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JET ITER-Like Wall - Overview and Experimental Programme

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ABSTRACT
This paper reports the successful installation of the JET ITER-like Wall and the realisation of its technical objectives. It also presents an overview of the planned experimental programme which has been optimised to exploit the new wall and other JET enhancement in 2011/12.

1. INTRODUCTION
The ITER reference materials [1] have been tested independently in tokamaks, plasma simulators, ion beams and high heat flux test beds. However, an integrated test demonstrating both acceptable tritium retention, predicted to be one to two orders of magnitude lower than for a carbon wall [2], and an ability to operate a large high power tokamak within the limits set by these materials has not yet been carried out. The ITER-Like Wall (ILW) which is now installed in JET comprises solid beryllium limiters and a combination of bulk W and W-coated CFC divertor tiles but with no active cooling. It is part of a package of upgrades to heating power, protection systems and diagnostics needed to fully exploit the ILW [3].

In preparation for the ILW, a programme of dedicated reference experiments was carried out with the carbon wall [4]. In particular, measurement of fuel retention in a range of scenarios and characterisation of carbon migration in scenarios which will be compatible with the new wall. Work is also well advanced in defining the 2011/12 JET experimental programme. A phased approach will be adopted which maximises the scientific output early in the programme on the basic materials and fuel retention questions whilst minimising the risk associated with operation in an all metal machine. However, re-establishing H-modes at similar power levels to those with the carbon walls is a priority for establishing reference plasma conditions. The JET upgrades also include an increase in neutral beam heating power, up to 35MW for 20s [5], this has led to a requirement that the most critical first wall Be and W components are monitored in real time by a new imaging protection system [6, 7, 8]. In the main chamber, an array of thermocouples has been fitted to unambiguously monitor the bulk temperature of critical tiles. Before this upgrade, only a divertor system was available which proved essential for interpretation of Infra-Red (IR) measurements of surface temperature and power loads [9]. Interpretation of IR will be even more challenging with an all metal wall due to reflection and uncertain emissivity. Safe expansion of operating space will also be a priority. Experiments will have to be carefully managed if they have the potential to jeopardise interpretation of the long term samples which are planned to be removed in a 2012 intervention. Here the concern is that significant mobilisation of molten material could potentially dominate the intrinsic migration due to intrinsic sputtering which is a key part of the baseline migration and fuel retention picture for ITER. The scientific mission will also be enhanced by new diagnostics and diagnostic enhancements many of which are aimed at characterising tungsten and beryllium sources and transport.

This paper reviews the preparation and installation of the ITER-like Wall and gives an overview of the experimental programme which is due to start in the summer of 2011. Particular emphasis is given to the contribution of both aspects to ITER preparation.

2. TRANSFORMATION OF THE JET INTERIOR

The ITER-like Wall Project had the objective to replace all the existing Carbon Fibre Composite (CFC) tiles in JET, Fig. 1, with beryllium as the dominant main chamber material with tungsten surfaces in the divertor [3, 10, 11, 12]. The project also had to minimise the impact of the materials changes on JET operational limits and work with the existing support structures [13, 14]. In the main chamber this was achieved by using bulk beryllium on Inconel carriers for the limiters with tungsten coated CFC [15] in some higher heat flux recessed areas, for example the neutral beam shine through areas, and beryllium coated Inconel elsewhere [16]. The divertor consists of W-coated CFC tiles [17, 15] and a single toroidally continuous belt of bulk tungsten at the outer strike point [18].

2.1 THE ITER-LIKE WALL

The scale of ITER-like wall project can be seen from its metrics but clear definitions are needed. A tile is regarded as a single piece of beryllium or CFC which in many cases may be part of an assembly. For example, each Outer Wide Poloidal Limiter assembly (OWPL) consists of an Inconel carrier supporting 7 beryllium tiles. An installable item, such as the OWPL assembly, is something the remote handling system carries into the torus as a single unit. On this basis the figures are:

Number of installable items:	2,880
Number of individual tiles:	5,384 Be tiles (~2 tons Be / ~ 1m^3)
	1,288 W-coated CFC
	9,216 W-lamellas in the bulk W tile (~2 tons W / ~ 0.1m^3)
Total number of tiles	**15,828**
Total number of parts:	**85,273 counting bulk W tile modules as one part**
Bulk W tile parts	191,664 including 100,080 shims

Procurement and assembly of the ITER-like Wall presented both technical and logistical challenges. Although many of the original tiles, Fig. 1, look similar in reality many were unique and there was incomplete recording of the "as installed" configuration. Optical scanners were used to check any of the original tiles removed from the machine which looked as if they might have been hand modified. A full stereo photographic survey of the naked wall was carried out after removal of the CFC tiles to help spot potential clashes with features not in the CAD models (anomalies). Despite these measures there several hundred anomalies were identified which were disruptive to the remote handling work and challenging to resolve since modifications to tiles contaminated with beryllium or trace tritium from the JET vessel is strictly controlled at JET. These challenges prolonged the shutdown by 4 months beyond the objective of 12 months. However, there were no gaps in the in-vessel work which was carried out seven days a week for 18 hours a day. Overall, the strategy to trial assemble and inspect, including remote handling tool fit check, all the new components on jigs representing the in-vessel support structures was very successful. Compared to previous shutdowns there were very few installation problems related to component quality which is particularly critical when remote handling is being used.

The anticipated JET operating limits with the new wall have been detailed by Riccardo [13]. The thermal limits are most fundamentally driven by relatively low melting point of beryllium (1356ºC), the robustness of tungsten coatings to slow [17] and fast [19] thermal cycles and by thermal limits of support structures for the bulk tungsten tile [[18]. Furthermore, the ITER-like Wall was designed to avoid exposure of beryllium tile edges with step sizes over 40μm in high heat flux areas [14] by shaping / shadowing by adjoining tiles [20]. Carrier to carrier tolerances were checked on jigs prior to installation using a hand held laser scanner (GapGun) [21]. These measurements were then repeated in-vessel remotely using the MASCOT manipulator so that any unexpected deviations could be investigated. This gives us high confidence that the most critical design parameters have been met.

NOTABLE FEATURES OF THE ITER-LIKE WALL

The completed ITER-like Wall is shown in Fig. 2. Apart from the obvious material changes, some of the most visible differences to the CFC wall are:

- No bolt holes are visible in the main limiter tiles and the installed modules are larger. Both of these aspects have helped to maintain the power handling.
- The upper dump plate now consists of ribs rather than a continuous sheet of tiles with beryllium coated Inconel plates between. This was because the CFC design had poor tolerance and low area utilisation.
- Half the inner wall guard limiters have recessed centre sections clad with W-coated CFC or Be coated Inconel. This was driven by the objective to maintain the power handling in NBI shinethrough areas and decouple it from plasma loads [13].
- The main limiters on the low field side of the machine (wide poloidal limiters) have optimised large format tiles and therefore lower temperature rise for a given power density than the thin CFC slices which they replaced [20].
- Parallel protection bars made from beryllium replace CFC plates on the lower and upper inner walls and upper outer wall. Using bars supported by Inconel carriers reduced the cost and electromagnetic forces without affecting performance.
- A number of dark inner wall guard limiter tiles are visible which are coated with surface markers for erosion measurements below 10μm. This is just one element of a complete refurbishment of the erosion deposition diagnostics [22], mostly this is a repeat of previous experiments but some systems have been optimised for the new materials.
- Fifteen diagnostic conduits were installed remotely along with the six cable looms. One of the conduits is just visible running along the wall above the inner wall guard limiters. These were a major challenge to manufacture and install remotely due to their size and complexity. Extending over one half of the machine, they feed an array of thermocouples and Langmuir probes in the most critical areas of the new wall.
- The 48 bulk tungsten tile assemblies each of which weighs 60kg were a major technical challenge to manufacture [18].

2.2 REMOTE HANDLING SYSTEMS

Due to the radiation level inside JET resulting from activation of the Inconel vacuum vessel, the ALARP (as low as reasonably practicable) requirement has meant that manual work had to be kept to the minimum practicable. Dose rates at the beginning of the shutdown were around 300μSv/hr falling to below 100μSv/hr by the end. There were three short manual interventions for tasks which were not feasible using remote handling but most of the component removal and installation was carried out in the four remote handling phases. The installation was successful because of rigorous development and testing of the 280 new pieces of tooling equipment required for the remote handling work and the use of "mock-ups" to refine hardware and procedures prior to the shutdown.

The efficiency of the in-vessel work also relied heavily on development of a second long remote handling boom (Octant 1) capable of delivering "Task Modules" loaded with tools and components to the place of work so the MASCOT manipulator on the existing JET boom (Octant 5) could work efficiently [23]. Without this upgrade each move to collect a component or tool from the Octant 1 port would have typically taken 20mins. Figure 3 gives an overview of the remote handling system. Components were delivered to or from the boom enclosure using a sealed iso-container or posting port. Personnel working inside the enclosure in pressurised suits would then populate the drawers of the task modules with tools and components as required by the plan. The task modules were then moved into the vessel using a series of pre-programmed moves which have an accuracy of about 1cm, the tiles and tools are handled by the MASCOT manipulator which is manually operated and has force feedback. A limit of 10kg was set on the weight of components which could be handled without addition mechanical support (e.g. 100kg winch).

3. PREPARATION OF THE 2011/12 JET PROGRAMME

Following a call to the EURATOM Fusion Associations participating in JET and a general planning meeting in November 2010 attended by representatives of the Associations, the European Commission and ITER, 205 experimental proposals were discussed and consolidated into 52 main experiments and 37 parasitic experiments for inclusion in the 2011/12 JET programme. The scope of the call was defined by the following headlines:

1. **Characterisation of the ITER-like Wall**
   1.1 Fuel retention and material migration
   1.2 Material limits and long term samples
   1.3 Transient and steady state power loads

2. **Exploration of ITER operating scenarios with the ITER-like Wall**
   2.1 Develop plasma scenarios
   2.2 Assess plasmas scenarios
   2.3 Explore scenarios in domains closest to ITER dimensionless parameters

3. **Physics issues essential to the efficient exploitation of the ILW and ITER**
    3.1 Divertor and Scrape-Off Layer physics
    3.2 Confinement, pedestal and ELM physics
    3.3 Disruptions, MHD and fast particle physics
    3.4 Diagnostic issues for ITER

In selecting the proposals for execution in 2011/12 considerable weight was given to the most urgent priorities for ITER for which the new wall materials and other upgraded JET capabilities would have the greatest impact.

3.1 2011/12 PROGRAMME STRUCTURE

Only two task forces have been appointed for exploitation of JET with the new wall. Task Force E1 has its main focus on expanding operating space and Task Force E2 in full scientific exploitation of that space. However, the need for full integration of both activities to optimise the achievement of the programme goals and protect the wall means that in reality the task forces now need a very close collaboration.

Previous JET experimental campaigns following shutdowns began with a restart/commissioning phase where the machine systems are brought close to full performance followed by a phase of scientific exploitation. The proposed 2011/12 programme is much more gradual in expanding performance with commissioning (Restart) phases interleaved with scientific exploitation as new capabilities such as heating power and protection systems are released, Fig.4. The programme progresses from ohmic plasmas to L-mode then low power H-mode and then expands the H-mode power and current and finally develops the hybrid scenario. This goes hand in hand with exploring the materials questions, exploring ELM mitigation and developing steady-state power load mitigation techniques. Linked with a programme of standard monitoring pulses and carbon wall reference plasmas, such an approach ensures that there is the maximum scientific return with the least risk to the wall. Exploration of the ITER relevant issues will also begin right from the machine conditioning phase through to first plasma and on to full performance. The very first week of operation will use ohmic plasmas to study beryllium, tungsten and residual carbon migration with a pristine wall which is unique opportunity to start from a well defined baseline surface condition prior to mixing.

Another very significant difference to previous JET operation is that a remote intervention into the vessel is planned in the second half of 2012 whose primary purpose is to remove long term samples for analysis and perform a systematic collection of dust. In the outline plan for the run up to this intervention, two weeks of JET operation under consistent plasma conditions are scheduled (~2000s of divertor operation). The aim here is to build up sufficiently thick deposits / fuel inventory that surface analysis will be capable of resolving them and link them to a specific ITER-relevant scenario. This should erase as much as possible memory of previous mixed plasma conditions which are always an issue for interpretation of long term samples.

Although tritium retention is one of the main issues to be addressed by JET, operation with tritium is not envisaged before 2015 [24]. Isotopic effects on retention are expected to be small and so regular gas balances will be carried out using the Active Gas Handling system to collect all the exhausted deuterium and other gases as has been carried out for the carbon wall phase of JET [25]. The wall temperature will be kept at 200ºC during plasma operations for maximum relevance to ITER. If fuel retention is found to be significantly higher than expected the temperature could be raised to 325ºC but this is not in the baseline plan.

CONCLUSIONS

The ITER-like Wall, upgraded neutral beams and enhanced diagnostics have now been installed in JET and the next big challenge will be to exploit it fully in support of ITER. To this end, preparation of the 2011/12 experimental programme is now well advanced and a new task force structure is in place which recognises the shift to a much more integrated and focused programme and need to minimise the risk to all metal wall whilst maximising the scientific output. The design of the JET ITER-like wall has already influenced ITER, for example in the methodology and tools applied to tile shaping, and this impact is certain to grow as JET returns to operation.

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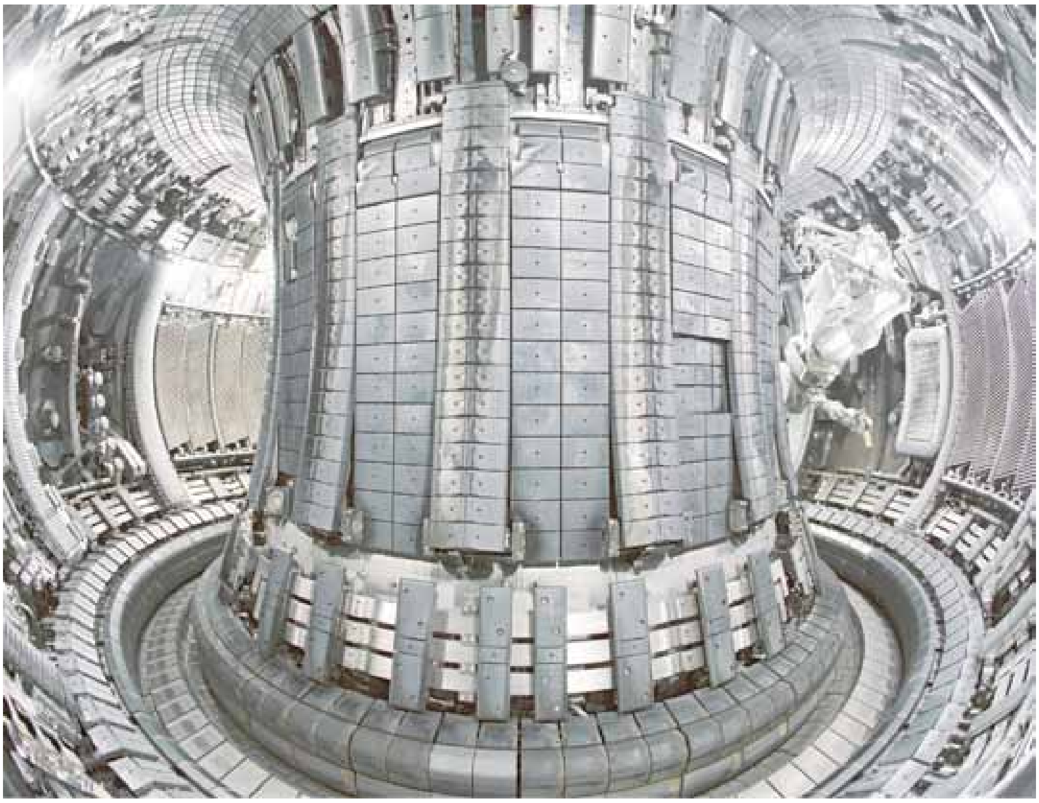


Figure 1 The JET carbon wall which had to be completely removed in the first stage of the shutdown.

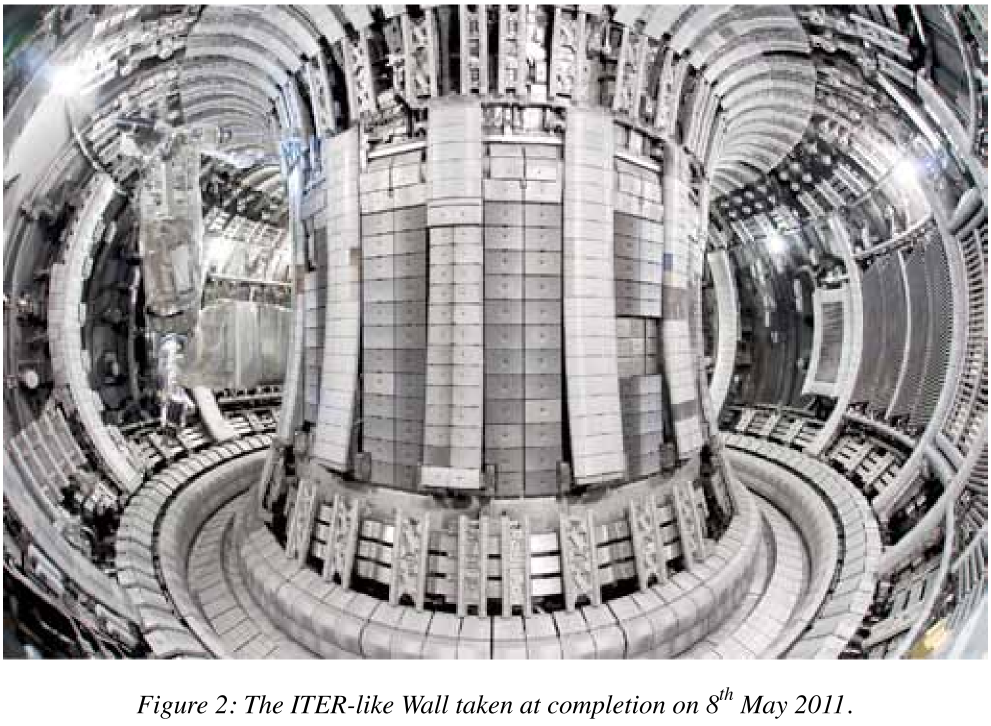


Figure 2: The ITER-like Wall taken at completion on 8th May 2011.

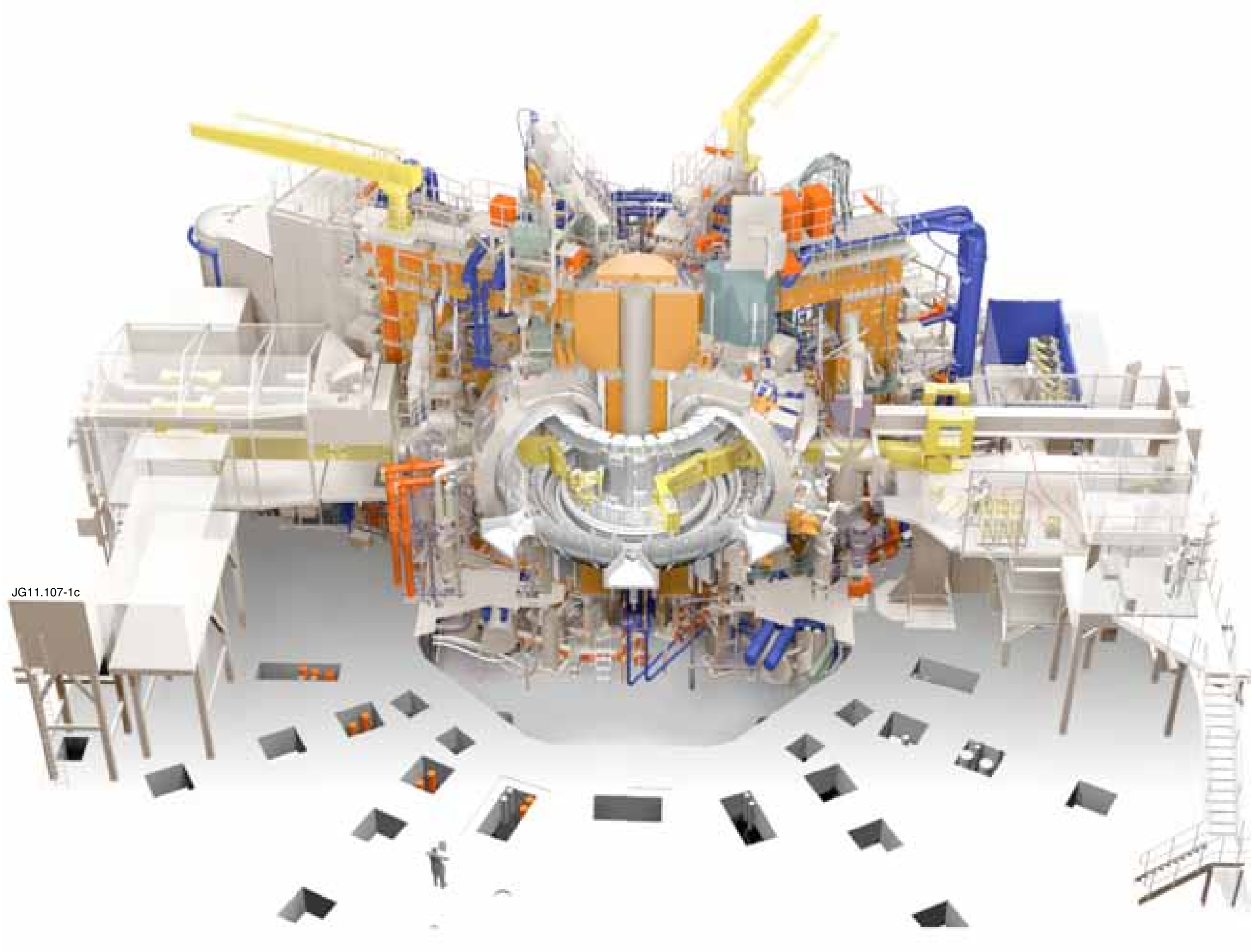
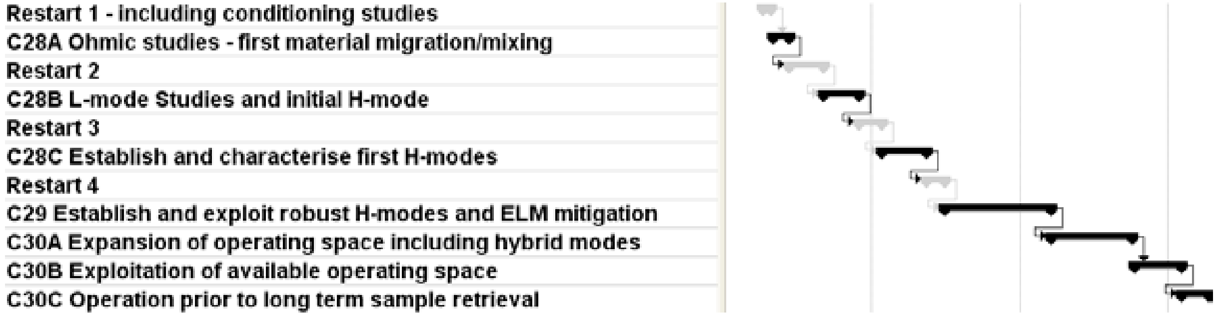


Figure 3: Overview of the JET remote handling system used to install the ITER-like Wall.



Figire 4: Type of phased campaign structure envisaged. Restart phases have an emphasis on commissioning with some parasitic scientific exploitation.