Progress in controlling tearing modes in RFX-mod

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Outline

• Tearing modes in RFX-mod

• Standard Virtual Shell experiments

• Closer Virtual Shell

• Active control experiments (m=1)
  – QSH induction (single mode)
  – LM mitigation (multiple modes)

• Open issues / Controller optimizations
Reversed Field Pinch Mode Classification

Internally non-resonant Resistive Wall Modes

- $m=1, n=-7$
- $m=1, n=-8$
- $m=1, n=-9$

"(Resistive kink) tearing modes"

- provide $J_\theta$ for the RFP configuration

Externally non-resonant Resistive Wall Modes

- $m=1, n > 0$
- $m=0, \text{ all } n$

Internally non-resonant Resistive Wall Modes

- $m=1, n=-5$
- $m=1, n=-6$
Single (SH) vs Multiple (MH) Helicity

- 3D viscoresistive MHD simulations (SpeCyl code with ideal wall boundary) have shown that the dynamo can be

Laminar (Single Helicity)

Good magnetic flux surfaces

Turbulent (Multiple Helicity)

Stochasticity by island overlap
Active induction of SH

- MHD simulations (DEBS) including active control of boundary radial field indicate that it is possible to stimulate the onset of a Single Helicity mode energy spectrum computed by DEBS in a run with complex gains

R. Paccagnella et al., IAEA 2006 paper THP3-19
Tearing Modes: Locking

- Last Closed Magnetic Surface is distorted by the tearing modes
- Modes tend to be phase locked and, in RFX-mod, are always wall locked
  - toroidally localized plasma wall-interaction

CCD image of C I(908nm): C influx

#18916 t=50ms

LCMF Distance from the wall

• If no LM mitigation technique is applied, the enhanced interaction induces
  – increased radiated power

  \[
  \phi_{LM} - \phi_{boio} \text{ (degree)}
  \]

  – enhanced non axisymmetric post shot vessel temperature increases, with m=1 pattern
The edge radial magnetic field is controlled by saddle coils

- Full coverage of vessel
- 4(pol) x 48(tor) = 192 saddle coils independently fed
- Can generate modes
  - m=1 n=-24 to +23
  - m=0 n=1 to 24
  - m=2 |n| =0 to 24

Radial field at 24 kAt

<table>
<thead>
<tr>
<th>Radial field at 24 kAt</th>
<th>&lt;B_r&gt; (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>50</td>
</tr>
<tr>
<td>@10Hz</td>
<td>35</td>
</tr>
<tr>
<td>@50Hz</td>
<td>12</td>
</tr>
<tr>
<td>@100Hz (I=16 kAt)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Radial field at plasma edge

Selective virtual shell

- **Virtual Shell (VS)**: active cancellation of radial magnetic field, at radius of 192 field sensors: analogy with passive cancellation by ideal superconducting shell [§]

- **Selective**: control system can act on modes selectively

- **Mode control in SVS**: non zero reference value; complex gains

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Standard Virtual Shell

- Reproducible increase of pulse length, compared to non-VS operations has been obtained
  - Limited by sustainment power
  - Reduced loop voltage

- Measured radial field at the edge is significantly reduced compared to non-VS
- A substantial reduction is observed on the tearing-branch of the edge radial field spectrum

*S. Martini, et al., 21st IAEA Fusion Energy Conference*
Virtual Shell: Spontaneous QSH

- In Standard Virtual Shell, especially at high current levels (0.8-0.9MA), Tearing Modes spectrum tends to n=-7 QSH more often.

**Quasi-stationary QSH**

- Normalized magnetic energy in the dominant mode

**Intermittent QSH**

- Normalized average magnetic energy in secondary modes

*P. Martin, ICPP 2006 – Kiev 22-26/05/2006. submitted to PPCF*
Virtual Shell: Spontaneous QSH

- Electron temperature and SXR emissivity increase in the plasma core

*a hot helical core is present for time periods \( \tau_E \)
Virtual Shell: Spontaneous QSH

- This behavior is observed in standard V.S. discharges, *without LM mitigation*.
  - Statistical indicators for QSH: “*probability*” and “*duration*” measurements

**DURATION:** longest QSH

**PROBABILITY:** $\frac{\text{sum(QSH periods)}}{\text{current flat-top}}$
Virtual Shell: Spontaneous QSH

- Both probability and duration increase with the level of plasma current
Outline

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  – OPCD

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Virtual Shell+OPCD

- Tearing mode spectrum is significantly affected when during OPCD operations

\[
\begin{align*}
V_q & \quad J_q \\
-2000 & \quad -1000 & \quad 0 & \quad 1000 & \quad 2000 & \quad 3000 \\
I_{\text{tor}} (A) & \quad t (s)
\end{align*}
\]

\[
\begin{align*}
V_B & \\
\text{plasma}
\end{align*}
\]

Virtual Shell + OPCD

- **OPCD** is an efficient way for inducing a Quasi Single Helicity state in the plasma.

- The transient QSH state is characterized by an *increased electron temperature* and *reduced chaos* thanks to the *reduction of secondary modes*.

- OPCD induced QSH states generally have smaller secondary modes with respect to spontaneous QSH States.
Virtual shell + OPCODE

- Thermal structures appear in the core of the plasma.

Double Filter temperature profile diagnostic

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• Open issues / Controller optimizations
• The Virtual Shell cancels the radial field at the sensor radius

• The Closer Virtual Shell approach perform feedback on “virtual” $b_r$ sensors closer (or farther away) to the plasma
  
  – Simultaneous measurement of radial AND toroidal component INSIDE the shell allows for “moving” the Virtual Shell closer to the plasma boundary:
  
  – A cylindrical vacuum model is assumed

$$b_r^{m,n}(r) = a^{m,n} I_m \left( \frac{n|r}{R_0} \right) + b^{m,n} K_m \left( \frac{n|r}{R_0} \right)$$

coefficients $a^{m,n}$ $b^{m,n}$ are computed at measurement positions...

$$-i \text{sgn}(n) b_\varphi^{m,n}(r) = a^{m,n} I_m \left( \frac{n|r}{R_0} \right) + b^{m,n} K_m \left( \frac{n|r}{R_0} \right)$$

... and used to extrapolate $b_r$ at desired radius
• Preliminary experiments have been performed @ 600kA+800kA
• A decrease of radial field @plasma surface is observed,

... but it is not monotonous with the effective plasma-closer shell distance
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    • Selective Virtual Shell
    • Non-zero Reference values
    • Complex Gains
  – LM mitigation (multiple modes)

• Open issues / Controller optimizations
• If the control of a tearing mode is switched off
  – discharge duration is significantly shortened for \( n = -7 \ldots -10 \)
  – This does not apply for \( n = -13 \)
natural evolution: Multiple modes

- When several tearing modes are not controlled, the higher $n$ mode tends to dominate the spectrum
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Non zero reference value

- The feedback law of the V.S. may include a non zero reference value for a mode

\[ b_{mn}^{ext}(t) = k_p \left( b_{r,mn}(t) - b_{ref,mn}(t) \right) + k_I \int dt \left( b_{r,mn}(t) - b_{ref,mn}(t) \right) \]

- QSH induction through a non zero reference value on n=-7 have been attempted on 800 kA discharges

- The V.S cannot match the reference amplitude, with the present choice of gains
Non zero reference value

- The mode phase can be controlled and slowly (10-20Hz) varied in time
• The phase of the plasma mode locks to the reference phase
  – Intermittent islands maxima correspond to the magnetic island O-point

• Even when a thermal island is not evident, the SXR profile is still asymmetric
  – “Center of mass” of SXR emissivity follows the rotation of magnetic island O-point
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• Open issues / Controller optimizations
• The V.S. feedback law can be modified, in order to apply a torque

\[ b_{mn}^{ext}(t) = k_p Ge^{i\Phi} b_{r,mn}(t) + k_I \int dt Ge^{i\Phi} b_{r,mn}(t) \]
• For a proper choice of the gain phase
  – a long lasting QSH spectrum may arise
  – the level of the radial field at the edge remains reasonably low

• the mode phase slowly rotates:
  – the effect is observed also on SXR profiles
  – intermittent SXR island occurs
Analytical torque model for complex gain

- The **imaginary** part of the gain gives a net torque
- The **real** part cancels the field
- The **sign of the imaginary** part determines the rotation direction
- If $|G|$ is constant, a tradeoff between high torque and low edge radial field need to be found

$$
A \frac{d\phi}{dt} = T_w + T_G + T_{vis} + T_{error}
$$

S.C. Guo, FT-NT01
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• Open issues
• The highest current operations (1MA) up to now have been possible only with LM mitigation schemes

• Reproducible discharges are obtained with reduced interactions with the first wall...
  – no localized increase of vessel temperature
  – no localized enhancement of $P_{\text{rad}}$

• ... but QSH probability is significantly reduced
LM mitigation

- The scheme is based on non zero reference value for \( m=1 \) edge radial field with relatively low amplitude and \( \Delta f \propto \Delta n \)
  - 1,-7 \( f= -20 \) Hz
  - 1,-8 \( f= -10 \) Hz
  - 1,-9 \( f= 0 \) Hz
  - 1,-10 \( f= 10 \) Hz
  - 1,-11 \( f= 20 \) Hz
  - 1,-12 \( f= 30 \) Hz

- The initial phase of the reference value is measured in real time measurements

- This scheme preserves the LM pattern and rotates it along the stationary 1,-9 mode.
- the \( m=0,n=1 \) mode rotates with the slinky: a torque is exerted on the \( m=0 \) modes.
Open issues / Controller optimization

• A residual “error” (i.e. mismatch between reference and measurement) remains
  – both in standard Virtual Shell and Closer Virtual Shell

• In particular, errors are not symmetric: shell asymmetries are responsible for different dynamic behavior of the edge radial field
  – toroidal asymmetry due to the presence of the toroidal gap
  – poloidal asymmetry in the regions of gaps of the mechanical structure and the shell

• Different modes require different gains: Mode Control schemes with different gains need to be developed
Residual error / Shell Asymmetries

- These issues are being addressed by means of an electromagnetic model of the control system

- Main features of the model  
  (state space representation)
  
  - **inputs**: 48x4 voltages applied by the power supply to the saddle coils
  
  - **outputs**: 48x4 magnetic fluxes measured by the sensor coils

\[
x' = Ax + Bu \\
y = Cx + Du
\]

\[
A = -L^{-1}R \\
B = L^{-1} \\
C = 1 \\
D = 0
\]

A. Soppelsa, G. Marchiori, to be published in Fusion Engineering and Design, 2006
1. Saddle coils inductance ($L$) and dissipation ($R$) matrices are composed by constant terms
   - four non-zero mutual inductances for each coil are considered
   - elements of $L$ and $R$, corresponding to selected locations, have been experimentally measured.

2. No coupling with plasma
   - current flowing into saddle coils is given by externally applied voltages only
   - Model computed currents correspond in fact to experimental measurements
E.M. model of active control system

3. Accurate (i.e. non sparse) mutual inductance between coils and sensors
   – Optimal number of non zero elements identified iteratively: \(1+3+2\times 6\times 4=52\) for each saddle-coil are included
   – frequency response is included

• The model reproduces the dynamical behavior of the system with an accuracy of 5%
  – open loop generation of harmonic \(m=0, n=4\)
  – closed-loop PI controller: cancellation of static disturbances produced by toroidal windings

• Work in progress:
  – determination of optimal PID gains for canceling time varying fields
  – optimization of PID gains for different sections
Beyond Virtual Shell

- Saddle coils generate low n modes (especially m=0) with low efficiency

\[
b_{rc, n}^{m, n} (r) = -\mu_0 K_m \left( \frac{|n| c}{R_0} \right) I_m \left( \frac{|n| c}{R_0} \right) \frac{n \Delta \phi}{2} \sin \left( \frac{n \Delta \phi}{2} \right) \sin \left( \frac{m \Delta \theta}{2} \right) I^{m, n} (r)
\]

- The saddle coils are located outside the shell
  - action on low n modes is delayed compared to high n

- To overcome these two issues: **Mode control with Shell Compensation**
  - the inverse of the shell transfer function for the modes is included in the gains
  - derivative gain needs to be included (a one pole filter is implemented in real-time)

\[
b_{coil}^{m, n} (r, t) = \left( K_P - \frac{K_I}{A^{m, n}} \right) b_r^{m, n} (r, t) + K_I \int_{t_0}^{t} b_r^{m, n} (r, \xi) d\xi - \frac{K_P}{A^{m, n}} \frac{\partial b_r^{m, n} (r, t)}{\partial t} - K_P b_r^{m, n} (r, t_0)
\]
Conclusions

- Virtual Shell scheme reduces significantly tearing mode edge radial field
  - less plasma wall interaction and lower loop voltage

- In standard V.S., spontaneous, long lasting, QSH spectra are observed at high currents.

- OPCD reproducibly increase the QSH probability

- Non zero reference values and complex gains allows to control phase of modes. Amplitude control needs to be optimized.

- Locked Mode rotation techniques are required, at present, to operate reproducibly at high current, due to non optimized controller.
  - algorithms experimented so far are not compatible with QSH

- Optimized feedback schemes are being developed