EFDA–JET–CP(08)04/08

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D. Guillaume, L. Hackett, D. Homfray, R. Lucock, A. Mackenzie, J. McKivitt,
R. Mooney, M. Sibbald, C. Portafaix, J.P. Perin, M. Reade, D. Sands, A. Saille,
I. Symonds, D. Wilson, L. Worth, L.R. Baylor, J. Caughman, A. Lukin,
A. Umov, S. Skoblikov, P. Reznichenko and JET EFDA contributors

The JET High Frequency Pellet Injector

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A. Géraud[1], I. Vinyar[2], A. Whitehead[3], M. Dentan[4], V. Hennion[4], M. Watson[3], K. Bell[3], P. Bennett[3], P. Butcher[3], D. Communal[5], F. Faisse[1], D. Garnier[3], J. Gedney[3], G. Gros[3], D. Guillaume[5], L. Hackett[3], D. Homfray[3], R. Lucock[3], A. Mackenzie[3], J. McKivitt[3], R. Mooney[3], M. Sibbald[3], C. Portafaix[1], J.P. Perin[5], M. Reade[3], D. Sands[3], A. Saille[1], I. Symonds[3], D. Wilson[3], L. Worth[3], L.R. Baylor[6], J. Caughman[6], A. Lukin[2], A. Umov[2], S. Skoblikov[2], P. Reznichenko[2] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1] CEA, IRFM, F-13108 Saint Paul Lez Durance, France
[2] PELIN LLC, 20a, Berezhkovskaya nab., Moscow, 121059, Russia
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4] EFDA-JET CSU, Culham Science Centre, Abingdon, Oxon OX143DB, United Kingdom
[5] CEA, INAC/SBT, 17 rue des Martyrs, 38054 Grenoble cedex 9, France
[6] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

** See annex of M.L. Watkins et al, "Overview of JET Results ",*
(Proc. 21 st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
25th Symposium on Fusion Technology, Rostock, Germany
(15th September 2008 - 19th September 2008)

ABSTRACT:
A new deuterium ice pellet injector has been installed on the JET Tokamak. It has the capability to inject both small pellets (adjustable volume within 1-2 mm^3) at high frequency (up to 60 Hz) for ELM mitigation experiments and large pellets (adjustable volume within 35-70mm^3) at intermediate frequency (up to 15 Hz) for plasma fuelling. It is based on the screw extruder technology developed by PELIN LLC and pneumatic acceleration. An injection line connects the injector to flight tubes conveying the pellets toward the plasma either from the Low Field Side or from the High Field Side of the torus. This injection line demonstrated an efficient pumping of the propellant gas together with the provision of the vacuum interface with the torus. Dedicated diagnostics allow accurate determination of the pellet speed and volume and good characterization of the extruded ice. After comprehensive local tests at JET, showing an excellent reliability for the whole range of pellet parameters, the system is now under final commissioning and preparation for the JET 2008 campaign.

1. INTRODUCTION

A new High Frequency Deuterium Pellet Injector, part of the JET programme in support of ITER (JET EP2), has been installed on JET at the end of 2007. Its main objective is the mitigation of the Edge Localised Modes, responsible for unacceptable thermal loads on plasma-facing components (and especially the new Berillium wall) when their amplitude is too high. Indeed it has been recently demonstrated on the ASDEX UPGRADE Tokamak that the ELM frequency can be imposed by the pellet injection frequency [1]. The energy ejected during each ELM being inversely proportional to the frequency, the capacity of injecting small pellets at typically three times (up to 50Hz) the intrinsic ELM frequency was the main performance required for the new injector. Moreover this injector was required to have the capability to inject large pellets for plasma fuelling. The most challenging component of the project was of course the injector itself. It was designed and built by PELIN LLC (St Petersburg, Russia) on the basis of the screw extruder technology developped by this company and already used on the pellet injectors installed on LHD [2] in Japan and on Tore Supra [3] in France. A prototype was first built to demonstrate the design capacity to meet the required performance both for ELM control (pellet volume 1-2mm^3, pellet speed 50-200m/s and frequency up to 50Hz) and for plasma fuelling (pellet volume 35-70mm^3, pellet speed 100-500m/s and frequency up to 15Hz). Such a performance was reached early 2007, allowing PELIN to build the final system, designed and manufactured in compliance with the JET Quality Assurance rules. The paper describes the final design of the injector and injection line together with the results of the commissioning tests.

2. THE PELLET INJECTOR

The final design, schematically presented on Fig.1, is very close to the design of the prototype [4]. Only the cutter system was changed, because the initial system using levers to move the cutters was found not to be reliable enough. The other parts are similar: one extruder with one large and two small channels in the extruder nozzle allows the formation of respectively either one continuous large ribbon of ice or two simultaneous continuous narrow ribbons. A set of electromagnetic cutters and fast valves controling short pulses of propellant gas (helium up to 20 bar) is used to respectively cut and accelerate the pellets. The high injection frequency for the small pellets is obtained by cutting alternatively pellets in the two small ribbons of ice. In order to get a longer flexibility, the length of the cylindrical pellets produced by the system can be adjusted within a factor two thanks to a movable plate, also used to select either production of the large ribbon or the production of the two small ribbons. It limits the effective nozzles aperture [4] so that the sections of the available ice ribbons are respectively $4 \times (2.8 - 5.6)\ mm^2$ and $1.2 \times (0.8 - 2.0) mm^2$. The maximum deuterium / hydrogen ice production rate of the installed system is $1400 mm^3/s$, consistent with the delivery of large pellets at 15Hz, which is the most demanding mode. The extrusion velocity through both small and large channels is estimated to 60-80mm/s. After cutting the pellets are accelerated by the propellant gas pulses in gun barrels (internal diameter 4mm, 1.25mm,1.25mm). The extruder is cooled down by cold helium gas at a temperature of about 5 K (a temperature down to 5.4 K was obtained on the extruder nozzle during tests) provided by a 1000 litres Dewar pressurized by a 40W heater able to evaporate up to 50l/h [4]. The measured maximum liquid helium consumption is 20l/h. The injector system is controled by a Progammable Logic Controler connected by http links to the JET control system (Codas) acting as a user interface.

Before being delivered to JET, the injector was extensively tested by Pelin in their Laboratory. The same tests were reproduced after installation on the JET Tokamak. Results with more than 100,000 pellets fired on target during 20s sequences with parameters covering the full requirements are presented on Fig.2. They are shown in term of reliability as a function of the pellet injection frequency for large and small pellets and for hydrogen and deuterium ice for different pellet speeds and lengths. The reliability is defined as the total number of unbroken pellets seen on the photo station at the injector exit, divided by the total number of requested pellets in each 20s sequence. For hydrogen pellets, mainly used for commissioning and adjustments, the reliability is better than 85% for the small pellets and better than 93% for the large pellets for all tested lengths, speeds and frequencies up to 50 for small pellets and 15Hz for large pellets. For deuterium ice, the reliability is better than 85 % for the small pellets and better than 95% for the large pellets whatever may be the tested lengths, speeds and frequencies up to respectively 67 for small pellets and 15Hz for large pellets. Reliabilities better than respectively 94% and 99% for medium lengths and speeds (dashed lines on Fig.2) have been obtained. A summary of the achieved performance is given in table 1 together with the requirements. It shows that the injector is perfectly in line with these requirements, with the exception of the maximum speed for large pellets (300m/s instead of 500m/s). During the development no particular effort was done to reach 500m/s because the JET flight tubes used to convey the pellets to the plasma will limit the maximum speed to about 300m/s. Therefore the maximum pellet speed allowed by the injector is the effective maximum speed achievable by the whole system. The pellet speed has typically a gaussian distribution with a standard deviation between 5 and 15%, depending on the pellet parameters.

3. INJECTION LINE AND PUMPING SYSTEM

The pellet injector is connected to the JET torus through an injection line and flight tubes. The injection line allows i) pumping of the propellant gas in its first stage, 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 design details are given in [4]. The injection line includes a fast 4-way selector able to change the flight tube to be used from any of the initial position (target or previously selected flight tube) in less than 50ms. Three flight tubes are available to inject pellets either from the Low Field Side (LFS) through an ICRH antenna (the local plasma perturbation driven by the pellets should allow in particular to check the resilience of the ITER like design of this antenna to edge density fluctuations), or from the High Field Side (HFS), or from a Vertical High Field Side (VHFS) injection point. Fig.3 shows the pumping system associated with the injector, the injection line and the flight tubes. The third flight tube is not represented here because, being mainly in the torus vessel, it is not pumped from outside. Thanks to the differential pumping system and its large pumping capacity, no trace of helium propellant gas was found in the plasma for the low frequencies tested so far. The VHFS flight tube is permanently pumped by a TurboMolecular Pump (TMP) except when used to inject pellets. In that case, the roots group takes over, the pressure in the line being liable to reach 1 mbar due to the pellet erosion. Interlocks based on the pressure measured in the volume pumped by the two large turbomolecular pumps or in the VHFS flight tube enable the opening of the torus valves. For safety reasons- 0.5 litres of solid or liquid hydrogen/deuterium being stored in the extruder - buffer chambers (2×100L) are connected to the extruder inlet and outlet (represented below the injector on Fig.3).

4. PELLET DIAGNOSTICS

The pellet injection system is equipped with a set of diagnostics aiming to help in the injector operation and to measure the injection parameters. From the injector to the torus end of the flight tubes, we have:

- a CCD camera allowing to monitor the quality and the dimensions of the extruded ice. Fig 4 shows a picture of the two small ribbons and a picture of the large ribbon.
- 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 (Fig.5).
- Microwave cavities for pellet size measurement, produced by ORNL [5] to complement the optical system (μC on Fig.3). Two cavities are installed downstream to the PELIN diagnostic chamber, respectively tuned for small and large pellets. Two other cavities are installed at the end of the LFS (tuned for small pellets) and VHFS flight tubes (tuned for large pellets). After calibration, the height of the gaussian shape signal gives the volume of the pellet.

CONCLUSION

JET is now equipped with a unique pellet injection system, exhibiting performance close to the requirements for the ITER pellet injector system. The capacity to inject both small and large pellets brings a wide flexibility responding to the needs for fuelling and ELM control experiments that are very different. First pellets have been injected on plasma, demonstrating that the whole system can be used for preliminary experiments.

ACKNOWLEDGEMENT

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the Task Agreement JW5-EP2-TA-HFP-03. The views and Opinions expressed herein do not necessarily reflect those of the European Commission.

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Parameter	**Required performance**	**Performance of the installed system**
NB pellet/pulse	unlimited	unlimited
Pellet Volume Vol. 1 Vol. 2	 1 to 2mm^3 35 to 70mm^3	 1 to 2mm^3 35 to 70mm^3
Injection freq.	up to 60 Hz for Vol.1 up to 15 Hz for Vol.2	up to 67 Hz for Vol.1 up to 15 Hz for Vol.2
Pellet material	Hydrogen, deuterium	Hydrogen, deuterium
Pellet velocity	50 to 200 m/s (Vol.1) 100to 500 m/s (Vol.2)	80 to 200 m/s (Vol.1) 100 to 300 m/s (Vol.2)
Reliability	98%	85 – 100%
LHe consumpt.	< 40 L/h	20 L/h

Table.1:Performance of the installed system

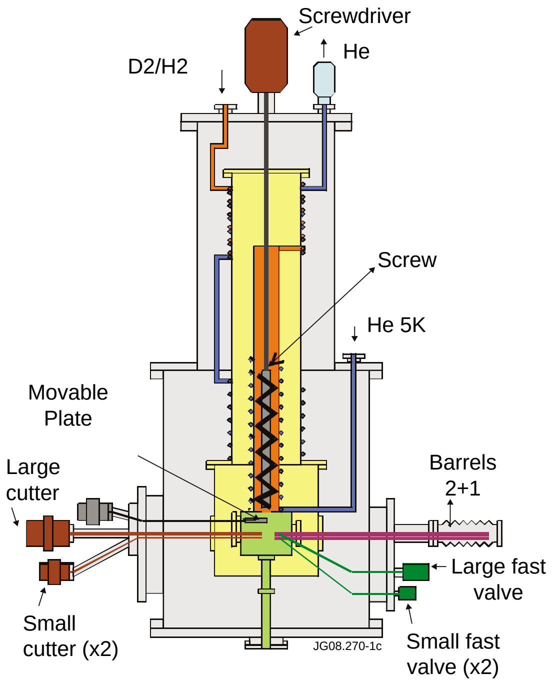

Figure 1: Schematic drawing of the PELIN pellet injector.

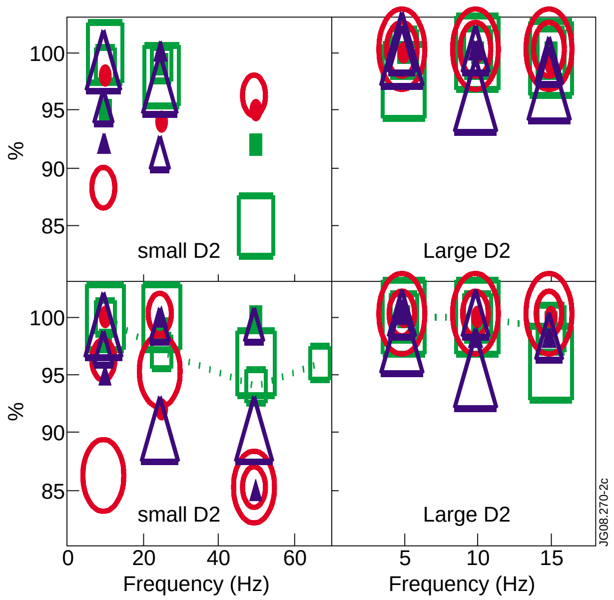

Figure 2: Final test results at JET for small (left) and large (right) hydrogen (top) and deuterium (bottom) pellet injections. Circles = 50m/s, square = 100m/s, triangle = 200m/s for small pellets and respectively 100, 200, 300m/s for large pellets, some attempts to inject at 400m/s large H2 pellets are represented by a +. The size of the symbols refers to the length of the pellets (small-medium-large).

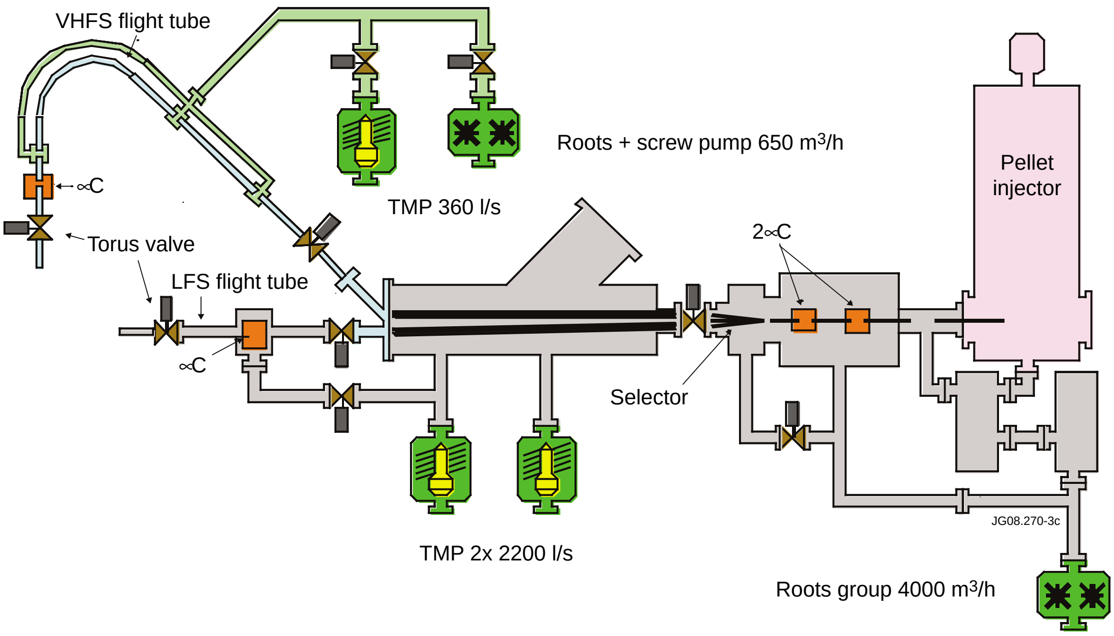

Figure 3: Simplified pumping diagram of the whole system.

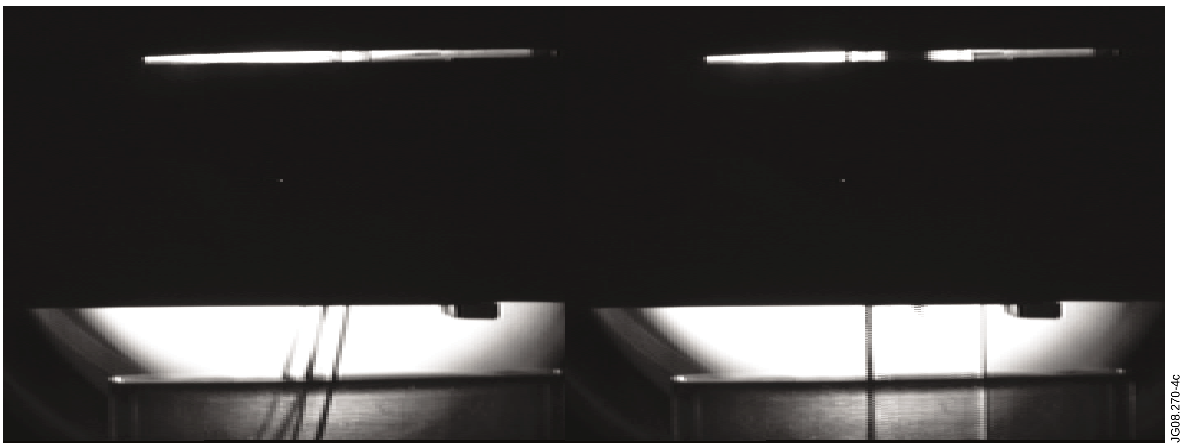

Figure 4: Extruded ice from the nozzles (top of the picture, the wide horizontal black stripe is the cutter system).

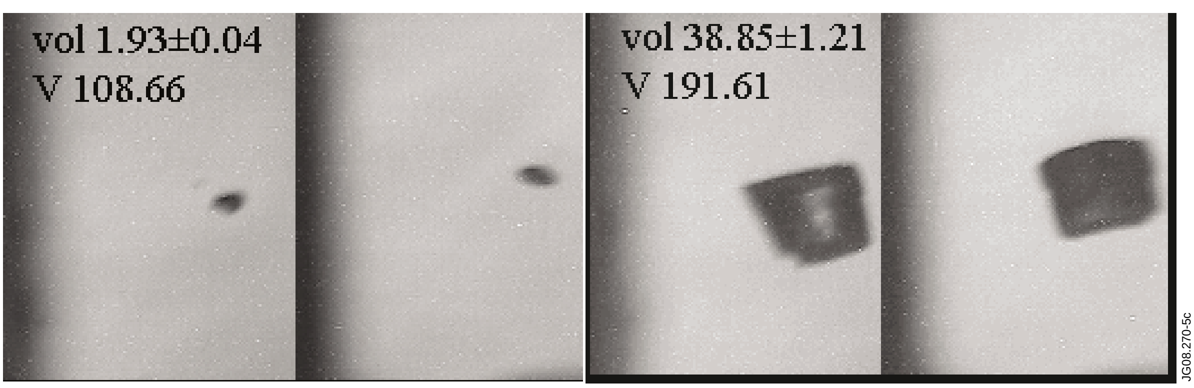

Figure 5: Double picture of a small (left) and of a large pellet (right) in flight with result of the pellet volume and velocity calculated by the Pelin sofware.