Contribution of Tore Supra in Preparation of ITER

B. Saoutic, on behalf of Tore Supra Team
Tore Supra, a large superconducting tokamak devoted to long duration discharges

- Second largest tokamak presently in operation
- Unique capability to **routinely** produce high power / long duration discharges:
  - 6 minutes discharges with 1GJ of injected/exhausted energy
  - 160 long duration discharges (>1 min) in 12 operation days
- Integrates all technologies for long duration discharges:
  - Superconducting coil
  - Powerful non inductive current drive systems
  - Actively cooled high heat flux plasma facing components
- Many of these features are common with ITER
- Naturally lead focusing Tore Supra programme towards support to ITER:
  - Development and tests in realistic tokamak environment of ITER relevant technologies
  - Operational issues in an actively cooled PFC environment
  - Physics of long pulse and steady state operation
Outline

- Testing ITER-relevant technologies during long duration discharges
- Advance in real time control of stationary states of plasma
- Preparing ITER operation
- Investigating transport and turbulence issues
- Conclusion and prospects
Testing ITER-relevant technologies during long duration discharges
Characterization of the properties of the PAM LHCD launcher

- New launcher built in the frame of the LHCD system upgrade
- Based on the Passive Active Multijunction (PAM) concept created for providing efficient cooling of the launcher in the ITER environment (neutron load)

- ITER requirements:
  - Efficient cooling
  - Long distance coupling
  - ELMs resilience
  - Power density 33 MWm⁻² at 5 GHz
  - Long pulse capability
PAM properties: low power reflection close to the cut-off density

- Lower RC at larger plasma launcher gap, when compared to fully active multijunction (FAM) launcher

- Coupling agrees with linear theory:
  - Experimental points match prediction from ALOHA code
Good coupling properties preserved during edge perturbation

- Supersonic Molecular Beam injection (SMBI) used to mimic ELMs
- At least intermediate power (1.5 MW) can be maintained during SMBI
Long pulse operation at ITER-relevant power density

- 2.75 MW coupled for 78 seconds
  - 25 MWm\(^{-2}\) at 3.7 GHz extrapolate to 33 MWm\(^{-2}\) at 5 GHz
- Low RC (2%) at large plasma launcher gap (10 centimetres)
- Efficient cooling

- Full CD regime for 50 s:
  - \(\eta_{CD} = 0.75 \times 10^{19} \text{ AW}^{-1}\text{m}^{-2}\)
  - Similar to FAM efficiency during GJ discharges

A. Ekedahl et al., EXW/P7-05, Friday morning

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Advance in Real Time control of stationary states of plasma
Five states of the current profile with increasing $P_{\text{LH}}$

- $q$ profile progressively evolves from monotonic to reversed ($q_{\text{min}} \sim 3/2$)
- Five states characterized by different MHD activity:

- Large oscillations $q = 3/2$ activity
- Increasing $P_{\text{LH}}$
- Hot core with no MHD MHD regime ($q=2$)
- Sawtooth disappears
Deriving a search and maintain algorithm for controlling current profile state

- State detection using:
  - $T_e$ crash period from ECE, Mirnov coils and time history of $P_{\text{LH}}$
  - Yields $\Delta P_{\text{LH}}$ for going towards the requested state

- Successful demonstration of:
  - Control of presence/absence of sawteeth with varying plasma parameters ($n_e$, $P_{\text{ICRH}}$, $I_p$)
  - Obtaining and sustaining hot core plasmas
  - Recovering from MHD regime

- Long pulse capability of Tore Supra allows to develop and demonstrate controls that pioneers the control of stationary burn phase in a reactor.

F. Imbeaux et al., EXS/P2-10, Tuesday afternoon
Preparing ITER operation
Determination of SOL parameters for ITER ramp-up limiter phase

- SOL parameters (i.e. power deposition) before X-point formation are crucial for ITER first wall design
- Present scaling law established from X-point plasma data:
  \[ \lambda_q = (1 \pm 1/3) \times 3.6 \times 10^{-4} R^2 P_{SOL}^{-0.8} q_a^{0.5} n_e^{0.9} Z_{eff}^{0.6} \]
- Specific experiments in limiter configuration on Tore Supra
  - 108 measurements out of 186 outside ± 50% uncertainty
  - A simple expression fits well Tore Supra data:
    \[ \lambda_q = (1 \pm 1/10) \times 0.025 P_{\Omega}^{-0.8} \]
- Experiments on other device needed to check the \( R^2 \) scaling
**Disruption mitigation studies**

- Test of MGI with various gases (He, Ne, Ar and He/Ar mixture):
  - No effect with Ne and Ar
  - Efficient suppression of runaway with He
  - No dependence with amount of injected gas (20-500 Pam³)

- Dynamic of gas penetration measured by fast imaging camera:
  - He penetrates much quicker (120 m/s) than Ar (20 m/s)
  - Density rise steeper and thermal quench triggered at higher density with He
  - Likely explains the RE suppression with He
  - Penetration depth independent of gas and injected amount
    - Cold front blocked at the q = 2 surface
    - Triggering of MHD when the cold front reach q = 2. Burst of energy expelled from the core ionized neutrals preventing further penetration

- Important insight in the mechanism at work during MGI:
  - A necessity for modelling and extrapolation to ITER

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**B. Saoutic**

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**F. Saint-Laurent** et al., EXS/P2-16, Tuesday afternoon
ICRH wall conditioning in the presence of a permanent $B_t$

- Thanks to permanent $B_t$ on Tore Supra, comparison between pulsed (1 sec.) and continuous (60 sec.) ICWC discharges:
  - Efficient isotopic ratio control with continuous discharge using He/H mixture: $\frac{H}{(H+D)} = 4\% \implies 50\%$ after 900 sec. cumulated ICWC
  - However, H retention 10 time higher ($3.2 \times 10^{22}$) than D exhaust ($3.4 \times 10^{21}$)
  - Pulsed discharge with sufficient pumping time in between for H removal
  - 1 sec. long pulse allows to exhaust D at the same rate than H retention

- Successful recovery from disruption using pulsed He ICWC:
  - He gas, $10 \times 2$ sec pulse every 10 sec
  - HD partial pressure and removal rate comparable to Taylor like pulsed discharge

D. Douai et al., FTP/P1-26, Tuesday morning
Investigating transport and turbulence issues
Influence of magnetic field ripple on spontaneous plasma rotation

- No strong external rotation drive expected on ITER:
  - Need to understand mechanisms underlying spontaneous rotation
- Variation of ripple amplitude at the edge $\delta_{\text{edge}}$ by varying $\Omega$ plasma size at constant $q_{\text{edge}}$:
  - Co-rotation observed at low $\delta_{\text{edge}}$
  - Ct-rotation observed at high $\delta_{\text{edge}}$
- Coherent picture when plotting $V_\Phi$ vs. $\delta$
  - Ripple induced toroidal friction that dominate at high $\delta_{\text{loc}}$
  - Turbulent processes that are likely the main drive at low $\delta_{\text{loc}}$

C. Fenzi et al., EX/3-4, Wednesday morning
Characterization of micro turbulence

- High resolution density fluctuation $k_\perp$ spectra from Doppler back-scattering reflectometry
- Shape well fitted with $e^{-\gamma k}$ by considering 2 regions:
  - Low $k$ (< 0.7): energy injection from main instabilities
  - High $k$ (> 0.7): energy transfer through cascade process

- Also fair fit of high $k$ by shell model:
  - Generalised to non local interaction of drift wave with meso-scale structure as zonal flows and GAM
  - Yields $k^{-3}/(1+k^2)^2$ with no fitting parameter (except fluctuation level), in the limit where disparate scale interaction dominates.

- Strongly suggests that interplay between fluctuations and meso-scale structure is a key ingredient for determining $k$ spectrum shape in the energy transfer region.

O. D. Gürcan et al., THC/P8-02, Friday afternoon
Influence of collisionality on turbulence spectra

- Dimensionless scans experiments for determining the effect of $\nu^*$
  - High k region: no significant change, $\gamma \approx 5.2$ for $\nu^* \times 4$
  - Low k region: flatter spectrum at higher $\nu^*$: $\gamma \approx 1.7$ for $\nu^* \times 4$

- Does not support standard explanation on effect of $\nu^*$ on ZF or TEM:
  - $\nu^*/\nu$ should:
    - stabilize TEM,
    - peaked ITG spectrum should dominate:
  - spectrum should peak

More work for theoretician…

L. Vermare et al., EXC/P8-19, Friday afternoon
Fluctuation measurements in Tore Supra validate gyrokinetic assumptions

- Non linear gyrokinetic simulations in quantitative agreement on:
  - Magnitude of effective heat diffusivity (from power balance analysis)
  - RMS values of density fluctuation (from fast sweeping reflectometry)
  - Wave number spectra in radial (fast sweeping reflectometry) and poloidal (doppler reflectometry) direction

- A major progress in comparing experiments & first principle simulations
  Y. Sarazin et al., THC/3-5, Thursday morning
**Dependence of heavy impurity transport on electron temperature gradient**

- Ni injection in sawtooth free plasma:
  - $\nabla T_e$ varied by changing ECRH deposition
- Specific behaviour of diffusion coefficient $D_{Ni}$ in the very core of the plasma ($\rho < 0.2$):
  - No strong variation of $D_{Ni}$ with $R/L_{Te}$ at $\rho = 0.4$
  - Strong increase of $D_{Ni}$ with $R/L_{Te}$ at $\rho = 0.1$, suggesting critical gradient ($\sim 7$) above which turbulent transport dominates

\[ \text{Graphs showing data points for } D_{exp} \text{ vs } R/L_{Te} \]
**Dynamic of turbulence in the plasma edge**

- Observation of filaments aligned with magnetic field from fast imaging:
  - Propagates in the SOL and inside the confined region
  - Filaments not a consequence of open field line topology
  - Only on the low field side for both cases

- Poloidal mapping of radial particle flux confirms LFS/HFS asymmetry:

- Electrostatic fluctuation measured by rake probe at plasma top:
  - Coherent and intermittent bursts in phase with E fluctuations
  - Corresponds to a net radial flux toward the wall
  - Radial flux at probe location from turbulence measurement & poloidal mapping agree

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Conclusion and prospects
Conclusion

• In the last 2 years, the programme of Tore Supra has focused on support to ITER:
  – successful validation of ITER-relevant LHCD launcher on long duration discharges
  – Development of advanced search and maintain control algorithm
  – New scaling law for $\lambda_q$ dependence for the ramp-up phase of ITER
  – Insight gained in MGI mechanisms for disruption mitigation
  – Demonstration of recovery from disruption with ICWC

• Significant results also obtained on more fundamental issues:
  – Competition between transport and ripple induced friction on plasma spontaneous rotation
  – Important insight gained on micro-turbulence characterization, impurity transport and edge transport
  – Experimental validation of first principle non linear gyrokinetic codes assumption
Short term prospects

• Because realizing high power / long duration discharges asks for comprehensive integration of physics and technology, Tore Supra programme naturally encompasses many issues of importance for ITER, ranging from fundamental physics to operational issues and technological tests.

• The contribution of the Tore Supra programme to ITER will even be amplified with the completion of the LHCD system upgrade that will allow:
  – to test technological objects in more stringent conditions
  – to extend the operational domain of long-duration discharges to higher plasma current and densities
Longer term prospects

• All the experience developed on Tore Supra towards realization of long duration discharge points to the vital necessity of qualifying actively cooled PFC in a realistic tokamak operational environment.

• IRFM is thus studying the possibility of implementing an actively cooled massive tungsten divertor in Tore Supra, in support of ITER.
Companion Presentation and Poster

- A. Ekedahl et al., EXW/P7-05, Friday morning
  - PAM results
- F. Imbeaux, G. T. Hoang et al., EXS/P2-10, Tuesday afternoon
  - Search and maintain algorithm
- F. Saint-Laurent et al., EXS/P2-16, Tuesday afternoon
  - Disruption mitigation
- D. Douai et al., FTP/P1-26, Tuesday morning
  - Ion cyclotron wall conditioning
- C. Fenzi et al., EX/3-4, Wednesday morning
  - Spontaneous rotation vs ripple amplitude
- L. Vermare et al., EXC/P8-19, Friday afternoon
  - Micro turbulence characterization
- O. D. Gürcan et al., THC/P8-02, Friday afternoon
  - Shell model
- Y. Sarazin et al., THC/3-5, Thursday morning
  - Progress in non linear gyrokinetic modelling
- R. Guirlet et al., EXC/P8-06, Friday afternoon
  - Impurity transport
- P. Tamain et al., EXD/P3-34, Wednesday morning
  - Transport and turbulence in the edge