Overview of the Magnet Design for the TEUFEL Microtron

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Abstract

To obtain proper transverse focusing in the TEUFEL microtron, rotated two-sector magnets will be used. These magnets offer two degrees of freedom, which can be optimized for maximum machine acceptance using a first order matrix theory and numerical orbit integration. The optimization procedure requires a description of the fringe fields, which are studied by way of numerical codes (POISSON, RELAX), analytical calculations (conformal mapping) and measurements. From these calculations, the optimum parameters have been estimated. These yield sufficient focusing properties (large acceptance) which are insensitive to design imperfections.

The optimum magnet configuration has been constructed and in this paper a comparison of orbit measurements and calculations is made.

1 INTRODUCTION

At the Eindhoven University of Technology, two racetrack microtrons are being designed and constructed. Instead of using the conventional layout with homogeneous bending magnets and quadrupoles in the drift space, we have opted for a combined-function two-sector design. The bending magnets have a valley/hill design and are slightly rotated in the median plane to obtain closed orbits [1]. This design uses edge focusing at the various field edges to keep the beam transversely stabilized.

One of both racetrack microtrons (called "RTM-Twente" or "TEUFEL microtron") will accelerate electrons from 6 to 25 MeV and serve as an injector for a free electron laser (TEUFEL project [2]). We aim to transport a peak current of 50 A, so the focusing strength of the two-sector magnet must be sufficient to conquer space charge forces. Our approach for the magnet design is to optimize the machine acceptance by varying the free parameters of the two-sector design.

The specifications of the second racetrack microtron ("RTM-Eindhoven") are very similar, but it will accelerate electrons from 10 to 75 MeV with a much lower peak current. Moreover, this machine has a larger separation between the two-sector magnets (2 m with respect to 0.9 m for TEUFEL). In this paper we will concentrate on the TEUFEL microtron, but mention some features of RTM-Eindhoven as well. We will start with a discription of fringe field properties which are used in subsequent ion optical calculations yielding the optimum sector design. We then examine the sensitivity of this design and end this paper with some first results of orbit measurements.

2 FRINGE FIELD PROPERTIES

In figure 1, an example of the field map of one of the two-sector dipole magnets is shown. The low- and high-field sector are clearly visible, as well as the rotation of the magnet in the median plane and the small negative field dip at the front caused by an active clamp.

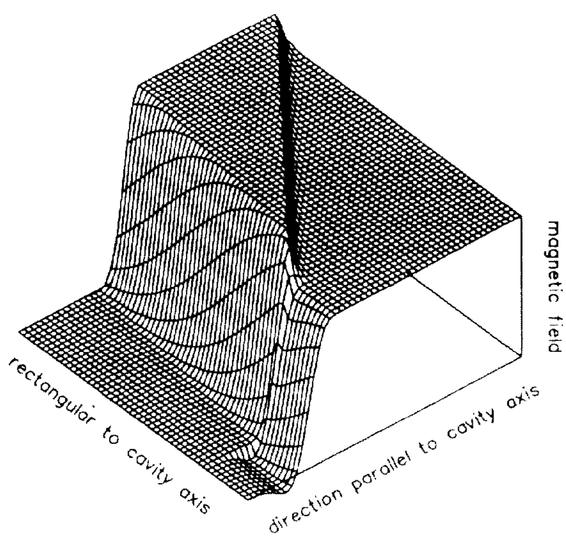

Figure 1: *Magnetic field map of a two-sector magnet in the median plane. The cavity is located towards the left in this picture*

In order to find the optimum shape of the sectors, we studied the transverse and longitudinal beam optics by a first order matrix description and by numerical orbit integration through generated field maps. Both descriptions need the fringe field properties as input. Although the considered geometry is obviously three dimensional, we first used the POISSON code to estimate the fringe field properties in two dimensions. Next, the method of conformal mapping [3] has been applied to get analytical expressions for the magnetic fringe fields. Finally, to examine realistic 3D configurations, the RELAX code has been used to solve the Laplace equation. Conformal mapping and RELAX assume that no saturation effects are present, which is valid for RTM-Twente with a maximum magnetic field of about 0.2 T.

In table 1, the value of the fringe field quantity EFB (effective field boundary) is listed as obtained by RELAX, POISSON, conformal mapping (CM) and measurements at three boundaries: from driftspace to the low field section (1), from driftspace to the high field section (2) and from the low field section to the high field section (3) in a given two-sector layout. From this, it is seen that there is agreement between RELAX, conformal mapping and the measurements. The results from POISSON deviate slightly.

For the RTM-Eindhoven, saturation effects may play an important role and will be studied further.

Table 1: *Comparison of the EFB value (in mm) at three boundaries as found from RELAX, POISSON, conformal mapping and measurements; see text for more details.*

	RELAX	POISSON	CM	Measurements
1	20±2	22.5	19.5	19±1
2	12±2	14.7	13.5	13±1
3	3±2	3.7	4.8	4±1

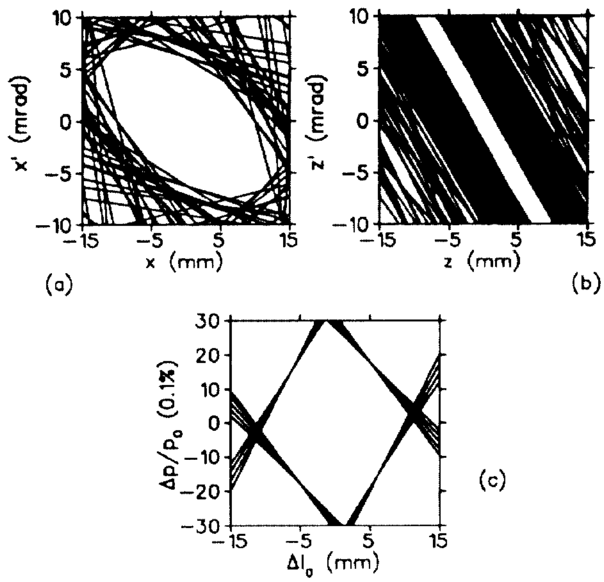

Figure 2: *Acceptance polygon in (a) the horizontal plane, (b) the vertical plane and (c) in the longitudinal plane.*

3 OPTIMUM PARAMETERS

Ion optical calculations (such as fringe field corrected matrix tracking and orbit integration) are used to locate the optimum two-sector configuration. This optimum has an acceptance area (enclosed by the acceptance polygon) of about 100 mm·mrad in both the horizontal and vertical plane, which is sufficient to match the emittance of 6 mm·mrad at 6 MeV from our photo-cathode injector. The shape of the acceptance polygon at injection is plotted in figure 2 with x, x', z and z' the maximum displacement and divergence in the horizontal and vertical plane, respectively. In the vertical plane, z is limited at 25 mm because of the vacuum chamber at injection. Δl_0 represents the path length difference with respect to the synchronous particle, which is proportional to the phase spread at injection (RF wavelength equals 23.1 cm). From the phase space plot for the longitudinal motion it is seen that the maximum energy spread $\Delta p/p$ at 6 MeV is about 3% at a synchronous phase of 18° and about 0.8% at extraction. Varying the synchronous phase, the maximum $\Delta p/p$ changes as predicted using Hamilton theory [4]. Another parameter we can use to check the result of the ion optical codes, is the conservation of normalized emittance, which is fulfilled indeed.

Besides the shape of the acceptance polygon in phase space, the motion of the beam can be made visible by plotting the beam envelope in the horizontal and vertical plane. This is shown in figure 3. From this it turns out that the tune ν_z is about 0.32.

Similar ion optical calculations have been done for the RTM-Eindhoven. The corresponding acceptance in both the horizontal and vertical plane can be made more than 50 mm·mrad. From the phase space plot in the longitudinal plane, it is found that the maximum energy spread $\Delta p/p$ is about 1% at injection and about 0.15% at extraction.

4 SENSITIVITY

An important aspect in the design of the two-sector magnet is the sensitivity of the acceptance for (1) mechanical errors and (2) model simplifications. For the RTM-Twente, the acceptance in both the horizontal and vertical plane does not change significantly, within and even outside the mechanical accuracy. However, when the fringe field quantity I_2 (expressing the defocusing effect of the fringe field) is changed within the measuring accuracy of 0.05 [3], the acceptance in the vertical plane changes about 15%. As the acceptance for RTM-Twente is already much larger than the value actually required, this will be no severe problem.

For the RTM-Eindhoven, however, the vertical acceptance is much more sensitive to this type of error, so a (more) accurate description of the fringe field is needed. At the moment, this problem is tackled using numerical tools combined with more complicated conformal mapping geometries.

As a result of the two-sector design, the electron beams experience differently shaped fringe fields when entering or leaving the magnet (hill or valley). Obviously, they also see different EFB's, which causes a non-180° bend. In order to compensate for this EFB difference (in the order of a few millimeters) we will add an active clamp at the entrance of the magnet. Orbit integrations through a numerically generated field map and measurements confirm the theoretical predictions and demonstrate the necessity of the active clamp for a perfect 180° bend

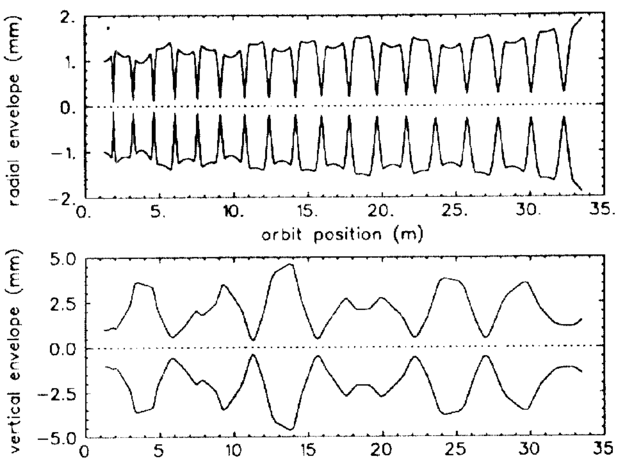

Figure 3: *Radial and vertical RMS beam envelope in RTM-Twente.*

5 ORBIT MEASUREMENTS

In order to verify the theoretical predictions on the focusing properties of the two-sector magnet, one could measure the fieldmap of the entire two-sector dipole magnet and use orbit integrations through this measured field map to calculate the transfer matrices, acceptance and beam envelope. This approach, however, suffers from the fact that, for accurate orbit integration, the *entire* field map needs to be measured with a fine grid, while most of the measurement data remains effectively unused.

As a quick and flexible alternative, one could use the measuring machine to follow the actual electron orbits *during measurement*. For this method, the measuring probe is located outside the magnet and initial conditions such a "velocity" and "energy" are set. A program can now repetitively measure the local field and move the probe through the median plane according to the equations of motion as though it was following the orbit of a real reference electron. This way, all the measurement points contribute to the final result. Additionally, one can easily measure the local field gradient rectangular to the orbit at each point of the obtained "orbit", so a first-order transfer matrix can also be calculated during the measurement.

The above method is applied to check the optical properties of our two-sector magnet. Table 2 compares some results of the measurements with calculations for half an orbit at 10.22 MeV. The active clamp that is required on the cavity axis is not yet constructed, so the orbits have a predicted bending error of 30 mrad. The measurements show a much larger value, which may be caused by the long tail of the fringe field that could not be measured entirely. The other parameters agree very well.

Finally, in figure 4, the field gradient rectangular to the orbit as predicted by calculations and as derived from measurements is drawn. The graphs are not exactly the same, which is caused by the fact that, for our calculations, a simplified edge field model is used which, however, does conserve physical properties of the real edge field (e.g. EFB value and focusing strength), hence the transfer matrices are (almost) equal.

Table 2: *Comparison of various orbit parameters between computer calculations and orbit measurements.*

parameter	measured	calculated
orbit length	1.0002 m	0.9984 m
bending angle error	58.8 mrad	30.6 mrad
radial matrix trace	-1.82	-1.82
vertical matrix trace	1.77	1.82

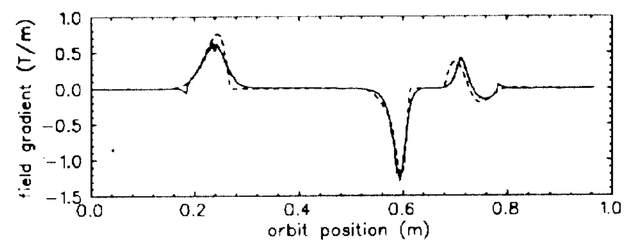

Figure 4: *Field gradient rectangular to the orbit as derived from measurements (drawn) and as predicted (dashed).*

6 CONCLUSIONS

Presently, we have designed the optimum shape of the two-sector magnets for the RTM-Twente and a two-sector magnet has been constructed. Preliminary orbit measurements show that the obtained data agrees with the predictions of calculations.

The optical properties of the RTM-Eindhoven have been calculated, but the acceptance in the vertical plane is sensitive for deviations of the (simplified) fringe field model, so a more accurate description using conformal mapping is started.

7 REFERENCES

[1] J.L. Delhez, G.A. Webers, J.I.M. Botman, H.L. Hagedoorn, D. Muzio, C.J. Timmermans - "*Electron beam focusing in a racetrack microtron by means of rotated two-sector dipole magnets*", to be published in Nucl. Instr. and Meth. in Phys. Res.

[2] J.I.M. Botman, H.L. Hagedoorn, G.A. Webers, J.L Delhez, G.J. Ernst, W.J. Witteman, E.H. Haselhoff - "*Update on the MicroFEL-TEUFEL project*", Proc. 2nd. Eur. Part. Accel. Conf., Nice, 1990.

[3] G.A. Webers, J.L. Delhez, J.I.M. Botman, H.L. Hagedoorn, J. Hofman, C.J. Timmermans - "*Fringe field calculations for the inhomogeneous Twente Eindhoven microtron magnets*", to be published in Nucl. Instr. and Meth. in Phys. Res.

[4] J.L. Delhez - "*The effect of space charge and fringe fields on the focusing of electron bunches in a 25 MeV racetrack microtron*", internal report VDF/NK 90.10, TUE, 1990.