ON THE POSSIBILITY OF ACCELERATING MULTIPLY CHARGED IONS IN THE CERN SYNCHROCYCLOTRON

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Abstract

Some problems related to the possibility of accelerating light ions in the CERN SC are studied. Deuteron capture conditions and the optimum radiofrequency versus time curve are calculated. Internal beam currents of some micro-ampères seem obtainable when using the calutron source as for protons. The same calculations were repeated for \( \text{He}^+ \) taking into account the charge exchange process in the vacuum. A transmission of between 5 and 10% has been calculated, giving some \( 10^{15} \) particles per second with a PIG source.

Introduction

In view of the interest in the possible production of light ion beams in the CERN SC, we have examined the problems posed by the acceleration of such ions. In the first chapter the acceleration of \( \text{d, } \alpha, \text{He}^+ \) is envisaged. These ions can be produced by a mid-plane hooded arc source as used in the improved CERN SC. The captured current is calculated for the case of deuterons. In chapter 2 the multiply-charged light ions which need a PIG type source at center and for which the acceleration poses specific problems, are studied. The case of \( \text{He}^+ \) is specially retained. In chapters 1 and 2 we have retained the following restricting hypotheses which should permit the adaptation of the improved SC without any fundamental transformation.

1) We preserved the present weak focusing field of the SC. In this case the final energies are as in Table 1.

Table 1: Final Energies of Light Ions in the CERN SC

<table>
<thead>
<tr>
<th>Ions</th>
<th>Final Energy (MeV)</th>
<th>Final Energy (MeV/nucleon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>602</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>363</td>
<td></td>
</tr>
<tr>
<td>(^3\text{He}^+)</td>
<td>914</td>
<td></td>
</tr>
<tr>
<td>(^4\text{He}^+)</td>
<td>726</td>
<td></td>
</tr>
<tr>
<td>(^6\text{Li}^+)</td>
<td>512.4</td>
<td>85.4</td>
</tr>
<tr>
<td>(^{12}\text{C}^+)</td>
<td>1029.6</td>
<td>85.8</td>
</tr>
<tr>
<td>(^{14}\text{N}^+)</td>
<td>1370.6</td>
<td>97.9</td>
</tr>
<tr>
<td>(^{20}\text{Ne}^+)</td>
<td>1402.0</td>
<td>70.1</td>
</tr>
</tbody>
</table>

2) We limit the radiofrequency of the accelerating voltage to some megahertz.

3) We do not change the present Dee; this means that acceleration on harmonics is excluded.

1. Completely Ionized Light Ions Acceleration

1.1 The two modes of acceleration

For deuterons, \( \alpha \) and \( \text{He}^+ \) two possibilities are studied with the improved SC. The so-called iso-geometric case which allows to use the same central geometry and source, for the protons, and the 30 kV acceleration case which allows to take the same Dee voltage as for the protons.

1.2 The "Iso-Geometric" case

This hypothesis keeps the same central geometry and orbits as for protons by adjusting the voltage of the RF with the given magnetic field. Then the radial quality of the beam is independent of the ion accelerated (if we neglect the space charge phenomena). The non-relativistic formula for the "iso-geometric" accelerating voltage is:

\[
V_{A} = V_{p} \times \frac{Z}{A}
\]

which gives for \( \text{d, } \alpha \) beams:

\[
V_{d, \alpha} = \frac{1}{Z} V_{p}.
\]

Following this hypothesis we will calculate the accepted deuteron mean current and the radial amplitude distribution using the program TOTAK described in reference 2). In section 1.2.3 we give the upper limits of the radial amplitude distribution (see ref. 2). These spreads are due to two effects:

1. the accepted phase range,
2. the spread due to the plasma conditions at the source slit.

For protons, the emittance due to the phase range has been computed from electrolytic tank measurements\(^4\) and used to get the radial quality, via the program TOTAK\(^2\). Since we can use the same central geometry as for protons\(^2\), \( \mu \), we may also use the computed proton source emittance (see ref. 2). The emittance due to the plasma has been taken equal to the proton case described in ref. 2 (260 mm mmrad). Then the parameters used for deuteron acceleration are:

1. \( V = 15 \text{ kV in the central region} \)
2. \( \mu \) (reduction of the energy gain due to the non-zero gap width in the central region) = 0.85.

The value of \( \mu \) goes to 1 as one departs from...
central region, as described in ref. 2.

3. The magnetic field used is the theoretical $K = 5$ deuteron field ($B_0 = 1.97$ Wb/m$^2$).

4. Four different values of $|f|$ have been taken between zero and 5.5 MHz/msec. That is roughly the range permitted with the rotating condenser of the improved CERN SC(5).

The mean accelerated current $i$ and the radial amplitudes $A_{55}$, $A_{50}$ are shown in Fig. 1 and Fig. 2. $A_{55}$ and $A_{50}$ are defined by the following conditions:

50% of the particles have amplitudes less than $A_{55}$
95% of the particles have amplitudes less than $A_{50}$

These results make probable an extraction efficiency similar to that of protons. The repetition rate used for the computation is 50 Hz.

1.2.2 Acceleration  Now we want

(a) to study the conditions under which there are no losses during acceleration, i.e. the bucket area $A$ will not diminish;

(b) to compute the acceleration time and the related limit on the repetition rate $R$ with $A = \text{constant}$. This will allow us to get the mean accelerated current $I$.

\[ I = \frac{R}{50} \text{ Hz} \]

(c) evaluate the power (averaged on an RF period) which must be furnished to the beam.

1.2.3 Bucket Area Conservation  The square of the bucket area is

\[ a^2 = \frac{\mu}{\pi} V \frac{E}{2f} \cos \phi \]

with $a = 128 \alpha^2 (\cos \phi)$, where the function $a(\cos \phi)$ is computed by Vogt-Nilsen.

As

\[ f = -\frac{2V K e^2}{E} \cos \phi \]

if we can retain the condition that during acceleration $a$ will be constant, we can compute for each initial value of $|\tilde{f}|$, the optimum curves $F(R)$, $f(R)$, $|\tilde{f}(t)|$ via the MSC computer program No. 46 (Fig. 4 to 8). The magnetic field and the energy gain per gap $\mu V$ used for these calculations are specified as follows.

1. $V = 15$ kV till $R = 60$ cm. After that radius there is a small drop to take into account the cut-back of the Dee.

2. As already specified $\mu$ tends towards 1 after the central region. The $K = 5$ central region field is fitted, at larger radii with the 1850 A SC field. The knowledge of $B(R)$ determines of course $E(R)$ and $f(R)$. As an indication the value of $K$ at $R = 1$ m and $R = 2.25$ m are given in table 2 together with the values of the kinetic energy $E_k$.

If the $|\tilde{f}(t)|$ of the machine is less than the optimum curve, i.e. if $a^2$ is increased during acceleration, the acceleration time increases and consequently the repetition rate decreases; in the opposite case there are current losses. It is for this reason that the curve just computed is called "the upper limit of $|\tilde{f}(t)|$".

If an increasing of $V$ versus radius can be realized the upper limit of $|\tilde{f}|$ increases.
1.2.4 Acceleration Time  

The acceleration time T given by the Program 4 is quoted in Table 2. The value of $R_r$ to get $I$ from the equation in section 1.2.2 is taken such that

$$R_r = 466 \, \text{Hz} \quad (\text{if } T > 466 \, \text{Hz})$$

$$R_r = \frac{I}{T} \quad (\text{if } T < 466 \, \text{Hz})$$

**Table 2: Acceleration Parameters for Deuterons in the CERN SC**

<table>
<thead>
<tr>
<th>$I$ (mA)</th>
<th>$R_r$ (Hz)</th>
<th>$T$ (msec)</th>
<th>$f_A$ (msec)</th>
<th>$f_0$ (MHz/msec)</th>
<th>$R$ (m)</th>
<th>$K$</th>
<th>$E$ (MeV)</th>
<th>$B_1$ (kW)</th>
<th>$B_2$ (kW)</th>
<th>$B_3$ (kW)</th>
<th>$B_4$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.86</td>
<td>243</td>
<td>4.11</td>
<td>2.67</td>
<td>0.15</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0.045</td>
<td>0.254</td>
<td>0.8587</td>
<td>1.43</td>
</tr>
<tr>
<td>5.2</td>
<td>260</td>
<td>3.85</td>
<td>2.5</td>
<td>0.25</td>
<td>1</td>
<td>1.25</td>
<td>90</td>
<td>3.57</td>
<td>8.16</td>
<td>8.50</td>
<td>5.83</td>
</tr>
<tr>
<td>5.04</td>
<td>292</td>
<td>3.41</td>
<td>2.22</td>
<td>0.8</td>
<td>2.25</td>
<td>1.38</td>
<td>70</td>
<td>3.41</td>
<td>7.95</td>
<td>8.00</td>
<td>5.32</td>
</tr>
<tr>
<td>6.24</td>
<td>342</td>
<td>2.92</td>
<td>1.9</td>
<td>2.08</td>
<td>2.25</td>
<td>1.38</td>
<td>395</td>
<td>3.41</td>
<td>7.95</td>
<td>8.00</td>
<td>5.32</td>
</tr>
<tr>
<td>7.74</td>
<td>387</td>
<td>2.58</td>
<td>1.68</td>
<td>3.5</td>
<td>2.25</td>
<td>1.38</td>
<td>70</td>
<td>3.41</td>
<td>7.95</td>
<td>8.00</td>
<td>5.32</td>
</tr>
<tr>
<td>8.00</td>
<td>440</td>
<td>2.27</td>
<td>1.48</td>
<td>5.34</td>
<td>2.25</td>
<td>1.38</td>
<td>70</td>
<td>3.41</td>
<td>7.95</td>
<td>8.00</td>
<td>5.32</td>
</tr>
</tbody>
</table>

In the table 2 is quoted also the the RF system should give to the beam, averaged during an RF period, for the radii $R = 0$, $R = 1$ m and $R = 2.25$ m. The circulating charge $C$ in the machine is

$$C = \frac{I}{R_r}.$$ 

The mean value of the current during a RF period due to this charge is

$$\frac{fI}{R_r}.$$ 

As the voltage drop per turn seen by the synchronous particle is

$$2 \, V \cos \phi_s,$$

we have

$$B_1 = \frac{fI}{R_r} \, 2V \cos \phi_s.$$
1.3 The 30 kV Accelerating Voltage Case

The technical feasibility from the RF point of view using a f(t) curve obtained from Program 4, has been studied by R. Hohbach. No calculations of currents and radial quality have been made up to now.

2. Light Multiply Charged Ion Acceleration

2.1 Introduction

We have investigated the $C_{12}^+$ and $N_{14}^+$ acceleration through the residual vacuum of the machine. The major problem is the particle loss due to change of charge state; this loss is determined by the pressure of the residual gas and by the speed of the acceleration, which has to be as high as possible. For this reason we have studied the acceleration of these ions by the iso-voltage mode (30 kV). For the following calculations we have made an estimation of the total charge exchange cross-sections by R. Hohbach. No calculations have been made up to now.

Table 3: Calculated Transmission for $C_{12}^+$ and $N_{14}^+$

<table>
<thead>
<tr>
<th>Limit Pressure (Torr)</th>
<th>$\cos \phi_5$ = 0.3</th>
<th>$\cos \phi_5$ = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 x $10^{-6}$</td>
<td>1.5 x $10^{-6}$</td>
<td>1.3 x $10^{-4}$</td>
</tr>
<tr>
<td>2.5 x $10^{-6}$</td>
<td>9.5 x $10^{-6}$</td>
<td>3.8 x $10^{-4}$</td>
</tr>
<tr>
<td>2.0 x $10^{-6}$</td>
<td>6.1 x $10^{-6}$</td>
<td>1.1 x $10^{-2}$</td>
</tr>
<tr>
<td>1.5 x $10^{-6}$</td>
<td>3.8 x $10^{-6}$</td>
<td>3.5 x $10^{-2}$</td>
</tr>
<tr>
<td>1.0 x $10^{-6}$</td>
<td>2.4 x $10^{-6}$</td>
<td>1.1 x $10^{-1}$</td>
</tr>
</tbody>
</table>

2.3 Transmission and Capture Calculations

2.3.1 Optimised f(t) law

The f(t) laws, optimized in such a way that the bucket area is conserved, are calculated for $N_{14}^+$ and $C_{12}^+$ (Fig. 10, 11).

Fig. 10 Optimum f versus Time Curve for $N_{14}^+$

These curves show a very fast variation of f during the first 80 μsec of the acceleration. This is due to the sharp decrease of the K(Z,A) value of the magnetic field between 0 (≈ 8) and 1 m (≈ 1.5), necessary to obtain a cos$\phi_5$ sufficiently high. This can be seen from the formulae

$$ f = \frac{1}{2} \left( \frac{E}{E_0} \right)^3 K(Z,A) \cos \phi_5 \sqrt{\frac{B^2}{2m^2}} E_0 \left( 1 + n \frac{1}{1-n} \frac{1}{\beta^2} \right) $$

$$ K(Z,A) = \frac{E}{\omega} \frac{d\omega}{dE} = 1 + n \frac{1}{1-n} \frac{1}{\beta^2} \sim 1 $$

The calculation of the captured $N_{14}^+$ current and of the transmission have been done with the f(t) law of Fig. 10, under the following hypothesis:

1. 30 kV Dee Voltage.
2. The particles that change charge during capture contribute to the space charge. In fact, we suppose that they do not touch an electrode before the end of the capture process.
3. The ions different from \( \text{N}^+ \) emitted by the source are quickly lost so they do not affect the space change during capture.

4. \( f_0 = -11 \text{ MHz/msec} \).

5. The central electrodes should permit clearance of the source for \( 0 < \phi < 70^\circ \) and confine the field at the centre as it was for the protons.

6. The cone angles and radius are the same as for the protons.

7. The repetition rate is 1000 Hz.

For the transmission a value of 5.7% was found (with \( p = 10^{-5} \text{ Torr}, T = 300^\circ \text{K} \)). As the \( \text{N}^+ \) current found in the P.I.G. Source at Harwell V.E.C.13 is

\[
I = I_s \times \delta
\]

where \( I_s \) = source current = 20 mA
\( \delta \) = abundance of the charge state of the ion = 0.6% for \( \text{N}^+ \),
\( \delta \) = isotopic abundance = 99%,

then

\[
I = 120 \mu\text{A}.
\]

If such a source is used, the accelerated current will be reduced to

\[
I = 15.0 \mu\text{A} = 1.9 \times 10^6 \text{ pp},
\]

owing to the combined effect of capture and transmission.

2.3.2 Constant \( f(t) \) law for \( \text{N}^+ \). The computations show that the beam is lost after 3 to 5 phase oscillations, i.e., between 40 and 60 cm radii, depending on starting conditions \( (\phi_0, t_0) \).

Conclusions

The possibility of capture deuterons in stable orbits is proved using the central geometry scheduled for the improved CERN SC. The conditions on the \( f(t) \) curve that allows to perform deuteron acceleration seem not to be serious. The computed radial amplitude distribution makes the computation of deuteron extraction efficiencies possible. The capture and transmission calculations for \( \text{N}^+ \) in the improved CERN SC seems encouraging. Therefore a technological study on this subject is not senseless.

List of Symbols

\[\begin{align*}
V_{A,Z} & \quad \text{Isogeometric acceleration voltage} \\
V_p & \quad \text{Proton nominal accelerating voltage} \\
Z_e & \quad \text{Charge of Ion} \\
A & \quad \text{Mass of the ion relative to the proton} \\
R_r & \quad \text{Repetition rate} \\
\dot{I} & \quad \text{Internal beam current at 50 Hz repetition rate} \\
I & \quad \text{Internal beam current at } R_r \text{ rep. rate} \\
e_E & \quad \text{Kinetic energy of the ion} \\
\phi_S & \quad \text{Synchronous phase} \\
e & \quad \text{Total energy of the ion} \\
f(t) = \frac{\omega(t)}{2\pi} & \quad \text{RF curve versus time} \\
\mu & \quad \text{Fraction of the energy actually gained by the ion owing to the presence of conical electrodes} \\
T & \quad \text{Length of acceleration cycle} \\
B_1 & \quad \text{Beam loading} \\
T_A & \quad \text{Acceleration time} \\
g & \quad \text{Number of accelerating gaps in one turn} \\
K & \quad \text{Bohm and Foldy factor} \\
b & \quad \text{Magnetic induction} \\
c & \quad \text{Light speed} \\
e_{E_{\text{op}}} & \quad \text{Rest energy of the proton} \\
e & \quad \text{Elementary charge} \\
\nu & \quad \text{Magnetic field index} \\
\nu = \frac{\beta c}{\gamma} & \quad \text{Speed of the ion} \\
R & \quad \text{Radius of the ion} \\
\rho_p & \quad \text{Rest energy of the ion} \\
\rho_p & \quad \text{Bohm and Foldy factor for the proton} \\
\alpha & \quad \text{Bucket area} \\
e & \quad \text{Total energy of the proton}
\end{align*}\]

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