H^- /D^- ION ACCELERATION TEST AND EXTRACTION ORBIT STUDY AT THE CYRIC 680-CYCLOTRON

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1. Introduction

As a part of development programs at the CYRIC 680 AVF cyclotron, we are studying high-current proton and deuteron beam extraction by mean of negative ion acceleration. Advantage of this method is not only the simplicity of extraction achieved by passing the accelerated H^- or D^- ions though an appropriately positioned thin foil to strip off the electrons but also the ease to determine the extracted beam energy by the position of the stripping foil. The charge-exchanged H^- or D^- ion is then deflected out into a suitable exit channel. A schematic drawing of the extraction process in the 680 cyclotron is illustrated in Fig.1.

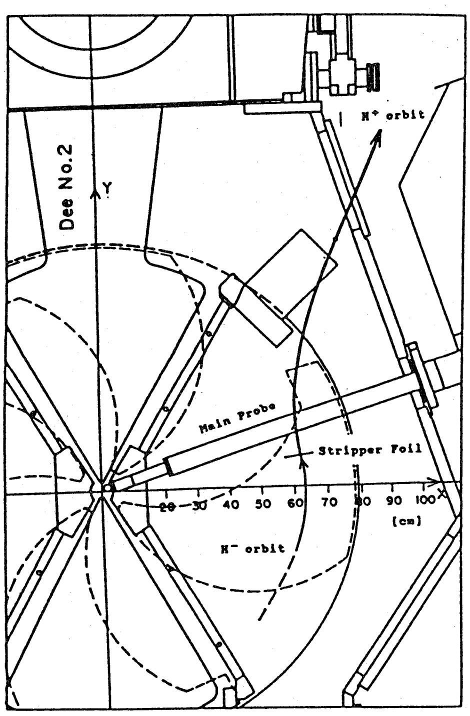

Fig.1 - Schematic drawing of the beam extraction.

The first trial of H^- ion acceleration test in our cyclotron was performed in August 1992. Two kinds of acceleration modes with harmonic number 2 and 3 were successfully tested. The cyclotron parameters in the both acceleration modes corresponded to the nominal proton energies of 15 and 35 MeV, respectively. The test still continues on the cyclotron. At the same time the extraction orbit study has been carried out.

In this report are discussed results of the H^- /D^- ion acceleration test, an analysis in terms of the vacuum pressure in the cyclotron based on the measured decrease of H^- beam current during acceleration, and some results of calculation of the extraction orbit properties.

2. H^- /D^- ion acceleration test

In the test of the H^- /D^- beam acceleration the hot-filament type PIG ion source, which is usually used for the acceleration of positive light ions, was used. To improve the negative ion beam intensity some developmental works, e.g. using various kinds of slit aperture of the ion source exit, have been done by using the otherwise the same ion source. The experimental results of H^- beam intensities with four different slit apertures are shown in Fig.2. The maximum beam intensity of about 5.5 μA at the probe radius of R=63 cm was obtained for the slit aperture of 0.5 mm wide and 6 mm hight with the arc voltage and arc current of the ion source of 250 V and 0.7 A, respectively. In this case the transmission ratio from R=15 cm to R=63 cm was observed to be about 50 % at the vacuum pressure of 5×10^{-6} Torr measured by an ion gauge positioned near the head of the vacuum pump. This clearly indicates that the vacuum pressure in the acceleration region of the cyclotron was not sufficiently low enough to avoid beam losses during acceleration. An example of the calculation of the vacuum pressure in the acceleration region by measured H^- beam loss is described in the following section.

In order to make a comparison between H^- and D^- for their dissociation losses by scattering with gas during acceleration, the transmission of the beams were measured as a function of the probe radius in the cyclotron under the condition of equivalent velocity and the almost same vacuum pressure. In this case, different factor of the ion gauge sensitivity for H_2 gas and D_2 gas was taken into consideration. The measurement for H^- of 12 MeV and D^- of 24 MeV showed the result that the similar transmission curves were obtained.

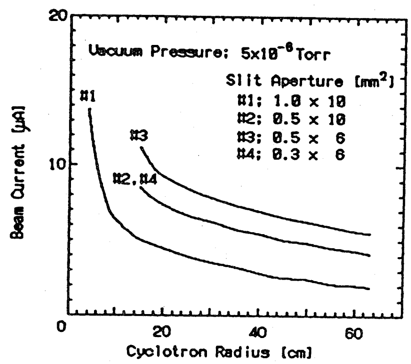

Fig.2 - The H^- beam intensity measured as a function of the probe radius with four different slit apertures of the ion source exit (acceleration of H^- ion up to 21 MeV).

3. Beam Losses by Dissociations

It is well known that negative ion beams are easily neutralized by scattering with gas and by electric stripping dissociation. The beam loss, however, of negative ions in the cyclotron occurs mainly by the gas scattering under the present conditions ,e.g., for the case of the internal ion source and the desired energy region. In order to estimate the vacuum pressure in the cyclotron, we made a calculation using the measured H^- beam current as a function of the probe radius. In the gas scattering process, we can introduce the following relation for the fractional beam loss per radial interval as ;

$$-\frac{1}{I(r)}\frac{dI}{dr} = 4\pi N_g(r)\sigma(E)\frac{E(r)}{\delta E}, \qquad (1)$$

where N_g is the number of H_2 gas molecules per unit volume and $\sigma(E)$ is the cross section of scattering for a H^- ion by a H_2 molecule as a function of the ion energy $E(r)$. The δE is the energy gain per turn, which can be represented as $\delta E = 4 \times q \times V_d \times \sqrt{3}/2$ or $\delta E = 4 \times q \times V_d$ corresponding to the harmonic number of h=2,4 or h=3 mode, respectively, for the 60 deg two-dee symmetrical system of the 680 cyclotron. Since the available data is insufficient for the cross section of single electron loss by H^- ion in the H_2 gas at the energy interval of 10 to 40 MeV, we made use of a curve obtained by a fitting to the experimental data reported by Tawara[1]. The plot of the cross section $\sigma(E)$ vs H^- ion energy obtained in this way is shown in Fig.3. We used this curve for the analysis of the measured H^- beams of 25 MeV as shown in Fig.4 by applying it to Eq.(1). Thus the number of density of H_2 molecules as well as the vacuum pressure in the cyclotron were obtained as a function of the radius. The result for the radial distribution of the vacuum pressures for two different gas flows to the ion source is plotted in Fig.5. The uncertainties of this result come mainly from the errors of numerical differentiation dI/dr, which were estimated to be $\pm 10 \sim \pm 30\%$ or so refer to the solid curves in Fig.5.

Concerning the beam loss by electric dissociation, an H^- ion its rest frame experiences an electric field due to motion in a magnetic field. The equivalent electric field [2] is given by ϵ (MV/cm) = 0.3 $\gamma\,\beta\, B_H$ (kG), where $\beta = v/c$, $\gamma = (1-\beta^2)^{-0.5}$ and B_H is the hill magnetic field. The electric field strength ϵ is related to the mean life time of H^- ion which has been investigated by several authors [2]. For example the hill field of 17.5 kG at maximum energy of 40 MeV for proton in the cyclotron, this electric field becomes 1.55 MV/cm, and the mean life time of H^- dissociation is about 100 ms from the Hiskes curve[2]. It is about 10^4 times longer than the ion traveling time in the cyclotron. Clearly the loss of H^- beam by the electric dissociation is negligibly small in our case.

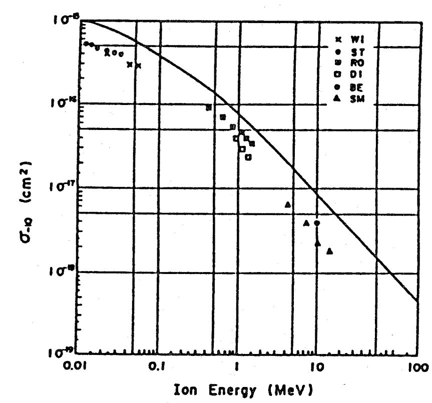

Fig.3 - The cross section (solid curve) of single electron loss of H^- ion in H_2 gas ($\sigma_{-10} cm^2/molecule$), made by fitting a curve to experimental data points indicated by various "dots" ($\sigma_{-10} cm^2/atom$) reported by Tawara [1].

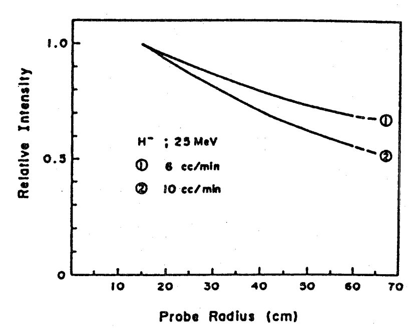

Fig.4 - Radial dependence of the H^- beam intensity of 25 MeV for two different H_2 gas flow rates.

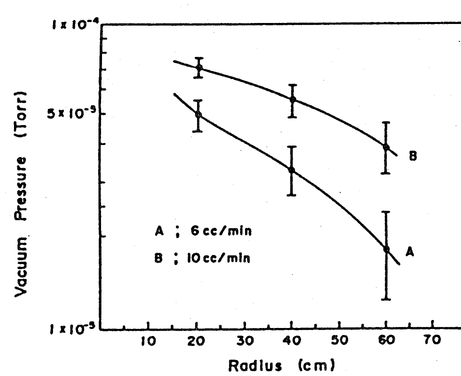

Fig.5 - The calculated vacuum pressure versus radius for two different H_2 gas flow rates.

4. Extraction orbit study

In calculating the extraction orbit, the numerical integration of the differential equations of the ion orbits were performed with the measured magnetic fields $B_z(r,\theta,0)$ of the cyclotron. To calculate the field components $B_r(r,\theta,z)$, $B_\theta(r,\theta,z)$ and $B_z(r,\theta,z)$ in the cylindrical coordinate system, using the Taylor expansion method near the median plane ;

$$
\begin{aligned}
B_r(r,\theta,z) &= z\frac{\partial B_z}{\partial r}(r,\theta,0) \\
B_\theta(r,\theta,z) &= \frac{z}{r}\frac{\partial B_z}{\partial r}(r,\theta,0) \\
B_z(r,\theta,z) &= B_z(r,\theta,0) - \frac{1}{2}z^2\left[\frac{\partial B_z}{\partial r^2}(r,\theta,0)\right. \\
&\quad \left. + \frac{1}{r}\frac{\partial B_z}{\partial r}(r,\theta,0) + \frac{1}{r^2}\frac{\partial B_z}{\partial \theta^2}(r,\theta,0)\right]. \qquad (2)
\end{aligned}
$$

The starting position of the extraction orbit, where the stripping foil is placed, was selected for obtaining a desirable extraction orbit in the cyclotron. The radial position of this point was determined by the actual H^- beam acceleration test to be the maximum radius of 63 cm, that is, just before the beam hits the existing deflector system used for normal positive ion beam extraction . To find the optimum azimuthal position, we tried the orbit calculation over and over again using the parameters of the equilibrium orbits. The adopted foil position is shown in Fig.6 together with the central ion orbit.

Horizontal and vertical amplitudes of the ion orbits were also calculated relative to the central orbit. The calculated ion trajectories are plotted in Fig.7. They behaved similarly as in a field free space, because the ions pass through almost perpendicularly to the steep decrease of the magnetic equipotential line in the fring field. Other details are given in the figure.

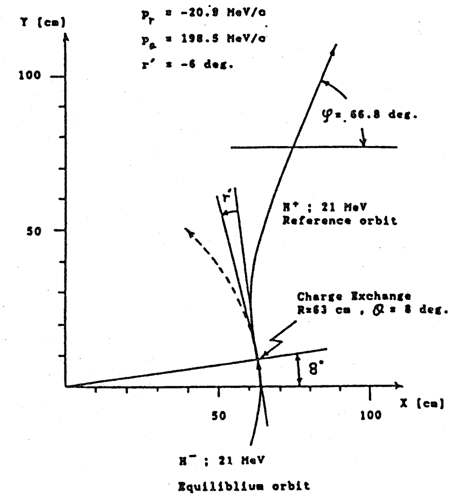

Fig.6 - The optimum radial and azimuthal position of the stripping foil for a desirable extraction orbits in the cyclotron ; the orbits for the H^- ion as well as the H^+ ion of 21 MeV are shown.

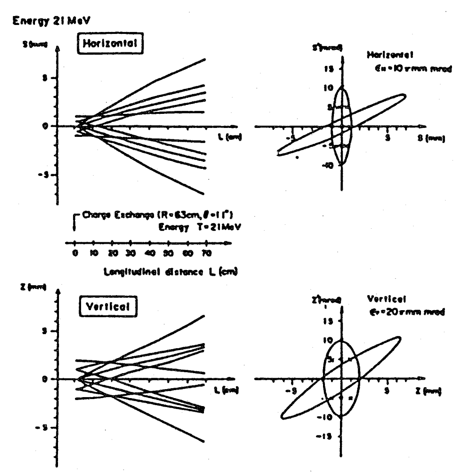

Fig.7 - The calculated trajectries of H^+ ions of 21 MeV in the horizontal and vertical planes with different initial condition contained in the both phase spaces as a function of the longitudinal distance from the stripping foil.

5. Outlook

In view of the successful results of the H^- /D^- ion acceleration test and the results of calculation of the extraction orbit, as described above, the program may possibly be realized. For the future, our effort will be extended to the improvement of the cyclotron vacuum pressure to avoid the beam losses due to stripping by the residual gas and to the development of a high current H^- /D^- ion source giving a beam of a hundred μA range at the cyclotron exit.

Acknowledgement

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[2] D. L. Judd, Nucl.Inst. and Meth. 18,19 (1962) 70.