FEASIBILITY STUDIES OF THE H^- ACCELERATION IN THE K130 CYCLOTRON IN JYVÄSKYLÄ.

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High intensities of proton beams are needed in the Jyväskylä cyclotron for radioisotope production and in some light ion induced fission experiments. At present the extraction efficiency of high-energy proton beams (1st harmonic) is 60-70 %. This limits the maximum extracted beam current to about 25 μA. In order to minimise activation of the cyclotron and to allow for higher intensities we have studied the possibility of H^- acceleration with stripping extraction. It was found that beam losses due to residual gas at a normal pressure of $p \sim 10^{-7}$ mbar in the cyclotron do not exceed a few percent as well as the beam losses due to electromagnetic dissociation of H^- ions accelerated up to 75 MeV are lower than 2 %. The beam optics calculations show that proton beam can be extracted with an efficiency of 100 % directed into the given region and then matched with the existing beam line. Some additional focusing for example using a passive channel inside the vacuum chamber is needed.

1 Introduction

The Jyväskylä cyclotron was initially designed for heavy ions. However, quite soon there was a large demand for light ions to be used in isotope production and in light ion induced fission experiments. In these runs activation of the cyclotron becomes a problem, especially because the extraction efficiency with these beams (1st harmonic mode) is only 60-70 %. Therefore a study of H^- acceleration and extraction was started.

The feasibility study has three main areas of interest: stripping due to electromagnetic dissociation, stripping due to residual gas and matching the beam into the existing beam line.

2 Losses due to Electromagnetic Dissociation

The electromagnetic dissociation depends highly on the beam energy and on the magnetic field. The focusing limit of the cyclotron for protons is 90 MeV but the highest energy needed in the isotope production has been 75 MeV. For this energy the magnetic field in the hill area is about 1.6 T.

2.1 Theoretical basis

The beam losses are calculated from equation:

$$\frac{dI}{I} = -\frac{dt}{\gamma\tau} \tag{1}$$

where γ is the relativistic factor and τ is the average life-time of the negative ion.

The lifetime τ empirically follows the form:

$$\tau(E) = \frac{A}{E}\exp\left[\frac{D}{A}\right] \tag{2}$$

where A and D are constants, and E is the strong electric field arising in the ions own coordinate system when the ion is moving in a magnetic field B

$$E = 0.3\beta\gamma B \tag{3}$$

where β and γ are the normal relativistic factors and B is measured in T and E in MV/m.

In the literature the two most known combinations of the constants A and D are:

Case 1: $A = 7.96\ 10^{-14}$ MV/cm, $D = 42.56$ MV/cm [1],

Case 2: $A = 2.47\ 10^{-14}$ MV/cm, $D = 44.90$ MV/cm [2].

Beam losses due to electromagnetic dissociation in the cyclotron can be calculated by integrating the equation (1) along the azimuth:

$$\frac{I}{I_0} = \exp\left(-\int_0^{\theta_k}\alpha(\theta)d\theta\right),\ \alpha(\theta) = \frac{1}{\gamma\omega\tau} \tag{4}$$

where θ_k is the final azimuthal angle on last turn of acceleration and $\omega = 2\pi f$, f being the frequency of revolution.

The integral in expression (4) in a periodic magnetic field can be presented as [3]:

$$\int_0^{\theta} \alpha(\theta) d\theta = N \sum_{i=1}^{M} \int_{\theta_{i-1}}^{\theta_i} \alpha(\theta) d\theta \quad (5)$$

where N is the number of periodicity of the magnetic structure, $\theta_i = \frac{2\pi}{N} i$ and $M = \frac{W_k}{(\Delta W)_0}$ is the number of turns, W_k being the final kinetic energy and $(\Delta W)_0$ energy gain per turn. In our calculations we have used a magnetic field that gives 76 MeV protons at the average radius of 94 cm which is the extraction radius for positive ions. The negative ions will be extracted before the ν_r=1 resonance and hence from a somewhat smaller radius. The energy gain per turn is 107 keV.

2.2 Results

Losses of H^- ions due to electromagnetic dissociation are found to be less than 2 %, but losses increase (exponentially) on radii larger than 85 cm (Fig. 1). Main losses of H^- ions take place in the hill region. The calculation shows that the parameters *A* and *D* of cases 1 and 2 give similar beam losses.

From figure 1 it is evident that at the present situation of final energy of W_k = 76 MeV and the magnetic field in the hill region $B_{max} \approx$ 1.6 T beam losses are very low. Increasing the magnetic field or energy only by some percents gives rise to significant beam losses, which means that the practical maximum of H^- energy is around 75 MeV.

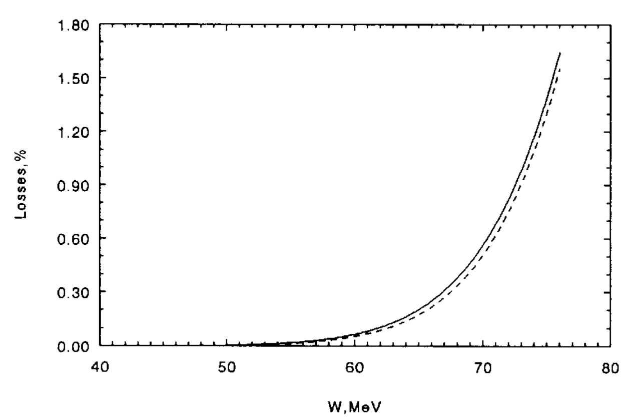

Figure 1: Losses of H^- ions (%) in the Jyväskylä cyclotron due to electromagnetic dissociation for parameters *A* and *D* of cases 1 (solid line) and 2 (dashed line).

3 The H^- Losses due to Collisions with Residual Gas.

The H^- ion is a weakly bounded system. As a result it may be easily destroyed in collisions with atoms and molecules of the cyclotron residual gas. In order to understand to what degree such destruction may restrict the H^- acceleration in the Jyväskylä cyclotron losses on the residual gas was studied.

3.1 The cross section data

The two main channels of the H^- destruction through a collision with a molecule A are:

1. $H^- + A \longrightarrow H^0 + \ldots$ neutralisation, (σ_{-10}) and
2. $H^- + A \longrightarrow H^+ + \ldots$ ionisation, (σ_{-11}),

where (σ_{-10}) and (σ_{-11}) are the cross sections of the reactions. As a rule the cross sections of neutralisation (σ_{-10}) exceed the ones of ionisation by one order of magnitude or more. In figure 2 the behaviour of the cross section (σ_{-10}) for some target molecules is shown.

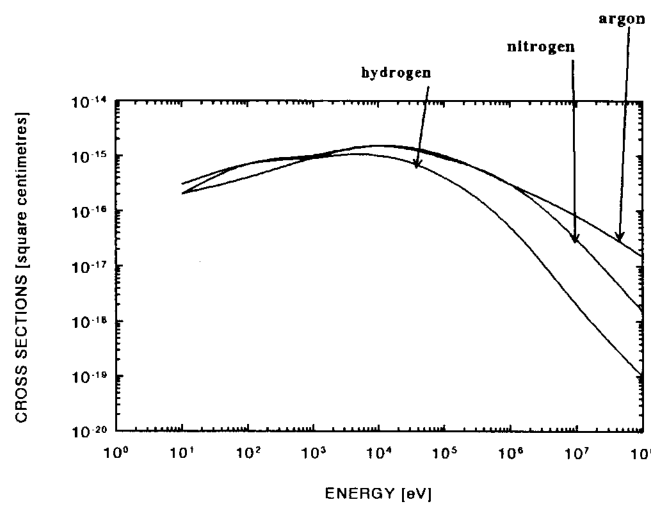

Figure 2: The H^- neutralisation cross sections (σ_{-10}) versus energy for some gases [4].

The cross sections have a wide maximum at the energy from 1 to 20 keV. Typical maximum values are almost 10^{-15} cm^2 and they weakly depend on the molecular mass of the gas. With the energy growth the cross sections decrease and the dependence on the masses appears. The heavier molecules the higher become the cross sections of neutralisation.

There are a lot of experiments on the loss cross sections for the energies below 1 MeV. The experimental data are summarised for example in [4]. In table 1 the cross sections are shown for the H^- energy of 14 keV that corresponds to the ion energy in the injection line.

For energies higher than 1 MeV the experimental data are very poor. The majority of authors use the data by Smythe and Toevs [5], who have carried out direct measurements in the range 4 – 18 MeV. The data are presented in the table 2.

Table 1: Partial and total cross sections of H- destruction for some gases at energy 14 keV [4].

Gas	σ_{-10} $[10^{-15}\,cm^2]$	σ_{-11} $[10^{-15}\,cm^2]$	σ $[10^{-15}\,cm^2]$
H_2	1.0	0.025	1.03
H_2O	0.8	0.08	0.88
N_2	1.5	0.15	1.65
O_2	1.0	0.15	1.15
Ar	1.5	0.15	1.65

Table 2: The total cross section of the H- destruction for some gases and for energies 4 - 18 MeV [5].

Stripping gas	Energy [MeV]	σ_{total} (per atom) $[10^{-18}\,cm^2]$
H_2	4.2	5.93±0.67
H_2	7.4	3.62±0.41
H_2	9.8	2.18±0.23
H_2	14.6	1.63±0.18
H_2	17.9	1.34±01.4
He	14.6	3.11±0.36
N_2	14.6	18.8±2.3
O_2	14.6	21.1±2.6
Ar	14.6	57.6±8.0

To carry out the calculation for all energies (up to 75 MeV) we are using the formula for the cross sections proposed by Gelfand et al. [6].

$$\sigma = \frac{\kappa \cdot M}{v^2} \qquad (6)$$

where σ is the total loss cross section for the reactions, v the particle speed, M the molecular mass of target atom (molecule) and κ=(40±5) cm^4 s^{-2} , coefficient common for all gases. The formula has a semi-empirical nature. The dependence $\sigma \propto \frac{1}{v^2}$ is obtained by the Born's approximation method, the constant in the form $\kappa \cdot M$ is obtained from experiments. Born's approximation can be reliably used for energies higher than 1 MeV.

3.2 Losses during acceleration

When the cross sections of beam losses in residual gas scattering are known as a function of energy, beam losses during the whole acceleration are obtained by integrating the losses over the energy. Figure 3 shows the results for several residual gases and pressures.

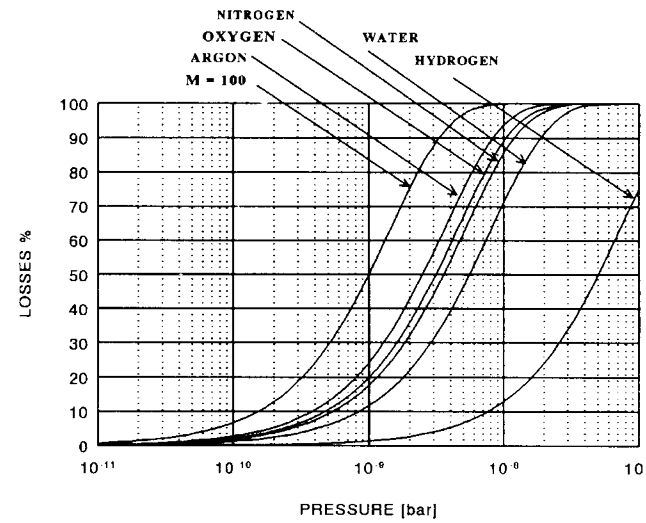

Figure 3: Losses of H- ions (%) during acceleration (E_{kin}^{max} = 75 MeV , ΔW = 104 keV/turn) for some residual gases.

3.3 Losses in the injection line

The beam energy in the injection line is constant and the losses can be calculated by direct integration of the expression (7) by using the cross sections data from the table 1. The results are presented in figure 4.

$$dI = -I \cdot N_L \cdot P_0 \cdot \sum_i a_i \cdot \sigma_i \cdot dZ \qquad (7)$$

where I is the beam intensity, N_L=2.7 ·10^{19} cm^{-13} (Loschmidt number), $\sigma_i = \sigma_{-10}+\sigma_{-11}$ is the total microscopic cross section of the H- destruction on gas i and a_i is the specific weight of gas i.

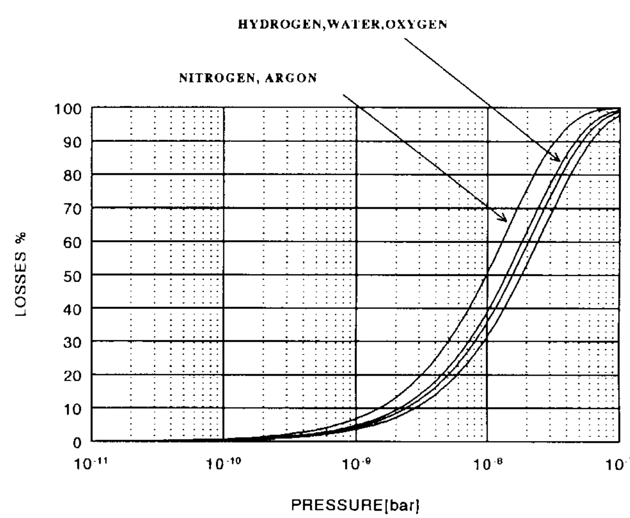

Figure 4: Losses of H- ions (%) in the injection (E_{kin} = 14 keV, length = 16 m), for different residual gases.

3.4 Results

The losses during acceleration rapidly increase with the increasing of the molecular mass of a gas. The measured gas composition of the Jyväskylä K130 Cyclotron vacuum is: H_2: 60 %, N_2: 24 %, O_2: 9 %, H_2: 3.3 %, (Ar, CO_2): 2.7 %. The water dominates because of its very low outgassing rate. It may be concluded from the calculations that the main losses will be from collisions with water and nitrogen molecules and for typical working pressures $(1\text{-}3)\cdot 10^{-10}$ bar will not exceed 6 %. In the injection line, where the working pressure is $1\cdot 10^{-10}$ bar, the losses on the any gas will not exceed 1 %.

4 Beam Extraction and Matching

The aim of the stripping extraction positioning was to match the beam into the existing beam line as near to the cyclotron as possible in order to be able to use the present beam line. This sets the limits for the stripper position which, on the other hand, has to be in the dummy dee region. Fortunately this was possible. Figure 5 shows the positions of some calculated trajectories for the extracted beam. In the present beam line there is a quadrupole singlet just at the beginning of the beam line. This quadrupole has to be moved forward to allow space for a dipole magnet that turns the stripped beam into the present beam line.

In addition to a new dipole magnet in the beam line focusing has to be added inside the vacuum tank. The simplest way is to add a passive focusing channel, which consists only of one iron plate.

5 Conclusions

The preliminary study shows that it is possible to accelerate H^- ions up to 75 MeV with only minor losses due to electromagnetic dissociation and destruction due to residual gas. It was also possible to match the stripped beam into the existing beam line so that only one dipole magnet has to be added outside of the cyclotron. This allows us to increase the proton beam intensities significantly.

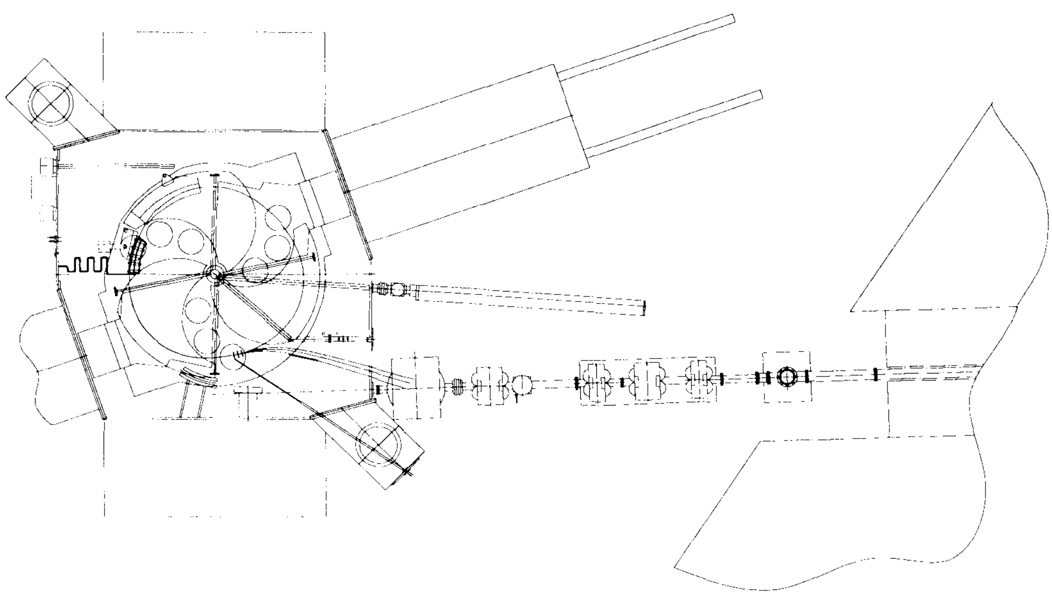

Figure 5: Layout of the Jyväskylä K130 cyclotron with the stripping extraction.

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