Investigation of steady-state tokamak issues by long-pulse experiments on Tore Supra

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on behalf of the Tore Supra Team

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Tore Supra: the first 20 years

• 1988: first plasma
  - superconducting toroidal field coils
  - non-inductive current drive capability (LHCD)

• 1999-2001: from superconducting to steady-state machine
  - actively cooled Plasma Facing Components (CFC)

• 2002-2003: fully non-inductive 1 GJ - 6 min discharges

• 2004-2006: ~ 10 MW (RF), long pulse experiments ($t \gg \tau_R$)

• ITER relevant issues:
  - dominant electron heating by ion tails, $T_e \sim T_i$
  - physics and control of steady-state plasmas
  - deuterium retention in long-pulse operation
  - fast-ion driven MHD modes
  - technology developments and tests in real machine environment

Outline

• Technology Developments
  ➢ ITER-like antenna
  ➢ Articulated Inspection Arm

  K. Vulliez FT/4-Rb
  M. Houry FT/P2-18

• Operational Issues
  ➢ Deuterium Inventory
  ➢ High Power Issues
  ➢ Sawtooth control by ECCD
  ➢ ECRH assisted start-up

  E. Tsitrone EX/9-1
  A. Ekedahl EX/P4-2
  J. Bucalossi EX/P6-12

• Physics Results
  ➢ Turbulence and Transport
  ➢ SOL Physics
  ➢ MHD

  J.P. Gunn EX/P6-32
  P. Maget EX/P9-9
  R. Sabot EX/P8-9

• Prospects and Strategy
Technology developments and tests in real machine environment

- ITER-like antenna
  - K. Vulliez FT/4-Rb

- Articulated Inspection Arm
  - M. Houry FT/P2-18
Validation of ITER-like ICRH antenna concept

- Goal: ICRH coupling with ELMs
- Conjugate T concept developed for ITER ⇒ load resilience
- ITER-like prototype antenna built at CEA (2003-2007)
- Antenna successfully tested on Tore Supra in 2007 campaign
- Fast load variations by matter injection (pellets, SMBI)

Follow-up: JET ITER-like antenna
Articulated Inspection Arm

M. Houry, L. Gargiulo et al., FT/P2-18

- Goal: demonstrate feasibility of robot inspection techniques for ITER, at high T and UH vacuum
- 9.5 m robot arm developed at CEA 2005-2007
- Sept. 2008: full deployment in Tore Supra (with CCD camera) at 120°, 1.4 \(10^{-5}\) Pa after baking at 200°
- Non-invasive technique: plasma experiments resumed with no conditioning problems afterwards
- Next steps: leak detection and laser tools
Operational issues

- Deuterium Inventory  E. Tsitrone  EX/9-1
- High RF Power Issues  A. Ekedahl  EX/P4-2
- Sawtooth control by ECCD  M. Lennholm, to be published
- ECRH assisted start-up  J. Bucalossi  EX/P6-12
D-retention in carbon machines:

$\sim 10 \div 20 \%$ from gas balance, $\sim 3 \div 4 \%$ from post-mortem analysis

To solve this discrepancy:

- dedicated campaign for controlled D wall loading
- dismantle a sector of toroidal limiter, tiles cutting
- extensive analysis programme, in EU framework

$(\text{Thermodesorption, Nuclear Reaction Analysis})$

• Conclusions:
  - no saturation of retention rate
  - $\sim 50 \%$ of D found in toroidal limiter
  - co-deposition dominates (90%)
  - erosion zones: penetration of 10 µm
    (filling up of CFC porosity)
  ⇒ towards an accurate D inventory

Injected gas ($\sim 19.3$ g D)

Wall loading ($\sim 10.4$ g D)
5 hours of plasma with no wall conditioning

- 220 discharges of 1-2 min, with 2 MW LHCD
- robust, MHD-safe, non-inductive scenario
- carbonisation + boronisation, then no conditioning
Disruptive operational limit due to C deposits

- Increasing disruptivity also limits high power ($P_{\text{tot}} > 8 \text{ MW}$)
- 140 disruptions analysed (IR images, UV spectroscopy, impurities)
- precursor identified: hot spot on toroidal limiter + UFO + MARFE
- More likely explanation:
  - poorly cooled thick C deposited layers heated by radiation
  - cracks in layers $\Rightarrow$ cooling decreases $\Rightarrow$ overheating
  - flakes detach $\Rightarrow$ UFO $\Rightarrow$ MARFE $\Rightarrow$ disruption
High power operation recovered by full PFC cleaning

- Full cleaning of PFCs (limiters, antenna bumpers, etc.)
- 0.8 kg of carbon recovered (available for analysis)
- After restart and antenna conditioning, $P_{tot} > 11$ MW attained in a few shots (close to nominal power)
- No disruption in all the power increase phase!

**Graph:****

- 2006 and 2008 data points
- Disruption / UFO indicated

**Images:**

- Before and after cleaning

Optimistic prospects for power upgrade
High power ICRH+LHCD discharges: bi-stable sawtooth behaviour

- **sharp transitions** of sawtooth amplitude and period
- likely related to fast ion tail stabilisation
- no intermediate values. **Threshold**?

![Graphs showing sawtooth amplitude and period transitions in high-power shots](chart.png)

![Sawtooth amplitude vs. number of shots](sawtooth_graph.png)
ECCD control of sawteeth in the presence of fast ion tails

- ECCD control by mirror movements (as foreseen in ITER)
- physics different from ohmic plasma (broad ECCD found to be effective)
- real-time control demonstrated, but difficult: system bi-stable

M. Lennholm, to be published
ECRH assisted start-up
(maximum electric field in ITER $E_T \sim 0.3 \, \text{V/m}$)

- ECRH: 1st harm. O-mode
  1 or 2 gyrotrons (0.3-0.5 MW)
- pre-ionisation at $\omega = \omega_c$
- successful assisted startup at $E_T = 0.15 \, \text{V/m}$, 7 mPa
- ECRH assisted startup used after 2 major shutdowns (poor machine conditioning)
- 2nd harm. X-mode also demonstrated at $B = 2T$, although less reliable

Townsend minimum field for breakdown

$E_{\text{min}}$ (V/m)

Pressure (mPa)

Dots:
- successful startup without ECRH
- with ECRH

$L = aB_T/B_{\text{stray}}$

EC resonance (high-field side)
Physics experiments on Tore Supra: models and codes validation

➢ Turbulence
  • L-mode dimensionless scalings
  • measured k-spectra vs gyrokinetic codes
    T. Gerbaud, to be publ.
    A. Casati, to be publ.

➢ Perturbative transport studies
  • heat pinch studies by mod. ECRH
    X.L. Zou, EPS 2008
  • particle transport: SMBI/pellet injection
    R. Bellessa, to be publ.
  • impurity transport: SMBI/laser ablation
    T. Parisot, PPCF 2008

➢ SOL Physics
  • fast electrons in the SOL
    J.P. Gunn EX/P6-32
  • $T_i$ and flows
    M. Kocan, to be publ.
  • RF-induced SOL modifications
    L. Colas, PPCF 2007

➢ MHD
  • double tearing modes
    P. Maget EX/P9-9
  • fast ion and electron modes
    R. Sabot EX/P8-9
Highlights of Physics results

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➢ SOL Physics
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     J.P. Gunn  EX/P6-32
     M. Kocan, to be publ.
L-mode dimensionless scalings: $\nu^*$
(measurements of $\tau_E$, $\chi_{\text{eff}}$ and $\delta n/n$)

$\nu^*$ varied by a factor 5
at constant $q$, $\rho^*$, $\beta$

B=2.4→3.8 T, $I_p = 0.8\rightarrow 1.2$ MA,
$n_{e0}\approx 4 \times 10^{19}$ m$^{-3}$, $P_{\text{heat}} = 0.8\rightarrow 1.6$ MW
$T_{e0} = 1.1\rightarrow 2.4$ keV

$\Rightarrow \nu^* = 0.13 \rightarrow 0.61$

$\delta n/n$ varies only for $r/a > 0.7$

Fast-sweep reflectometry

Doppler reflectometry

$\rho=0.8$

$k_\theta = 7 \pm 1$ cm$^{-1}$

$k_\theta = 8 \pm 2$ cm$^{-1}$

$k_\theta = 9 \pm 2$ cm$^{-1}$
Impurity transport studies: laser blow-off, supersonic injection

- Injection of N, Al, Cr, Ni, Ge ($7 < Z < 30$ in centre)
- Decay time from soft X-rays and UV spectroscopy
- **Stationary** gas injection analysis $\Rightarrow V/D$
- **Transient analysis** (LBO or SMBI) $\Rightarrow V$ and $D$
- Comparison with **QualiKiz** code (C. Bourdelle, PoP 2007)
- Turbulent $V$ inward, dominated by curvature term

T. Parisot, PPCF 2008
R. Guirlet, EPS 2008

N supersonic + stationary

$D_{\text{trans+stat}} \ (m/\text{s})$

$V_{\text{trans+stat}} \ (m/\text{s})$

Curvature + compression

Ni central soft-X ray
N central soft-X ray
Ni source, LBO (Ni V)
N source, SMBI (N IV)
MHD: fast ion modes  
(ICRH driven fast ion tails)

- 40-70 kHz modes observed by reflectometry during strong ICRH (H minority heating)  
- Identified as Beta Alfvén Eigenmodes (BAE)  
- Measured frequency vs dispersion relation  
- Experimental vs theoretical threshold  
(C. Nguyen, PoP, to be published)

\[
\frac{n_H}{n_e} \frac{B}{\sqrt{T_e}} > c_1 F \left( c_2 \frac{n_e}{n_H} \frac{P_{\text{ICRH}}}{T_e} \right), \quad F(x) = \frac{1}{x^{3/2} \exp(-x^2)}
\]

\[
\omega = \frac{1}{R} \sqrt{\frac{T_i}{m_i} \left( \frac{7}{2} + 2 \frac{T_e}{T_i} \right)}
\]
MHD: fast electron modes
(LH driven fast electron tails)

- 2-20 kHz modes observed by fast ECE
- Likely (precessional) electron fishbones
- Frequency/ mode-number jumps observed
- Concomitant with nonlinear $T_e$ oscillations
- At jumps, fast electron redistribution

R. Sabot  EX/P8-9
A. Macor, to be publ.
Tore Supra: the next 10 years

- **2009-2010:** new LH launcher (PAM), 16 new cw klystrons $\rightarrow P_{\text{LH}} > 6$ MW
  - PAM $\rightarrow$ test of ITER LH launcher technology $\rightarrow$ Hoang IT/P7-1
  - $V_{\text{loop}} = 0$ shots at higher $I_p$ and $n_e$, better ICRH coupling, higher confinement
  - Proposed upgrade: 4-5 MW ECCD for control and scenario flexibility
  $\rightarrow$ Tore Supra should operate until the start of ITER

- Steady-state scenarios in ITER still to be developed
  - Conceptual, operational and computational issues $\rightarrow$ G.G., ITPA-SSO IT/P6-4

- Steady-state physics and technology integration: a challenge
  - Significant worldwide effort required in the next 10-20 years
  - EAST, KSTAR, SST1, JT60-SA will be the pillars of this programme, whenever attaining full performance steady-state operation

- Tore Supra is a strategic asset of the international fusion programme
  - fully operational steady-state tokamak for physics and technology tests
  - will bridge the gap from now $\rightarrow$ new steady-state machines
Tore Supra orals and posters

Tuesday Oct. 14
M. Houry  Development and operation of an ITER relevant inspection robot  FT/P2-18

Wednesday Oct. 15
E. Tsitrone  Deuterium inventory in Tore Supra: reconciling particle balance and  EX/9-1
post-mortem analysis

A. Ekedahl  Operational limits during high power long pulses in Tore Supra  EX/P4-2

Thursday Oct. 16
J. Bucalossi  ECRH assisted plasma start-up in the Tore Supra tokamak  EX/P6-12
J.P. Gunn  Suprathermal electron beams and large sheath potentials generated by the  EX/P6-32
RF antennae in the SOL of Tore Supra

Friday Oct. 17
E. Tsitrone  Deuterium inventory in Tore Supra: reconciling particle balance and  EX/9-1
(postal)
post-mortem analysis

R. Sabot  Observation of fast particle modes in Tore Supra  EX/P8-9
P. Maget  MHD modes associated to hollow current density profile configuration:  EX/P9-9
experiment and modelling

Saturday Oct. 18
K. Vulliez (rapp. M. Nightingale)  Validation of the load-resilient ICRF antenna concept on  FT/4-Rb
ToreSupra plasmas