CONVERSION STUDIES FOR THE UPPSALA SYNCHROCYCLOTRON

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Abstract

Results from model measurements of magnet and RF systems for a 185 MeV sector-focusing synchrocyclotron are presented. Taking advantage of the phase stability acceleration of different ions may be performed over a large energy range without the use of correction coils.

1. Introduction

The design study for the improvement of the 185 MeV synchrocyclotron at the Gustaf Werner Institute aims to convert the accelerator into a multi-particle variable-energy machine with high intensity and favorable time structure of the beams[1).

The modification of the accelerator consists in changing the pole gap configuration of the present cyclotron magnet in order to obtain an increasing field with radius. The reduced bandwidth makes it possible to replace the present rotating condensor by an electronically tuned broadband system. The magnetic field will be chosen to lie between the isochronous fields for protons and heavy ions (Fig. 1). A change of ions species then requires a change of RF parameters only.

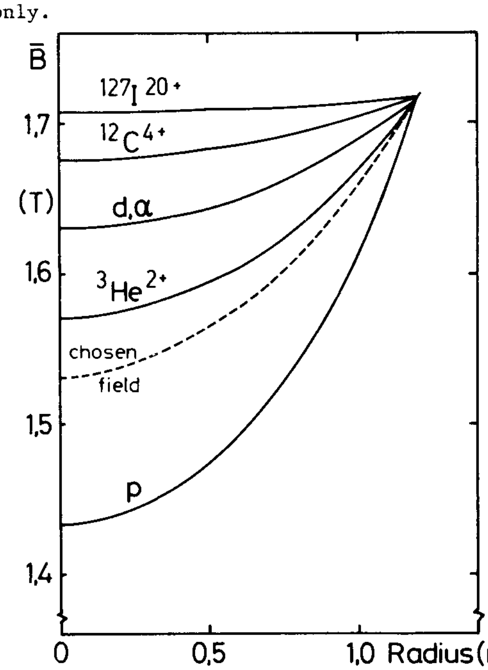

Fig. 1. The isochronous fields for some ions and the average field at highest excitation.

2. Model magnet measurements

The design of the pole-gap geometry[2)] which is nearly finished is a result of orbit calculations coupled with magnetic field measurements on a model magnet in the scale 1:4. A field measurement device has been built with eight Hall-plates mounted on an arm turnable in steps of 0.1° around the centre of the magnet.

The accuracy in each measured field point is ± 1 gauss. Average fields, particle equilibrium orbits and focusing conditions are computed by a modified version of a program obtained from the Michigan State University.

Three pairs of sectors are mounted on the flat pole-faces of the model magnet. The pole diameter is 700 mm with a pole gap of 85 mm and the sector thickness is 20 mm.

The shimming procedure towards the wanted radial shape of the magnet field was complicated by non-uniform saturation of the iron sectors from excitation to excitation. Fig. 2 shows the radial behaviour of the mean field for one of the first pole configurations which were measured.

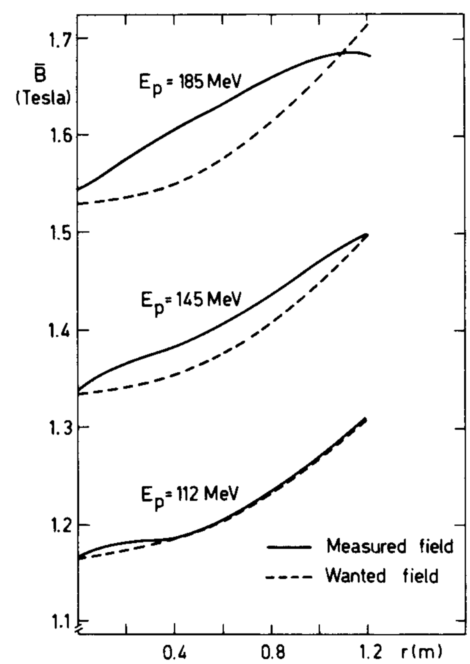

Fig. 2. A comparison between measured and wanted average fields at three magnet excitations.

In order to compensate for the effects of saturation holes were drilled in the hill sectors in such a way that the magnetization was about the same at all radii. The holes were drilled from the pole side with a depth of 16 mm evenly distributed over the inner parts of the sectors. The effects of various hole diameters are seen in Fig. 3 for two extreme excitations. Field measurements 5 mm out of the median plane did not show any flutter effects in the field due to the holes.

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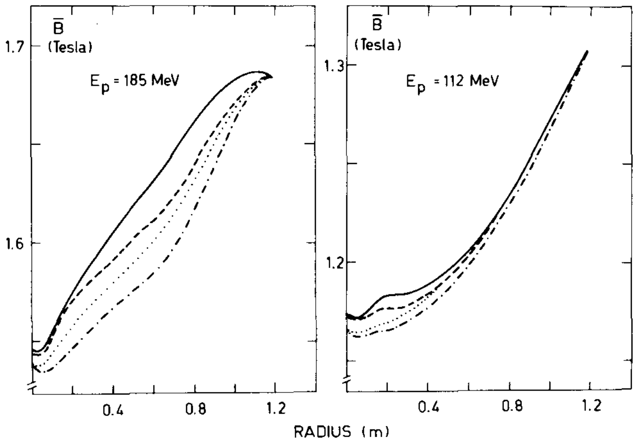

Fig.3. Measured average fields at two magnet excitations, ——— without holes, — — — with holes Ø 9 mm, ... with holes Ø 11 mm, —.—.— with holes Ø 13 mm.

A negative field gradient at small radii has been introduced in order to obtain strong axial focusing of the particles during the first few turns. A magnetic cone with variable height is obtained by iron cylinders movable vertically in the centre of the pole gap of the model magnet. The outer diameter of each cylinder is 22 mm and the wall thickness is 2 mm.

The resulting axial stability conditions for the final pole-gap configuration at various magnet excitations are shown in Fig. 4. The design goal of a ν_z-band of 0.1 - 0.3 has been obtained everywhere apart from a region near extraction radius for the low excitation. A slight re-shimming of the valley gap at these radii will be performed in combination with the shimming of the extraction system.

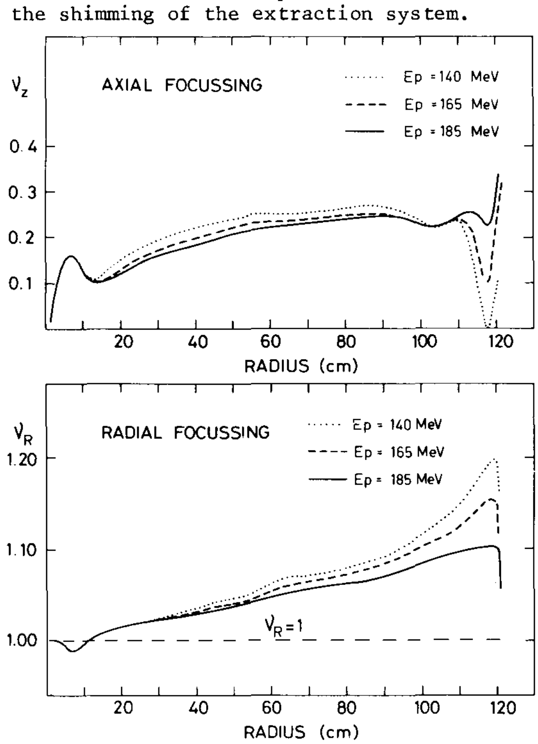

Fig. 4. Axial and radial stabilities at various magnet excitations.

The lower part of Fig. 4 shows the radial focusing term as function of radius. While the magnetic cone is important for good axial stability at small radii, it involves difficulties concerning the radial stability because the ν_R = 1 resonance has to be passed. Any first harmonic contribution to the field in this region causes movement of the orbit centres which results in increased radial amplitudes. With the insertion of valley coils at the critical radii, first harmonic amplitudes have been reduced to < 2 gauss.

The influence of the magnetic field on the phase stability is given by the factor

$$K = -\frac{d\omega}{\omega} \Big/ \frac{dE}{E}$$

which is calculated in the equilibrium orbit program. The behaviour of K as function of radius is shown for the acceleration of protons at three magnet excitations (Fig. 5). The phase stability becomes weaker at lower energies. At $E_p \approx$ 120 MeV the mean field more or less coincides with the isochronous field and the phase stability is lost. The corresponding stability conditions for deuterons (and α-particles) are shown in Fig. 6. In this case the critical region arises at the highest excitation where the mean field comes close to the isochronous fields for these particles resulting in small K-values especially at large radii.

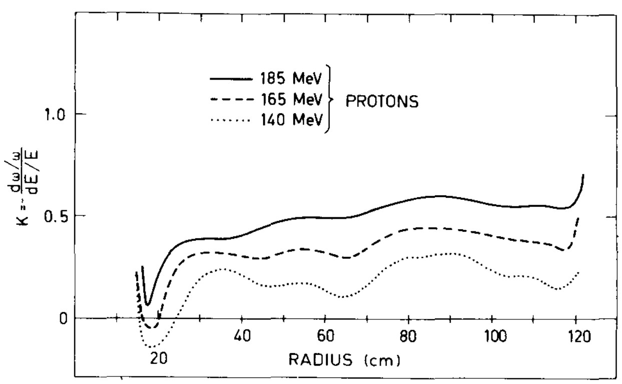

Fig. 5. Phase stability conditions for protons at various magnet excitations.

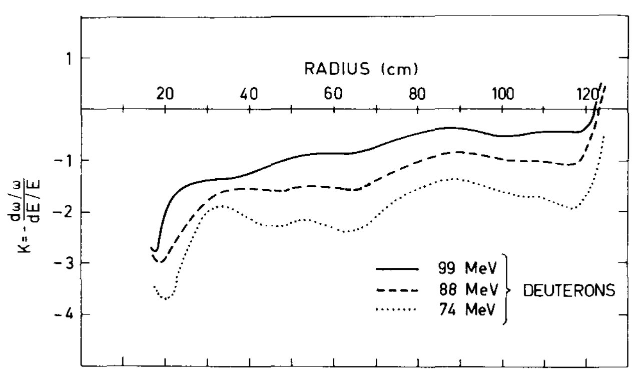

Fig. 6. Phase stability conditions for deuterons at various magnet excitations.

3. The Radiofrequency System.

The lowered bandwidth requirements in the sector-focused synchrocyclotron makes it possible to replace the present mechanically tuned system by electronically tuned systems, either broadband amplifier systems[3] or systems synchronously tuned by saturation of ferrites (the latter principle is used in the beam stretching system of the Leningrad synchrocyclotron[4]).

The orbital frequency ranges of some ions at highest magnet excitation are given in Table 1. Acceleration of protons makes it necessary to operate the RF system at frequencies near 25 MHz. Since so far no saturable ferrites have been found with low losses ($tg\delta \approx 10^{-2}$) in this frequency range, the work is now concentrated on broadband amplifier systems.

Table 1. The orbital frequencies of some ions at highest magnet excitation.

particle	f_{start} (MHz)	f_{final} (MHz)	rel. bandw. (%)	max. kin.energy (MeV)
p	24.09	21.80	(-)9.96	185
d	12.05	12.39	2.80	99
α	12.13	12.46	2.73	198
$^{12}C^{6+}$	12.13	12.47	2.73	595
$^{12}C^{4+}$	8.09	8.55	5.54	268
$^{40}Ca^{10+}$	6.07	6.48	6.56	505

Different electrode configurations have been studied[1,5,6]. The preferred solution is two diametrically opposed 90° electrodes (Fig. 7). This lay-out permits operation on the fundamental frequency of the ions as well as on the 2nd and 3rd harmonic overtones.

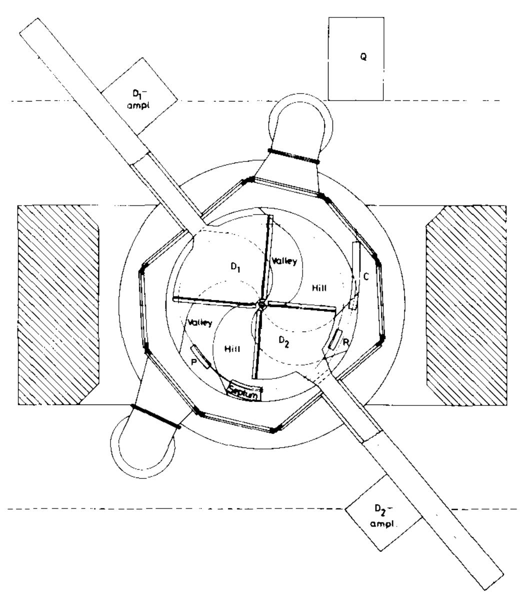

Fig. 7. Lay-out of the synchrocyclotron with two diametrically opposed 90° electrodes.

Measurements have been performed on a full scale model of a resonator with a 90° electrode. The Dee has a radius of 128 cm, a thickness of 6 cm and an aperture of 4 cm. The Dee is tuned by a shorted coaxial line with a characteristic impedance of 20 ohm. The resonant frequency is adjusted by variation of the length of the coaxial line by means of sliding short circuit contacts. The resonant frequency versus the length of the coaxial line (measured from the vacuum tank wall situated at 1.6 m radius) is given in Fig. 8.

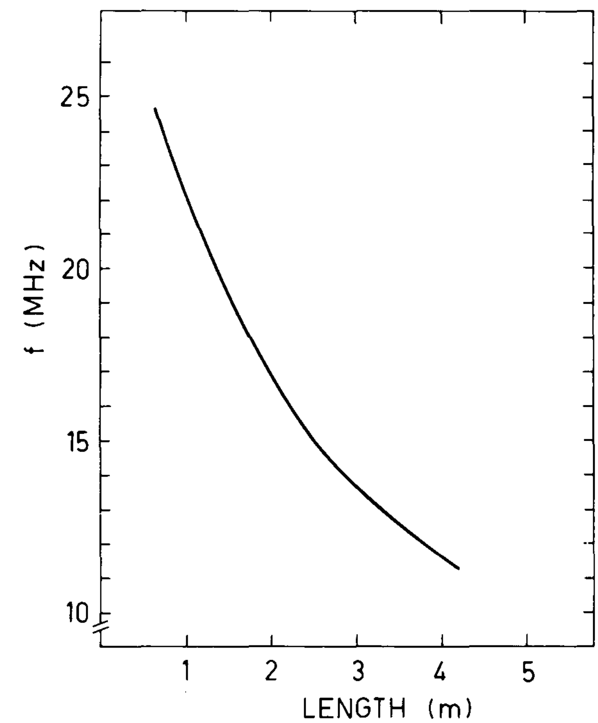

Fig. 8. The resonant frequency of the model resonator versus the length of the coaxial line.

Another important parameter for a resonator in a broadband system is the energy stored in the electric and magnetic fields at a certain Dee voltage. This can be expressed by the "resonator impedance" Z defined by[7]

$$W_{stored} = \hat{U}^2_{Dee}/(2 \cdot \omega \cdot Z)$$

Z was determined by measuring the parallel resistance R_p of the Dee at resonance and by measuring the bandwidth between the points where the real and imaginary parts of the impedance of the Dee are equal, using the relation

$$R_p = Z \cdot Q$$

where Q is the quality factor of the resonator. The results are given in Fig. 9.

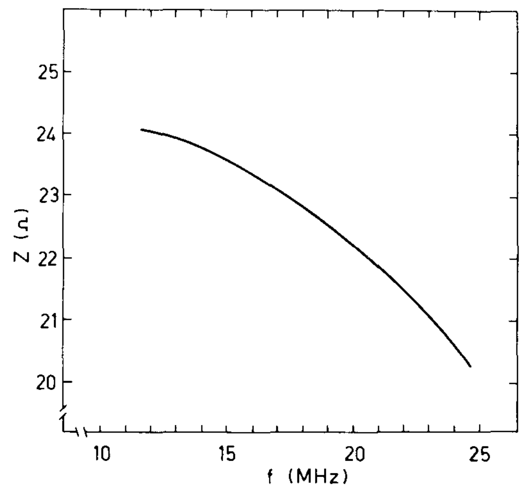

Fig. 9. The resonator impedance (Z) as function of resonant frequency of the model resonator.

Each power tube will be coupled to its resonator by a transmission line connected to a point near the short circuit of the resonator. It has been shown that it is possible to achieve a coupling with two peaks in the passband in this way. The bandwidth between the peaks can be adjusted by making this point movable. The resonators will be equipped with water-cooled damping resistors movable along the line. The anodes are tuned by variable capacitors.

The Dee voltage attainable over a certain frequency band can be limited by the limits set for total power or anode dissipation. Since an electronically tuned system may well be used as a beam stretching system on a lower power level during a substantial part of the time, the time averages of the total power consumption and anode dissipation can be kept below these limits. The factor which will limit the Dee voltage in this case will be the product of the maximum, RF anode voltage and maximum RF anode current[7]. Supposing 13 kV (peak) and 68 A (peak) respectively for the power tetrode Eimac 4 CW 100,000E the Dee voltages given in Table 2 can be attained. If the systems operate in the main accelerating mode at full Dee voltage 30 % of the time and in beam stretching mode 70 %, the total power consumption would be approx. 150 kW per system.

References:

1) Förslag till ombyggnad av synchrocyclotronanläggningen vid Gustaf Werners institut, Uppsala 1965.
2) P.U. Renberg, K.W. Ståhl and A. Åsberg: Modellstudier av polgapskonfigurationer för sektorfokuserande synkrocyklotron. GWI-PH 9/74, Uppsala 1974.
3) A. Susini: Some wideband coupling circuits, Cern 64-48, 1964.
4) Beam stretching system for 1 GeV LNPI synchrocyclotron, UDK 621.384.65, Leningrad 1972.
5) 11th European Cyclotron Progress Meeting, Louvain-la-Neuve, May-June 1974.
6) B. Lundström: Studier av högfrekvenssystem till sektorfokuserande synkrocyklotron, GWI-PH 10/74, Uppsala 1974.
7) Giannini-Susini: Optimisation des paramètres des systèmes accélérateurs HF à large bande, Cern 68-18, 1968.

Table 2. Maximum Dee voltage and the corresponding energy gain per turn and unit charge using Eimac 4CW100,000E tetrodes ($h=f_{RF}/f_{ion}$)

particle	h	f_{centre} (MHz)	rel. bandw. (%)	Max.Dee voltage (kV peak)	Max. gain per turn and charge (keV)
p	1	21.95	9.96	13.6	38
d	1	12.22	2.80	27.5	78
	2	24.44		25.7	103
α	1	12.30	2.73	27.5	78
	2	24.60		25.7	103
$^{12}C^{6+}$	1	12.30	2.73	27.5	78
	2	24.60		25.7	103
$^{12}C^{4+}$	2	16.64	5.54	19.1	76
	3	24.96		18.3	52
$^{40}Ca^{10+}$	2	12.65	6.52	18.0	72
	3	18.83		17.6	50

DISCUSSION

B. LUNDSTRÖM: I have no figures. We have considered accelerating heavy ions like ^{127}I. It is possible that in the future we can include this. It is not under immediate consideration.

J.A. MARTIN: Do you have plans for iodine acceleration now?

B. LUNDSTRÖM: We have no plans at the present, but there is nothing from the RF point of view which excludes this.

P. MANDRILLON: What happens for the cos φ_S value at centre? $K = -(d\omega/\omega)/(dE/E)$ is going to zero!

B. LUNDSTRÖM: In the centre of the machine we expect cos $\varphi_S \approx 0.2$ and then growing with acceleration -- during the main part of the acceleration to about 0.5.

P. MANDRILLON: I have seen in your picture that you are going through $K = 0$? What happens at this point?

B. LUNDSTRÖM: For protons we pass this region very quickly. There would not anyhow be any complete phase oscillations in this region. For protons we will only have approximately 15 phase oscillations during the complete acceleration.

J.A. MARTIN: You mentioned the magnetic field requirements for $^{127}I^{20+}$. Have you estimated the vacuum requirements?

J.A. MARTIN: What will be the vacuum requirement?

B. LUNDSTRÖM: I am sorry, I cannot answer that question right now. Of course we will have to have a good vacuum in this case.

F.G. TINTA: In which way do you plan to sweep the frequency, if the rotating capacitor is going to be eliminated? What Q factor do you expect to have?

B. LUNDSTRÖM: We will have broadband amplifier systems with the frequency generators swept. The resonators will be damped by adjustable damping resistors and the amplifiers will be coupled to the resonators in a mode with two peaks in the passband. The Q value would be different for different cases. The lowest used Q value would be about 40.

R. COHEN: How do you vertically focus the ions heavier than the protons in the central region? They will be very strongly defocused by the RF since $K < 0$.

B. LUNDSTRÖM: We have a magnetic cone giving a falling field in the centre yielding axial focusing. For very heavy ions we have considered external injection. In this case there will be no problem. But with an internal source it would be a problem.