Integration of High Power, Long Pulse Operation in Tore Supra in preparation of ITER

M. Chatelier, on behalf of Equipe Tore Supra
Tore Supra, large superconducting tokamak devoted to long-duration, high performance discharges

- 3rd largest tokamak
- Operation of the cryo-magnetic system for 18 years
- All PFCs actively cooled

- 6 min discharges (2003) with 1 GJ injected/exhausted energy
  \[ P_{\text{LHCD}} = 3 \text{ MW} \]
  \[ I_p = 0.5 \text{ MA} \]
  \[ n_{e0} = 2.5 \times 10^{19}\text{m}^{-3} \]
Large margin towards higher power long discharges

- Convective losses routinely handled by the TPL (3-5 MWm\(^{-2}\))
- H/CD systems initially designed for 30 sec operation; ongoing upgrade (see Beaumont et al., IT/2-5)
  \(\Rightarrow\) towards 10-12 MW for 1000 sec, near Greenwald

- Tore Supra current program:
  \(\Rightarrow\) Investigation NI discharges
  \(\Rightarrow\) Preparation scenarios & techniques for high power long pulse operation (based on LHCD & ICRH)
CIMES project
(2008, continuous Current drive)

CIEL project
(2003, active cooling)
Outline

• Safely operating Tore Supra at multi-MW level
• Multi-MW long duration discharges results
• Integrating operational controls for steady-state scenarios
• Turbulence measurements and local transport analysis
• Plasma wall interaction during long discharge operation
• Technological developments for long discharge operation follow-up
• Conclusions and prospects
Safely operating Tore Supra at multi-MW level
10 MW in TS representative of ITER operation in term of averaged power density & heat exhaust

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<th>ITER</th>
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| $P_{\text{inj}} / \text{Vol}$
(0.43 MWm$^{-3}$)     | 360 MW |
| $P_{\text{inj}} / \text{Surf}$
(0.16 MWm$^{-2}$)     | 130 MW |
| $P_{\text{inj}} / R_0$
(4.4 MWm$^{-1}$)       | 30 MW  |
| $P_{\text{nom}}$     | 150 MW |
|                      |        |

- **Power density**
- **Radiated power**
- **Convected power**

$\alpha$
Handling localized heat loads

• LHCD launcher
  ➔ A: fast electrons
  ➔ B: fast ion direct losses
  ➔ C: Arcing

• ICRH antenna
  ➔ A: fast electrons
  ➔ B: fast ion direct losses
  ➔ C: Rectified sheath

(see Goniche et al. EX/P6-12)
Safely operating Tore Supra at 10 MW level

- 20 areas monitored delivering Real Time IR signals
- Each used in RT controller with specific safety strategy
Multi-MW long duration discharges results
Significant ion heating at high Greenwald fraction

- $I_p = 0.9\ \text{MA};\ n_{e0} = 5 \times 10^{19}\ \text{m}^{-3};\ 8.4\ \text{MW H/D minority}$
- $T_i$ close to $T_e$
- $H_{\text{ITER-L}} = 1.3$
Toroidal rotation observed with ICRH

- Suggests sheared rotation
- Could explain confinement improvement through ITG and TE modes stabilization (Kinezero)
Long sawteeth-free discharges with ICRH & LHCD

- \( I_p = 0.6 \) MA; \( n_{e0} = 4 \times 10^{19} \) m\(^{-3} \); \( q(0) \) above 1
- Reminiscent of hybrid scenarios, but \( q \) profile controlled by LHCD

\[ P_{\text{tot}} = 6.3 \text{ MW} \]
\[ P_{\text{ICR}} = 3.1 \text{ MW} \]
\[ \beta_N = 0.83 \]
\[ \text{Greenwald fract.} = 0.93 \]
\[ \text{non-inductive fract.} \approx 50\% \]
Integrating operational controls for steady-state scenarios
Optimising plasma performance reliability

- Fully NI long discharges prone to MHD activity
- Small MHD free operating window (see Maget et al. EX/P8-21)
- RT current profile control:
  - Actuator LHCD $n_{\parallel}$
  - Sensor HXR width
- Combined with control of:
  - $I_p$ (LHCD power)
  - Flux consumption (primary)
- Triple control at low loop voltage ($< 10$ mV) (see Joffrin et al., EX/1-6)
**Integrating plasma optimisation and safe operation**

- RT IR safety + triple control
- Discharges 70 sec / 7MW controlled in MHD free window
- Pioneers integration work for ITER when combining:
  - global performance
  - profile shaping
  - plasma stability
  - PFCs protection

![Shot 36192 (B_T=3.7T, n/n_G=0.65)](image)

- Upper graph: $P_{LH}$ [MW] and $P_{FCI}$ [MW]
- Lower graph: $n/\nu$, $T_{IR}$ [°C], LH-power [MW]
Turbulence measurements and local transport analysis
Neoclassical level pinch observed inside $q=1$ in $\Omega$ plasma

- Progressive density build-up during sawtooth recovery
- Inward pinch
- Low diffusion
- Vanishes with high CD and/or heating power

See Hennequin et al., EX/P4-36
**$\beta$ scaling experiments in L mode**

Supported by density fluctuation measurements

- Two sets of discharges
  - $\beta_n = 0.5 / B$
  - $T = 3.8T$
  - $\beta_n = 0.2 / B$
  - $T = 3.2T$
  - Matched $\nu^*$, $\rho^*$ & $q$ profiles

- Weak $\beta$ degradation.
- $\beta$ exponent: $-0.2 \pm 0.15$
- Global confinement $-0.2 \pm 0.4$
- Effective diffusivity
- ITER L-mode scaling $-1.4$

- Supported by density fluctuation measurements

- Bias in extraction of dimensionless scaling law
Plasma wall interaction issues during long discharge operation
Fuel retention in Carbon walls

- Long term constant retention rate observed (50-80% injected flux)
- Repetitive behaviour on 3 consecutive shots (15 min)

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Type of retention</th>
<th>Saturat.</th>
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<tbody>
<tr>
<td>Adsorption in C porosity</td>
<td>Transient</td>
<td>Yes</td>
</tr>
<tr>
<td>Implantation</td>
<td>Permanent</td>
<td>Yes</td>
</tr>
<tr>
<td>Codeposition</td>
<td>Permanent</td>
<td>No</td>
</tr>
<tr>
<td>Bulk diffusion &amp; trapping</td>
<td>Permanent</td>
<td>No</td>
</tr>
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</table>

\[ D/C = 0.1 \]
**Bulk diffusion, a credible retention mechanism**

- Evidenced in laboratory experiments at high fluence ($f_l$)
- Key parameter: exposure time
- Retained fraction $\propto (fluence)^{0.5}$

- Simple model: implantation up to saturation + evolution retained fraction $\propto (fluence)^{0.5}$
- Needs to be refined

**Extrapolation to ITER:**
- Bulk diff. possible, but $\propto f_l^{0.5}$
- Codeposition ($\propto f_l$) still major concern
- Detritiation difficult for both
Flows in the SOL: a common physics for divertor and limiter machine

- Half recycling at each strike zone + uniform radial outflux from core => nearly stagnant flow at Mach probe

Evidence of strong outflux across the outboard midplane

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<tr>
<th></th>
<th>HFS</th>
<th>BOT</th>
<th>LFS</th>
<th>TOP</th>
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<tbody>
<tr>
<td>Uniform outflux</td>
<td>&lt; 0</td>
<td>≈ 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Localized outflux</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
<td>≈ 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Measured</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
<td>≈ 0</td>
<td>&gt; 0</td>
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- Large SOL width when unobstructed by outboard limiter
- SOL fed by long range parallel bursty transport events located near the outboard midplane (see Gunn et al., EX/P4-9)
Technological developments for long discharge operation follow-up
Articulated Inspection Arm operational in 2007

- In vessel remote handling light payload carrier (10kg)
  - able to reach all part of TS chamber without breaking vacuum
- 8-meter long, 5 modules with 2 actuated joints each
- Prototype module tested under ITER representative conditions

...
Conclusions and …

• After 3MW/LH 6mn discharges of 2003, Tore Supra has performed high power long pulse discharges (5-10MW, 20-60s) still far from the limits of the actively cooled pump limiter

• Substantial progress in real time control of safe HF -non inductively driven and heated - discharges:
  - Minority ICRH & LH driven steady state discharges
  - Real time control of antennas temperature
  - Real time control of current profile

• Extensive density fluctuation measurements bring coherence in transport and stability studies

• Large and continuous D absorption by the C wall suggesting large bulk diffusion process at work

• Edge particle radial transport primarily on the outboard side consistently with Langmuir probe measurements
... Prospects

- **Enhancement of the LH power & duration in preparation (CIMES project: 6-8MW, 1000s)**
  - Steady state high power non inductive real time controlled discharges
  - Physics of non inductive discharges

- **Preparation of articulated inspection arm for several purposes**
  - Visual inspection of PFCs
  - Vacuum leak test
  - D recovery … under real conditions of temperature/vacuum

- **Pursue building experience in integrating ITER relevant constraints for high power operation in actively cooled environment**

  Complementary of JET (& ASDEX-U) with all metal wall and high NBI
• Monday 16\textsuperscript{th}
  \(\Rightarrow\) E. Joffrin et al., EX/1-6

• Tuesday 17\textsuperscript{th}
  \(\Rightarrow\) Semerok et al., IT/P1-15
  \(\Rightarrow\) Garbet et al., TH2-2, Beyond scale separation in gyrokinetic turbulence
  \(\Rightarrow\) Bécoulet M. et al., IT/P1-29, Modelling of edge control by ergodic fields in DIII-D, JET and ITER

• Wednesday 18\textsuperscript{th}
  \(\Rightarrow\) Durocher et al., FT/1-5

• Thursday 19\textsuperscript{th}
  \(\Rightarrow\) Hogan et al., EX/P4-8, Mechanisms for carbon migration and deuterium retention in Tore Supra CIEL long discharges
  \(\Rightarrow\) Gunn et al., EX/P4-9
  \(\Rightarrow\) Hennequin et al., EX/P4-36

• Friday 20\textsuperscript{th}
  \(\Rightarrow\) Goniche et al. EX/P6-12

• Saturday 21\textsuperscript{th}
  \(\Rightarrow\) Libeyre et al., IT/2-1Ra, Remaining issues in superconducting magnets for ITER and associated R&D
  \(\Rightarrow\) Beaumont et al., IT/2-5
  \(\Rightarrow\) Huysmans et al., TH/P8-2, MHD stability in X-point geometry : simulation of ELMs
  \(\Rightarrow\) Maget et al. EX/P8-21
Discriminating spurious overheated zones

- High temperature measured on poorly adherent objects
- Identified by follow-up of reference discharges
- Spurious zones excluded from monitored area

![Graph showing temperature over time with highlighted Q1 and Q2 intervals and a temperature difference threshold of ≥ 200°C.]

![Image of a topographic map highlighting B4C flakes with a temperature contour line at 37421.]
Permeation through open pores

Molecular "diffusion"

Trapping sites

Transient retention
(Phase 1)

Long term retention
(long pulse / high flux)

[H. Atsumi et al., JNM 313-316 (2003)]