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Vacuum system of the neutral beam injectors at the stellarator TJ-II

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Abstract

In the fusion plasma experiment TJ-II, two neutral beam injectors provide 2 MW heating power to the plasma. Beam losses occur at different stages due to collisions of beam ions or neutrals with surrounding H_2 molecules. Efficient use of the injected gas is of utmost importance, in order to minimize losses while ensuring optimum neutralization. In the design phase of the vacuum system, extensive use of the computer code OPTIMUS has been made. Calculations show that in order to keep reionization losses at an acceptable level, the maximum allowed pressure during the beam pulse is 10^{-4} mbar, which requires an installed pumping speed of 350,000 l/s. Titanium getter pumps have been chosen as the primary vacuum system for these injectors. Base pressures in the range of 5×10^{-9} mbar are attainable with titanium pump operation.

1. Introduction

In the current experimental phase of the TJ-II stellarator, low density, high electron temperature plasmas are created by means of electron cyclotron resonance heating, using two microwave launching lines at 53.2 GHz with a total injected power of 600 kW. In the second experimental phase, dense, high beta plasmas will be studied, with neutral beam injection (NBI) as the main plasma heating. Two beamlines in a tangential Co-Counter configuration will inject two H^0 beams of energy between 30 and 40 keV, and 2 MW total injected power [1].

Two injectors formerly in use on the Advanced Toroidal Facility (ATF) at Oak Ridge National Laboratory in USA, have been loaned to Ciemat, where they are presently being commissioned. The auxiliary systems (high voltage power supplies, vacuum system, cooling system and control and data acquisition systems), have been supplied by Ciemat. For the vacuum system in particular, the original design has been substantially altered: titanium getter pumps have been chosen over cryopumps, and the overall pumping capacity has been doubled.

The 100 A ion beam is generated at the duoPiGatron ion source by an arc discharge in hydrogen, extracted and accelerated at the grids, neutralized at the neutralizer and transmitted through the injector and duct (see Fig. 1). Of the 4 MW ion beam generated at the ion source, only 1 MW neutral beam reaches the plasma, due to losses of geometrical and collisional origin. Geometrical losses due to the finite divergence angle of the beam accounting for a beam transmission around 65%, have been described elsewhere [2].

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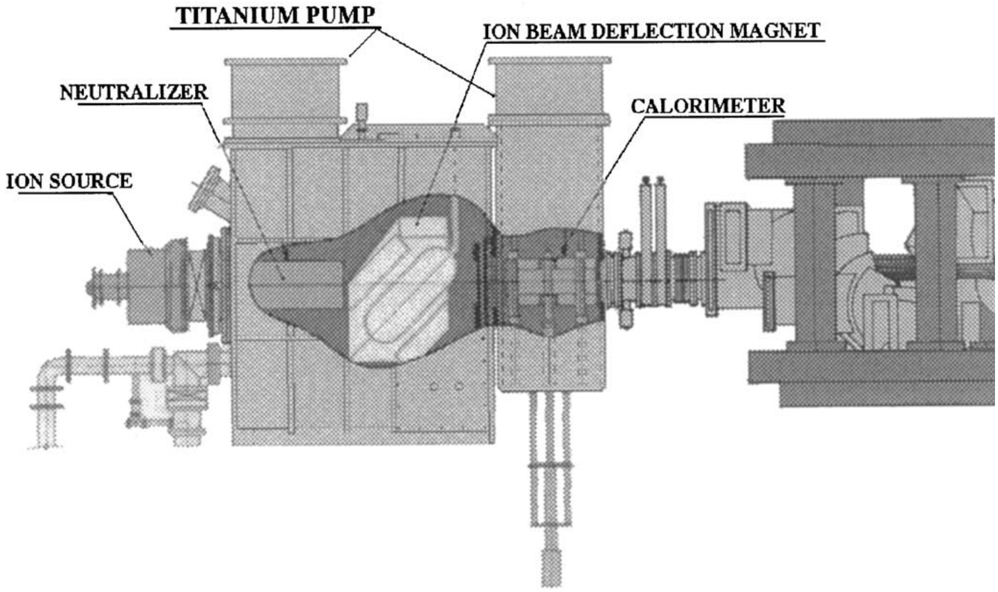

Fig. 1. Side view of one injector.

The collisional losses occur at three stages: at the accelerator grids (5%), where ions colliding with gas molecules give rise to an off optics beam component, at the neutralizer, where the average equilibrium fraction for the three ion species present (ions of energy $E = 40\,\mathrm{keV}$, $E/2$ and $E/3$ at rates 80:10:10) is around 60%, and at the duct region, where the reionization losses are the greatest (10%).

The flow rate of H_2 gas necessary for plasma formation and beam neutralization is around 30 mbar l/s. It is injected at both the ion source and neutralizer through piezoelectric valves, and diffuses through the grids, beam box and duct. Gas desorbed from metallic surfaces hit by beam particles, also contributes to the reionization losses.

Efficient use of the injected gas is of utmost importance, in order to minimize losses while ensuring optimum neutralization. DuoPIGatron sources have high gas efficiency (around 35%) as well as high arc efficiency (0.56 A/kW) [3]. On the other hand, fast vacuum pumps are needed to keep down the base pressure in the beam box during the 300 ms beam pulse.

Titanium getter pumps have been chosen as the fast pumping system due to their simplicity of operation and maintenance. To estimate the number and distribution of panels necessary to fulfil our requirements, we have made use of the computer code OPTIMUS.

2. OPTIMUS code

The power not transmitted through the system (reionization, geometrical losses and the fraction of beam not neutralized) is deposited mainly on the accelerator grids, neutralizer cell, ion dump and duct apertures. All these fast particles will hit the walls of the vacuum vessel and may desorb gas molecules from the walls. The inflow of gas molecules due to desorption contributes to the increase of residual gas, which produces an increase in the reionization losses. Since this effect could be unfavourable, the calculation of the pumping requirements is very important in the design of the vacuum system.

These pumping requirements have been determined by performing detailed gas flow calculations using the code OPTIMUS. This code, originally written in Max-Planck-Institut für Plasmaphysik of Garching (Germany) [4], is a computer program for analysing the influence of various parameters on the characteristics of a neutral injection beam. Essentially, the code calculates the pressure distribution, the beam losses and the neutral power injected into the torus for a system modelled by a number of interconnected chambers, into which a given gas flow is injected with given distributed pumping speeds.

The underlying geometrical model of our injector system consists of seven sectors (Fig. 2): ion source, neutralizer, two vacuum chambers (the first one is split in two sectors), and the torus port hole which is also split into two sectors. It is assumed that pumping systems are installed in sectors 3 and 5.

In Table 1 the geometrical and reionization losses and the transmitted power are shown when the pumping speeds in the calorimeter chamber are modified. As can be seen in the table, a pumping speed higher than 100,000 l/s is absolutely necessary to avoid excessive reionization losses. Without this condition, the reionization losses become 24% of the beam and the transmitted power into the torus falls down to 725 kW. However, a pumping speed of 120,000 l/s, which shows only 10% of reionization losses and 1174 kW of transmitted power, seems to be enough for our requirements.

Under these conditions, the main parameters of the injector system, the transmitted power and the power loss distribution are summarized in Fig. 3.

3. Titanium pumps

Our titanium getter pumps follow closely the design of those at Asdex Upgrade (AUG) [5]. As can be seen in Fig. 4, the titanium wires hang from their feed-throughs in the centre of a U-shaped cell

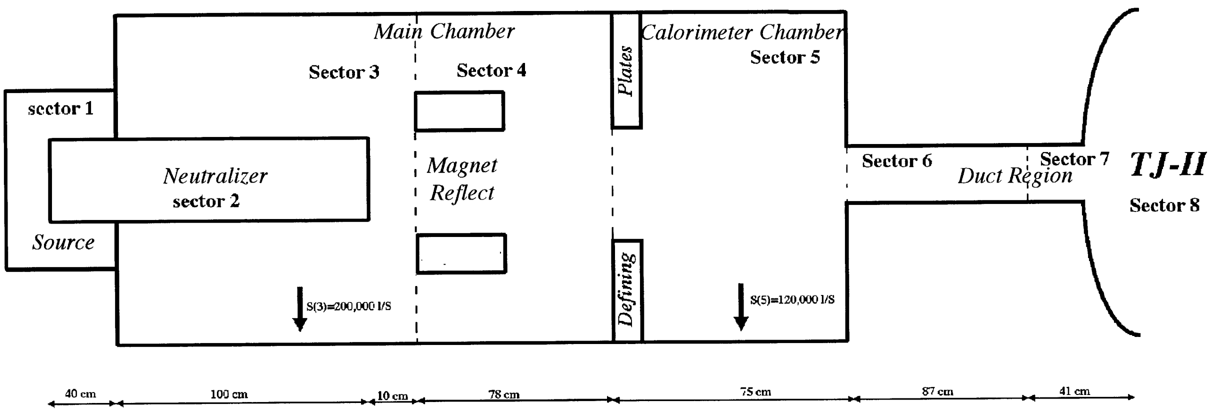

Fig. 2. Geometrical model of beam line conductances, as used in OPTIMUS.

Table 1
Losses inside the beamline and power into the torus as a function of pumping speed at the calorimeter box

Total pumping speed (l/s)	Calorimeter chamber pumping speed (l/s)	Total geometrical losses (%)	Total reionization losses (%)	Transmitted power in the torus (kW)
200,000	0	22.7	24.2	725
260,000	60,000	25.7	12.2	1083
320,000	120,000	26.3	10.0	1150
400,000	200,000	27.2	9.5	1174

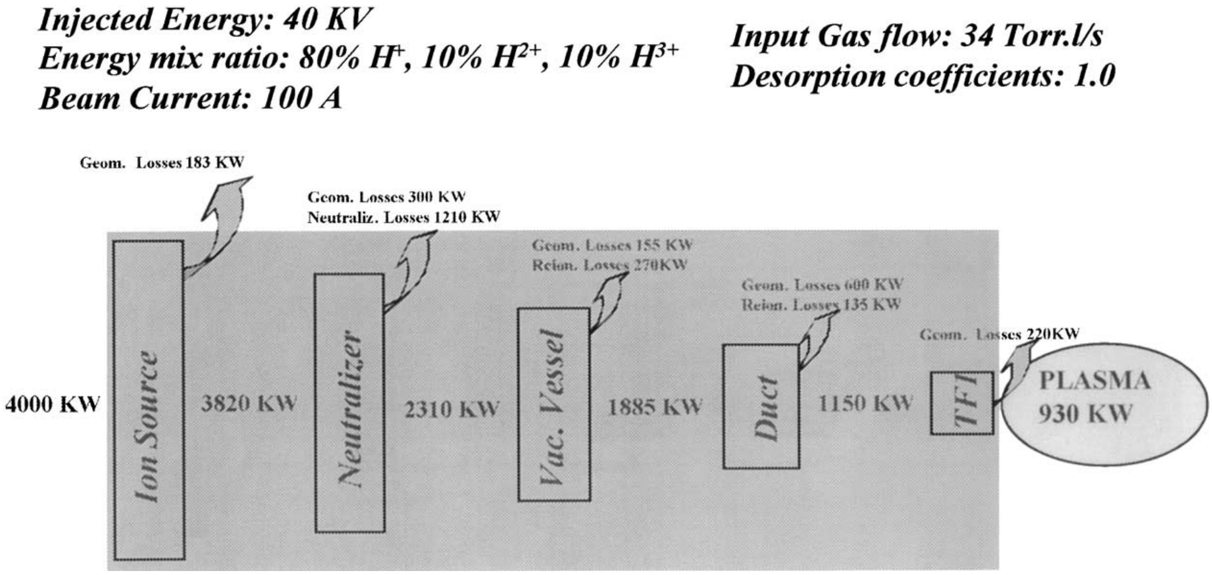

Fig. 3. Beam losses from ion source to plasma, along the beam path.

made up of three assembled panels. The wires, factory manufactured, are made of four wires of tungsten, molybdenum and titanium of different thicknesses, wound in an intertwined manner. The panels are made of cast aluminum with a corrugated surface. The corrugated quality of the panels and their disposition in U-cells multiply the specific pumping speed of a smooth surface of aluminum by a factor 9, making the overall pumping speed of these pumps comparable to that of a chevron-like cryopump of similar size.

The basic pump design of our injectors consists of four of these cells assembled together, hanging from a rectangular flange. There are two kinds of pumps according to their lengths: 0.9 m long pumps and 2.0 m long pumps. We will install 3 "short" pumps on each injector, one in the main box and two in the calorimeter box, each of them with a pumping speed of 60,000 l/s. One "long" pump will be installed in the main box, with a pumping speed of 140,000 l/s. The total installed pumping speed in one injector adds up to 320,000 l/s. Due to space constraints inside the beam boxes, the pumps must sit on top of coupling pieces added to the injectors in order to increase their effective height by 30 cm. Increasing the pumping speed above this value is nevertheless difficult for conductance reasons.

The main difference with respect to the original system is the installation of two pumps in the calorimeter chamber. The great advantage of these pumps is that they perform differential pumping on the duct, where high levels of released gas are expected due to beam particle impacts on the 20 cm diameter diaphragm placed at the exit of the calorimeter chamber. The gas released from the copper surface through thermal desorption (peak temperatures of 250°C can be attained), increases the beam reionization levels in that area and hence the surface impacts of the fast ions newly created. This self-enhanced reionization, also known as "beam blocking", must be clearly avoided.

As has been mentioned, one of the great advantages of the titanium getter pumps is their simplicity of operation. The panels are water cooled through pipes embedded in the aluminium. The water flow is 2.4 m^3/h for the four pumps in one injector, supplied by the NBI cooling system. Calorimetric estimates show this flow to be sufficient to ensure that pumps are cooled down in <30 min. Only a few safety requirements must be fulfilled: during titanium evaporation, the

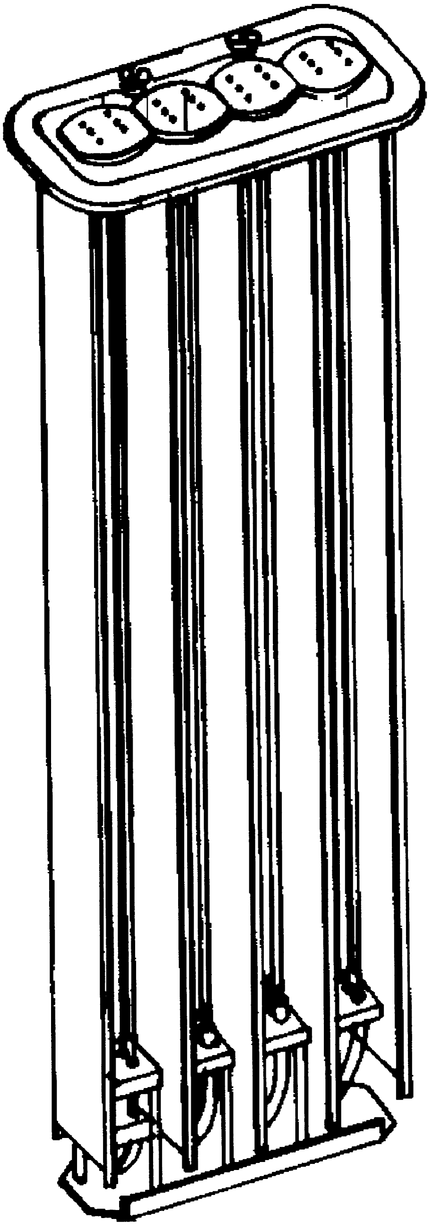

Fig. 4. Modular Ti pumps.

magnetic fields must be shut down for wire protection, and the isolation valve with TJ-II closed.

A secondary vacuum system is needed to secure a base pressure below 2×10^{-3} mbar during titanium evaporation. The system is composed of a rotary-turbomolecular pump set, with a pumping speed of 1500 l/s. During first tests, the obtained pressure with this secondary system is 2×10^{-7} mbar. Leak tests have shown the leak rates to be below 10^{-9} mbar l/s. Measurements with a mass spectrometer show water as the main impurity.

To estimate the number of Ti evaporations per day we have calculated the total gas load per injector in one day of operation, and used AUG measurements of titanium consumption. During normal operation, we will have one 300 ms beam pulse every 5 min, with several short conditioning pulses (20 ms) in between. This means a total gas load of 4000 mbar l/day in one injector. If, according to AUG data the titanium consumption is 0.0125 g/mbar l of hydrogen, then the titanium consumption is 50 g/day. If, again following AUG, the amount of evaporated titanium during a typical run is 0.78 g/m of wire, then every day, evaporation of 34 m of wire must be performed. Therefore, only two complete evaporations per day will be necessary (there are 18 m of available wire per injector), during which the TJ-II magnetic fields must be switched off. This is a very convenient scenario, since even sharing one power supply for several pumps, one complete evaporation will take only 35 min, which will interfere little with the TJ-II operation.

The pumps have been manufactured partly by industry (titanium wires and aluminum panels) and partly at the Ciemat workshops. Collaboration with the Max Plank Institute of Plasma Physics at Garching, has been essential.

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