VACUUM FOR CYCLOTRON BEAM TRANSPORT LINES

J. PIVARČ*

Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions
Dubna, Head Post Office, P.O. Box 79, 101 000 Moscow, Russia

The main vacuum relations as a basic for understanding the vacuum system configuration of cyclotron beam transpot lines are given. The effects of gas desorption on vacuum equilibrium and stability are also summarized. One self - neutralization model of beams by ionization of the residual gases in cyclotron beam transport lines is discussed.

1 Introduction

The vacuum system for the beam transport line of the cyclotron is one of the main components of the transport line. The required operating pressure range for the vacuum system of the cyclotron beam transport line is 10^{-4} - 10^{-9} Pa. Basically, it consists of stainless steel and copper. The beam tubes are pumped with turbomolecular, cryosorption, getter - Ti - sublimation, NEG pumps combined with sorption and rotary pumps. Other suitable combinations of the vacuum pumps as well as the pressure measuring gauges are shown in Figure 1.

This paper reports in detail scaling relationships used in the vacuum system design of the cyclotron beam transport lines as well as gas desorption processes influencing the beam transport in the cyclotron beam pipes.

Detailed discussion on the self - neutralization process for the cyclotron beam transport technology is given. It includes an analysis of electron production and loss in a plasma potential distribution.

2 Scaling relationships

The highest obtainable average pumping speed of the beam transport line vacuum system of the cyclotron strongly depends on the beam pump conductance. To illustrate this important limitation caused by the finite conductance, let us consider the system shown in Figure 2. In the molecular flow regime the flow of molecules along the vacuum pipe to the nearest pump is expressed by the equation

$$Q(x) = -w\frac{dp}{dx} \qquad \frac{dQ}{dx} = Aq \tag{1}$$

where Q is the gas flow (Pa m^3 s^{-1}), w is the specific molecular conductance (m^4 s^{-1}) (w = LC), C is the conductivity (m^3 s^{-1}), p is the pressure inside the pipe (Pa), A is the specific surface area (m) (A = F/L), F is the surface area (m^2) and q is the specific outgassing rate (uniform) (Pa m s^{-1}). These equations can be combined to give

$$w\frac{d^2p}{dx^2} = -Aq \tag{2}$$

together with the boundary conditions of this simple problem

$$\left.\frac{dp}{dx}\right|_{x=L/2} = 0 \quad \text{and} \quad p|_{x=0} = \frac{AqL}{S} \tag{3}$$

which follow from the evident symmetry considerations. As the solution we can find a well known parabolic pressure profile along the beam pipe

$$p(x) = Aq\Big(\frac{Lx - x^2}{2w} + \frac{L}{S}\Big). \tag{4}$$

The maximum pressure occurs at the midpoint between pumps

$$p_{max} = Aq\Big(\frac{L^2}{8w} + \frac{L}{S}\Big). \tag{5}$$

For the beam pipe the average pressure is more relevant

$$p_{av} = \frac{1}{L}\int_0^L p(x)dx = Aq\Big(\frac{L^2}{12w} + \frac{L}{S}\Big). \tag{6}$$

* Permanent address: Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, SK-842 28 Bratislava, Slovak Republic.

and

$$C_2 = \frac{AqL}{S}(1+e^{-rL})^{-1}.$$

Usually, the vacuum system is designed with respect to s≪w. In this configuration one can obtain

$$C_1 \cong C_2 \cong C_o = \frac{Aq}{2}\frac{L}{S}. \qquad (10)$$

The equation (9) is reduced to

$$p(x) = C_o(e^{rx} + e^{-rx}) + \frac{Aq}{s} \qquad (11)$$

and the average pressure is determined by

$$p_{av} = \frac{C_o}{rL}(e^{rL} - e^{-rL}) + \frac{Aq}{s} \cong \frac{2AqL}{S}. \qquad (12)$$

It is evident that the lowest achievable pressure depends only on the ratio of 2AqL/S[1].

3 Desorption of gases

The pressure from 10^{-4} - 10^{-9} Pa must be maintained inside the cyclotron beam transport lines and its beam pipe in despite of:

- The thermal outgassing of surfaces;
- Outgassing due to the desorption of weakly bound molecules on the walls of the vacuum system;
- The ions induced by extracted and accelerated ions;
- The diffusion of hydrogen from the walls of the vacuum system;
- The neutral gas produced inside the transport beam lines;
- The desorption of molecules generated by hard X - ray bremstrahlung.

To establish the required pressure for a given pumping speed the average thermal outgassing rate and the total average desorption rate must be below certain definite values[1].

4 One self - neutralization model of beam

One self - neutralization model of beam has also been published in the papers[2-3]. It is assumed that the electron production is due mainly to collisions between beam ions and gas atoms and electron loss is to be due to scattering out of the potential well of the beam. It holds that the electron production rate is given by

$$\frac{dn_e}{dt} = n_i n_o \sigma_{io} v_i \qquad (13)$$

and the electron loss rate is given by

$$\frac{-dn_e}{dt} = \frac{n_e}{\tau} e^{\frac{-\phi}{T}} \qquad (14)$$

where n_i is the ion density of the beam, n_o is the neutral density, σ_{io} is the cross section for ionization of the atoms by the beam ions, v_i is the beam ion velocity, n_e is the electron density, τ is the time for scattering of electrons by the ions in the beam, ϕ is the plasma potential (eV) and T is the electron temperature (eV).

The energy input is estimated from the heating rate of the electrons by the beam ions being $n_e m_e v_i^2/2\tau$ where m_e is the electron mass. Hamilton[2] calculated the energy loss from the system by means of the ionization cross section σ_{io}, by the charge exchange cross section σ_x and by the transport potential energy ϕ from the system. He derived for the energy loss a rate of $n_i n_o v_i(\sigma_{io} + \sigma_x)\phi$ for the energy loss.

Finally, it is assumed that the beam ion density n_i is approximately the same as the electron density n_e, i.e. $n_e \approx n_i$. The effect of slow ions is also neglected completely. Afterwards the two equations for particle and power balance can be reduced to the form

$$n_o \sigma_{io} v_i = \frac{1}{\tau} e^{\frac{-\phi}{T}} \qquad (15)$$

and

$$n_o(\sigma_{io} + \sigma_x) v_i \phi = \frac{m_e v_i^2}{2\tau}. \qquad (16)$$

Further $W = \frac{Mv_i^2}{2} = eV$ where eV is the energy and M is the mass of ions, respectively. Hence

$$\frac{\phi}{T} = 2.3 log\left(\frac{M}{m_e}\frac{\phi}{eV}\frac{\sigma_{io} + \sigma_x}{\sigma_{io}}\right). \qquad (17)$$

For typical parameters of the hydrogen beam at energy W = 10 keV and pressure p = 10^{-4} Pa

$J = 0.1$ mA cm^{-2}	$v_i = 1.4 \times 10^8$ cm s^{-1}
$n_i = 4.46 \times 10^6$ ions cm^{-3}	$n_o = 2.645 \times 10^{10}$ cm^{-3}
$\sigma_{io} = 0.2 \times 10^{-16}$ cm^2	$\sigma_x = 4.3 \times 10^{-16}$ cm^2

is the ratio

$$\frac{\phi}{T} = 10.622 + 2.3 log(\frac{\phi}{T}). \qquad (18)$$

One can see that the potential $\phi \approx 7.9$ eV for the temperature of electrons $T_e = 0.6$ eV.

The electrons produced by ionization have, in general, a finite energy of several volts which must contribute to the energy input. If $\sigma_{io} \rightarrow 0$ and $\sigma_x \rightarrow \infty$ the energy transported away from the system by the cold ions comes from the beam ions directly but not from the electron gas.

The assumption of quasi - neutrality is also conserved when the beam density J is introduced for $n_i \approx n_e$ by equation

$$J = 0.5 n_e m_e v_i^3 \left(\frac{\sigma_{io}}{\sigma_{io} + \sigma_x}\right) \frac{e^{\phi/T}}{\phi}. \tag{19}$$

In order to illustrate results by the last equation Figure 4 and Figure 5 are shown.

The maximum derived beam potential energy ϕ is 8 eV at the different electron energies T and the different mean current densities. It is also seen a maximum of the density J at the electron temperature T = 0.6 eV and the beam potential $\phi = 1$ eV. Definite maximum exists also at the higher electron energies but it is shifted to the higher values of the potential Φ.

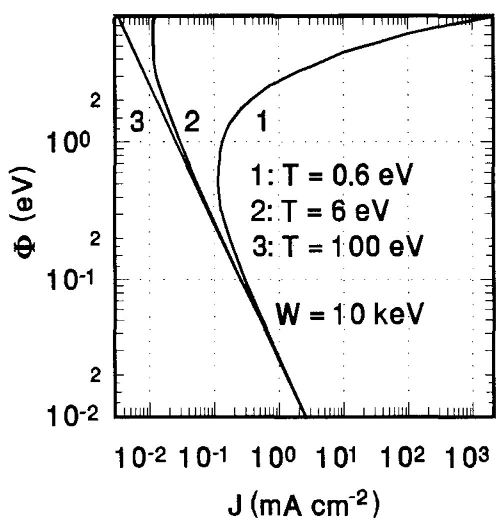

Figure 4: Mean current density J as a function of beam potential ϕ for three different electron temperatures T (T = 0.6, 6 and 100 keV) at energy of protons W = 10 keV.

If we considere only the losses due to collisions between beam ions and residual gas atoms and electron losses which are to be due to scattering out of the potential well of the beam, the losses of ions can be given by

$$\frac{-dn_i}{dt} \le 79.240 n_e p \frac{(\sigma_{io} + \sigma_x)\phi}{m_e v_i} e^{\frac{-\phi}{T}} \tag{20}$$

where the ϕ is the plasma potential (eV), T is the electron temperature (eV), p is the pressure of residual gas (Pa) at the ambient temperature of 20 °C and other quantities are in SI units. Using just this ratio one can see the linear dependence of the ion losses of the pressure p.

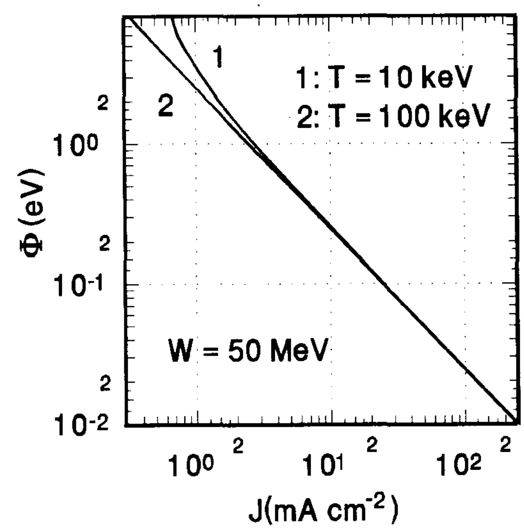

Figure 5: Mean current density J as a function of beam potential ϕ for two different electron temperatures T (T = 10 and 100 keV) at energy of protons W = 50 MeV.

The complete discussion of the self - neutralization process for the beam transport technology is complicated. It must include not only an analysis of electron production and loss in a completely self - consistent potential distribution, but also it has to include beam fluctuations, magnetic fields and three dimensional variation of the beam density.

5 Conclusion

The present work describes not only the scaling relationships used at the construction of the cyclotron beam transport line vacuum systems but also provides the new data in the region of the self - neutralization beam process.

References

1. J. Pivarč, J. Vac. Sci. Technol. **A12(5)**, 2716 (1994).
2. G.W. Hamilton, Proc. of Symp. of Ion Sources, Brookhaven BNL 50310, 171 (1971).
3. T.S. Green, Reports on Progress in Physics **37**, 1257-1344 (1974).