CHARGE EXCHANGE LOSSES DURING CYCLOTRON ACCELERATION: EXPERIMENT AND THEORY

R. A. Gough* and M. L. Mallory**

Abstract

Quantitative estimates of charge exchange (CE) losses during acceleration are very important in the design and operation of heavy ion cyclotrons. Such estimates have been made using a vacuum model computer code which was developed to establish vacuum requirements for the MSU superconducting heavy ion cyclotron. This code uses pressure and cross-section data to calculate the radial loss of beam due to charge exchange. Since CE cross sections and radial pressure profiles are not always well known, certain specific measurements have been made using the LBL 88-Inch Cyclotron to provide experimental data needed to test the code. These include measurements of pressure versus radius under vacuum conditions closely approximating those existing during acceleration of $^{14}N^{4+}$ and $^{40}Ar^{8+}$ beams. Beam intensity versus radius data demonstrating transmission losses for three beams are presented. Comparisons with theoretical predictions are given.

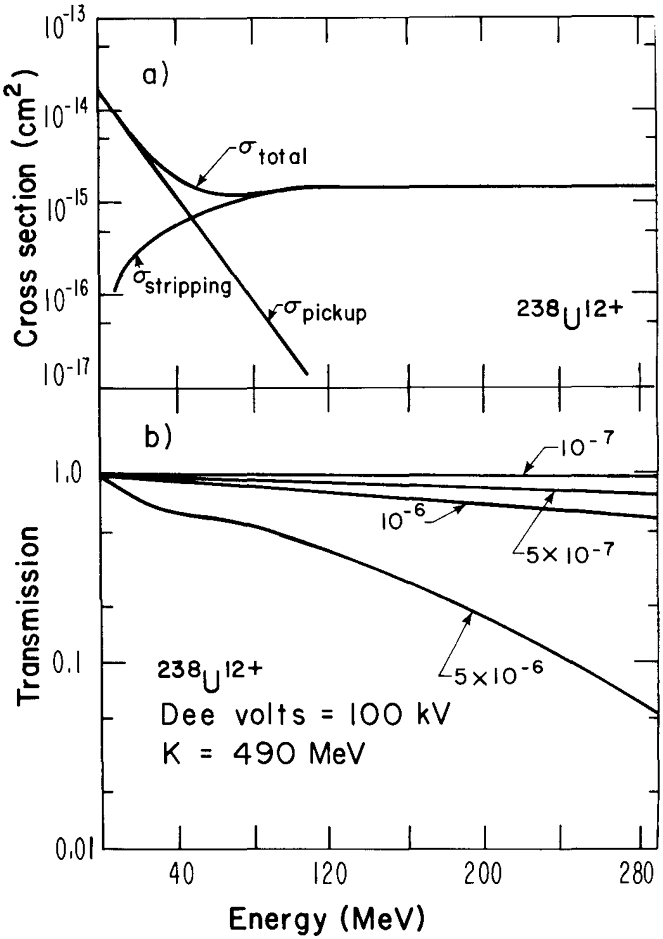
Introduction

The vacuum requirements for heavy ion acceleration in cyclotrons in the past have depended primarily upon the experimental measurements of beam attenuation data and the associated problems of data interpretation. A preferable approach is the construction of a theoretical model that calculates the necessary vacuum requirements for any beam desired. In recent years, advances in theory and experimental measurements of charge exchange loss cross sections have made it possible to construct such a vacuum model for heavy ion cyclotron acceleration. However, many simplifying assumptions are made in the model and a check upon the model validity versus the experimental beam attenuation results is required. The following sections contain a brief outline of the vacuum model, experimental descriptions of the 88-Inch Cyclotron equipment used for vacuum measurements, followed by comparison of calculated attenuation losses with experimental results observed on the 88-Inch Cyclotron in Berkeley.

Heavy Ion Vacuum Model

Transmission of a heavy ion beam through a cyclotron is generally described by the function $\exp(-\sigma px)$ where σ is the charge exchange cross section, p is the pressure and x is the path length. The CE losses for heavy ion acceleration are composed of charge pickup and charge stripping processes (i.e. $\sigma = \sigma_p + \sigma_s$). The charge pickup process dominates at low energy. No theoretical model of charge pickup cross section as a function of energy (relevant to cyclotrons) exists. Recently Olson and Salop[1] have developed theoretical equations for charge pickup at very low energy, i.e. essentially zero energy for cyclotrons. Another cross section data point for charge pickup can now be obtained from a different kind of experimental data. Namely, Betz[2] has derived an empirical equation for relating the energy at which the accelerated ion of charge q is in equilibrium with the charge pickup and charge stripping processes. Hence, at that energy the charge pickup cross section is equal to the charge stripping cross section and this value can be obtained from the Bohr-Leinhardt equation.[3] It is then assumed that the pickup cross section between these two points is given by $\sigma_p(E) = \sigma_p(E{=}0)\, e^{-\gamma E}$, where σ_p is the pickup cross section, E is the energy, γ is the constant for the two pickup cross section points described above. Examination of experimental cross section data with this assumption reveals good agreement.

The charge stripping cross section has used the Bohr-Leinhardt equation,[3] with the loss cross section set constant after the ion velocity exceeds the outer electron velocity of the accelerated particle. An example of the cross section calculated from this model is shown in Figure 1(a) for $^{238}U^{12+}$.



XBL 789-1779

Fig. 1. a) The theoretical loss cross section for $^{238}U^{12+}$ is shown. It is composed of a low energy portion due to charge pickup, and a high energy portion due to charge stripping. b) The transmission of $^{238}U^{12+}$ through a K = 490 MeV, 3-dee cyclotron is shown for various pressures. Greater than 90% will be transmitted for a pressure of 10^{-7} Torr.

---

* Present address: Lawrence Berkeley Laboratory
Berkeley, California 94720

** Present address: Michigan State University
East Lansing, Michigan 48824

0018-9499/79/0400-2384$00.75 ©1979 IEEE

The transmission of the particles thru the accelerator is numerically calculated for each turn assuming circular orbits. Input parameters are the dee angle, dee voltage, number of dees, the rf harmonic number and the cyclotron K value. The pressure is assumed to be constant and the calculations are done for a series of pressure values. Figure 1(b) shows the transmission results for $^{238}U^{12+}$ in a K = 490 MeV cyclotron with three dees for various pressures. These calculations indicate that for pressures better than 5×10^{-7}, more than 75% of the $^{238}U^{12+}$ beam will be transmitted from the center region to the point of extraction.

Pressure Measurements at the 88-Inch Cyclotron

The Berkeley 88-Inch Cyclotron has a 25,000 ℓ main vacuum chamber consisting of an accelerating region or dee tank and a large volume RF resonator tank. The schematic in Fig. 2 indicates the location of four LN$_2$-trapped diffusion pumps; two in the dee tank and two in the resonator tank. Also shown is a cryogenic pumping surface (0.39 m^2 at ~20°K) which was in operation during all of the measurements reported here.

The total pumping speed on the acceleration chamber is calculated to be 15,000 - 20,000 ℓ/s. The pumping speed inside the dee is significantly lower than on the dummy dee side. Rates-of-rise measurements indicate the total tank leak rate to be typically 0.02 Torr-ℓ/s.

There are many problems associated with determining the pressures at various points within the accelerating region under operating conditions. For example, at the 88-Inch Cyclotron both the pressure and the sensitivity of the tank ion gauges exhibit a small dependence on the main magnet field strength. The compression on the main seal increases with increasing magnetic field, reducing the leak rate through the metal gasket. Magnetic shielding is utilized where practical to minimize the effects of stray field on the ion gauges. There is, nevertheless, an apparent vacuum improvement of up to 20% due to the combined effects of the magnetic field. Another problem is the location and type of vacuum measuring gauges and gas loads entering the acceleration chamber. Figure 2 indicates the location of a vacuum analyzer and five ionization gauges, four of which are used in normal operation. Ion gauges designated IG02 and IG03 as well as the vacuum analyzer are located on the RF resonator tank, considerably removed from the accelerating region. IG02 is an LN$_2$-trapped gauge. IG06 is very close to the cryopanel and its reading when the cryopanel is operating is therefore lower than the pressure encountered by the beam. IG10 is a nude gauge and perhaps provides the best single measurement of the pressure at the beam platter during normal operation.

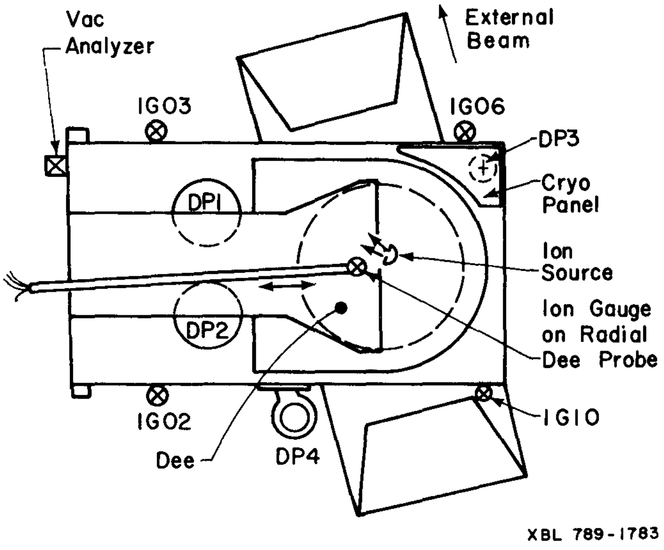


Fig. 2. Plan view schematic of the Berkeley 88-Inch Cyclotron showing the location of pumps and vacuum gauges. The ion gauge on the radial dee probe was used for measuring the pressure inside the dee.

In order to estimate the pressure within the dee, where the pumping speed is the most limited, a VG1A type ion gauge was mounted on a remotely controlled dee probe shaft (see Fig. 2) of the type normally used to obtain intensity vs radius data. Figure 3 shows the radial pressure profiles obtained under various ion source gas flow rates of argon and nitrogen. Since, for these tests, neither the main field nor the ion source arc was on, the indicated flow rate of gas into the source represents the actual flow of gas into the accelerating chamber. When the source is operating, not all of the indicated gas flow enters the accelerating region - a substantial fraction is "pumped" by the source itself. Recent

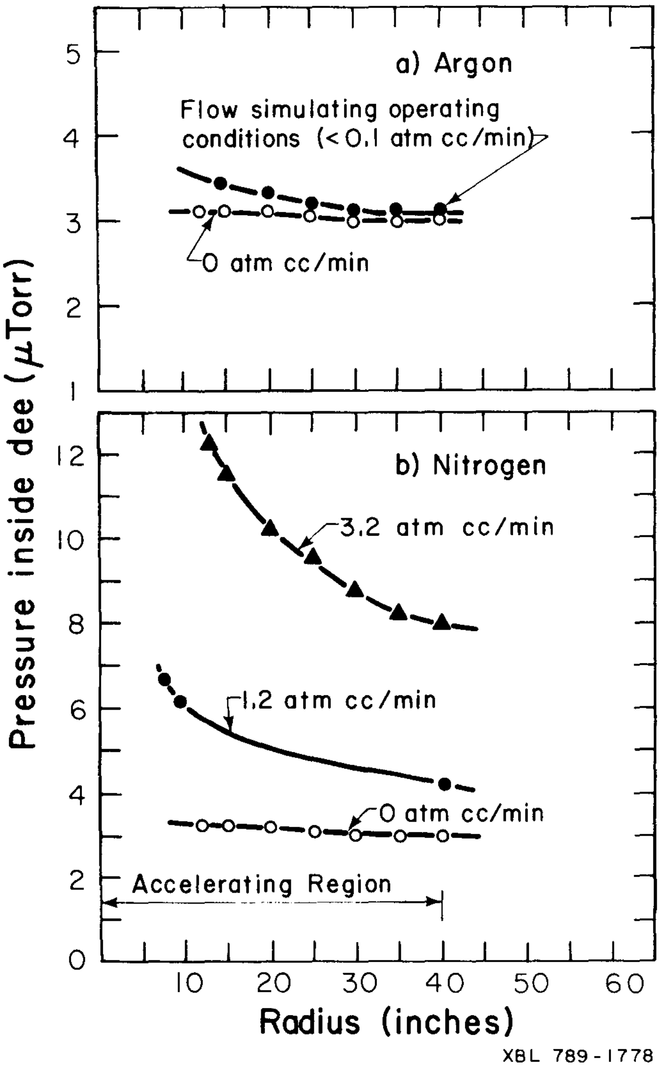


Fig. 3. Pressure vs. radius data inside the dee for a) argon and b) nitrogen source gas under various flow conditions.

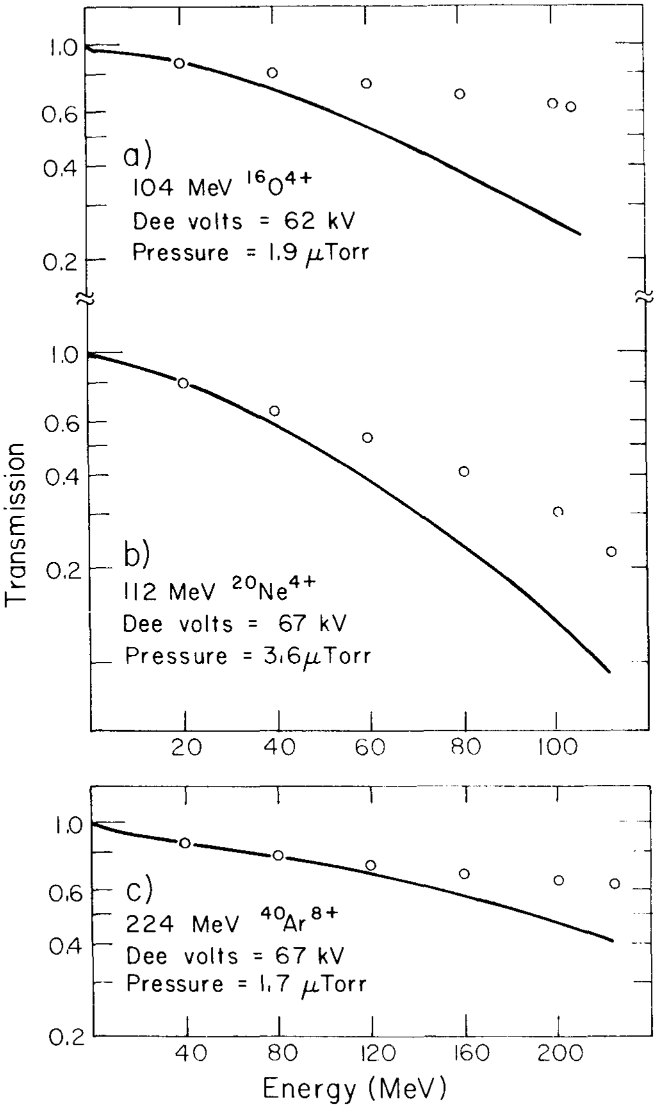
measurements of this effect using the internal PIG source of the 88-Inch Cyclotron indicated that for O_2 gas only 5-20% of the measured flow actually entered the dee tank. The variation depended on the mode of arc operation - for low gas flow conditions (2.5-3 atm cc/min) only ~5% of the flow entered the tank, while for high gas flow ($\gtrsim$5 atm cc/min) about 20% entered the tank. Oxygen, being very chemically active, may not be typical in this respect. We have observed, for example, that when operating the source with oxygen gas, an unusually high flow rate is required in contrast to comparable operation with other gases like N_2 or Ne.

Another problem which arises in these measurements is estimating the composition of the gas in the dee tank. Using Ne background gas instead of N_2, for example, when calculating the CE losses for a 112 MeV $^{20}Ne^{4+}$ beam increases the predicted attenuation by a factor of two. The vacuum analyzer on the RF resonator tank of the 88-Inch Cyclotron indicated N_2 and O_2 to be by far the strongest components in the residual gas spectrum under all operating conditions considered here. In the dee tank the component due to the source gas will certainly be higher than was measured by the vacuum analyzer. However, considering the measured source gas flow rates, the source pumping effect and the total vacuum tank leak rate of ~1.6 atm cc/min (based on total rates-of-rise measurements) it seems likely that N_2 and O_2 have the largest partial pressures of all the gases even in the accelerating region. This assumption is made in considering the sensitivity of the ion gauges to different gases[4] and in choosing the background gas used in the transmission calculations presented below.

Comparison of Calculated and Measured Transmission

Calculations were made for three different beams run at the 88-Inch Cyclotron: a) 104 MeV $^{16}O^{4+}$ b) 112 MeV $^{20}Ne^{4+}$ and c) 224 MeV $^{40}Ar^{8+}$ and the results are shown in Fig. 4. For these calculations an average accelerating chamber pressure was estimated for each case at a radius corresponding to 60% of full energy. For the 104 MeV $^{16}O^{4+}$ case, the pressure inside the dee was normalized to the data of Fig. 3b with a flow corresponding to 95% source pumping, a value determined at the time of the transmission measurement. The pressure in the dummy dee half of the acceleration chamber was assumed to be 10% higher than the average of IG06 and IG10. No reliable transmission data could be obtained below 20 MeV due to the uncertain contribution of out-of-phase beam to the dee probe current signal. Figure 4(a) shows the calculated and measured transmission for the 104 MeV $^{16}O^{4+}$ beam.

To obtain the calculated transmission curve for the 112 MeV $^{20}Ne^{4+}$ beam shown in Fig. 4(b) and the 224 MeV $^{40}Ar^{8+}$ beam shown in Fig. 4(c) a similar procedure for estimating the average tank pressure was followed except that the ion source was assumed to pump only 50% of the Ne or Ar gas supplied to it. The argon calculation is not sensitive to this assumption since, as can be seen from Fig. 3(a), the amount of Ar required to run the ion source has very little effect on the dee tank pressure. The Ne and Ar transmission results were taken during the same run under the same cyclotron tuning conditions - only a slight change in frequency separates the two beams. No reliable transmission data could be obtained below 1 MeV/nucleon in these cases due to the uncertain contribution of out-of-phase beam to the dee probe current signal. It should be noted that the cryopanel does not pump Ne, making the vacuum analysis for this case less certain.



XBL 789-1777

Fig. 4. Comparison of theoretical and measured transmission curves for three 88-Inch Cyclotron beams: a) 104 MeV $^{16}O^{4+}$, b) 112 MeV $^{20}Ne^{4+}$, c) 224 MeV $^{40}Ar^{8+}$. The calculated results are shown as a solid line and the circles represent measured data points.

Discussion of Results

Given the uncertainties in the molecular cross section data and in the estimates of the actual pressures under operating conditions, the agreement seen in Fig. 4 is thought to be reasonably good. For example the calculations could be brought into excellent agreement with the data if estimates of the pressures or the cross sections were 1.5 to 2.5 times too high.

It is extremely useful to operating cyclotrons to be able to predict transmission losses for new beams and for very low intensity beams where traditional dee probe current monitoring systems lack sensitivity. It is even more useful for new cyclotrons or other accelerators to predict vacuum requirements early in their design stage. Further comparisons of the type described in this report would be useful in refining the vacuum model code. Furthermore, with sufficient care in the analysis of the vacuum in the accelerating region, it should be possible to make improved measurements of molecular cross section data. A cyclotron is well suited to this task since the energy dependence of the molecular cross sections comes directly from the transmission data.

Acknowledgements

The authors wish to express their appreciation for the help of the 88-Inch Cyclotron staff. Particular thanks are due to D. Elo, and D. Clark for their useful comments and encouragement.

This work was done with support from the U. S. Department of Energy.

References

1. R. E. Olson and A. Salop, Phys. Rev. A, vol. 14, no. 2, 579 (1976).
2. H. P. Betz, IEEE Trans Nucl. Sci., NS-19, no. 2, 249 (1972).
3. H. P. Betz, Rev. of Mod. Phys., vol. 44, no. 3, 465 (1972).
4. See for example, Scientific Foundations of Vacuum Technique, 2nd ed. by Saul Dushman, J. M. Lafferty, ed. (1962) John Wiley and Sons, Inc.