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A MODIFIED REGENERATIVE EXTRACTION SYSTEM FOR A SYNCHRO-CYCLOTRON

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(Presented by G.T. de Kruiff)

In the existing regenerative extraction systems for synchro-cyclotrons the regenerator excites a forced radial oscillation of a frequency equal to the cyclotron frequency at the last equilibrium orbit. The choice of regenerator strength as a function of radius is made such as to give the required turn separation at the magnetic channel entrance with the smallest possible axial blowup of the beam. During the deflection process the beam trajectories pass the two radial nodes N1 and N2 on the last equilibrium orbit (Fig. 1). The increasing axial blowup during deflection and the large radial divergence of the beam on its way out from N2 decrease the fraction of the regenerated beam which will enter the magnetic channel. Although a further revolution through the regenerator would give an increased radial deflection, making the field-reducing magnetic channel superfluous, the resulting radial and axial divergences would make the useful part of the regenerated beam rather small.

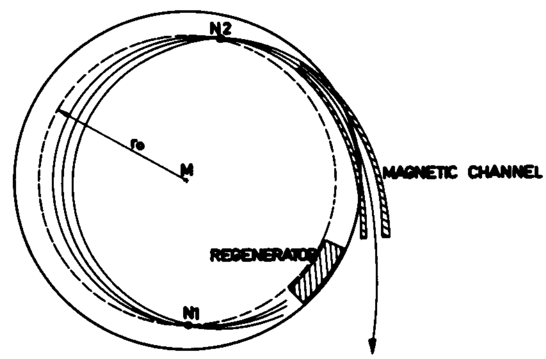

Fig. 1 Regenerative extraction system without compressor.

To deflect a large fraction of the internal beam without using a field reducing magnetic channel, a new device, which we shall call the "compressor", has been proposed by one of the authors. The compressor, giving a negative field bump, is placed 30° behind the regenerator in the direction of the circulating beam. The effect of the compressor on the regenerated beam is noticeable only during the last revolution. In combination with a

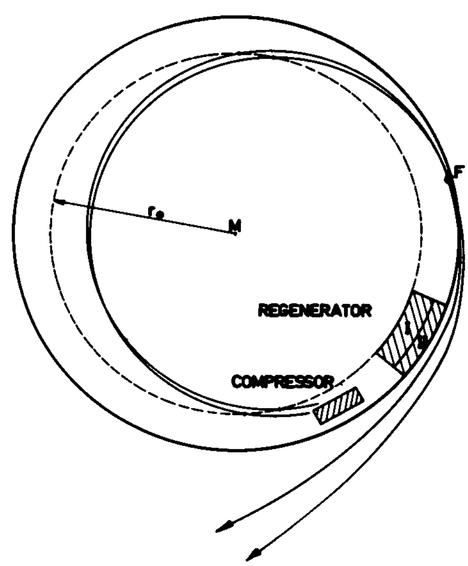

Fig. 2 Regenerative extraction system with compressor.

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modified and extended regenerator field the regenerated beam is brought to a radial focus F at the edge of the pole near the regenerator (Fig. 2).

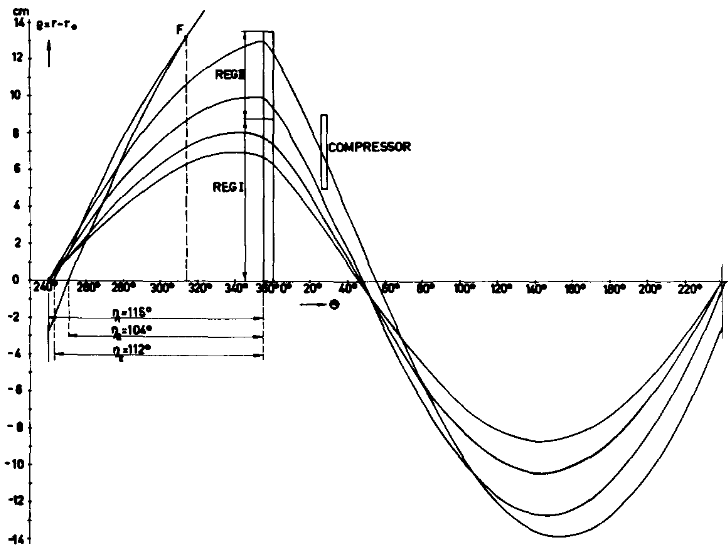

Fig. 3 Radial oscillations of two particles in the extraction system.

The regenerator field consists of two regions (Fig. 3) : the first, by which a forced radial oscillation with constant phase is excited; and the second, which is seen by the beam only during the last revolution, and which is adjusted to the compressor to shift the phase of the oscillation, depending on its amplitude, to give the required radial focus.

A deflection system incorporating a compressor was constructed for the first time in the deuteron synchro-cyclotron which was constructed for the II Physikalisches Institut of the University of Göttingen. The main characteristics for this machine are :

Deuteron energy	27 MeV at 75 cm radius.
Particle α energy	54 MeV at 75 cm radius.
Pole diameter	180 cm.
Deflection radius	75 cm.

<u>Calculations</u>

<u>Radial Oscillations</u>. The regenerator and compressor fields can conveniently be determined from the phase diagram representation (Fig. 4) of the radial oscillations about the radius r_0 = 75 cm. We solved the approximate equation

$$\frac{d^2r}{d\vartheta^2} = - r\,\frac{rB(r) - r_0B_0}{r_0B_0}\,, \qquad (1)$$

for a number of oscillation amplitudes, using the measured values of B(r).

The effect of the regenerator on the oscillating beam trajectories is given by

$$\begin{aligned} r(0+) &= r(0-), \\ r'(0+) &= r'(0-) - \left(\frac{r}{r_0}\right) I(r), \end{aligned} \qquad (2)$$

and the effect of the compressor by

$$\begin{aligned} r(30+) &= r(30^\circ-), \\ r'(30+) &= r'(30^\circ-) - \left(\frac{r}{r_0}\right) C(r)\,. \end{aligned} \qquad (3)$$

Here (0−), (0+) and (30°−), (30°+) denote the positions just before and just after passing the regenerator or compressor respectively. The regenerator and compressor integrals I(r) and C(r) are defined by

$$I(r) = \int \frac{(\Delta B)_{reg.}}{B_0} \, r d\vartheta, \tag{4}$$

$$C(r) = \int \frac{(\Delta B)_{compr.}}{B_0} \, r d\vartheta. \tag{5}$$

The first region of the regenerator, characterized by the phase angle η, of the oscillations (see Fig. 1), determines the increase in amplitude of the successive revolutions. During the last revolution the particles pass the second region of the regenerator. Here the phase of the oscillation is shifted, depending on its amplitude. The compressor, placed 30° behind the regenerator, shifts the phase of the oscillations somewhat while compressing the spread of oscillation amplitudes in the regenerated beam. The combined effect of regenerator and compressor gives a radial focus F, 285° after passing the compressor (Fig. 3).

The final choice among the many possible regenerators designs is made after taking into consideration axial limitation of beam size and convenience for realizing the necessary field

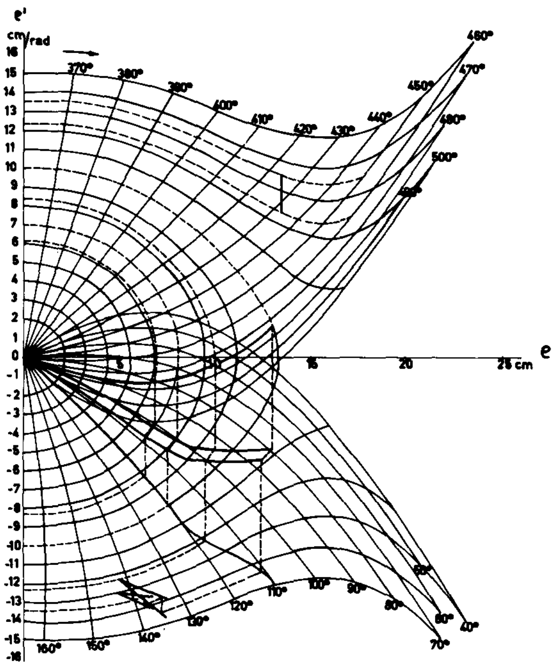

Fig. 4 Phase diagram of radial oscillations. r_0 = 75 cm, $B(r_0)$ = 14,205 gauss.

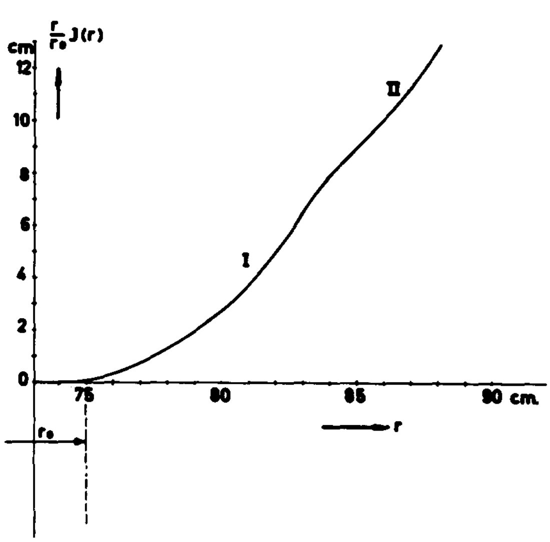

Fig. 5 Regenerator integral.

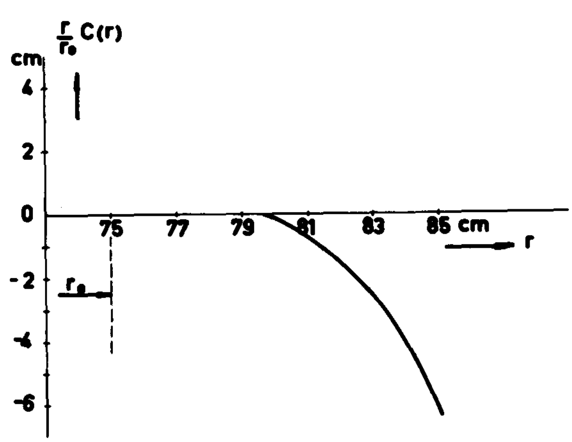

Fig. 6 Compressor integral.

deformations to produce the wanted regenerator and compressor integrals (Fig. 5 and 6).

Axial Stability. By calculating the fundamental solutions of the axial differential equation

$$\frac{d^2z}{d\vartheta^2} = z \cdot \frac{r^2}{r_0 B_0} \frac{dB}{dr} , \qquad (6)$$

using the radial solutions of equation (1) one obtains the transfer matrices of the vector $\begin{pmatrix} z \\ z' \end{pmatrix}$ during the deflection process. The effect of the regenerator and compressor on the axial vector may be written in matrix form

$$\begin{pmatrix} 1 , & 0 \\ \frac{r}{r_0} \frac{dI(r)}{dr} , & 1 \end{pmatrix}$$ for the regenerator and

$$\begin{pmatrix} 1 , & 0 \\ \frac{r}{r_0} \frac{dC(r)}{dr} , & 1 \end{pmatrix}$$ for the compressor.

For one of the radial oscillations, as presented in Fig. 3 and 4, we have also followed in the z-z' diagram those particles which were originally, i.e. before deflection, contained in an ellipse having maximum amplitude z_{max} = 1 cm and $z'_{max} = z_{max} \sqrt{0.11} = 0.33$ cm/rad. (Fig. 7). n = 0.11 is the field index at the deflection radius r_0 = 75 cm.

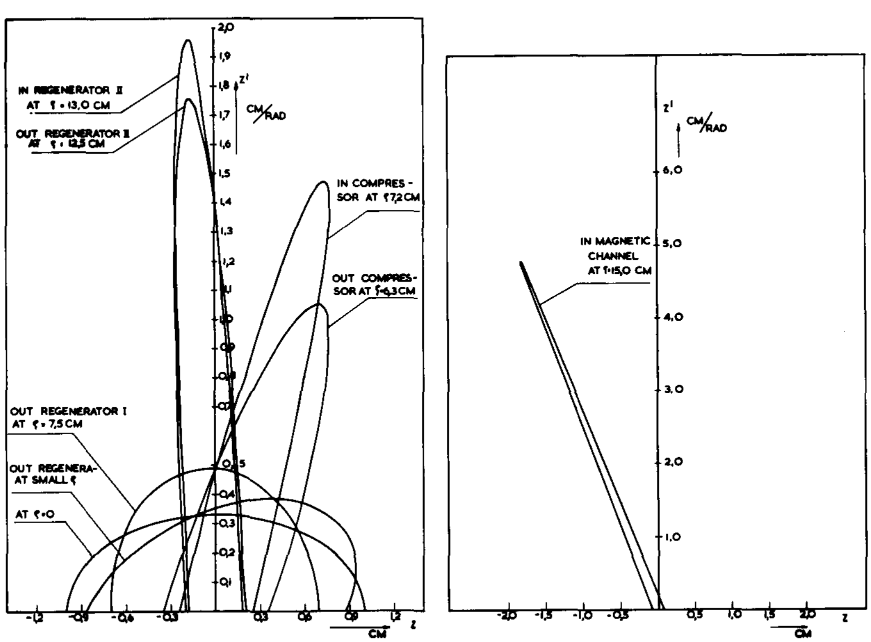

Fig. 7 Axial structure of beam.

<u>Magnetic Channel</u>

From the ellipses in Fig. 7 it is clear that there is a considerable increase in axial oscillation amplitude, due to the extended regenerative action. At the last orbit the deflected beam is strongly converging to an axial focus behind the regenerator.

To limit the amplitudes of the vertical oscillations during traversal of the fringing field, while keeping the radial divergence within bounds, three channel segments have been used : segments I and II, having strong positive gradients of 1.200 gauss/cm and 2.000 gauss/cm respectively, and segment III enhancing the negative gradient of the fringing field.

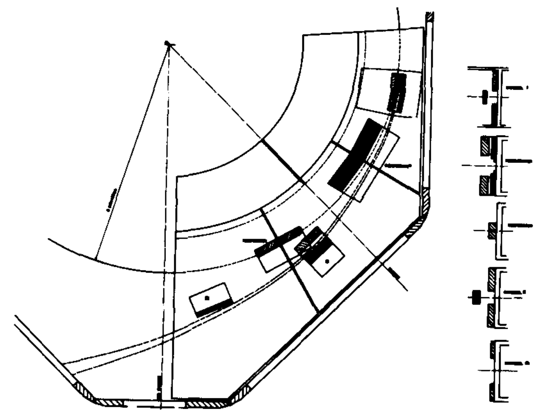

Fig. 8 Layout of extraction system.

Fig. 8 gives the layout of the system. The shims which were placed in the field to compensate for field distortions and to make final adjustments of regenerator and compressor fields are not shown. The regenerator, compressor and channel segments are mounted on C-shaped aluminium frames, which are fixed to aluminium plates on the poles of the magnet.

<u>Measurements</u>

After the iron configurations, which should produce the required field shape, were calculated, final corrections were made by trial and error. A floating wire was used before the final assembly of vacuum chamber, etc., to line up the magnetic channel segments, and to check the positions of regenerator and compressor with respect to the deflection radius and the "last revolution" orbits.

After the deflection system was mounted in the vacuum chamber and an internal beam was obtained, a radial displacement of the regenerator by 2 mm was necessary to bring the beam out.

The regenerated beam which can be brought out of the vacuum chamber represents 15% of the internal deuteron beam. The maximum extracted beam intensity was 4,5 μA, of which 3 μA could be brought to focus on a 2 x 3 cm spot in the experiment room.

References

K.J. Le Couteur and S. Lipton, Phil.Mag. <u>46</u>, 1265 (1956).
K.J. Le Couteur, Proc. Royal Soc. <u>A232</u>, 236 (1955).
N.F. Verster, U.S. Patent No 302 4 379.
G.T. de Kruiff and N.F. Verster, Philips Technical Review, <u>23</u>, No 12, 381 (1961/62).