BEAM LOSS DUE TO THE CHARGE EXCHANGE WITH THE RESIDUAL GAS IN THE FLNR HEAVY ION CYCLOTRONS

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Abstract

A simulation program was developed to calculate the pressure distribution and the beam loss due to the charge exchange cross section in the FLNR heavy ion cyclotrons. A series of measurements was carried out to evaluate the beam loss. These measurements and the pressure distributions were compared with the program results.

1 INTRODUCTION

The compact type cyclotrons U-400 and U-400M provide accelerated heavy ion beams (with ion charge-to-atom mass ratio z/A from 0.03 to 0.2 for U-400 and from 0.1 to 0.5 for U-400M and over a wide range of energy per nucleon up to 20 MeV/amu and 100 MeV/amu respectively). At present, these two cyclotrons are being equipped with ECR ion sources and axial injection systems [1]. Previously PIG ion sources were used, which can now be used as alternative sources for the U-400 cyclotron. The loss of the intensity of the beam due to its charge-changing collisions with the residual gas molecules is determined by the cross sections for the loss process over a wide range of energy and depends on the pressure distribution in a cyclotron. The average pressure inside the cyclotron is a function of the vacuum chamber's conductivity, the pumping speed of the pumps, the gas loading from the internal ion source such as a PIG source and the outgassing. Five oil diffusion pumps (both for the U-400 and for the U-400M cyclotron) with a total pumping speed of 20000 l/s are used in order to provide an average pressure of $(0.5\div1)\cdot10^{-6}$ Torr inside each cyclotron.

The computer simulation program VACLOS using EXCEL has been developed to determine the beam loss caused by the charge-changing collisions between various heavy ions and residual gas molecules in a cyclotron. This program includes the following main parts:

– the determination of the pressure distribution inside the cyclotron;

– the evaluation of the ion charge changing cross section;

– the calculation of the transmission factor for different ion beams.

2 RADIAL PRESSURE DISTRIBUTION

The total gas loading in the cyclotron vacuum chamber involves the following main components:

– the working gas flow from the internal ion source (usually for a PIG source, $Q\cong(3\text{-}6)\cdot10^{-3}$ Torr·l·sec^{-1} for Xe or Kr working gas and $Q\cong(6\text{-}9)\cdot10^{-3}$ Torr·l·sec^{-1} for Ar or N_2),

– the thermal outgassing from the surfaces of the constructional materials (the specific static outgassing $q\cong1\cdot10^{-5}$ Torr·l·sec^{-1}·m^{-2} in the steady state),

– the atmospheric gas flow through the micro-defects in the vacuum chamber (it was found experimentally to be no more than 10% of the thermal outgassing [2]).

We can disregard the ion stimulated desorption, because in the optimal regime of beam focusing it is significantly less than the thermal outgassing for ion beam intensities of $1\cdot10^{11}\div1\cdot10^{15}$ s^{-1}.

For the case of the cyclotron geometry with azimuth symmetry and an internal gas flow inside the cyclotron, the pressure profile is expressed by the equation:

$$P(r) = P_0 + \frac{Q}{G_{R-r}}, \qquad (1)$$

where $P_0=P(R)$ is the pressure at the pump's positions, Q is the gas flow rate due to the ion source, G_{R-r} is the gas flow conductivity, R is the vacuum chamber radius.

The radial gas flow conductivity inside the vacuum chamber of the cyclotron can be obtained from the Knudsen formula:

$$G_{R-r} = \frac{4}{3}\nu_a \frac{1}{\int_r^R \frac{\Pi(x)}{F^2(x)}dx}, \qquad (2)$$

where ν_a is the molecular average thermal velocity, Π, F are the perimeter and cross section of the azimuth periodic segment (hill and valley of the magnet poles) of the vacuum chamber.

From equations (1) and (2), we can get the pressure profile resulting from the gas loading of the internal ion source:

$$P(r) = P_0 + \frac{3nQ}{2\pi\nu_a}\frac{1}{h^2}\left[\ln\frac{R}{r} + \frac{nh(R-r)}{\pi Rr}\right], \qquad (3)$$

where n is the number of the pole sectors, h is the axial gap between the magnet poles.

The pressure produced by the thermal outgassing is presented by:

$$P'(r) = P'_0 + \int_r^R \frac{q\Pi}{G'_{R-r}}dx + \frac{1}{G'_{R-r}}\int_0^r q\Pi dx, \qquad (4)$$

where q is the specific static outgassing, and P_0 or P_0' is the pressure at the pump's position.

Equation (4) leads to:

$$P'(r) = P_0' + \frac{3nq}{\pi h^2 \nu_a}\Bigg[\frac{\pi}{4n}\left(R^2 - r^2\right) + $$
$$+ \frac{3}{2} h(R - r) + \frac{nh^2}{\pi} \ln\frac{R}{r} \frac{\pi}{2n} R_0^2 \ln\frac{R}{r} -$$
$$- hR_0 \ln\frac{R}{r} - \frac{hR_0^2(R - r)}{2Rr} -$$
$$- \frac{nh^2 R_0(R - r)}{\pi R r}\Bigg] \qquad (5)$$

where r changes from R_0 to R'.

Then the average pressure in the periodic segments (hill, valley and regarding the dee's position) of the vacuum chamber was calculated. The results are in good accordance with the previous measurements [3].

The intervals of working pressure for the U-400 cyclotron equipped with either an ECR or a PIG ion source are presented in Figure 1.

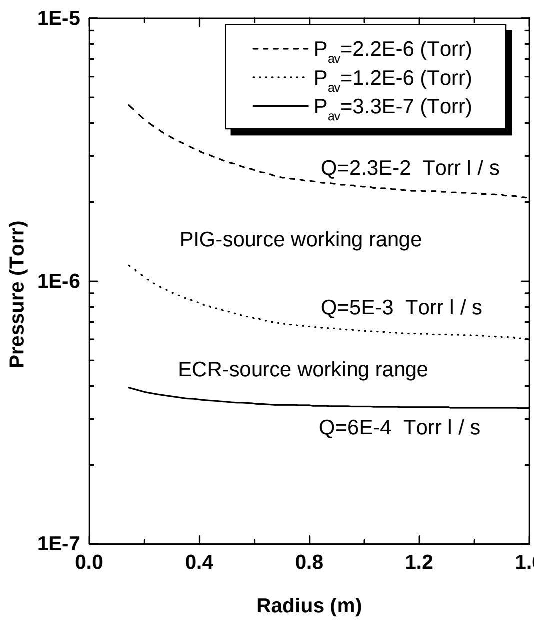

Figure 1: The calculated radial pressure distribution for the U-400 cyclotron, being equipped with an ECR or a PIG ion source, at the corresponding average pressure at the extraction radius R=160 cm ($q = 1\cdot10^{-5}$ Torr·l·sec^{-1}·m^{-2}) for $_{14}$N beams.

3 ION BEAM LOSS

In the case of beam losses due to the charge exchange between the ions and the residual gas the transmission efficiency T of an accelerator over pathlength L is:

$$T = \exp\left\{- 3.3 \times 10^{16} \int_0^L P(\ell)\sigma(\beta) \cdot d\ell\right\}, \qquad (6)$$

where P is the pressure in Torr, $d\ell$ is an element of the pathlength in cm, β is the relative velocity (v/c) and σ is the sum of all the relevant capture and loss cross-sections in cm^2/molecule.

Several analytical and semi-empirical models [4-9] have been applied to the calculation of the cross-sections, and, obtained as a result, the transmission factors of every model were compared with the experimental data on the vacuum losses of accelerated heavy ions in the U-400 and U-400M cyclotrons.

The best accordance with the experimental data has been found for the joint model of the two following models :

$$\text{I.} \qquad \sigma_C = 2 \times 10^{-15} z^2 (137\beta)^{-5} \qquad (7)$$

$$\sigma_L = 2 \times 10^{-15} (1 + z)^2 (137\beta)^{-5} \times \times \exp\left(- \frac{2(z - \overline{z}) + 1}{2d^2}\right) \qquad (8)$$

Where the mean charge value $\overline{z}$ is approximated by $\overline{z} = Z_p\left\{1 - C \cdot \exp(- 137\beta\delta)\right\}$, C≅1 has a very weak dependence on the atomic number Z_p, $\delta = 0.3443 - 0.0667 \ln(Z_p)$ and the standard deviation is given by $d = 0.27\sqrt{Z_p}$ in a residual gas such as N_2 or

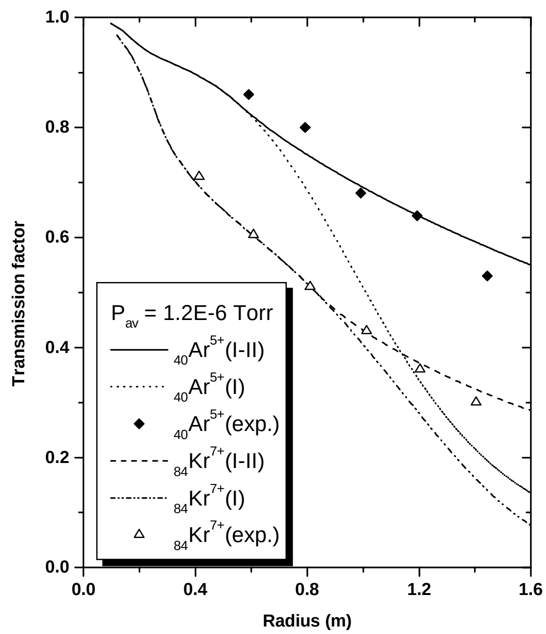

Figure 2: The transmission factor for the cyclotron equipped with a PIG ion source, calculated in accordance with the two models (joint I-II and I), as compared with the experimental data for accelerated ions $_{40}Ar^{5+}$ (up to 9 MeV/amu, Q=6.5·10^{-3} Torr·l·s^{-1}) and $_{84}Kr^{7+}$ (up to 4 MeV/amu, Q=6·10^{-3} Torr·l·s^{-1}) at an average pressure of P_{av}=1.2·10^{-6} Torr (considering radial pressure distribution) at the extraction radius R=160 cm.

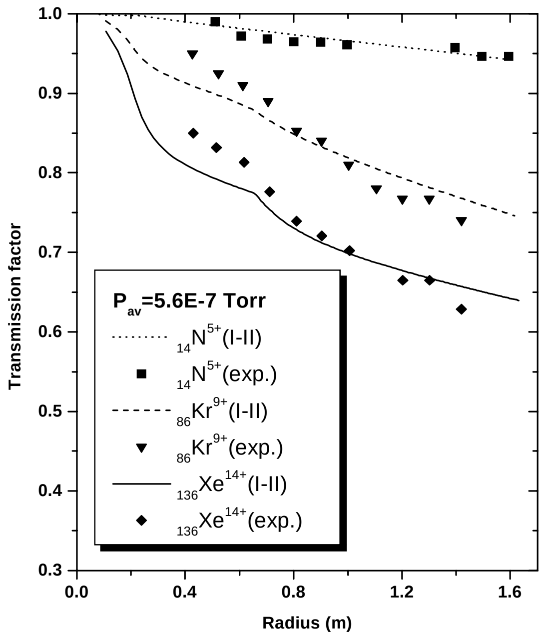

Figure 3: The transmission factor for the cyclotron equipped with an ECR ion source, calculated in accordance with joint model I-II, as compared with the experimental data for accelerated ions $_{86}Kr^{9+}$ (up to 6 MeV/amu) and $_{136}Xe^{14+}$ (up to 6 MeV/amu) in the U-400 cyclotron and $_{14}N^{5+}$ (up to 53 MeV/amu) in the U-400M cyclotron at an average pressure of $P_{av}=5.6\cdot10^{-7}$ Torr (considering radial pressure distribution) at the extraction radius R=160 cm.

air [4];

II. $$\sigma_C \cong 3 \times 10^{-28} z^{5/2} \beta^{-7} \quad (9)$$

$$\sigma_L \cong 9 \times 10^{-19} z^{-2/5} \beta^{-2} \quad [5]. \quad (10)$$

In the joint (I-II) model we used the first (I) model for ions energy up to 1.5 MeV/amu and the second (II) model for higher energy. For other residual gases except N_2 we used this joint model for cross section calculation with a factor of $\sqrt{M / M_0}$, where M / M_o is the ratio between the molecular masses of the gas and N_2.

Such an approach allowed us to obtain quite satisfactory accordance with the experimental data as shown in figures 2-3. Figure 2 also shows the comparison between the two models. Figure 4 represents the examples of the estimations based on the joint (I-II) model for the acceleration of $_{40}Ar^{5+}$ up to 9 MeV/amu and $_{84}Kr^{7+}$ up to 4 MeV/amu in the U-400 cyclotron and $_{14}N^{5+}$ up to 53 MeV/amu in the U-400M cyclotron.

4 CONCLUSION

The above described vacuum loss simulation program VACLOS allows one to estimate quite satisfactorily the transmission factors of any accelerated ions in a wide range of ion energy and gas loading in different operation regimes both with an ECR and with a PIG ion source, that is important for analyzing and forecasting the efficiency of a cyclotron with the definite vacuum system.

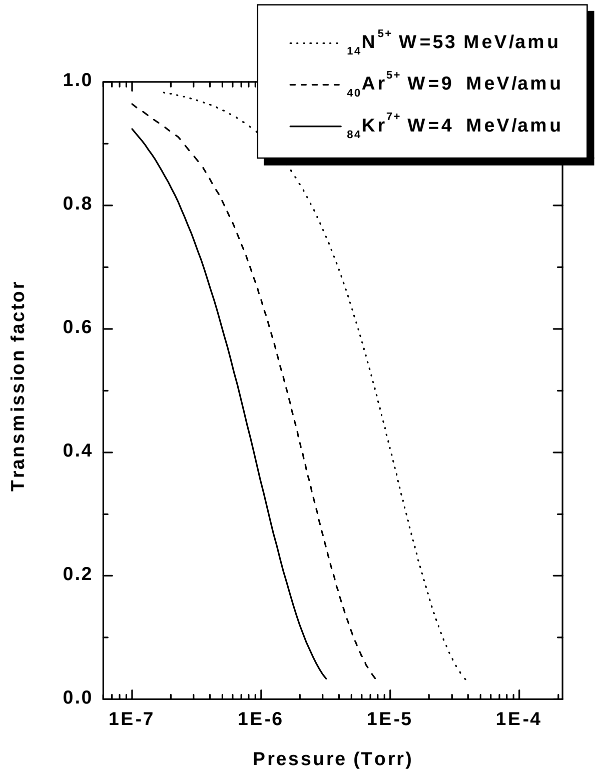

Figure 4: The transmission factor calculated by the joint I-II model versus the average pressure at the extraction radius R=160 cm for accelerated ions $_{40}Ar^{5+}$ (up to 9 MeV/amu) and $_{84}Kr^{7+}$ (up to 4 MeV/amu) in the U-400 cyclotron and $_{14}N^{5+}$ (up to 53 MeV/amu) in the U-400M cyclotron.

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