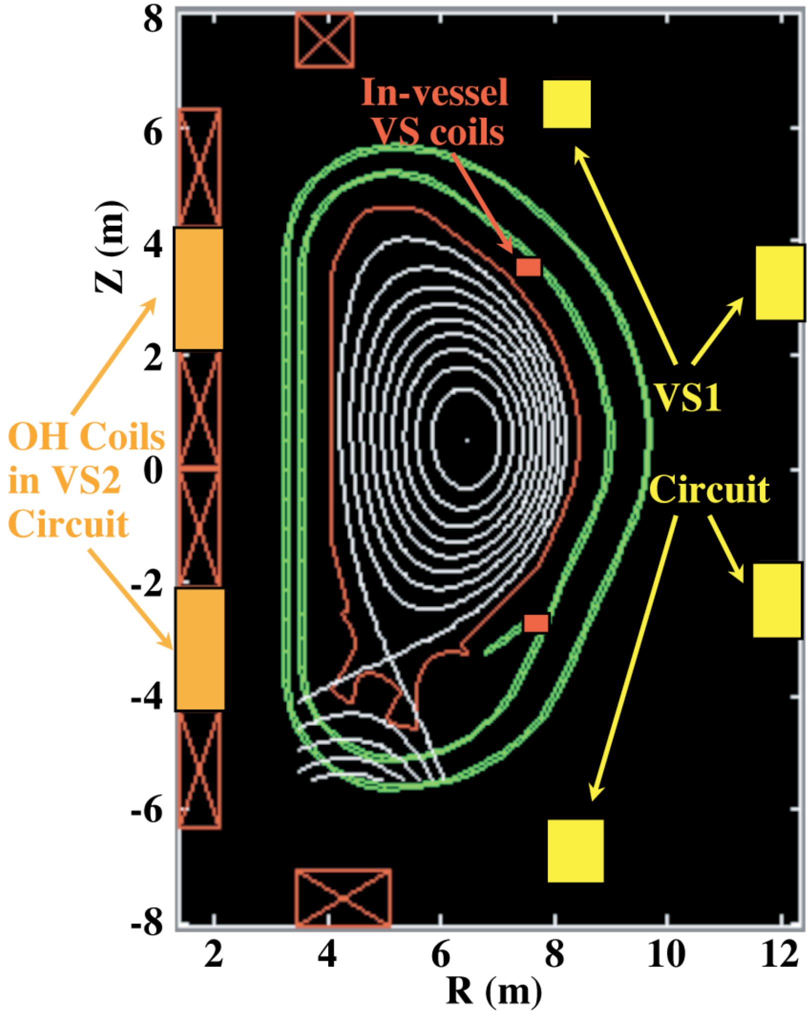
**Presented at the
22nd IAEA Fusion Energy Conference
Geneva, Switzerland
October 13–18, 2008**

ITER System Geometry



Overview

- **ITER vertical stability control is challenging:**
  - Controllability is marginal with baseline system at $\ell_i(3)>1.0$, $\kappa=1.85$
  - ℓ_i (3)>1.2 can occur in ohmic/L-mode, rampdown, high-q plasmas
  - Allowable number of vertical control loss events is limited

- **Metrics for vertical control performance include:**
  - Stability margin m_S ($\sim \tau_Z/\ \tau_W$ = vertical growth time/wall time)
  - Maximum controllable displacement ΔZ_{max}

- **Experiments in Alcator C-Mod, DIII-D, JET, NSTX, and TCV have helped guide performance requirements for ITER:**
  - Quantifying operational performance metrics
  - $\Delta Z_{max}/a > 5\%$ needed for robust operation
  - ITER baseline system capability: $\Delta Z_{max}/a = 2\%$
  - In-vessel coils planned for ITER expected to provide $\Delta Z_{max}/a > 5\%$

Why Baseline ITER07 Has Overall Degraded Vertical Control Margins Relative to ITER EDA

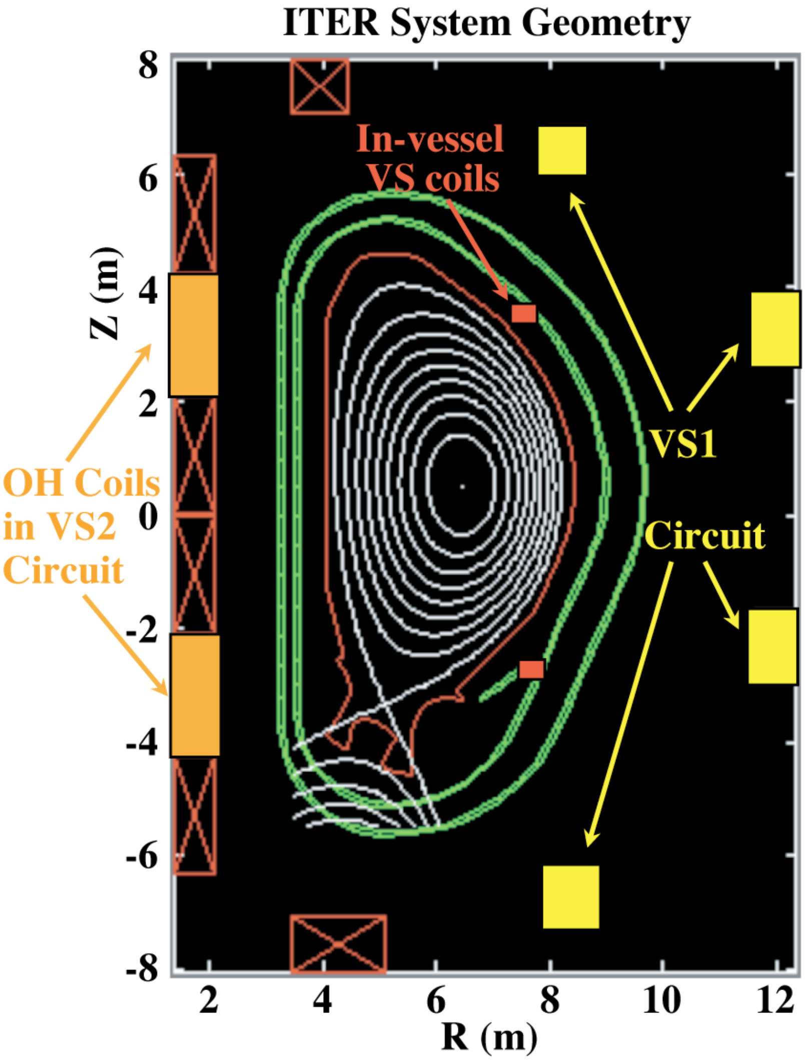
- Size was reduced to reduce cost
- Coils were consolidated (number reduced) to reduce cost
- Plasma elongation was increased to recover some performance
- Approximately fixed shielding depth caused PF coils to move farther away from plasma as fraction of minor radius
- Power supply capabilities and coil operating points were not increased to compensate sufficiently

ITER EDA 98 ITER 07

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

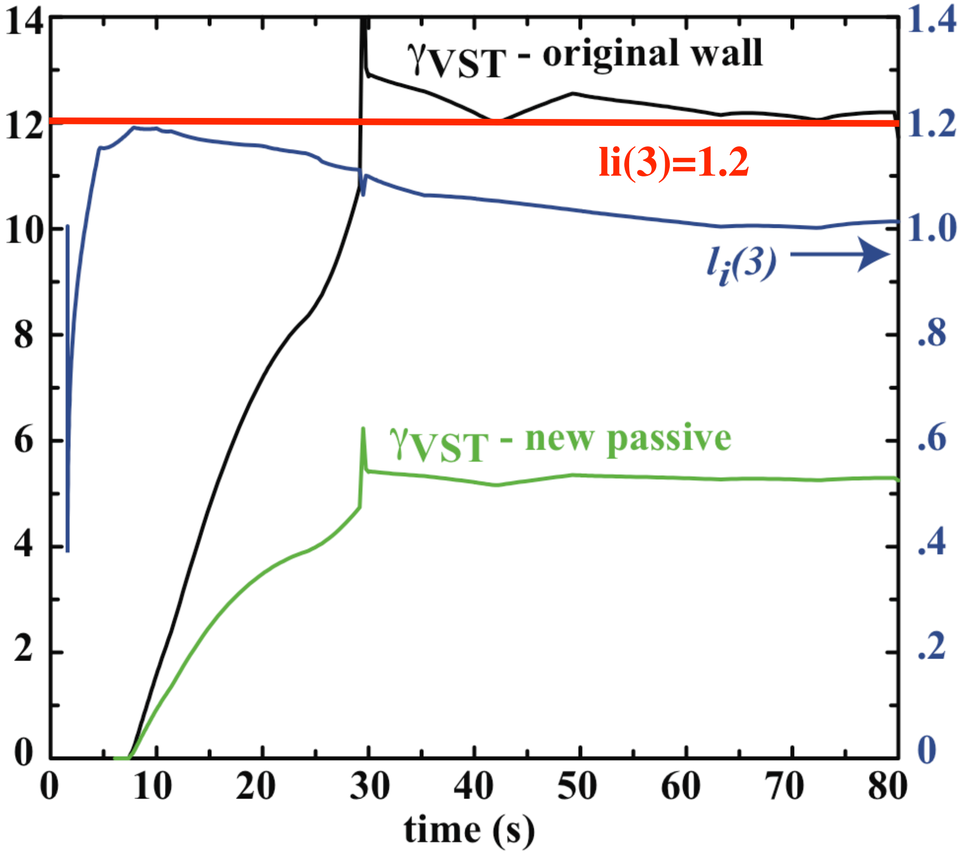
- Proposals to enhance VS system include (from 2007-08 Design Review/STAC studies):
  - Increase VS1 voltage to 9 kV
  - Use “VS2” circuit = 2 central solenoid coils (6 kV)
  - Add in-vessel passive stabilizers
  - Add in-vessel VS coils mounted on vessel wall behind blanket modules



Baseline Scenarios Challenge Vertical Control Capability of Baseline Control System

- $\ell_i(3)=1.0$, $\kappa=1.85$ (γ_Z~12) is marginally controllable by baseline VS1 system
- Potentially uncontrollable $\ell_i(3) > 1.2$ can occur in baseline startup scenario, in high q_{95} operation, or in rampdown
- New large bore startup can help by keeping ℓ_i to < 1.2, but still > 1.0, so control still marginal with baseline VS1
- Passive structure additions can reduce growth rate and enable reliable vertical control, BUT
  - Reduce controllability of boundary, divertor
  - Shield magnetics, reducing accuracy of reconstruction

Corsica Large Bore ITER startup



VST: Corsica Vertical STability package

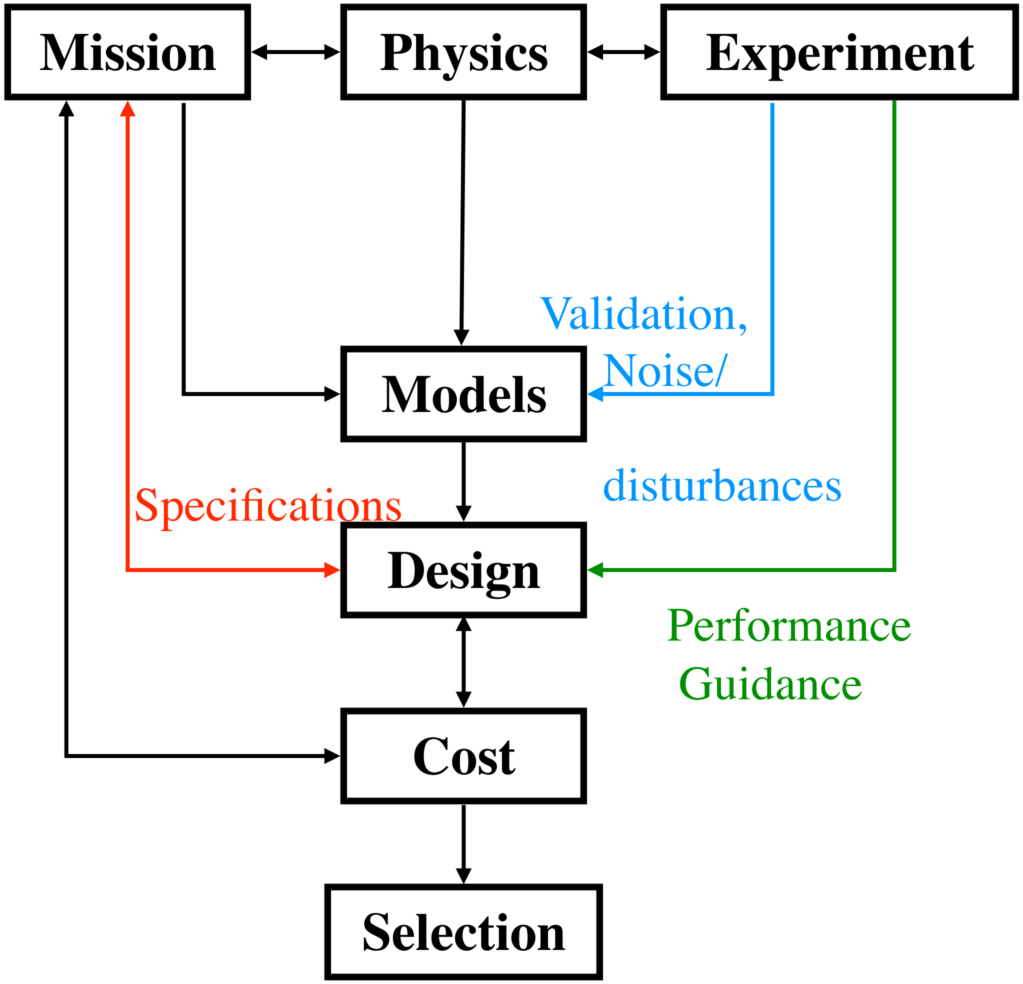
Experiments are Essential to Provide Guidance for Operational Robustness, Noise, Disturbances

- Control design requires validated models, specification of robustness needed, specification of noise and disturbance environment

- There is no fully predictive capability for noise/disturbance environment expected in ITER

- Experiments can provide:
  - Model validation
  - Data on robustness experience
  - Validation of metric calculations
  - Data on metric performance
  - Data on noise/disturbance environments
  - Opportunities to test control approaches

- Metrics quantify performance needs



Machine Design Requires Performance Metrics for Vertical Control

- **Stability margin $m_S \sim \tau_Z/\tau_W = \gamma_W/\gamma_Z$** describes distance from ideal limit in γ-space, primarily linear performance:
  - Absolute growth rate performance measure
  - Useful, but what we really want to quantify is distance from maximum controllable boundary
  - $m_s/m_{s(min)}$ quantifies distance from controllable boundary [where $m_{s(min)}$ is the minimum controllable m_s]

- **n/n_{CRIT}** describes distance from ideal limit in decay index space, more directly mapped to physics performance (principally β and β_N):
  - Absolute "physics" performance measure
  - Useful, but doesn't map well to control aspects
  - Small changes in proximity to ideal limit produce large changes in growth rate

- **Maximum controllable displacement ΔZ_{max}** describes nonlinear control performance (but also aspects of linear) including voltage saturation, current limits:
  - Absolute performance relative to disturbance/noise coupling to vertical displacement
  - $\Delta Z_{max}/\langle\Delta Z\rangle_{noise}$ reflects "how much more ΔZ disturbance or noise" can be tolerated
  - $\Delta Z_{max}/a$ is geometry-independent scaling to compare machines' operational boundaries

Stability Margin Is a Measure of Margin Relative to Ideal Limit

- Stability margin m_s is measure of instability growth time normalized by effective wall time:

$$m_s \equiv \lambda\left\{L^{-1}L_*\right\}_1 \approx \frac{\tau_z}{\tau_w}$$

(L=mutual inductance matrix, L_*=effective inductance matrix including plasma. $\lambda\{\}_1$ denotes dominant eigenvalue)

- Definition depends on inductive coupling only: independent of resistive circuit characteristics

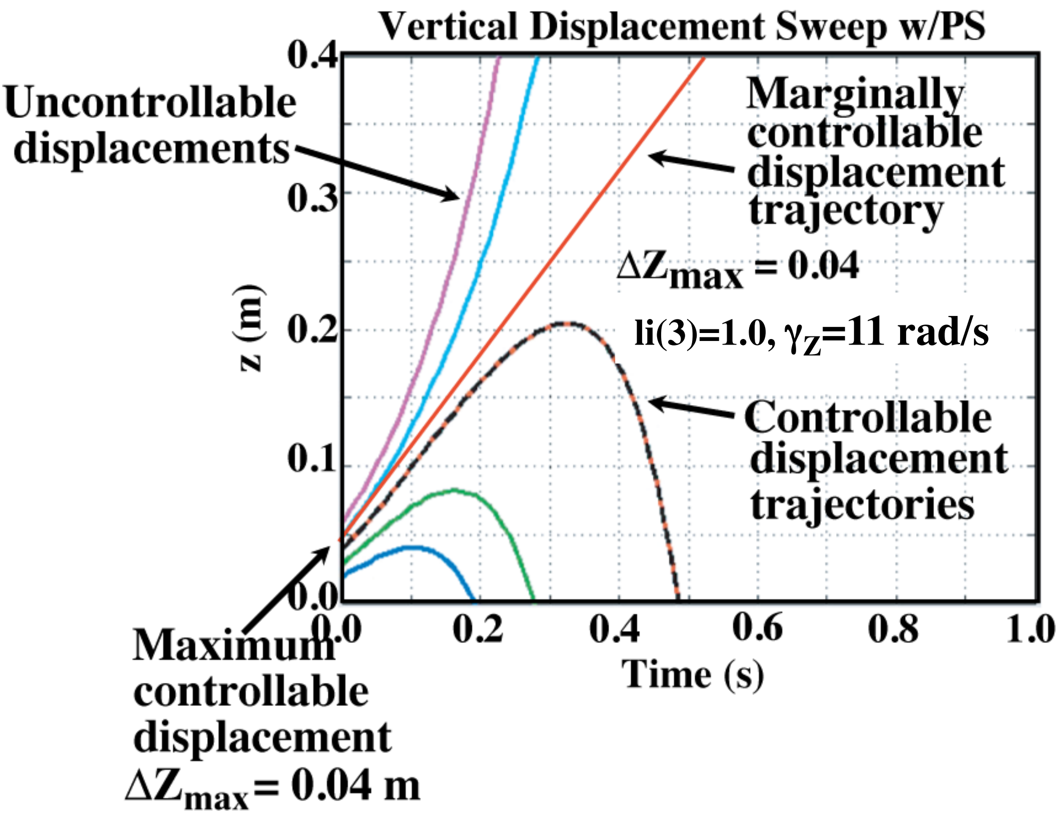
- Applicable to systems in which vessel and coils have very different characteristic decay times (then τ_w is an effective hybrid time)

- Quantifies "margin" relative to ideal limit (corresponding to m_s=0)

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

- ΔZ_{max} = maximum displacement beyond which VDE cannot be reversed
- Plasma allowed to drift for distance ΔZ
- Fully saturated step voltage commands applied to all power supplies in vertical control circuit to apply maximum/fastest radial field to oppose VDE (note in some devices current limits are the limiting aspect); vary ΔZ to find ΔZ_{max}
- At same time apply constant shape circuit voltages which would keep constant shaping current if no perturbation (i.e., V=const for Cu, V=0 for SC)
- NOT a true control demonstration, but reflects "best possible"
- $\Delta Z_{max}/a$ is a machine-independent metric to provide guidance to ITER from present devices

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



Uncontrollable displacements

Marginally controllable displacement trajectory

$\Delta Z_{max} = 0.04$

li(3)=1.0, γ_Z=11 rad/s

Controllable displacement trajectories

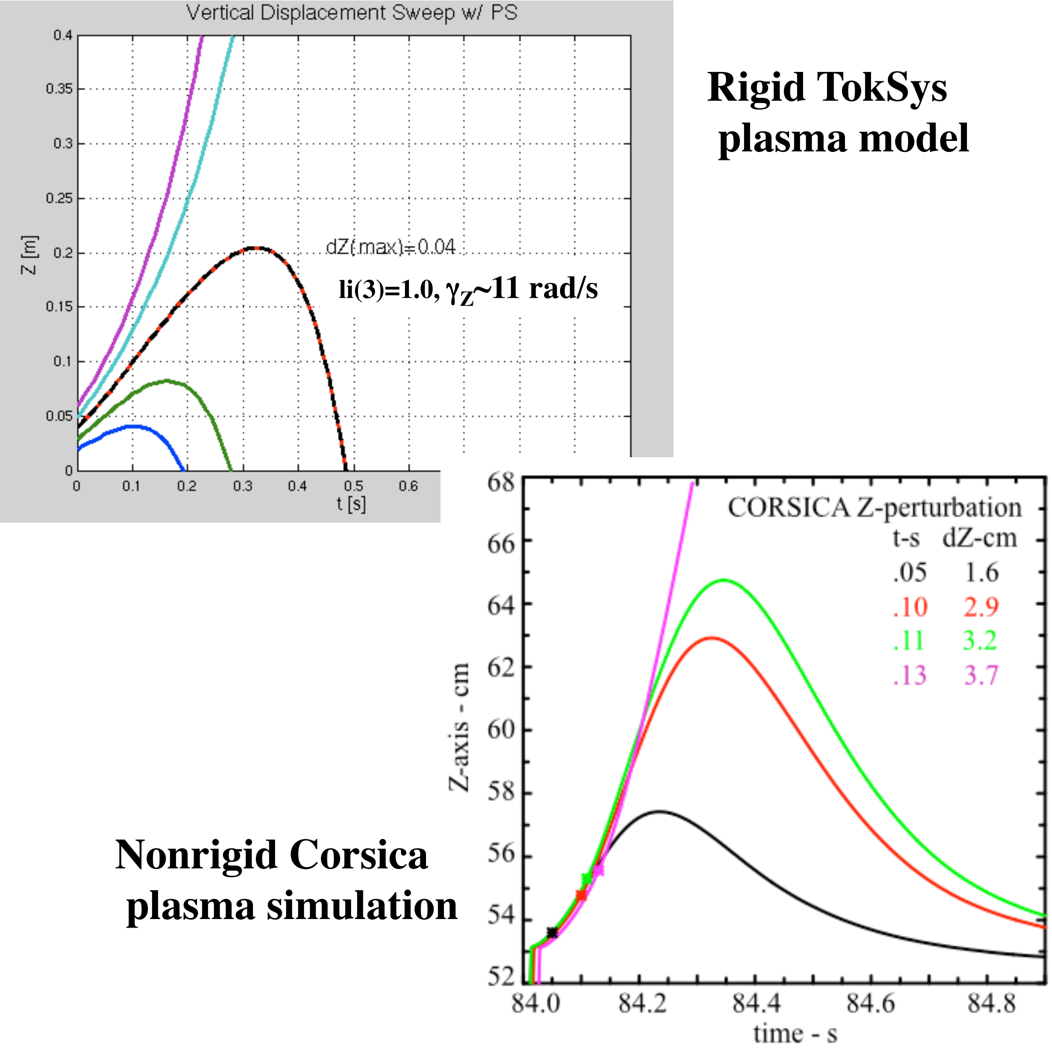
Maximum controllable displacement $\Delta Z_{max} = 0.04$ m

ITER Analyses Find $\Delta Z/a$~2% for Baseline Design and $\ell_i(3)$=1.0 Equilibrium

- Analysis of VS1 circuit (6 kV limit on P2-5) to find point plasma can be turned around

- Linear rigid TokSys model finds max controllable vertical displacement of ~ 4.2 cm ($\Delta Z_{max}/a$ ~ 2%)

- Nonlinear nonrigid Corsica simulation finds ΔZ_{max}~3.5 cm ($\Delta Z_{max}/a$ ~ 2%)



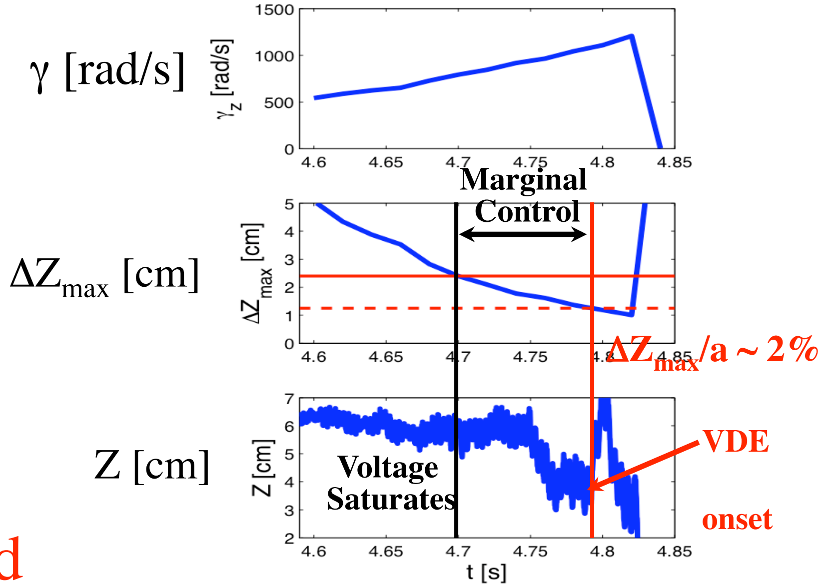
Rigid TokSys plasma model

Nonrigid Corsica plasma simulation

Calculated ΔZ_{max} in DIII-D and C-Mod Drops Below $\Delta Z/a$ ~ 4% Just Before VDE Onset

- **Experiments in DIII-D and C-Mod changing elongation to find limit to vertical control**
- **$\Delta Z_{max}/a$ ~ 2% guarantees VDE**
- **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

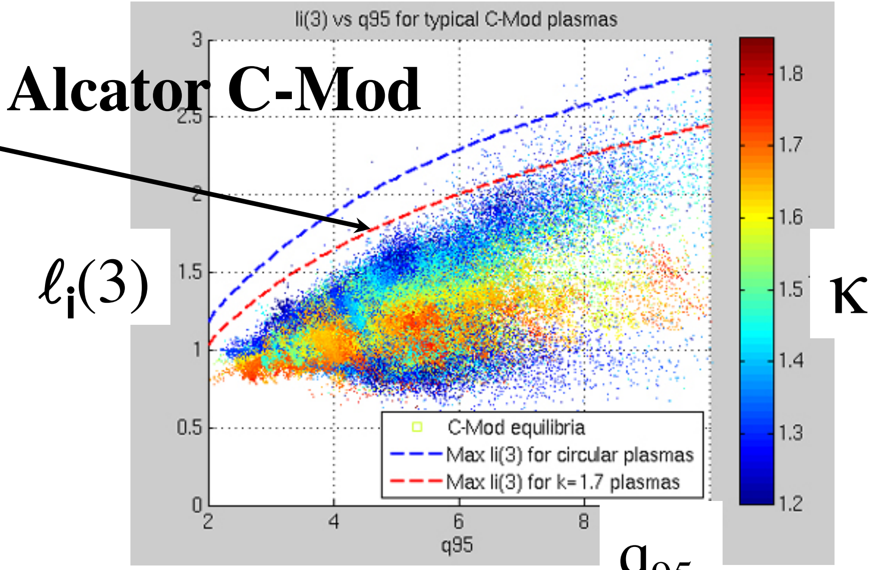
Alcator C-Mod and DIII-D Data Show $\ell_i(3)$~1.2-1.3 Attainable at q_{95}=3.0

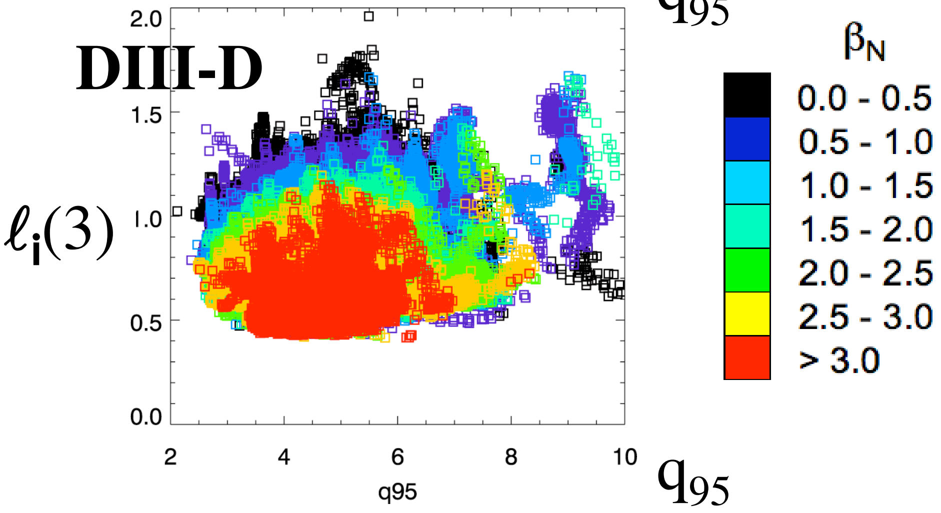
- Analytic model relating ℓ_i, kappa, q_{95} matches maximum experimental ℓ_i values in Alcator C-Mod

- Increasing q_{95} increases ℓ_i range

- Increasing ℓ_i increases vertical growth rate

- If ITER operates at low current (high q_{95}) the elongation must be reduced in order to maintain vertical control



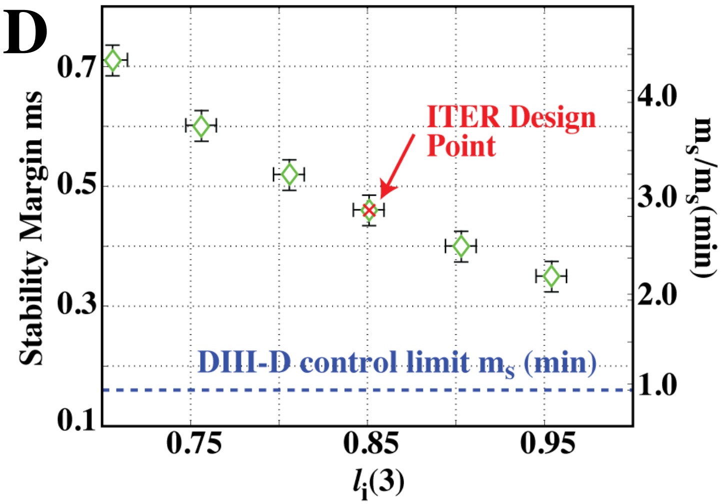


ITER $\ell_i(3)=0.85$, $\kappa=1.85$ Design Point Has Same Relative Stability Margin in DIII-D, Alcator C-Mod, ITER

- DIII-D $m_S/m_{S(min)}$ ~ 3:
  - m_S~0.45 for ITER similar shape/ℓ_i
  - $m_{S(min)}$ control limit ~ 0.16
- Alcator C-Mod $m_S/m_{S(min)}$ ~ 2:
  - m_S~0.50 for ITER similar shape/ℓ_i
  - $m_{S(min)}$ control limit ~ 0.26
- ITER $m_S/m_{S(min)}$ ~ 2 (baseline):
  - m_S~0.70 for baseline shape/ℓ_i
  - $m_{S(min)}$ control limit ~ 0.37
- By this metric, control of the ITER baseline design point is equally robust in DIII-D, Alcator C-Mod, and ITER

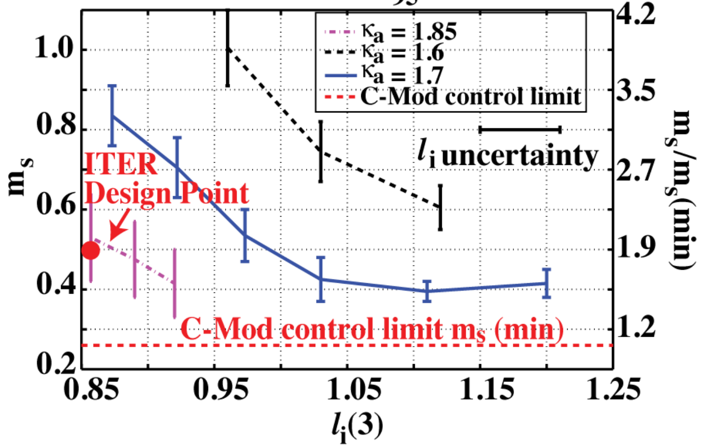
DIII-D

DIII–D ITER Similarity Stability Margin vs $l_i(3)$



Alcator C-Mod

Stability Margin for ITER-like C-Mod plasmas, q_{95} = 3.0, 3.5



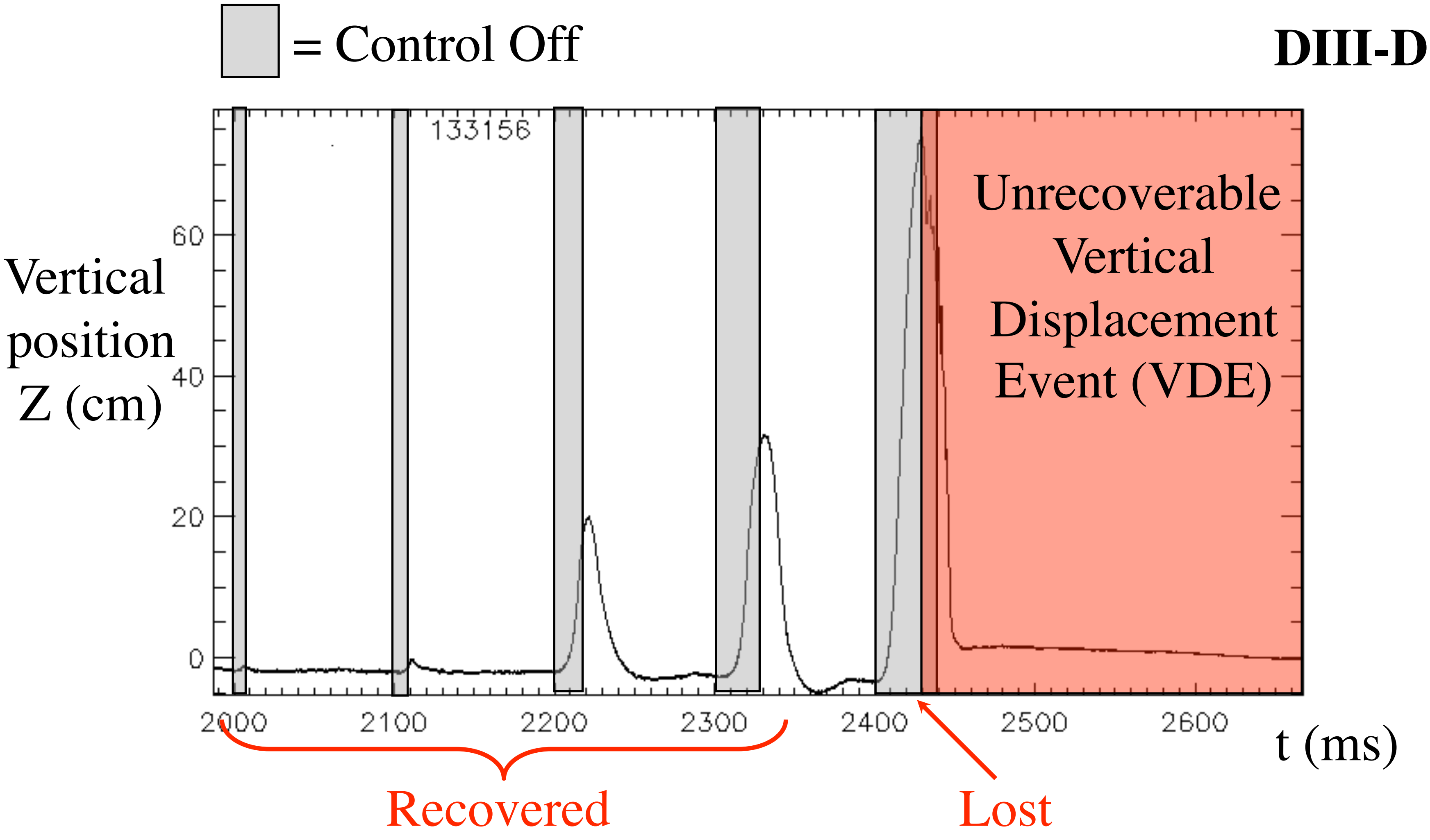
ITPA Stability Group Joint Experiment to Provide Vertical Stability Guidance to ITER

- **Goals:**
  - Determine experimentally the **maximum controllable growth rate** and **$\Delta Z_{max}/a$** (also "safe" operating values, "robust" operating values)
  - Provide data to validate calculations of maximum controllable **$\Delta Z_{max}/a$**
  - Determine RMS Z^*I_p, $d(Z^*I_p)/dt$, spectra without PS, without plasma, with plasma (+PS)
  - Characterize relevant disturbances and degree of excitation of unstable mode
  - Provide guidance to ITER design on operation limits, robustness/"safe" operation regimes, noise environment

- **Experiments:**
  - Increase elongation in steps, holding for periods > $10\tau_Z$ to determine controllability boundaries
  - Using targets near maximum kappa, freeze coil commands to disable vertical control for period to allow VDE, then apply explicit step command to control coils (in some cases, simply restore control)
  - Study response to explicit disturbances near control limits (e.g. beam drops, H→L transitions, impurity gas injection…)
  - **Machines Participating: Alcator C-Mod, ASDEX-Upgrade, DIII-D, JET, NSTX, TCV**

Varying the Control Off Time Varies Vertical Displacement to Search Large ΔZ Space in One Shot

DIII-D



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

- Elongation κ_a varied, vertical control disabled for varying periods

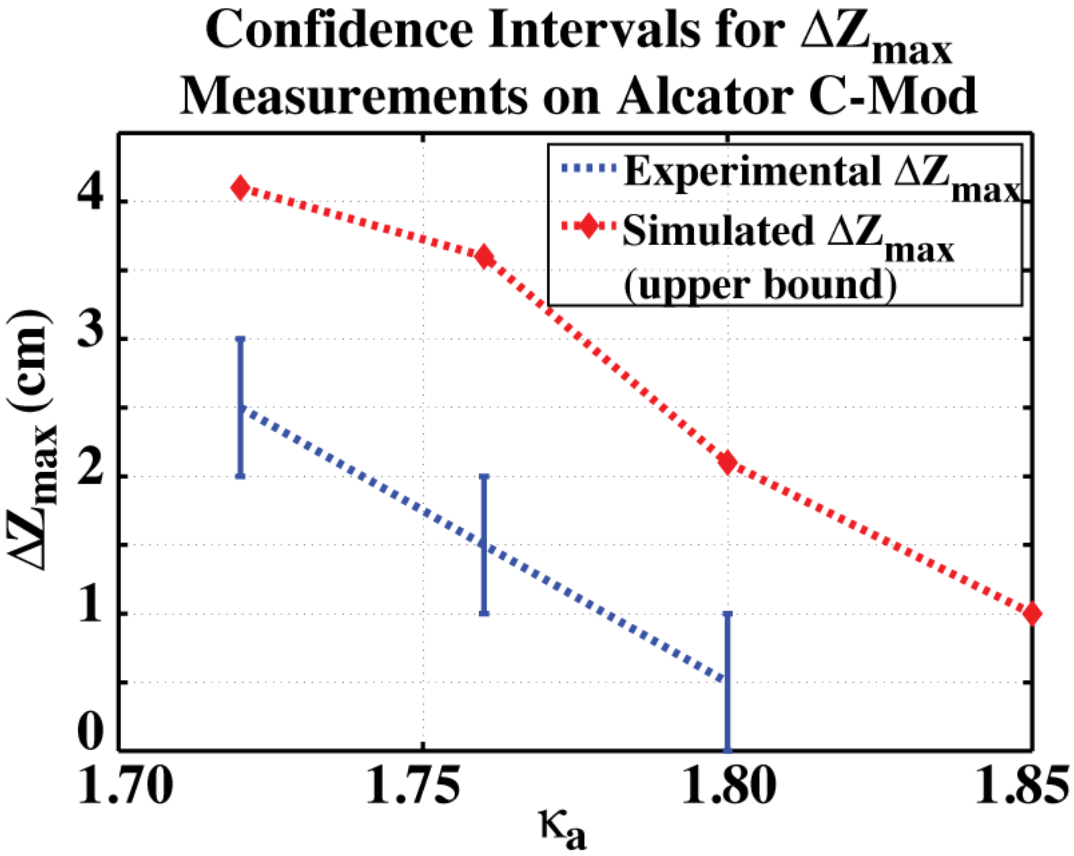
- Several discharges at each κ_a

- Upper bound of calculated

  ΔZ_{max} for discharges at each κ_a is ~2x experimental value.

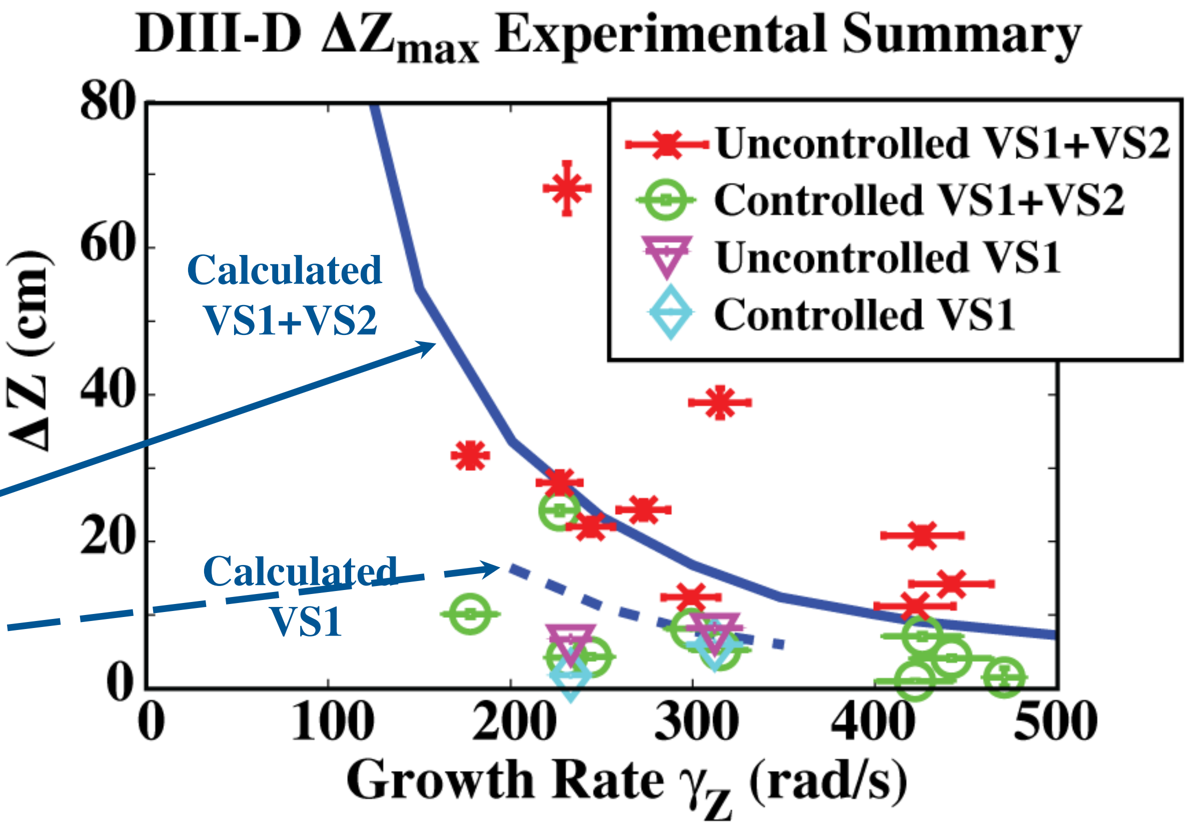
- Maximum reliable controllable displacement $\Delta Z_{max}/a$ ~ 5% (1cm/21cm)

- 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
- Vertical control disabled for varying lengths of time
  - Produces varying displacements
- Use of inboard+outboard coils ~ doubles ΔZ_{max} of outboard-only
- Calculated value agrees reasonably well with experimental ΔZ_{max}



VS1 = outboard coilset

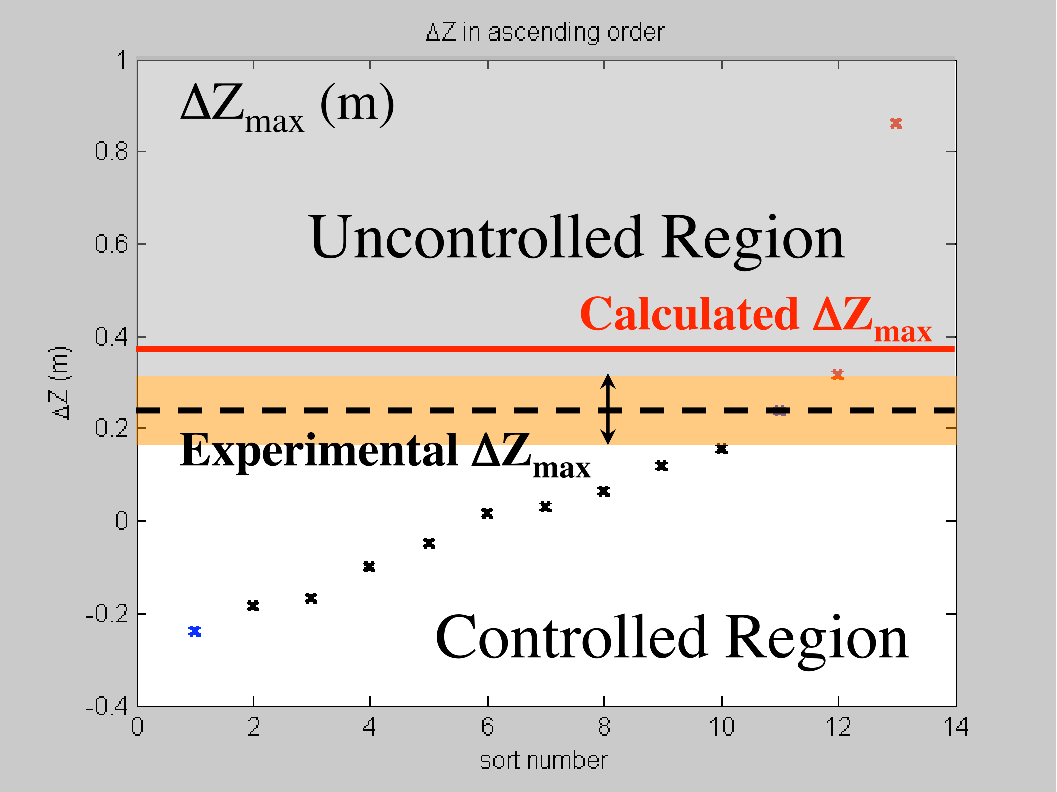
VS2 = inboard coilset

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 ΔZ cases

- Experimental ΔZ_{max} ~ 0.24 ± 0.08:
  - Interaction with limiter occurs at ΔZ ~ ±0.24 m; position restored but with large loss of beta…
  - Plasma completely lost vertically at ΔZ ~ 0.32 m
  - Largest clear controlled point at ΔZ ~ 0.16 m

- Calculated value:
  - ΔZ_{max} ~ 0.37
  - ~30% above experimental mean



Sorted Experimental Shot Index

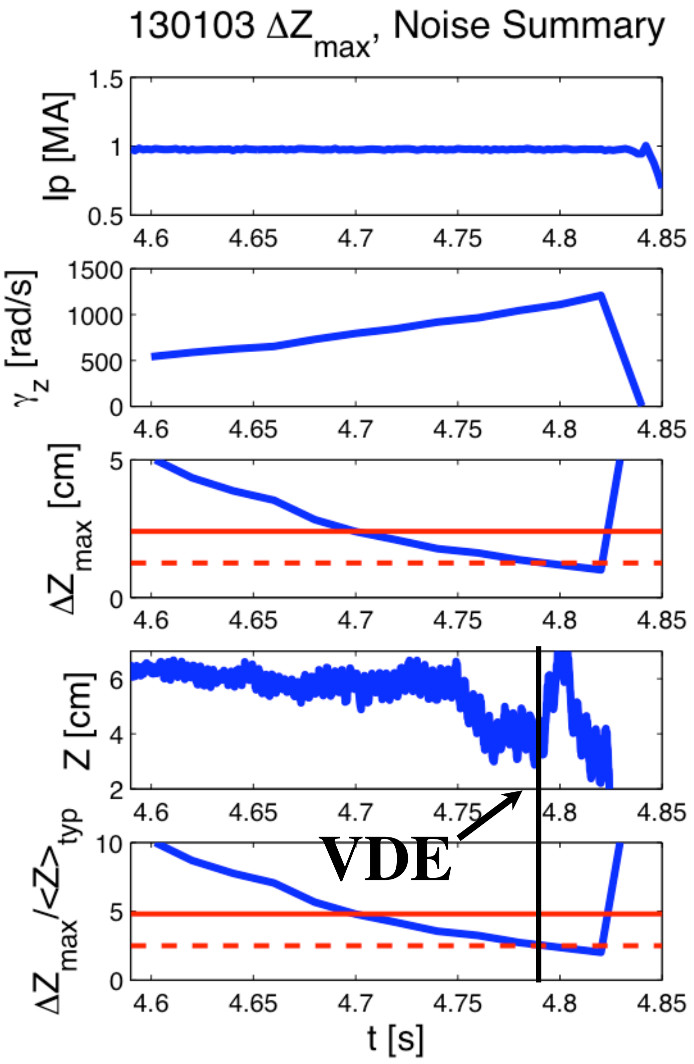
Multi-machine Noise Data Shows $<Z>_{noise}/a \sim 0.5–1\%$

- Data represents all sources of noise in real-time vertical position estimator for each device ($<Z>_{noise}$ = 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 $<Z>_{noise}$
- Implies $\Delta Z_{max}/a \sim 5\%$ corresponds to $\Delta Z_{max}/<Z>_{noise} \sim 5–10$ 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 $\Delta Z_{max}/\langle Z\rangle_{noise}$ ~ 2–3 Assures VDE

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



Performance Equation Based on Ability of Active Coil(s) to Turn Plasma Trajectory Around

- **Assumptions:**
  - Plasma trajectory well-described by axisymmetric circuit equation
  - Plasma response linear (e.g., nonrigid perturbed equilibrium, rigid current-conserving…)

Plasma response terms

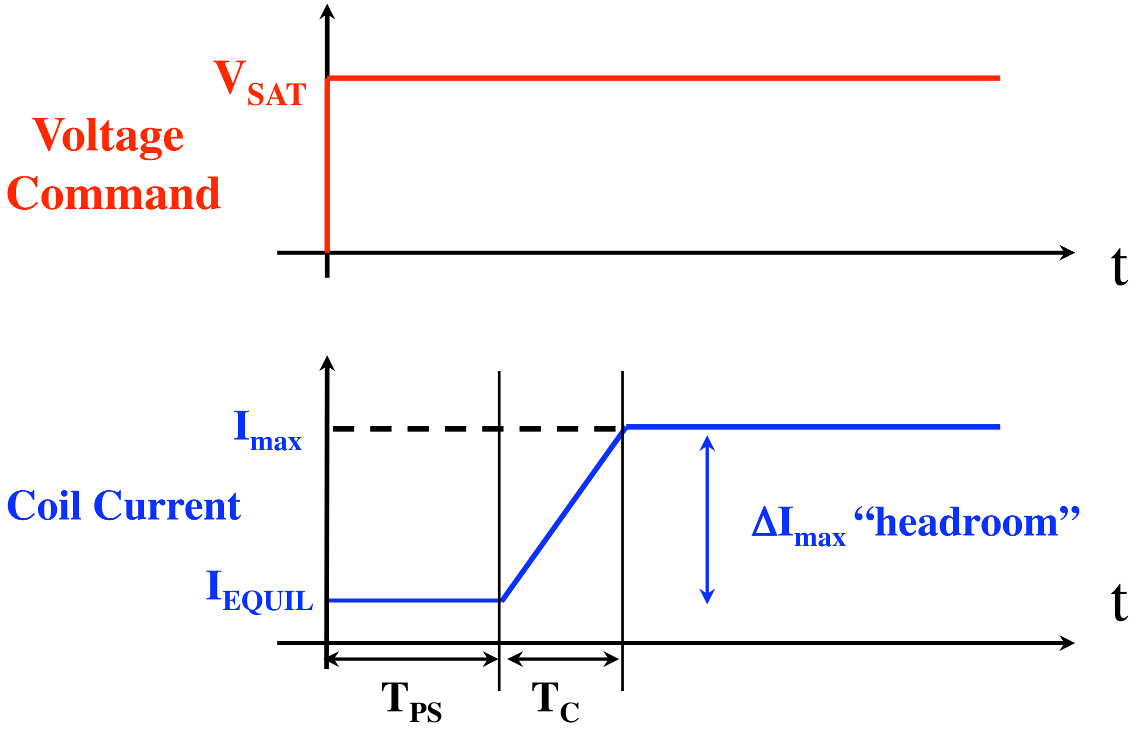
$$L_V\dot{I}_V + R_V I_V + \boxed{\frac{\partial\psi_V}{\partial z}\frac{\partial z}{\partial I_V}}\dot{I}_V = -(M_{VC} + \boxed{\frac{\partial\psi_V}{\partial z}\frac{\partial z}{\partial I_C}})\dot{I}_C = L_V\dot{I}_V + R_V I_V + \boxed{X_{vv}}\dot{I}_V = -(M_{VC} + \boxed{X_{VC}})\dot{I}_C$$

Effective inductances including plasma response:

$$\boxed{L_{*V}}\dot{I}_V + R_V I_V = -\boxed{M_{*VC}}\dot{I}_C$$

Simple Power Supply + Coil Response Dynamics Model

- Saturated voltage
- Coil response approximated by ramp (exact for SC)
- Pure transport delay T_{PS}
- Ramp time T_C determined by ΔI_{max} “headroom” available from given equilibrium current I_{EQUIL}



During current ramp:

$$I_C(t) = \frac{V_{sat}}{L_C} t \qquad T_C \sim \frac{\Delta I_{max} L_C}{V_{sat}}$$

Performance Equation Quantifies Some Effects of Key Physics and Control Aspects on ΔZ_{max}

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

- $\Delta Z_{max} \propto V_{sat}$
- When limited by current headroom, $\Delta Z_{max} \sim\propto \Delta I_{max}$
- $\Delta Z_{max} \propto \gamma_z^{-1} = \tau_z$
- Usable current headroom for 90% ΔZ_{max} : $\Delta I_{usable} \sim 2.3 V_{sat} /(L_C \gamma_z)$
- Strong functional dependence on T_{PS}, but weak if $T_{PS} << \gamma_z^{-1}$ (as is case in ITER)

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
  - In-vessel coils being designed to provide $\Delta Z_{max}/a > 5\%$
  - $\Delta Z_{max}/a \sim 5\%$ corresponds to $\Delta Z_{max}/\langle Z\rangle_{noise} \sim 5–10$ in present experiments
  - Discrepancies between calculation and experiment emphasize need for margin in design

- **Analytic theory of ΔZ_{max} performance:**
  - $\Delta Z_{max}/a \propto V_{SAT}/\gamma_Z$ (if voltage limited)
  - $\Delta Z_{max}/a \propto \Delta I_{MAX}$ (if current limited)