Vertical Stability Diagnosis and Control in ITER

Paul Hughes

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
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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 indicate 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
- Discharge time constant ~14s

VS2 Circuit: CS2U & CS2L central solenoid coils
- Superconducting Nb$_3$Sn 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 \(~0.25\)s  
Typical initial displacement after MD \(~10-20\)mm  
Vertical instability growth time \(~60-160\)ms
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ITER Operational Considerations

Operational Parameters
\( l, \kappa \)

Operational Control Limits
\( m_s, \Delta Z_{\text{max}} \)

Feedback Control Figures of Merit
\( \Delta \tilde{Z}_a \) and \( \Delta \tilde{Z}_n \)
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Operational Parameters: \( l_i \) and \( \kappa \)

In a circular plasma, \( l_i(3) = \frac{2 \int B_0^2 dV}{R(\mu_0 I_p)^2} \)

Normalized for ITER's plasma shaping, \( l_i(1) = \left[ \left( \frac{\mu_0 I_p}{\int dl_0} \right)^2 2\pi R \int dA_{\phi} \right] \frac{2 \int B_0^2 dV}{R(\mu_0 I_p)^2} \)

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

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

\( l_i \) should be \textit{smaller} in ITER
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Operational Control Limits: $m_s$

- Stability margin as function of $l_i$, $\kappa$, $q_{95}$
- $l_i$ will be smaller in ITER
  - Higher $m_s$ for a given $\kappa$
  - $q_{95}$ 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 $m_s(\text{min})$ of machine's coils, structure, PS, etc.
  - Seems to be found *empirically* for each machine
  - ITER expected to have $m_s/m_s(\text{min}) \sim 2$, comparable to DIII-D and C-Mod
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Operational Control Limits: $\Delta Z_{\text{max}}$

Defined by $\Delta Z_{\text{max}} \approx -\frac{\partial z}{\partial I_s} v_z u_z L_{s}^{-1} b_c \frac{V_{\text{sat}}}{\gamma_z} e^{-\gamma_z T_{ps}}$

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

Implications:

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

For a very fast power supply, $\Delta Z_{\text{max}}$ becomes mostly independent of growth rate

With $\Delta I_{\text{max}}^2$, if $\Delta I_{\text{max}}^2 L_{\gamma_z} V_{\text{sat}} < 1$, $\Delta Z_{\text{max}} \propto \Delta I_{\text{max}}$

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

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

For Example:

Using only VS1, $\Delta Z_{\text{max}} \sim 4$cm ITER rampup
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Figures of Merit: $\Delta \tilde{Z}_a$ and $\Delta \tilde{Z}_n$

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

Many machines see $\langle \Delta Z_{\text{noise}} \rangle_{\text{rms}} \sim 0.01a$, 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), $\Delta \tilde{Z}_a \sim 4\%$

from Humphreys (2009)
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Specific Challenges

H-Mode implies ELMs
  ELM-induced difficulties
  Solutions

ITER Scaling
  Challenges of ITER's size
  Solutions
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Specific Challenges and Solutions

*Edge Localized Modes*

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

Work on JET indicates illusory $\Delta Z$ from ELMs may be suppressed with careful tuning of gain on magnetic sensors
- ELM control methods may reduce magnitude of noise
  - Pellet injection
  - Jogging
Specific Challenges and Solutions

*ITER Scaling Issues*

- Stable $\Delta \tilde{Z}_a > 5\%$ region of means $\Delta Z_{max} > 10\text{cm}$ (!)
- VS1 + VS2 (PF2-5, CS2U, CS2L): $\Delta \tilde{Z}_a \sim 4\%$
- NSTX study: machine properties can *reduce* effective $\Delta Z_{max} \sim 20\%$
  - 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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References
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