Extraction and central region calculations for the minicyclotron ILEC

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Abstract

The small Isochronous Low Energy Cyclotron for 3 MeV protons will come into operation this year. The machine is equipped with pairs of 2nd and 6th harmonic dees to achieve flattop acceleration. The main features will be reported. Many orbit calculations have been carried out to get insight in aspects of single turn extraction, phase dependency and energy spread. The calculations revealed that the application of three diaphragms in the centre of the machine is required to obtain an energy spread of no more than 10^{-3} at reasonable beam currents.

Introduction

The date of first operation of the Isochronous Low Energy Cyclotron for 3 MeV protons at EUT has been delayed due to problems with the RF system. The machine has been designed by the university staff-group with great support of students. It is almost completely constructed mechanically as well as for the RF power and electronics in the university workshops. The capital investment without salaries amounts roughly US $ 200.000 for materials, power supplies and vacuum equipment.

The objectives of the ILEC project together with its main features have already been described in ref. 1. In table 1 the machine parameters are summarized. Acceleration up to a fixed energy of 3 MeV for protons will be achieved with a second harmonic double dee system and a pair of sixth harmonic dees for flat-topping to obtain low energy spread in the accelerated beam. The second harmonic dees are placed on two opposite valleys of the four-fold symmetrical pole faces of the magnet. The sixth harmonic dees are placed on two opposite hills. The pole faces are copper plated to form grounded parts of the RF power circuit.

In the last few years quite an extensive use has been made of computer programs to perform orbit calculations for the study of the central region features and in the extraction region for the design of a passive magnetic channel. The calculations were based upon measured magnetic field values and electric field values obtained with the computer code RELAX3D (2). From the central region study energy versus phase relations have been deduced, which give insight in the application of a set of 3 diaphragms for the selection of a beam with high intensity and minimum energy spread.

The passive magnetic channel

After passing the extractor, the accelerated beam enters the fringe field, where the negative gradient has a strong defocussing effect in the horizontal plane on the beam (see fig. 1).

We have chosen to use a passive magnetic channel in order to achieve proper refocussing. This channel has been placed as close as possible to the extractor (see fig. 1). This means that it has been mounted inside one of the two second harmonic dees. A passive magnetic channel generally consists of 3 iron rods (3) which enclose the extracted beam (see fig. 2a). If the iron rods are magnetically saturated, the additional magnetic field, caused by the bars, can be calculated analytically (4). The calculations are performed in a program called CHANNEL. With this program we designed the passive magnetic channel for ILEC, which had to meet strict geometrical requirements, arising from its positioning inside a 2nd harmonic dee.
This limits the length of the channel to 10 cm and its height to 1.5 cm. Calculations show that a focussing channel of 10 cm length should produce a gradient of 6 T/m. The gradient has to be present over a radial width of 1.5 to 2 cm. In fig. 2b the calculated additional magnetic induction and its gradient are given. Figure 3 illustrates the focussing effect of the channel (cf. fig. 1) on the extracted beam. A "dummy" channel has been placed in the opposite 2nd harmonic dee to avoid the introduction of a 1st harmonic perturbation in the cyclotron magnetic field. This dummy channel is an exact copy of the "real" one.

As a result of the gradient of the magnetic induction in the fringe field, the passive magnetic channel experiences a force. The radial component of this force is most important. At a radius of 20 cm in a valley, we find a radial component of $F_r = -210$ N (the minus-sign means directed towards the centre of the cyclotron).

Central region calculations

The program CENTRUM1 is used for orbit calculations in the central region. This program integrates the equations of motion following from the Lorentz force acting on a particle.

Central orbit calculations in a cyclotron require a detailed knowledge of the electric field. The electric field in the centre of ILEC has been calculated with the program RELAX3D (2). This program solves the Laplace or Poisson equation for a general geometry consisting of Dirichlet and Neumann boundaries, lying approximately on a regular 3-dimensional grid. We used a rather fine grid with a gridspacing of 0.5 mm and dimensions (i.e. the number of points in x-, y- and z-direction) of 201 x 281 x 17 points, in order to get a detailed mapping of the central electric field. CENTRUM1 uses the electric field shape obtained with RELAX3D in a rectangular area of 8 x 12 cm around the cyclotron centre. This area is smaller than the actually calculated area (10 x 14 cm) in order to minimize possible errors at the edges of the grid. Outside this region the following Gaussian approximation (5) for the electric field component E_y, normal to the accelerating gap is used:

$$E_y = E_{max} \exp\left[-\frac{1}{2}(y/\Delta y)^2\right] \tag{1}$$

where Δy is related to the gapwidth W and the dee aperture H by:

$$\Delta y = 0.2\ H + 0.4\ W \tag{2}$$

and y is the distance normal to the middle of the gap.

The magnetic field in the median plane of the cyclotron has been mapped with the aid of automatic computer controlled equipment with as active element a Hall probe.

The results of our calculations with CENTRUM1 are shown in figs. 4 and 5. In fig. 4 a stroboscopic view of the motion of the orbit centre during the first eight turns is given for three different values of the high frequency starting phase of the particle, relative to the RF signal. For an optimal acceleration process the position of the orbit centre after a few turns should not differ too much from the centre of the cyclotron (6). This is the case for starting phases between $-90^{\circ} < \phi_{hf,0} \leq -40^{\circ}$.
Starting phases with $\phi_{hf,0} \leq 90^{\circ}$ are not included in the calculations, because in that case the puller has a positive voltage.

In fig. 5 the high frequency phase ϕ_{hf} and the centre position phase ϕ_{cp} (7) are given as a function of the turnnumber n. The centre position phase should go to zero after a few turns, in order to obtain maximum energy gain at a gap crossing. For a well centered beam the centre position phase will become equal to the high frequency phase. It is clear from fig. 5 that ϕ_{cp} and ϕ_{hf} approach each other after a few turns but don't go to zero. However a phase interval of 30 degrees width around a starting phase of $\phi_{hf,0} = -60^\circ$ will give a well centered beam with a reasonable current (the puller voltage has reached half of its minimum value) and a value of ϕ_{cp} which is not too high.

The flattopping system of ILEC (1) consists of 2 sixth harmonic dees (see table 1). A necessary condition for the successful application of flattopping in the starting phase interval given above is that the extraction energy reaches its maximum value for the starting phase of $\phi_{hf,0} = -60^\circ$ (i.e. the middle of the interval). The extraction energy E_{ex} has been calculated by using the output of CENTRUM1 as input for the program EXTRACTION, which is better suited for orbit calculations outside the central region. The results are given in fig. 6. Under "normal" operating conditions (i.e. the RF frequency ν_{RF} is twice the isochronous frequency ν_{iso}) the extraction energy doesn't reach its maximum value for $\phi_{hf,0} = -60^\circ$ (curve (a)). This is caused by the fact that under these conditions the centre position phase keeps its value of about 25° (see fig. 5) during the entire accelerating process. If the RF frequency is slightly lowered with $\Delta\nu_{RF}$ the residual phase of 25° will decrease each turn with an amount of $\Delta\phi_{cp}$. The relation between $\Delta\phi_{cp}$ and $\Delta\nu_{RF}$ can be approximated by:

$$\frac{\Delta\nu_{RF}}{2\nu_{iso}} = \frac{\Delta\phi_{cp}}{4\pi} \qquad (3)$$

The desired extraction energy versus starting phase relation can be obtained by choosing $\Delta\nu_{RF}$ (or $\Delta\phi_{cp}$) so that the average centre position phase during the acceleration process becomes zero. A reduction of the RF frequency with $\Delta\nu_{RF} = 120$ kHz ($2\nu_{iso} = 43.34$ MHz) roduces curve (b), which indeed has its maximum for $\phi_{hf,0} = -60^\circ$.

Curve (c) shows the energy-phase relation that is found when flattopping is included in the numerical calculations. The effect of this system on the extraction energy spread is quite spectacular. In the interval $-65^\circ \lesssim \phi_{hf,0} \lesssim -55^\circ$ the energy spread $\Delta E_{ex}/E_{ex}$ decreases from 0.17% without flattopping to 0.038% with flattopping.
In the interval $-65^\circ \lesssim \phi_{hf,0} \lesssim -45^\circ$ an even greater decrease from 1.11 % to 0.059 % is found.

The selection of the starting phase intervals given above can be realized by using three diaphragms (8). The first two are placed in the second turn of the beam with azimuthal positions: $\theta = -28^\circ$ and $\theta = +28^\circ$. Both diaphragms have a variable radial position ($\Delta r_{max} = \pm 0.5$ cm). The third diaphragm is mounted on the internal target, which is movable along the axis $\theta = -165^\circ$. Calculations with the third diaphragm placed in the eighth turn show that by using an aperture of 1 mm for all three diaphragms, the starting phase interval $-75^\circ \lesssim \phi_{hf,0} \lesssim 45^\circ$ can be selected. A smaller interval can be selected by using narrower apertures. The efficient use of the diaphragms is caused by the strong dependence of the particle energy on the starting phase which is present in the first stage of the accelerating process.

The main objective of the ILEC project is the production of a 3 MeV proton beam with a maximum energy spread of 0.1 % and a high current, which allows us to study the influence of space charge effects (9) on the beam. Our calculations have shown that by application of the flattop principle and a set of diaphragms this objective can be reached quite well. The magnetic channel keeps the beam nicely focussed when it passes through the fringe field.

References

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Magnet system	**R.F. system**
4-fold rotational symmetry	two coupled dees
radial hills (40°, gap 33-36 mm)	2nd harmonic acceleration
flat valleys (50°, gap 50 mm)	push-push mode
pole radius: 20 cm	dee angle: 50°
extraction radius: 17.3 cm	gap voltage: 36 kV
final energy: 2.9 MeV	dee/dummy-dee gap: 8 mm
average magnetic field: 1.43 T	vertical aperture: 15 mm
field flutter: ≃ 0.25	voltage stability: < 10^{-4}
field stability: $2 \cdot 10^{-4}$	frequency: 43.5 ± 0.5 MHz
main coils: 2 x 140 A x 192 turns	frequency stability: 10^{-7}
power consumption: 6.3 kW	drive: < 10 kW class AB
weight: 3 tons	coupling: capacitive
harmonic corr. coils	Q-value: 2000
on hills : 2 x 2 x 2	rough tuning: moving short
on valleys: 3 x 2 x 2	fine tuning: capacitive
Flattop system	**Vacuum system**
2 separate 6th harmonic dees	working pressure: 10^{-5} torr
dee angle: < 40° (r-dependent)	oil diffusion pump: 3000 l/sec
gap voltage: ≃ 3.5 kV	rotary pump: 20 m^3/h
dee/dummy-dee gap: 6 mm	vacuum chamber
vertical aperture: 15 mm	length : 1200 mm
Q-value: 500	width : 720 mm
	heigth : 125 mm
	material : aluminium
Ion source	**Extraction system**
self heated cathode PIG	electrostatic deflector and
source (Bennett type)	passive magnetic focussing
anode material: copper	channel
cathode material: Tantalum	

Table 1: Machine parameters of the ILEC minicyclotron

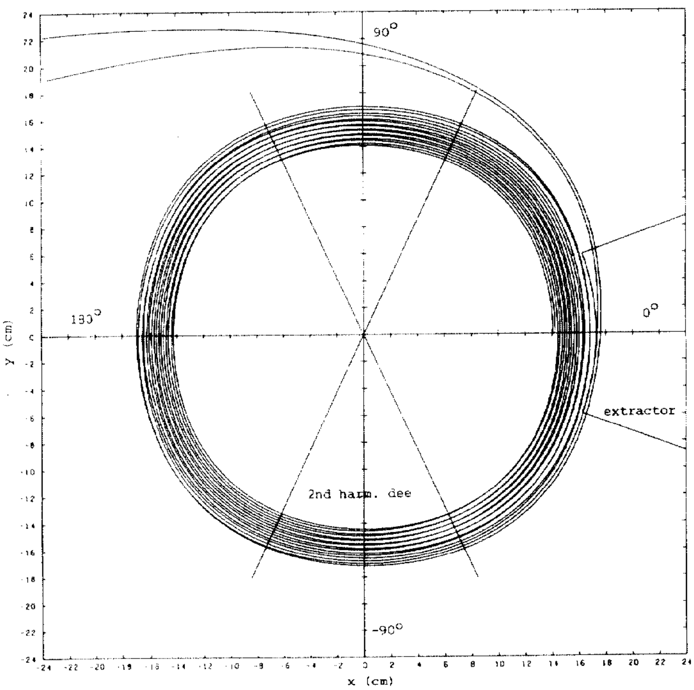

Fig. 1: Defocussing effect of the fringe field on the beam.
Starting conditions: E_o = 2 MeV, V_{dee}= 36 kV; emittance: 15 mmmrad; extraction voltage: 18.8 kV over 4 mm.

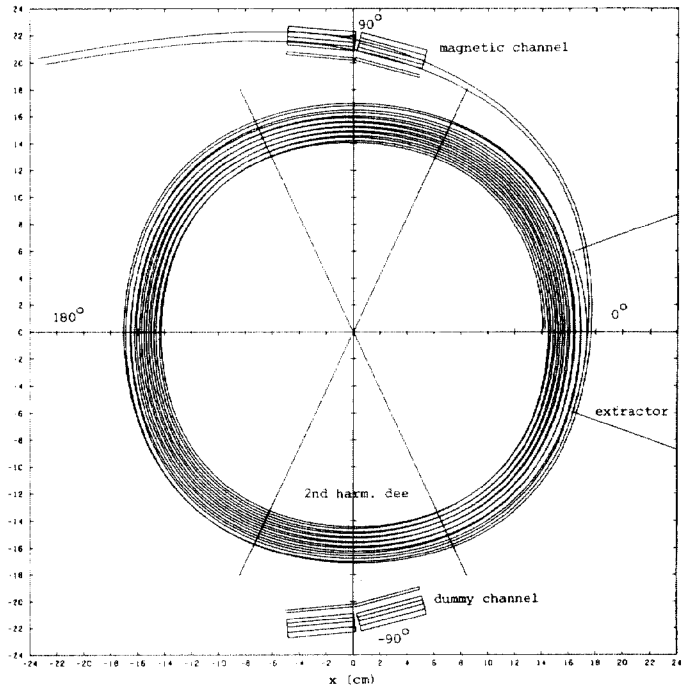

Fig. 3: Focussing effect of the channel on the beam.
Operating conditions: see fig. 1

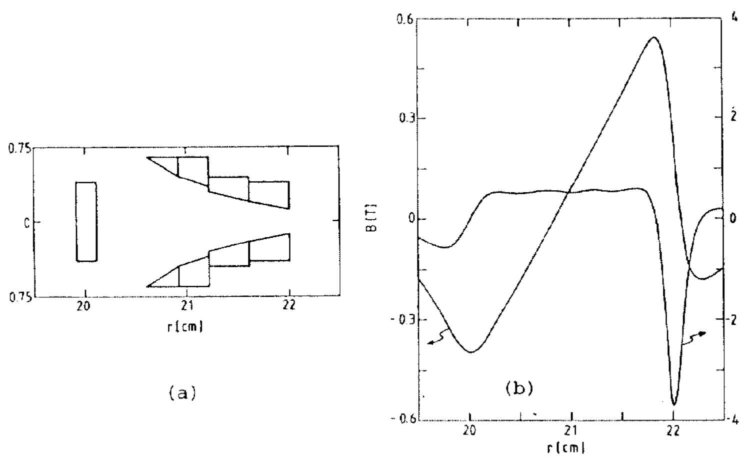

Fig. 2: (a) Cross section of the ILEC passive magnetic channel
(b) Calculated additional magnetic induction and gradient produced by the channel

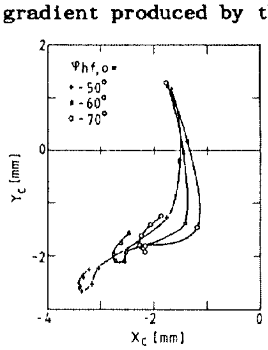

Fig. 4: Motion of the orbit centre during the first eigth turns (V_{dee} = 36 kV, E_o = 1 eV)

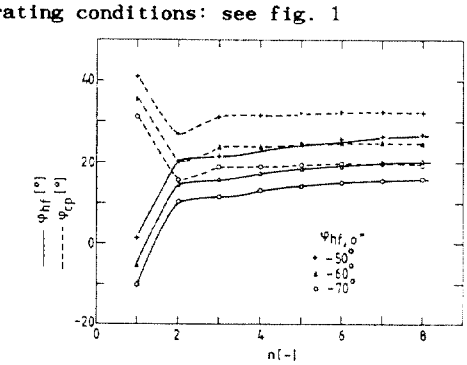

Fig. 5: High frequency and centre position phase as a function of the turnnumber n.

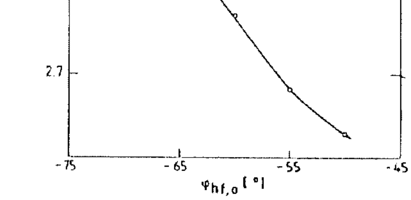

Fig. 6: Extraction energy as a function of the starting phase $\phi_{hf,0}$:
(a) ν_{RF} = 43.34 MHz, V_{dee}= 36 kV, V_{flat}= 0 kV
(b) ν_{RF} = 43.22 MHz, V_{dee}= 36 kV, V_{flat}= 0 kV
(c) ν_{RF} = 43.22 MHz, V_{dee}= 36 kV, V_{flat}= 4.5 kV