Vacuum Requirements and Neutral Beam Transfer in a Neutral Injection Beam Line. Application to the Wendelstein 7 A Neutral Injectors.

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Abstract

A computer program for studying the influence of the various beam line parameters in a neutral injection system on the neutral power transferred to the torus is described. It assumes steady state conditions and depends mainly on the solution of a nonlinear system of equations. Application to the W 7 A neutral injectors shows that the major part of the beam power is lost by the unavoidable partial neutralization and the finite beam divergence.

1. INTRODUCTION

Neutral injection heating experiments at IPP are planned for the near future in the W 7 a stellarator and in the ASDEX tokamak. In the course of the technical preparation, a computer program has been written which allows the simple study of the influence of various beam line parameters on the neutral power injected into the torus. The schematic shape of a beam line which should be applicable to most injection experiments is shown in Fig. 1. In principle, it works as follows:

An ion source provides a hydrogen plasma. From its surface, ions are accelerated in a multiaperture grid structure to the desired beam energy. This beam of fast ions (with given optical characteristics), accompanied by a thermal gas flow, enters the neutralizer region. Here partial neutralization of the ions by charge exchange takes place. To preserve the beam optical characteristic, this region has to be shielded against magnetic stray fields. The neutralizer is followed by a drift region, equipped with an effective pumping system, which lies in front of and/or between the main field coils. In this space, the non-neutralized ions are deflected by magnetic fields and, owing to reionization of the neutrals in the residual gas, the neutral particle current decreases. After the drift region the beam enters the torus.
The parameters which mainly influence the available neutral power (for given beam energy, current and emittance) are:
- total length of the beam line
- pressure in the ion source
- composition of the beam
- conductance of the grid structure
- length and conductance of the neutralizer
- pumping speed, capacity and conductance of the vacuum system
- desorption of gas by fast particles
- beaming effects of the gas flow

In the following, the model used in the program is outlined. Then a description of the assumptions for the various components of the beam line is given. Finally, the application of the program to the special case of the W 7 a injectors is discussed.

2. THE MODEL

The main purpose of the program is to calculate the pressure and gas flow distributions in the beam line and their influence on the ions and neutrals. Without the ion beam, the pressure is determined by:

- the gas flow out of the source
- the parameters of the vacuum equipment.

If a time independent pumping speed is assumed (disregarding for example saturation effects of the pumps), stationary conditions will be achieved after a time given approximately by

$$t = V/S \qquad \begin{array}{ll} V: & \text{volume of the beam line} \\ S: & \text{total pumping speed} \end{array}$$

This time will normally be short compared to the injection pulse length. When the beam is turned on, three effects which influence the pressure distribution will happen:

1. Unneutralized ions from the neutralizer will be deflected in the magnetic fields.
2. Fast neutrals will be lost owing to the finite divergence of the beam, especially at diaphragms.
3. Reionized neutrals in the drift space will be swept out of the beam by the magnetic fields.

All these fast particles will hit the wall and may desorb gas molecules adsorbed at the walls. The desorption coefficient

$$\gamma = \frac{\text{number of desorbed molecules}}{\text{incident fast particle}}$$

is a rather unknown quantity and will depend on the wall material, the temperature and the residual gas. This additional gas flow has two effects:

1. Owing to desorption in the neutralizer itself, the probability of neutralization increases.

2. Owing to the increase of the pressure in the drift region, more particles will be lost by reionization and will lead to further desorption.

Because of the fact that this additional gas flow is a non-linear function of the pressure, it is convenient to calculate the final conditions in an iterative manner. First the pressure is calculated without beam effects. Then the additional gas flow and its influence on the pressure distribution is determined. The new pressure yields new different gas flow and so on. The iteration is terminated when the change in the distribution is below a certain limit.

3. DESCRIPTION OF THE ELEMENTS OF THE BEAM LINE

In this section the assumptions for the various parts of the beam line used in the program are explained in more detail.

a) The ion source and the grid structure

The parameters involved in the calculations are:

- pressure in the source
- beam composition and current density
- geometrical shape of the grids
- extraction voltage.

The beam composition and the current density may be a function of the source pressure and are considered as input parameters for the program. The extraction voltage determines the cross-sections for neutralization and reionization. The only value calculated in the program is the conductance of the grid structure. Assuming molecular flow and neglecting the possibility of pumping between the grids, the conductance is calculated from /1/

$$C_o = \left(\sum_{i=1}^{N} \frac{1}{C_i} \right)^{-1}$$

$$C_i = 44{,}5 \cdot A_i \cdot K \quad [\ell/\text{sec}]$$

N : number of grids
A : "effective hole area" of grid i in cm^2
K : Clausing factor of one hole given in /1/.

It is clear that this calculation is rather rough and can be more refined, e.g. in the formalism as given by Oatly /2/. But owing to the main uncertainty, namely the gas temperature, this approximation was regarded as good enough. For one grid structure investigated, the formula predicted the experimental value within 10 %/3/.

b) The neutralizer

After the extraction grids, neutralization of the fast ions takes place. For H^+ ions, the percentage of neutralization is given by /4/

$$f^o = \frac{\sigma_{10}}{\sigma_{10} + \sigma_{01}} \left(1 - \exp\left(- nx \left(\sigma_{10} + \sigma_{01}\right)\right)\right)$$

σ_{10} : neutralization cross-section
σ_{01} : reionization cross-section
n : density of the gas
x : length of the beam path in the gas

In practice, the ion beam consists of three different species, e.g. H^+, H_2^+ and H_3^+ which deliver H^+ ions and H^o atoms with the energies E, E/2 and E/3 respectively. Detailed calculations for the composition of the beam leaving the neutralizer, including the complicated neutralization of molecules, were done by Berkner et al./5/. In our program it is assumed for simplicity that the neutralization cross-sections of the molecules are equal to the cross-sections for the corresponding energy/atom of an ion (i.e. disregarding dissociation or neutralization of the molecules). This may be a slight underestimation of the neutralizer efficiency.

The target thickness is determined by the gas flow out of the source, the conductance and the length of the neutralizer, additional gas due to desorption and perhaps gas from external sources. In the present calculations, the neutralizer is assumed to be of rectangular shape, tapered along the path of the beam in such a way that the inner walls of the neutralizer are directed to the outer perimeter of the torus port hole. This should give the maximum necessary transparency for the beam and the minimum conductance for the gas. The conductance is then given by the approximate formula /1/:

$$C_1 = \frac{44{,}5 \cdot A}{1 + \frac{3}{16} \frac{H \cdot \ell}{A}} \quad \ell/\text{sec}$$

A : mean area of the cross-section in cm**2

H : mean perimeter in cm

l : length of the neutralizer in cm

Again it was decided not to use better formulae owing to the inherent uncertainties, mainly the temperature of the gas and the gas flow pattern from the source. Furthermore the conductance may be influenced by corrugation of the inner surfaces of the neutralizer /6/. More detailed calculations of the conductance can very easily be included in the program.

At the end of the neutralizer a pressure drop is assumed, calculated by multiplying the conductance of the exit opening with the gas flow. The target thickness for neutralization is then given by

$$n\,x = \ell_N \cdot \frac{P_1 + (P_2 + P_s)}{2} \cdot 3{,}2 \cdot 10^{16} \quad cm^{-2}.$$

P_i : pressure in Torr, for the notation see Fig. 1.

c) The vacuum chamber

The neutralizer is followed by the drift region which has to incorporate the vacuum pumps. We have divided this region into two parts by a diaphragm. The main task of this one is to prevent the main part of the gas flow out of the neutralizer from going directly into the space between the coils, i.e. to reduce the solid angle for the streaming component of the gas flow. The reason for this is that outside the coils one can normally install a more effective pumping system than in between. The effect of the diaphragm can be reduced by the possible occurrence of a beamed gas flow, i.e. the gas flow may have a preferential direction /7/. If the distribution of the gas flow is known, its effect can be included for the simple case that cylindrical symmetry is assumed around the beam axis with a mean circular area equal to the actual cross-section of the beam. Normally a cos ϑ distribution with respect to the beam axis is used.
The pumping speeds can be calculated with respect to the specific speeds of the pumps themselves and the conductances given by the geometrical conditions. Nevertheless, for more complicated systems, the effective pumping speeds have to be determined independently.

d) Reionization, geometrical losses and ion dump

As mentioned above, a number of processes may cause an additional gas flow due to desorption of molecules from the walls. In particular, the following effects are considered:

1. Neutrals, leaving the neutralizer, may suffer reionization in the residual gas. The fraction of reionized particles, for one energy, is given by

$$f_r = 1 - \exp\left(- \sigma_{10} \cdot p \cdot x \cdot 3{,}2 \cdot 10^{16}\right)$$

p: mean pressure (in torr), averaged over the distance x (in cm). It consists of the pressure of the residual gas and of the contribution of the directed gas flow with thermal velocity.

The ions thus produced are deflected in the magnetic fields and will hit the walls.

2. Owing to the finite divergence of the beam, a fraction of the particles will be lost at beam defining apertures. For a simple approximation, the total loss is calculated to be

$$F_G = \exp\left(- (\varphi/\varphi_e)^2\right),$$

φ: mean angle at which the torus port hole is seen by the source

φ_e: mean divergence of the beam (1/e-width).

For a given distance x along the beam path, the fractional loss due to finite divergence is assumed to be

$$f_G = F_G \cdot \frac{x}{\ell_b}$$

ℓ_b : length of the beam line

If one combines 1. and 2., the inflow of gas molecules due to desorption for a given distance x along the beam path is given by

$$Q = 0.18 \cdot \gamma \cdot I\,(f_G + (1-f_G) \cdot f_r)$$

γ : desorption coefficient

I : particle current (in eq. A) entering the distance x

Q : gas flow in torr*l/sec

3. The third source of additional gas flow is the ion dump, i.e. that place where the non-neutralized ions hit the wall. The position of the dump depends on many parameters and cannot be calculated with this program. Here it is possible to locate the ion dump, i.e. the corresponding desorption area, at three different places (the two vacuum chambers and the diaphragm). The gas flow is given by:

$$Q_i = 0.18 \cdot \gamma \cdot I_i$$

I_i : particle current (in equiv. A) into section i of the dump.

These three different processes are calculated for the five assumed sections of the beam line (neutralizer, first and second vacuum chambers, diaphragm and torus port hole) separately and lead to the additional gas flow Q_N, Q_G, Q_B, Q_D and Q_T.

e) The pressure distribution

If stationary conditions and a pressure in the torus equal to zero are assumed and simple assumptions are made concerning the flow of the desorbed gas, the following set of equations is obtained (for the notation reference is made to Fig. 1):

$$Q_o = (p_o - p_1) \cdot C_o$$

$$p_1 = p_2 + \frac{Q_o}{C_1} + \frac{Q_N}{2C_1}$$

$$p_2 \cdot S_1 = Q_o(1-b) + Q_N + Q_G + \frac{Q_B}{2} - (p_2-p_4) \cdot C_2 .$$

$$p_3 = \frac{p_2+p_4}{2} + \frac{Q_B}{4C_2}$$

$$p_4 \cdot S_2 = Q_o \cdot b + (p_2-p_4) \cdot C_2 + \frac{Q_B}{2} + Q_D + \frac{Q_T}{2} - p_4 C_3$$

$$p_5 = \frac{p_4}{2} + \frac{Q_T}{4C_3}$$

b : fraction of the gas flow Q which goes directly into the second chamber owing to the beaming effect.

In solving this system, one gets expressions for the pressure distribution in the different parts of the beam line which depend only on p_o, geometry, pumping speed and the Q_i, which are functions of the pressure themselves, and are given in the previous sections.

4. THE WENDELSTEIN 7 A NEUTRAL INJECTORS

In the following, the results of the calculations for the W 7 a beam line are presented. The geometry at this device is not very suited to neutral injection. The port holes are very small ($\lesssim$ 10 cm ∅) and the space between the main field coils is narrow (width ∿ 20 cm). To avoid severe geometric losses, one has to make the distance between the source and the torus as short as possible. As a consequence, a short neutralizer requires a high gas flow for effective neutralization and this calls for an effective pumping system. In the calculations, a number of parameters were fixed more or less before the design of the beam line was done. Furthermore, there are parameters which were demanded by physical and technical considerations. In particular, the following quantities were not varied unless otherwise stated.

1. The ion source

total current: 30 A, independent of pressure
conductance of the grids: 945 l/sec
acceleration voltage: 30 kV
beamlet divergence: $\pm$ 1.5° (1/e width)
The beam composition is a function of the source pressure as for example shown in Fig. 2 which is taken from ref. /8/.

2. The neutralizer

The end of the neutralizer was kept fixed 20 cm outside the main field coils where the magnetic stray field is $\leq$ 100 G. A variation of the beam line length is thus connected with a variation of the neutralizer length by

$$\ell_N = \ell_b - 102 \text{ cm}$$

The neutralization and reionization cross-section per molecule, the maximum attainable value f_o^∞ for the three different species and the e-folding neutralizer gas thickness are /4/:

$\frac{E}{keV}$	$\frac{\sigma_{10}}{10^{-17}\ cm^2}$	$\frac{\sigma_{01}}{10^{-17}\ cm^2}$	f_o^∞	$\frac{t}{mTorr \cdot cm}$
30	42	16	0.72	48.8
15	71.6	10.8	0.87	34.3
10	80.0	8.8	0.90	31.9

3. The pumping system

With the exception of (4.d) the intrinsic pumping speeds are assumed to be 70,000 l/sec and 30.000 l/sec in the two chambers respectively. These values were calculated for two possible systems to be attainable.

4. The torus port hole

   The length of this structure is fixed by design considerations at 24 cm. The conductance is roughly calculated to be 1000 l/sec.

To look at the different influences of the free parameters and to optimize the beam line design, the following calculations were done:

a) The length of the beam line

One of the main characteristics for the design is the total length of the beam line. If the length is varied, the neutralization efficiency and the geometrical losses counteract. To illustrate this, in Fig. 3 the neutral power into the torus is shown as a function of the length. Parameter is the source pressure, i.e. the beam composition. With increasing length first the neutralization efficiency and hence the neutral power increase. Then the enhanced geometrical losses lead to a decrease of the power. Therefore, for each source pressure, there exists an optimum length. This is shown in Fig. 4, together with the maximum available power.
One sees that it is best to use a high neutralizer gas flow and a short beam line because of the high neutralization efficiency and the small geometrical losses. Reionization due to poorer pressure is only a small effect (if the assumed pumping speeds can be maintained).

b) The capacity of the pumps

A high pressure in the source means high gas flow out of the source and a considerable gas load for the pumps. In the calculations a constant pumping speed was assumed, independently of the gas load. Two different pumping systems for the W 7 a injectors have been discussed up to now:

1. Titanium sublimation pumps: Using these pumps, one has a strong dependence of the pumping speed on the gas load /9/. For the layout of the pumping system a sticking factor of 0.03 is assumed. This corresponds to a maximum gas load of approximately 5 monolayers, i.e. around $7 \cdot 10^{-5}$ Torr*l/cm^2. Within the practical geometry of the beamline, this leads, for a gas pulse length of 0.3 sec, to a maximum permissible gas flow of less than 12 Torr * l/sec into the first chamber, and 5 Torr*l/sec into the second one. (This given boundary is not very sharp and further investigations have to be done).

2. Volume Getter Pumps: Here the restriction is not the gas flow but the space needed for achieving the pumping speed required. Nevertheless, in this case as well, the gas load should be small to reduce the time needed for the activation of the pumps.

Fig. 5 shows the gas flow to the two pumps. The parameter is the distance between the end of the neutralizer and the diaphragm ("gap length"). This distance determines:
- the direct fraction of the gas flow into the second chamber
- the effective pumping speeds in the two chambers.

The conductance of the diaphragm varies a little with the gap length because its area can be reduced if the gap length is increased. One sees that for a gap length between 20 cm and 30 cm the source pressure should be less than 14 m Torr, if the assumed values for the titanium pumps are used. This would cause an optimum length of the beam line of around 150 cm. By using Volume Getter Pumps one could increase the pressure. Fig. 6 shows the neutral power as a function of pressure for a constant beam line length of 150 cm. It can be seen that around 20 kW are lost by fixing the length to 150 cm compared to the maximum available power, shown in Fig. 4. In the following calculations we assume this length, a gap length of 20 cm and a source pressure of 12 mTorr.

c) The influence of the pumping speed

For the design of the pumping system it is useful to determine the influence of the pumping speed on the neutral power. Fig. 7 shows this quantity as a function of the effective pumping speed in chamber II. The parameter is the pumping speed of the first pump. It can be seen that if one exceeds a certain minimum pumping speed (e.g. $S_1 \geq 20\,000$ l/sec, $S_2 \geq 15\,000$ l/sec) the increase of the neutral power does not depend very sensitively on the increase of the pumping speed. If titanium pumps are used, one requires for capacity reasons such a great area that the actual pumping speed will be much higher. For the Volume Getter Pumps this weak dependence will be a beneficial effect for the design.

d) The influence of the desorption

It is rather uncertain what the desorption coefficient γ may be. It depends on the material and the temperature of the walls as well as on the instantaneous conditions within one gas pulse, owing to cleaning effects by fast particles, and on the residual gas pressure.

In the calculations $\gamma = 1$ is normally assumed. This may be too low at the beginning of the pulse and too high at the end. To get a feeling for the dependence on γ, the neutral power is shown in Fig. 8 as a function of the desorption factor. A rather strong dependence can be seen. This has to be taken into account for the design of the beam line, perhaps by using special materials, e.g. titantium plates for the ion dump and a good pumping efficiency in the neighbourhood of diaphragms.

e) Maximum available power

It was pointed out by several authors /10, 11/ that for a given geometry and vacuum system only a certain maximum current can be transported across the drift region, if one includes reionization and desorption. Fig. 9 shows, as an analogon, the available neutral power into W 7 a as a function of the ion current. The parameter is the effective pumping speed in the second vacuum chamber. It is clearly seen that in this iterative calculations as well, for a given design of the beam line, the available power has an absolute maximum (for given energy). This cannot be overcome by increasing the current.

5. SUMMARY AND CONCLUSIONS

The structure of a simple program which allows the study of the influence of the various parameters of a beam line on the neutral power is described. The essential part of this program is a set of equations, for a steady state, which determines the influence of a pressure distribution in the beam line on the gas flows and vice versa. All the other quantities used are more or less chosen for the special case of the injection at W 7 a and may easily be substituted for other applications by changing subprograms.
For the W 7 a injectors, in Fig. 10 the various "loss processes" and their mutual relations are summarized for the standard parameters. If one starts with an extracted ion power of 900 kW (30 A, 30 kV), owing to the finite neutralization efficiency one loses 210 kW (line 1). If the geometrical losses are included one obtains 478 kW (line 2). If one considers that the pumping speed is not infinite but 70,000 l/sec and 30,000 l/sec respectively, one loses 3 kW (line 3). Owing to the effect of desorption in the neutralizer, one gains 2.5 kW (line 4), but the total power is decreased by 17 kW if the desorption in the other parts of the beam line is included. If one takes into consideration the fact of the cos ϑ flow pattern at the end of the neutralizer (direct gas flow into the second chamber and along the beam path) one arrives at a neutral power of 454 kW. If one includes the flow pattern, given by Dayton for l/r = 10, which may describe the given geometry approximately, one finally has a power of 447 kW into the torus.

It is clearly seen that the gross effects are the incomplete neutralization (in this case on an average 94 % of the maximum value of f_o are achieved), and the geometric losses. The other processes play a minor role in the balance of the power lost along the beam line.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS:

Fig. 1: Schematic drawing of the beam line. The quantities indicated refer to the conductances, pumping speeds, gas flows and pressures in the different parts of the beam line. In particular, they have the following meanings:

- P_o : source pressure
- P_1 : pressure at the beginning of the neutralizer
- P_s : pressure drop at the exit of the neutralizer
- P_2 : pressure in the first vacuum chamber
- P_3 : maximum pressure in the disphragm
- P_4 : mean pressure in the second vacuum chamber
- P_5 : maximum pressure in the torus port hole
- C_o : conductance of the grids
- C_N : conductance of the neutralizer
- C_2 : conductance of the diaphragm
- C_3 : conductance of the torus port hole
- Q_o : gas flow out of the source
- Q_N : desorbed gas flow in the neutralizer
- Q_G : desorbed gas flow in the first chamber
- Q_B : desorbed gas flow in the daiphragm
- Q_D : desorbed gas flow in the second chamber
- Q_T : desorbed gas flow in the torus port hole
- S_1 : effective pumping speed in the first chamber
- S_2 : effective pumping speed in the second chamber

Fig. 2: Species composition calculated for the sources used in the W7a neutral injectors /8/. The fraction refers to the electric power of the species.

Fig. 3: Neutral power into the torus vs. beam line length. Parameter is the source pressure, i.e., the beam composition.

Fig. 4: Maximum available power and optimum length as a function of the source pressure.

Fig. 5: Gas flow at maximum power into the two pumps as a function of the source pressure. Parameter is the distance between the neutralizer end and the diaphragm.

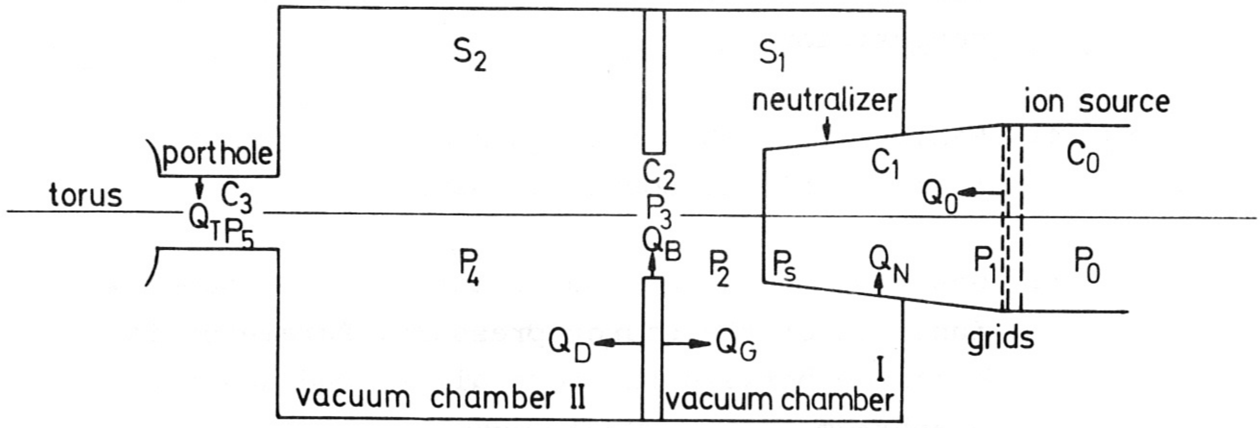
Fig. 6: Neutral power into the torus as a function of the source pressure for a beam line length of 150 cm.

Fig. 7: Neutral power into the torus as a function of the effective pumping speed in the second vacuum chamber. Parameter is the pumping speed of the first pump.

Fig. 8: Neutral power into the torus as a function of the desorption rate. All other quantities are kept fixed at the standard values.

Fig. 9: Neutral power into the torus as a function of the ion current. The maximum power is mainly determined by the reionization due to the increased desorption.

Fig. 10: Relation of the different "loss processes" in the W 7a injectors for the standard parameters.



Schematic drawing of the beam line model

Fig. 1

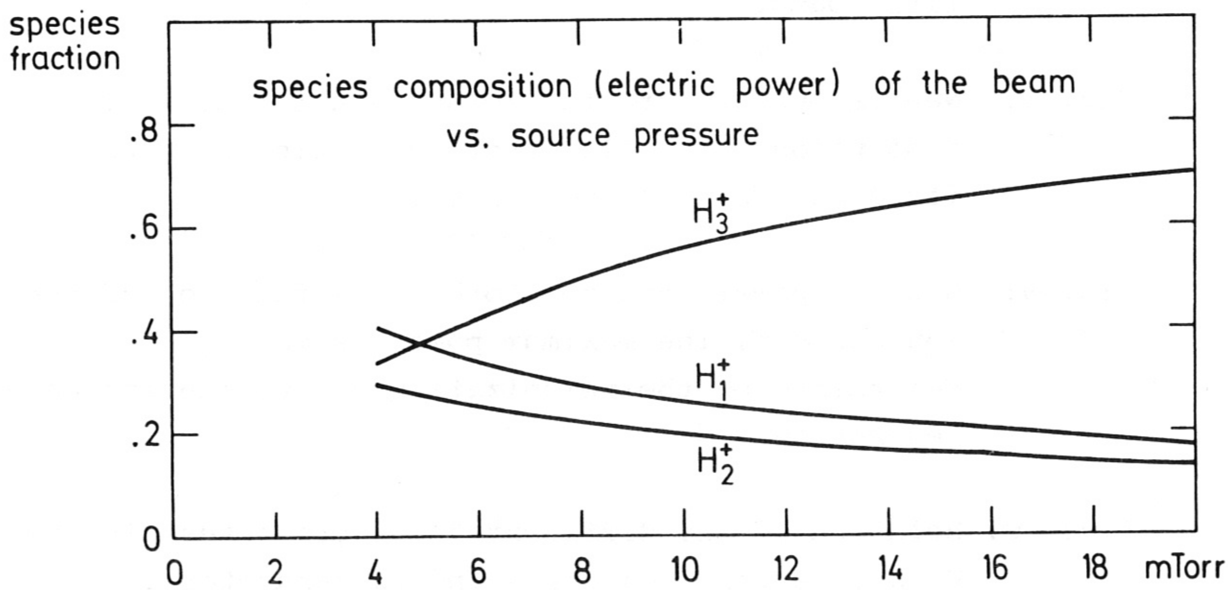


Fig. 2

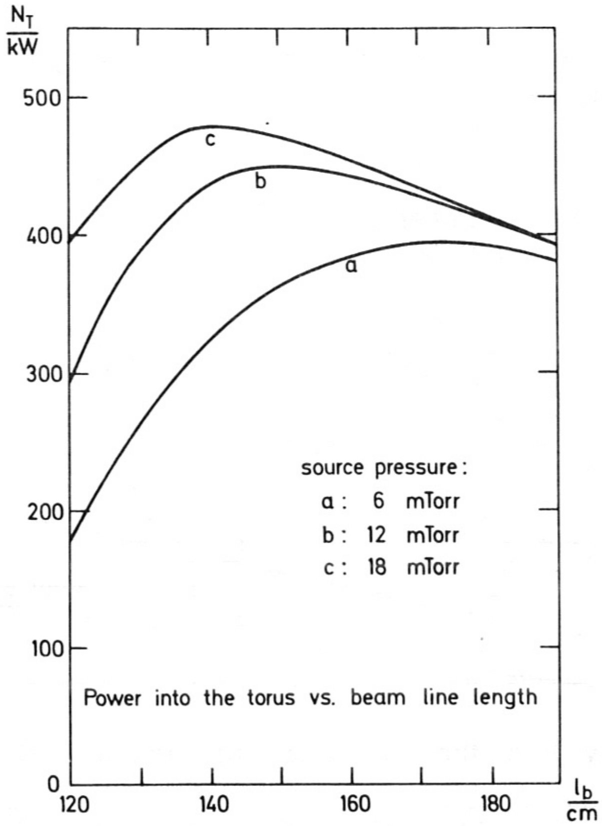

N_T / kW
500
400
300
200
100
0
120
140
160
180
l_b / cm
a
b
c
source pressure:
a : 6 mTorr
b : 12 mTorr
c : 18 mTorr
Power into the torus vs. beam line length

Fig. 3

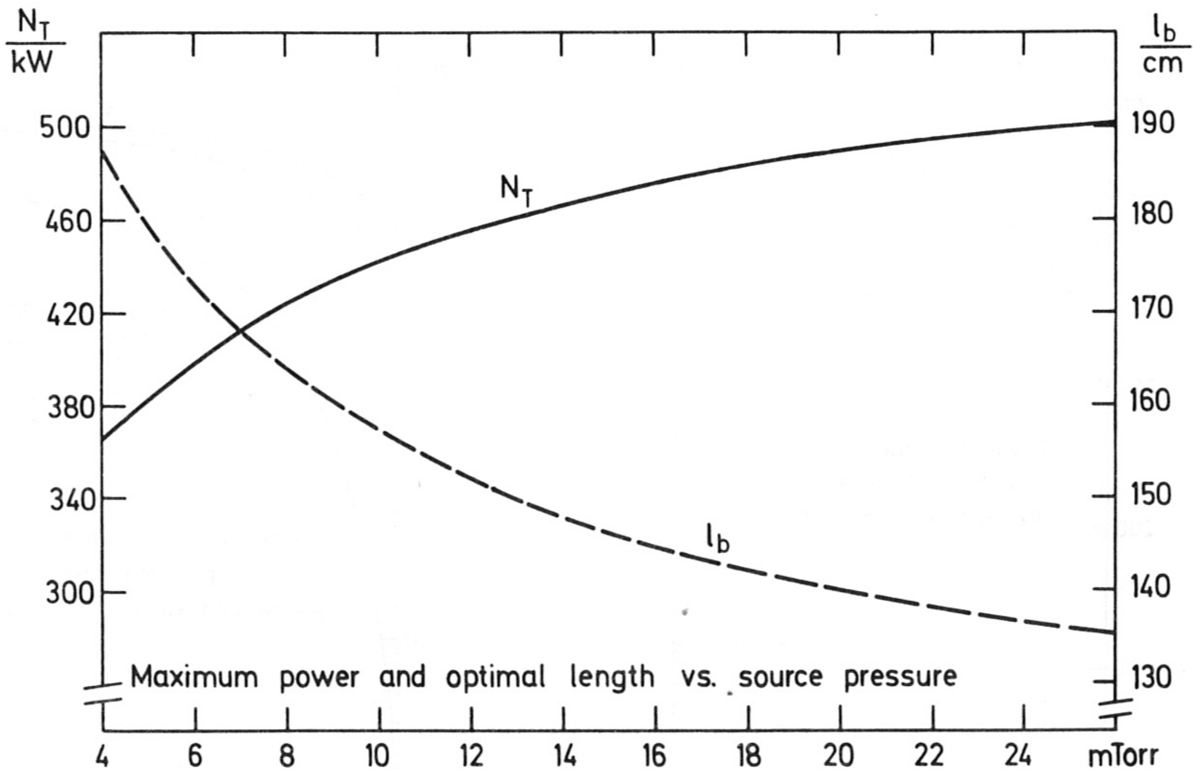

N_T / kW
500
460
420
380
340
300
l_b / cm
190
180
170
160
150
140
130
N_T
l_b
Maximum power and optimal length vs. source pressure
4
6
8
10
12
14
16
18
20
22
24
mTorr

Fig. 4

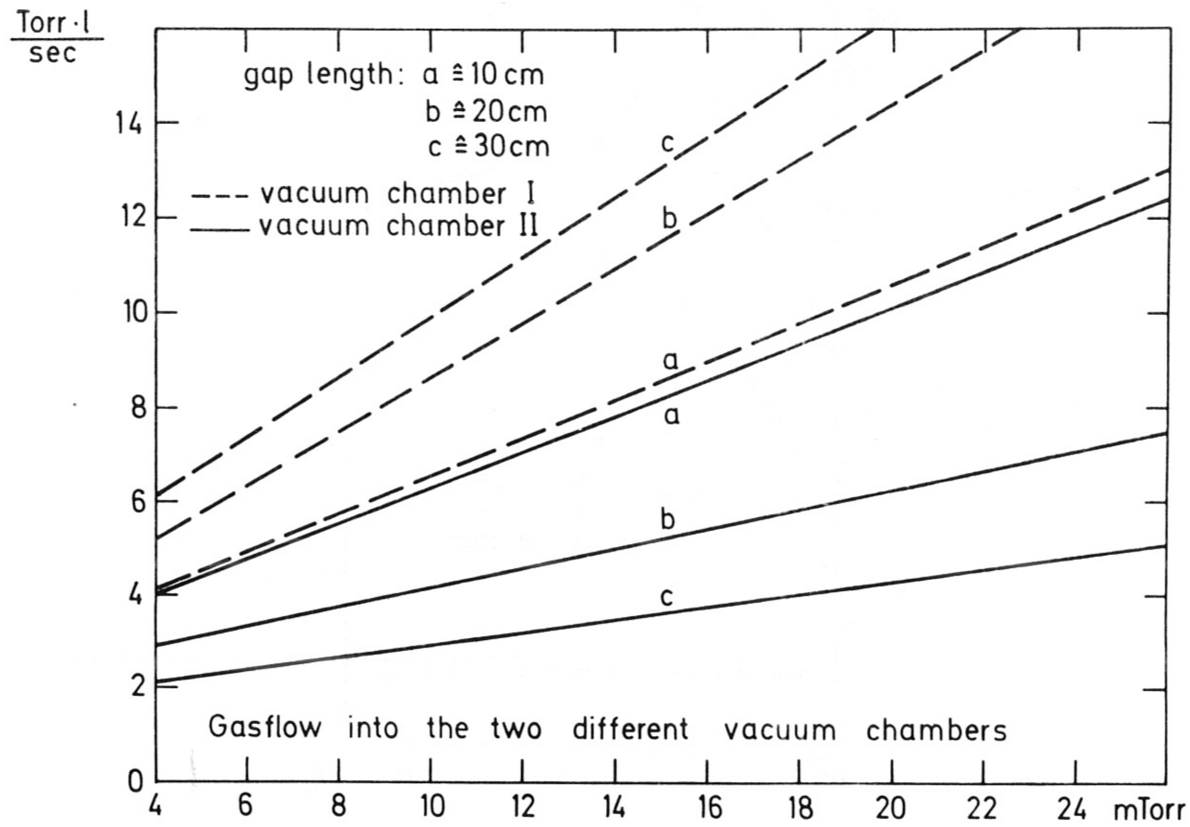


Fig. 5

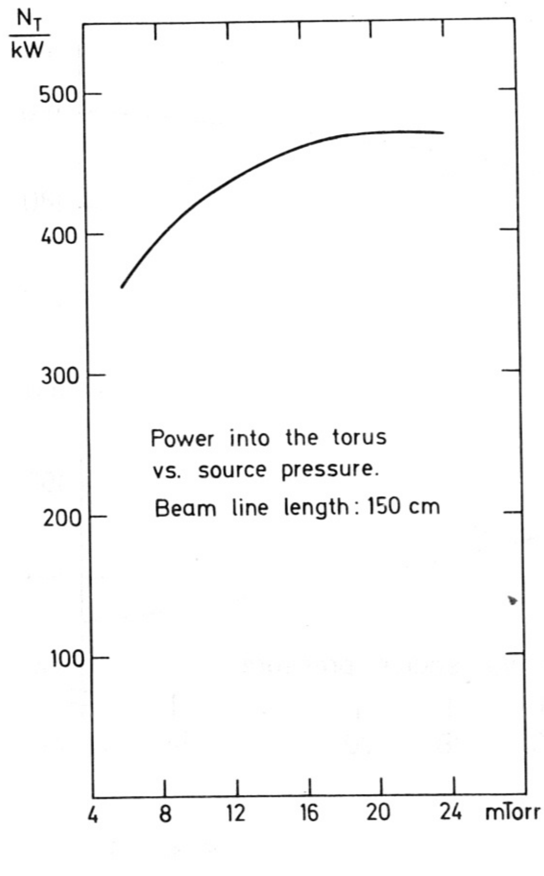


Fig. 6

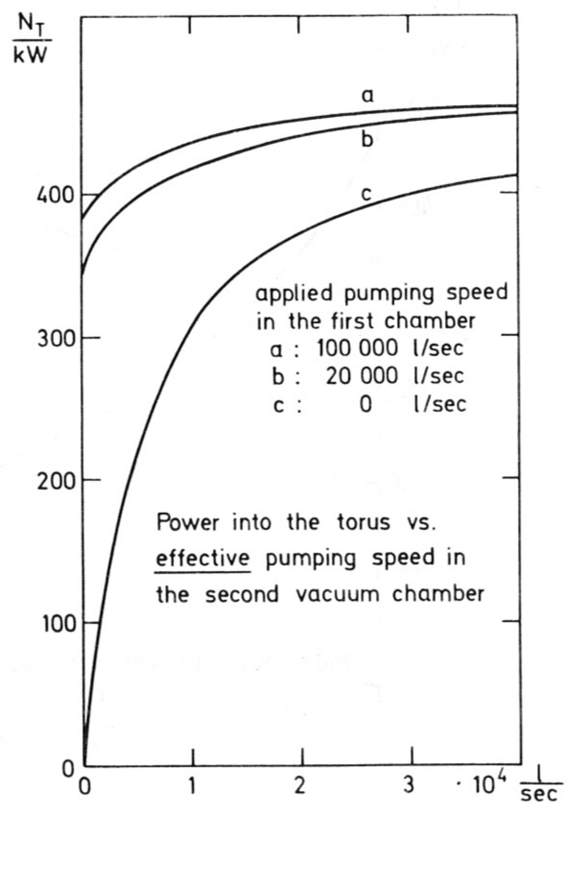


Fig. 7

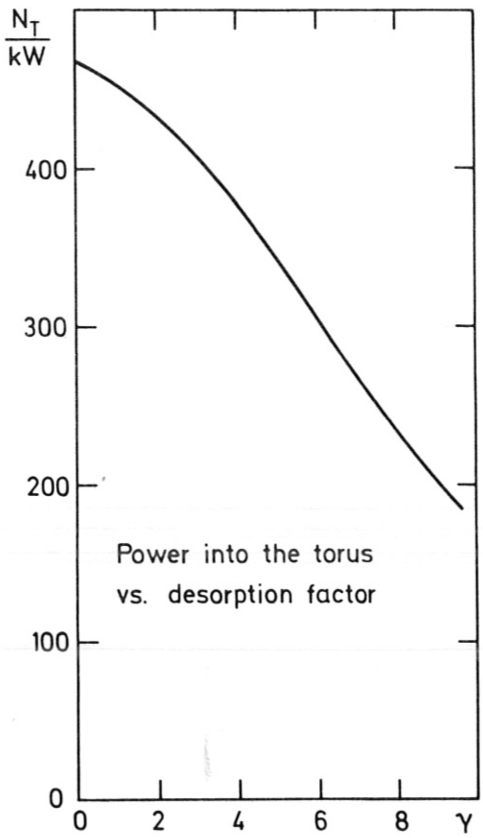


Fig. 8

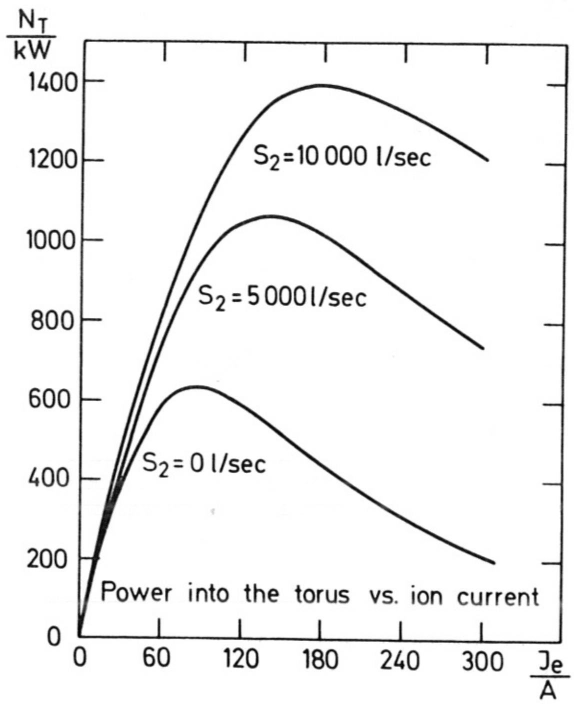


Fig. 9

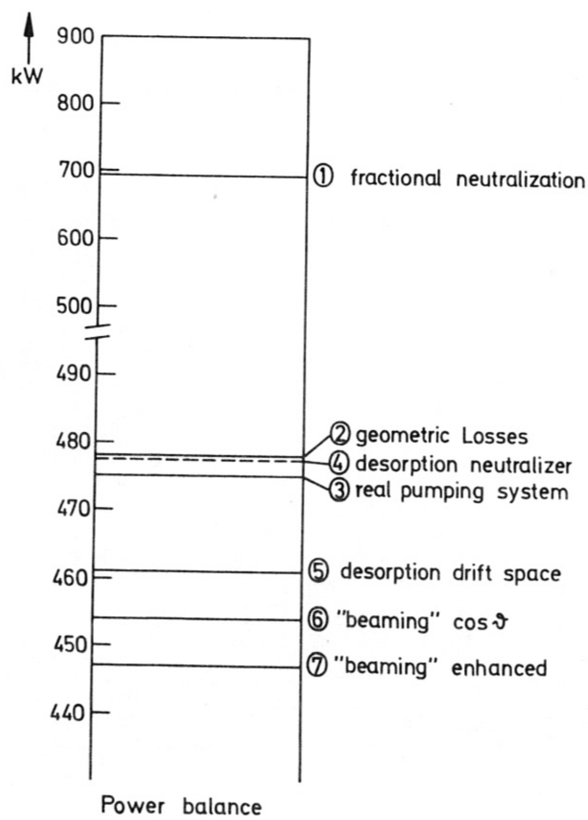


Fig. 10