Potential research programme for JET with W wall and ECRH

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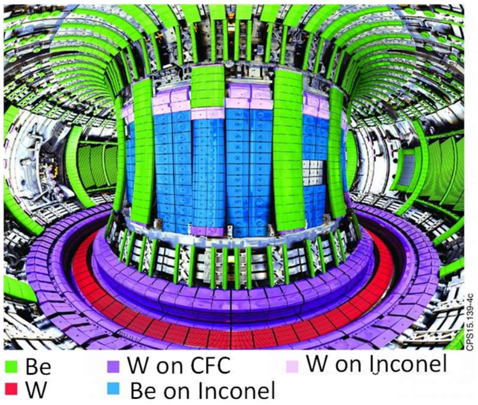

Fig. 1: From JET-ILW to W wall. Beryllium (green) to be replaced with W-covered graphite/CFC tiles, naked Inconel in remote areas (blue).

JET is a currently the only **DT**-capable tokamak worldwide, within a fully integrated plant. We propose a research plan for an extension of JET's operations (for at least 10 years) to explore and prepare experimentally the **ITER re-baselining** [1] choices: replace the Be wall with a (largely) **tungsten wall**, including a **boronization** system and add **10 MW of ECRH** to the existing heating capability of 30 MW of NBI and 6 MW of ICRH. Highlights of this **research plan** are presented, focusing on JET's uniqueness and the ultimate goals of these upgrades, to be delivered before the ITER **DT** campaigns begin.

ECRH and a W wall are expected to substantially alter and expand the operating space of JET plasmas, **beyond** the achievements of the experimental campaigns **DTE2** [2] and **DTE3** [3]. ITER-operating scenarios such as Baseline and Hybrid would be optimised anew in **D** and **DT**.

Hybrid scenarios in **D** and **DT** with JET-ILW aimed to **maximize fusion output** in **DT**. The optimal plasmas developed, leading to **fusion energy records**, had moderate (peaked) n_e, low collisionality, high β, hot ions, central NBI power deposition, high q_{95}, low q-shear and moderate ELMs [4]. ECRH and ECCD can provide core electron heating, W control and q-profile control, while ICRH can be used for ion heating [5] (as planned for ITER). That strategy might enable access to **higher T_i** in core and pedestal, **higher β** regimes with higher **p_{fast}** content, and possible **turbulence stabilisation**. At higher T_e, fast ion populations (NBI, alphas, IC) could be larger because their energy content depends on the slowing down time, which scales as $Te^{3/2}$. Fast particles and their effects would then be easier to detect. At higher T_e, the ion heating fraction by NBI ions will increase (because the critical energy increases with T_e). This could boost the fusion reactivity further. Hybrids provided the basis for plasmas especially designed to investigate **α-physics** and **AEs** in the recent **DT** campaigns [6, 7], as well as the **Tritium-rich** plasmas that achieved fusion energy records [8], which can be taken further.

Baseline plasmas, on the other hand, were developed in JET-ILW to maximise **thermal fusion** output [9]. This led to high current, high density plasmas with flat profiles that suffered from poor NBI core penetration and W accumulation, mitigated in part by high fuelling and ELM-flushing for W control [10]. Re-optimization of such scenarios in **D** and **DT** would be investigated with boronization, **impurity seeding** [11, 12], enhanced **central heating**, sawtooth control and pellets, aiming for **long stationary phases. Small/no ELM regimes** [13] might be obtained in more fusion relevant conditions, as the additional ECRH power would enable H-mode studies at **higher current** and/or field, with plasmas simultaneously closer to fusion relevant pedestal, **f_{GW}, β, ν^***. Conditions for confinement saturation and/or **T_i clamping** with central ECRH and ICRH at high density could be investigated In long pulses and with modulated gas inlet, ECRH, ICRH, NBI detailed transport studies would become possible. Operation without a **divertor cryo-pump** in **D** could mimic ITER's relatively low pumping capacity (this is a size effect, with great impact on **Tritium consumption**).

Isotope studies, such as transport, confinement and L-H transition threshold, would be possible at higher field and/or current, and with different combinations of heating systems to elucidate the influence of rotation, E_r, ∇p and electrostatic vs. electromagnetic effects. **DT** mixtures with low **T** content, as in the ITER low activation phase, would provide unique insights.

Fusion technology, safety, diagnostics: Once appropriate plasmas are developed, many issues could be addressed in **DT campaigns** [14, 15], some with existing systems, others with minor modifications or upgrades. For instance, existing cooling loops could be monitored to quantify **Activated Corrosion Products**. **Water activation** by 14 MeV neutrons could be measured better than in DTE3 (improved instrumentation). Measurement of **Single Event Effects** would be improved by locating the equipment in the Torus Hall. Programmed exposure of ITER and DEMO **material samples** to neutron fluxes in the KN2 system could be arranged to study **Short Term Activation** of nuclides. **Fusion power measurements** are particularly important, as the ITER regulator requires frequent measurements using two independent methods, with at least 10% accuracy. We could measure the **DT** fusion power with 14 MeV neutron and 17 MeV gamma ray spectroscopy along a known collimated line of sight, inferring the total fusion power **avoiding** long and time-consuming **in-vessel calibrations** [16]. **Boron-alpha gamma**

measurements with ^{4}He+^{10}B reactions, essential for α measurements in the re-baselined ITER, could be tested in **D** and **DT** [17]. The **LID-QMS** diagnostic, tested at JET in 2023 [18], is now foreseen as **Tritium monitor** diagnostic in ITER. Programmed experiments would provide **Tritim retention** measurements from specific types of plasmas and wall conditions.

A **pristine W wall** can be installed by Remote Handling. The expected **increase in W sputtering** would require **Boronization**, as in ITER. Boron deposits and layer life-time, B transport to remote areas, dust formation and **D** and **T** retention could be studied starting from a clean W first wall free from low Z PFC materials (no C or Be in-vessel) in order to understand accumulation dynamics. The new wall and LID-QMS diagnostic enable studies of recycling, particle balance (**D** and **T** inventory monitoring) and wall cleaning techniques such as ICWC. Investigation of the plasma startup **burn-through** and stray radiation during **ECRH-supported limiter phases** with plasma currents above 1 MA is ITER-relevant even in **D**. W is also likely to affect plasma **disruptivity** and **runaways**, and it may be necessary to re-optimise **disruption mitigation** [19]. Installation of a 2nd Shattered Pellet Injection system could be considered.

Feasibility & Timeline: the JET tokamak is in a fundamentally **sound** state and given funding it could be ready for restart in ~6 months. There is **enough Tritium** left on-site for future **DT** campaigns. A JET extension would begin with inspection, refurbishment and maintenance of the **existing infrastructure**, such as the Active Gas Handling System, cryogenics and cooling plant (replace/repair elements, add He liquefiers), baking plant, Glow Discharge Cleaning electrodes, power supplies, etc... The proposed upgrade would lead to a review of the **neutron budget** and the **Safety Case**, redefining the neutron limit. Detailed planning for the upgrades could take place in parallel with short and focused **Deuterium experimental campaigns**. Experiments not executed or finished in earlier JET campaigns due to tight deadlines could become possible in addition to new proposals. The timeline might be 2025-2027 design & **D** ops, 2028-2030 installation of upgrades, 2030-2035 experimental campaigns in **D**, **DT** (including **T-poor** mixtures to mimic ITER's low activation campaign), **D** (and/or **H** for specific isotope studies).

Electron Cyclotron Resonance Ssytem: a project for ECRH and ECCD is available [20, 21], previously costed and approved. A set of **170 GHz** gyrotrons would operate in X-mode 2nd harmonic resonance at 3T. Testing **multifrequency** gyrotrons (with matched windows) to reach higher fields would be an additional asset. Cooled steerable antennae would enable targeted

ECRH and ECCD. Based on STEP estimates, it’s expected that, from project start, the first 4-5 MW could be available in 5 years, followed by additional 2-4 MW per year to be delivered in the following years.

W wall: the wall change is to be based on the JET-ILW project [22], which required an 18-month shutdown. The initial idea is to replace Be tiles with W-coated CFC tiles, and install clean Inconel tiles in the inner wall (or coat with W? simulations needed). An adequate boronization system would need to be developed to handle the increased W source.

Control systems: JET already has **integrated** control systems, but the upgrades would justify a revision of the existing data acquisition (especially real-time) and control systems for wall & divertor protection, disruption avoidance & disruption mitigation, control of heat deposition, q-profile, ITB location, MHD, NTM, detachment, dud detection, termination, runaways, etc… with multiple actuators. ITER-like architecture could be tested, including various potential applications of AI.

Mitigating operational **risks** for **re-baselined ITER** necessitates new developments: targeted experiments and the **training of the next generation** of scientists, technicians, and engineers for ITER and other future fusion experiments. Nuclear expertise in the Tritium technology field is scarce and will fade if not nurtured. Extended operation and upgrade of the JET facilities, as described here, is the ideal vehicle to maintain momentum towards the goal of producing fusion energy and accelerate ITER **DT** operations, certainly in view of the delays announced recently. It would complement efforts undertaken in other facilities worldwide.

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