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

R. Giannini CERN, Geneva, Switzerland
P. Mandrillon Groupe GANIL, Institut de Physique Nucléaire, Orsay, France

Abstract

Some problems relating to the possibility of accelerating light ions in the CERN SC are studied. Deuteron capture conditions and the optimum radio-frequency 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 N^{5+}_{14} taking into account the charge exchange process in the vacuum. A transmission of between 5 and 10% has been calculated, giving some 10^{10} 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 d, α, He^{2+}_3 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 multi-charged light ions which need a PIG type source at center and for which the acceleration poses specific problems, are studied. The case of N^{5+}_{14} 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

Ions	Final Energy (MeV)	Final Energy (MeV/nucleon)
p	602	
d	363	
$^3He^{2+}$	914	
$^4He^{2+}$	726	
$^6Li^{2+}$	512.4	85.4
$^{12}C^{4+}$	1029.6	85.8
$^{14}N^{5+}$	1370.6	97.9
$^{20}Ne^{6+}$	1402.0	70.1

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

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, α and He^{2+}_3 two possibilities are studied with the improved SC. The so-called iso-geometric case which allows to use the same central geometry and source as 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[1]

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 :

$$V_{A,Z} = V_p \times \frac{Z}{A}$$

which gives for d, α beams :

$$V_{d,\alpha} = \frac{1}{2} V_p \ .$$

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 $|\dot{f}|$ for deuterons compatible with the requirement that the bucket area remains constant during acceleration. The knowledge of the radial amplitude distribution makes the computation of the deuteron extraction efficiency possible[3].

1.2.1 Deuteron Current and Radial Quality in the Capture Region The program TOTAK needs as Input Data the emittance at the beginning of the acceleration, say the curvature centers and momentum spreads. 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) 4)], 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 mrad). Then the parameters used for deuteron acceleration are

1. V = 15 kV in the central region .
2. μ (reduction of the energy gain due to the non-zero gap width in the central region) = 0.85. The value of μ goes to 1 as one departs from

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 609-613

central region, as described in ref. 2.

3. The magnetic field used is the theoretical K = 5 deuteron field (B_o = 1.97 Wb/m²).

4. Four different values of $|\dot{f}|$ 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_{95}, A_{50} are shown in Fig. 1 and Fig. 2. A_{50} and A_{95} are defined by the following conditions:

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

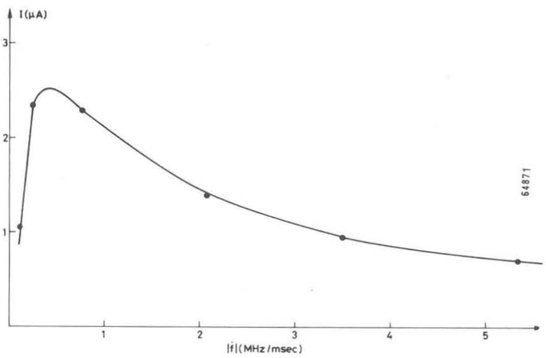

Fig. 1 Mean Accelerated Deuteron Current

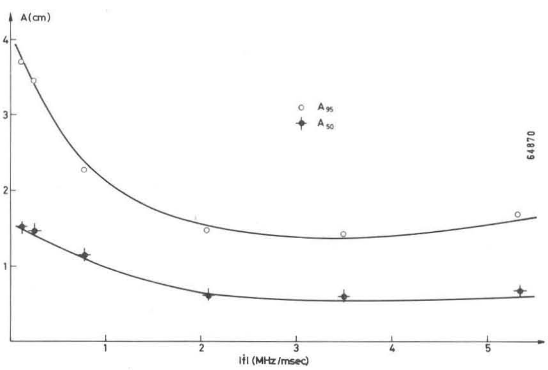

Fig. 2 Deuteron Radial Quality

Moreover the complete radial amplitude distribution is shown in Fig. 3.

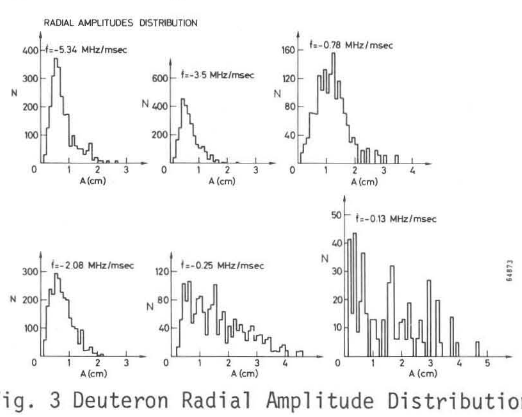

Fig. 3 Deuteron Radial Amplitude Distribution

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 <u>Acceleration</u> 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_r with A = constant. This will allow us to get the mean accelerated current I.

$$I = \frac{R_r}{50\ \text{Hz}}\, i$$

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

1.2.3 <u>Bucket Area Conservation</u> The square of the bucket area is

$$\alpha^2 = \frac{\mu}{\pi^3} V \frac{E}{2f^2K}\, a\,(\cos\phi_s)$$

with $a(\cos\phi_s) = 128\,\alpha^2(\cos\phi_s)$, where the function $\alpha(\cos\phi_s)$ is computed by Vogt-Nilsen[6]. As

$$\dot{f} = -\frac{2\mu\ VKf^2}{E}\cos\phi_s$$

if we can retain the condition that during acceleration α will be constant, we can compute for each initial value of $|\dot{f}|$, the optimum curves $|\dot{f}(R)|$ $f(R)$, $|\dot{f}(t)|$ via the MSC computer program No. 4[6])(Fig. 4 to 8). The magnetic field and the energy gain per gap μV 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 μ 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 $E_s(R)$ 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 knetic energy E_k.

If the $|\dot{f}|(t)$ of the machine is less than the optimum curve, i.e. if α^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 $|\dot{f}|(t)$".

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

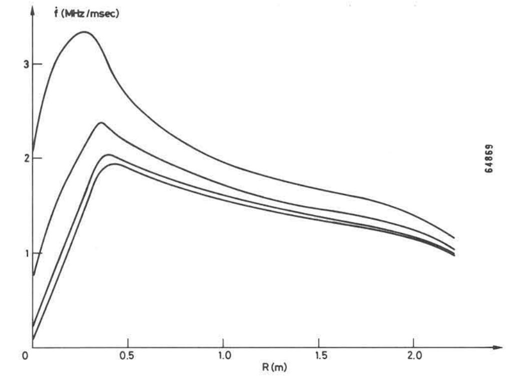

Fig. 4 Deuteron Optimum $\dot{f}$ versus Radius

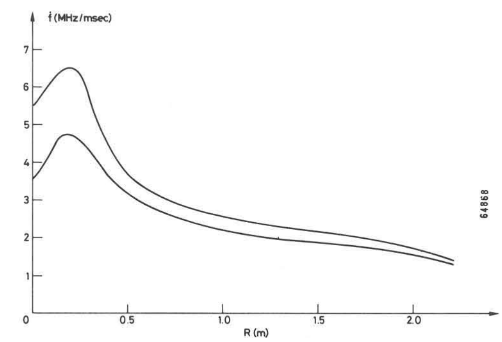

Fig. 5 Deuteron Optimum $\dot{f}$ versus Radius

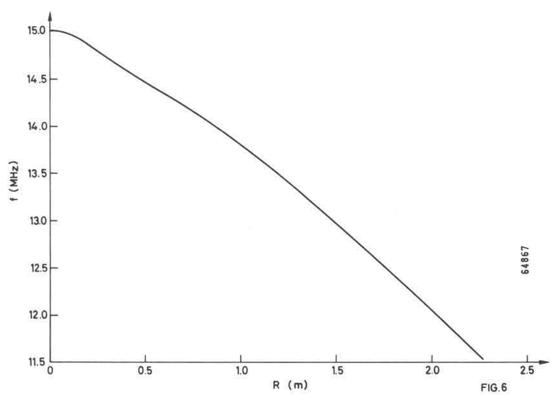

Fig. 6 Deuteron Optimum f versus Radius

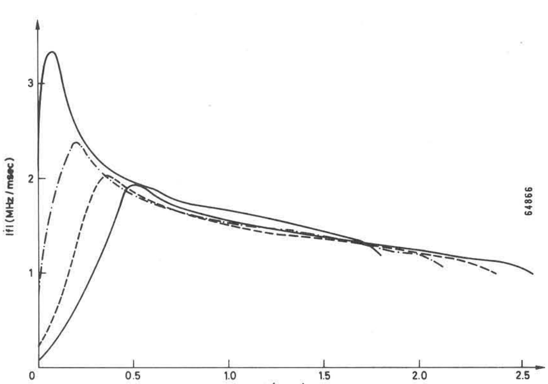

Fig. 7 Deuteron Optimum f versus Time

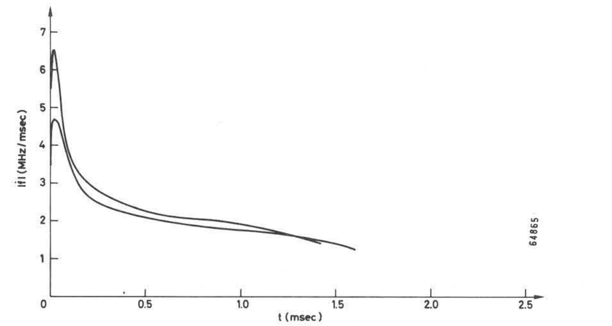

Fig. 8 Deuteron Optimum $\dot{f}$ versus Time

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 1 from the equation in section 1.2.2 is taken such that

$$R_r \begin{array}{l} = 466 \text{ Hz (if } 1/T > 466 \text{ Hz)} \\ = 1/T \quad \text{(if } 1/T < 466 \text{ Hz)} \end{array}$$

Table 2: Acceleration Parameters for Deuterons in the CERN SC

I (μA)			4.86	5.2	5.84	6.84	7.74	8.80
R_r (Hz)			243	260	292	342	387	440
T (msec)			4.11	3.85	3.41	2.92	2.58	2.27
T_A (msec)			2.67	2.5	2.22	1.9	1.68	1.48
$\|\dot{f}\|_o$ (MHz/msec)			0.15	0.25	0.8	2.08	3.5	5.34
R(m)	K	E (MeV)	B_1 (kw)	B_1 (kw)	B_1 (kw)	B_1 (kw)	B_1 (kw)	B_1 (kw)
0	5	0	0.045	0.254	0.8587	1.43	1.66	1.90
1	1.25	90	3.57	8.16	8.50	5.83	4.48	3.77
2.25	1.38	395	3.41	7.95	8.00	5.32	4.04	3.34

In the table 2 is quoted also the power B_1 which 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[7]. 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}^{4+} and N_{14}^{5+} 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[8][9][10][11][12] versus energy for the N_{14}^{5+} in a diatomic residual gas (Fig. 9).

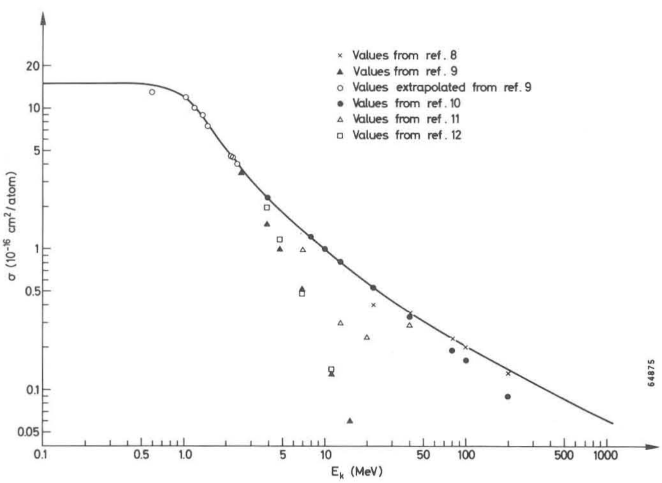

Fig. 9 Total Charge Exchange Cross-Section versus energy for N_{14}^{5+} in a Diatomic Residual Gas

2.2 Transmission Calculations

To find the combined effect of gas-pressure and acceleration we have calculated the transmission coefficient of C_{12}^{4+} and N_{14}^{5+} ions through the SC, for the synchronous phase, taken as constant. The results are summarized in Table 3.

Table 3: Calculated Transmission for C_{12}^{4+} and N_{14}^{5+}

Limit Pressure (Torr)	$\cos\phi_s = 0.3$ C_{12}^{4+}	N_{14}^{5+}	$\cos\phi_s = 0.5$ C_{12}^{4+}	N_{14}^{5+}
3×10^{-6}	1.5×10^{-5}	7.5×10^{-7}	1.3×10^{-3}	2.1×10^{-4}
2.5×10^{-6}	9.6×10^{-5}	7.9×10^{-6}	3.8×10^{-3}	8.6×10^{-4}
2×10^{-6}	6.1×10^{-4}	8.2×10^{-5}	1.1×10^{-2}	3.5×10^{-3}
1.5×10^{-6}	3.8×10^{-3}	8.6×10^{-4}	3.5×10^{-2}	1.4×10^{-2}
1×10^{-6}	2.4×10^{-2}	9.1×10^{-3}	1.1×10^{-1}	5.9×10^{-2}

2.3 Transmission and Capture Calculations

2.3.1 Optimised $\dot{f}(t)$ law The $\dot{f}(t)$ laws, optimized in such a way that the bucket area is conserved, are calculated for N_{14}^{5+} and C_{12}^{4+} (Fig. 10,11).

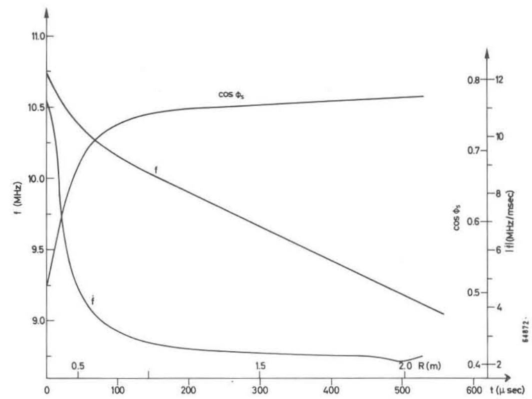

Fig. 10 Optimum $\dot{f}$ versus Time Curve for N_{14}^{5+}

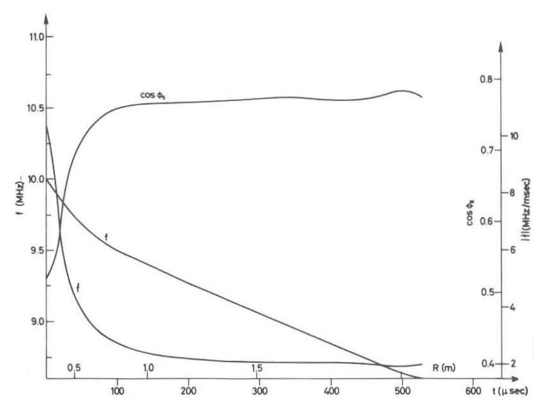

Fig. 11 Optimum $\dot{f}$ versus Time Curve for C_{12}^{4+}

These curves show a very fast variation of $\dot{f}$ 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 $\cos\phi_s$ sufficiently high. This can be seen from the formulae

$$\dot{f} = \frac{g}{2} \left(\frac{Z}{A}\right)^3 K(Z,A) \cos\phi_s \ V \frac{B^2 c^4}{2\pi^2 E_{op}^3}$$

$$K(Z,A) : - \frac{E}{\omega}\frac{d\omega}{dE} = 1 + \frac{n}{1-n}\frac{1}{\beta^2} \sim 1 + n \left(1 + \frac{A^2}{Z^2}\frac{E_{op}^2}{\beta^2 R^2 c^2}\right).$$

The calculation of the captured N_{14}^{5+} current and of the transmission have been done with the $\dot{f}(t)$ 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 N_{14}^{5+} emitted by the source are quckly lost so they do not affect the space change during capture.
4. $\dot{f}_o$ = -11 MHz/msec.
5. The central electrodes should permit clearance of the source for $0 < \phi < 70^o$ 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 $p = 10^{-6}$ Torr, $T = 300^oK$). As the N_{14}^{5+} current found in the P.I.G. Source at Harwell V.E.C.[13] is

$$I = I_s \tau \delta$$

where I_s = source current = 20 mA

τ = abundance of the charge state of the ion = 0.6% for N_{14}^{5+}

δ = isotopic abundance = 99%,

then

$$I = 120 \ \mu A .$$

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

$$I = 15.0 \ nA = 1.9 \times 10^{10} \ pps,$$

owing to the combined effect of capture and transmission.

2.3.2 Constant $\dot{f}(t)$ law for N_{14}^{5+} 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 (ϕ_o, t_o).

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 N_{14}^{5+} in the improved CERN SC seems encouraging. Therefore a technological study on this subject is not senseless.

List of Symbols

$V_{A,Z}$	Isogeometric acceleration voltage
V_p	Proton nominal accelerating voltage
Ze	Charge of Ion
A	Mass of the ion relative to the proton
R_r	Repetition rate
i	Internal beam current at 50 Hz repetition rate
I	Internal beam current at R_r rep. rate
eE_k	Kinetic energy of the ion
ϕ_s	Synchronous phase
eE	Total energy of the ion
$f(t) = \frac{\omega(t)}{2\pi}$	RF curve versus time
μ	fraction of the energy actually gained by the ion owing to the presence of conical electrodes
T	Length of acceleration cycle
B_l	Beam loading
T_A	Acceleration time
g	Number of accelerating gaps in one turn
K	Bohm and Foldy factor
B	Magnetic induction
c	Light speed
eE_{op}	Rest energy of the proton
e	Elementary charge
n	Magnetic field index
$v = \beta c$	Speed of the ion
R	Radius of the ion
eE_o	Rest energy of the ion
K_p	Bohm and Foldy factor for the proton
a	Bucket area
eE_p	Total energy of the proton

References

1. P. Mandrillon Projet Pascal, Université de Lyon (Octobre 1972)
2. S. Comiti, R. Giannini, MSC IR 72-3
3. P. Mandrillon : Thèse de Docteur Ingénieur à l'Université de Grenoble (1971)
4. S. Comiti, R. Giannini CERN Report 70-9
5. R. Hohbach Private Communication
6. N. Vogt-Nilsen MSC-NP Group Computer Programs
7. R. Hohbach Study on the feasibility of a conversion of the improved SC to accelerate also d, α, He^3, CERN/MSC/73-2.
8. H.V. Isaila, K. Prelec and M.G. White Acceleration of heavy ions at the Princeton particle accelerator, IEE-Tr. No. 19, April 1972
9. V.S. Nicolaiev et al. JETP 13 (1961) 695
10. J.R.J. Bennett Private Communication
11. J.R. MacDonald and F.W. Martin Private Communication
12. H. Betz and Ch. Schmelzer Report UNILAC 1-67 (1967) Heidelberg
13. J.R.J. Bennett The production and acceleration of heavy ions in the Harwell variable energy cyclotron. Proceedings of the 5th International Cyclotron Conference, Oxford 1969, Butterworths pp. 499.