Chapter 5: MHD, Disruptions and Control (MDC)

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Rationale of the chapter

The chapter discusses **2 aspects**:

1) In what way MDC **impacts the programme**, e.g. by impacting/limiting plasma scenarios
2) What **MDC-related research** can be done in DTT.

Both aspects are discussed to some extent in **each of the sections**.

One key point is the **strong similarity between DTT and ITER** in terms of **actuators for MHD control and disruption mitigation** and **operation timelines**.

5.1 Important features of DTT

- **Large nominal B_t and I_p** → β_N relatively modest but potentially large disruption loads
- Operation at **reduced B_t and I_p** but relatively high input power **planned**, in particular during the **first phase of operation**, where **large β_N** values may be reached.
  - May allow investigating **advanced scenarios**, in a complementary role to JT-60SA.
- While reference scenarios in **single null configuration with q_{95}=3** are **rather standard** from an MDC point of view, **other scenarios** (e.g. negative triangularity) will explore **less well known territory**.
- DTT will comprise two **key actuators** for MHD control: a **powerful ECRH system** and a set of in-vessel **Non-Axisymmetric (NA) coils**.
  - Similar to ITER

5.2 MHD stability and control

5.2.1 Assessment of ‘basic’ MHD stability for DTT scenarios

- Ideal and (classical) low n resistive **MHD stability studies** have been performed for the **E1 (full power) and Day0 scenarios** in the positive triangularity configuration using **CHEASE and MARS** [Fusco EPS 2022, Crisanti IAEA 2023].

- When sawteeth are not included in the model, **q=1 radius** predicted with **JINTRAC** [Casiraghi PPCF 2023] is **quite large** (e.g. $\rho_{tor}\approx 0.55$ in the E1 scenario) and q is flat in the core with a low q_0.
  - ECCD cannot affect this situation much.
  - This results in a large **internal kink mode** being unstable.
  - At higher n’s, **infernal modes** are found in the E1 scenario, which may limit the achievable plasma performance. In the Day0 scenario, infernal modes are stable due to the lower pressure gradient.

- For the **E1 scenario**, a sensitivity study to q_0 and β was performed [Fusco EPS 2022, Crisanti IAEA 2023]. Unstable external kink modes were found, but only at values of q_0 or β far above what is expected from the integrated modelling → **Do not expect RWMs**
  - Note: NA coils too slow for RWM control

5.2 MHD stability and control

5.2.2 Sawteeth

- Sawtooth model included in some **JINTRAC** simulations [Casiraghi PPCF 2023].
- Kadomtsev **complete reconnection** model predicts a **long sawtooth period** (0.72 s) and **large crashes** ($\Delta T_e \approx 5.1$ keV).
- An **incomplete reconnection** model may be more realistic. Preliminary JINTRAC simulations suggest that this will result in a **shorter sawtooth period** and **smaller crashes**. More accurate JINTRAC simulations are planned.
- The possibility to **control sawteeth** by modifying the current density profile in the core using **ECCD** appears **limited** in the E1 scenario [Baiocchi NF 2023, Casiraghi PPCF 2023].
- **Impact of fast ions** and possibility to control sawteeth using **ICRH not yet investigated**.

5.2 MHD stability and control

5.2.3 Neoclassical tearing modes

5.2.3.a NTM stability and dynamics

- In order to assess the stability and impact of NTMs in DTT scenarios and to evaluate the ECH&CD power required for their stabilization or suppression, an **NTM module** has been developed by ISTP-CNR and SPC-EPFL and installed in **JINTRAC** and the **European Transport Solver**.

- At **nominal B_t**, β_N is expected to remain moderate, suggesting that **NTMs should not be a critical issue**. However, large sawteeth are predicted in the E1 scenario, which may trigger NTMs. The evolution of m/n=3/2 and 2/1 NTMs has been evaluated both with JINTRAC and ETS → Saturate at **moderate amplitudes** (island width up to ~10% of the minor radius) but **may lock**.

- DTT also plans operating at **reduced B_t** (typically 3 T). **Hybrid and advanced tokamak scenarios** at reduced B_t are in preparation (see Ch. 2) and should achieve **high β_N** (up to 2.5), implying **more unstable conditions for NTMs**. In some conditions (flux pumping), moderate 3/2 modes may in fact be beneficial in controlling the core pressure and safety factor profile.

5.2 MHD stability and control

5.2.3 Neoclassical tearing modes

5.2.3.a NTM avoidance and control

- NTM avoidance in DTT will rely on the flexible heating system with **>20 MW of ECH&CD** on **equatorial real-time-steerable launchers** capable of changing the deposition profile from narrow to wide regions in the core plasma [Baiocchi NF 2023], enabling the **optimization of the current and pressure profiles**.

- The development of NTM control in DTT can be of **support to the ITER and JT-60SA exploitation**. NTM can be **controlled/suppressed** by **raising the current inside the island via ECH&CD**. In DTT, **upper EC launchers, real-time-steerable** and delivering **up to 7.2 MW** at 170 GHz with good CD efficiency at q=3/2 and 2/1) will be available.

- JINTRAC simulations for the **E1 scenario** find that a **full suppression of the 2/1 NTM** can be obtained by **intervention** with **ECH** or **modulated ECCD** [Granucci IAEA FEC 2023]. ECH intervention needs to be early (island width = 2-3 cm), which is demanding for the control system. Modulated ECCD intervention is more efficient.

- Work on DTT may also help bring to higher TRLs NTM control schemes envisaged for **DEMO**, e.g. using a **(quasi-) in-line ECE** diagnostic. The latter would require integrating an ECE diagnostic in the ECH&CD upper launchers and/or installing additional ECE antennas in free upper ports, possibly real-time steerable.

5.2 MHD stability and control

5.2.4 Pedestal and edge localized modes

- **Pedestal height and width** used as BCs in the integrated modelling of DTT scenarios have been obtained with **Europed** [Casiraghi NF 2021, Casiraghi PPCF 2023] which uses the EPED1 model. **JALPHA** workflow also recently adopted at ENEA.
  - **Sensitivity studies**, in particular wrt. the density at the separatrix, find a moderate effect [Casiraghi NF 2021].

- **Size and duration** of **hypothetical Type I ELMs** have been estimated for the E1 scenario based on existing scalings [Casiraghi PPCF 2023]. However, it is to be noted that, given the **high density at the separatrix**, the E1 scenario might be in a **Type II or small ELM regime**. This question requires further modelling.

- **ELM control with RMPs** may be used in DTT to avoid damage to PFCs, with strong relevance to ITER and future reactors. **3 rows of 9 NA coils** (similar to ITER). **Optimal NA coils current distributions** have been calculated based on resistive **plasma response** computed with **MARS-F** [Pigatto NF 2024]. The development of ELM suppression will be **part of the general development of H-mode scenarios** discussed in Chapter 2.

- Besides active ELM control, an important research topic in DTT will be the development and study of **small ELMs and ELM-free regimes**, as discussed in Section 8 of Chapter 2.

5.2 MHD stability and control

5.2.4 Error fields

- The **NA coils** will be used to **minimize error fields** in addition to controlling ELMs.
  - These 2 tasks could be performed simultaneously by all NA coils or with different dedicated subsets of NA coils.

- Error fields expected from **manufacturing and assembly errors** of DTT coils have been calculated using a stochastic procedure. **50 kAt of NA coils** currents should be sufficient to correct the so-called 'three mode error index' under 50 ppm with a 95% probability [Albanese FED 2023].

- Metrics including the **plasma response** to error fields, such as the so-called **'overlap' criterion adopted in ITER** [Park NF 2008], shall be applied to DTT. This will be a crucial task for proper correction.

- Error fields will be estimated using **vacuum shots** and **identification studies with plasma** during the **early operation** of DTT. The main method will be the novel **non-disruptive compass scan** [Piron IAEA FEC 2023], which is supported by the ITPA MDC group. Experimental results will be complemented with **plasma response modelling with MARS-F and GPEC**, which will be used to calculate error field correction recipes.

5.3 Disruptions

5.3.1 Disruption budget and monitoring

- Disruptions are a **serious matter** for DTT due to its **relatively large size and large B_t and I_p**.
- **Global disruptivity** in DTT estimated to 30 % based on experience from present machines, with unmitigated disruptions at full performance representing 20 % of all disruptions, i.e. ~1000 events over the life of DTT.
- The DTT **mechanical structures** were **designed to withstand these ~1000 full performance disruptions**, assuming that half of them could be VDEs in the worst conditions [Crisanti IAEA 2023].
- **TQ and CQ characteristic times** estimated according to scalings [Hender NF 2007]. → Minimum CQ duration ≈4 ms. Much longer CQ durations (40 ms) also considered, based on observations from machines with a **metallic wall**.
  - Longer CQ could imply larger EM and thermal loads due to larger and longer lasting halo currents.
- **EM loads** have been calculated with **MAXFEA** and **Carma0NL**.
  - Forces and current paths in 3D structures also calculated with **ANSYS** using plasma evolution from MAXFEA.
  - A further benchmark of the plasma evolution will be carried out with **JOREK**.
- Disruptions will be **monitored**, in particular their TQ and CQ timescales as well as induced and halo currents (using **Rogowski coils and shunts**) and mechanical loads (using **strain gauges**).
  - Measurements will be **compared to the above-mentioned dimensioning simulations**. **If discrepancies are found**, simulations will be run again with more realistic parameters and the **disruption budget will be updated**.

5.3 Disruptions

5.3.2 Disruption prevention and avoidance

- **Key topic** for **future machines** like ITER and DEMO.

- **Similarities between DTT and ITER**:
  - Development of DTT PCS follows the same guidelines as those used for ITER, with reduced complexity. This includes in particular the implementation of **exception handling** (EH).
    - A **Matlab simulation platform for the DTT PCS** is under construction, aiming at closed loop plasma scenario simulations, which will be useful to develop safe scenarios, EH, fast I_p ramp down strategies, etc.
  - Similar **actuators** (and diagnostics) for disruption prevention and avoidance: e.g. ECH&CD, NA coils.

  → DTT may act as a **test bed** for disruption prevention and avoidance algorithms and strategies for ITER. Preliminary discussions have started between DTT and IO on this topic.

5.3 Disruptions
5.3.3 Disruption mitigation and disruption physics (1/2)

- Again a **key topic** for **future machines** like ITER and DEMO.

- Like ITER, DTT will be equipped with a Disruption Mitigation System (DMS) based on **Shattered Pellet Injection** (SPI).
  → Also in this area, DTT may act as a **companion to ITER** and joint efforts will be valuable.
  Note: No tokamak so far has used **SPI as a routine DMS**, in contrast to what is planned for DTT and ITER.

- The DTT **SPI system** will comprise 2 (optionally 4) multi-barrel injectors in 2 toroidally opposite upper oblique ports. Appropriate pellet dimension preliminarily estimated to 10^{23} atoms (≈14 mm pellet radius). Injection velocity foreseen to be >300 m/s → Flight time <10 ms.

- Option of an additional **Massive Gas Injection** (MGI) system considered for **early operation** of DTT.

- Work is ongoing to **simulate with JOREK SPI/MGI-mitigated DTT disruptions**.
  - One of the aims is to assess if the baseline design with two SPIs is appropriate or if two additional SPIs are required.

- A **disruption prediction algorithm** needs to be developed for DTT. The development of such algorithms is an active research topic [Pautasso NF 2018].

5.3 Disruptions

5.3.3 Disruption mitigation and disruption physics (2/2)

- DTT will produce valuable data to **test disruption models** in an **unusual range of parameters** (e.g. high field, high density).
- DTT will allow investigating the physics of disruptions in **Negative Triangularity** (NT) configurations, which may receive interest in relation with possible NT reactor design studies.
- Last but not least, DTT may allow assessing how **liquid metal divertors** cope with **TQ heat loads**.

5.3 Disruptions

5.3.4 Runaway electrons

5.3.4.a RE generation and avoidance

- Note: RE **avalanche gain** in DTT will be (like for all present machines) **many orders of magnitude smaller** than in ITER or DEMO
  → Relevance of DTT to ITER and DEMO in terms of RE generation/avoidance is limited.

- **Not clear if natural disruptions will produce RE beams** in DTT.
  - Full W wall may lead to slow CQ, which tends not to promote RE generation, cf. JET [de Vries PPCF 2012].
  - On the other hand, DTT will operate at higher I_p and B_t than JET, which promotes RE generation.

- **JOREK simulations are planned** in order to assess RE generation in natural DTT disruptions.

- Even if RE beams turn out to occur in natural disruptions, it is **likely that they may be avoided in SPI- or MGI-mitigated DTT disruptions**. This will also be assessed with JOREK.

- In addition, recent experiments in several devices have shown that the application of **3D fields may reduce the RE current**. Use of **NA coils** is considered in order to study this on DTT.

5.3 Disruptions

5.3.4 Runaway electrons

5.3.4.b RE mitigation

- Since the generation of multi-MA RE beams seems very difficult to avoid in ITER and DEMO (at least during the nuclear phase of operations), **mitigation of and/or resilience to RE beam impacts** is a **crucial topic** for these machines.

- Concerning ITER, it is hoped that **H_2 SPI into RE beams** will lead to a **benign termination** like observed in present machines.
  - This strategy **will be tested in DTT**.

- Concerning EU DEMO, the current strategy for resilience to RE beam impacts is based on **sacrificial limiters**.
  - Design studies regarding possible sacrificial limiters in DTT are ongoing, which may be an area for collaboration between the DTT and EU DEMO teams.
  - **JOREK simulations** are ongoing or planned to study the dynamics of RE beams and their termination in both machines [Vannini APS 2023].

5.4 Other control aspects

- Plasma position and shape control are discussed in Appendix XXX.

→ Remove this sub-section?

5.5 Relevant diagnostics

- Wide poloidally and toroidally distributed set of **in-vessel mineral-insulated-cables pick-up coils** and **low-temperature co-fired ceramics magnetic sensors** with a **sensitive band expanding above 1 MHz**

- **Equatorial ECE system** with adequate spatial (**1 cm** in X2 mode) and temporal (**5 μs**) resolution to diagnose **NTMs** and a broad coverage from the HFS to LFS (in O1 mode) allowing diagnosing **sawteeth**

- **SXR** and **bolometer tomography** systems will allow investigating the interplay between **MHD activity and impurities.**

- **CXRS** will allow measurements of **plasma rotation.**

- Two diagnostic systems are planned to measure **bremsstrahlung radiation from REs** in the **hard X-ray/gamma-ray** (HXR/GR) energy range, meant to be available respectively for Day 0 and Day 2.
    - **Day 0 system** = four HXR/GR detectors using BC-509 liquid scintillator at different toroidal positions in the torus hall, complemented, at each position, with one neutron monitor using NE213 liquid scintillator and one GR monitor using NaI(Tl) inorganic scintillator, designed based on experience from the FTU tokamak. Primary goal = **machine protection**.
    - **Day 2 system** = set of GR detectors to be installed together with neutron detectors in the horizontal neutron camera of DTT. The detectors are cylindrical LaBr3(Ce) crystals as those used in JET [Nocente PPCF 2020], observing the plasma through 9 collimated lines of sight and equipped with neutron attenuators to enable measurements of the energy spectrum of the bremsstrahlung radiation emitted by confined REs. Primary goal = **physics investigations**.