Injection and stripping of a heavy ion beam in the Orsay cyclotron

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1. INTRODUCTION

The ALICE[1,2] project consists in injecting a 1 MeV/amu heavy ion beam with a charge to mass ratio $Z_i/A \geqslant 0{\cdot}1$ into a stripping target located on the appropriate equilibrium orbit in the cyclotron.[3]

This injection raises the following problems:

(a) knowing the capabilities of the linac with respect to the charge-to-mass ratio, and the ionisation distribution of the stripped ions, what range of ions can be accelerated by the cyclotron?

(b) given the beam emittance at the exit of the linac and the cyclotron acceptance, how is the matching to be realised?

(c) how good can the acceleration of the stripped beam be, bearing in mind that the linac and the cyclotron have different frequencies?

(d) finally, what is to be done about the limited lifetime of the stripping targets, since one of the main goals of the programme[4] is to obtain $\sim 10^{12}$ Kr ions per second for 24 h at this point in the machine?

2. IONS ACCEPTED BY THE CYCLOTRON

2.1 *Injected trajectories; general description*[5]

Assume all the different ion beams pass through a point M (Fig. 1) with the same velocity v at an angle α measured with respect to an arbitrary direction.
The choice of the ion mass A and incident charge Z_i fixes the radius of curvature ρ_i of the injected trajectory and thus ρ_s, the radius of curvature of the subsequent equilibrium orbit, if the value of α is kept constant. Consequently, Z_s is determined by:

$$B\rho_s = B\rho_i \frac{Z_i}{Z_s}$$

where B is the magnetic field value, assumed constant in this first approximation.

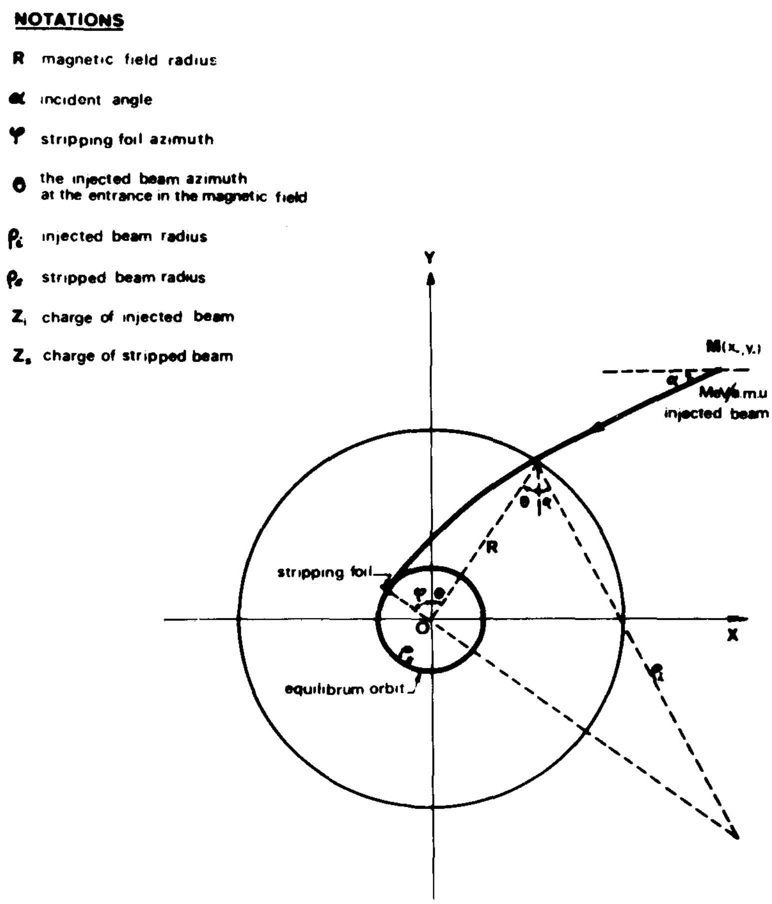

Fig. 1. Principle of injection

In order to be able to choose A and Z_i as well as Z_s it is necessary to be able to vary α as a function of A and Z_s/Z_i. If θ is the azimuth at which the trajectory enters the field B, the variations of:

$$\Psi = \theta + \alpha \qquad \text{are given by}$$

$$\cos \Psi = \frac{R^2 - \rho_s^2 + 2\rho_i\rho_s}{2R\rho_i}\,.$$

where R is the radial extent of the magnetic field B.

Let $\qquad x = Z_s/Z_i$, then $\cos \Psi$ becomes:

$$\cos \Psi = \frac{a + bx}{c}$$

where a, b, and c are parameters depending only on the energy and on the ratio A/Z_S.

On the other hand, since α and θ are related through the position of M, α is determined by the choice of A/Z_S and Z_S/Z_i.

Apart from α, it is interesting to know the variations of φ, the azimuth of the stripping target, also determined by A/Z_S and Z_S/Z_i. The formula:

$$\sin(\theta + \varphi) = \frac{x}{x-1} \sin \Psi$$

is readily derived and gives the variations of φ (see Fig. 2).

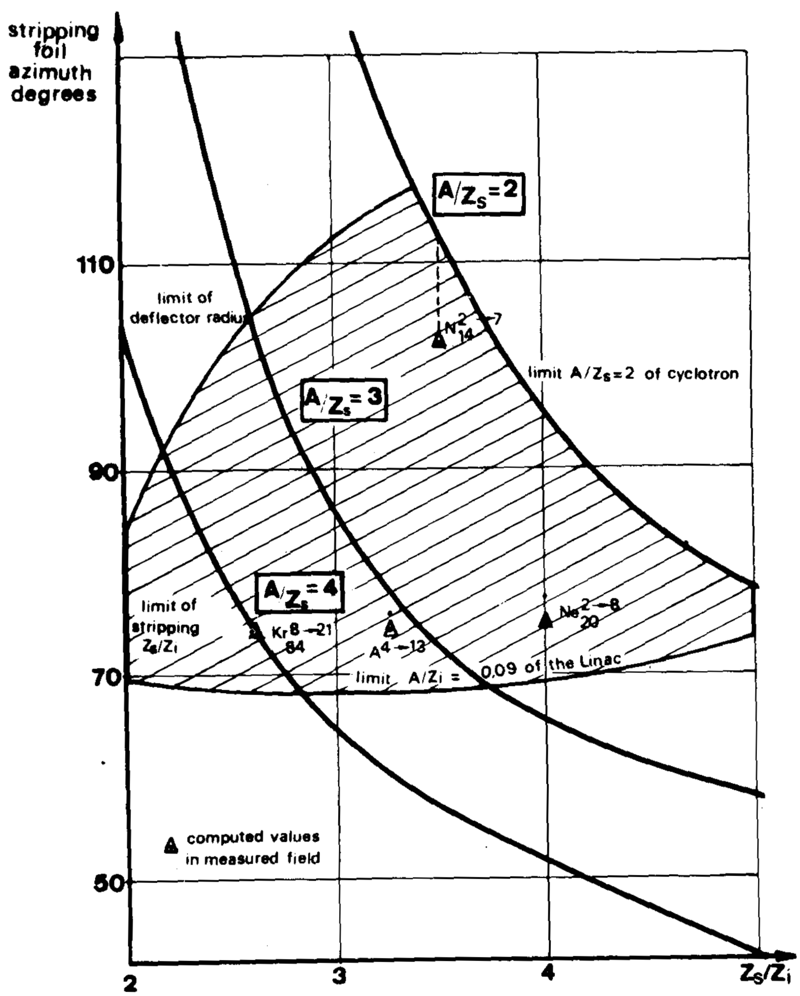

Fig. 2. Stripping foil azimuth as a function of ratio Z_S/Z_i (stripped charges to injected charges)

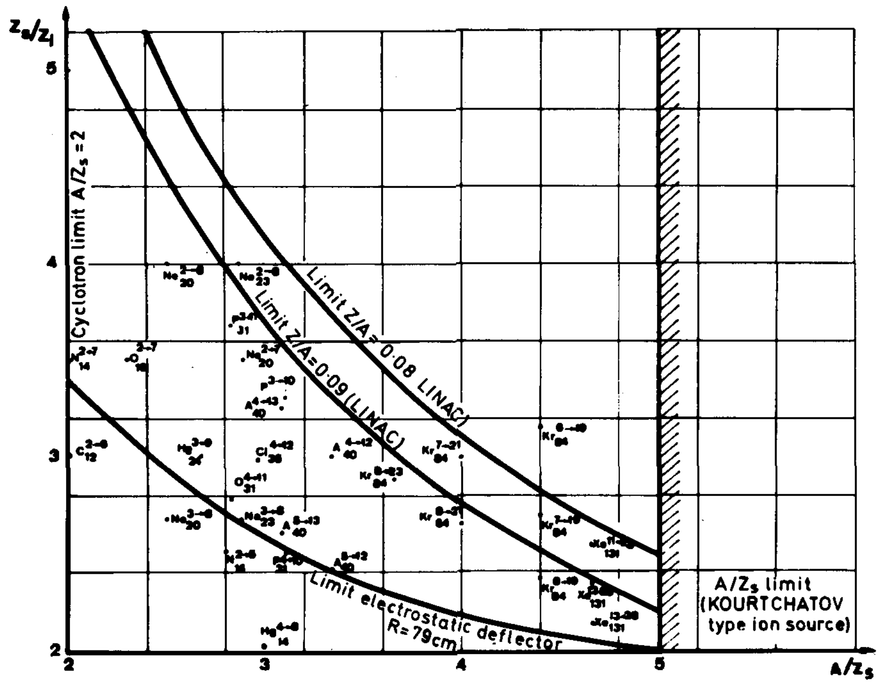

Fig. 3. Ratio stripped charge Z_s *to injected charge* Z_i *as a function of ratio mass number* A *to stripped charges* Z_s

The variations of α and φ are in fact limited by other factors, namely:

$Z_s/A \leqslant 0{\cdot}5$ for the accelerated ions in the cyclotron.

$Z_i/A \geqslant 0{\cdot}1$ or $0{\cdot}09$ for the ions in the linac.

$Z_i/Z_s \geqslant 1$ (stripping is then of no interest).

$A/Z_s \leqslant 5$ due to the ion source which for large A (i.e. $A = 131$) delivers charges of the order of $Z_i \lesssim A/10$.

the location of the electrostatic deflector in the cyclotron.

Fig. 3 summarises the capabilities of the project.

2.2 *Comparison with the results obtained with the real field geometry*

We have computed the trajectories of $N_{14}^{2\to7}$, $Ne_{20}^{2\to8}$, $A_{40}^{4\to13}$, $Kr_{84}^{8\to21}$, in the non-uniform magnetic field of the cyclotron. The results shown in Fig. 2 agree fairly well with the case of a uniform field since there is a difference of only 2° at most in the azimuthal position of the stripper except for nitrogen where the deviation reaches 10°. The large deviation in this case is due to the fact that with the incident angle α having its smallest value, the particle remains a longer time in the fringing field.

In conclusion, to accelerate all the above-mentioned ions it is necessary to have:

(a) a steering magnet, located as close as possible to the fringing field,

to vary the incidence angle α over a range of ±4° per tesla metre and
(b) a movable stripping target covering a range of 40° in azimuth and from 20 to 45 cm in radius.

3. BEAM TRANSPORT AND MATCHING

The beam has to be guided from the linac to the cyclotron and its emittance must match the acceptance of the machine.

3.1 *Phase space initial conditions*

We assumed an emittance of 22·5 π mm mrad at 1 MeV/amu, which is in agreement with the observed impact sizes, and an energy spread $\Delta E/E$ of ±0·5%. These figures are of the same order of magnitude as for similar machines.

In the horizontal plane, the cyclotron acceptance is determined by the separation between the first two revolutions and by the value of ν_r. With rf voltage ranging from 50 to 70–80 kV, the turn separation is of the order of 5–7 mm; the best acceptance computed was a spot size 6 mm wide with a ±7·3 mrad divergence. At the end of acceleration, the beam reaches a 9 mm maximum width.

In the vertical plane, we are limited by the dee aperture; the computations have shown that a spot height of 14 mm with a ±2·4 mrad divergence would give a maximum amplitude of 23 mm on the first turns, which is then progressively damped to 12 mm at the extraction radius.

3.2 *Focusing and bending elements*

The beam transport path extends over 27 m and involves a total angular deviation of 150°. This is due to the relative location of the linac and the cyclotron on the one hand and to the limited choice in the location of the stripper on the other.

Basically the system consists of (Fig. 4):

(a) an achromatic combination $D1$ with three components: two 45° bending magnets and a singlet at the centre of symmetry, and
(b) a combination $D2$ consisting of a 60° bending magnet, the cyclotron fringing field, and two intermediate singlets which provide quasi-achromaticity.

A steering magnet at the entrance of the cyclotron gives the correct direction of launching.

3.3 *Beam matching*[6]

The beam phase space ellipses given by the cyclotron acceptance [Fig. 5(a)], are transferred back to the entrance of $D2$ [Fig. 5 (b)]. A first triplet located at the linac exit, provides a phase ellipse of the same shape [Fig. 5 (c), 5(d)] as the

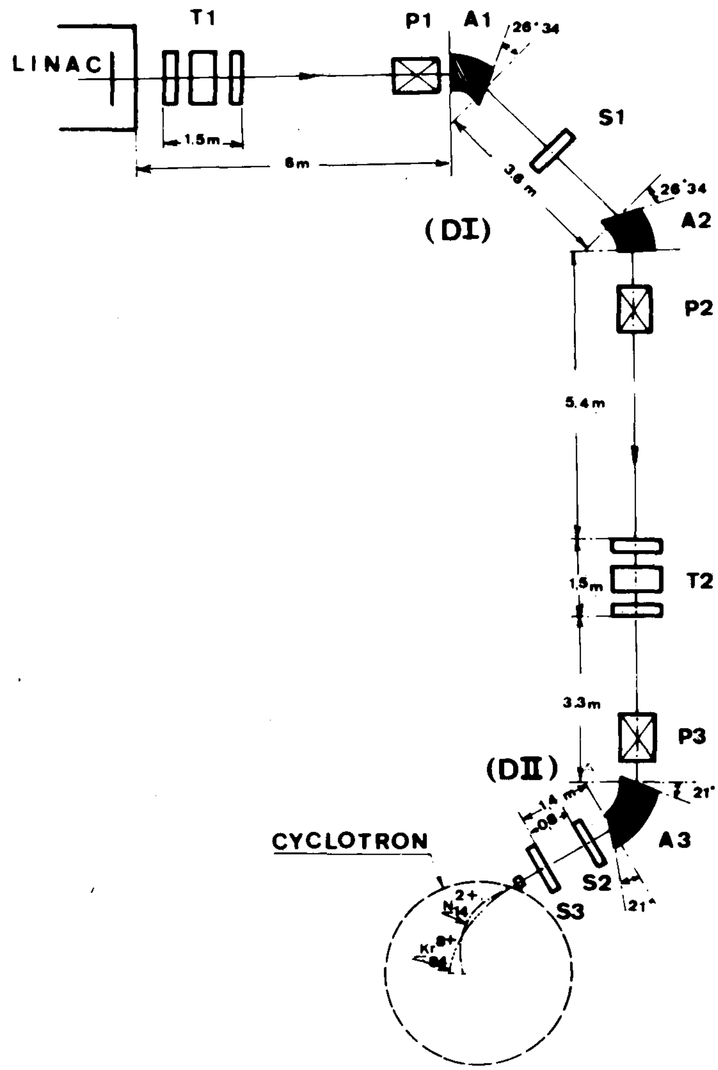

Fig. 4. Beam transport elements

one at the entrance of $D2$ [Fig. 5(d)] ; a second triplet is only used to rotate this ellipse [Fig. 5(e)] .

The main troubles in this transfer system came from $D2$: the cyclotron fringing field generates a strong vertical divergence; in order to get the proper vertical dimension on the stripping target, it is necessary to have some focusing elements as close as possible to the cyclotron, that is to the yoke and the oscillator. We used a programme[7] which calculates the optimum gradients for the best matching and which traces the beam envelope.

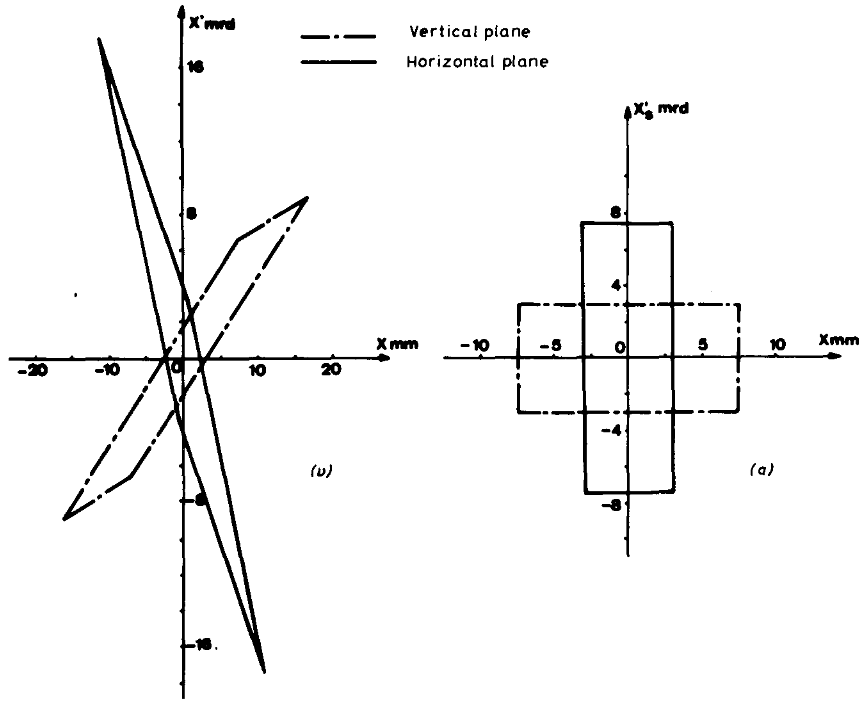

Fig. 5(a). Cyclotron acceptance

Fig. 5(b). Bending system D2*acceptance (entrance)*

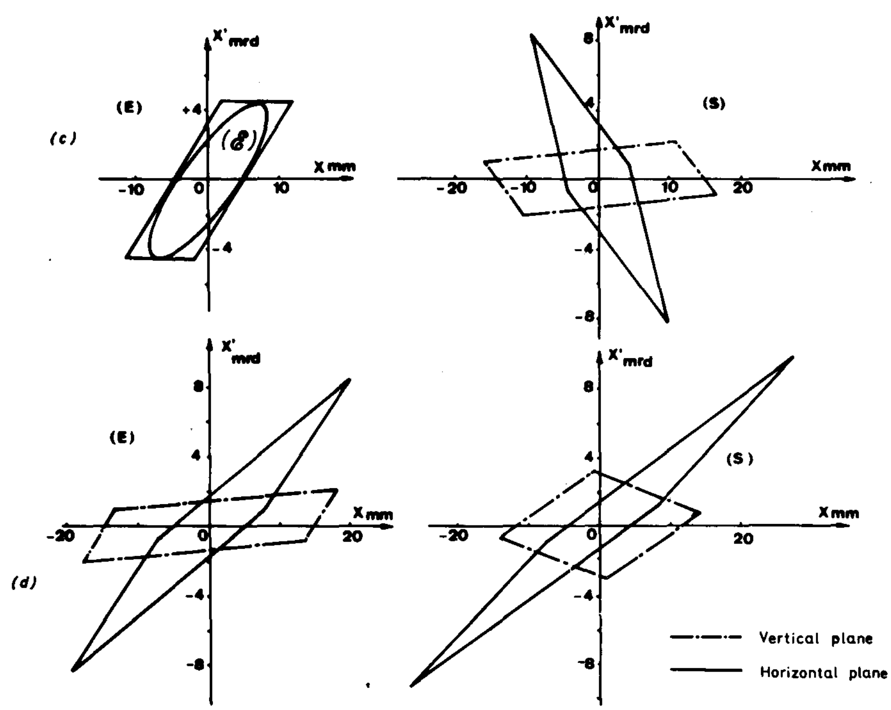

Fig. 5(c). Triplet T1 *acceptance*

Fig. 5(d). Bending system D1 *acceptance*

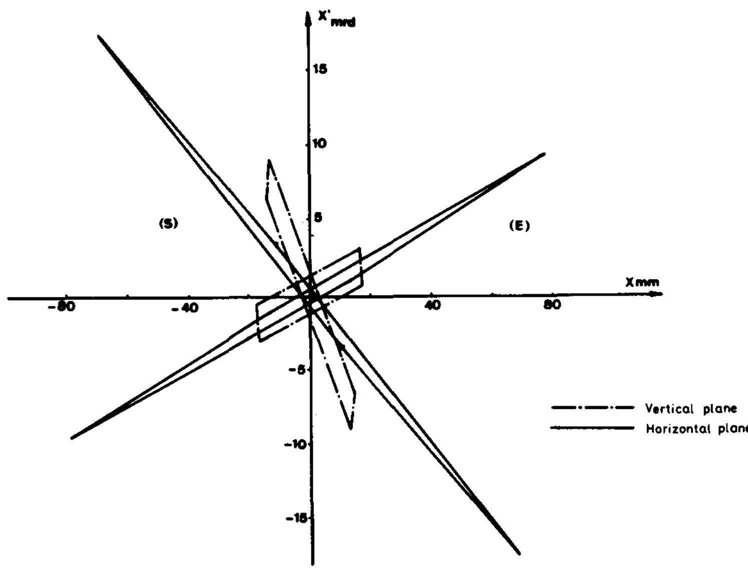

Fig. 5(e). Triplet T2 *effect*

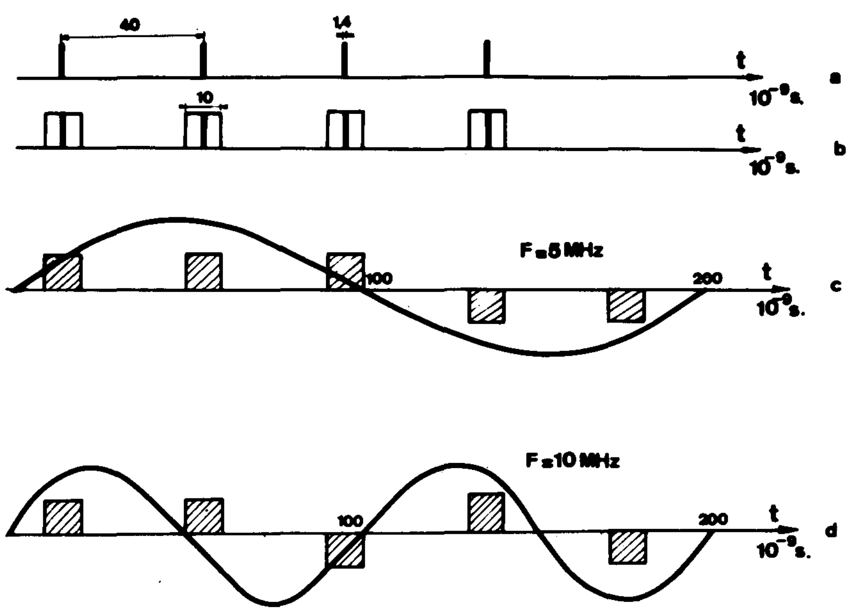

Fig. 6. Rf acceptance of the cyclotron

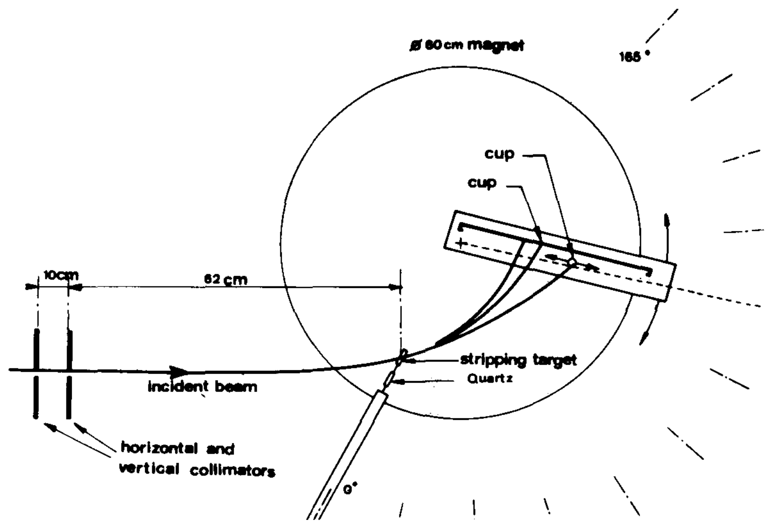

Fig. 7. Experimental set-up for stripped beam analysis

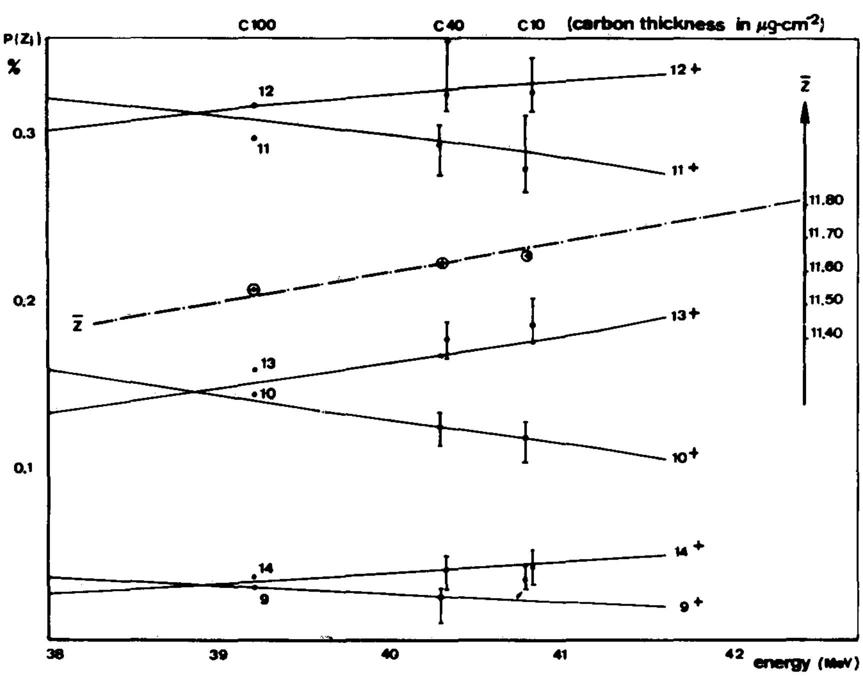

Fig. 8. Ionisation distribution for 40 MeV argon ions passing through 10, 40, and 100 μg/cm² carbon foils, compared with Betz and Schmelzer's results

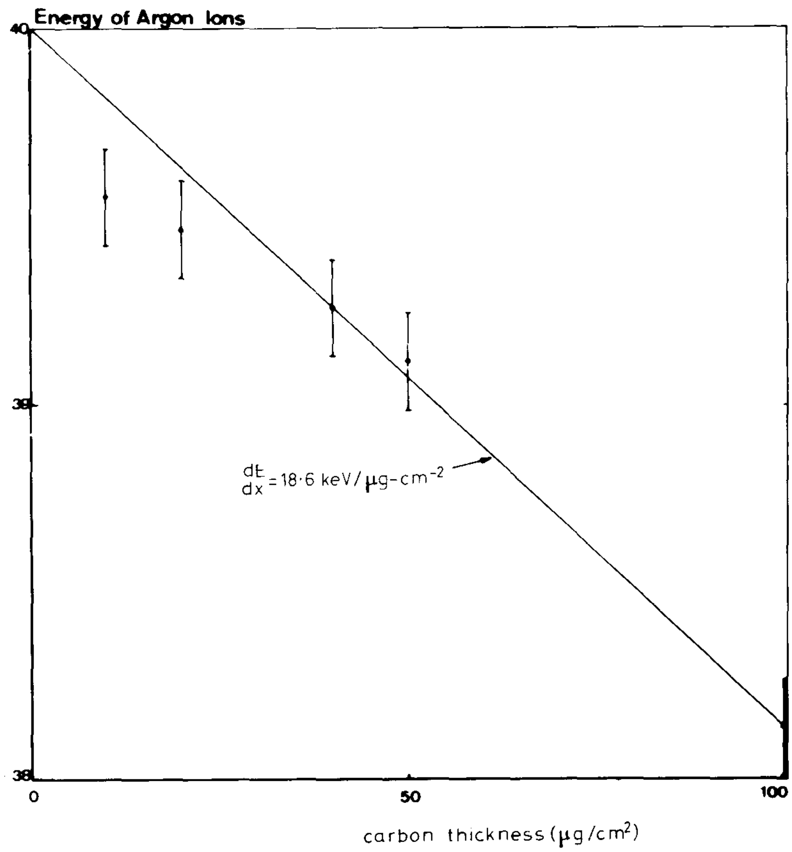

Fig. 9 Energy loss of 40 MeV argon ions in carbon

4. RF CONSIDERATIONS

A peculiarity of the system is that the linac works on a fixed frequency (25 MHz) while the cyclotron frequency ranges from 5 to 10 MHz according to the charge-to-mass ratio.

The phase bunching given by the linac extends over 12°, so that the bunches at $v = 0{\cdot}15 \times 10^8$ m/s are 1·4 ns long with intervals of 40 ns [Fig. 6(a)]. The debunching over the 27m separation between the linac and the cyclotron due to the 1% energy spread results in the bunches being 10 ns long at the end [Fig. 6(b)]. Consequently, these bunches fill between 18° (for $F = 5$ MHz) and 36° (for $F = 10$ MHz) of phase interval with respect to the cyclotron rf and there are respectively between three and five bunches per rf cycle [Figs. 6(c) and 6(d)].

But on the average, 40% fall in the positive portion of the sine wave, and since in order to miss the stripper after the first revolution, the rf voltage gain has to be between V_{max} and $\sim V_{max} \times \sqrt{3}/2$, the final accelerated proportion is of the order of 20% (1 bunch per cycle).

Also the two radiofrequencies are not necessarily multiples of each other

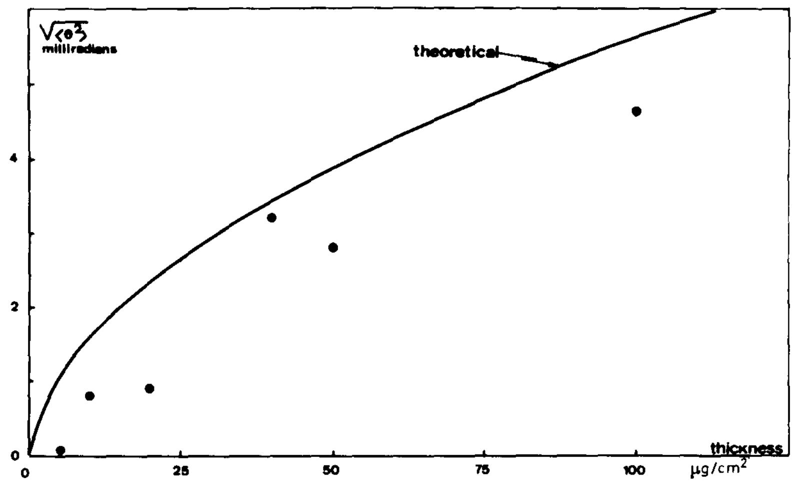

Fig. 10. Scattering of 40 MeV argon ions in carbon compared to results of multiple scattering theory

and therefore there is a continual shift of the phase of the bunches and thus a modulation in intensity and in energy.

The energy spread in consecutive bunches which is an inherent property of the system, is its biggest drawback and sets a lower limit to the energy spread of the extracted beams.

In fact, due to the debunching, the initial energy spread (1%) increases by a quantity $\leqslant 1{\cdot}6\ Z_s/A\%$ and due to the energy modulation, it only increases by a quantity $\leqslant 2\ Z_s/A\%$. The latter does not cause deterioration of the extracted beam quality. In addition to this, the beam has to go through the dee and is thus subject to a maximum energy variation of $\sim 12\ Z_i/A\%$, which will result in a spatial spread on the stripping foil of 4·5 mm. However, due to the rf acceptance, this figure does not exceed $2\ Z_i/A\%$.

5. STRIPPING

5.1. *Tests on solid targets*

In order to make preliminary studies on solid strippers, a switch, located at the exit of the linac, sends the beam to an analysing magnet containing the set-up shown in Fig. 7: the different components of the stripped beam are analysed by a radially moving Faraday cup, while another cup standing behind, is used as a monitor. With this system, we have already made[8] some measurements (with the cyclotron beam only): Fig. 8 shows an ionisation distribution obtained with argon ions through carbon, compared with the semi-empirical predictions by Betz and Schmelzer[9] with which the agreement is excellent. Figs. 9 and 10 show results of energy loss and scattering measurements.

5.2. *The target changer*

Since we plan to inject different ions at different energies, the stripping target position must be adjustable in order for the injected orbit to fit a closed orbit both in radius and tangent. We have designed a mechanism similar to a cyclotron ion source probe with radial and angular displacements. This system is of course entirely remote controlled.

The experience of other laboratories has shown that carbon is the cheapest, least dangerous stripping material and has an average lifetime comparable to the better-known beryllium oxide. We will use self-supporting foils, 10–20 $\mu g/cm^2$ thick; although this thickness may be changed since a range of 5–200 $\mu g/cm^2$ can easily be obtained. The carbon films will lie on *C*-shaped frames with a 0·5 mm diam. tungsten wire constituting the fourth side; when high intensities are needed, this wire has to be shaded by another wire located upstream and thermally isolated from the first one. The acceptance of the cyclotron requires 6 mm wide by 15 mm high foils; the foils are grounded but not cooled. The target position reproducibility is 0·5 mm in both directions.

We actually have very little information on the ageing of the foils under bombardment by high intensities of heavy ions beams, so we have made provision for a system of rapid change similar to that of a slide projector: a magazine contains 49 targets in line along an axis and each of them stands up into the beam in its turn. In the worst case, the foils should last about half an hour each under a flux of about 10^{12} particles/s cm^2, which provides a quasi-continuous operation for 24 h; replacing the whole set of targets should take about the same time as changing the ion source (<1 h).

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