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Neutral Beam Evolution in the KSTAR NBI Test Stand

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Abstract

The pressure distributions in the test stand built for developing KSTAR NBI ion sources were obtained using a network system composed of conductance elements modeling the ion source, the neutralizer, and other beam line components. The allowable regime was defined on the coordinates of the gas supply rate to the ion source and the neutralizer, considering the proper conditions of the three critical parameters, the ion source pressure for good arc discharge, the pressure integral in the neutralizer for sufficient neutralization, and the chamber pressure for minimum neutral beam loss. The neutral beam evolution along the path from the ion source extraction grid to the calorimeter through the neutralizer, the bending magnet and the vacuum chamber was estimated for typical pressure distributions.

Keywords : neutralizer, neutral beam, pressure distribution, operation regime

1. Introduction

A neutral beam test stand is set up to examine ion sources developed for the KSTAR (Korea Superconducting Tokamak Advanced Research) NBI (neutral beam injection) system. The test stand is equipped with a 60 m^3 vacuum chamber, an ion source (IS), and one set of beam line components including a source exit scraper/optical multi-channel analyzer (SES/OMA) chamber, neutralizer, bending magnet, ion dump and calorimeter (refer to Fig. 1). The KSTAR NBI system will produce 8 MW neutral beam to heat the plasma in the tokamak with three ion sources per beam line.

The ion beam extracted from the ion source is gradually converted to neutrals through collisions with gas molecules as flowing downward, while the neutral beam is simultaneously transformed to ions little by little. Therefore, the neutral fraction of the beam at any position is determined by the balance between the neutralization and ionization, which depends on the beam energy, interaction cross-sections and the gas pressure integral ($\overline{P} \cdot L$; average pressure × travel length) or the line density (average gas molecule density × travel length) experienced by beam particles. The effective neutralizing region covers the full path just after the ion source extraction grid to the neutralizer exit. If the integral pressure is not enough to obtain a sufficient neutral beam fraction, excessive energy will be deposited

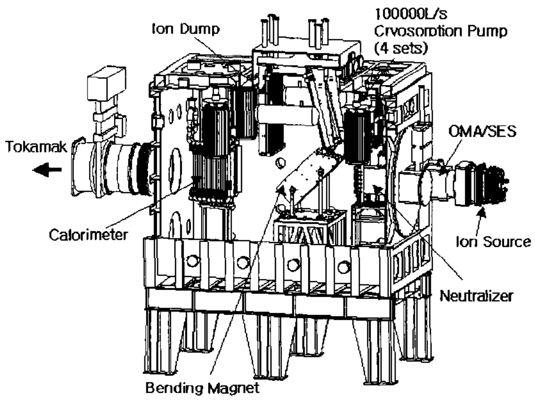

Fig. 1. Overview of the KSTAR NBI test stand.

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to the ion dump. On the other hand if the gas pressure is too high, permanent beam loss by scattering will significantly increase and the amount of the neutral beam attainable from the NBI system will be greatly reduced.

A 5500 L/s TMP (effective pumping speed is about 4200 L/s) is installed on the NBI test stand for roughing, conditioning, and sometimes short-pulse experiments. A 200,000 L/s cryosorption pump (among 4 sets of 100,000 L/s cryosorption panel, usually 2 sets in operation, 2 sets in stand-by) is used for long-pulse beam extraction experiments. Though the ion source is normally not evacuated separately, an auxiliary pump, if necessary, can be installed on the OMA chamber near the ion source exit. The vacuum chamber, the ion source and the neutralizer must have their own pressure ranges to acquire a maximum amount of the neutral beam. To get a required pressure pattern, it is necessary to control the gas flow spatially.

In this paper, the evolution of the neutral beam along the beam line composed of mainly the neutralizer, bending magnet and vacuum chamber, in typical pressure distributions obtained under the gas supply requirements to get powerful arc discharges in the ion source and sufficient pressure integrals in the neutralizer, is investigated.

2. Equilibrium of Neutralization and Ionization

The ion beam extracted from an ion source filled with hydrogen plasma usually comprises three ion species of the same energy; mainly H^+, the rest H_2^+ and H_3^+. Some fraction of the fast positive ions is converted to fast neutrals by capturing electrons from gas molecules. Most molecular ion species (H_2^+, H_3^+) are fully dissociated during the neutralization process, and generated neutrals have one half or one third of the ion beam energy. Only the neutrals from atomic ion species have full energy. The neutrals can capture electrons further, though not frequently, and become negative ions.

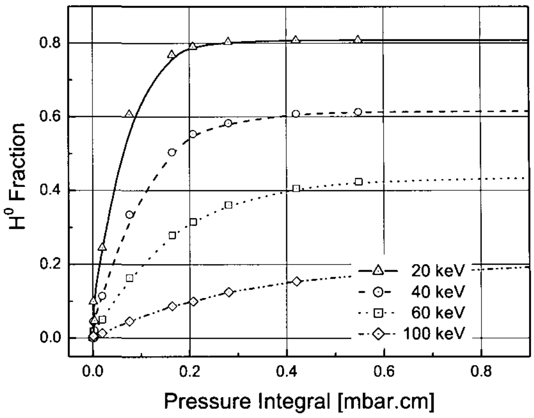


Fig. 2 Evolution of hydrogen neutrals as a function of the pressure integral.

Figure 2 shows the evolution of positive ions (H^+), negative ions (H^-), and neutrals (H^0) of the H family as passing through gas molecules for 4 values of the beam energy, which are obtained by solving analytically or numerically three differential equations expressing the particle balance between H^0, H^+ and H^-. The neutral fraction becomes saturated when reaching equilibrium of neutralization (H^+, $H^- \rightarrow H^0$) and ionization ($H^0 \rightarrow H^+$, H^-) depending on the interaction cross-sections [1,2]. The saturated neutral fraction is inversely proportional to the beam energy in approximation. The required pressure integral for saturation of the neutral fraction increases monotonically with the beam energy.

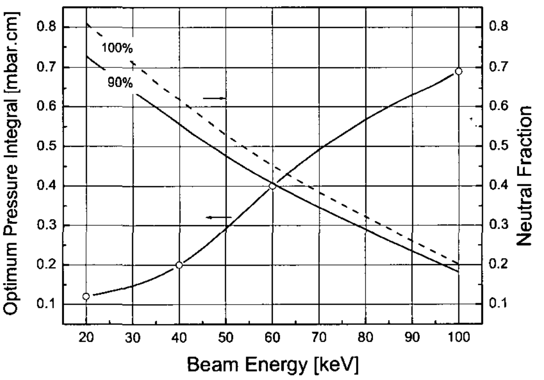


Fig. 3. Optimum pressure integral as a function of the beam energy. The change in saturated and 90% level of the maximum neutral fraction is also shown.

Figure 3 summarizes the relation between the beam energy and the optimum pressure integral at which the neutralizing efficiency reaches a 90% level of the saturated value. The optimum neutral fraction becomes less than 30% for the beam energy above 80 keV, which would be considered a practical limit for the acceleration voltage of the hydrogen beam.

3. Pressure distribution along the beam line

The ion source, the neutralizer, the vacuum chamber, the fueling system and the pumping system can be as a whole represented by a network system consisting of several conductance elements as in Fig. 4. The ion source has also a complicated structure of gas flow paths, and total conductance is separately evaluated to be 1920 L/s. P_{IS}, P_N, and P_{ch} are the pressures in the ion source, the neutralizer, and the vacuum chamber, respectively. Q_c and Q_N are the external gas supply to the ion source and the neutralizer, respectively. Q_b denotes the ion beam flow rate that is a loss in the gas flow at the ion source and later becomes a gas source in the vacuum chamber.

If there is no beam extraction from the ion source, Q_b equals zero, and a balance between the gas fueling and the gas outflow is kept locally in the ion source. However, during beam extraction operations the portion according to the extracted beam moving directly to the vacuum chamber does not contribute to the gas flow. Therefore, at the same external gas supply the pressure of the ion source is reduced when compared with static pressure and there is even back flow to the ion source from the neutralizer when Q_c is zero. To sustain the pressure of the ion source in a constant level during a beam extraction, the gas fueling rate should be increased by the same amount as the beam current (beam current 1 A=0.1265 T[K]/273 mbar·L/s=7.49 sccm), i.e. $(Q_c)_{\text{beam-on}}=(Q_c)_{\text{beam-off}}+Q_b$. Q_{IS}, the gas outflow from the ion source or the effective gas supply to the ion source, can be defined as $Q_c=Q_b+Q_{IS}$. By comparing above relations Q_{IS} equals $(Q_c)_{\text{beam-off}}$.

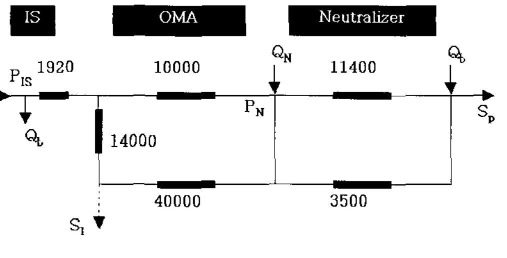
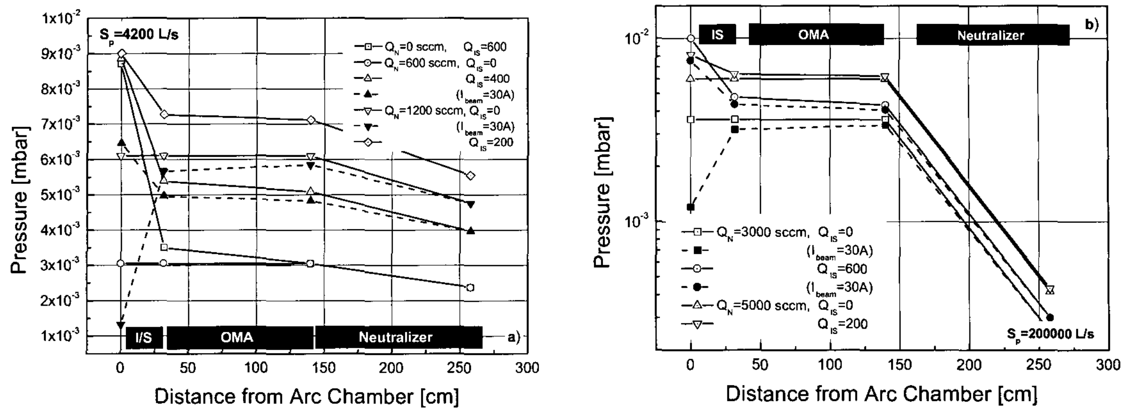


Fig. 4. Network system simulating the beam line components for vacuum analysis. Numbers represent conductance values [L/s] calculated considering real geometrical structures and dimensions of the beam line. Q_{IS} is given by $Q_c - Q_b$. S_I and S_p denote the pumping speeds at the OMA chamber and the NBI chamber.

Several algebraic equations, each obeying a gas flow balance at a node of the conductance network in Fig. 4, are established with respect to the pressure. The linear simultaneous equations can be solved for pressures by a matrix operation with known parameters. If pressures are given the equations will be solved for the parameters such as the gas supply rate, the pumping speed, and even the conductance.

Figure 5 shows the typical pressure distributions along the beam line from the ion source to the exit of the neutralizer, for the cases of S_p=4200 L/s and S_p=200,000 L/s, as changing gas supply rates. In both cases S_I is set to be zero. A large pressure drop occurred at the grid assembly of the ion source when Q_{IS} is not zero, while the pressure is constant from the ion source to the entrance of the neutralizer when Q_{IS} is zero. The pressure drop at the grid assembly is proportional to Q_{IS} and does not depend on the pumping speed in the vacuum chamber. The variation of the pressure in the passage between the ion source and the neutralizer is nearly flat because of the large conductance. There is considerable drop in the pressure through the neutralizer, which is proportional to $Q_{IS}+Q_N$. A key point for designing the pressure distribution along the beam line is how to adjust properly the pressure drops at the grid assembly and the neutralizer. In the case of Q_N=0



(a) (b)

Fig. 5. Pressure distribution along the beam line for several gas fueling conditions when (a) S_p=4200 L/s and b) S_p=200,000 L/s.

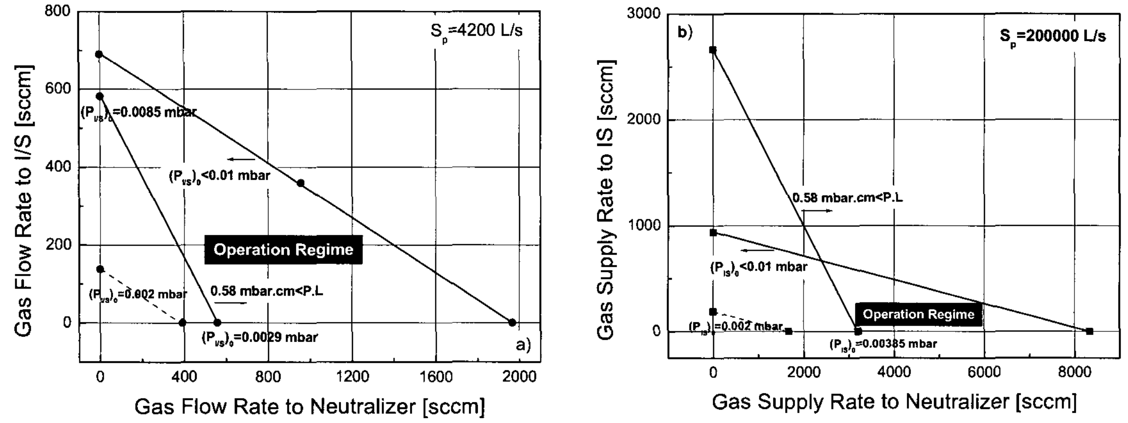
the pressure of the ion source may become too high if raising the average pressure in the neutralizer region to a certain required level. The pressure of the ion source can be moderated if controlling the pressure of the neutralizer in a proper range by mainly Q_N, not by Q_{IS} alone.

In Fig. 5 it is found that in the case of S_p=4200 L/s the ion source can not be operated in a long pulse mode, because the chamber pressure is too high to maintain the neutral beam in the downstream of the bending magnet due to frequent ionizations, and the stray heat load to surrounding unshielded components will be intolerable. When S_p is 200,000 L/s it is more difficult, compared with the case of S_p=4200 L/s, to adjust the pressure of the ion source so that it does not exceed a certain level, and simultaneously the pressure in the neutralizer does not drop below a required level, because the high pumping speed in the vacuum chamber prevents the pressure buildup in the neutralizing region which has a comparatively large conductance. Therefore large gas supply to the upstream of the neutralizer is necessary to keep the average pressure in the neutralizer high enough in spite of the huge pumping speed in the vacuum chamber.

4. Operation Regime

The pressure in the ion source has an optimum range, namely 2×10^{-3}~10^{-2} mbar, determined by the arc discharge condition, heat load to the plasma grid, and electrical breakdown between the acceleration grids. If the pressure in the space between the grids should be far below that of the arc chamber of the ion source an additional pump has to be positioned near the exit of the ion source. Fortunately the 10 mm gap between the grids of the present ion source can stand the voltage of 100 kV at the pressure below 0.01 mbar, then it is safe to say that an additional pump is not necessary if the pressure of the arc chamber of the ion source is kept below 0.01 mbar. To obtain a sufficient pressure integral, for example $\overline{P}\cdot L$>0.58 mbar·cm (to reach the 90% level of max. neutral fraction for 80 keV beam), the average pressure in the passage between the ion source exit and the bending magnet must have a lower limit such as $\overline{P}>2.5\times10^{-3}$ mbar.

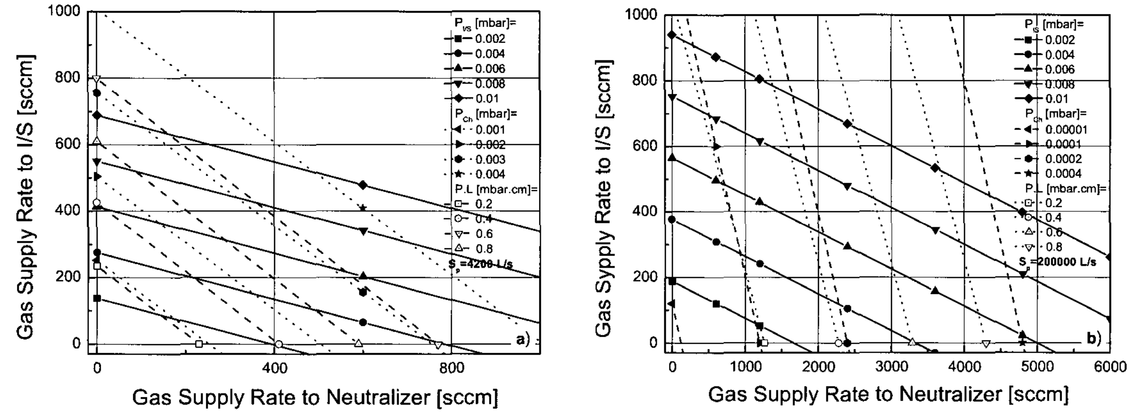
The allowable regime can be defined on the coordinates of the gas supply rate to the ion source and the neutralizer as described in Fig. 6, for the cases of S_p=4200 L/s and 200,000 L/s. The upper limit of the gas supply rate is given by mainly the optimum range of the discharge pressure of the ion source, and partially the electrical breakdown condition between the acceleration grids, while the lower limit by the minimum pressure integral required in the neutralizing region. Sometimes two pressure requirements might be in conflict



(a)

(b)

Fig. 6. Allowable regime of the gas flow rate when (a) S_p=4200 L/s and (b) S_p=200,000 L/s.



(a)

(b)

Fig. 7. Integrated diagram of the gas flow rate to obtain a required level of the pressures in the ion source, neutralizer, and the chamber when (a) S_p =4200 L/s and (b) S_p=200,000 L/s.

if the gas is supplied to the ion source only. It is necessary to provide additional fueling to the neutralizer to control effectively the pressure distribution. When S_p is 4200 L/s, and Q_N is zero, assuming the above requirements, $P_{IS} < 0.01$ mbar and $\overline{P} \cdot L > 0.58$ mbar·cm, Q_{IS} has a narrow allowable range from 580 to 690 sccm. If Q_N has a value higher than 560, Q_{IS} can be zero to attain the same condition as before.

In the case of S_p=200,000 L/s it is inevitable to introduce a lot of gas directly into the neutralizer to provide a proper pressure pattern, while the required gas supply to the ion source increases only a little compared with the case of S_p=4200 L/s, and then the overall operation regime seems shifted linearly to a higher Q_N. To satisfy the condition $\overline{P} \cdot L > 0.58$ mbar·cm Q_N should be larger than 2000 sccm.

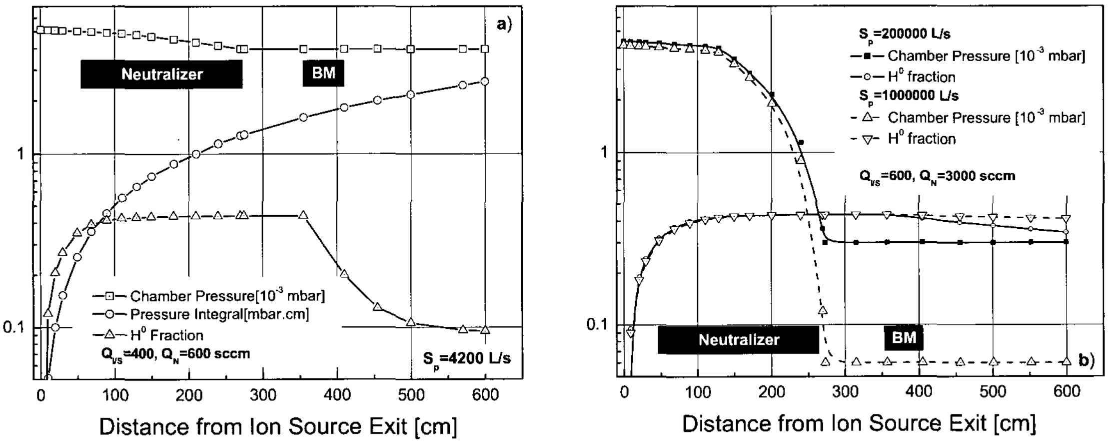
Figure 7 gives more detailed and integrated information about the proper range of the gas flow rate required to control reasonably the pressures of the ion source, the neutralizer and the vacuum chamber in a desired pattern. The final allowable regime is obtained as a common region satisfying the three conditions as follows; $\alpha < P_{IS} < \beta$ (space between two solid lines), $P_{ch} < \gamma$ (left side of a dotted line) and $\delta < \overline{P} \cdot L$ (right side of a dashed line) where α, β, γ and δ are chosen values. Fig. 6 was a simplified version of Fig. 7, neglecting the requirement for the chamber pressure and assuming maximum conditions. Depending on the pumping speed the chamber pressure may be the most critical parameter difficult to control. In the Fig. 7, there is practically no common allowable regime if the conditions, $P_{ch} < 0.0005$ mbar for S_p=4200 L/s, and $P_{ch} < 0.00001$ mbar for S_p=200,000 L/s, must be satisfied. When S_p is 200,000 L/s, a narrow region between the two lines satisfying the conditions $P_{ch} < 0.0002$ mbar (corresponding to $\overline{P} \cdot L <$ ~0.43 mbar(cm) and 0.4 mbar·cm $< \overline{P} \cdot L$ (corresponding to ~$0.00018 < P_{ch}$) seems to be the optimum one attainable in the present beam line configuration of the test stand, though the chamber pressure is a little bit high and the pressure integral looks insufficient.

5. Neutral beam evolution in typical pressure distributions

As already mentioned the ion beam and the neutral beam are reversibly converted to each other moving in gas molecules, while the total number of beam particles is kept nearly constant if there is no or slight beam loss. The intrinsic beam loss due to the beam divergence in the present geometries of the beam line components is practically below 10% in the path from the ion source to the calorimeter (~5.5 m).

In the passage of the bending magnet the ion beam is removed from the beam flow and deposited to the ion dump located on the top of the bending magnet by the deflection in the magnetic field, and the deflected ion beams do not have any more chance of being converted again to the neutral beam. Therefore, some part of the neutral beam permanently disappears in the path below the bending magnet. If the chamber pressure is not low enough to ignore the beam-gas interaction, the fraction of the survived neutrals up to the calorimeter becomes very small.

Figure 8 shows that the neutral fraction, defined as the ratio of the neutrals counted at a position to the total ions extracted from the ion source, is steeply decreased in the path after the bending magnet and the reduction is unacceptable when the pumping speed is 4200 L/s. The final neutral fraction goes down below 10% after 5.5 m travel because of high chamber pressure of 4×10^{-3} mbar for S_p=4200 L/s and Q_{tot}=1000 sccm, where $Q_{tot}=Q_{IS}+Q_N$. In the figure when the pumping speed is 200,000 L/s and Q_{tot} is 3600 sccm, the chamber pressure is about 3×10^{-4} mbar and the loss in the neutral fraction in the chamber is about 8%. If the pumping speed will be improved to be 1,000,000 L/s, the chamber pressure is 6×10^{-5} mbar and the loss of



(a) (b)

Fig. 8. Neutral beam evolution in a practical pressure distribution when (a) S_p=4200 L/s and (b) S_p=200,000 L/s and 1,000,000 L/s.

the neutral beam at downstream of the bending magnet can be reduced to below 2%.

For maximizing the high energy neutrals supplied to the tokamak from the NBI system, it is essential to maintain the pressure of the NBI chamber as low as possible. The chamber pressure is linearly dependent on the gas throughput and inversely on the pumping speed, and then the solution to reduce the pressure looks very simple. However, it is basically difficult to decrease the chamber pressure by reducing the gas supply because of the lower limit in the arc chamber pressure and the pressure integral to be kept in the neutralizer. Moreover it is expensive and technically complicated to provide a huge vacuum pump in the order of 10^6 L/s. Now it might be worthwhile to pay attention to another solution such as lowering the conductance of the neutralizer, which saves the gas supply to get the same pressure pattern especially in the neutralizer and consequently decrease the chamber pressure. It seems desirable to redesign the present neutralizer duct to have a compact size as close to the beam cross-section as possible if it can endure the heat load from the beam.

6. Conclusions

The pressure distribution in the test stand for developing KSTAR NBI ion source were obtained by solving the matrix equation describing the gas flow balance in the network system composed of conductance elements modeling the ion source and the neutralizer.

The operation regime of the beam line was defined on the coordinates of the gas flow rate to the ion source and the neutralizer considering the conditions for the three parameters: the ion source pressure for good discharge, pressure integral for sufficient neutralization, and the chamber pressure for the minimum loss of the neutral beam.

The neutral beam evolution along the beam line mainly composed of a neutralizer, a bending magnet, and a vacuum chamber was estimated for typical pressure distributions. When the pumping speed is 200,000 L/s, the final neutral fraction after 5.5 m traveling is about 36% with 8% beam loss in the chamber. To attain a sufficient neutral fraction and simultaneously to minimize the beam loss in the current test stand, both the gas flow rate and the pumping speed should be increased. However, that solution is not economic. It is highly recommended to redesign the present neutralizer duct to have a compact size as close as possible to the beam cross-section.

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