Feedback control on EXTRAP-T2R with coils covering full surface area of torus

presented by Per Brunsell

P. R. Brunsell¹, D. Yadikin¹, D. Gregoratto², R. Paccagnella², Y. Q. Liu³, T. Bolzonella², M. Cecconello¹, J. R. Drake¹, M. Kuldkepp⁴, G. Manduchi², G. Marchiori², L. Marrelli², P. Martin², S. Menmuir⁴, S. Ortolani², E. Rachlew⁴, G. Spizzo², P. Zanca²

1) Alfvén Lab., Association EURATOM-VR, Royal Inst. of Technology, Stockholm, Sweden
2) Consorzio RFX, Associazione EURATOM-ENEA sulla fusione, Padova, Italy
3) Dept. of Appl. Mechanics, Association EURATOM-VR, Chalmers Univ. of Technology, Gothenburg, Sweden
4) Dept. of Physics, Association EURATOM-VR, Royal Inst. of Technology, Stockholm, Sweden

Per Brunsell, Feedback control on EXTRAP-T2R
Outline

1. EXTRAP T2R reversed field pinch
2. Cylindrical linear MHD model for RWMs in RFP
3. Active MHD mode control system on T2R
4. RWM feedback control experiments using 4x32 coils (full surface cover)
5. Mode control feedback experiments
   - $b$-radial sensors
   - $b$-toroidal sensors
6. RWM feedback control experiments using 4x16 coils (partial array, coupled unstable modes)
7. Open loop control, simulation of RWM feedback control
EXTRAP T2R reversed field pinch

EXTRAP T2R vessel and shell during assembly at Alfvén laboratory, KTH, Stockholm

Copper shell
- two layers
- 1 mm thickness

Machine parameters:
- major radius $R_0=1.24$ m
- plasma minor radius $a=18$ cm
- shell norm minor radius $r/a = 1.08$
- shell time constant $\tau_{ver}=6$ ms
- plasma current $I_p=80$ kA
- electron temperature $T_e=250$ eV
- pulse length $\tau_{pulse} < 60$ ms

Pulse lengths $\tau_{pulse} >> \tau_{ver}$ allow studies of RWM stability and methods for active control of RWMs
Cylindrical linear MHD model for RWMs in RFP

- RWM is described by the marginal linearized ideal MHD equation
- thin wall boundary condition
- wall time const $\tau_w = \mu_0 \sigma_r \delta_w = 2 \tau_{ver}$
- resistive wall mode growth rates $\gamma_{m,n}$

For the RFP:
- RWMs due to non-resonant, current driven, ideal MHD $m=1$ kink modes
- mode stability is unaffected by sub-Alfvenic plasma rotation
- $m>1$ are stable
- finite range of unstable $m=1$ with different toroidal mode number $n$
- range increases with aspect ratio
- EXTRAP T2R: 16 unstable modes

Per Brunsell, Feedback control on EXTRAP-T2R
B-radial flux loop sensor arrays on T2R

2-D magn diagnostic flux loop array
- 256 loops, 4 poloidal, 64 toroidal pos
- Resolves $m=1$, $-32 < n < +32$

2-D feedback sensor flux loop array
- 128 loops, 4 poloidal 32 toroidal pos
- Resolves $m=1$, $-16 < n < +16$

- Inside shell, $r_s/a = 1.08$
- Each loop extends:
  - 90° poloidally, 5.6° toroidally
- “$m=1$” series connected:
  - out - in
  - top - bottom

Per Brunsell, Feedback control on EXTRAP-T2R
Active saddle coil arrays on T2R

2-D array 4x16 coils (50% cover)
- 64 coils, 4 poloidal, 16 toroidal positions

2-D array 4x32 coils (100% cover)
- 128 coils, 4 poloidal, 32 toroidal positions

- Outside shell $r_c/a = 1.3$
- Each saddle coil extends:
  - $90^\circ$ poloidally, $11.25^\circ$ toroidally
- "m=1" series connected

Per Brunsell, Feedback control on EXTRAP-T2R
Active control system

Audio amplifiers
- 1 Hz - 25 KHz
- current < 20 A

Saddle coils
- L/R time 1 ms
- field < 3 mT

Digital controller (RFX)
- 64 inputs/outputs, 100 μs cycle
- 400 MHz CPU, signal processing implemented in software:
  - real time FFT, calc $b_{1,n}$
  - intelligent shell feedback
  - mode control feedback
  - open loop operation

Plasma - wall system

Sensor flux loops

Per Brunsell, Feedback control on EXTRAP-T2R
m=1 mode spectrum with different coil arrays, for n=+6 coil current harmonic

Side band harmonics: $\Delta n = 16$
- **With feedback control, linear coupling of side band modes**
- **pairs of coupled unstable RWMs**

Side band harmonics: $\Delta n = 32$
- Mode amplitudes two times higher
- **No coupled unstable RWMs**
Cylindrical linear MHD model
Plasma response to external field

**Mode wall time** $\tau_{m,n}$ - diffusion of a field
Fourier harmonic through the wall

**Without plasma**, the radial field harmonic at the wall $b_w = b_{r,m,n}(r_w)$ is obtained from an ordinary diff. equation

$$\tau_{m,n} \frac{db_w}{dt} + b_w = b_{w}^{ext}$$

**With plasma**, the corresponding equation describing the plasma response to the external field includes the **RWM growth rate** $\gamma_{m,n}$

$$\tau_{m,n} \frac{db_w}{dt} - \gamma_{m,n} \tau_{m,n} b_w = b_{w}^{ext}$$

The plasma response
- amplifies the field for $\gamma_{m,n} \tau_{m,n} > -1$
- attenuates the field for $\gamma_{m,n} \tau_{m,n} < -1$

Per Brunsell, Feedback control on EXTRAP-T2R
Range of $m=1$ RWMs observed in EXTRAP T2R

- **black:** Measured $m=1$ ampl.
- **blue:** MHD exponential growth
- **red:** Estimated field error

- Exp. and MHD RWM growth are in agreement for $n=-10, +5$
- Disagreement for $n=+2$ can be explained by field errors

Assuming MHD growth rates, the field errors are estimated from the MHD model:

$$b^\text{err}_w = \tau_{m,n} \frac{db^\text{meas}_w}{dt} - \gamma_{m,n} \tau_{m,n} b^\text{meas}_w$$

- Experimental RWM growth is in agreement with the MHD model assuming field errors in the range 0.02 - 0.2 mT

Per Brunsell, Feedback control on EXTRAP-T2R
Preliminary results with 4x32 coils feedback (EPS 2005, Tarragona)

Intelligent shell fb with 4x32 coil array, non-optimized P-control (low feedback gain)
- \( m=1 \) rms amplitude suppressed with feedback
- \( n=-12 \) tearing mode wall locks around \( t=15 \text{ ms} \) w/o feedback
- **With feedback, tearing mode rotation is sustained**
  - Plasma toroidal rotation is estimated from OV impurity Doppler shift.
  - **With feedback, plasma rotation velocity is higher**

Per Brunsell, Feedback control on EXTRAP-T2R
RWM feedback control with the full 4x32 coil array

Intelligent shell feedback with PID-control (higher feedback gain)

- **red**: Reference shot w/o fb
- **black**: Shot with
  - With 4x32 coils all unstable RWMs are individually controlled (no coupled modes)
  - **All unstable RWMs are suppressed** ($n=-11...-2$, $n=+1...+6$) (16 modes)
  - **Feedback results in a three-fold increase of the discharge duration**
  - **Stabilization is achieved for 10 wall times (60 ms)**
RWM feedback control with the full 4x32 coil array

black: w/o fb
blue: intelligent shell fb (PID control)

32 Fourier modes are controlled (both stable and unstable)
Per Brunsell, Feedback control on EXTRAP-T2R

Tearing mode rotation with full feedback control

The shot length is limited by the power supply for the vertical field.

Wall locking of tearing modes ($n=-12,-13,14$) is avoided with fb.

Tearing mode rotation is sustained throughout the pulse.
Metal lines for the discharges with and without full feedback control

Mo = limiters
Cr = stainless steel vacuum vessel

The spectral line intensities for metal components of the wall are reduced with feedback.
Modelling of m=1 RWM feedback control with cylindrical linear MHD model for the RFP

m=1 sensor field harmonics produced by m=1 coil current harmonics in array with N coils in toroidal direction. In vacuum, steady state:

\[ b_{n,\text{vac}}^{\text{coil}} = I_{n'} M_n, \quad n = n' + qN \]

with plasma:

\[ P_n(s) = \frac{b_{n,\text{pl}}^{\text{coil}}}{I_{n'}} = \frac{M_n}{\tau_n(s - \gamma_n)} \]

Mode control with individual feedback gains \( G_n \) (current control): \( G_n = \text{coil current Fourier harmonic/ sensor field Fourier harmonic} \)

\[ b_n + P_n(s) \sum_{q} G_{n+qN} b_{n+qN} = b_n^{\text{pert}} \]

Modes \( n=n'+qN \) are linearly coupled through feedback coils. With no coupled unstable modes, the critical gain for stability is obtained from:

\[ 1 + G_n P_n(s_n) = 0 \]

For stabilization: \( \text{Re}\{s_n\} < 0, \quad G_n M_n > \tau_n \gamma_n \)
Linear MHD prediction of minimum feedback gain for m=1 mode stabilization (current control)

Cylindrical linear MHD model is used for estimation of required feedback gains.
Minimum loop gain \( G \) for stabilization (for case with no coupled modes):
\[
G = G_n M_n > \gamma_n \tau_n
\]

\( G_n = \frac{I_{\text{coil}}}{b_{\text{sensor}}} \)
\( M_n = \frac{b_{\text{sensor,coil}}}{I_{\text{coil}}} \) (vac, DC)
\( \gamma_n \) RWM growth rate
\( \tau_n \) wall time for mode \( n \)

The highest gain is obtained for the \( m=1, n=-11 \) mode:
\( G > 0.7 \)
Mode control fb of n=-11 with Br sensors - variation of proportional feedback gain

Vary loop gain G
black - no fb
red: G = 0.32
blue: G = 0.45
magenta: G = 0.65
cyan: G = 1.3

Linear MHD predicted gain for stabilization is
G > 0.7

Gain required for suppression is in agreement with linear MHD prediction
Mode control of $m=1,n=-11$ with B-radial sensors and complex proportional fb gain: vary phase

Complex loop gain $G=|G|\exp(i\varphi)$
Vary phase $\varphi$
(at $|G|=1.3$)
black - no fb
red: $\varphi = 0^\circ$
blue: $\varphi = +30^\circ$
magenta: $\varphi = +60^\circ$
cyane: $\varphi = -30^\circ$

*Best suppression of both br and bt at $\varphi = 0^\circ$*
Feedback control with array of b-toroidal sensors

Sensor array of 4x32 small b-toroidal pick-up coils.
m=1 connected in pairs (top to bottom, out to in) 90° phase diff. of br and bt harmonics is expected bt coils are off-center the active coil: toroidal angle shift 2.8° For m=1, n=-11 mode: the added phase diff. is 2.8° x 11 ≈ 30°

Phase difference of br and bt sensor fields for m=1, n=-11 is 90°+30°=120°
Mode control of m=1, n=-11 with B-toroidal sensors and complex proportional fb gain: vary phase

Complex fb gain
G=|G|exp(i \( \varphi \))

Vary phase \( \varphi \)
(at |G|=0.65)
black - no fb
red: \( \varphi = 45^\circ \)
blue: \( \varphi = 90^\circ \)
magenta: \( \varphi = 120^\circ \)
cyan: \( \varphi = 150^\circ \)

**Suppression of br and bt at predicted phase** (\( \varphi=120^\circ \))
Mode control of $m=1$, $n=-11$ with B-toroidal sensors
vary complex proportional fb gain

Complex gain $G=|G|\exp(i\,\varphi)$
Vary gain $|G|$ at $\varphi=120^\circ$
black - no fb
red - $|G|=0.081$
blue - $|G|=0.16$
magenta - $|G|=0.32$
cyan - $|G|=0.65$

Suppression improves with gain as expected
Comparison of b-radial and b-toroidal sensors for mode control of m=1, n=-11 mode

Complex gain
\[ G = |G| \exp(i \varphi) \]
black - no fb
red: b-tor sensor
\( G=0.65, \varphi = 120^\circ \)
blue: b-rad sensor
\( G=0.65, \varphi = 0^\circ \)
br field is more suppressed with br sensor (bt field is similarly suppressed)
Feedback control of coupled m=1 modes with different n for partial array (4x16 coils)

4x16 array fb: N_c=16 active coils, N_s=32 sensors in toroidal direction
Pairs of unstable coupled m=1 modes n, n’ with |n-n’|=16 (e.g. -11,+5)
Mode control with 32 individual feedback gains.

\[ P_n(s) = \frac{b_n^{coil,pla}}{I_{n'}} = \frac{M_n}{\tau_n(s-\gamma'_n)} \quad b_n + P_n(s)(G_n b_n + G_n' b_n') = b_n^{pert} \]

Two coupled equations, introduce the intermediate growth rate \( \gamma_{n,n'} \):

\[ \gamma_{n,n'} = (g_n \gamma_n' + g_{n'} \gamma_n) / (g_n + g_{n'}) \]

Intelligent shell: Equal fb gains, coupled modes are in anti-phase, \( b_n/b_n' = -1 \).
Sum of modes at coil positions is suppressed, but each coupled mode grows with the intermediate growth rate \( \gamma_{n,n'} \).

Mode control with complex gains: Rotating modes with complex growth rates \( \gamma_n, \gamma_{n'} \) are stable if \( \text{Re}\{\gamma_{n,n'}\} < 0 \), feedback control drives mode rotation

\[ \Omega_n = \Omega_{n'} = - \text{Im}\{\gamma_{n,n'}\} \].
Comparison of intelligent shell and mode control fb with 4x16 coil array for coupled modes n=-11, +5

- **red**: Reference shot
- **blue**: Intelligent shell fb
- **black**: Mode control fb with different complex gains for the coupled modes
  - Intelligent shell fb ineffective for coupled modes
  - Mode control fb suppresses rotating coupled modes
  - Mode control fb induces mode rotation.

Phases computed at an active coil position
Mode control feedback of selected target modes with 4x16 coil array

- **red**: Reference shot
- **black**: Mode control feedback (real gain).

- $n=-11, -10, -9, -8$ are selected as “target modes”
- **Feedback is disabled on all other modes.** (including the coupled modes $n=+5, +6, +7, +8$)
  - The target modes are stabilized ($n=-11, -8$)
  - Other modes are unaffected ($n=+2$)
  - Coupled modes are affected ($n=+5$)
Open loop control of RWMs

Pre-programmed coil current step-pulse is applied at t=8 ms.

- \( n=+6 \) mode has a shot-to-shot reproducible phase, due to machine field errors
- amplitude and phase of the \( n=+6 \) coil current is selected to cancel the RWM

- The RWM is suppressed
- The suppressed field is sum of inherent RWM and the plasma response to a constant external field.
Simulation of feedback control with the cylindrical MHD model

Intelligent shell feedback control with 4x16 coils.

Time traces for the coupled modes m=1, n=(-10, +6).

black: Shot with feedback
blue: Shot without feedback
red: Simulation

A single current harmonic m=1, n=+6 controls both coupled modes.

Explained by n=-10, +6 error fields being in phase at active coil positions.

*Simulation of feedback shot is in agreement with measurement*
Summary

1. Feedback control with full 4x32 coil array
   - All 16 unstable RWMs are individually controlled
   - With fb: Suppression of all unstable RWMs throughout the discharge duration (10 wall times)
   - Higher plasma toroidal rotation, sustainment of tearing mode rotation, three-fold increase of the pulse length

2. Mode control feedback
   - Loop gain for suppression in agreement with linear MHD model
   - Complex gain produce slow mode rotation
   - First comparison of b-radial and b-toroidal sensors

3. Feedback control with partial 4x16 coil array, coupled unstable RWMs
   - Intelligent shell fb ineffective for stabilization of coupled modes
   - Mode control fb with complex gain suppresses rotating coupled modes