Vertical Stability Diagnosis and Control in ITER

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Measurement and Feedback

ITER Operational Considerations

ITER-Specific Challenges

Vertical Stability Diagnosis and Control in ITER

Measurement and Feedback

Vertical Position Measurement
- Magnetometry and reflectometry

Vertical Velocity Measurement
- Saddle-loops and pickup loops

Active Stability Feedback
- VS1 and VS2 circuits plus proposed VS3

Passive Stability Feedback
- Vacuum vessel and conducting blanket support structure

Vertical Stability Diagnosis and Control in ITER

Vertical Position Measurement

Magnetic field measurements

41 full flux loops, 36 internal and 5 external

Rogowski coils for halo currents

External hall effect sensors

60 B_{Tan} and 60 B_{Norm}

100s of inductive probes for B_{Tan} and B_{Norm}

Used for...

Equilibrium reconstruction

Vacuum flux and driven coil currents

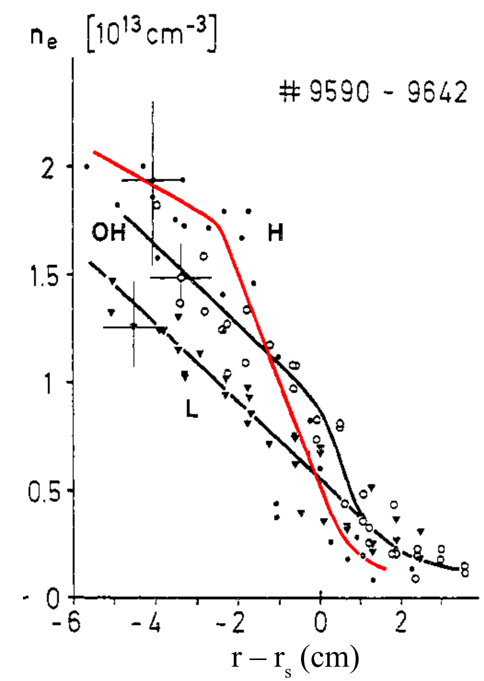
Position reconstruction from reflectometry

Reflectometry limited for probing in H-mode

Pedestal too steep for typical resolution

Can watch position of fixed density point at edge

Pedestal acts as stable plasma 'wall'



from Wagner (1984)

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Vertical Velocity Measurement

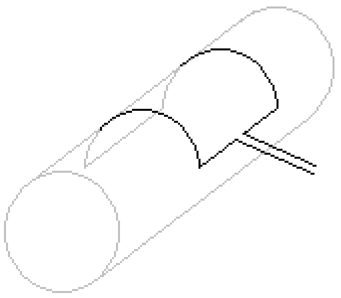
Saddle loops

Area-measurements of $\dot{B}_{Norm}$

More than 120 in-vessel saddle loops

Usually integrated to get B_{Norm},

but $\dot{B}_{Norm}$ can indiciate plasma movement

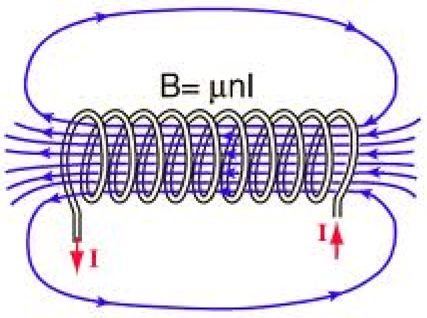


Pickup coils

Analogous to guitar pickups

Point-measurements of $\dot{B}$

$$B = \mu n I \Rightarrow \dot{B} = \mu n \dot{I} = \frac{\mu n V}{L}$$



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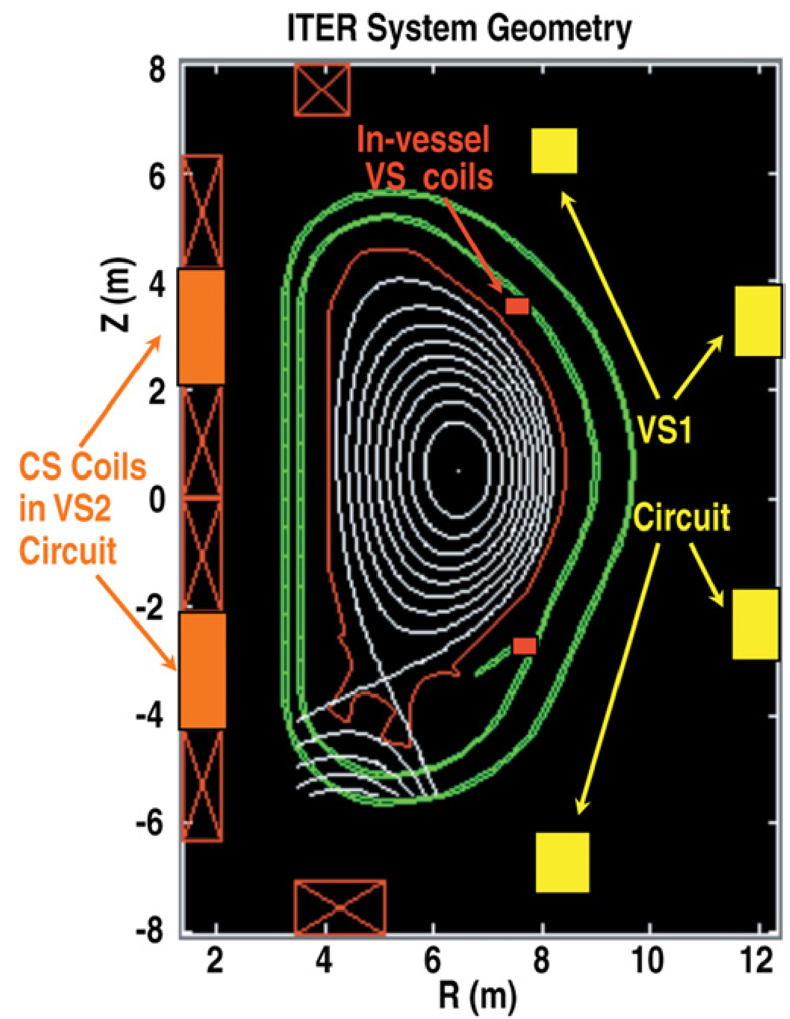
Active Stability Feedback Systems

- VS1 Circuit: PF2-5 outboard poloidal coils
    - Superconducting NbTi coils
    - 2/3 of PF: total ~40 MA-turns
    - Dicharge time constant ~14s

- VS2 Circuit: CS2U & CS2L central solenoid coils
    - Superconducting Nb_3Sn coils
    - 1/3 of CS: total ~45 MA-turns
    - Discharge time constant ~7.5s

- VS3(?): New (proposed?) in-vessel VS coils
    - Standard copper coils



from Humphreys (2009)

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Passive Stability Feedback Systems

Stainless steel vacuum vessel wall

- As well as suppressing ripple, enhances stability
- Together with blanket supports, $R_t \approx 7.7\mu\Omega$

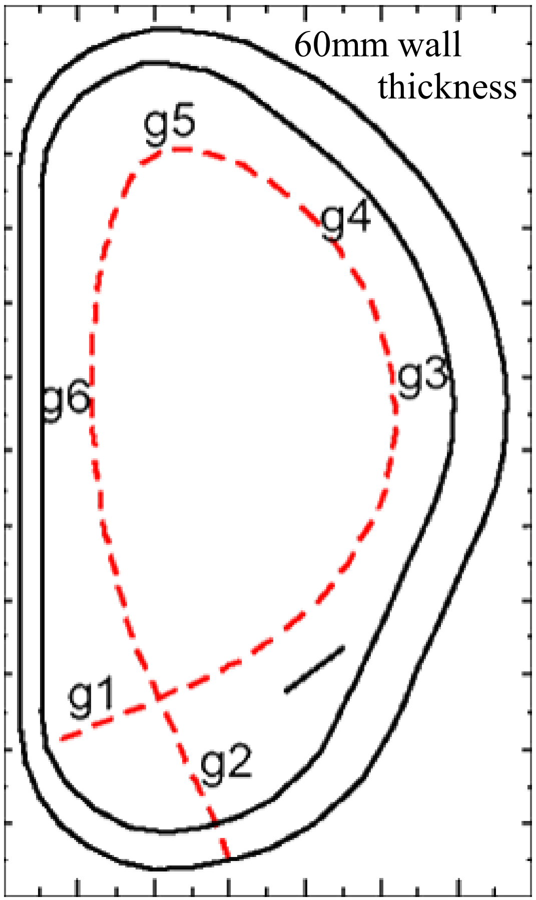
Toroidally continuous conducting blanket supports

- Improve up/down symmetry for plasma position
- Reduce displacement after disturbance by ~50%

Vacuum vessel vertical displacement characteristics

- Vertical displacement VV mode time constant ~0.25s
- Typical initial displacement after MD ~10-20mm
- Vertical instability growth time ~60-160ms

g1..g6 mark specified gaps between separatrix and PFC



from Gribov (2007)

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ITER Operational Considerations

Operational Parameters

l_i, κ

Operational Control Limits

m_s, ΔZ_{max}

Feedback Control Figures of Merit

$\Delta \tilde{Z}_a$ and $\Delta \tilde{Z}_n$

Vertical Stability Diagnosis and Control in ITER

Operational Parameters: l_i and κ

In a circular plasma, $l_i(3) = \dfrac{2\int B_\theta^2 dV}{R(\mu_0 I_p)^2}$

Normalized for ITER's plasma shaping, $l_i(1) = \left[\left(\dfrac{\mu_0 I_p}{\int dl_\theta}\right)^2 2\pi R \int dA_\phi\right] \dfrac{2\int B_\theta^2 dV}{R(\mu_0 I_p)^2}$

However, most analysis simply uses $l_i(3)$

It can be shown that $l_i(3) \leqslant \left[\dfrac{1}{2} + \ln\left(q_{95}\right)\right] \dfrac{2\kappa_a}{1+\kappa_a^2}$ to 1st order for a "top-hat" current

l_i should be *smaller* in ITER

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Operational Control Limits: m_s

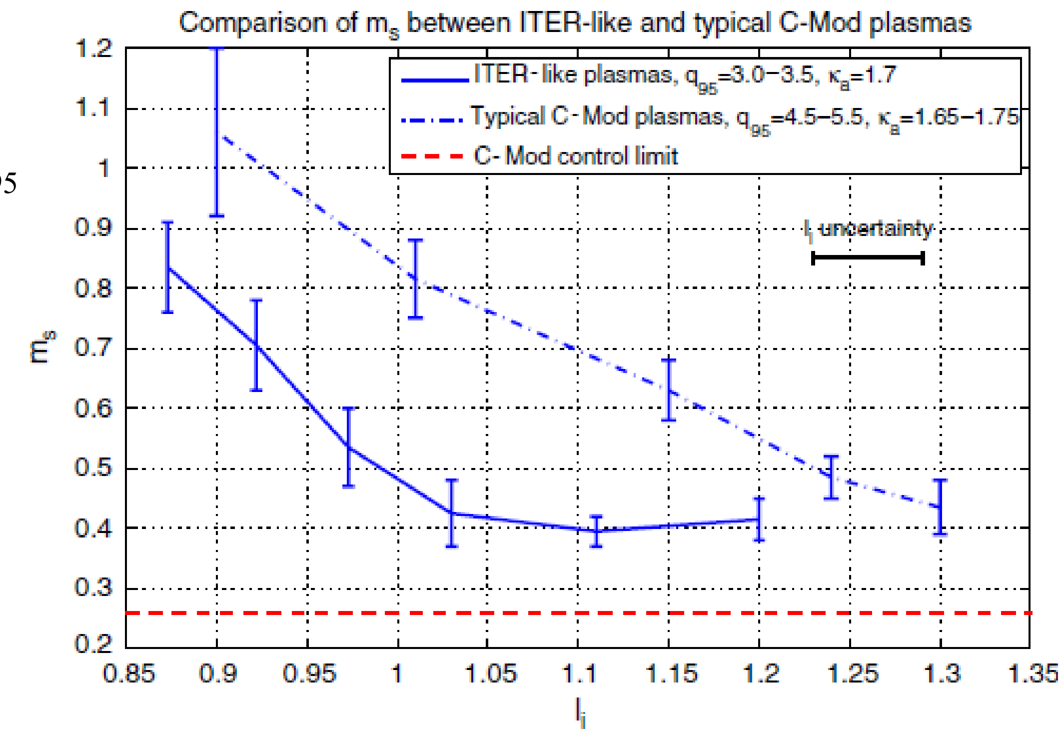
Stability margin as function of l_i, κ, q_{95}

l_i will be smaller in ITER

Higher m_s for a given κ

q_{95} much lower in ITER

Suggests overall lower m_s in ITER operating regime



However: m_s is not necessarily a good cross-machine figure of merit!

More useful when normalized against m_s(min) of machine's coils, structure, PS, etc.

Seems to be found *empirically* for each machine

ITER expected to have m_s/m_s(min) ~ 2, comparable to DIII-D and C-Mod

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Operational Control Limits: ΔZ_{max}

Defined by $\Delta Z_{max} \approx -\frac{\partial z}{\partial I_s} v_z u_z L_{*s}^{-1} \vec{b}_c \frac{V_{sat}}{\gamma_z} e^{-\gamma_z T_{PS}}$

Coil geometry effects from $\frac{\partial z}{\partial I_s}$ and u_z

Implications:

$\Delta Z_{max} \propto \gamma_z^{-1}$ for a slow power supply

For a very fast power supply, ΔZ_{max} becomes mostly independent of growth rate

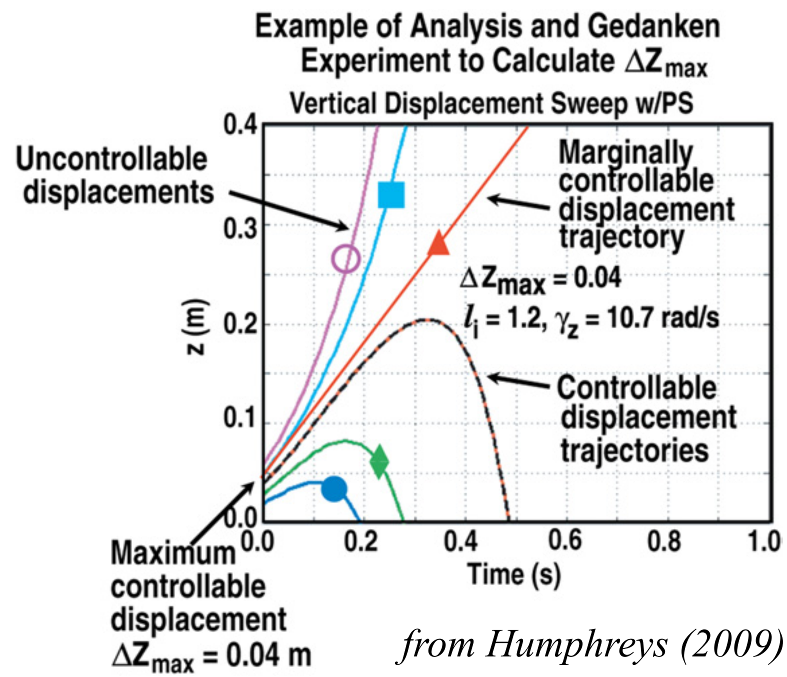
With ΔI_{max}, if $\Delta I_{max} L_c \gamma_z / V_{sat} < 1$, $\Delta Z_{max} \propto \Delta I_{max}$

$\Delta Z_{max} \propto V_{sat}$

Individual coil set effectiveness scales like $\frac{\partial z}{\partial I_s} v_z u_z L_{*s}^{-1} \vec{b}_c$

For Example:

Using only VS1, $\Delta Z_{max} \sim$ 4cm ITER rampup



from Humphreys (2009)

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Figures of Merit: $\Delta\tilde{Z}_a$ and $\Delta\tilde{Z}_n$

$$\Delta\tilde{Z}_a \equiv \frac{\Delta Z_{max}}{a} \qquad \Delta\tilde{Z}_n \equiv \frac{\Delta Z_{max}}{\langle \Delta Z_{noise} \rangle_{rms}}$$

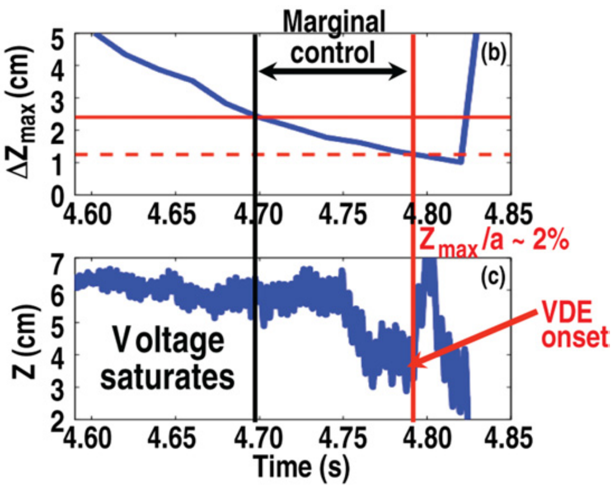
Many machines see $\langle \Delta Z_{noise} \rangle_{rms} \sim 0.01a$, suggesting $\Delta\tilde{Z}_a$ is a good enough measure

$\Delta\tilde{Z}_a < 2\%$ represents high risk of VDEs

$2\% < \Delta\tilde{Z}_a < 4\%$ characterizes marginal control

$\Delta\tilde{Z}_a > 5\%$ stable in C-Mod and DIII-D

In ITER, using only VS1 (aka PF2-5), $\Delta\tilde{Z}_a \sim 2\%$
Even using VS1 + VS2 (PF2-5, CS2U, CS2L), $\Delta\tilde{Z}_a \sim 4\%$



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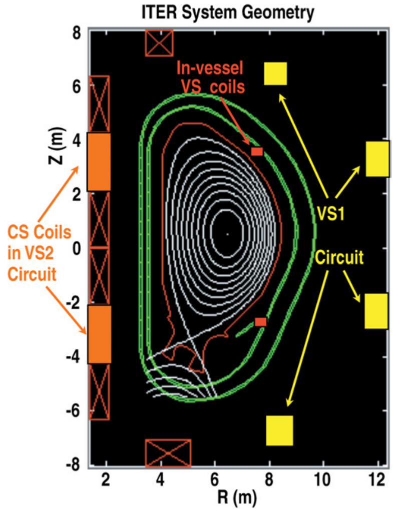

from Humphreys (2009)

Vertical Stability Diagnosis and Control in ITER

Specific Challenges

- H-Mode implies ELMs
  - ELM-induced difficulties
  - Solutions

- ITER Scaling
  - Challenges of ITER's size
  - Solutions

Vertical Stability Diagnosis and Control in ITER

Specific Challenges and Solutions

Edge Localized Modes

- Characteristically associated with H-mode
- ELMs can displace the plasma vertically
- ELMs can also falsify plasma ΔZ
  - Moves pedestal position relative to bulk plasma
  - Generates extra B_{norm} noise
- Effectively decreases $\Delta \tilde{Z}_n$

- Work on JET indicates illusory ΔZ from ELMs may be suppressed with careful tuning of gain on magnetic sensors
- ELM control methods may reduce magnitude of noise
  - Pellet injection
  - Jogging

Vertical Stability Diagnosis and Control in ITER

Specific Challenges and Solutions

ITER Scaling Issues

Stable $\Delta \tilde{Z}_a > 5\%$ region of means ΔZ_{max} > 10cm (!)

VS1 + VS2 (PF2-5, CS2U, CS2L): $\Delta \tilde{Z}_a \sim 4\%$

NSTX study: machine properties can *reduce* effective ΔZ_{max} ~ 20%

- Nonaxisymmetries of passive components?
- Nonlinear effects from plasma-limiter interactions?
- Other unidentified effects?

Vertical instability growth times as short as 60ms

Proposal (approved?) to include in-vessel VS3 coils

Ongoing study should clarify effects of asymmetries and nonlinearities

Vacuum vessel design should minimize asymmetry effects (e.g. ripple)

dz/dt of current centroid monitored at 1kHz

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