

## BEAM LOSS FROM CHARGE CHANGING COLLISIONS IN A CYCLOTRON

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The present upgrade plan of the NSCL requires the coupling of the K500 and K1200 superconducting cyclotrons, with the K500 beam injected by stripping inside a dee of the K1200. The installation of the stripper mechanism inside the dee prevents the operation of a possible third cryopanel inside that same dee. The loss of transmitted beam intensity in a cyclotron due to charge changing collisions with the residual gas molecules involves the cross sections for the loss process over a wide range of energy per nucleon ( $E/A$  typically  $0.015 Q/A$  at injection to  $1000 (Q/A)^2$  at extraction in the K1200). In the operating pressure range, the beam loss is non-linear with pressure for ions that have large cross sections, such as  $U^{35+}$ . We performed an experiment in which the beam intensity out of the cyclotron was measured with one cryopump bypassed and compared this to the normal configuration, with and without gas being added to the vacuum through an external valve and flow meter. We measured the pressure in the beam chamber with a nude ion gauge fitted to a beam probe with the magnet carefully degaussed. Additional experiments have been performed with other ions to study the validity of empirical formulas for vacuum attenuation.

### 1 Introduction

The cyclotrons at the NSCL have produced many species of beams with a wide range of energy. Beam loss due to vacuum attenuation depends on the integral of the product of the pressure and total cross section for changing the charge on the ion. The residual gas composition indicated that small air leaks were still present; therefore nitrogen was often the most abundant molecule. Since the operating pressure in the cyclotrons was approximately  $10^{-6}$  torr, on the border for significant beam loss for some ions, we needed a quantitative assessment of beam loss. We have found that flowing oxygen gas into the electrostatic deflectors has the beneficial effect of reducing the leakage current from the cathode and improving the voltage holding capability. This added gas obviously will cause some loss of beam from the increased frequency of collisions, but in many cases some gas flow to the deflectors can be tolerated. Also, the proposed project to couple the K500 and K1200 cyclotrons<sup>1,2,3</sup> to increase intensity and energy of beams will require adding a stripper foil mechanism to the K1200 which, for mechanical reasons, will be installed in the location of one of the cryopumps.

To assess the adequacy of the planned cryopumping system we decided to measure transmission of  $U^{35+}$  through the K1200 with 1 and 2 cryopumps operating and with different gas input. We also inserted a probe carrying a nude ionization gauge inside the cyclotron to compare with the standard vacuum gauge readings. We calculated the transmission from models and cross section data in the literature for comparison with experimental results. We measured beam loss for particles other than U in both cyclotrons for comparison.

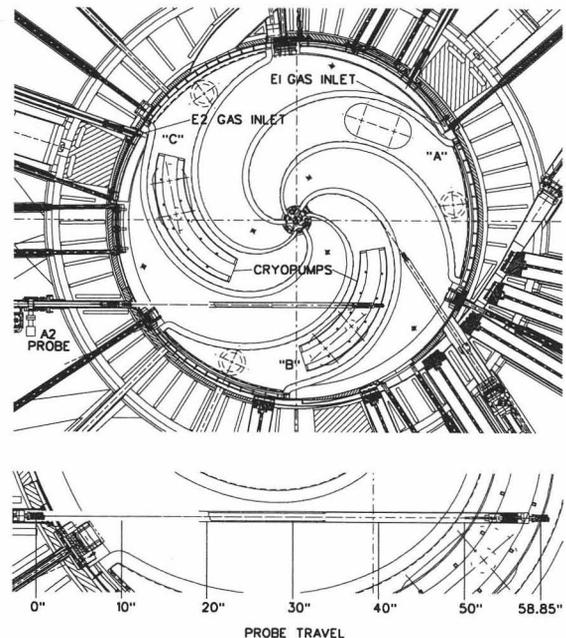


Figure 1: Plan view of K1200 with detail of the path of the vacuum probe.

### 2 Experiments with K1200

#### 2.1 Internal vacuum probe

The vacuum probe was an adaptation of the beam probe labelled "A2" in Fig. 1. The normal beam sensing head was replaced with a nude ion gauge. The probe tube was extended so the vacuum gauge could reach into dee "B", over the cryopump. The ionization gauge was usable only when the cyclotron magnet was degaussed to 30 gauss or below. For this purpose a Hall plate for reading the vertical magnetic field was installed on the probe axis 6 inches from the center of the ion gauge active volume.

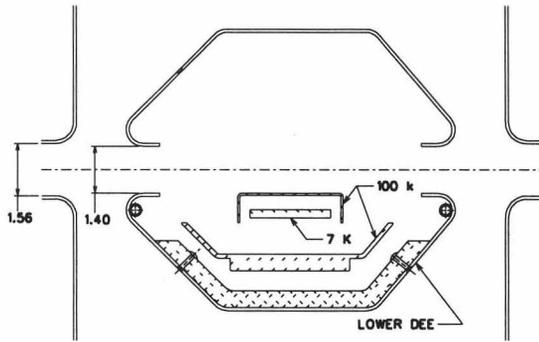


Figure 2: Vertical section of the K1200 cryopumps. The dee and hill gap dimensions are shown in inches.

The currents in the magnet coils were adjusted to cancel the remanent field inside the cyclotron. The sensitivity of the ionization gauge to the strength and orientation of the magnetic field were calibrated in a separate vacuum chamber using a Helmholtz coil to produce magnetic field. The scale factor is  $(1+0.0071 B_z)$  for normal field and  $(1+.0286 B_z)$  for reverse, with  $B_z$  in gauss. The measured pressure data were corrected using that factor with the corresponding measured  $B_z$ . The vacuum probe could be operated only with the radio frequency turned off, but this made no difference since the pressure on the external gauge did not change appreciably when the rf was running.

Figure 2 is a vertical section through the cryopumps. The radiation shield was cooled to a temperature of 100 K with liquid nitrogen; the liquid helium cooled panel temperature was 7 K. Its area, counting both sides, is 890 cm<sup>2</sup>. Both components are made of copper. The estimated pumping speed of each panel is 2500 l/s.

Figure 3 shows the pressure as a function of position along the probe axis. Measurements with 1 cryopump (C) and 2 cryopumps (B & C) in operation are shown. The pressure is measurably lower above the working cryopump than it is on the hill, but there are no large or unexpected variations. When gas is supplied to one of the deflectors the pressure increases as the probe approaches the source of gas (E1). The standard vacuum gauge, above dee "A" and outside the cyclotron, reads a consistently higher pressure than the vacuum probe, by a factor of 2 to 5, depending on pressure and which gas inlet location is used. This is in contrast to the similar comparison for the K500 cyclotron<sup>4</sup>, where the pressure inside and the external gauge reading were approximately equal.

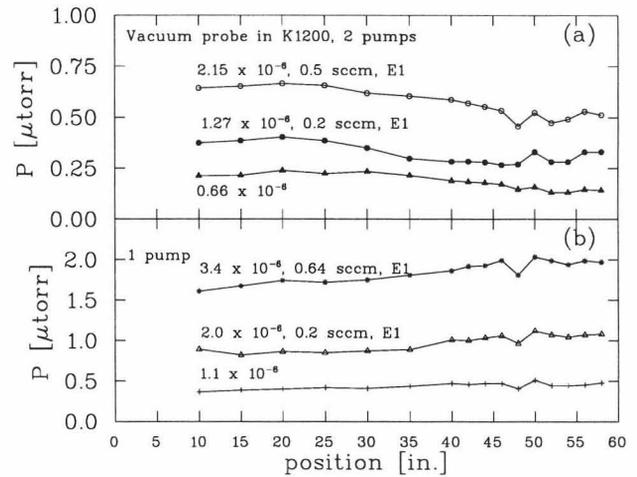


Figure 3: Vacuum probe measurements: P vs. radius with oxygen flow and ion gauge vacuum, in torr, as a parameter. (a) 2 cryopumps, (b) 1 cryopump.

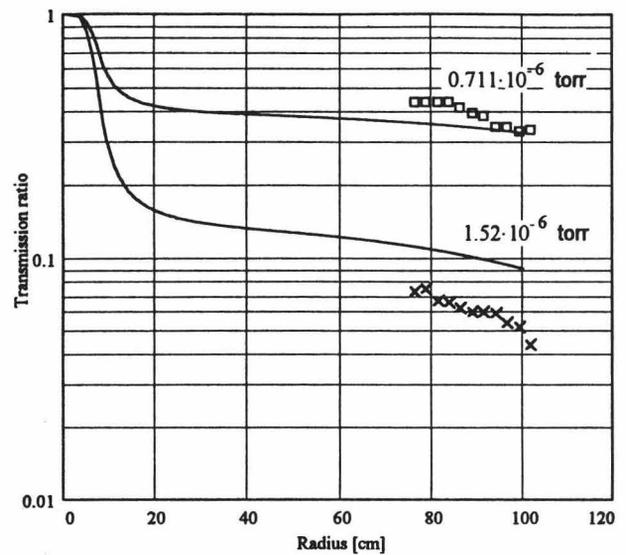


Figure 4: K1200 Transmission as a function of probe radius for <sup>238</sup>U<sup>35+</sup> with 2 cryopumps.

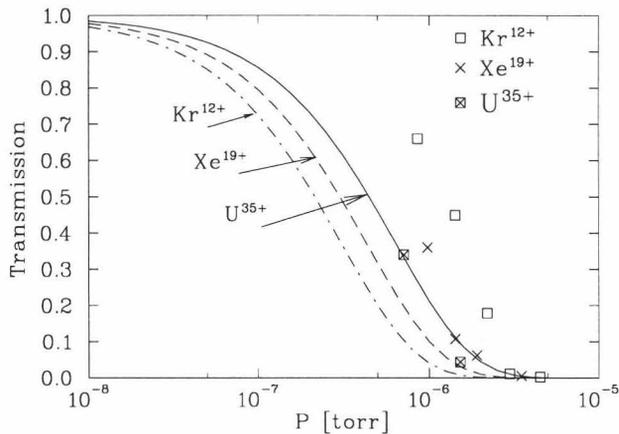


Figure 5: K1200 Transmission to extraction radius vs. pressure (2 cryopumps): 20 MeV/u  $^{238}\text{U}^{35+}$ ,  $^{129}\text{Xe}^{19+}$  and  $^{82}\text{Kr}^{12+}$ . Curves are calculated (see text); points are measured. All three ions have the same charge to mass ratio.

## 2.2 Beam transmission

Fig. 4 shows beam transmission from the entrance of the cyclotron to the probe as a function of the probe radius with cryopumps "B" and "C" in operation. The curves were calculated using the expressions given by Betz and Schmelzer<sup>5</sup> with empirical parameterization for the equilibrium charge<sup>6</sup> to estimate the sum of cross sections for capture and loss of one electron (in  $\text{cm}^2/\text{atom}$ ), which was taken to be the cross section for beam loss. At the lowest energies, below approximately 0.1 MeV/u, the cross section was dominated by electron capture and was independent of energy. Ref. [7] defines a value that we take as the total cross section at energies below the energy where the Betz-Schmelzer formula becomes equal to it.

The pressure reading from the external ionization gauge was used to label the curves and was the pressure value used to calculate charge changing cross sections. The measured transmission was roughly in agreement with the calculated transmission. The ion source bias voltage was 8.3 kV; the number of turns was 800.

The beam current injected into the cyclotron is the denominator for the transmission ratio. For the uranium experiment, the measured value included not only  $\text{U}^{35+}$  but also approximately an equal amount of  $^{129}\text{Xe}^{19+}$  which remained in the ion source from its use for tuning the beam transport and the cyclotron. The normalization for the  $\text{U}^{35+}$  transmission ratios is uncertain. A constant injected intensity was assumed for the entire experiment.

Fig. 5 compares transmission up to extraction radius for ions of 3 elements, Kr, Xe and U. The uranium measurements agree with the calculated curve. The Kr data

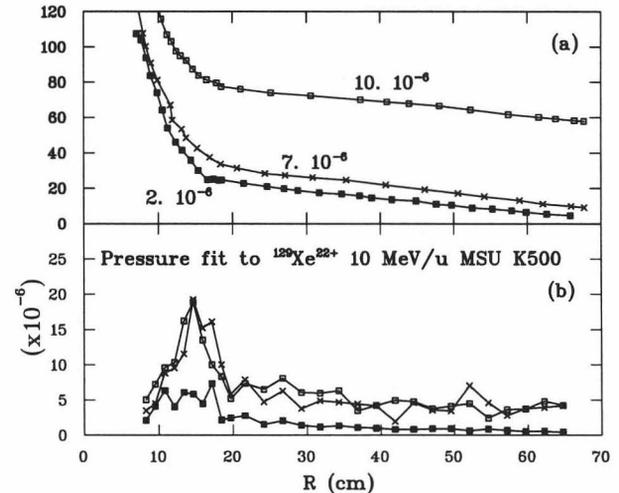


Figure 6: (a) K500 beam intensity vs. radius for  $^{129}\text{Xe}^{22+}$ . (b) Pressure profile inferred from the data in (a).

show the greatest discrepancy, equivalent to a factor of 8 in pressure, i.e. the calculated cross section is too large.

## 2.3 Beam Attenuation with Oxygen vs. Air

When oxygen gas was let into the vacuum the beam attenuation was higher than for the same pressure with air let in. The difference was not very much and was comparable to the deviations between the calculated and measured transmission ratios. For simplicity we have presented data with air as the dominant residual gas.

## 3 K500 beam attenuation and pressure profile

The K500 cyclotron at MSU was equipped with 2 cryopumps, like the K1200. The beam probe moved on a spiral track on the center of a magnet hill and was usable for beam current measurements over the radius range from 9 cm to beyond the extraction radius, 65 cm. A  $^{129}\text{Xe}^{22+}$  beam was accelerated to 10 MeV/u with 240 turns. The measured intensity vs. radius showed that most of the beam was lost relatively near the center, in general agreement with the estimated energy dependent charge changing cross section (see Fig. 6a).

The probability of a particle in the beam making a collision that changes its charge during one turn around the cyclotron is proportional to the average pressure along the path. A first approximation to the average pressure was the external ionization gauge reading (independent of radius). It was possible to extract the average pressure as a function of radius from the variation with radius of the measured beam current on the probe inside the cyclotron. The fractional loss of beam intensity between two positions of the probe determined the pressure

in that small radius interval using the cross section for changing charge state at the average beam energy in the interval. This produced the pressure profiles in Fig. 6b.

The pressure profiles showed a peak at 15 cm radius. We do not believe this peak was the result of high pressure in that region, e.g. from a leak at that radius, because the radial width was narrow and the height varied with the externally supplied gas flow introduced near 70 cm radius. The variations in path length caused by the expected phase history of the beam were taken into account in the analysis to deduce the pressure profile. Above 30 cm radius the pressure profiles were changing slowly and were within a factor of 2 of the the external ionization gauge. This is within the expected range of error for the cross section estimate.

#### 4 Conclusions

The coupled cyclotron project requires that the transmission of the K500 and K1200 each be 90% or more. The losses due to vacuum will be negligible in the K1200, due to the combination of energy and charge state. For the K500 the pressure that is predicted to result in a 5% loss of intensity (240 turns, 65 cm extraction radius) is in the range  $0.5$  to  $1 \times 10^{-7}$  torr for the heavier ions (Kr to U). This pressure will be achievable with the improved vacuum system.

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