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Progress in preparing RT control schemes for DT operation in JET

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Introduction

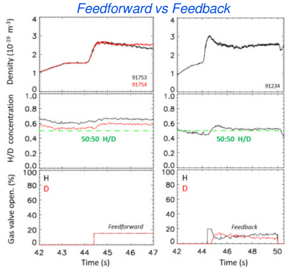
- JET uniquely offers the possibility of study DT plasmas' behaviour in conditions and dimensions approaching those required in ITER and fusion reactors in its future DT campaign, planned in 2020 (DTE2) [1].
- With respect to the previous DT campaign which took place in 1997 (DTE1) [2], the Carbon wall has been changed to an ITER-like wall with a Tungsten divertor and a Beryllium first wall, the total auxiliary power has been increased to 40 MW and a wide coverage of diagnostics has been installed.
- When operating JET in DT, each plasma discharge will be a precious resource, being both T and neutron budget limited. To ensure robust and lasting DT scenarios, while gathering the maximum information and experience from them, new plasma control schemes have been designed and sophisticated algorithm for monitoring plasma evolution have been developed.

Novel controllers for DT

Isotope ratio controller

- To achieve the right 50:50 D,T fuel concentration which maximizes nuclear fusion processes, the isotope ratio controller has been developed.
- This controller relies on visible spectroscopy for inferring the isotopic ratio at the plasma edge and acts in RT on the gas valve opening.
- To deliver a reliable tool for D,T operation, the isotope ratio controller has been tested in H,D plasmas (1.4 MA, 2.3 T).
- By using gas opening in feedforward, the desired H/D concentration is obtained in various attempts. On the other hand, by using gas opening in feedback, the desired concentration is straightforwardly achieved.

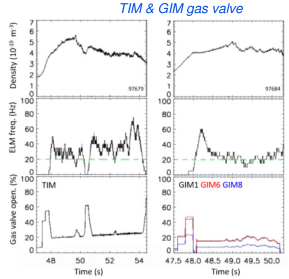
Feedforward vs Feedback



ELM frequency controller using D and T valves

- During JET operation, the ELM frequency controller helps in flushing Tungsten from the plasma edge and maintaining the energy released per ELM low enough to avoid damaging on plasma facing components.
- The ELM frequency controller relies on the fact that the ELM frequency increases with gas injection rate. When the ELM frequency drops below a threshold, the controller generates a requested valve opening for the gas injection module (GIM) used, taking the drop in the reservoir pressure into account.
- In preparation to DT operation, the use of multiple gas valves, including the new five T gas injection modules (TIMs), for ELM frequency control has been investigated. An ad-hoc algorithm, which takes into account both the pressure and temperature dependence of the gas reservoir and the piezoelectric valve crystals' hysteresis, has been developed.
- The ELM frequency controller has been successfully tested in D plasmas (2.4 MA 3.4 T) using multiple GIM and TIM valves.

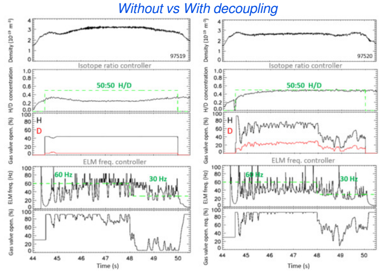
TIM & GIM gas valve



Decoupling scheme for isotope ratio and ELM frequency controllers

- To achieve high plasma performance regimes during DT operation, multiple SISO controllers will be run simultaneously and it is important that they can operate together.
- To assess how strongly coupled are these controllers, dedicated RT tests have been performed. Such tests reveal that the isotope ratio controller interferes with the ELM frequency controller:
  - When requiring 60 Hz ELM frequency, the ELM frequency controller required so much D gas that the isotope ratio controller reached saturation level and couldn't provide the required 50:50 H/D concentration.
- A decoupling algorithm has been thus developed. Within the decoupler, the requested valve opening from the ELM frequency control, instead of being sent to the corresponding gas valve, it is sent to the isotope ratio controller and multiplied each of the outputs to the D and H gas valve opening.
- Such a decoupling scheme has been tested in a D plasma (1.4 MA 1.8 T):
  - a stationary 50:50 H/D concentration has been achieved and despite the reduction on gas to control the ELM frequency, from 60 Hz to 30 Hz, the H/D concentration is kept constant.

Without vs With decoupling



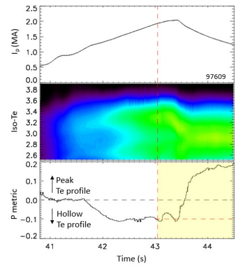
Dud detector

- During D,T operations, care has to be taken to reduce the T inventory as much as possible, to minimize any escape of T, while restricting the total number of D,T neutrons which are generated, in order to limit the activation of the machine.
- To this aim, a RT algorithm, named dud detector, has been developed. The dud detector calculates and monitors the time evolution of various plasma performance indicators, which can be used to trigger an alarm if the plasma is not behaving as expected [4].
- Recently such a detector has been implemented in a sophisticated Plasma Event TRiggering and Alarms system (PETRA) [5]. The metrics that have been included are the NBI power delivered, $H_{IPB98(y,2)}$ and the neutron rate normalized to the square of the plasma stored energy R_{nt}/W_p^2.
- The dud detector has been tested in RT. Once the alarm is raised, an ad-hoc plasma termination, named jump to termination (JTT), starts.

RT test to be performed

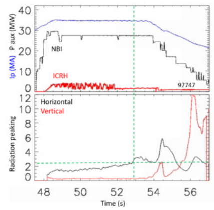
Temperature hollowness detector

- Core impurity accumulation has been a matter of concern for JET operation being this event responsible for plasma disruptions.
- When this event occurs, a hollow plasma temperature profile develops, causing a modification of the plasma current density, and thus the q profile. It has been shown statistically that after this chain of events [7], an MHD instability, with 2/1 poloidal/toroidal mode number, develops. The mode amplitude increases in time until JET protection system fires the disruption mitigation valve.
- An algorithm based on temperature profiles from electron cyclotron emission (ECE) diagnostic has been developed and allows for detecting hollow temperature profile [8].
- When $P = Tc_{ore} - T_{edge} / T_{edge} < -0.1$ then the temperature hollowness detector raises an alarm, and afterwards the plasma termination is initiated.



Radiation peaking control

- In combination with ELM frequency controller, RT indicators based on bolometric signals has been exploited to avoid impurity accumulation. Such indicators are the horizontal radiation peaking, defined as the ratio between central and off axis bolometer channels, and the vertical radiation peaking, the ratio of two channels, one above and one below the plasma mid-plane.
- These metrics allow to monitor the development of radiation peaking in different regions of the plasma, i.e. in the core and at the edge, respectively, and are thus used in conjunction.
- When the 2.5 MW threshold on horizontal radiation peaking is reached, around t=52.85 s, the plasma would not recover and the RT protection system triggers a JTT.



Advanced algorithms for disruption avoidance/mitigation

- In JET, the interest on machine learning guided disruption avoidance/mitigation algorithms steadily increases over the years:
  - RT bolometry tomography algorithm, which can estimate the amount of radiated power from different region of interests [6],
  - a generative topographic mapping (GTM) algorithm [9], which computes the probability of disruptive evolution for core and edge radiative collapse
- Such algorithms, included in PETRA system, can be exploited to identify brand-new detectors for detecting off-normal events or pre-disruptive states and to monitor the plasma performance behaviour. In future, once established their robustness and reliability, they can be used to steer experiments away from the operating conditions that inevitably lead to plasma disruptions.
- Moreover, efforts have been dedicated to adapt RAPTOR suites to JET plasmas [10]. Such a tool, which uses machine learning approach in combination with model-based predictions, can be used both offline, for investigating plasma dynamics and detecting diagnostic faults, and in integrated control once it will be imported in RT data network.

Conclusions

- Forthcoming JET DT operation will provide a unique opportunity to investigate several physics, engineering and technology open issues towards ITER operation.
- A number of novel RT controllers have been developed, each contributing to support a safe, reliable and high performing DT campaign. Such controllers have been tested in H,D plasmas and are ready for exploitation.
- Advanced tools for detecting pre-disrupting states have been developed, using machine learning technique, such as bolometry tomography and GTM, also combined with sophisticated plasma models, such as RAPTOR. These tools allow the identification of optimal actuator trajectories to improve the plasma performance, supporting the plasma scenario development, and can be exploited in RT in the near future.

JET — Università degli Studi di Padova — Consorzio RFX Ricerca Formazione Innovazione — CCFE Culham Centre Fusion Energy — IST — ENEA — EPFL — Laboratorio Nacional de Fusión

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