Control of a burning fusion plasma:

a multi-disciplinary scientific challenge

Tony Donné
3 of the 7 ITER Challenges*

- 10 x hotter than the sun
- Controlling solar flames
- Magnetic insulation

*following Lopes Cardozo
In practice: Many instabilities

Ideal: Nested flux-surfaces

Magneto-hydrodynamics: The theory to describe plasma and instabilities
Fusion plasmas are highly structured

Modelling of cold pulse experiment

E. Min, PhD thesis
Transport by plasma fluctuations

Hot magnetized plasmas are highly structured

Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

Science 281, 1835 (1998)
Obtaining a fundamental understanding of basic processes

The sawtooth instability

In theory there is no difference between theory and practice. However, in practice there is.

Lars Sonneveldt, Thesis TU Delft
2D ECE Imaging

- 2D microwave camera
  - ECE-Imaging → electron temperature
  - Collaboration with UC-Davis, PPPL (& Postech, Korea)
  - Visualization of structures:
    - 3 PRL’s on sawtooth crash, tearing mode suppression
A Rijnhuizen specialty: sawtooth control

View of crash of sawtooth at HFS

- Crash is local in poloidal plane (~10 cm opening)
  - Crash is observed everywhere in high field side
  - A few attempts (pointed $T_e$ contours near the mid-plane) are made before the final puncture (#6 & #7)

Radial speed
(4 cm/15 $\mu$sec = 2.7 x $10^5$ cm/sec)
Comparison with full reconnection model

- Remarkable resemblance between 2-D images of the hot spot/Island and images from the matured stage of the simulation result of the full reconnection model (Sykes et al.)

Simulation result of the full reconnection model from A. Sykes and Wesson:
Formation of island indicates reconnection at the low field side.

H. Park et al.,
Comparison with the quasi-interchange model

- No clear resemblance between 2-D images of hot spot/island and projected images from the quasi-interchange model
- This model does not require any type of magnetic field reconnection

H. Park et al.,
Comparison with ballooning mode model at LFS

- **Similarities**
  - Pressure finger in early stage of simulation at low field side (middle figure) is similar to those from 2-D images ("a sharp temperature point")
  - Reconnection zone is localized in the toroidal plane (1/3 of the toroidal direction is opened)

- **Differences**
  - Heat flow is highly collective in experiment and stochastic process of the heat diffusion is clear in simulation.

Simulation results from Nishimura et.al.
Plasma condition ($\beta_p \sim 0.4$ and $\beta_t \sim 2\%$) is similar to the experimental results

Plasma parameters

\[ B(T) = 2T \]
\[ I(P) = 300 \text{ kA} \]
\[ T(0) \sim 1 \text{ keV} \]
\[ \text{Ne}(0) \sim 2.5 \times 10^{13} \text{ cm}^{-3} \]

ECH \sim 300 \text{kW}, 0 - 0.4 \text{sec}
ICRF \sim 150 \text{kW}, 2 - 3 \text{sec}
NBI (?), 2 - 3 \text{sec}.

Plasma rotation speed
\sim 50 \text{km/s}
Is understanding needed for control?

- Even though the detailed physical processes (esp. turbulence) taking place in a tokamak plasma are not fully understood we can control the plasma.

- A better understanding could lead to improvements in control and performance.
Control of plasma instabilities

Electron Cyclotron Resonance Heating & Current Drive
Experiments with predefined launcher

m = 2 suppression in TEXTOR

Sawtooth (de)stabilisation in TEXTOR

Close collaboration with TU/e
Control of Neoclassical Tearing Modes in TEXTOR

2 step process:
- Heating
- Suppression

I. Classen,
Control of Neoclassical Tearing Modes in TEXTOR

(#99183: 400kW ECRH)

Every frame 1 rotation period (2ms)

Total movie 200 ms

I. Classen, 
98 (2007) 035001
Time evolution of the island

Initially flat island $\rightarrow$ ECRH heated $\rightarrow$ Suppressed
Optimized MHD control system: In-line ECE

- Sensor and actuator in a single system
- Proof-of-principle experiment on TEXTOR (within TEC)
- NanoWatt signal level in MegaWatt environment
Searching the resonance
Temperature perturbations due to NTM

(NTM = Neoclassical Tearing Mode)
System tracks a moving NTM
System tracks O-point of island
How to control a burning plasma

Dominant alpha heating
Fast particle instabilities
\[ d + t \rightarrow \text{He (3.5 MeV)} + n \text{ (14 MeV)} \]

**ITER:**
- Net energy amplification
- \( Q = \frac{P_{\text{fusion}}}{P_{\text{input}}} \approx 10 \)
- Alpha particles have enough power to heat the plasma (\( Q > 5 \): burning plasma)

**Present devices:**
- \( Q = \frac{P_{\text{fusion}}}{P_{\text{input}}} \approx 1 \)
- Only 20% of power stays in plasma
Control of MHD modes in present plasmas

MHD modes largely controlled via pressure profile

Main actuator:
  external heating
Control of MHD modes in present plasmas

Limited possibilities for control by external heating

Emphasis on localized heating & current drive for control
New physics in burning plasmas

Alpha particles directly interact with MHD modes and vice versa

⇒ We want to understand this

So we need knowledge on:
• MHD physics
• Physics of fast particles
• Advanced Control Processes

And tools:
• Diagnostics
• Electron Cyclotron Current Drive

External heating

Localized current drive
Alfvén waves are transverse waves that travel along the magnetic field lines at $v_A$

Alfvén speed: $v_A = B / (\mu_0 n_i m_i)^{1/2}$

$\omega = k_{||} v_A$

In a Tokamak: Periodicity $\Rightarrow$
with $k_{||} \sim |n - m/q|$
Alfvén waves in the continuum are strongly damped

\[ \gamma \sim d \frac{(k \parallel v_A)}{dr} \]
A propagation gap occurs at the Bragg frequency

- Destructive interference between counter propagating waves
- Bragg frequency: \( f = \frac{v}{2\Lambda} \)
- \( \frac{\Delta f}{f} \sim \frac{\Delta N}{N} \)

for shear Alfvén waves

- \( f = \frac{v_A}{2\Lambda} \), where \( \Lambda \) is the distance between field maxima along the field line

\[ \Lambda = q (2\pi R) \]

\[ \Rightarrow f_{\text{gap}} = \frac{v_A}{4\pi qR} \]

\[ \Rightarrow \Delta f \sim \frac{\Delta B}{B} \quad (\Delta B \sim a/R) \]
Frequency Gaps and the Alfvén Continuum depend on position

- Counter-propagating waves cause frequency gap
- Coupling avoids frequency crossing (waves mix)
All periodic variations introduce frequency gaps

<table>
<thead>
<tr>
<th>BAE</th>
<th>“beta” compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAE</td>
<td>“toroidicity” m &amp; m+1</td>
</tr>
<tr>
<td>EAE</td>
<td>“ellipticity” m &amp; m+2</td>
</tr>
<tr>
<td>NAE</td>
<td>“noncircular” m &amp; m+3</td>
</tr>
<tr>
<td>MAE</td>
<td>“mirror” n &amp; n+1</td>
</tr>
<tr>
<td>HAE</td>
<td>“helicity” both n’s &amp; m’s</td>
</tr>
</tbody>
</table>

Shear Alfvén wave continuua in an actual stellarator

Spong, Phys. Plasmas 10 (2003) 3217
‘Defects’ cause modes in the gaps

Magnetic shear \((dq/dr)\) creates extrema
Radially extended Alfvén eigenmodes are more easily excited.

Continuum Mode Structure

Where gap modes exist, the eigenfunction is regular & spatially extended.

Reversal in q $\Rightarrow$ RSAE (or AC)

TAE

Pinches, Ph.D. Thesis
AUG diagnostics to measure them: ECEI
Mode structure of RSAEs

Many RSAEs observed, with different poloidal mode numbers and radial harmonics

Amplitude and mode structure for selected frequencies

Relative amplitudes around 1%

Clear imaging in this case possible due to both SVD and Fourier frequency selection
Mode structure simulations

AUG

DIII-D
Energetic Particle Modes
To take home

- Understanding of fusion plasmas is continuously improving
  - This can lead to higher performance & better control algorithms.

- Many instabilities can be controlled in present devices
  - Much work to be done for burning plasmas because of the dominant alpha heating.
  - This involved a tight interaction of plasma physicists, control engineers and mathematicians.