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## Overview of the EUROfusion Tokamak Exploitation Programme in support of ITER and DEMO

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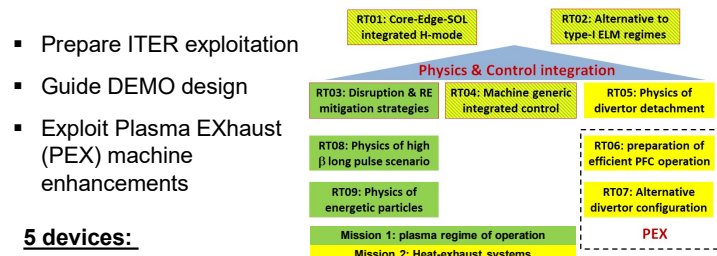
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### EUROfusion Tokamak Exploitation programme developed within the European Fusion Roadmap:

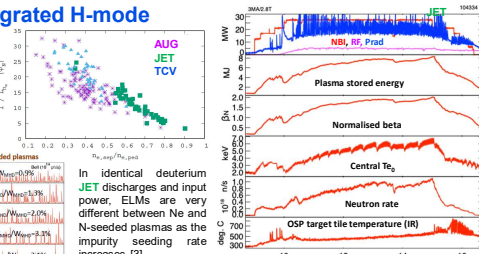


### ASDEX Upgrade (AUG), MAST-U, TCV, WEST and JET (2022-2023)

Tokamak exploitation operates a fraction of typically 30 to 45% of the time of each machine, except JET: 100%.

#### 1- Core-Edge-SOL integrated H-mode

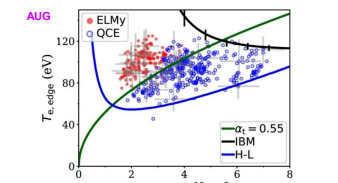
Strong link exists between pedestal pressure and  $n_{e,ped}/n_{e,0}$  [1]. Experimental results have shown that  $n_{e,ped}/n_{e,0}$  and  $(V_{th}n_{e,ped})_0=1$  are strongly correlated [2]. JET:  $\beta_p=1.5$  to  $3.2$  MA &  $B_T=1.7$  to  $2.9$  T. AUG:  $\beta_p=0.6$ ,  $1.0$  MA &  $B_T=1.9$ - $2.5$  T. TCV:  $\beta_p=170$  kA &  $B_T=1.4$  T.



→ Transition high power H-mode scenario at low core and pedestal collisionality (i.e. large plasma current) compatible with detached divertor achieved in the recent DTE3 campaign. Note: these data are recent and therefore not yet fully validated.

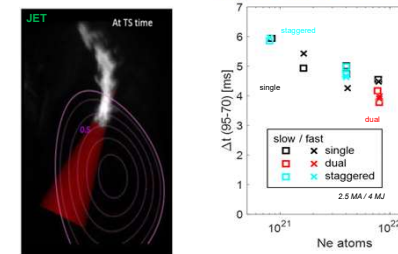
3MA/2.8T DT pulse in JET (DTE3 campaign) demonstrating core edge integration: with partial detachment via the control of target tile temperature with Neon seeded, small ELMs (AT=20C), at high plasma current (3MA) and low collisionality.

#### 2- Alternative to type-I ELM regimes



Negative trianguarity (NT) studies in TCV: Temperature peak at the outer strike point higher in NT than in positive trianguarity (PT) [5]. Experiments and simulations points towards lower  $\lambda_{ci}$  in NT configuration L-Mode compared to PT L-Mode [6]. Power exhaust in NT remains challenging:  $\blacklozenge$  Typically, shorter connection length  $\blacklozenge$  Indication of a smaller heat-flux, with  $\blacklozenge$  Lower divertor pressure, hinting at different particle confinement

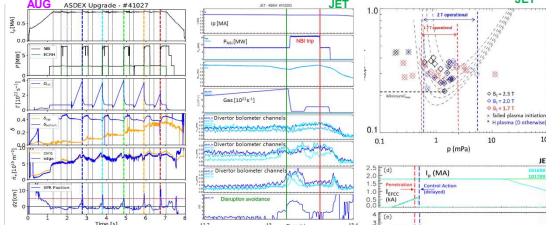
#### 3- Disruption and run-away mitigation strategies



$H_{\alpha}$  cloud recorded by the JET fast camera at the time of the pellet penetration and Thomson scattering edge measurement. The overlaid equilibrium is the last prior to the pellet arrival. Reproduced from [7].

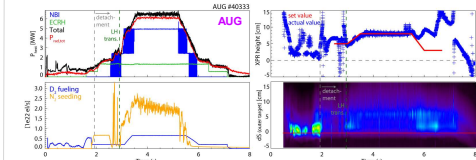
SPI can prevent the toroidal asymmetrical phase of the Vertical Displacement Event (VDE), i.e. AVDE and the exponential growth of the plasma current centred vertical position (Zc) is interrupted and then stabilized. Reproduced from [9]. The vessel reaction forces are strongly reduced in mitigated VDEs and that the difference in the energy deposited to the beryllium upper dump plates is about 5 times less than for an unmitigated VDE.

#### 4- Machine generic integrated control



Disruption proximity control in AUG (left) and JET (right): The upper triangularity  $\delta_{up}$  is an effective actuator for the H-mode density limit (HDL) disruption avoidance on AUG [10]. Automation of the dynamic pulse schedule has proven successful to scan the operational space of the HDL without disruption.

#### 5- Physics of detachment

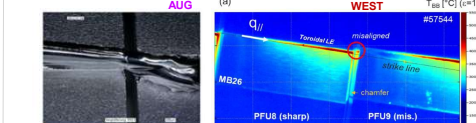


X-point Radiation control in AUG [13]: The XPR is induced by impurity seeding during the heating phase. It can be monitored in real-time and regulated by nitrogen injection. The active XPR control enabled the first demonstration of maintaining detachment throughout a full discharge including the transitions in and out of H-mode, featuring full detachment with a 90% radiation fraction. The ELM suppression, connected to a high location of the XPR, is also observed in the whole parameter range. The XPR can now routinely be reproduced in SOLPS simulations for AUG [14] and TCV [15]. Detachment control is now obtained in TCV, WEST (in L-mode) and JET.

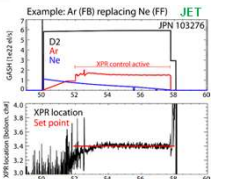
Breakdown studies (JET): Toroidal field versus pedestal gas pressure, both at the time of breakdown, for Ion Cyclotron assisted breakdown discharges with  $B_T = 1.7$  T (red squares),  $B_T = 2.0$  T (blue squares), and  $B_T = 2.3$  T (black squares). Reproduced from [12].  $E_{ped} = 0.33$  V/m with  $BT = 1.7$  T is achieved under conditions which EC breakdown assistance with 170 GHz waves would not work in ITER. Experiments also on-going in WEST and AUG.

New error field (EF) identification method tested on MAST-U and JET: increasing probing field is applied until a magnetic island forms. This event is detected by the locked mode detector and the plasma control system engages asynchronous control waveforms healing the magnetic island: the EF current is reduced to remove the island drive, and 2) the density is increased, to stabilize the island. Reproduced from [11].

#### 6- Preparation of efficient PFC operation

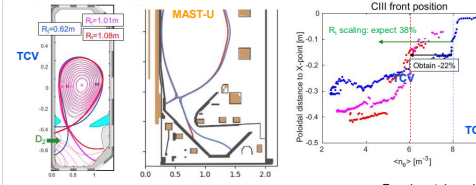


Studies of poloidal gaps: Right: infrared image of the plasma facing unit with 1.5mm misalignment in WEST reproduced from [17]. Left: zoomed-in final deuterium profile near the gap in AUG reproduced from [18]. MEMENTO modelling is indicating that the melt will relatively freely cross the gaps without penetrating into the gap [19]. Experiment in WEST, using a dedicated PFU with exposed PFU leading edge has allowed the benchmarking the MEMENTO code under a regime of shallow melting



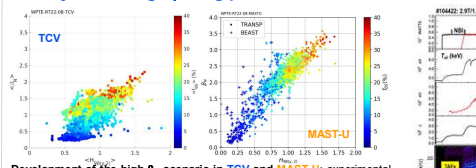
Tritium removal after JET DTE2 Campaign by different methods deduced from subdivisor residual gas analysis data: 1- baking; 2- 240C baking (extrapolated); 3- ICW & plasma inner divertor deposits; 4- Baking during ICW; 5- glow discharge; 6- total. Reproduced from [20]. Baking removes about 60% of the tritium.

#### 7- Alternative divertor configuration



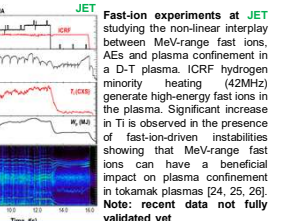
Alternative divertor studies with long legs shapes  $\square$  In TCV: CII front movement (and LPs) show partially reduced detachment threshold with increasing Leg. Reproduced from [21]  $\square$  In MAST-U: Near-ideal detachment threshold reduction in extreme, more strongly shaped MAST-U divertor. Reproduced from [22]

#### 8- Physics of high beta long pulse scenario



Development of the high  $\beta_p$  scenario in TCV and MAST-U: experimental database achieved with NBI on both devices (ECHRH in TCV) showing the confinement enhancement factor with color denoting the bootstrap current fraction. This work is due to continue in current and future campaigns [23].

#### 9- Physics of energetic particles



Fast-ion experiments at JET studying the non-linear interplay between MeV-range fast ions, AEs and plasma confinement in a D-T plasma. ICRF hydrogen minority heating (42MHz) generate high-energy fast ions in the plasma. Significant increase in Ti is observed in the presence of fast-ion-driven instabilities showing that MeV-range fast ions can have a beneficial impact on plasma confinement in tokamak plasmas [24, 25, 26]. Note: recent data not fully validated yet

Conclusion: The EUROfusion Tokamak Exploitation Work Package coordinated experiments between the 5 devices (AUG, JET, MAST-U, TCV and WEST) having different but complementary capabilities have demonstrated the benefit of this approach for answering key questions for ITER such as disruption mitigation, detachment control or the qualification of ITER grade components.

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