EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)05/21

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Preprint of Paper to be submitted for publication in
Proceedings of SOFT 2002 (Helsinki, Finland, 9–13 September 2002)

ABSTRACT

Guiding systems used for transfer of cryogenic pellets to the tokamak inboard currently undergo optimisation to possibly extend the operational range of Inboard pellet injection scenarios. Work reported here has been concentrating on experimental studies and calculations of pellet mass loss during transfer in a guiding tube as a function of pellet parameters such as velocity and ice composition, and guiding track characteristics such as vacuum conductance, geometry, size and shape of cross-section. Results from ASDEX Upgrade and ORNL systems suggest, that centripetal loads on the pellets due to small radii bends in the systems strongly increase the erosion of pellet ice. A deleterious effect of accumulated gas due to sublimated D_2-ice blocking the tube and eroding subsequent pellets has been found. However, an efficient vacuum pumping set up for a given pellet repetition rate can significantly improve the mass conservation with respect to closed tube systems as calculations for ASDEX Upgrade and JET systems confirm.

1. INTRODUCTION

Extending the operational range of pellet injection scenarios using the magnetic high field side in tokamaks [1, 2, 3] requires increasing attention for optimised pellet guiding systems. Approaching larger size tokamaks, in particular ITER, guiding systems have to cover everlonger distances to transfer pellets from the pellet accelerator to the torus inboard. Whilst high pellet transfer speeds are the foremost requirement, mass conservation is crucial to achieve substantial mass deposition in current devices and to tailor guiding track and pellet extrusion size requirements in future machines. In the mean time the need to study geometrical and vacuum characteristics of pellet guiding systems has led to the design and construction of new tracks in devices such as JET, ASDEX Upgrade, DIII-D, JT60-U and LHD. Notably, this implementation of tracks on present machines has to cope with the specific landscape of existing diagnostics and heating systems in the vicinity of the tokamaks constraining in particular access to the inboard side.

The aim of the work reported here was to establish how the optimisation of pellet guiding tracks towards higher pellet transfer speeds affects the mass transfer. Pellet mass losses in guiding tracks are thought to occur due to the breakdown of the Leidenfrost effect [4] consisting in the formation of a thin layer from evaporated pellet gas underneath the cryogenic pellet on contact with the room temperature guide track, inhibiting immediate sublimation of the pellet. However, breakdown of this mechanism can occur in curved sections of the track when the centrifugal load on the pellet can overweigh the internal pressure of the gas cloud leading to increased pellet erosion. Further, measurements to quantify the sublimated ice and the required vacuum conductance for two track pumping configurations were taken, analysed and used to calculate an operational diagram for vacuum pumping requirements as a function of pellet speed and repetition frequency.

2. APPARATUS AND EXPERIMENTAL METHOD

Table 1 gives a summary of the experimental set up at ASDEX Upgrade and JET/ORNL. The main known parameters influencing mass loss in pellet guide track systems are also indicated.

JET/ORNL

The flight tube assembly at JET shown in Fig.1(a), due for commissioning in September 2002, uses a large radius, s-type geometry with a circular tube cross-section. To maximise the radii of curvature an S-shaped trajectory was chosen with the second bend representing a 160°-u-turn to match the vertical injection port. The guiding track is a 10mm ID stainless steel tube capable of handling 4 and 5mm pellets. A simple cable tray design has been adopted to host the 100mm ID main pumping line running in parallel to and entering the track at three stages. The 8m long line was projected to pump out evaporation from 5Hz pellets at 300m/s. Diagnostics of this layout also include a direct mass measurement using a microwave cavity. In preparation of the JET installation a full size mock-up of the stainless steel tube was designed and built at ORNL. Measurement were focused on pellet survival rates, thus single pure D2- pellets were fired using a gas gun. The tube here was pumped only from the upstream side, so that any propellant gas would lag the pellet on the downstream end.

ASDEX UPGRADE

The track at ASDEX Upgrade schematised in Fig.1(b) uses a looping geometry with maximised curvature radii [5]. Two development stages of the loop's central half ellipse, were used. In the first set up (Loop1) the tube section consisted of two concentric circular tubes, a 7mm internal diameter (ID) inner teflon tube glued into and supported by an outer copper tube. Vacuum pumping was arranged from both ends of the section by 570 l/s turbo-molecular pumps. In Loop2 the whole track was equipped with a rectangular cross-section, the central part of which opened up to the inside curvature by 100 perpendicular, 2mm slots per meter. This track made from a microwave tube was embedded into a 40mm ID, flexible vacuum hose system with a conductance 40 times larger than that of Loop1.

Pellets were shot by a centrifuge in sequences of 5 - 10 at a time with the cryostat yielding an ice slab for up to 80 pellets per extrusion. Shadowgraphic video diagnostics at the end of the loop enabled to assess the quality and size of pellets. Mass losses were measured directly with a microwave interferometer which, however, was not available for each series, and indirectly by measuring pellet dimensions from calibrated 2D images of the video diagnostic. The velocity measurements were done with a series of laser diode arrangements at four sites along the track.

3. EXPERIMENTAL RESULTS

Figure 2 shows the pellet transfer efficiency (defined as the number of whole pellets arriving in the plasma divided by the number of pellets accelerated by the centrifuge) from Loop1 as a function of pellet speed and composition. At pellet speeds v>500m/s a higher strength of ice made from doped D_2 was revealed. Doping in larger fractions such as 2% N_2 was found to worsen the pellet strength slightly. Also shown is the test result from ORNL, where pellets did not survive fully intact at v>500m/s. Notably, pellets in the transition region between 350 - 500m/s emerged in relatively large sections from the tube.

Figure 3 shows results from direct and indirect mass loss measurement in Loops1 and 2 averaged over pellet sequences of 5-10 pellets. Pellets doped with 0.5% N2 show in both loops an increase in mass conservation by 10-15% with respect to pure D2-pellets. In addition, 5 - 10% less mass is lost in Loop2 than in Loop1 at slow and medium speeds. Again doping with 2% N2 did not improve mass conservation.

To identify the influence of varying pellet frequencies on transfer performance, pellet speed changes through the guide track were recorded over pellet sequences of 5 - 10 pellets. As shown in Fig.4a for the example of v = 880m/s, a steadily increasing speed loss was found which saturates after 6 - 7 pellets. The speed loss is higher at a higher pellet frequency, however, at smaller pellet speeds the the effect is quite weak. In Loop2 the speed loss dynamics was observed to be in stark contrast to Loop1. As can be seen from Fig.4b, the speed loss is high after the first pellet, but stagnates thereafter and falls below that of Loop1 after 5 or more pellets.

4. DISCUSSION

Pellet Composition:

Figs. 2 and 3 demonstrate that some pellet hardening has been achieved doping the D_2-pellets with 0.5% N_2. This was confirmed later on in first plasma discharges refueled with pure and doped pellets, where doped pellets showed deeper penetration [1].

Sliding Friction:

This type of friction depends mostly on the centrifugal load on the pellet which itself is a function of pellet speed, track geometry, both longitudinal and transversal. Since the ASDEX Upgrade track has only 15% of its length in a straight line section, the sliding friction is most evident with unproportionally large mass losses at v = 880m/s. At high speed the gas cloud underneath the pellet cannot match the force of the non-linearly increasing pressure of the bends forces stronger erosion of the pellet. Using $F = \rho_g \cdot R \cdot T_p \cdot A_p$, where $\rho_g = \rho/M$ is the gas density of D_2, $T_p = 20K$ the gas temperature, R the gas constant and A_p the pellet surface; the expansion force in the gas layer can be estimated at 80 mN. In contrast, the centripetal force on a pellet at v = 880m/s in an average 3m bend radius is about 200mN.

Hidden in the average mass loss in Fig.3 is the interesting effect observed for each first pellet in sequences in of Loops 1 and 2. The relatively large speed loss (Fig. 4b) per pellet in Loop2 can be linked to an increased evaporation rate, which could be explained by a much larger contact area in rectangular tracks (with side walls also shaving ice off the pellet surface) with respect to that in circular tubes.

***Gas friction and Tube Length*:**

More in general, speed loss observations could be explained by a gas “blocking” effect where sublimated gas from the first pellet of the sequence is not pumped away in time for the subsequent pellet as shown in Fig.4a. Using the mass loss from the graph in Fig.3 as a rough guide an estimate of the gas resistance induced by the sublimated gas on the track gives about 2% speed loss for v=

560m/s and 3% for v= 880m/s. Fig.4b demonstrates the effect of the different pumping configurations in Loop1 and 2 at ASDEX Upgrade. Despite the stronger gas friction per pellet the sequence of pellets is not affected by accumulating gas.

Using the main pumping characteristics for ASDEX Upgrade and JET and estimating evaporation rates as function of mass loss and pellet frequency, steady stage pressures (p) were calculated with $p \cdot V = G/M \cdot R \cdot T_p$ (V – volume to be pumped, G – weight of mass loss) as a function of tube length. Fig. 5a shows the resulting operational diagram for Loop2 at ASDEX Upgrade where a medium mass loss of 40% (attributable to a pellet at v = 560m/s) defines the maximum tube length which can be evacuated to a base pressure of 5x10-4 for a given pellet frequency. The JET flight tube geometry induces on average less centripetal pressure on the pellets with a ratio of 1:1 between straight and curved track lengths. Scaling the mass loss measurements form ASDEX Upgrade on to JET with an maximum pellet speed of 400m/s an average mass loss of 25 - 40% can be assumed for the JET track. As shown in Fig.5b calculations of the reuired pumping capability suggest a maximum tube length of 2.6m for typical pellet frequencies of 4Hz. This is slightly longer than the 4m long segments pumped from both sides.

CONCLUSIONS.

The main conclusion from ASDEX Upgrade experiments is a substantial decrease in pellet mass erosion by gas friction in a well-pumped guiding track such as Loop 2. However, the increased erosion of pellet surface in a rectangular track with respect to a circular one means that the choice of track cross-section in future systems has to be a trade off between maximum pellet speed achieved in rectangular tracks and pellet erosion. As a first result of the studies an option of a pumping reinforcement was introduced at the front end of the half ellipse with a 3m long, 200mm ID chimney acting as a buffer volume in a section of increased pellet evaporation. This is directed at pumping efficiently pellet repetition rates of up to 60Hz (Fig.5b) routinely required in a number of fuelling studies [3]. Future operation of the new JET guiding track is supported by vacuum pumping capability which should allow to minimise mass losses due to gas friction at pellet fueling frequencies of 4 - 6Hz and pellet speeds of up to 400m/s.

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Time (s)	ASDEX Upgrade		JET/ORNL
Nominal Pellet Mass, Size,	1.5 mg, 2 mm		13 mg, 4 mm
Pellet Speed	240 - 880 m/s		160 - 400* m/s
Centripetal Load On Pellet	0.05 - 3 bar		0.1 - 1.8 bar
Length of System	17 m		15 m
Ratio Straight/ Curved Section Lengths	0.15		1
Pellet Composition	D2 + (0.5 - 2)% N2		D2
Pellet Frequency	5 - 23 Hz		1 - 5 Hz
	LOOP1	LOOP2	
Cross-section Tube	Circ.	Rectang	Circular
Ratio Tube Size/ Pellet Size	3	3.2	2.2
Min. Vacuum Conductance at 1e-3 mbar	S = 0. l/s	S = 7 l/s*	S = 0.2 l/s

JG03.567-1c

Table 1: Pellet and Guide track characteristics affecting mass transfer into plasma,
***Bold face: Parameters varied in study**.*
**Speed expected to reach at JET,*
***Conductance calculated assuming 40mm ID tube due to slot arrangement.*