Resonance free or precessional extraction–a comparison

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ABSTRACT

Using the measured four sector field of the AEG Compact Cyclotron, precessional extraction ($\nu_r < 1$) has been studied and compared with 'resonance-free extraction' ($\nu_r > 1$).

1. INTRODUCTION

A technical description of the AEG compact Cyclotron (fixed field version) and its characteristic parameters has been given by E. Hartwig in this conference.[1]

The following results have been limited to the extraction of a proton beam.

2. MAGNETIC FIELD AND BEAM DYNAMICS

The extraction studies to be described here were carried out with a magnetic field, measured at a 1: 2·4 scale model of the AEG Compact Cyclotron. The co-ordinate system is defined as pointed out in Fig. 3 of reference 1. The resulting radial (ν_r) and axial (ν_z) oscillation numbers due to the proton field have been plotted in Fig. 1 as a function of the radius. The three main resonances follow each other closely. For acceleration of protons, the harmonic number is 2. Using a maximum voltage of 44 kV at the four gaps of the two-dee-system, one gets the particle motion in the radial phase space plotted in Fig. 2.

The orbit separation, due to an energy gain per turn of 110 keV is about 1·1 mm at the extraction radius. A total turn number of 200 yields a maximum proton energy of 22 MeV. Over the energy range from 13·5 MeV to 22 MeV (90 turns out of 200 total for the complete acceleration) the magnitude of orbit displacement does not exceed 0·5 mm. A phase space area associated with this accelerated orbit will have a completely negligible amount of coherent oscillation over this energy range.

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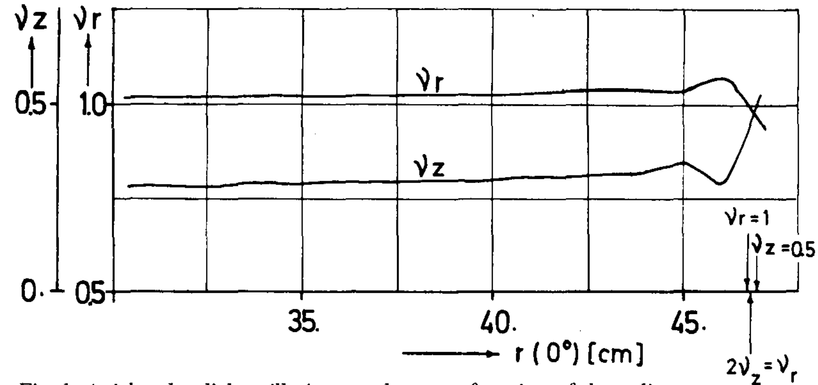

Fig. 1. Axial and radial oscillation numbers as a function of the radius

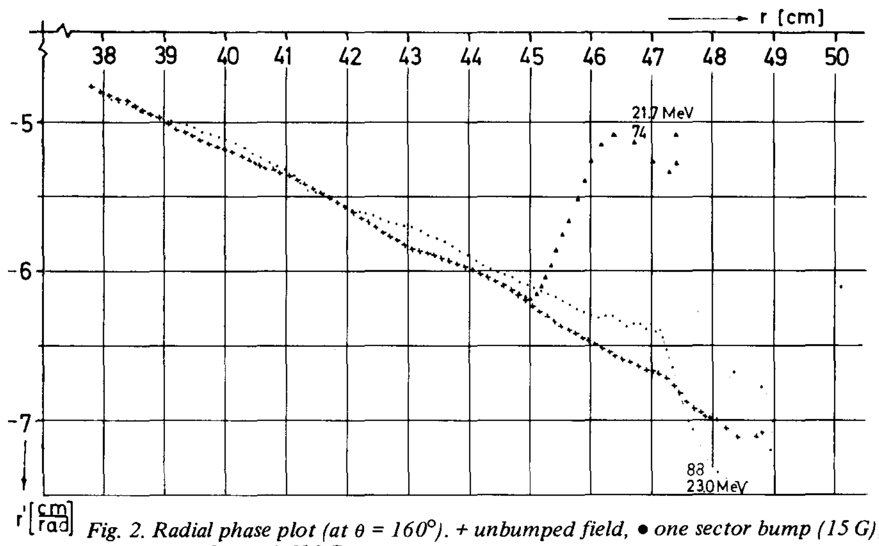

Fig. 2. Radial phase plot (at θ = 160°). + unbumped field, ● one sector bump (15 G), ▲ two sector bump (±110 G)

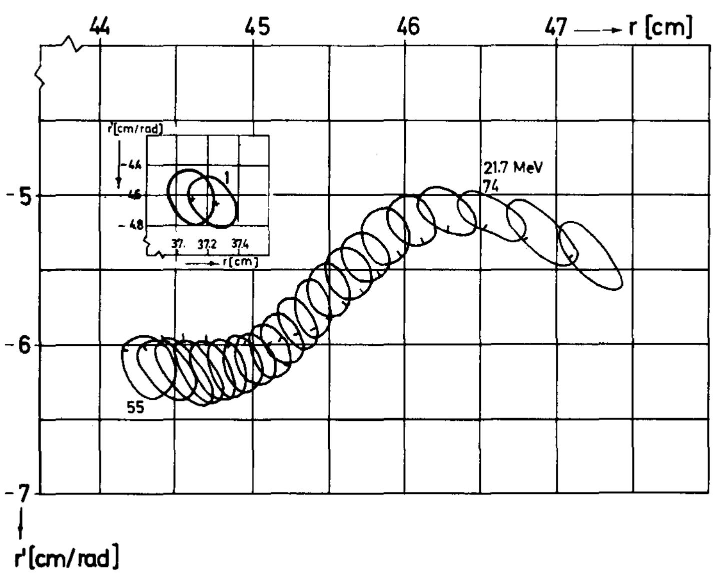

Fig. 3. Radial phase space turn pattern (at θ = 160°) for 'resonance free extraction'. Insert shows the phase space area at the starting point

3. EXTRACTION

High current of an extracted beam demands an additional turn separation. Several methods for 'artificial' turn separation are known. For the fixed energy compact cyclotron, two extraction modes have been considered, 'resonance free extraction'[3] ($\nu_r > 1$) and precessional extraction[2] ($\nu_r < 1$).

3.1. *Resonance free extraction (RE)*

Resonance free extraction has been studied theoretically for a low energy cyclotron, using a four sector field.[3] Since the extraction occurs before reaching

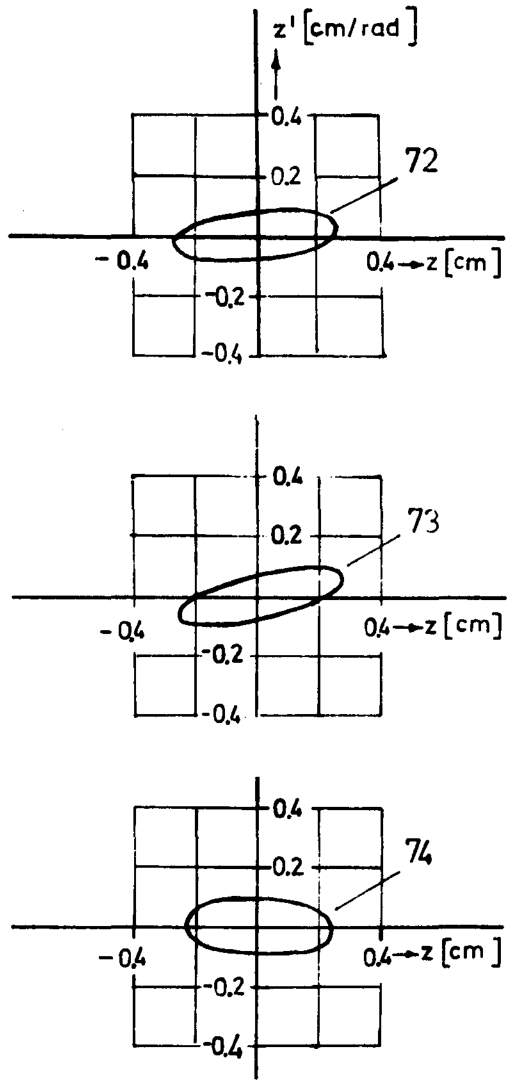

Fig. 4. Axial phase space area for the orbits 72, 73, 74 (turn numbers correspond to those given in Fig. 3)

the resonances $\nu_r = 1$, $2\nu_z = \nu_r$ and $\nu_z = 0{\cdot}5$ no axial blow up of the extracted beam will be expected.

A suitable combination of the first and second field harmonics yields an additional turn separation. To realise an orbit separation of 3 mm at the entrance of the electrostatic deflector ($\theta = 160°$) a two sector bump has been superimposed on the isochronous field. We used a bump strength of +110 G for $22{\cdot}5° \leqslant \theta \leqslant 62{\cdot}5°$ and −110 G for $202{\cdot}5° \leqslant \theta \leqslant 242{\cdot}5°$. The radial increase of the field bump extended over 2·4 cm and started at a radius of 46 cm.

Starting on a fixed point at 13·5 MeV with the same initial conditions used for the unbumped field, the beam was accelerated to the extraction radius. The phase plot for the end of this orbit is shown in Fig. 2 by triangles (turns are numbered from the starting point of the calculation not from the centre of the machine). The maximum turn separation was 3·2 mm, and occurred at $\theta = 160°$. Beam extraction can be performed at turn 74, i.e. before reaching the resonances. The energy of the extracted proton beam is 21·7 MeV.

A set of orbits was calculated using the same initial conditions as above (see Fig. 2). The incoherent radial amplitude at the starting point was 1·5 mm. A phase plot of the last orbits has been depicted in Fig. 3. Axial stability of the particle beam is important for a successful extraction. Since RE takes place before reaching a resonance, no blow up of the beam will be expected. Fig. 4 demonstrates this, using an axial betatron amplitude of 2·5 mm.

3.2. *Precessional extraction (PE)*

There is a lot of theoretical and experimental experience concerning extraction at $\nu_r < 1$. A test for extracting a high current deuteron beam has been performed at the Jülich isochronous cyclotron by AEG.[4]

The bump strength can be estimated by Eqn (3) of reference 2. For realisation of the first harmonic, we used for the calculations a *one* sector bump

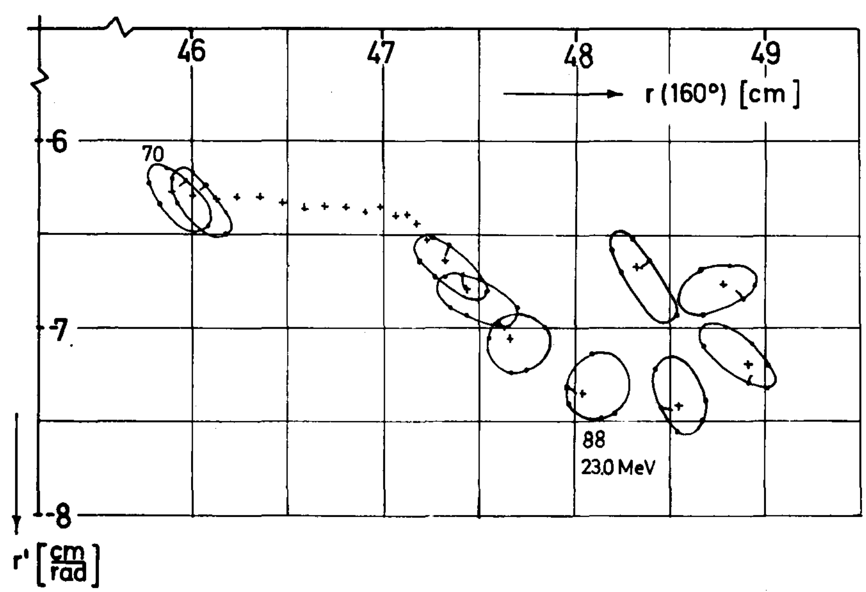

Fig. 5. Evolution of the radial phase space during resonance extraction (at θ = 160°)

($22 \cdot 5° \leqslant \theta \leqslant 62 \cdot 5°$) of +15 G, increasing linearly over two pole gap lengths ($38 \cdot 8 \leqslant r \leqslant 50 \cdot 9$ cm). The first harmonic field bump used here corresponds to that produced by the trim coils positioned in the hill sectors of the cyclotron. The final energy for this field was designed to be 23·0 MeV ($\nu_r = 0 \cdot 85$). Rf (43·035 Mc/s) and starting phase (+30°) have been optimised. Fig. 2 gives a radial phase plot starting with the same conditions as in 3·1 (dots). Maximum orbit separation of 5 mm appeared at $\theta = 160°$. Fig. 5 shows the evolution of the radial phase space area from turn 70 to 92 (numbering of turns as indicated in 3.1). The size of the eigen-ellipse at the starting point at 13·5 MeV was chosen so that the incoherent radial amplitude was 1·5 mm. Passing of the resonances gives no noticeable deterioration of the beam quality. Originally overlapping orbits have been separated; it is evident, that this can be achieved only with a beam of an infinitesimally small phase width and adequate stability of the cyclotron.

A difficulty associated with the extraction at $\nu_r < 1$ is the axial growth of the beam, when passing the coupling resonance, as demonstrated in Fig. 6. The initial axial amplitude was 2·5 mm. The ellipse rotates rapidly from turn to turn, which results for a multiturn extraction in a large enveloping phase space area.

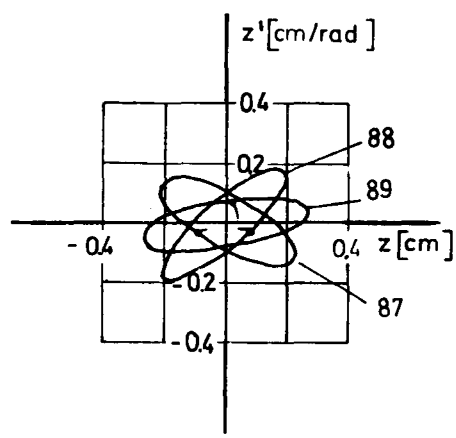

Fig. 6. Axial phase space area for precessional extraction (turn numbers correspond to those of Fig. 5)

4. COMPARISON BETWEEN THE TWO EXTRACTION MODES

Since RE occurs at a smaller radius than PE, the energy of the extracted beam is lower. In the case under consideration here, the energy difference is 1·3 MeV.

The field strength of the electrostatic deflector needed for the beam extraction is nearly the same for both cases: RE takes place at smaller radii but has a greater r'. For the magnetic field used here the electric field strength was about 20% lower for RE than PE.

A difficulty of the PE is the possible axial growth of the beam, when passing the coupling resonance. Applying multiturn extraction mode, particles of different neighbouring orbits will be extracted. Consequently, the axial phase space area resulting from ellipses of the different orbits is much larger for PE than for RE. A comparison of Figs 4 and 6 illustrates this effect.

Important for RE is the required sharp radial increase of the magnetic field bump. Realisation of this bump by iron shims has been proposed elsewhere,[3] but it seems difficult to get a negative field bump this way. On the other hand, extraction at $\nu_r < 1$ needs a slow (adiabatic) increase of the bump strength, which can easily be achieved by the trim coil system.

REFERENCES

1. Hartwig, E., 'AEG Compact Cyclotron', Proceedings of this Conference, p. 564.
2. Gordon, M. M., *I.E.E.E. Trans. Nucl. Sci.* **NS-13**, 48, (1966).
3. Mahrt, R. and Böttger, O., *Nucl. Instr. Meth.* **71**, 45, (1969).
4. Thimmel, H., On the beam extraction of the Jülich Isochronous Cyclotron, European Cyclotron Meeting, CERN (1968).