EFDA–JET–CP(06)04–11

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** See annex of J. Pamela et al, "Overview of JET Results",*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
SOFT Conference,
(Warsaw, Poland 11th – 15th September 2006)

ABSTRACT:
A new deuterium ice pellet injector is in preparation for JET. It will have the capability to inject both small pellets (variable volume within 1-2 mm^3) at high frequency (up to 60 Hz) for ELM mitigation experiments and large pellets (volume within 35-70mm^3) at moderate frequency (up to 15 Hz) for plasma fuelling. It is based on the screw extruder technology developed by PELIN and pneumatic acceleration. An injection line will connect the injector to the flight tubes already in place to convey the pellets toward the plasma either from the Low Field Side or from the High Field Side of the torus. This injection line enables (i) the pumping of the propellant gas, (ii) the provision of the vacuum interface with the torus and (iii) the selection of the flight tube to be used via a fast selector. All the interfaces have been designed and a prototype injector is being built, to demonstrate that the required performance is achievable.

1. INTRODUCTION

As approved by the EFDA Steering Committee in early 2005, a new High Frequency Pellet Injector (HFPI) is being assembled, as part of the JET programme in support of ITER. Its main objective is the mitigation of the Edge Localised Modes (ELM), responsible for unacceptable thermal loads on the wall when their amplitude is too great. Indeed it has been recently demonstrated on AUG [1] that the ELM frequency can be imposed by the pellet injection frequency (pace making). The energy ejected during each ELM being inversely proportional to the ELM frequency (as for natural ELM), the ability to inject small pellets at typically three times the intrinsic ELM frequency (up to 50-60Hz) in order to reduce the energy ejected per ELM is the main performance required from the new injector.

The development of this injector was motivated by the inability of the centrifugal injector already installed on JET to reach such a high injection frequency. Nevertheless, this centrifuge will be kept in place and the new High Frequency Pellet Injector (HFPI) will be installed close to it in such a way that both injectors could be operated simultaneously - for example plasma fuelling using the centrifuge and ELM control using the HFPI will be possible. Each injector will be equipped with a fast selector allowing the selection of the flight tube to be used to convey the pellets toward the plasma, either from the Low Field Side (LFS) or from the Vertical High Field Side (VHFS) or obliquely from the High Field Side (HFS) to the Torus.

2. THE PELLET INJECTOR

The injector is being designed and built by PELIN (Russia) on the basis of an injector installed in 2003 on Tore Supra [2]. A prototype is being assembled, which should demonstrate the ability to meet the required performance both for ELM control (variable pellet volume 1-2mm^3, pellet speed 50-200m/s and frequency up to 60Hz) and for plasma fuelling (variable pellet volume 35-70mm^3, pellet speed 100-500m/s and frequency up to 15Hz). Table 1 summarizes the required parameters. The injector is based on the screw extruder technology developed by PELIN [3], which allows the injection of an unlimited number of pellets with a very high level of reliability. A single extruder with two small nozzles and one large nozzle allows the production of either two simultaneous continuous small ribbons or one continuous large ribbon of hydrogen or deuterium ice. The maximum production rate of the extruder is expected to be 1500mm^3/s of hydrogen or deuterium ice. Cylindrical pellets are cut from the different ribbons by the sharp edge of thin wall tubes of fixed diameter moved axially by three solenoid actuators (prototype already successfully tested up to 48Hz). Then a short pulse of propellant gas (Helium up to 20bar), driven by three electromagnetic valves, accelerates each pellet in three gun barrels (1.25mm, 1.25mm and 4mm). The high frequency for the small pellets is obtained by cutting pellets alternately from the two small ribbons of ice. A movable plate with two small and one large rectangular holes acting as secondary nozzles allows both the selection of the pellet size range and the adjustment of the pellet length. The overall pellet injector system and the detail of the size range selection and length adjustment system are respectively shown on Fig.1 and Fig.2. By moving the plate, it is possible to exactly or partially align either the small nozzles of the extruder and the corresponding small holes of the plate or the large nozzle of the extruder and the large hole of the plate as illustrated in Fig.2. Cold Helium gas (4.8K) is used to cool down the extruder. The gas is provided from a 1000 L Dewar pressurized by a 40W heater able to evaporate 50L/h. This cold gas is transferred to the injector cryostat by a special cryoline developed by CEA: helium gas enters the cryoline at the top of the Dewar at a temperature of about 10K and is cooled down by circulating in a heat exchanger at the bottom of the Dewar at the temperature of the LHe bath (4.2K) before being pushed through the external standard part of the cryoline toward the HFPI cryostat. For safety - 0.5 litres of solid or liquid hydrogen/deuterium being stored in the extruder - buffer chambers are connected to the extruder inlet and outlet. The quality and the dimensions of the three extruded ribbons of ice are monitored by a CCD camera viewing the ice at the exit of the nozzles. Another CCD camera coupled to a set of optical barriers, for pellet velocity measurement, is installed on a diagnostic chamber located at the injector exit. Specific software has been developed by PELIN to re-construct the pellet volume from a CCD picture, recording a combination of two mutually perpendicular views of the pellets from an appropriate optical system installed in the diagnostic chamber.

3. THE INJECTION LINE

For a pumping system of reasonable size to cope, the propellant gas must not exceed 1.5 times the pellet content, i.e. 0.5 and 11 Pa.m^3/pellet respectively for small and large pellets. This propellant gas is not acceptable in the plasma. An injection line has been designed to connect the injector to the flight tubes already in place on the JET machine [4]. It will allow i) pumping of the propellant gas, ii) selection of the flight tube to be used, iii) measurement in-flight of the pellet mass and iv) pumping of a part of the gas produced from the pellet erosion inside the flight tubes. The whole injection line is shown in Fig.3. The propellant gas is mainly pumped by a 4000m^3/hour roots group connected to a first volume of about 0.1m^3. Inside this first volume, a straight guide tube (inner diameter 9mm, length 1.2m) allows to convey the pellets toward a second stage. This tube presents a small conductance for the gas. Its upstream side has a funnel shape (i.d.15mm, half angle 0.6∞) in order to collect pellets exiting the injector barrels after a free flight of about 100mm in the diagnostic chamber. Microwave cavities for pellet size measurement, produced by ORNL [5] to complement the optical system, and a fast 4-way selector, described in the next section and shown on Fig.4, complete the first stage of the pumping system. Then, after passing through an isolation valve separating the two pumping stages, the pellets enter a second volume (50L) in one of the three guide tubes, selected by the 4-way selector. This volume is pumped by two 2200L/s turbomolecular pumps. Since pellets produced by the JET centrifugal pellet injector also must be injected through the same three JET flight tubes, the second volume includes a second set of three guide tubes in a branch connected to the centrifuge. Three short straight tubes with conical entrances are used to collect pellets from the three tracks of each injector, and to inject them into the three JET flight tubes (Fig.4). All the guide tubes incorporated in the injection line are 9 mm (inner diameter) stainless steel tubes with an internal finish of 0.8µm and a minimum radius of curvature of 1m. Calculations of the pressure inside the 3 consecutive volumes connected by conductances, representing the two volumes of the injection line and the torus vessel, have been performed to determine the required pumping speeds. The following assumptions have been made: i) steady state being reached very quickly for injection at frequency higher than 10Hz, the calculation is carried out for steady state, ii) the source in the first volume is the propellant gas (0.5 $Pa.m^3$/pellet, 60Hz or 11 $Pa.m^3$/pellet, 10Hz) and the source in the second volume is the gas produced from the pellet erosion in the JET flight tubes (typically 20% in the LFS flight tube and 30% in the VHFS flight tube), iii) the flow is laminar between the two volumes of the injection line and molecular between the second volume and the JET vessel. The result, for the pumping speeds mentioned above, is a pressure of about 100 Pa in the first volume and about 10^{-2} Pa in the second one, which are compatible with the proposed pumps. This simulation included calculation of the pressure rise inside the flight tubes due to the pellet erosion. It revealed that the pumping system associated with the flight tubes must be improved. Thus a $650m^3/h$ roots group backed by a screw pump will be installed on the pumping station located in the middle of the VHFS flight tube. The LFS flight tube will be pumped by the two large TMPs of the injection line. The third (HFS) flight tube, being almost entirely inside the vessel, cannot be pumped and its use is expected to be limited to short bursts of pellets at low frequency.

4. THE FLIGHT TUBE SELECTOR

A selector system has been developed by CEA to route the pellets through the JET flight tube required for the plasma experiments (three possible flight tubes: LFS, HFS or VHFS). A fourth position of the selector allows pellets to be fired onto a target plate. As shown on Fig.4, a short (0.5m) straight tube, with a conical entrance, can rotate ($\pm 1.2^o$) via a knee joint to align its downstream edge with one of the three guide tubes or to fire pellets onto the target plate. The tube is moved vertically and horizontally and maintained in place by two push-pull solenoids (Binder Magnetics GHU5104) having a stroke of ± 4.5 mm. The 4 possible positions are located at the corners of a 9mm square at the solenoids axis location. Appropriate electronics control the currents in the two coils of the two solenoids, enabling: (i) fast discharge of the energy from the coils which maintain the tube in a given position, (ii) fast displacement toward the new position using an additional adjustable power supply (35-120V, duration 3-30ms), (iii) the holding of the new position in steady state at reduced currents to limit coils heating. A prototype selector has been built and typical transition times of 30ms have been measured.

When pellets are fired onto the target for test and adjustment purposes, the gas produced by the sublimation of the ice in the selector is pumped by the roots group connected to the first volume via a by-pass pipe.

5. PROJECT STATUS AND KEY MILESTONES

The project is led by the EURATOM-CEA Association with the support of the JET Operator for the preparation and the installation of all the necessary JET interfaces, and the support of JET CSU for the management of contracts. The design of the whole injection line and JET interfaces is now complete, the Contract with the injector manufacturer is running and most of the calls-for-tender related to the other procurements have been launched. Next key milestones are:

- beginning of October 2006: test of the injector prototype at PELIN Laboratory
- November 2006: new platform (see Fig.5) required to install the new system, in place
- June 2007: test of the final injector at PELIN Laboratory, before shipment
- End of August 2007: test of the whole system in the JET torus hall
- End of September 2007: end of commissioning on JET

CONCLUSION

A new hydrogen/deuterium pellet injector capable of injecting small pellets for ELMs mitigation experiments and large pellets for plasma fuelling is in preparation for JET as part of the JET-EP2 programme. This injector is fully ITER relevant apart from tritium aspects. The project, launched in early 2006, is progressing as scheduled. All the results obtained so far are fully satisfactory. The injector will be installed on JET in August 2007 and commissioned in September 2007.

ACKNOWLEDGEMENT:

The project team would like to thank ORNL for the preparation and test of a mock-up of the JET LFS flight tube (initially designed for 4mm pellets) with 1mm pellets - results are successful up to 200m/s, which is appropriate for ELM control experiments - and for the supply of the microwave cavities for pellet mass measurement.

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Parameter	**Required performance**
NB pellet/pulse	Unlimited
Pellet Volume	
Vol. 1	Adjustable 1 to 2mm^3
Vol. 2	Adjustable 35 to 70mm^3
Injection frequency	10 to 60 Hz for Vol. up to 15 Hz for Vol.2
Pellet material	Hydrogen, deuterium
Pellet velocity	Adjustable 50 to 200m/s for Vol.1 Adjustable 100 to 500m/s for Vol.2
Reliability	98%
LHe consumption	< 40 L/h
Availability	> 1 million

Table 1: required performance

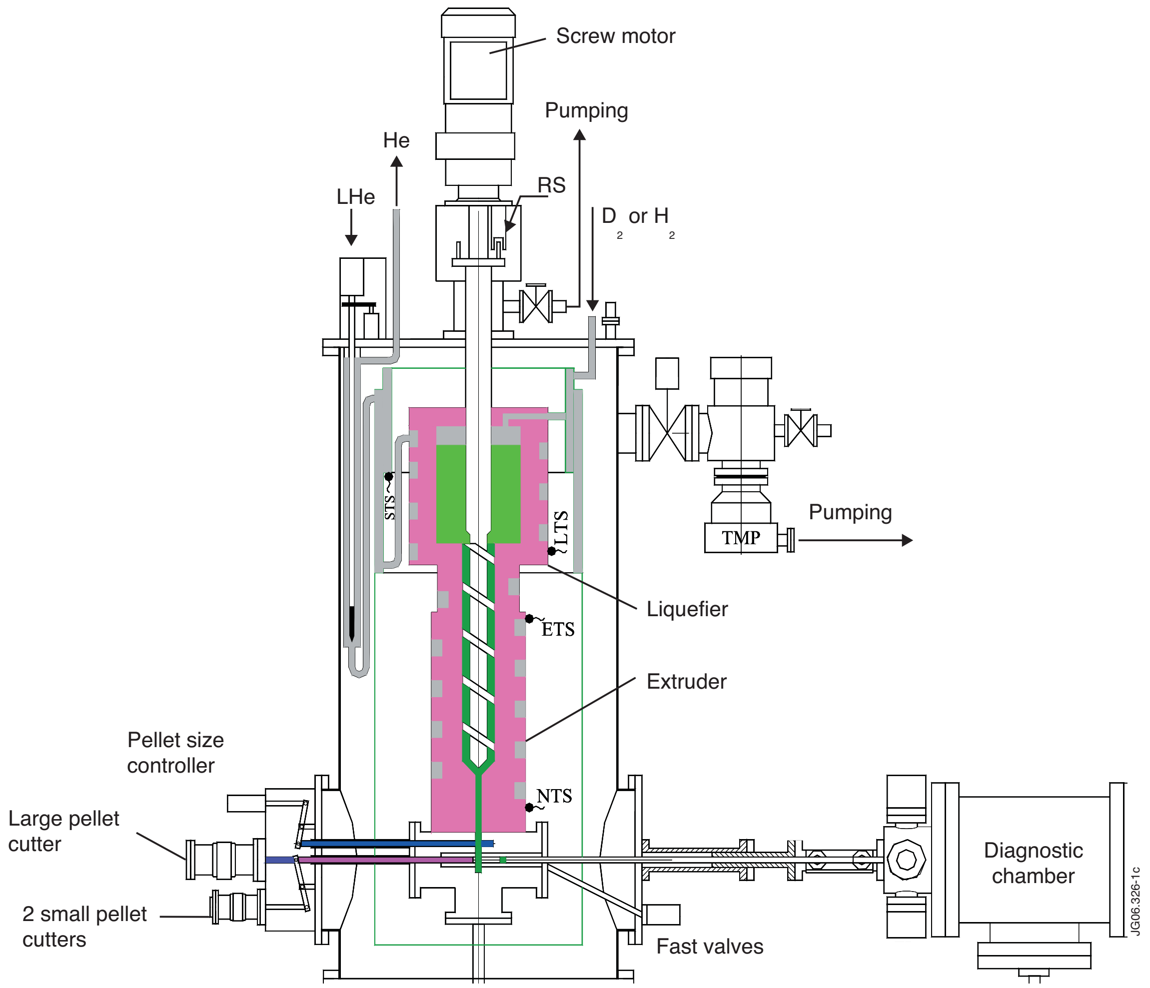

Figure 1: Schematic drawing of the PELIN pellet injector.

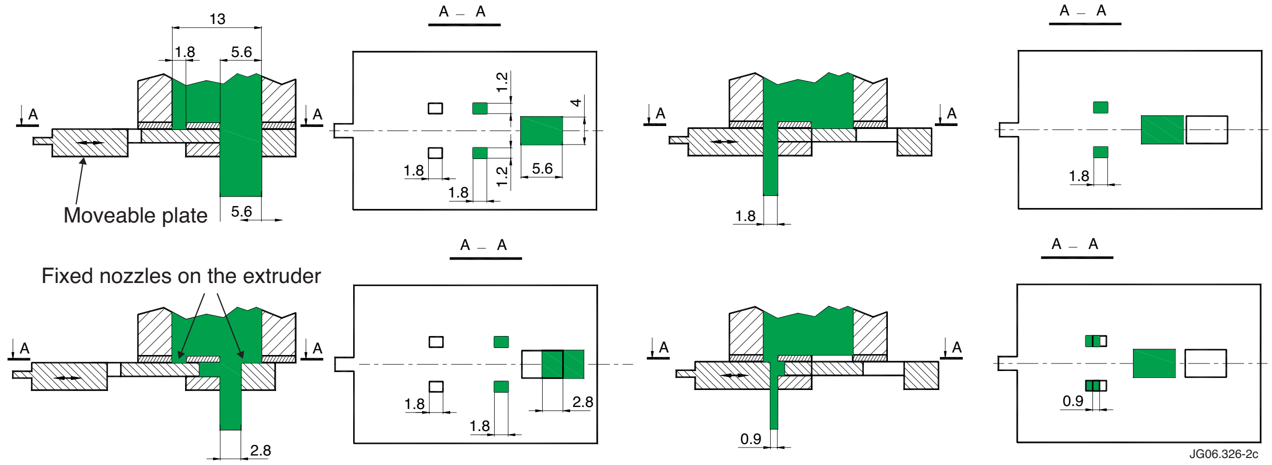

Figure 2: Size controller system.

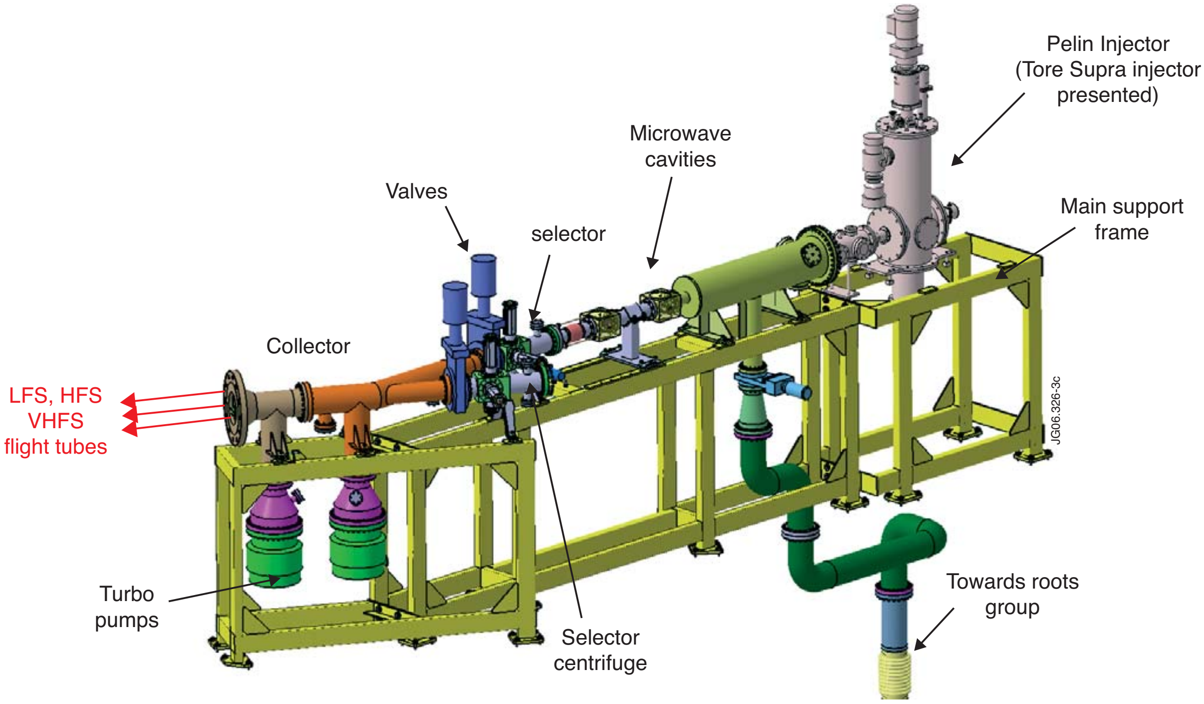

Figure 3: Overall drawing of the injector - injection line assembly.

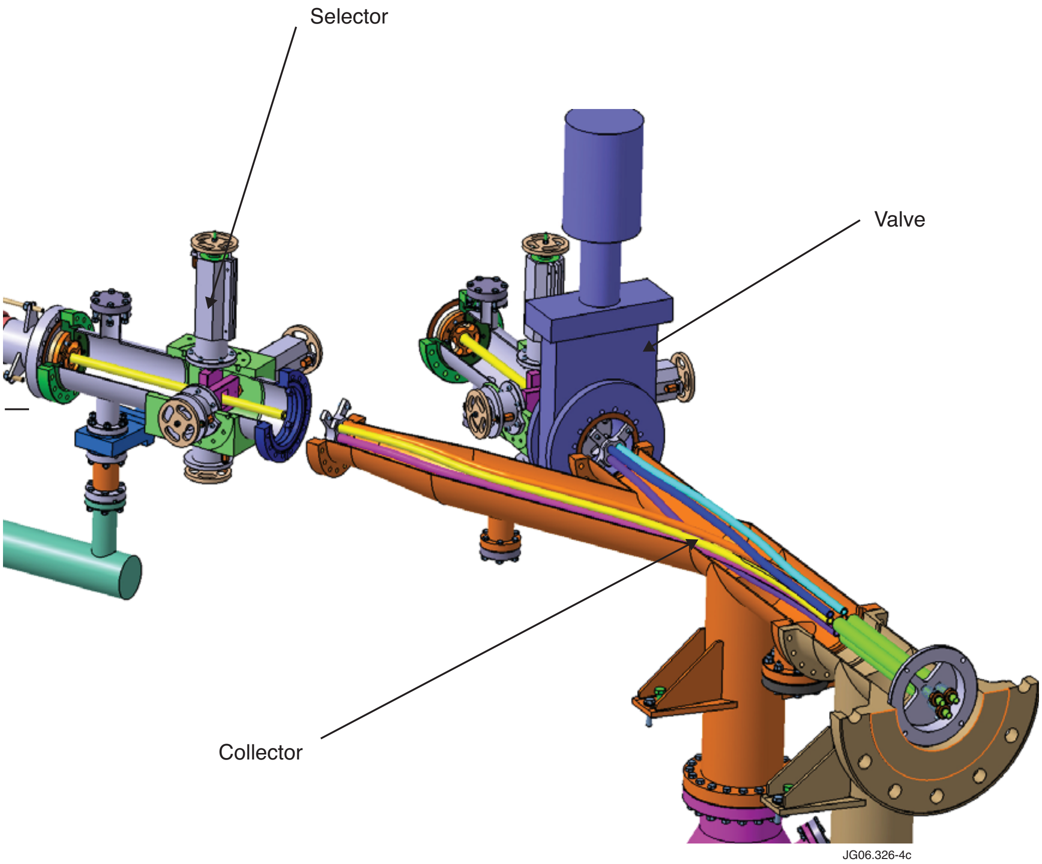

Figure 4: Detail of the selector and internal guide tubes systems.

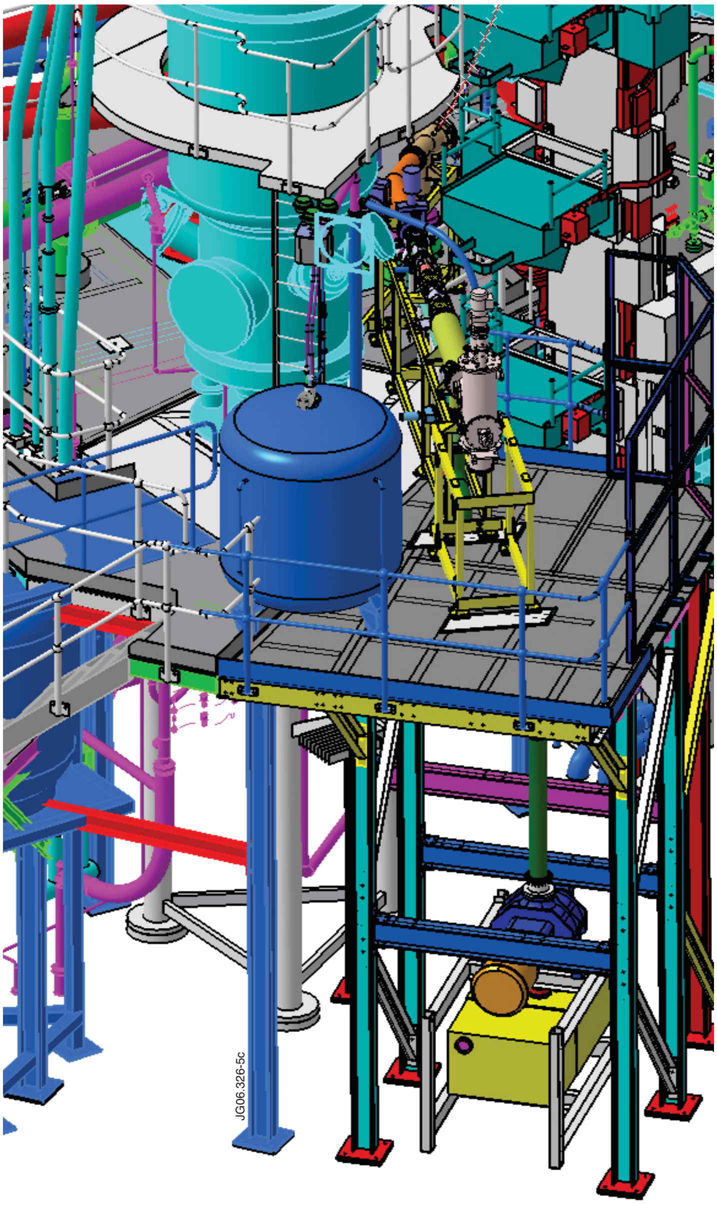

Figure 5: Installation on JET