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Operational aspects of the JET Tritium Introduction Modules

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As part of the JET Programme in Support for ITER, campaigns with pure Tritium (TT) fuel and Deuterium-Tritium (DT) mixture are planned at JET. Unlike the previous DT campaign at JET, these campaigns require a much higher tritium flow rate, particularly, the TT campaign. Five tritium introduction modules (TIMs) fed from the Active Gas Handling System (AGHS) are to be installed; three 1n the divertor region, one in the mid-plane and another on outer top of the machine. The TIMs location, design and operational characteristics were chosen so that most Deuterium experiments can be matched in Tritium.

The TIMs purpose is to supply precisely controlled quantities of tritium to the JET machine by controlling the piezoelectric valve opening, which is located after the reservoir volume. The reservoir contains tritium at a sub-atmospheric pressure (charged initially to ~800mbar). Prototype valves developed by VAT Vacuumvalves AG with a stroke of 260 µm with a valve orifice area of 2.5 mm^2 are presently being tested aiming at a maximum flow of 1.6 bar.l/s with tritium at 800 mbar.

This paper presents statistics to justify the operational requirements and details the TIM design while describing also the operation sequence.

Keywords: JET tokamak, Tritium, Nuclear fusion, Piezoelectric valves.

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1. Introduction

Unlike the previous JET Deuterium-Tritium (DT) campaign [1], The foreseen pure Tritium (TT) fuel and DT mixture campaigns [2-3] will require much higher tritium flow rate, particularly, the all tritium campaign. In order to replicate the past deuterium experiments in tritium, it is required to inject similar amounts of tritium as the deuterium used in historical pulses as analyzed in the second chapter.

Tritium is a low half-life radioactive particle, therefore a safety case for operation with tritium was elaborated [4-5]. As part of satisfying this safety case, the TIM design [6] ensures secure containment of the tritium by restricting operation to sub-atmospheric pressures. In addition, it was necessary to develop a high flow piezo-crystal actuated dosing valve capable of meeting the strict requirements of the UKAEA-CCFE standards (tritium class 1 - the same as the all-metal Ultra High Vacuum Valves). This places restrictions on the materials used, fabrication methods, and leak limits. Also, since no human intervention is foreseen during the campaigns involving the usage of tritium, the TIM design has to include redundancy to avoid a serious degradation on the experimental operational space.

In addition, Tritium accountancy will play a critical role in the future Tritium campaigns. In total 60 grams of tritium will be used and recycled through the Active Gas Handling System (AGHS). Safety considerations limit the quantity of Tritium inside the JET tokamak to 15 grams, implying that the tritium calculation pre-pulse, correct operation during the pulse and accountancy after it have to be accurate and reliable.

This paper is organized as follows; in chapter two and three the past JET pulses are statistically analyzed to provide guidance to the TIMs design and their respective machine locations are detailed in chapter four and five respectively. The tritium management is discussed in chapter six and in chapter seven the preliminary results are presented before the conclusion in chapter eight.

2. Past experiments statistics

The TIMs location, design and operational characteristics were chosen so that most of the past deuterium experiments can be matched in tritium. A total of 6000 JET pulses (from pulse 85000 to pulse 90999) containing diverse plasma experiments were analyzed with a python script that calculated what would be the TIMs opening percentage if they were to replicate the discharge in tritium in function of several candidate configurations. As there are only five independent tritium lines available from AGHS [7], a study was made to determine the ideal number of main chamber and divertor TIMs.

Equation 1 and 2 represent the gas flow incident on two main regions, the main chamber and the divertor. It is necessary to distinguish between these two regions since the fueling efficiency in the divertor is lower than in the main chamber due to the location of the JET cryogenic pumps [8]. The fuel location is also important for other systems such as ICRH, because the fueling location influences its coupling with plasma [9].

$$MCF(t)=\sum_{i=1}^{8} GIM_i F(t) \qquad (1)$$

$$DF(t)=\sum_{i=9}^{12} GIM_i F(t) \qquad (2)$$

The main chamber flow (MCF) is defined by the sum of deuterium gas flows from Gas Introduction Module (GIM) 1 to GIM 8 while the divertor flow (DF) is defined by adding the flows from GIM 9 to GIM 12. Assuming that the flow is proportional to the valve opening percentage and the reservoir pressure (in reality the second derivative of the flow versus pressure curve is slightly positive). We have:

$$MCO(t)=100\times\frac{MCF(t)}{P_{MC}(t)\times Max_{TF}\times n_{mc}} \qquad (3)$$

$$DO(t)=100\times\frac{DF(t)}{P_{D}(t)\times Max_{TF}\times n_{d}} \qquad (4)$$

Where Max_{TF} is the maximum tritium flow at 1 bar per TIM, n_{mc} and n_d are the number of TIMs in the main chamber and divertor groups respectively, P_{MC} and P_D are the reservoir pressures of the main chamber and divertor groups respectively, $MCO_{\%}$ and $DO_{\%}$ are the valve openings in percentage for the main chamber and divertor groups respectively.

Since the reservoir volume is fixed, the reservoir pressure diminishes at a rate given by equations 5 and 6.

$$\frac{dP_{MC}}{dt}(t)=\frac{MCF(t)}{R_v\times n_{mc}} \qquad (5)$$

$$\frac{dP_{D}}{dt}(t)=\frac{DF(t)}{R_v\times n_{d}} \qquad (6)$$

Where, R_v is the reservoir volume.

Assuming that all TIMs groups have an identical reservoir volume of 10L per TIM and a maximum flow rate of 1.6 bar.l/s x 2 = 3.2 bar.l/s (each TIM as two valves as detailed in chapter 4) at 800 mbar of pressure, the total amount of pulses (out of 6000 analyzed) which the maximum TIM opening during the pulse is within different percentage intervals is detailed on table 1.

Table 1. Feasibility of 6000 deuterium pulses in tritium for different number of TIMs with a maximum throughput of 1.6 bar.l/s at 800 mbar per injector valve. Pulses requiring an opening greater than 100% were deemed as not possible

Interval	1 M.C. TIM	**2 M.C. TIMs**	1 DIV. TIM	2 DIV. TIMs	**3 DIV. TIMs**

<10%	4872	5843	4588	5323	5652
>10% <50%	1080	156	1110	635	319
>50% <75%	29	0	124	4	18
>75% <100%	7	0	29	11	5
Not possible	12	1	149	27	6

Furthermore, three situations were analyzed regarding the maximum tritium flow rate at 800 mbar, the flow rates analyzed were 1.6 bar.l/s, 1.2 bar.l/s and 1 bar.l/s, the results of this analysis is depicted in the bar graph of figure 1.

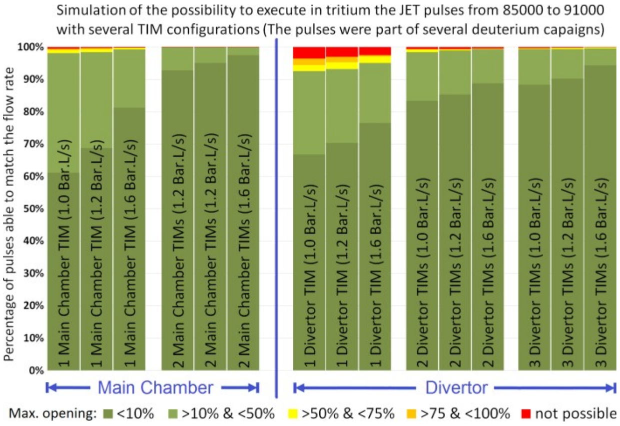

Fig. 1. Feasibility percentage of 6000 deuterium pulses in tritium for different number of TIMs with a maximum throughput of 1.6 bar.l/s, 1.2 bar.l/s and 1 bar.l/s at 800 mbar for a different quantity of TIMs per location.

As detailed in figure 1, the ideal distribution to be able to replicate most past experiments (given the constraint of having only 5 TIMs) would be 2 main chamber TIMs and 3 divertor TIMs, also if the piezo-electric valve performance does not provide the full 1.6 bar.l/s at 800 mbar and instead provides only 1 bar.l/s, the impact of the ability to reproduce past pulses in tritium is not very large. Only 7 out of 6000 pulses would not be possible to be replicated with the 1.6 bar.l/s case versus 12 or 20 out of 6000 in the 1.2 bar.l/s and 1 bar.l/s cases respectively.

3. Operational requirements

As detailed in the previous chapters, in order to avoid tritium leakage, the Tritium Introduction Modules (TIMs) are required to stay at sub-atmospheric pressure, but since the number of TIMs locations are limited by the number of tritium lines provided from the AGHS, the flow per each TIM has to be high enough to support regular machine operation. To further reduce the tritium release probability, the TIMs are secured by a secondary container containing a recirculating nitrogen gas with tritium detection, as detailed in figure 2.

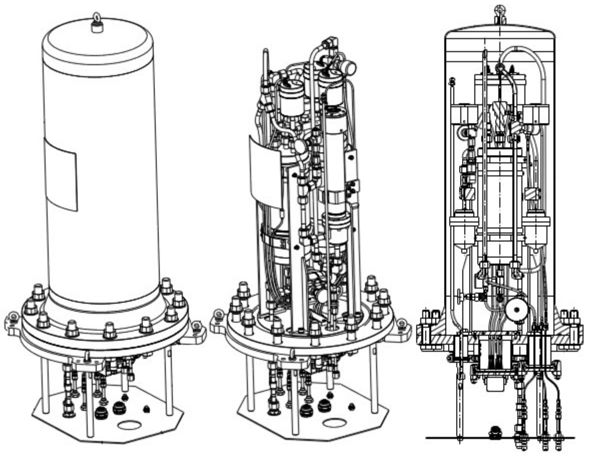

Fig. 2. Tritium introduction modules CAD design.

4. TIM design

Since machine access will be severely limited, the TIMs were designed to accommodate a reliable and redundant operation while maximizing the operational space. Each TIM includes two 5L reservoirs and two high flow piezoelectric valves (1.6 bar.l/s each) that can be operated together or independently, thus maximizing the system flexibility and compatibility with different experiments requirements. The low reservoir volume combined with a high flow valve requires a precise control of the valve opening in order to reproduce a pre-set gas flow waveform, this is achieved by adjusting the opening request according to the reservoir depletion throughout the pulse. The TIM internal schematic is detailed in figure 3.

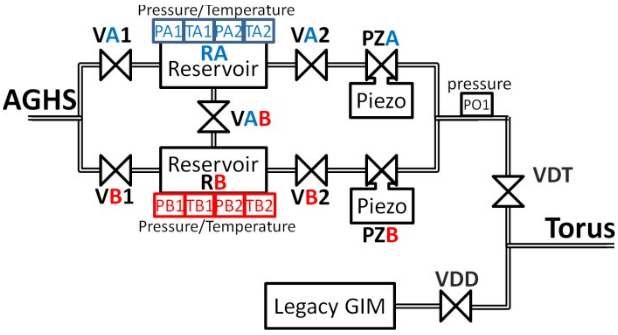

Fig. 3. Internal TIMs schematic detailing the redundant gas paths to the machine.

Each TIM two gas paths to the torus and if there is any fault in one of the paths, the other can still be operated although reducing the operational space. Since the precise control of the tritium inventory is a key feature, each reservoir has two pressure gauges and two temperature sensors.

As can be observed in figure 3, the TIMs gas injection point to the torus is shared (except TIM15) with a legacy GIM, meaning that only one can be operated at any time, this was a compromise to avoid extra pipework in the vacuum vessel.

Since AGHS is responsible for the TIM gas top-up, the VA1, VA2 and VAB valves are controlled by AGHS via a PLC, while the remaining valves are controlled by CODAS [10], via the same PLC.

5. Machine location for the modules

Five Tritium Introduction Modules (TIMs) fed from the AGHS are to be installed; three in the divertor region, one in the mid-plane and another on outer top of the machine. Of the five feed lines from AGHS, only 4 lines have the option to be served by three AGHS reservoirs (vacuum, D_2, T_2 or mix). The fifth line can only have two connections; meaning that one of the TIMs will be T_2 only (cannot be filled with D_2 from AGHS).

The previous JET DT campaign had only one tritium injection point, on octant 6 mid-plane. This module (GIM15) will be removed and replaced by TIM 15. The other four TIMs are multiplexed with the legacy Gas Introduction Modules (GIMs) to avoid extra vessel pipe work, the name of the new TIMs was chosen to match the number of the corresponding GIM location, for example TIM7 shares the injection point with GIM7 as depicted on figure 4.

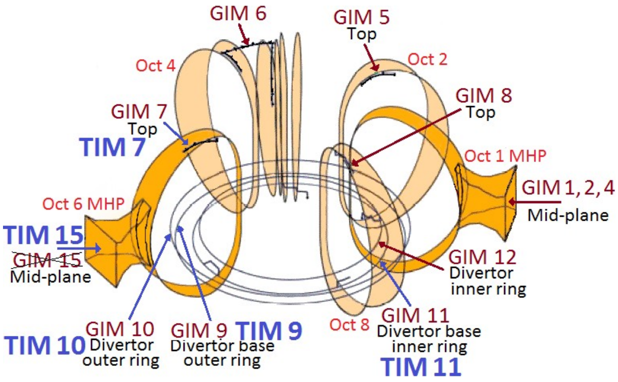

Fig. 4. Machine location of the tritium insertion modules together with the location of the legacy GIMs.

The main chamber TIMs were selected in locations that avoid over-pressuring the NBI duct while the divertor TIMs location was selected according to the most used GIMs during experiments.

6. Tritium management

The TIM reservoir pressure top-up will be requested by the session leader (SL) and engineer in charge (EiC) and AGHS will fill the requested TIM reservoirs. After a pulse is completed the SL has the option to continue to use TIM at a lower pressure due to the pressure drop of the last pulse, or the SL can request a top-up of the TIM reservoir from AGHS. The flow chart of the TIM state machine is detailed in figure 5. Each TIM gas top-up is expected to take up half hour (depending on the starting pressure) since the AGHS tritium volume limited in pressure therefore it has to be expanded several times to provide up to 800 mbar to the TIM reservoir.

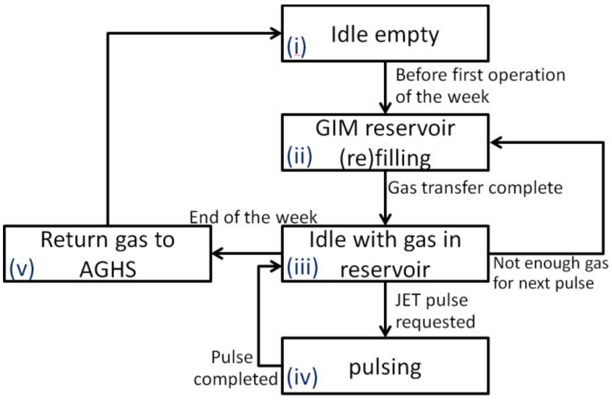

Fig. 5. State machine for TIM operation.

AGHS will have a total tritium inventory of 60g which will be recycled many times over. After separation from the other gases [11] the recycled tritium is to be stored in uranium beds before feeding again the TIMs reservoirs.

The Safety case for tritium operation specifies that only 15g of tritium can be inside the machine at any given time (TIM reservoirs are excluded), imposing restrictions on the tritium usage during a pulse. Based on observations from the deuterium campaigns [12] the JET metallic wall [13] is expected to retain tritium up to a total of 4g, leaving only 11g of tritium injection (including NBI contribution [14]) before a cryostat panel regeneration is needed, so a precise control of the tritium inventory and location is essential.

7. Tritium introduction modules prototype

In order to test the novel design of the piezoelectric valve and its operational characteristics, a new gas introduction module (GIM3) with the prototype piezoelectric valve was positioned in the Octant 6 main horizontal port near the future TIM15 location.

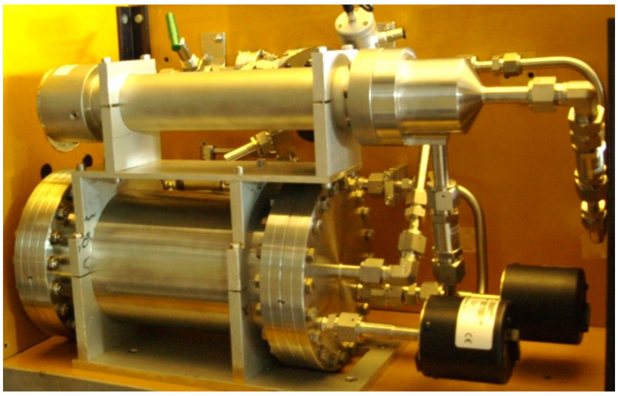

Fig. 6. GIM3 as installed on the machine. 5L reservoir on bottom and piezoelectric valve on top.

After testing, the maximum flow rate of GIM3 was calculated to be about 1.6 bar.l/s in deuterium at 800 mbar or about 2 bar.l/s when in hydrogen at 800 mbar. If scaled by the square root of the mass ratio this equates to about 1.15 bar.l/s in Tritium at 800 mbar, meaning that it is still below the desired value of 1.6 bar.l/s, but as described in chapter 2, even if the prototype is not improved, it would still enable the reproduction of most past pulses.

As all other GIMs installed at JET, due to the usage of a piezoelectric crystal as main component to control the valve opening, there is an intrinsic hysteresis effect, this effect can account for 10% of the full voltage range (which is a quite meaningful effect for the precision of lower flow requests). The usage of a strain gauge on the piezo crystal is being evaluated to correct this problem in real-time, but either because the necessary electronics might not survive the radiation [15] or simply due to installation time constrains this solution might not be adopted. If this strain gauge correction is not available, full characterization of the piezoelectric crystal would be necessary to correct this hysteresis effect through voltage request compensation.

8. Conclusions and future prospects

In order to comply with the safety requirements, the TIMs had several design constraints, this led to development of a high flow low reservoir piezoelectric valve. In turn this leads to challenging operation conditions where the precise control of the tritium inventory is key for the operational time optimization point of view. The TIM design features a redundant design that depending on the mode of operation can provide a precise control or a large tritium injection.

A prototype TIM was installed in JET to provide operational experience with high flow valves and low reservoir gas amount. The achieved flow rate, if scaled to tritium, would be about 1.15 bar.l/s. The proposed system of TIMs with this flow performance would allow replicating the vast majority of the past experiments in a pure tritium campaign.

A key controllability issue remains to be improved, due to the piezoelectric crystal hysteresis, we need either to correct the crystal displacement in real-time by reading this displacement with a strain gauge or if this is not possible (due to hazardous environment [15]), develop a hysteresis compensation model.

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