Operational experience with the H⁻beam of the Milan cyclotron

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ABSTRACT

The purpose of this contribution is to report what has been learned from the operation of the Milan cyclotron, which in the past few years has been used mainly to accelerate H^- ions in the energy range from 20 to 45 MeV.

The extracted proton beam, obtained by stripping of the H^- ions is determined by the characteristics of the acceleration and extraction processes. In practice one wishes to know how the quality and geometry of the external beam depend on the factors controlling the injection, acceleration, and stripping of the H^- ions. The influence of these factors has therefore been investigated, and results will be presented on the effects of (i) dynamics of the last orbits before extraction, (ii) positioning of the ion source, (iii) magnetic field tuning, (iv) rf voltage, etc. The experimentally determined limits for the stability of some of the above parameters will be indicated.

A brief description of the extraction and combination device will be given, followed by a discussion of the convenience of using stripping foils of variable inclination, to improve the matching of the extracted beam with the transport system.

1. INTRODUCTION

The beam normally used at the Milan cyclotron is obtained by stripping the H^- internal beam at energies from 20 to 45 MeV. The various beams are directed along the same external line by means of a combination magnet and by varying the stripper position radially and azimuthally with a procedure similar to that already illustrated by other authors.[1,2]

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2. LAYOUT AND GENERAL BEAM CHARACTERISTICS

The general layout of the extraction and combination region is given in Fig. 1.

To vary the energy from 20 to 45 MeV, the stripper, consisting of an Al foil 0·2 mg/cm^2 thick, is moved from a radius of ~50 cm to ~70 cm. To direct various energy beams to the combination magnet centre, the stripper azimuthal position is varied by $-14°$ to $+6°$ with respect to the centre line of one of the Thomas hills. Each stripping probe position can be reproduced to within 0·3 mm.

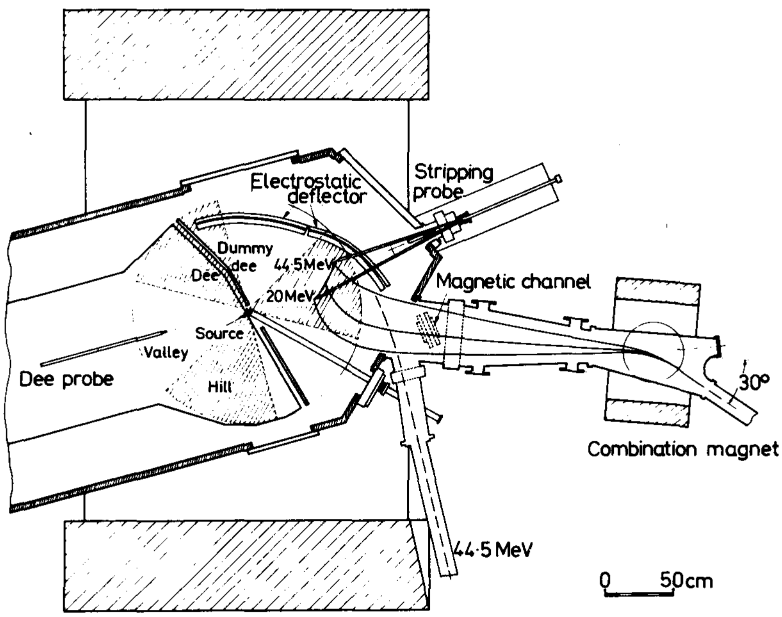

Fig. 1. General layout of extraction and combination area

The beam stripping is made in this region for two basic reasons: first, so as to leave inside the vacuum chamber the electrostatic deflector used for extracting the fixed energy beam of 45 MeV; second, to avoid too many modifications in the vacuum chamber structure.

The beam behaviour in the extraction region has been analysed by two computer programs with which, using the measured magnetic field values, the stripping foil positions corresponding to possible positions of the combination magnet and the optical characteristic of the magnetic field crossed by the protons could be determined.

In the region crossed by the protons emerging from the machine, the magnetic field is radially focusing at beam energies higher than 30 MeV, vertically focusing at lower energies and, in the region of 30 MeV, the field index along the trajectory is on the average between 0 and 1. It is evident that at lower energies, the superimposing of a horizontal defocusing with a greater energy dispersion will give inferior beam characteristics.

The beam combination is obtained by a magnet with cylindrical poles of 40 cm diam., placed at ~2 m from the cyclotron pole edge. This magnet also gives a beam deflection of ~30°. Once deflected, the variable energy beam is transmitted in 5 beam lines, 15° apart, by means of a switching magnet.

Table 1 shows various characteristics of the external beam.

Table 1. BEAM CHARACTERISTICS

Beam energy (MeV)	20·7	31·5	43·0
Extracted current (μA)	3·0	2·3	1·5
Horizontal emittance (mm mrad)	58	35	27
Vertical emittance (mm mrad)	40	35	35
Duty cycle (*FWHM*, %) max.	6·0	7·2	8·0
min.	1·6	2·2	1·4
Energy spread (*FWHM*, keV)	200 (at 24 MeV)	200	250 (at 36 MeV)
Transmission, %	20	35	50

The beam intensity, corresponding to 100% of that incident on the stripper, is measured as it leaves the machine.

Vertical and horizontal emittances have been measured, just outside the fringing field, intercepting the beam path with grating slits 0·5 mm wide, 6 mm apart for horizontal emittances, and 5 mm apart for vertical ones; the beam density distribution was recorded by a 1 mm wide density probe placed at 673 mm from the grating.

The energy spread was measured at the end of a beam line ~12 m long which presented a transmission of ~30%. The C^{12}(p, d) C^{11} reaction was used; the beam energy spread was determined with an error of ±15%.

The duty cycle measurements were made by detecting the protons elastically scattered from an aluminium target by means of a plastic scintillator and

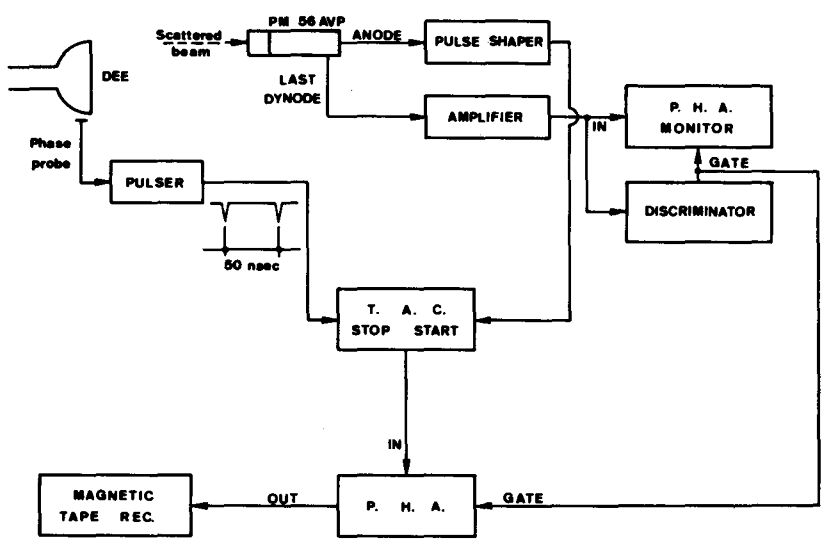

Fig. 2. Block diagram of duty cycle measurement system

measuring the time interval between the arrival of a proton and that of a standard impulse of 1 ns, synchronised with the dee rf voltage.

A block diagram of the measuring device is shown in Fig. 2.

The obtainable resolution is considered better than 100 ps. The measurement was made, at ~10 m distance from the cyclotron, at the end of a line transmitting 70-80% of the beam. The values shown in Table 1 for the three energies considered are, respectively, the maximum and minimum obtained by suitably varying some acceleration conditions such as the dee voltage, the source-puller position and the magnetic-field tuning. The measurements were made without using defining slits at the centre.

The last figures in the table give the transmission through a beam line which provides at the scattering chamber a beam 5×5 mm^2 in cross-section and having a 5×5 mm mrad divergence.

3. OBSERVATIONS ON BEAM ACCELERATION AND EXTRACTION BY STRIPPING

The results of various experimental studies made to improve the extracted beam characteristics will now be discussed. .

3.1. *Coherent oscillation effects on the extracted beam*

For normal acceleration conditions the dee voltage is about 40-45 kV; no beam definition systems are used in the central region,[3] except a puller and a flag fixed to the source chimney to intercept the protons. The source is positioned so as to improve the internal beam intensity, the position thus obtained usually corresponding, within 2 or 3 mm, to that foreseen theoretically. After this, the rf voltage and the magnetic field are re-adjusted for maximum transmission along the beam lines.

With this procedure a radial behaviour of the beam density of the type plotted in Figs 3(a) and 3(b) is normally obtained.

Density peaks that correspond to the first beam revolutions can be observed up to ~20 cm radius, and after that radius density variations due to coherent oscillations can be clearly seen.

In Figs 3(c) and 3(d) the theoretical development of a particular trajectory, represented in the phase space (r, p_r), is shown for comparison.

Correlating the transmissions of the transport system with the stripping foil positions and the beam density behaviour, we were able to conclude that the maximum transmission value is always obtained when the stripper is placed at radii where the internal beam density is lowest. This confirms that, also accelerating with negative ions, the presence of coherent oscillations is an advantage for extraction.

The influence of the coherent oscillations on the external beam characteristics was determined by deducing the horizontal emittance figures; to this end the stripping foil was placed in positions corresponding to the minimum and maximum radial density distributions [points A and B of Fig. 3(b)]; Figs 4(a) and 4(b) show the results obtained with the stripper in A, Figs 4(c) and 4(d) those corresponding to B.

It is seen that while in position A, the emittance value is 70 mm mrad, in position B it becomes in practice 170 mm mrad. In B positions the beam characteristics prove to be worse because, as appears from an examination of the

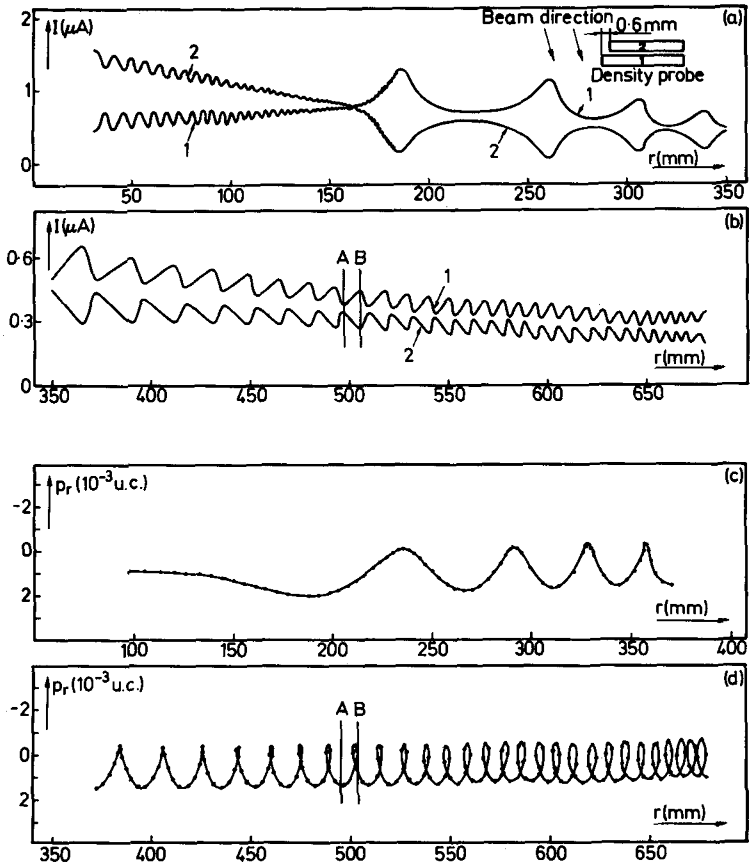

Fig. 3. (a) and (b): internal beam density distribution good for extraction in position A, (c) and (d): radial phase space plot of an off-centre particle, each point corresponding to two particle revolutions

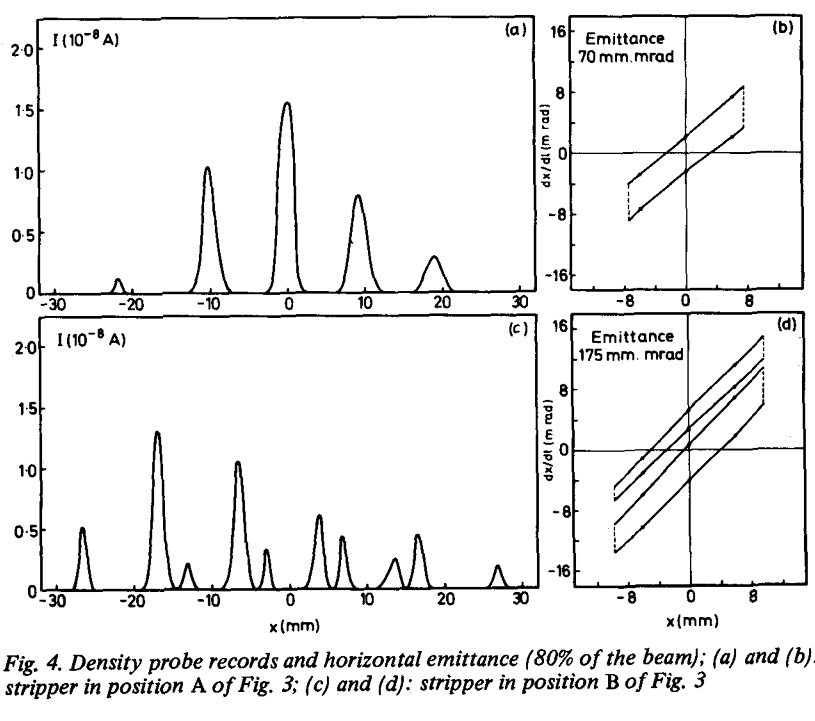

Fig. 4. Density probe records and horizontal emittance (80% of the beam); (a) and (b): stripper in position A of Fig. 3; (c) and (d): stripper in position B of Fig. 3

diagram 3(d), the beam consists of particles with p_r values grouped round two different values; also the energies of this group of particles are different, the variations corresponding to several (4 or 5) revolutions. It can therefore be expected that in *A* the external beam energy spread will be less than in *B*. The measurements made at 31·5 MeV at minimum and maximum density confirmed this expectancy [see Figs 5(a) and 5(b)].

In making these measurements, instead of moving the stripper to pass from minimum to maximum beam density, the dee voltage was varied by about 1 kV.

In Fig. 5(c) the beam energy spectrum obtained by intercepting two-thirds of the beam with a probe placed at an azimuthal distance of half a betatron oscillation from the stripper, is shown. The energy spread obtained with this method at 31·5 MeV was ~0·3%. This result was arrived at because the radial extension of the effective part of the stripper is ~2 mm.

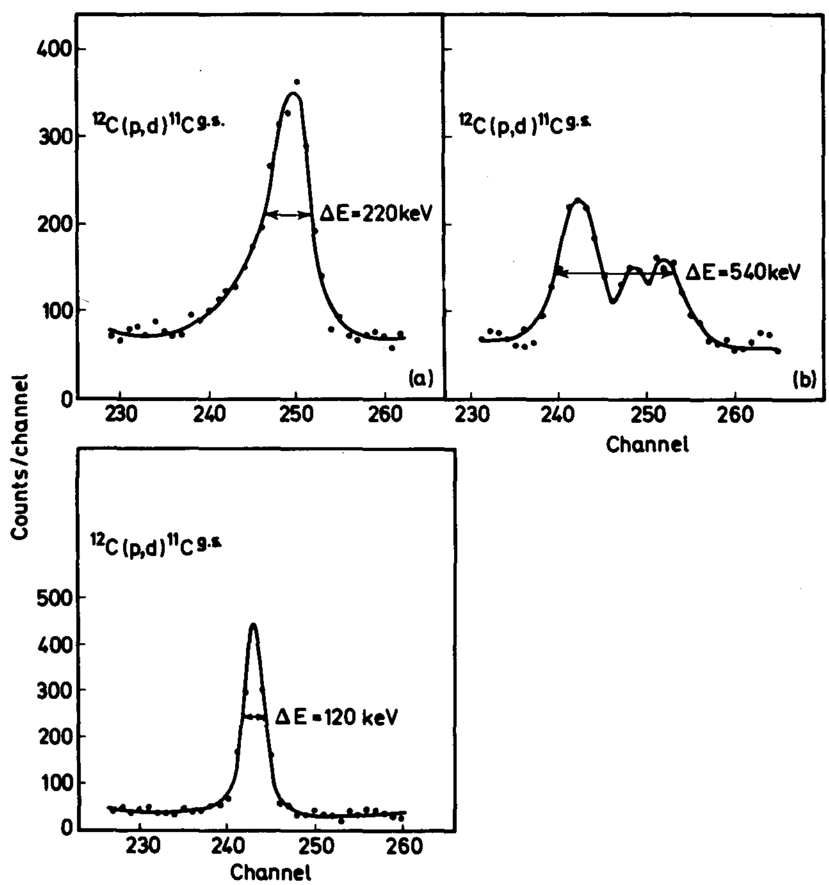

Fig. 5. Energy spectrum of the C^{12} *(*p, d*)*C^{11} *deuterons obtained by the 31·5 MeV beam: (a) stripper in position* A *of Fig. 3; (b) stripper in position* B *of Fig. 3; (c) reducing the beam intensity to one-third by the internal probe; the proton beam spread becomes 100 keV (*FWHM*)*

3.2. *Influence of magnetic field and rf voltage variations on duty cycle*

In normal working conditions the duty cycle was ~3-4 ns/50 ns (see Table 1). A typical figure obtained at 43 MeV with the method described in Section 2, is shown in Fig. 6(a).

By moving the source with respect to the puller a duty cycle reduction to 0·7 ns/50 ns was obtained, with an intensity reduction of 10-20.

Keeping the rf voltage constant and slightly increasing the magnet current in

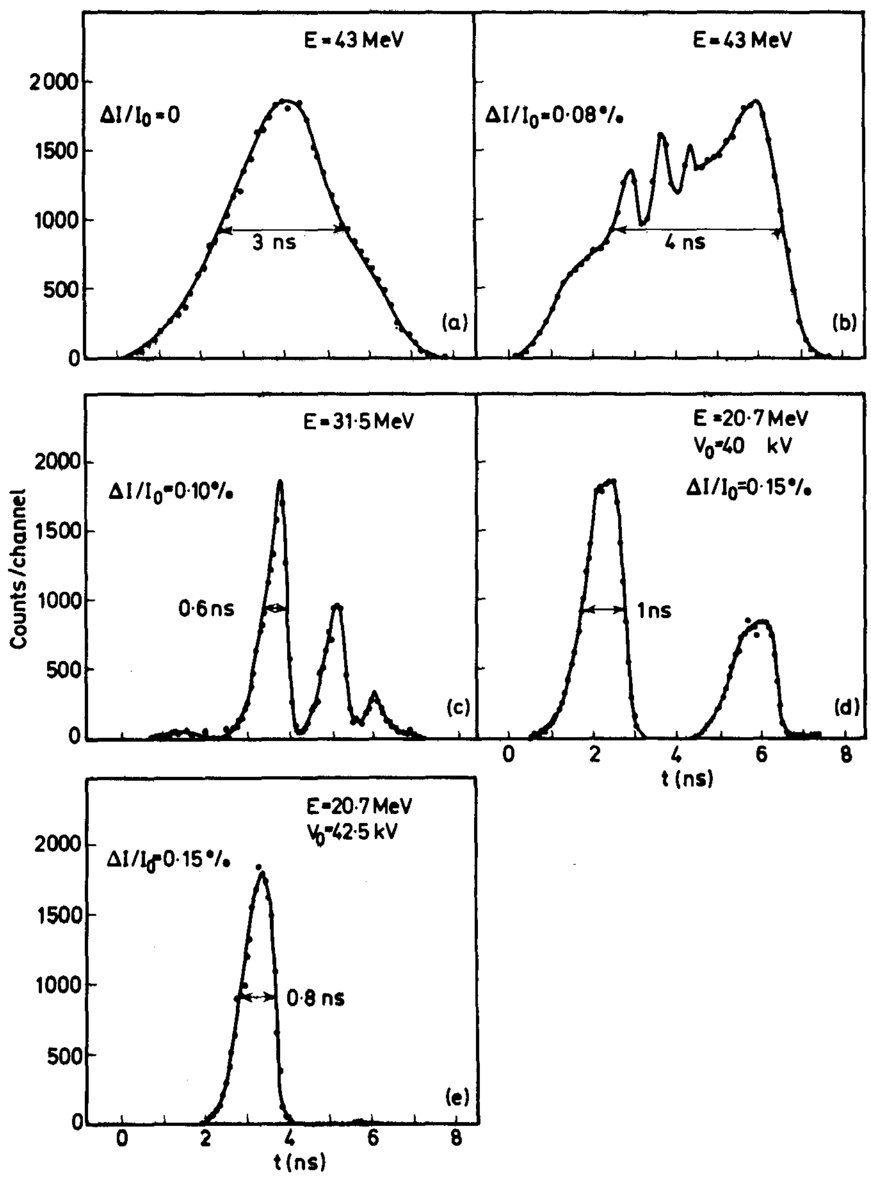

Fig. 6. Typical time structures of external beam pulses for various conditions of magnet current I *and rf voltage* V_0. *Rf period is 50 ns*

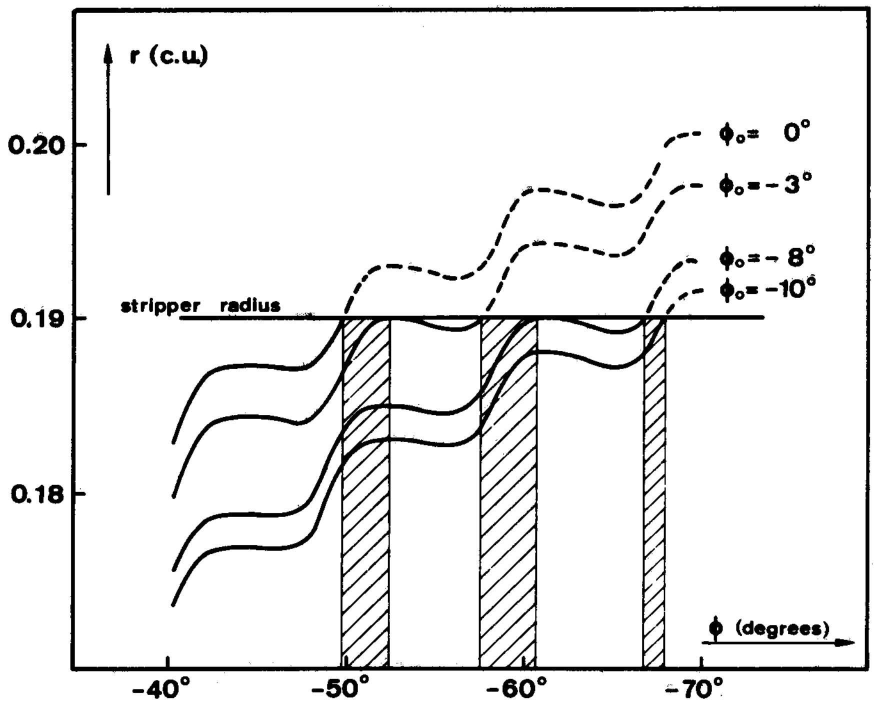

Fig. 7. Radial behaviour of the beam vs phase φ, computed for various initial phases φ_0 in the extraction region

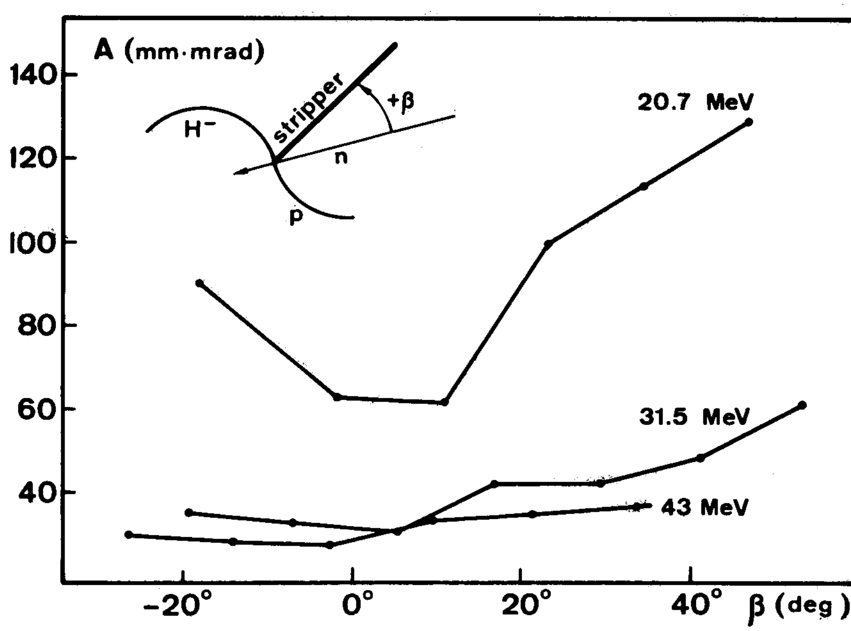

Fig. 8. Horizontal emittance (80% of the beam) vs β

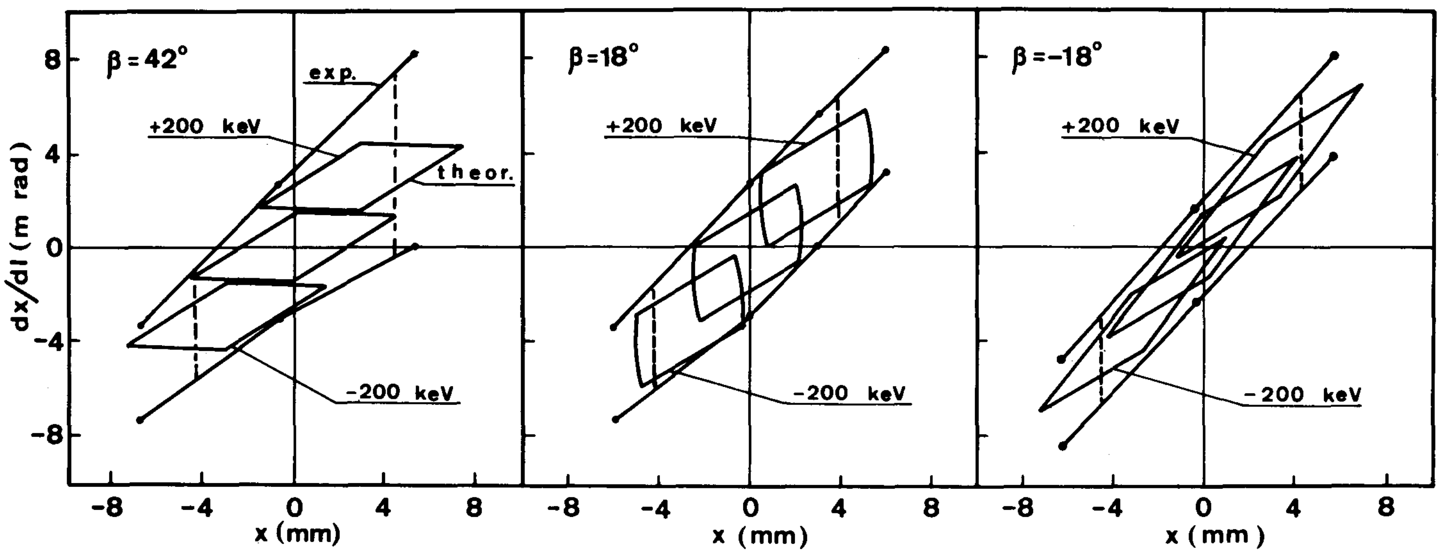

Fig. 9. Theoretical and experimental emittance figures for various β values. The surface between dashed lines is related to 80% of the beam intensity (31·5 MeV)

relation to the resonant value, the temporal beam structures shown in Figs 6(b), 6(c), and 6(d) were obtained for 43, 31·5, and 20·7 MeV energies. As can be seen from these figures, the peak structure of analysed pulses becomes more marked, passing from 43 to 20·7 MeV.

Appropriately increasing the rf voltage, some of the peaks disappear; at 20·7 MeV, for instance, we have the situation shown in Fig. 6(e), where the lower peak has completely disappeared, while the remaining peak shows a width of 0·8 ns (*FWHM*). In this case the beam intensity was not reduced by more than a factor of 3.

To interpret this situation theoretically we determined the trajectories of a bunch of particles with equal initial position and speed, but different initial phases in a magnetic field varied by 3 to 4/10 000 in relation to the resonant magnetic field.

At the stripper azimuthal position and in the vicinity of the extraction radius, for some particles considered, the values of r vs φ are shown in Fig. 7. When the radial oscillation amplitude, increasing progressively at the approach of the decelerating value $\varphi = -90^\circ$, is such as to produce negative radial gain, the beam extraction occurs in two or three bunches clearly distinct from one another.

3.3. *Effect on external beam characteristics of varying the angle between beam and stripper*

We finally investigated the effect of varying the angle between the stripper and the equilibrium orbit on the horizontal emittance values. At 20·7, 31·5 and 43 MeV, the behaviour of the emittance surfaces corresponding to 80% of the beam in relation to the angle β between the stripper and the normal to the equilibrium orbit, are shown in Fig. 8.

It can be noted that the influence of this parameter on the horizontal emittance surface increases noticeably with the lowering of the energy.

For any one energy, however, the effect of that angle on horizontal emittance figures is not negligible. From the experimental and theoretical studies carried out, it was shown that this effect could be exploited to reduce the beam energy spread simply by collimating the beam with a slit placed at the exit from the machine. An example of how the emittance figure depends on the stripper angle is shown in Fig. 9, where the theoretical figures have been calculated for a beam having, at the stripper, a radial extension of +1 mm and an angular divergence of +3 mrad and for an energy spread of +200 keV.

It may be interesting to underline that with this method, the horizontal emittance figure can be varied within certain limits without altering the vertical one.

The practical use of the results illustrated in this paragraph has enabled us to improve the emittance and energy spread by more than a factor of 2 in relation to those previously obtained. To make use of these effects currently, a stability of at least 2 in 10^5 in the magnetic field intensity, and of 1 in 10^3 in dee voltage, is necessary.

DISCUSSION

Speaker addressed: G. Dutto (Milan).

Question by E. G. Auld (UBC): What is the operating vacuum in the cyclotron and what is the energy gain per turn?

Answer: The pressure is 6 to 7 $\times$ 10^{-6} torr and the energy gain per turn is 80 to 100 keV.

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3. Castiglioni, M., Dutto, G., Fois, M., Resmini, F., Strini, G., Succi, C., and Tagliaferri, G., *Nuovo Cimento* **41B,** 244, (1966).