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NBI Related Gas Sources in the TJ-II Stellarator

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Macarena Liniers, F. Martín-Díaz, J.A. Sebastián, G. Wolfers, R. Carrasco, B. Rojo, F. Miguel, E. Sánchez, F. Martín†, E. de la Cal, J.M. Fontdecaba, E. Ascasíbar, J. Guasp, and the TJ-II team

Laboratorio Nacional de Fusión, Avda. Complutense 40, 28040 Madrid, Spain

Introduction Neutral Beams contribute to plasma fuelling as fast ions confined in the magnetic field, but also through two additional mechanisms: a fraction of the hydrogen gas injected in the NBI plasma source is injected in the machine through the NBI duct alongside the beam. And the fast particle impacts on the vacuum chamber wall give rise to re-emission of the gas adsorbed in the wall between plasma pulses. These two gas sources can be treated as a kind of gas puffing.

In TJ-II, where the NBI system consists of two injectors of 34 keV energy and 1,4 MW total power [1], the contribution of the re-emission is important considering that 11% of the calorimeter power is intercepted in the beam entrance area [2]. In order to characterize these gas sources, fast pressure gauges have been symmetrically located at the four machine periods. It has been observed that the pressure distribution in the machine during the plasma pulse (< 200 ms) presents a high degree of inhomogeneity. The gas conductance between two machine periods has been experimentally determined using pure gas pulses, and the "local" character of the gas sources has been thus established.

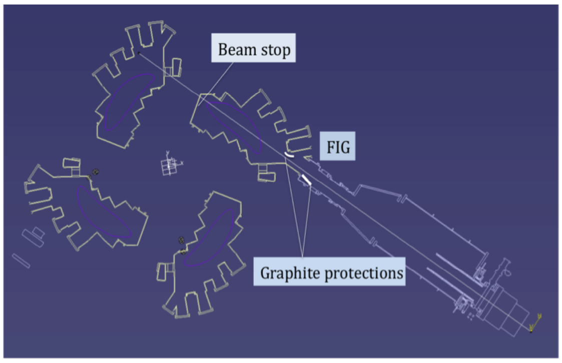

Figure 1: CATIA drawing with a section of TJ-II vacuum vessel and NBI#1 through a horizontal plane containing the beam axis

The conductance values have been used in the analysis of pressure signals during beam pulses to obtain quantitative information on the re-emitted gas flows.

Gas dynamics in TJ-II: Conductance between periods TJ-II is a four period stellarator of the heliac type, with major radius R=1.5 m. The high helicity of TJ-II can be best appreciated through the comparison between the plasma minor radius (0.2 m) and the toroidal field coils swing radius (0.28 m). Figure 1 shows a CATIA drawing of the intersection between the vacuum vessel outer wall and a horizontal plane containing the beam axis. In this view, the vacuum vessel has the appearance of four disconnected volumes. Although this discontinuity is only apparent, it does illustrate the effect of the geometry on the propagation of gas particles through the machine. The overall helical geometry, combined with the vacuum vessel design (welded plane wall sectors) determines the gas conductance of the machine.

To obtain a realistic estimate of the conductance between two periods, the pressure traces of four symmetrically located Fast Ion Gauges [3] have been analysed for gas pulses injected in the machine through the NBI ducts. The experimental layout can be seen in Figure 2. Two Penning gauges are installed near the beam ports (D8 and C1) and two Bayard-Alpert gauges are located at sectors D1 and B2. The two Fast Ion Gauges inside the beam boxes (BB1 and BB2) are used in the evaluation of the injected gas flows. The hydrogen gas is injected using the Ion Source piezo-electric valves in both Beam Injectors.

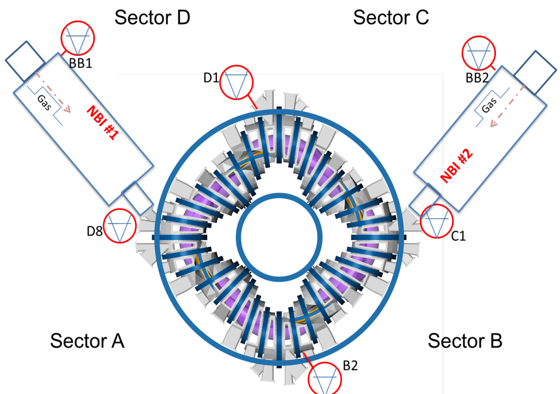

Figure 2: Experimental layout. Four Fast Ion Gauges are installed on each of the TJ-II four periods.

When a square-wave gas pulse is injected in the machine through the duct of NBI#1, the gas flows to the neighbouring periods and is pumped away by TJ-II turbomolecular pumps (one pump per period). By adjusting the injected flow, a quasi-steady state can be obtained as shown in Figure 3, where the pressure traces of the five involved Fast Ion gauges are shown.

In Figure 4 a simplified model of the machine from the point of view of gas flow is presented. The machine is modelled as four equal volumes (V_P) connected through conductances C_{ij}. The flow between volume i and volume j can be written as:

$$Q_{ij} = C_{ij}(P_j - P_i) \qquad (1)$$

Where $P_{i,j}$ take on the pressure readings of the four pressure gauges (D8, D1, C1, B2)

The injected gas flow through any of the NBI ducts is:

$$Q_{0i} = C_{Di}(P_{BBi} - P_i)$$

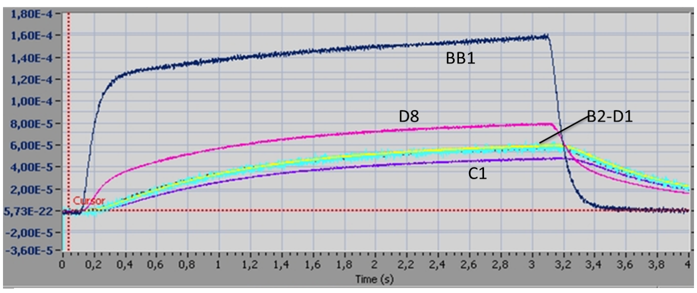

Figure 3: Pressure signals from the 5 Fast Ion Gauges for a 3 s square-wave Gas pulse from NBI#1. Pressure unit is mbar.

Each of the four volumes has a turbomolecular pump of pumping speed S_i. The gas flow through pump i is written:

$$Q_{Si} = S_i P_i \qquad (2)$$

The equation describing the variation in the amount of gas in volume 1 when a beam is injected through duct#1 is:

$$\frac{d(P_{D8}V_P)}{dt} = Q_D + C_{D1}(P_{BB1} - P_{D8}) - C_{12}(P_{D8} - P_{D1}) - C_{14}(P_{D8} - P_{B2}) - S_1 P_{D8} \qquad (3)$$

Where Q_D is the gas flow re-emitted from the wall.

For a gas pulse, in steady state, Q_D =0 and , $d(P_{D8}V_P)/dt \approx 0$, so the four flow-balance equations can be written:

$$\begin{aligned} Q_{01} &\equiv C_{D1}(P_{BB1} - P_{D8}) = Q_{12} + Q_{14} + Q_{S1} \\ Q_{12} &= Q_{23} + Q_{S2} \\ Q_{23} &+ Q_{43} - Q_{S3} = 0 \\ Q_{14} &= Q_{43} + Q_{S4} \end{aligned} \qquad (4)$$

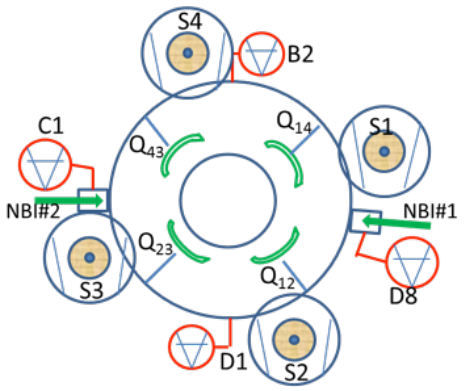

Figure 4: simplified model of TJ-II gas flows as described by eqs. 3 and 4

A fifth equation describes the global flow balance (all the injected gas is pumped away by the turbomolecular pumps):

$$Q_{0i} = Q_{S1} + Q_{S2} + Q_{S3} + Q_{S4} \qquad (5)$$

A similar set of equations can be written for the steady state flows established when gas is injected through duct#2. A homogeneous set of linear equations is obtained, with 8 independent equations, and 10 unknown variables: the 4 conductances between periods C_{ij} (to take into account the lack of exact symmetry in the gauges locations), the 2 conductances of the ducts C_{Di} (to allow for small differences in internal pumping inside the beam boxes) and 4 pumping speeds S_i (since some divergence from nominal values is frequently observed). Limits can be readily set for the 10 variables, based on simple estimates (conductances) or nominal values (pumping speeds).

In order to find the "optimal" solution a Monte Carlo approach has been adopted: a stochastic search is carried out in the variables space within their allowed limits, and for each set of 10 random numbers an evaluation of the "unbalance" (UB) of the equations is obtained, comparing the terms containing the S_i with those containing the conductances and establishing the percentual relative differences. Along the optimization procedure, priority is given to the Global Unbalance (GUB) corresponding to the total flow balance (eq. 5). After a great number of repetitions (100 million) an optimal set of values is chosen among those with minimum GUB (<30%) and minimum total UB.

The optimal set of values is presented in table I.

Estimate of Re-emitted Gas flow Figure 5 shows the pressure traces for a NBI#1 beam pulse of 100 ms in the absence of magnetic field. The pressure distribution along the torus is highly inhomogeneous for the pulse duration. Analysis of the duct pressure signal (D8) using equation 3 yields the evolution of the re-emitted gas. Table II presents the injected and re- emitted flows as well as the flows between machine periods and to the turbomolecular pump.

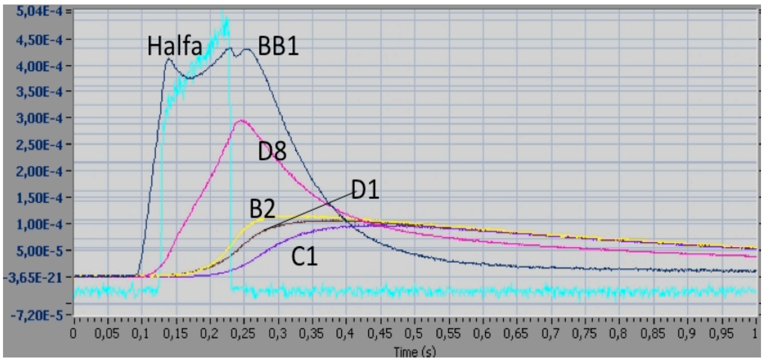

Figure 5: Pressure traces of the 5 Fast Ion Gauges during NBI#1 beam pulse (100 ms). Pressure unit is mbar.

Table I: optimal set of values for the conductances and pumping speeds (all variables in $l.s^{-1}$)

C_{12}	5026.0
C_{23}	4900.0
C_{34}	4901.0
C_{41}	5128.0
S1	1208.0
S2	1051.0
S3	1500.0
S4	1086.0
C_{D1}	4082.0
C_{D2}	4071.0
GUB	28 %

The magnitude of the re-emitted flow at the end of the pulse is at least a factor 5 that of the injected flow or the propagating flows, therefore establishing the "local" character of the observed pressure rise in the duct region.

Table II: The re-emitted flow Q_D as obtained from eq. (3). All quantities in mbar.l.s-1

t(s)	**$D(P_{D8}V_P)/Dt$**	**$C_{D1}(P_{BB1}-P_{D8})$**	**$C_{12}(P_{D8}-P_{D1})$**	**$C_{14}(P_{D8}-P_{B2})$**	**$S1*P_{D8}$**	**Q_D**
0.13	1.95	1.32	0.12	0.12	0.02	**0.89**
0.18	2.75	0.98	0.65	0.67	0.17	**3.26**
0.23	3.75	0.67	1.15	1.08	0.33	**5.64**

Conclusions An estimate of the gas conductance in TJ-II has been experimentally obtained by studying the gas flows during gas pulses injected from the NBI systems. The obtained value, around 5000 l.s-1, has been used to estimate the gas flow re-emitted from the wall during a beam pulse. The flow of re-emitted gas in the beam entrance area is much larger than the flows to neighbouring periods, which leads to the observed inhomogeneity of the pressure distribution during beam pulses.

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