High-Speed Pumping System Characteristics of 2 MW Neutral Beam Injector Based on Ti Gettering

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Abstract. The 15 kV, 2 MW neutral beam injector (NBI) was developed for C-2U magnetic trap experiments. Important part of the NBI is efficient pumping system which provided a good vacuum condition during beam pulse. The pressure rise during the NBI operation and accompanying gas flow to the fusion device is a negative factor both for the beam transportation and for fusion experiment. The high-speed pumping system based on four Ti-bar arc-discharge evaporators placed inside LN2-cooled volume was developed and successfully used in vacuum chamber of the 2 MW NBI. The results of calculations and tests are presented both at the room and at the LN2 temperatures of the gettered surface. Achieved pumping speeds are about 10^5 and $4 \cdot 10^5$ l/s correspondingly. Also gas capacitance of the gettered surface and conditions of uniform gettering were established.

1. INTRODUCTION

For the experiments at C2U machine [1] powerful neutral beams have been made by Budker Institute [2]. The system of 6 injectors with 15 keV energy and 30 ms pulse duration should provide 10 MW of total power in neutral particles. A distinctive feature of these injectors is high current of neutral particles - up to 120 A. To provide such neutral flux ion current up to 150-160 A is required. Applied arc-discharge plasma generator has gas efficiency about 50%, which determines the gas flow from the ion source to the 30 l·torr/sec. Furthermore, the initial beam aperture is 340 mm that means a large gas conductance of the neutralizer and leads to the need for additional gas puff in the neutralizer. Thus, the total flow of associated gas from the injector is about 50 l·torr/sec. For the successful FRC experiment "cold" gas flow from the each beam system should not exceed the level of 2 l·torr/sec. A high-speed pumping system is required to reach that value of the flow rate. Thus we chose the titanium gettering pump cooled to liquid nitrogen temperature.

2. BEAM DUCT CONSTRUCTION

The design of the injector is shown in Fig. 1. Due to short beam duct's length a differential pumping, typical for neutral beam injectors [3], had to be abandoned. The beam main vessel has inner copper layer which has thermal insulation from the wall and can be cooled down to the liquid nitrogen temperature. The surface is coated by fresh titanium film and works as a getter pump. Four identical titanium arc evaporators are inserted through the ports on the tank's front side. Evaporators are straight titanium rods with 800 mm in length placed parallel to the beam axis and equipped by arc ignition device and arc suppressor unit at the rod end closing to carrying flange. To increase the active pumping surface area the fins (12 rings 5 cm width) are added to the copper layer. The total inner surface area is about 6 m^2. Titanium getter pumps are widely used to pump hydrogen, where the sticking coefficient for titanium film is 5% at room temperature and 20% at the liquid nitrogen temperature [4]. The expected pumping speed for hydrogen should reach 10^5 and 4×10^5 l/s, respectively.

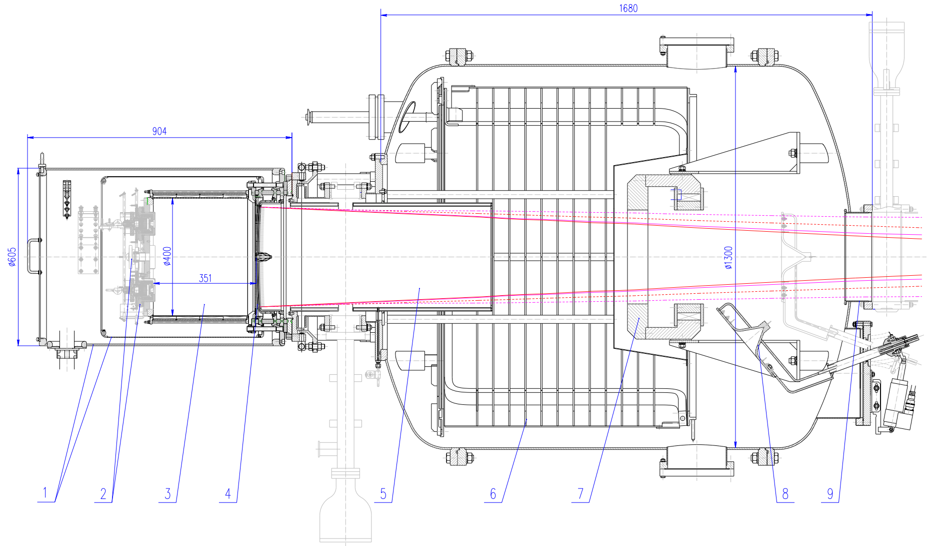


FIGURE 1. Injector layout: 1- magnetic screen; 2- one of the 4 arc generator; 3- plasma box; 4- accelerating grids; 5- neutralizer; 6- getter surface; 7- bending magnet; 8- beam dump-calorimeter (“out” position); 9- gate valve 12” ID;

The modeling of gas flows using Monte Carlo method was carried out for the described construction. Gas flow from the emitter is estimated as Q=50 l·torr/s. Gas line density in the neutralizer is $\langle nl \rangle = 1.1 \times 10^{16}$ cm^{-2}. Charge-exchange cross-section for protons at E=15 keV energy is 7.25×10^{-16} cm^2, according to [5]. Gas target thickness is $\sigma\langle nl \rangle = 7.96$ and the neutralization efficiency of the target is close to equilibrium. The output gas flow rate for ribbed internal cylinder titanium coated surface cooled down to liquid nitrogen temperature is about $Q = 1.5$ l·torr/s (2.9% of total gas flow from the ion source).

3. TITANIUM EVAPORATOR’S CONSTRUCTION

The arc discharge titanium evaporators are described in details in [6].The evaporator’s design has been refined; its drawing is shown in Fig. 2. All structure is placed on standard CF100 flange.

The arc discharge has current up to 300 A, that corresponds to the evaporation rate about 20 mg / sec, and the cathode spot moves along the surface of titanium rod with a linear speed about 10 m/s. Arc suppressor is installed at the junction of the titanium rod and the supporting structure.

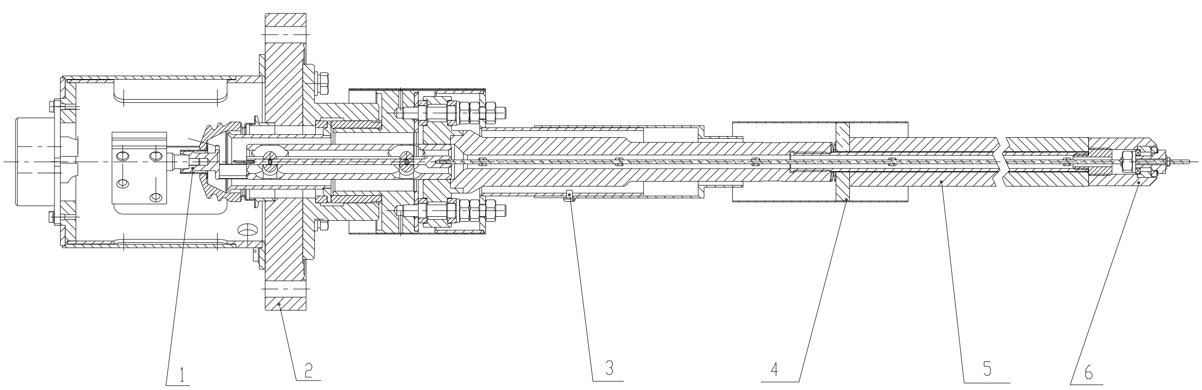


FIGURE 2. Titanium evaporator drawing. 1 – electrical feedthrough; 2 – CF100 flange; 3 – floating screen; 4 – arc suppressor unit; 5 – titanium rod; 6 – ignition unit.

4. THE PUMPING SPEED MEASUREMENTS METODOLOGY

The standard method of the pumping speed measurements consists of pressure measurement in the chamber at known gas flow rates. The problem with this measurement in our conditions is that vacuum gauges have large error and slow response time. That makes difficult measurements with a nominal gas flow rate (50 l*torr/sec). Another problem is that we should measure gas pressure inside the getter, and it is different from the pressure in the other parts of the vessel. The getter has openings at the ends (entry and exit of the beam) with about 350 mm diameters, and as a result, their conductivity is comparable with the expected pumping speed rate (80 thousands l/s and 400 thousands l/s).

The following actions have been carried out to improve measurement: getter's rear side has been removed to provide good gas conductivity to the vacuum chamber, whereby getter area decreased from 6 to 5 m^2. A solenoid gas puff valve has been calibrated at different durations of the opening and the different pressures above the valve. The vacuum gauge also has been calibrated.

The valve calibration was done by pressure measurement in the vacuum tank after a certain numbers of gas puff pulses. Baratron gauge with accuracy about 1% was used for this calibration. The measurements were made at different durations, allowed taking into account the time of valve closing, which proved to be 5 ms.

The gauge GP-390 with fast recording unit was used for vacuum measurements. It was calibrated at different emission currents using calibrated gas puff valve into the vacuum chamber of known volume.

The results of the calibrations are shown in Fig.3

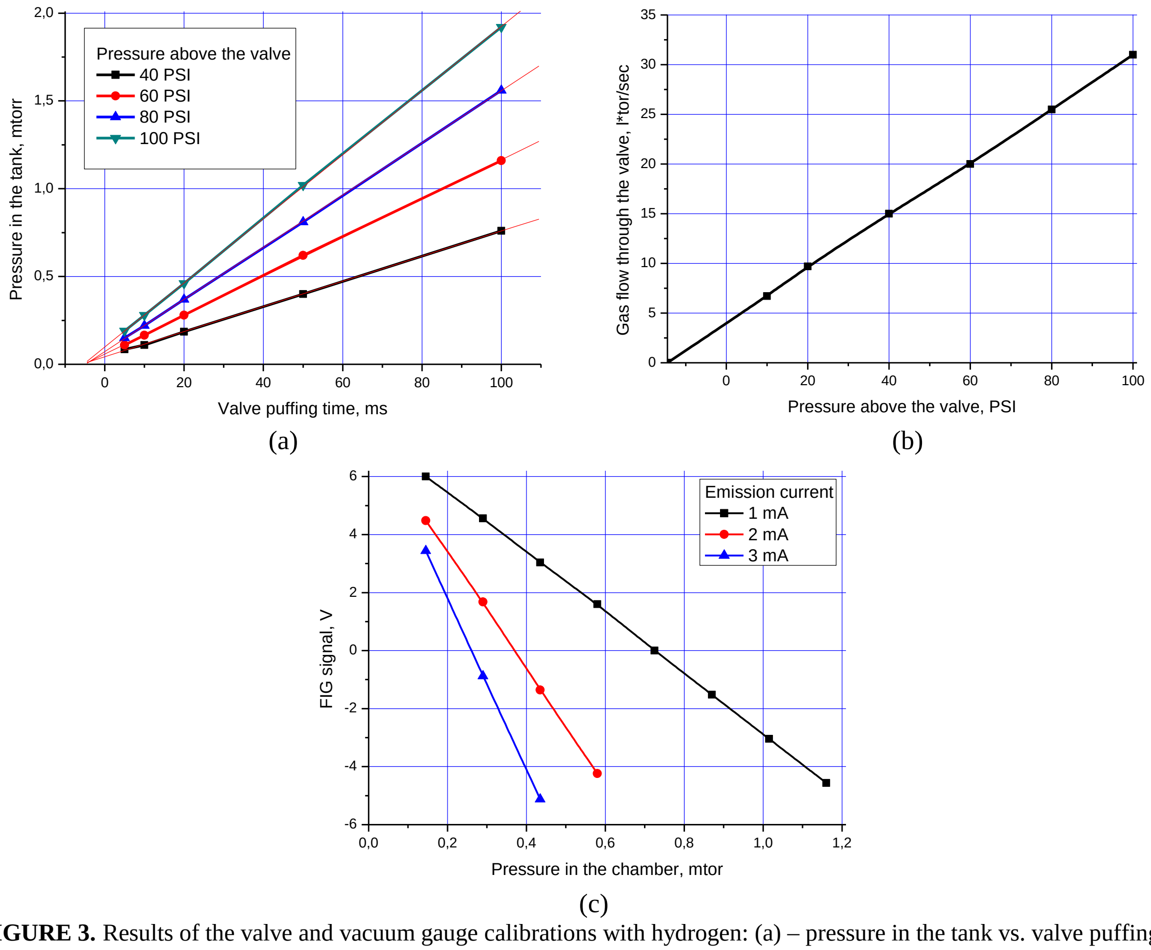
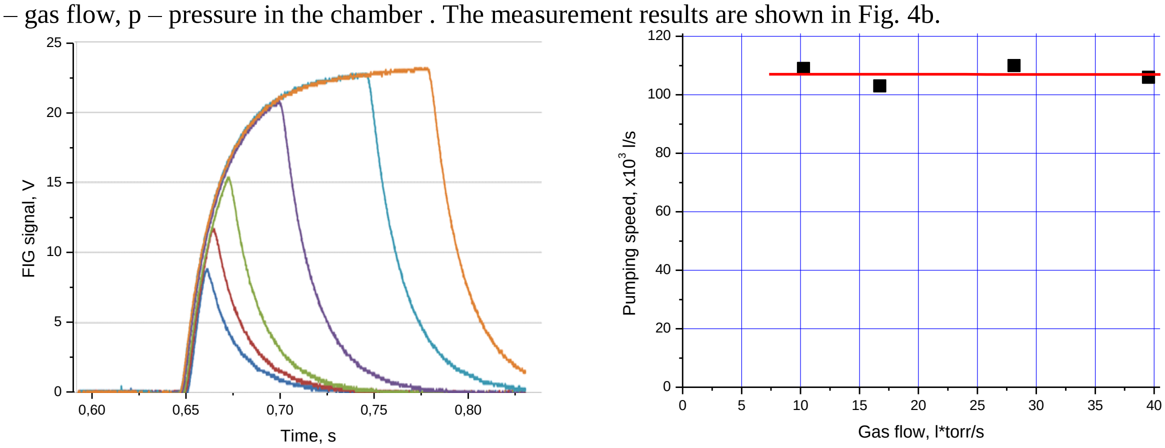


FIGURE 3. Results of the valve and vacuum gauge calibrations with hydrogen: (a) – pressure in the tank vs. valve puffing time at different pressures above the valve; (b) – gas flow through the valve vs. pressure above the valve; (c) – gauge calibration for different emission current.

5. MEASUREMENTS OF THE GETTER PUMPING SPEED

To achieve the nominal pumping speeds prolonged conditioning of the titanium getter is required because freshly titanium evaporators and getter itself have a significant amount of deposited impurities at the surface: nitrogen, oxygen, hydrocarbons and water. These impurities do not almost diffuse into the titanium film and significantly reduce its efficiency. The conditioning took about 6 min of arc discharge per Ti rod. With all duty factors it took 2 days of the whole system conditioning.

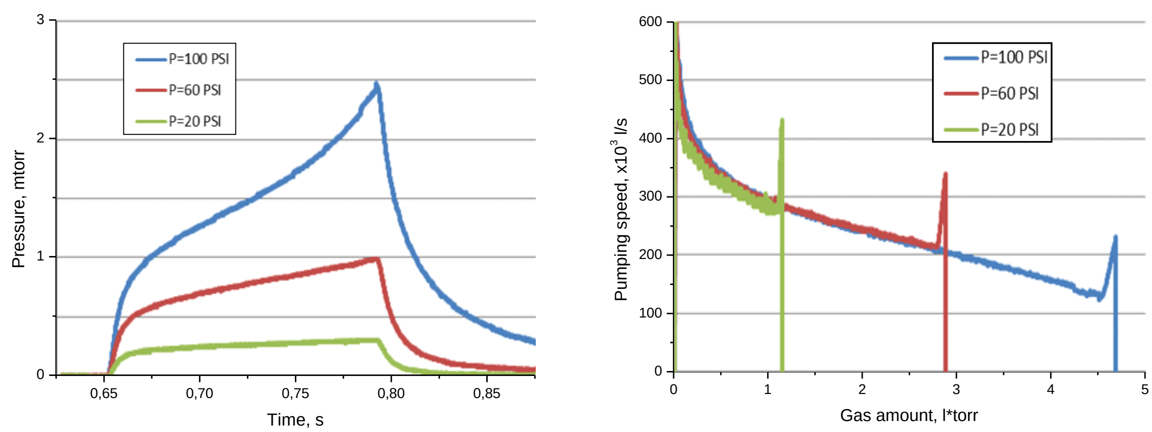
The first measurements were made at room temperature. Typical signals from the vacuum gauge with different gas puff durations are shown in Fig. 4a. After 100 ms gas puffing the pressure inside the chamber does not change significantly, and pumping speed could be calculated by a simple formula U = F / p, where U – pumping speed, F – gas flow, p – pressure in the chamber . The measurement results are shown in Fig. 4b.



(a) (b)

FIGURE 4. (a) – signals from the vacuum gauge at different durations of the gas puffing; (b) – Measured pumping speed of the warm Ti-getter pump for different gas flow rate

Due to the fact that at LN2 temperature the hydrogen diffusion deep into titanium surface is almost negligible and surface saturation and adsorption ratio reduction are happened. The rate of pressure changing in the chamber should be taken into account to calculate the real pumping speed: $U = \frac{F}{P} - \frac{\frac{\partial P}{\partial t} \cdot V}{P}$, where $\frac{\partial P}{\partial t}$ – the pressure changing rate, V-chamber's volume. The graphs of the pressure in the chamber and pumping speed depending of the absorbed gas amount for various gas flows are shown in Fig. 5.



(a) (b)

FIGURE 5. (a) – pressure in the chamber for different gas flow rate; (b) – getter pumping speed vs. absorbed gas amount for different gas flow rate

The initial pumping speed corresponds to a table value of hydrogen sorption rate on the titanium film at LN2 temperature – 20%. At sorption of about 4 l·torr of hydrogen pumping speed decreases by factor of e.

The titanium film re-deposition is required to regenerate the getter. During that procedure the pressure in the chamber is increasing. So for the warm getter pressure jumps up to 10^{-6} torr and for the cold - less than 10^{-7} torr. The pumping speed for different numbers of gettering pulses has been measured. To regenerate the getter at least 80 of 0.5 seconds pulses of the evaporating discharges are required.

CONCLUSIONS

1. After the getter venting on atmosphere pressure the pumping ability is restored after about a day of Ti gettering (0.5 seconds per minute).
2. For the titanium film regeneration at LN2 temperature about 80 titanizing cycles with 0.5 s duration is required, or 0.8 grams of evaporated titanium.
3. During a gettering procedure the pressure in the chamber is increasing up to 10^{-6} torr for the warm getter, and less than 10^{-7} torr - for the cold.
4. Pumping speed of the warm getter for hydrogen is – $1{,}1\cdot10^{5}$ l/s which corresponds a table value of the sticking coefficient – 5%.
5. Pumping speed of the getter cooled to LN2 temperature for hydrogen is $4\div5\cdot10^{5}$ which also corresponds a table value of the sticking coefficient – 20%.
6. At 4 l·torr of sorbed hydrogen pumping speed decreases by e times.

ACKNOWLEDGMENTS

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