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ELECTRON AND PLASMA PHYSICS

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THE 50 MeV RACETRACK MICROTRON
AT THE ROYAL INSTITUTE OF TECHNOLOGY
STOCKHOLM

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Abstract

The development, construction, and operation of a pulsed 50 MeV two-sector racetrack microtron is described. The machine has internal electron gun injection and uses a biperiodic standing wave linac for the acceleration. Electrons with energies between 3 MeV and 55 MeV can be extracted. Orbital stability is ensured by an inverted magnetic field along the fronts of the main magnets.

CHAPTER 1

Introduction

Microtrons possess a number of favourable properties. They combine high electron beam currents, approaching those of linear accelerators, with the sharp energy definition inherent in machines with magnetically guided beams. The conventional circular microtrons, however, are impractically large and heavy for energies above, say, 20 MeV due to the restrictions on magnet field strength set by the resonant conditions and the limited energy gain in a single accelerating gap. The demand on the homogeneity of the magnetic field becomes furthermore severe at high energies as both the number of orbits and their average length increase. For many applications such as radiation therapy, production of short-lived isotopes, production of fast neutron beams and for the free-electron laser somewhat higher energies are desirable. Here the racetrack microtron (RTM) offers a compact and efficient construction.

In this paper we will describe a RTM for energies up to 55 MeV built at the Royal Institute of Technology in Stockholm. Besides applications in basic research this energy region was believed to cover most of the practical uses mentioned above.

The design aimed at an accelerator capable of delivering an average current during the pulse of 10 mA at 50 MeV with 2 MW drive. It was planned to use injection at some tenths of kilovolts from an internal gun without choppers or bunchers. The energy should be continuously variable from a few MeV and up. This meant that the electrons had to be extracted from different orbits and that the energy gain per turn had to be variable to cover the energy step between two successive orbits.

The microtron was provisionally assembled during 1974 and gave

its first weak beam of 25 MeV electrons at the end of that year. Since then it has reached design energy and current. With about 2.5 MW klystron power a beam power of 1 to 1.5 MW can be reached at any energy within the continuous interval from 6 to 55 MeV and at some energies around 3 MeV. It has been in use for radiation physics experiments since 1977. The machine has previously been described only briefly (1).

CHAPTER 2

Design considerations

Racetrack microtrons are nowadays described in textbooks (See for instance Ref. 2) and several machines have been built (3-9), so the principle of operation is well established. We will therefore just briefly recapitulate the resonance conditions.

Three major approximations are used in the analysis below: The width of the magnetic fringe-fields is assumed negligible (hard edge field), the electron velocity is in all orbits assumed equal to that of light and transit time effects in the linac gaps are neglected.

Fig. 1

General lay-out of a racetrack microtron

The basic lay-out of a two-sector microtron is shown in Fig. 1. Electrons are injected into the linac with a total energy of $E_{inj} = m_0 c^2 + \text{kinetic energy}$. On each passage through the structure they gain an energy, E_r . To achieve resonance two conditions must be fulfilled: The revolution time in the first orbit must be an integral multiple, μ , of the rf period, $\frac{1}{f}$, and each revolution time must exceed the preceding one by another integral multiple, ν , of the period:

$$T_1 = 2 \frac{s}{c} + \frac{2 \pi}{e B_r c^2} (E_{inj} + E_r) = \frac{\mu}{f}, \quad (1)$$

$$\Delta T = T_n - T_{n-1} = \frac{2 \pi}{e B_r c^2} E_r = \frac{\nu}{f}, \quad (2)$$

where s is the field-free distance between the magnets and B_r the strength of the homogeneous magnetic field corresponding to the energy gain per turn, E_r . These equations give:

$$E_r = \frac{\nu}{\mu - \nu - \frac{2 s}{\lambda}} E_{inj}, \quad (3)$$

$$B_r = \frac{2 \pi f E_r}{e c^2 \nu}, \quad (4)$$

where $\lambda = \frac{c}{f}$.

The important points to note are that the magnetic field strength is proportional to the resonant energy gain as in the circular microtron, but that the denominator of Eq. 3 can be chosen at will. Contrary to the case of the circular microtron it can be less than one by adjusting the distance between the magnets. In this way the energy gain per orbit and thus the magnet field strength is in the hands of the designer. As magnets can easily be made with much stronger fields than the 0.1 to 0.2 teslas, that are employed in circular microtrons, the racetrack version can be very compact.

The problem of choosing appropriate parameters according to Eqs. 3 and 4 is quite different for small and for large microtrons. In high energy machines full use must be made of Eq. 4 in order to reach the desired maximal energy. It can be expressed:

$$\begin{aligned} E_{max} [\text{MeV}] &= N E_r + E_{inj} \approx \\ &\approx \lambda [\text{cm}] B_r [\text{T}] \nu \frac{N}{2.1} + E_{inj}. \end{aligned} \quad (5a)$$

Here the mode number, ν , and the number of orbits, N , should be

kept as small as possible in order to maximize the phase acceptance and to minimize phase errors due to imperfections of the construction. We believe that proper behaviour of the accelerator - without excessive demands on magnetic field homogeneity, stabilization of coil currents and rf voltages, and contribution of beam-steering devices - requires designs with $N v \leq 20$. The field strength in ordinary steel magnets should furthermore be limited to about $B_p \leq 1.6$ T.

Taking into account these restrictions the expression above transforms to:

$$E_{\max} [\text{MeV}] \leq 15 \lambda [\text{cm}] + E_{\text{inj}}. \quad (5b)$$

A long wavelength has therefore to be chosen for high energies.

In microtrons for less than 100-150 MeV maximal energy, on the other hand, it is worth-while from the point of view of economy and simplicity to keep all parameters away from the respective limits, but otherwise the design can be fairly free.

In general, compactness asks for a strong magnetic field and a high energy gain per turn, as the rf wavelength cannot be arbitrarily short. The need for high power rf generators and for wide enough apertures of the accelerating structure sets a lower limit around $\lambda \geq 5$ cm. A long wavelength (and a mode number, v , greater than one) will also help to provide space for focusing and correcting elements in the return parts of the orbits, the orbit distance being roughly equal to $v\lambda/\pi$.

With a high resonant energy gain much rf power is needed unless the linac is very long, which is expensive and complicates the synchronism of the first orbit. The phase error, however, can be reduced by the use of a high injection energy, which can be advantageous also because it moves the returning first orbit away, so that the beam may clear the linac without a by-pass arrangement.

An elegant way of reducing the phase error and simultaneously avoiding problems with the first return path is described in Ref. 7.

High magnetic field and high energy gain per turn implies that both the mode number and the number of orbits are small. This means simplified preservation of synchronism but a larger absolute and relative energy dispersion.

In the actual RTM the approximations behind Eqs. 1 and 2 are justified by the following construction details, described more extensively later in the text: Auxiliary magnets with inverted field (10) give real orbit lengths that are close to the ideal ones. The magnet distance is short enough and the energy gain in the linac is high enough to maintain synchronism even in the first orbit. Finally, the linac is graded, having a shortened distance between the first two resonator gaps, so that the energy gain on the first passage is nearly the same as in later orbits despite the moderate injection energy.

CHAPTER 3

General design

From the considerations in the preceding chapter we have chosen the following basic parameters for the 50 MeV microtron:

Number of orbits	3 - 15
Energy gain per orbit	2.7 - 3.7 MeV
Rf frequency ($\lambda=10$ cm)	2998 MHz
Magnetic field strength	0.56 - 0.77 T
Mode number μ	11
Mode number ν	1
Distance between magnets	0.49 ± 0.01 m
Kinetic injection energy	30 ± 10 keV

This fairly conservative choice leads to the design shown in Fig. 3. The physical dimensions are: Length between magnet backs: 143 cm, height: 43 cm, iron width: 55 cm. The pole gaps are 16 mm and the main and auxiliary poles have the dimensions 55 cm x 25 cm and 61 cm x 1 cm respectively. The magnets weigh 600 kg (iron) + 50 kg (copper) each.

The linear accelerator is a 26 cm long standing-wave coupled structure (11) with four full and, at the ends, two half accelerating cavities. Five coupling cells transfer energy between the accelerating cavities. The aperture is 10 mm in diameter.

Fig. 2.
Photograph of the microtron

Fig. 3.
Perspective view of the microtron

Three separate stainless steel tanks constitute the vacuum system. Two of them, using the poles of the magnets as top and bottom, are equal and made up by flat frames. The third, larger, tank is placed between the other two and contains the linear accelerator and the injection and extraction devices.

The central tank and one of the magnet tanks are firmly bolted

together, but the remaining magnet tank is connected to the others with 16 stainless steel bellows, one for the common orbit and one for each of the 15 return orbits. Thus, this magnet and its tank can be moved by a small motor in order to vary the distance between the magnets so that Eq. 3 can be satisfied for different resonant energy gains.

All connections between the tanks and between tanks and end plates and lids are sealed with rubber O-ring gaskets in such a way that the electrons never reach the seals. So far none of the O-rings has therefore been damaged.

A 450 litres per second turbo pump gives a final vacuum better than 10^{-4} Pa (10^{-6} torr). In order to prevent oil from the fore-vacuum pump from entering the system two measures are taken: The backing line is equipped with a valve and a sorption trap. The valve is never opened unless the turbo pump is rotating.

CHAPTER 4

Magnets

The equations for resonant electron acceleration (page 6) were derived under the assumption that the magnetic field at the bending magnet edge abruptly falls to zero. The magnet sectors, however, have significant fringing fields which distort the orbits and destroy axial orbit stability. Moroz (12) and Roberts (13) proposed the use of sectional (four sectors) fields in order to obtain axial stability, and a few racetrack microtrons were built using this type of focusing (3, 4).

Another method to obtain axial focusing (10) is to use auxiliary magnets parallel with and near the edge of the main magnet sectors. The auxiliary poles with opposite excitation to that of the main poles give a field profile which has a region with inverted polarity. Besides giving the electrons axial stability the auxiliary magnets correct the first orbit so that the shape of the orbit resembles the "sharp edge" case and its length approximately satisfies the resonant condition, Fig. 4.

The requirements on the magnetic field homogeneity within the main magnets are similar to those in the circular microtron (14). They are less stringent in the direction parallel to the linac axis than perpendicular to it. Certain restrictions which influence the magnet design have to be imposed on the field distribution in the transition regions between the main magnets, auxiliary poles and field free space. Extensive computer simulations of electron orbits in the RTM have shown that the field gradient in the first region should be as large as possible and that the auxiliary field should have a short fringe region.

Fig. 4.

Orbit trajectories

- - - - - ideal trajectory with hard-edge field
- . - . - trajectory without fringing field correction
- trajectory with the actual auxiliary field

A strong field gradient between the main and the auxiliary poles is necessary in order to keep the phase error introduced in the first few orbits by the auxiliary field small enough as compared to the hard edge case. A short distance between the auxiliary poles and the main magnet, however, gives a high flux density in the auxiliary pole due to flux leakage from the main pole.

With all the above mentioned considerations taken into account the form of the magnet shown in Fig. 5 results from computations made with the program MAGNET (15), which was offered by CERN.

The iron slabs of the main magnets are machined from 60 mm thick ARMCO iron sheets. Stainless steel bars machined to within ± 0.01 mm are used to define the pole distance in order to compensate for a small gradient of the main magnetic field.

The main coils have 40 turns and are wound of 7 mm square copper wire with a 5 mm diameter bore for water cooling. Maximum excitation current is 170 A and the corresponding dissipation for

both coil-pairs is 5.6 kW. The auxiliary coils have 240 turns of 2.5 x 1 mm copper wire, their dissipation is low and no water cooling is necessary.

Fig. 5.

Magnet sector design

1. Main magnet	4. Auxiliary magnet coils
2. Main magnet coils	5. Vacuum chamber (nonmagnetic)
3. Auxiliary magnet	6. Iron screens
7. Air gap	

The auxiliary pole pieces are mechanically and magnetically connected to the main magnet and have the same yoke. Another possibility would have been to provide the auxiliary poles with a separate yoke replacing the iron screens in Fig. 5. Both designs have advantages and disadvantages. With a common yoke, part of the main flux returns through the auxiliary poles and considerably reduces (by more than 30 per cent) the necessary excitation current of the auxiliary poles. This is a useful property because little space is available for the coils of the auxiliary magnet. The drawback is the coupling between the magnetic circuits. A change in the excitation of one circuit changes the magnetic field distribution in both the main and auxiliary field.

The computations of the magnetic field distribution have shown that the magnetic flux density in the iron everywhere is moderate which guarantees that the field distribution in the gap does not change appreciably when the magnetic field is varied. There is, however, a section (A-A' in Fig. 5) in the auxiliary polepieces

where the magnetic flux density is high. This is caused by the required small distance between the main and the auxiliary poles, which results in high leakage flux density from the main magnets. The shape of the auxiliary poles and the chosen distance of 15 mm reduces the flux density in this region to less than 1.6 T.

A typical field distribution in the median plane of a bending magnet at an excitation current of 145 A, corresponding to an energy gain of 3.3 MeV per turn, is shown in Fig. 6. The field was measured in the middle of the magnet along a line parallel to the linac axis.

Fig. 6.

Magnetic field strength in the median plane

Fig. 7.

Enlargement of the "homogeneous" part of Fig. 6

———— magnet 1
 - - - - - magnet 2

A greater scale (Fig. 7) reveals that the magnetic field inside the main magnets is far from being homogeneous. The error is in the order of 0.5 per cent and depends on the excitation, i.e. the resonant energy gain. For all excitations the difference between the two magnets is small.

In the region between the magnets the leakage fields from the main magnets add and the resulting field strength varies between 2 and 6 mT. This field would distort the first orbit, and in order to decrease the stray field in this region soft iron sheets are placed on each side of the main vacuum chamber, Fig. 5. The stray field is in this way reduced to below 1 mT.

The stainless steel bellows which allow a change of the distance between the magnets contain iron tubes which screen and shorten the fringing fields of the auxiliary poles. This increases the distance between the return path of the first orbit and the linac axis. No such screens are necessary on the other side of the return paths. The strength of the auxiliary magnetic field on that side can be adjusted so as to give closed orbits.

The reproducibility of the magnetic field strength and distribution is seriously influenced by eddy currents in the large iron slabs if the excitation is suddenly changed. Ramp generators are therefore used to control the increase and decrease of the excitation currents. The starting of the current ramps is programmed in order to give a standardized cycling.

CHAPTER 5

Linear accelerator

The accelerating device of the microtron is a $1/2 \pi$ -mode biperiodic linear accelerator. Two different types of structure have been used, one side-coupled and one online-coupled.

A perspective view of the online linac is shown in Fig. 8, a photograph of the side-coupled linac in Fig. 9.

As mentioned in Chapter 3 the linear accelerator is symmetric

with a half resonator at each end. Such a construction shortens the distance between the first and the second gap center by about a quarter of a full gap width. This grading increases the phase acceptance. The shorter gap also reduces the defocusing action on the injected beam.

Fig. 8.

Perspective view of the online-coupled linear accelerator

Fig. 9.

The side-coupled linear accelerator

The shape of the accelerating cavities was optimized for a high shunt impedance by means of a computer program (16). For both structures the computed Q -value is about 13500, the measured one about 12000. The computed shunt impedance is about 75 Mohm/m. The $1/2 \pi$ -mode resonant frequency is 2998 MHz and the electric length of the structures is 250 mm.

The axial electric field distribution of the on-line structure is

shown in Fig. 10.

Fig. 10.

Linac axial electric field

● measured
x computed

The cavities of the structures are made of OFHC copper, machined on a copying lathe. All parts are brazed together in a hydrogen atmosphere. Coarse tuning is performed prior to brazing, fine tuning is done after brazing of the whole structure by mechanical deformation of the cavity gaps and with the aid of small tuning screws (17).

The inner diameter of the accelerating cavities of the linac is 78 mm, while the distance between the common and the first straight path is only 31.5 mm. In order to make a free passage for the returning electrons in the first orbit a hole is drilled along the whole length of the linac. The cavities are then closed again by a copper tube which is brazed to the structure (See Fig. 11).

Fig. 11.

Position of the first orbit in the linear accelerator

For symmetry reasons a similar copper tube is brazed also on the opposite side of the cavities.

The rf generator is a klystron designed and made at our institute. It can deliver up to 9.5 MW to the load. The coupling to the linac is adjusted to $\beta = 4$. A grid modulated triode oscillator, with a pulse length variable between 0.1 and 7 μ s, is used as a driver for the klystron. The modulator is of conventional construction with variable prf, from single pulses to 300 s^{-1} . A de-Qing network is included in order to stabilize the klystron pulse voltage.

CHAPTER 6

Injection

Contrary to the S-band circular microtron, in which the limited space between the resonator and electron orbits can only accommodate a very simple electron injector, the RTM in principle offers the possibility of using a more elaborate injection system. However, a rather simple electron gun with an emittance matching approximately the racetrack admittance has proved to be a very efficient injector. An injection system including a buncher might yield somewhat higher acceptance but considering the complications associated with such an injection we believe that the improvement is not sufficient to justify its introduction.

An obvious and simple injection method would be to use a hollow gun with its cathode surrounding the common orbit as shown in Fig. 12.

Appreciable experimental effort was devoted to such a gun until it could be demonstrated by calculations (20) that its beam emittance can only be made to cover a minor part of the RTM admittance. This is shown in Fig. 13 where three typical computed gun emittances are plotted together with the computed RTM admittance (Chapter 8). The radial direction is chosen to illustrate the worst case because the radial admittance is smaller than the axial one.

Fig. 12.

Hollow gun injection

1. LaB_6 cathode	5. Ceramic ring
2. Ceramic washers	6. Focusing electrode
3. Rhenium heater	7. Anode
4. Tantalum support	8. Linac

Fig. 13.a.

Fig. 13.b.

Fig. 13.c.

Computed emittances of three hollow guns with different electrode geometries together with the computed radial RTM admittance.

- Admittance of the RTM.
- Emittance of the hollow beam guns,
- . - . - . 70 per cent of the beam current
- - - - - 95 per cent of the beam current

The geometrical differences between the two guns corresponding to Figs. 13.a and 13.b are only a few tenths of a millimetre. Tolerances of that magnitude are difficult to maintain when the cathode and the anode are cold, and almost impossible when the cathode is heated. The experimental guns have shown, accordingly, poor reproducibility.

If the emitting surface of the cathode has a suitable radius of curvature the divergence of the emitted beam can be made smaller, Fig. 13.c. However, the most dense parts of the emittances will not be closer to the origin. In the radial direction the gun emittance therefore will still not match the admittance of the RTM. The computations have also shown that the geometrical tolerances are more critical with a curved cathode. No such gun was tested experimentally.

The only possibility of improving the matching of the hollow gun emittance to the admittance of the microtron would be to increase the distance between the gun and the linear accelerator.

Anyhow, a few versions of hollow guns were tested. Their cathodes were indirectly heated lanthanum hexaboride rings with an internal diameter of 10 mm (Fig. 12). As shown by the calculations electron capture with hollow gun injection was low and the beam current never exceeded one third of the current reached with other injection methods.

Fig. 14.
"Chicane" injection

Side injection with a three magnet system (21), often named "chicane", as shown in Fig. 14 was used in the RTM most of the time.

The electron beam from the gun was bent about 45 degrees in the injection magnet before it entered the first linac resonator. As indicated in the figure the two upstream magnets were able to compensate for the influence of the injection magnet on the returning orbits. The two outer magnets were connected and regulated in series whereas the middle magnet could be separately adjusted. All magnets had approximately the same peak magnetic field (40 mT) and were housed in the same iron box. The power consumption of the unit was only three watts, but still it had to be water cooled.

In order to reduce the inflexion angle and the distance between gun and linac the injection system was later modified as shown in Fig. 15 which also gives an idea of the way the compensation magnet affects the returning first orbit.

Fig. 15.

Two-magnet injection

The gun is now moved closer to the common orbit. Instead of the previous 45 degrees injection angle to the common orbit it is now about 33 degrees. With the correspondingly lower injection magnetic field and thermally better design of the two magnets water cooling is no longer necessary.

The "chicane" injection system is supposed to be the ideal one and should produce minimum effect on the returning orbits. The

more simple system with just one compensating magnet has turned out to be satisfactory and furthermore to give a higher capture efficiency.

Several versions of side-injection electron guns with different geometries have been used and almost continuous effort has been devoted to cathode development.

Fig. 16.

Side-injection gun electrode arrangement

1. Anode	3. Rhenium heater strip
2. Heater lead	4. Cathode button
5. Thermal shield and focusing electrode	

The gun cathode (Fig. 16) is a 2.5 mm diameter cylindrical lanthanum hexaboride button operated at a temperature of 1750 to 1800 K. At the normal operating voltage the cathode has to supply a temperature limited emission current of a few hundred mA, sometimes up to 1 A. The cathode is press-sintered in a graphite jig, part of which is left around the cathode button to serve as a high temperature chemical isolation. The graphite lined button is then brazed into a tantalum tube which in the same operation is also brazed to a rhenium heater strip. The brazing filler is a titanium-tantalum alloy which has good flow on graphite, tantalum and rhenium.

About 35 W (at 1.7 V) of cathode power is required to reach the operating temperature.

The gun can be raised or lowered and rotated around the vertical

axis by two small motors so that the height of the gun and the injection angle can be adjusted under operation.

Fig. 17.
Side-injection gun

The same computer program (20) was used to determine the electrode dimensions of the side-injection gun. Fig. 18 shows the computed emittances as seen at the linac entrance together with the calculated admittances of the RTM. The emittances fill just a small part of the admittance areas. It can therefore be expected, and this is confirmed by experience, that a replacement of the cathode does not appreciably influence the capture of the machine.

Fig. 18.
Computed emittances of the side-injection gun
together with the admittance of the RTM.

————— RTM admittance.
Side-injection gun emittance,
- - - - - 150 mA pulse current,
- . - . - . 300 mA pulse current.

For simplicity in the manufacture the gun was made symmetric al-

though the radial and axial admittances are not equal. In order to get a fair matching in both planes the injection magnet poles were given a 17 degrees slanted edge, Fig. 15.

CHAPTER 7

Extraction

The extraction of the electron beam from different orbits is done according to the principle described in Ref. 6.

A small magnet, movable along the front of magnet 1, deflects the beam to be extracted by a small angle (≈ 100 mrad), as shown in Fig. 19.

Fig. 19.

Extraction from optional orbit

After having passed the field-free region between the bending magnets the beam enters the other 180 degree magnet at the position of the penultimate orbit and therefore leaves the magnet one orbit distance on the opposite side of the common straight path and with the same small angle to the edge of magnet 2. The beam passes through the waveguide before entering the beam transport system of which the first section is magnetically screened.

In the waveguide the microwave field adds to the electrons a positive or negative (depending on tuning) energy in the order of a

few tens of keV. The beam is also somewhat bent by the magnetic field. The reason for letting the beam pass through the waveguide is simply that other extraction methods were contemplated when the accelerator was designed.

The extraction method employed has the advantage that the extracted beam forms an almost completed orbit before the electrons leave the machine. The angle missing a full revolution is just equal to the previous deflection (here 0.1 radian). The system is therefore only weakly chromatic and most of the remaining dispersion could furthermore be canceled if the 360 degree revolution were completed by the aid of an extra magnet outside the microtron.

On passing magnet 2, the outgoing beam crosses twice the fringe region at an oblique angle. The direction is such that this means a rather strong radial focusing and, despite the action of the auxiliary field, axial defocusing. The radial focusing results in a cross-over so that the electron beam is divergent in both directions when it leaves magnet 2.

The direction of the extracted beam varies slightly from orbit to orbit. Three factors are responsible: The deflection of the electron beam in the auxiliary field is energy dependent, the distance between successive orbits is not constant but varies because of phase oscillations and the magnetic field has irregularities which influence the position and direction of the beam. In order to keep the extracted beam centered in the beam transport system a small magnet (Fig. 19) can be added just before the beam leaves the accelerator. This magnet compensates for the directional errors.

The described method of extraction can have the result that the output beam becomes contaminated by electrons with a few MeV energy. This reveals an unforeseen - but not unknown - effect of the auxiliary magnets: The combination of two contradirectional magnetic fields on either side of the linac may act as a pure mirror. Electrons entering the magnet system along a normal to the edge leave the magnet on the same normal, provided their energy has a certain value (22,7).

This energy is often present in the electron beam after one passage through the linac either if part of the electrons are accelerated during the flanks of the rf pulse or because the energy

spectrum of the linac is broad even under steady state conditions. This permits electrons with energies within a certain range to reenter the exit hole of the linac after reflection. Many of these electrons are in phase for acceleration backwards through the linac, and after passing the other 180 degree magnet they may find their way out of the machine along the extraction channel.

In the actual RTM the conditions for this kind of recirculation are such that the low-energy electrons get an energy of between 2.5 and 4 MeV, at a resonant energy gain of 3.3 MeV/turn. A simple obstruction in the right hand side magnet prevents them from leaving the machine as indicated in Fig. 20.

Fig. 20.

Reflection and recirculation of low-energy electrons

CHAPTER 8

Electron orbits and phase stability

Beam optics computations can be used to determine the necessary parameters for an accelerator, but the results can also be used for a better understanding of beam dynamics. A computer program, RCTRAK (18), was therefore developed to enable the simulation of electron orbit behaviour in the RTM.

The program integrates the equation of motion. It uses computed field components (16) in the linac and the actual magnetic field. The magnetic field distribution (for various excitations) was measured in the median plane in the middle of the bending magnets

along a line parallel to the linac axis (Fig. 6). The computed field distribution in the linac cavities is fairly accurate for a single resonator as long as there is rotational symmetry. It is taken as the best available basis for the cavity fields (Fig. 10.) in spite of the fact that the real structure includes asymmetries due to the coupling holes between the cavities and the copper tubes for the first return orbit (Fig. 11.).

The program takes into account different types of misalignments both of the linear accelerator and of the bending magnets. There also exists a possibility of introducing magnetic field distribution errors in the median plane in the direction perpendicular to the axis of the linac.

The program uses a coordinate system according to Fig. 3. based upon a perfectly aligned RTM. The linac axis is perpendicular to the two bending magnets and lies in the common median plane. The origin is situated at the point where this axis crosses the symmetry plane of the linac. All simulated misalignments are related to this coordinate system.

The simulations were done for an ideal machine without alignment errors and with a homogeneous magnetic field in the gaps of the main magnets as well as for the case of the actual field and randomly generated alignment errors (within reasonable limits). Each of the alignment errors was also simulated separately in order to show its influence on the behaviour of the accelerator.

Some of the more important results of these simulations will be described in the rest of this chapter.

Unless otherwise stated all results refer to a resonant energy gain of 3.3 MeV per turn resulting in an electron energy of 50 MeV after 15 orbits.

8.1. Phase motion

The phase acceptance of the RTM is a rather complicated function of different machine parameters.

A comparison between the phase acceptances of a linac equipped on the injection side with a full and a halfcell respectively shows that the halfcell has the advantage that it brings about a more

efficient bunching and the possibility of using a lower injection energy (Fig. 21). This is due to grading, as the distance between the first two cavity centers is reduced in the halfcell case.

Fig. 21.

Relative energy error vs phase after the first transit through the linac. The phase is reduced to the symmetry plane of the linac, the parameter is the injection phase.

- halfcell at the injection side and 30 keV injection energy
- - - - - fullcell at the injection side and 100 keV injection energy

The phase acceptance of the RTM as a whole is, with a given linac configuration and resonant energy gain, a function of the injection energy. In order to be stably accelerated the electrons must pass the linac at the correct phase in the second orbit. However, the phase at which they are bunched during the first linac passage depends both on the injection energy and on the rf field strength. The revolution time in the first orbit depends on their energy and on the distribution of the magnetic field in the inhomogeneous parts. There exists just one best combination for matching the phases and the revolution times and this makes the phase acceptance injection energy dependent. Fig. 22 shows the measured beam current (in arbitrary units) given as a function of injection energy for two different resonant energy gains.

Fig. 22.

Beam current as a function of injection energy

- - - - - 2.8 MeV/turn

————— 3.3 MeV/turn

The computations (and experiments) show that the inhomogeneity inside the main magnets (Fig. 7) does not appreciably influence the phase stability of the microtron. This is principally due to the fact that the phase compression at the first transit through the linac results in a very well phase bunched beam. Fig. 23. shows the computed phase oscillations in some orbits, the area shown includes 80 per cent of the beam current in the corresponding orbit. The figure is only illustrative; a different tuning or different alignment errors will result in another, but similar, distribution of the phase oscillations.

Fig. 23.

Computed phase oscillations

- . - . - . limit of the phase stable region for
resonant phase angle of 108 degrees

The beam remains well bunched in all orbits but the phase oscillations are larger than the theory of the undisturbed oscillations predicts. The distance between two successive orbits is therefore not constant and equal to λ/π but fluctuates slightly around this value as can be seen in Fig. 24.

Fig. 24.

Computed and measured current density in different orbits

The beam current variation as a function of the distance, s , between the bending magnets (with all other machine parameters held constant) is shown in Fig. 25.

Fig. 25.

Influence of the distance between the bending magnets,
energy gain 3.3 MeV per turn

————— computed
o measured
- - - - - distance according to Eq. 3.

If on the other hand the beam current is optimized for each s value a somewhat broader maximum is obtained. The distance

between the 90 per cent current points is in this case 1.5 mm. Even if only one fixed energy gain is desired, it seems to be wise to construct the machine so that the distance between the magnets can be varied.

8.2. Alignment errors

Both computations and experiments show that for the stability in position of the orbits it is imperative that the two bending magnets and the linear accelerator are correctly aligned. The beam, that is reflected many times between the magnets, will otherwise tend to drift away, in analogy with a beam of light between two non-parallel mirrors. Errors in machining and in mounting of the magnets are likely to be systematic and will therefore have similar effects.

Fig. 26 shows the three errors of interest in alignment of the bending magnets.

Fig. 26.

Angular alignment errors

In both the radial and the axial direction there is a symmetry such that the electrons enter and leave a magnet at the same angle to the magnet edge. The angle of direction of the straight parts of an orbit will therefore on each revolution tend to increase by 2α and 2β respectively, towards the sides where the distance between the magnets increases. The cumulative effect is the same in all orbits while the focusing in the linac and the auxiliary fields becomes weaker as the energy increases. The compensation is thus rather poor and the beam will therefore either drift away or perform antidamped oscillations around the ideal position. In racetrack microtrons with more than just a few orbits it is prac-

tically impossible to cope with the " α " and " β " errors without turning the magnets under operation or using specially designed compensating or focusing devices.

An error in the radial direction acts only on the straight parts of the orbits but axial errors also give helical paths in the gaps of the bending magnets. A " β " type error is thus more severe.

To show the relative importance of the alignment errors we give the resulting shifts of the beam position after N orbits, if focusing effects are disregarded:

$$\Delta_{\alpha} = 2 s N (N + 1) \alpha, \quad (6)$$

$$\Delta_{\beta} = \left(\frac{8 N + 1}{12} \lambda v + 2 s \right) N (N + 1) \beta, \quad (7)$$

$$\Delta_{\gamma} = \frac{\lambda v}{2\pi} N (N + 1) \gamma. \quad (8)$$

The relations can easily be derived under the assumption that the radii of curvature of the orbits in the magnetic fields are proportional to the orbit number, $r_n = n\lambda v/2\pi$, i.e. the kinetic injection energy is much smaller than the resonant energy gain and that α , β and γ are all very small.

In the actual RTM, where $s = 0.5$ m, $\lambda = 0.1$ m, $v = 1$ and $N = 15$ this gives:

$$\Delta_{\alpha} \approx 240 \alpha \text{ m},$$

$$\Delta_{\beta} \approx 480 \beta \text{ m},$$

$$\Delta_{\gamma} \approx 4 \gamma \text{ m}.$$

For comparison, the total length of the fifteen orbits is 27 m.

A numerical simulation of the alignment errors of the bending magnets shows the need for compensating devices. The simulation was performed with the actual fields including the focusing effects of the linac and of the auxiliary magnets. Each error was treated separately while the other machine parameters were optimized.

Assuming that the maximum acceptable deviation of the orbit is in the order of 1.5 to 2 mm, the computations show that the permissible alignment errors are about

$$|\alpha| < 0.015 \text{ mrad},$$

$$|\beta| < 0.01 \text{ mrad}.$$

For both types of errors the position of magnet 2 is less critical as the linac focusing partially corrects for an eventual displacement immediately after the orbits leave this magnet. The computa-

tions show that the effect is especially pronounced in the case of the " β " error where the tolerance for magnet 2 is ten times larger than for magnet 1.

These tolerances are far more stringent than one could expect to meet just by mechanical alignment and positioning of the magnets. It should be pointed out that even if both magnets are perfectly adjusted geometrically, small differences between the actual distributions of the fringing fields can result in an electrical deviation from parallelism of the same kind as an " α " or " β " type error. The lack of parallelism must therefore be compensated for.

When this was understood we tried to adjust the position of the magnets by shifting them mechanically. The variation of the angles α and β was measured by looking at a horizontal and a vertical scale at 10 m distance through a telescope fixed to the magnet which was tilted. We soon learned, that it is necessary to measure the shift of the magnet to an angle less than 0.1 mrad.

Instead of using complicated mechanical remote controls of the position of the two bending magnets, the compensation was performed electrically by the following arrangements.

Fig. 27.

Arrangement for correction of radial alignment errors

In order to compensate for the " α " error slits have been cut in the four polepieces of the auxiliary magnets, so that the pole tip consists of a row of "teeth", one pair for each orbit. Around these teeth coils were wound in such a way that the number of turns changed in even steps from tooth to tooth. The direction of winding was reversed in the middle to save space, Fig. 27. Thus, with one power supply per magnet, one could superimpose on the

auxiliary field a correcting magnetic field proportional to the orbit number, i.e. to the total energy of the electrons in the orbit. The beams in all orbits could therefore be bent the same angle as if the whole magnet were turned (19).

For the compensation of the " β " error a ladder-like row of small magnets is arranged along the front of magnet 1, Fig. 28.

Fig. 28.

Arrangement for correction of axial alignment errors

In analogy with the " α " correction these magnets were provided with coils, having the number of turns proportional to the orbit number, so that the beam was bent the same axial angle in each magnet gap. The device acted upon all return orbits from the second to the fifteenth.

The two designs for correction of the " α " and " β " errors were used for some years but have been changed as described in Part 8.3.

The " γ " error gives just a parallel shift of the beam position in the misaligned magnet. The permissible misalignment is consequently 50 times larger than for the " β " type error,

$$|\gamma| < 0.5 \text{ mrad.}$$

Over the 550 mm length of the magnet poles this means a 0.3 mm shift of the median plane. This should not, and it did not, represent a problem when assembling the machine.

Besides the angular errors, there can also exist a parallel shift of the bending magnets so that their median planes do not coincide. The resulting deviation of the central orbit is, due to the axial focusing of the auxiliary fields, quite moderate, unless the distance between the bending magnets is very long. The permissible error is for this RTM in the order of

$$|h| < 0.3 \text{ mm}$$

which is far larger than the assembling accuracy.

Two more alignment errors remain: the axial and the radial misalignment of the linear accelerator against perfectly aligned bending magnets. Practically, however, these errors cannot be distinguished from the " α " and " β " errors, even though they are different in nature. The effect is not cumulative and the corresponding requirements on alignment accuracy are thus about 20 times less stringent, being in the order of 0.2 mrad in the axial and 0.4 mrad in the radial direction. The radial error can be compensated for directly by the " α " compensating coils because one can in this way set the edge of each of the bending magnets independently perpendicular to the linac axis. The compensation of the axial error could be performed by a small magnet, similar to one of the magnets in Fig. 15 and placed on the common orbit at the exit side of the linac, but it was never tried experimentally. None of the errors is critical. In the horizontal direction this is confirmed by the operation of the microtron: Only a few per cent of the beam current can be gained by energizing both instead of just one of the two correcting coil groups.

In some simulations the behaviour of the microtron was computed for randomly generated alignment errors. In many respects this behaviour turned out to be similar to that of a perfectly aligned machine. Small differences, however, could be noted. This is shown in Fig. 29, where b, b1 and b2 demonstrate the computed displacement due to random errors of the electron beam as it enters the linear accelerator. b1 and b2 show the influence of two different excitations of the " α " compensating coils, whereas b is the compensated case. The simulated angular errors were in all three cases 0.66 mrad for the one and -0.41 mrad for the other magnet.

The computations of the RTM admittances, described later in 8.4, have shown small deviations due to the alignment errors.

8.3. Magnetic field irregularities

The deficiency in the magnetic field homogeneity (Fig.7) and the difference between the average field strength of the two bending magnets has the consequence that the radii of curvature of the orbits in the magnets become varying and different. Even without alignment errors these differences cause small displacements. This can be seen in Fig. 29, where the computed displacement of

the "center of gravity" of the electron beam at the entrance into the linear accelerator is shown by the black circles, a. All other magnetic field and alignment errors are excluded.

Fig. 29.

Position of the electron beam center at the entrance of the linear accelerator

From Fig. 29 it can be concluded that the difference between the field distribution of the two magnets does not disturb the electron orbits to a dangerously high degree.

Any magnetic field variation in the y direction (i.e. perpendicularly to the linac axis, see Fig. 3) gives asymmetries. It is therefore, contrary to the above mentioned error in the z direction, very serious. Even in an ideally aligned RTM the electrons will no longer cross the field-free region between the magnets along paths parallel to the linac axis.

To calculate the order of magnitude of the error which can be tolerated we can assume that the error exists only in one of the magnets and that the magnetic field there has a constant gradient,

$$B(y) = B_0 \left(1 + \frac{1}{B_0} \frac{\Delta B}{\Delta y} y \right). \quad (9)$$

The electron orbit inside this magnet will slightly differ from a semicircle. The beam will therefore be displaced and make an angle to the normal of the edge when leaving the magnet. The displacement, however, is more than ten times smaller than the displacement that results from the directional error and can therefore be neglected.

Assuming, as earlier, that the radii of curvature of the orbits in the magnetic field are proportional to the orbit number, n , the direction of the beam will each revolution be changed by an angle

$$e_n = \frac{1}{B_0} \frac{\Delta B}{\Delta y} \frac{\lambda}{4} n. \quad (10)$$

The effect is cumulative and the total displacement after N orbits is

$$\Delta_e = \frac{v\lambda s}{12} N (N+1) (N+2) \frac{1}{B_0} \frac{\Delta B}{\Delta y} \quad (11)$$

if all focusing is disregarded. With $v = 1$, $\lambda = 0.1$ m, $s = 0.5$ m and $N = 15$, as in the actual microtron, this gives:

$$\left| \frac{1}{B_0} \frac{\Delta B}{\Delta y} \right| < 0.0003 \text{ m}^{-1},$$

in order to keep the largest displacement less than the bore hole radius of the linac. This corresponds to a maximal error of 0.1 mT out of 0.7 T over the 0.5 m width of the main magnet.

A constant field gradient is a severe condition. In practice the magnetic field will probably show an irregular type of error. Such a kind of error will lessen the requirements on the magnetic field homogeneity.

As a consequence of small inhomogeneities in the magnetic field there will in general exist weak field components in both the y and the z direction. Apart from being focusing or defocusing these components can also give a net axial deflection.

This effect and the influence of the field irregularities on the radial motion are so harmful that - despite the focusing in the linear accelerator and the auxiliary magnetic fields - the requirements on the homogeneity of the magnetic field can hardly be satisfied even with great precautions in magnet design and construction.

In the actual RTM the errors are randomly distributed with an amplitude of about ± 0.5 mT both in the main and in the auxiliary magnets. The computation, where such a type of error in the actual magnetic field was simulated, shows that the displacement exceeds the limits of the bore hole of the linac before the fifteenth orbit is reached. Experimentally, by changing the excitation of the auxiliary magnets, the " α " and " β " correction devices, and the injection magnets one was able to evade the problem so that all fifteen orbits were obtained. All adjustments were very critical. Small changes of the above mentioned excitations or a rotation of the gun made the beam unstable. We believe, that the beam grazed the linear accelerator when the instabilities appeared.

The random nature of the field errors makes all earlier mentioned generally acting compensations less effective. The arrangements for correction of alignment errors have therefore been rearranged. The " β " correction magnets are excited in five separate groups and the coils on magnet 1 for the " α " error correction have been rewound and each tooth pair is now excited separately while the coils on magnet 2 no longer are used. (Except for the realisation of the windings, Figs. 27 and 28 in Part 8.2. are still valid). This step has had a remarkable effect on the behaviour of the accelerator. The stability of the beam is greatly improved and the capture of the injected current has increased by about 50 per cent approaching the theoretical values of an ideal RTM. Calculations show that these measures keep the displacement of the orbits to within a fraction of a millimetre at the entrance into the linac so that similar corrections on the other side of the straights are unnecessary. Compare Fig. 29, where the individual beam steering magnets were not used.

8.4. Admittances and emittances

The influence of the actual linac design on the phase acceptance was described in Part 8.1. A halfcell at the entrance side of the linear accelerator, however, also has a beneficial effect on the admittance of the RTM. As the velocity of the injected electrons is rather low, they have to enter the first cavity early during the accelerating half period in order to match the phase region. This means that the focusing force at the entrance is weaker than the defocusing force at the exit of the gap. The shorter cavity gap and the shorter distance to the next gap makes the net defocusing effect less pronounced when the first cavity is a halfcell. It is obvious from this discussion, that the phase acceptance and the admittance are intimately interrelated.

Simulations have shown very small differences in the admittance of the microtron with and without alignment errors. Fig. 30, which shows the radial and the axial admittance, can therefore be assumed to be representative for this RTM. A simulation with alignment errors was chosen in order to show the asymmetries caused by the errors. The admittance would have quite another form if a full cavity were used at the injection side.

Fig. 30.

Axial and radial admittance

- more than 50 degrees of phase accepted
after 15 orbits
- - - - - more than 20 degrees of phase accepted
after 15 orbits

The computed beam emittances decrease with increased orbit number, due to the increase in energy, being $17 \cdot \pi$ mm mrad axially and $6 \cdot \pi$ mm mrad radially in the third orbit and $2.6 \cdot \pi$ mm mrad axially and $2.4 \cdot \pi$ mm mrad radially in the fifteenth orbit (95 per cent of the beam current). The form of the emittance, especially the axial one, changes from orbit to orbit. This is mainly due to the axial focusing action of the auxiliary fields and also - to a lower degree - to focusing in the linear accelerator. Typical axial emittances are shown in Fig. 31 for the fourth and fifteenth orbit at the entrance into the extraction magnet. The influence of nonlinear focusing effects is clearly visible.

Fig. 31.

Computed axial emittance in the fourth and fifteenth orbit

- 80 per cent of the beam current
- - - - - 95 per cent of the beam current

CHAPTER 9

Electron beam measurements

In the preceeding chapters some results were given from measurements of magnetic fields, linear accelerator electric field etc. In this chapter we give some additional information on microwave power relations and on measurements on the electron beam.

A typical distribution of currents in the orbits of the RTM is given in the Table 1. In these measurements the injection pulse current was 100 mA. Thus the current figures for the various orbits also show the capture in per cent of the injected current.

Table 1.

orbit nr.	3	4	5	6	7	8	9
pulse current mA	24.2	23.6	23.5	23.3	22.3	20.7	20.4
orbit nr.	10	11	12	13	14	15	
pulse current mA	19.3	18.5	18.0	17.8	17.6	17.5	

The accelerator was adjusted for optimum current in the fifteenth orbit (50 MeV) and only the microwave power was changed as the currents in the inner orbits were measured on a Faraday thick copper target movable with the extraction magnet along the edge of magnet 1. More than 15 per cent of the injected current can easily be found in the fifteenth orbit.

Incident and reflected microwave power in the linear accelerator waveguide have been measured for different beam currents and linear accelerator voltages. For example at a resonant energy gain of 3.3 MeV per turn and a beam current of 21 mA at 50 MeV the waveguide is terminated with a matched load and the total incident power is 2.25 MW. In this case the power distribution is such that 1.0 MW is required to compensate for the losses in the linear accelerator and waveguide channel, 1.0 MW goes into beam power and the

rest - 0.25 MW - is spent on the acceleration of error phase electrons. A similar investigation at an acceleration of 2.7 MeV per turn shows that also in this case 10 - 12 per cent of the incident power is lost to electrons that will lose phase during the first transits through the linear accelerator.

The maximum pulse current that has been attained at 50 MeV is about 30 mA. At this beam current the capture was 14.6 per cent and the total input microwave power about 3 MW.

The rf efficiency, defined as the quotient between beam power and total microwave power, can for a final energy of 50 MeV reach 50 per cent.

Fig. 32.

Optimum injection voltage and magnet distance

———— injection voltage
 - - - - - magnet distance

Most of the time the RTM has been in operation it has been run with an energy gain of 3.33 MeV per turn simply for the reason that with the fifteen orbits its maximum energy becomes 50 MeV - the design energy. Other acceleration energies can be used by changing linac voltage, magnetic fields and distance between the magnets. The range within which the acceleration can be varied is 2.7 - 3.7 MeV per turn. The lower energy limit is set by the minimum distance that can be attained between the magnets (minimum length of the stainless steel bellows described in Chapter 3). The available magnet current sets the high energy limit. The electron capture is fairly independent of the energy gain except for the high energy side where the compensation for magnetic field irregularities is not sufficient. Fig. 32 shows a diagram of the

optimum injection voltage and magnet distance as a function of the energy gain per turn.

The RTM can also be operated in other modes than the fundamental one with parameters $\nu=1$ and $\mu=11$ (Chapter 3). An interesting mode which can be run within the available magnet distances is the one with mode numbers $\nu=2$ and $\mu=12$, the "half mode". The linear accelerator voltage is approximately the same as that used in the fundamental mode but the magnetic field is halved (Eq. 4). The time difference in completing two successive orbits is in this mode two rf periods and the distance between orbits becomes $2\lambda/\pi$ instead of the usual λ/π in the fundamental mode. Thus the half mode orbits will be found at the positions of second, forth, sixth etc orbits of the fundamental mode.

In normal operation, i.e. in the fundamental mode, it is not possible - due to the size of the extraction magnet - to extract orbits inside the third one (about 10 MeV). In the "half mode", however, a 6 MeV beam can be extracted at the position of the normal forth orbit. The capture is good; about 23 per cent of the injected pulse current can be found in this orbit.

Direct extraction at the linac energy, about 3 MeV, can be done by lowering the magnetic field strength to one third of the normal value, and the beam will be found at the position of the normal third orbit. The capture is in the order of 25 per cent.

The emittances of the extracted electron beam have been measured with the aid of a movable slit, defining the transverse coordinate, and a wire, scanning the angular distribution. With 20 mA pulse current the 47 MeV axial and radial emittances were found to be $3.0 \cdot \pi$ mrad mm and $2.6 \cdot \pi$ mrad mm respectively. Here the definition of the emittance is taken as the phase space area within the contour of constant linear radiance ($d^2I/dx \cdot dx'$ or $d^2I/dy \cdot dy'$) that contains 85 per cent of the beam current.

The experimental set-up, however, had several imperfections: First, the 1 mm slit and its holder - originally used for much lower energies - were partly transparent to the electrons and, secondly, the 0.5 mm tungsten wire was mounted about 15 mm outside the 0.08 mm aluminium vacuum window. This has extended the measured "tails" of the angular distributions and caused a rather high background current. The part of the beam cut away by the emittance borders is therefore probably overestimated.

It is interesting to note that the measured (and the computed) axial emittance is greater than the radial one. As the RTM is equipped with axially focusing auxiliary poles one would have expected the opposite. The most probable explanation is that the contra-fields introduce aberrations (see Fig. 31 and appendix of ref. 6), and indeed, the measured positional and angular current distributions are far from Gaussian.

Finally, measurements of the energy spread have shown minimum values ranging from slightly above ± 0.5 per cent at 6 MeV trough ± 0.15 per cent at 30 MeV down to ± 0.05 per cent at the highest energies. The maximal widths of the various energy spectra, resulting from different parameter settings, were about 50 per cent higher. These figures fit rather well the theoretical results given in Fig. 23.

By varying the machine parameters it was found that, with constant main magnetic field, the mean energy of the electron beam in a certain orbit is influenced mostly by the linac voltage. A variation of the amplitude of the accelerating voltage changes the resonant phase of acceleration and thus the frequency of the synchrotron oscillations. As discussed in Chapter 8.1 this influences the energy of the whole beam.

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THE 50 MeV RACETRACK MICROTRON AT THE ROYAL INSTITUTE OF
TECHNOLOGY, STOCKHOLM

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The development, construction, and operation of a pulsed 50 MeV two-sector racetrack microtron is described. The machine has internal electron gun injection and uses a biperiodic standing wave linac for the acceleration. Electrons with energies between 3 MeV and 55 MeV can be extracted. Orbital stability is ensured by an inverted magnetic field along the fronts of the main magnets.

Key words: microtron, racetrack microtron, electron accelerator