HIGH QUALITY BEAMS WITH PRECESSION INJECTION

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Summary

By controlling the initial conditions of injection of a precession injection cyclotron, an acceptance in the space and time domain could be determined giving a small horizontal betatron motion. Experiments are described. Numerical and experimental results are given.

Introduction

It has been demonstrated [1,2] that a cyclotron with an azimuthally varying field may be equipped with external injection, using the precession motion along a hill-valley boundary as a means to transport particles from the outside to the central region of a specially adapted magnet field, see fig.1. Such an injection system has been built into the Delft 12 MeV isochronous cyclotron. Beams of more than 100 μA could be accelerated. During the experiments with this system, it became markedly clear that it was easy to handle.

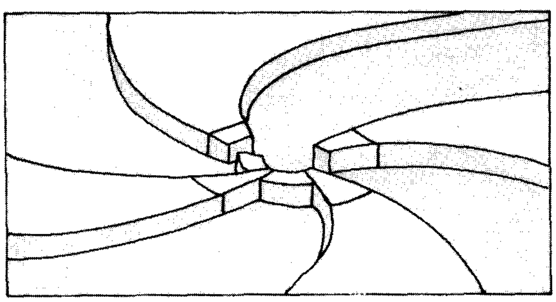

Fig.1. Shape of the magnet pole in the central region of a precession injection cyclotron.

However, measurements showed that a large incoherent horizontal betatron motion was present during acceleration. Although in many applications this is acceptable, small incoherent oscillations must be realised in a good precession injection cyclotron.

Both with beams in the cyclotron and by numerical methods, the betatron motion has been studied. To be able to do this, not only the space variables had to be taken into account, but also the time structure of the beam. In the following it will be shown how a small incoherent horizontal betatron motion may be realised in a precession injection cyclotron.

The equilibrium orbit

A reference orbit can be determined by integrating backwards in time from an equilibrium orbit in the normal acceleration regime. For small deviations in space and in time, this reference orbit can be considered as an equilibrium orbit, provided the energy deviation is small. In many cases we are not interested in the actual orbit of a particle as long as its betatron motion is small. Then an energy deviation may be translated into a shift in the equilibrium orbit away from the reference orbit. This we will do here.

Numerical analysis

First, it was both numerically and analytically established that the horizontal and vertical betatron motions could be considered as linear and independent. Thus for the horizontal betatron motion, the following are variables during precession: the transverse deviation from the equilibrium orbit ξ, the angular deviation ξ', the energy deviation ΔE from the injection energy E_i, and the time deviation ΔT from a reference position on the reference orbit. During acceleration, ξ, ξ', and ΔT remain, while the energy deviation has vanished, provided ξ and ξ' are taken relative to the equilibrium orbit belonging to the energy the particle has.

The transformation from the precession at a point directly after the inflector, to the acceleration regime at about 15 cm radius, could be given as

$$\begin{pmatrix} \xi \\ \xi' R \\ \tau \end{pmatrix}_{acc} = \begin{pmatrix} 17 & 6 & 2.2 & 3.2 \\ -21 & -7 & -2.3 & 46 \\ 1.1 & 0.4 & 0.3 & 0.3 \end{pmatrix} \begin{pmatrix} \xi \\ \xi' R \\ \tau \\ \varepsilon \end{pmatrix}_{prec} \qquad 1)$$

with R = mean radius of curvature, $\tau = \Delta T/T \times 10^2$, T = period of one particle revolution, $\varepsilon = \Delta E/E \times 10^2$.

The transformation shows a number of interesting properties. First, the elements of the matrix connecting ξ and $\xi' R$ are relatively large. As a consequence a bad matching in the precession will give rise to large betatron amplitudes during acceleration. Second, the betatron amplitude is dependent on the phase at which the particle enters the precession. Third, there exists phase compression. Fourth, there is a strong dependence on the injection energy, but with an electrostatic preaccelerator energy deviations are generally very low.

The inflector may be represented, setting $\varepsilon = 0$, as

$$\begin{pmatrix} \xi \\ \xi' R \\ \tau \end{pmatrix} = \begin{pmatrix} 0.3 & 3.4 & 0 \\ -0.28 & 0.14 & 0 \\ 0.46 & 0 & 1 \end{pmatrix} \begin{pmatrix} \xi \\ \xi' R \\ \tau \end{pmatrix} \qquad 2)$$

Combining 1) and 2), and setting $\tau = 0$, gives

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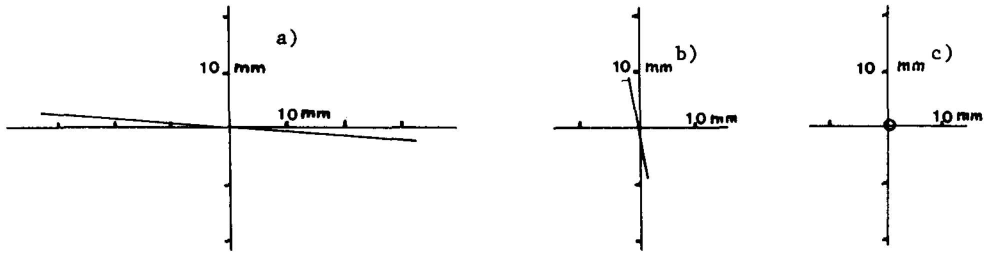

Fig.2. Phase plane of horizontal betatron motion at a)inflector entrance, b) after inflector, c) at 15 cm radius in the cyclotron during acceleration.

$$\begin{pmatrix} \xi \\ \xi' R \\ \tau \end{pmatrix}_{acc} = \begin{pmatrix} 4.4 & 58.6 & 2.2 \\ -5.4 & -72.4 & -2.3 \\ 0.36 & 3.8 & 0.3 \end{pmatrix} \begin{pmatrix} \xi \\ \xi' R \\ \tau \end{pmatrix}_{prec}$$

Fig.2 gives the transformations 1), 2) and 3) for $\varepsilon = 0$, $\tau = 0$.If the injected beam is ill matched, large betatron oscillations will follow during acceleration.

Experiments

The first experiments with a precession injection cyclotron took place with a d.c. beam (although with a macro duty cycle to minimize radiation). To analyse the relationship between the initial conditions at injection and the betatron motion during acceleration, the beam line connecting the preaccelerator and the cyclotron was modified, see fig.3. In the beam line a set of vertical slits with an aperture of 1 mm is placed. The first slit is at A, directly after the extraction chamber of the ion source. The second slit is placed at B, directly after the bending magnet BM. These slits bring the emittance of the preaccelerator down to less then 2 mm-mrad. After the second slit are deflection plates at C, which can be driven at a frequency half of that of the dee. Then after the deflection plates, at D, a third slit is placed. The beam passes the third slit only during the small fraction of the acceleration period when the deflection plates are excited.

Experiments were carried out as follows:

a) With no voltage on the deflection plates, the beam was brought into the cyclotron in the precession mode and measured by a target intercepting the precession beam. This was done by the steering magnets, quadrupoles and bending magnet before the deflection plates. Then with the quadrupoles and the steering magnets after the third slit, the initial conditions of the injection could be chosen, spatially. For a typical set of initial conditions, a beam current of more

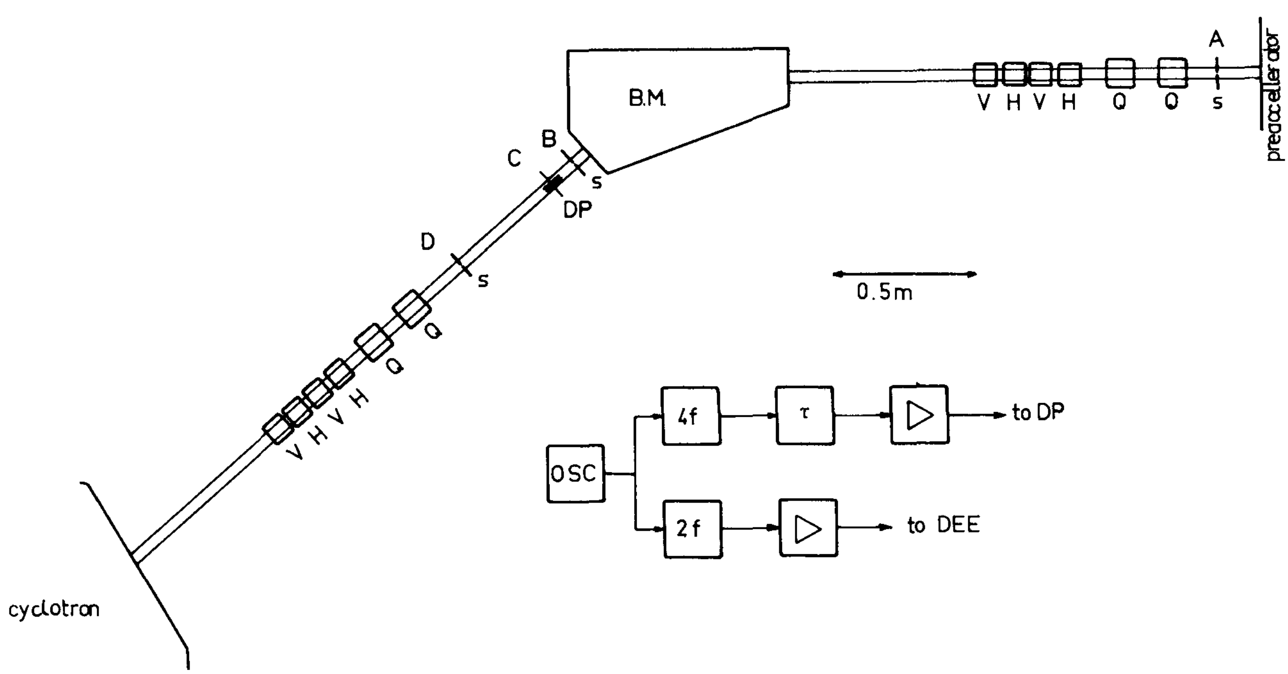

Fig.3. Diagram of the beam line

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then 20 μA would be thrown on the target in the precession.

b) The deflection plate voltage was turned on. The inflection plates are tuned, so that a good sinusoidal voltage will appear on the deflection plates. In this way it is certain that the beam passes the third slit at zero deflection plate voltage. If this would not be the case, a phase shift with reference to the acceleration voltage would occur.

c) The target in the precession beam is drawn back and used in the acceleration regime in combination with a second target, to perform shadow measurements. The shadow measurements usually were performed with 25, 50 and 75 percent on one target with the other at constant radius, while the sum current of the targets would be monitored for constancy.

By determining the ratio between the current on a target in the precession (where there is no influence of the phase at which particles are injected) with the deflection plates turned on and off, the length of the beam pulses could be determined. A typical length would be 2 percent of an acceleration period, giving, at a frequency of 20.25 MHz, a pulse duration of 1 nanosecond.

Experimental results

It appeared that the moment of injection was the parameter which could shift the beam most.

Fig.4 gives the results of a set of measurements where the parameters ξ and ξ' were varied over a phase area of about 20 mm-mrad, such that the beam current would remain constant between 80 and 100 percent.

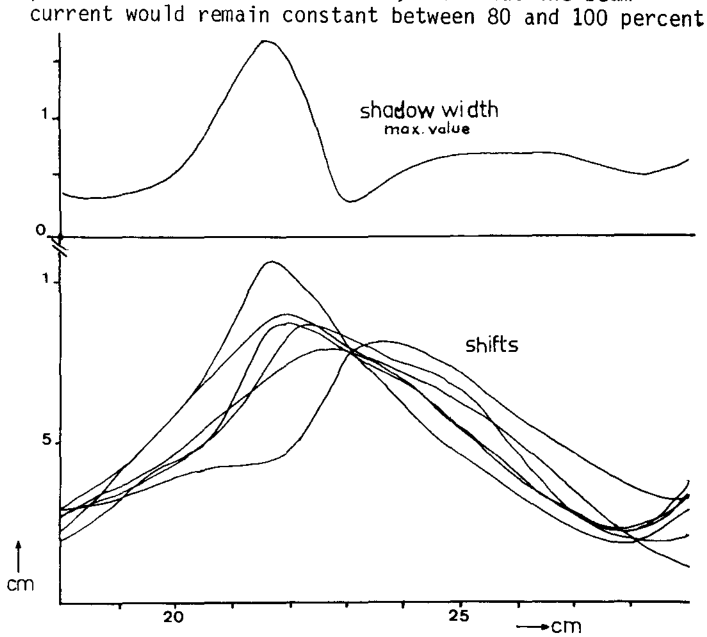

Fig. 4. Beam shift and shadow width when the spatial initial conditions at injection are varied

During the measurement of a particular set of initial conditions, the phase difference between acceleration voltage and deflection voltage has to be kept constant since a detuning of the dee will give a phase shift. Therefore it would be better to use the dee voltage itself to drive a phase lock system, keeping the two voltages of deflection plates and dee at a constant phase difference.

During the experiments, ξ, ξ', τ, inflector voltage, acceleration voltage, magnet field and acceleration frequency were varied.

The shadow width and also the coherent betatron motion showed not much change. This was typical for these experiments. It shows that the acceptance of the cyclotron is large enough to handle the beam of a good preaccelerator.

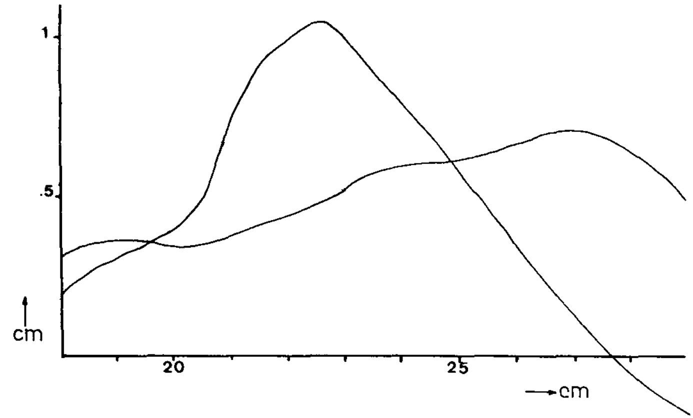

Fig.5. Beam shift when the phase at which beam pulses are injected is varied.

Fig.5 gives the results of a change in the phase of the injected beam pulse. To minimize changes in the whole system, at every radius six shadow measurements were made in succession, i.e. three at a fixed phase difference and then three with a fixed phase shift of 5 nanoseconds. The results shown are particularly striking. In both cases the shadow width is not large, but the coherent betatron amplitude changes considerably. From this we may conclude that, were both beam parts injected, the resultant shadow width would be much larger. Thus, if a d.c. beam is injected, the phase spread of that beam will give a large incoherent betatron motion.

The acceleration voltage is not an important parameter. At first a large dependence was observed, but this could be reduced to an existing phase dependence of the dee amplitude control. After the monitoring of the phase difference between acceleration voltage and deflection voltage, the dependence had almost vanished. Between acceleration at 28 kV and 16 kV dee voltage, only a small increase in shadow width was observed, and only a small shift in beam position.

The magnet field is an important parameter. If the magnet field is changed over 2×10^{-4}, the beam shifts several mm. Since in normal practice the magnet field stability is better, this parameter can be made negligible.

The acceleration frequency is not important, but it has its normal influence on the isochronism.

The inflector voltage can be used to shift the beam orbits, but then care must be taken to adjust for the right initial conditions. In order to obtain a large range of initial conditions, it is necessary to change the settings of the steering magnets next to the cyclotron when the inflection voltage is changed.

Fig.6 shows the results obtained with the present set-up and some results with the original system.

Conclusions

The observed importance of the phase at which particles enter the cyclotron leads to several conclusions:

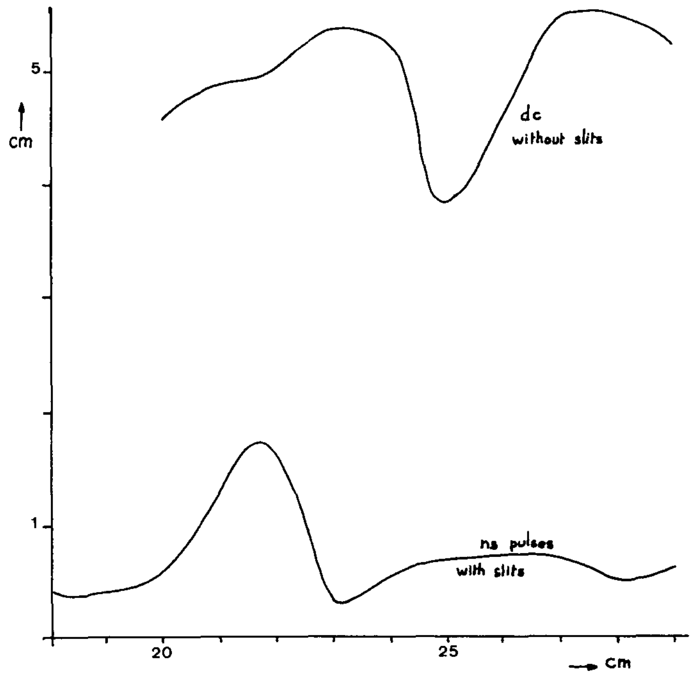

Fig.6. Results of shadow measurements with a system with injected d.c. beam, and without slits in the beam line, and a system with slits and a nanosecond beam chopper

a) In the case of a cyclotron used for the production of radio isotopes, a large shadow width is no disadvantage. In that case there is no need to take special measures. Advantages would be the ease of handling of this process, the large beam efficiency and the fact that the continuity of production could be enhanced by using several ion sources. These ion sources would not be in a radiation enviroment.

b) In the case of a cyclotron where small beam intensities are sufficient, a beam chopper system as described above may give good performance. This system would have the added advantage of a beam of extremely short beam pulses.

c) In the case of a cyclotron where both a large beam current and a high beam quality are desired, a beam buncher will decrease the phase width of the internal beam and thus will generate a good beam quality.

References

1) W.A.van Kampen and J.Liedorp, Experientia Suppl. (Zürich)23(1975)254-8
2) W.A.van Kampen and J.Liedorp, Nucl.Instr.and Meth. 140(1977)219-26

** DISCUSSION **

H. SCHREUDER: You told us something about the coupling between the time and the horizontal motion in the normal acceleration mode. Could you also comment on the complementary effects --I mean the coupling from initial horizontal beam quality to time structure in the circulating beam?

W. VAN KAMPEN: Well, theoretically, if we look at a transformation matrix we see that there is a compression of the phase length from the injection process to the acceleration regime. The factor in the matrix is smaller than one and it gives a time compression. So we think that there is actually phase compression present, but do not yet have the instrumentation at our disposal to measure it. We hope to establish this soon experimentally.

W. JOHO: Your new system created a lot of enthusiasm and interest at the 1975 Zurich conference. Did somebody follow up this idea in the meantime and plan precession injection in his cyclotron?

W. VAN KAMPEN: As far as we know, there are no plans for a new precession injection cyclotron at the moment. We think that such a cyclotron would have many advantages for a user, but it seems to be a large step to make the decision to build one.

G. DUTTO: Is it possible to use precession injection in a compact cyclotron?

W. VAN KAMPEN: Precession injection can be used in a compact cyclotron. In this case it may be necessary to choose inflector plates with smaller vertical dimensions. In our case these plates are 50 mm high, to be sure without further computations that no vertical components of the electrical inflector field would be present near the injected beam.

K. ERDMAN: What acceleration voltage did you use on the dee during the study?

W. VAN KAMPEN: Our normal accelerator voltage is 28 kV. We also accelerated the beam with a voltage as low as 16 kV, which gave no problems provided we injected at a suitable electrical phase.