MAGNETIC FIELD CALCULATION AND SHIMMING OF THE SELF–EXTRACTION CYCLOTRON

W. Kleeven, W. Beeckman, S. Lucas, S. Zaremba, D. Vandeplassche, Y. Jongen, IBA Belgium

Abstract

The self-extraction cyclotron is a 14 MeV H+ machine from which the beam extracts without a deflector. This is achieved with a special shaping of the magnetic field. Detailed 3D magnetostatic models have been constructed of this cyclotron, in order to accurately calculate the extraction process. Shimming of removable pole tips has been used to isochronize the machine and to remove harmonic errors. A software simulation of the shimming has been made, in order to accelerate the convergence of this process. First extracted beam has been obtained. There is good agreement between the calculations and measurements. Results of TOSCA calculations, mapping and shimming are presented.

1 INTRODUCTION

The project is discussed in the invited paper[1].

2 MAGNETIC FIELD CALCULATIONS

The extraction of the beam requires a complicated magnetic circuit with unconventional features: i) an intrinsic 2-fold symmetry with two long sectors and two short sectors, ii) hill gaps with a quasi elliptical shape which, moreover, are different for the short and long poles, iii) a groove machined in one of the long sectors providing a kind of magnetic septum and also the beginning of the extraction path (Figure 1), iv) for magnetic symmetry, a second groove on the opposite sector, but moved slightly outward in order to avoid extraction on the wrong side (introducing an intrinsic 1st harmonic), v) (optionally) the presence of two opposed Sm-Co harmonic kickers, at an azimuth of $\pm 90^\circ$ with respect of the groove, kicking the last internal orbit into the field dip of the groove, vi) the presence of harmonic coils, vii) the presence of a Sm-Co gradient corrector radially focusing the beam before it exits from the vacuum chamber.

Figure 1: The removable pole tip with the evolved groove

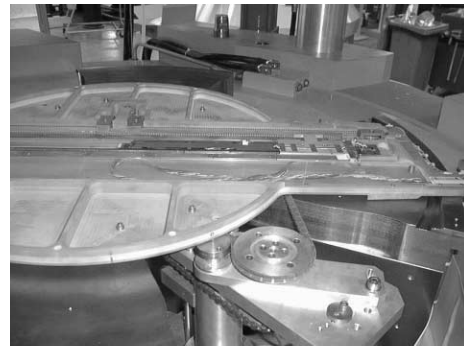

Figure 2: The mapping system installed in the cyclotron

A large part of the developement has been devoted to the calculation of the magnetic field. The OPERA3D software from Vector Fields was used. Because of the complexity of the magnetic field, a fully parameterized generator of the TOSCA input file was developed as a separate C-program. All important features of the cyclotron such as pole radii, pole angles and pole gap as a function of radius, extraction groove, central plug geometry, yoke dimensions, pumping holes, main coil dimensions, beam exit ports etc, are automatically generated with this program. Full 360° models were obtained by calculating two independent 180° models and joining them together in the middle of the valley. In this way the asymmetry due to the two different grooves could be included using about 300.000 nodes. The fields produced by the permanent magnet elements and harmonic coils were calculated separately and then super-imposed to the main field.

3 MAPPING SYSTEM

A computer controlled mapping system allows for a 2D-positioning of a Hall probe (Bell BHT-910). Two DC motors are used for the azimuthal and radial movement respectively. A feedback system is used for accurate positioning, including optical encoders for the measurement of the actual radial and azimuthal coordinates. An additional encoder is used for the azimuthal zero calibration. The radial zero is automatically found by the use of limit switches. An industrial computer controls the movement and the data acquisition. An additional PC provides a graphical menu-driven user interface. The mapping software allows full freedom in the definition of the grid, including variable step sizes and mapping of separate zones simultaneously. A PT100 is used to monitor the temperature of the Hall probe. An signal unit is used to i) supply stable currents to the Hall probe and the PT100 (100 mA and 1 mA respectively), ii) amplify the Hall and PT100 signals (100x), iii)

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feed all relevant signals to a digital multimeter with incorported multiplexer (Keithley 2000 SCAN).

4 SHIMMING STRATEGY

Three ingredients are needed to remove the field errors: i) a way to quantify the field errors, ii) a reasonable prediction of the required pole edge modification and iii) a precise calculation of the effect of any given pole edge modification. Having this, an iterative process can be used to find an accurate estimate of the required shimming. The three tools have been developed for the self-extraction cyclotron.

Because of the intrinsic asymmetry of the magnet, not only the isochronism but also first and second harmonics are shimmed. These field errors are determined from closed orbit properties (Fourier analysis on circles would lead to large errors near the grooves). The isochronism error is calculated (as usual) from the particle revolution frequency. For the harmonic errors there are two different ways namely i) using Fourier analysis on the closed orbit and ii) using closed orbit displacement (harmonic 1) or closed orbit deformation (harmonic 2). Both methods have been implemented and give good results. As an example we use the following formula for finding the first harmonic cosine component from the closed orbit shift[2]:

$$A_1 = -2(\nu_r - 1)\frac{r(0^\circ) - r(180^\circ)}{r(0^\circ) + r(180^\circ)}B_{ave}(r), \qquad (1)$$

where ν_r is the radial betatron frequency and B_{ave} is the average field. Similar equations are used for the 2nd harmonic[3]. To remove a first harmonic, we shim the two pole edges located closest to the harmonic 1 as illustrated in Figure 3. Assuming a hard edge model of the hill and valley fields, we find the the following reasonable prediction for the shimming of edge 1:

$$\delta_1 = \left(\frac{\sin(\alpha_2 - \phi_1)}{\sin(\alpha_2 - \alpha_1)}\right)\frac{\pi H_1}{B_h - B_v} \qquad (2)$$

where H_1 and ϕ_1 are the amplitude and phase of the first harmonic. Similar formulas are found for edge 2 and for shimming of a 2nd harmonic[3].

For an accurate calculation of its effect, the shimming is considered as a superposition of cuts of quadrilaterals where each quadrilateral corresponds with the movement of one point on the pole edge from the old to the new position. This is illustrated in Figure 4. It is further assumed that the effect of each quadrilateral is proportional to its surface. With this assumption it is sufficient to make a series of TOSCA simulations of separate tetra-lateral cuts (see the lower right of Figure 4) at sufficient radii and for all pole edges. A real shimming can be de-composed into a superposition of these separate cuts using a big matrix which relates the effect (average field, first or second harmonic) at a certain radius in the machine to a well defined cut at a given radius and pole edge. This method strongly accelerates the convergence of the shimming process[3].

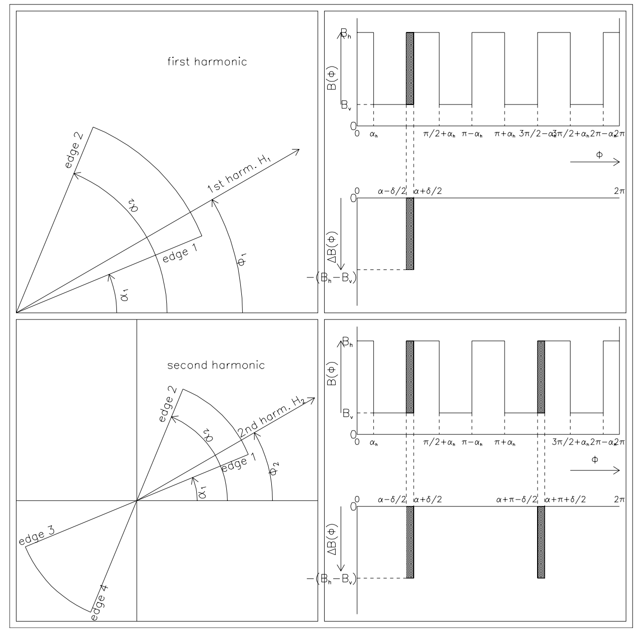

Figure 3: Hard edge model of the field used for the reasonable prediction of the shimming of harmonic errors

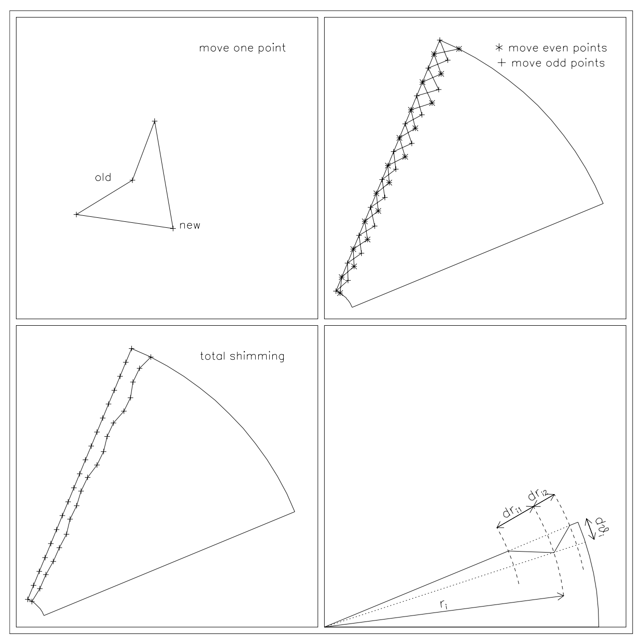

Figure 4: For the TOSCA calculation, the shimming is considered as a superpostion of cuts of quadrilaterals

5 FIELD MAP ANALYSIS

Software has been developed for the analysis of a field map. The main steps are the following: i) convert Hall voltages to magnetic field using a polynomial calibration and correct for Hall probe temperature changes ii) check the raw data for possible errors in the sequence of probe movements iii) correct all possible drifts in the field by using the center field as a reference iv) interpolate the field

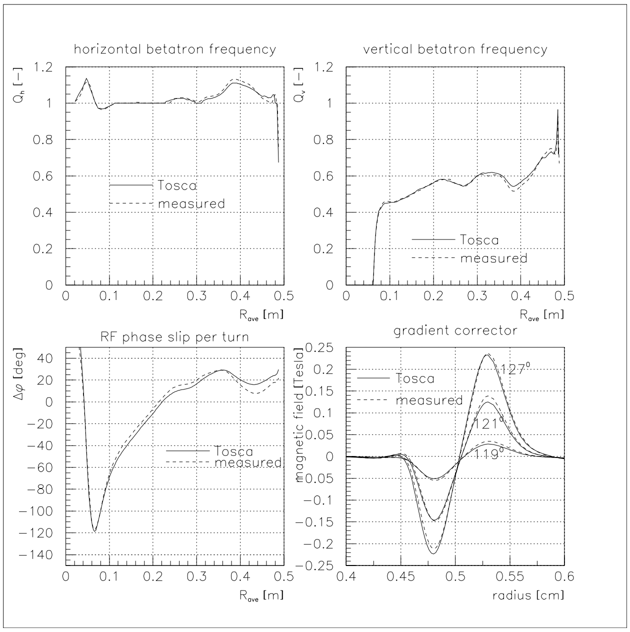

Figure 5: Comparisson between results of TOSCA and field measurements

from the mapping grid to the closed orbit grid v) determine the field errors by making a closed orbit analysis vi) make a reasonable prediction of the required shimming vii) accurately calculate the field errors that would remain when this shimming would be applied viii) repeat the previous two steps until the remaining errors are considered small enough ix) prepare new pole edge files for machining. After machining of the pole tips a new mapping is made and the above process is repeated.

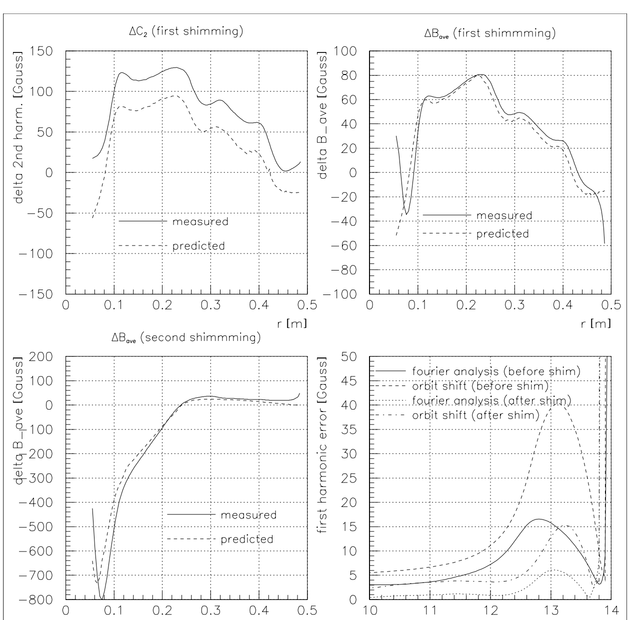

Figure 6: Comparisson between predicted and measured effect of pole edge shimmings

6 SOME RESULTS

In Figure 5 we compare the betatron frequencies and RF phase shift in the TOSCA field and the field map of the cyclotron before the shimming. Note that the ν_r locks to 1 over a wide range of closed orbits, due to the $2\nu_r = 2$ resonance. After shimmimg, this resonance is removed. In the lower right figure, we compare calculated and measured fields in the gradient corrector at a few different azimuths. In all cases there is excellent agreement.

In Figure 6 we compare the predicted effect of a shimming with the measurement. The upper left figure shows the change of a second harmonic in the first shimming. The next two figures show a change in average magnetic field. It can be seen that the predictions are accurate. The last figure shows the removal of a first harmonic error close near extraction. This figure also compares the two different ways of quantifying a first harmonic as explained before.

In Figure 7 we show some properties of the final field map. It is seen that the final RF phase slip is less than $\pm 8°$. The lower left figure shows the initial (before shimming) and final harmonic errors. Both first and second harmonic have been substantially reduced. The lower right figure illustrates the fast convergence of the shimming process.

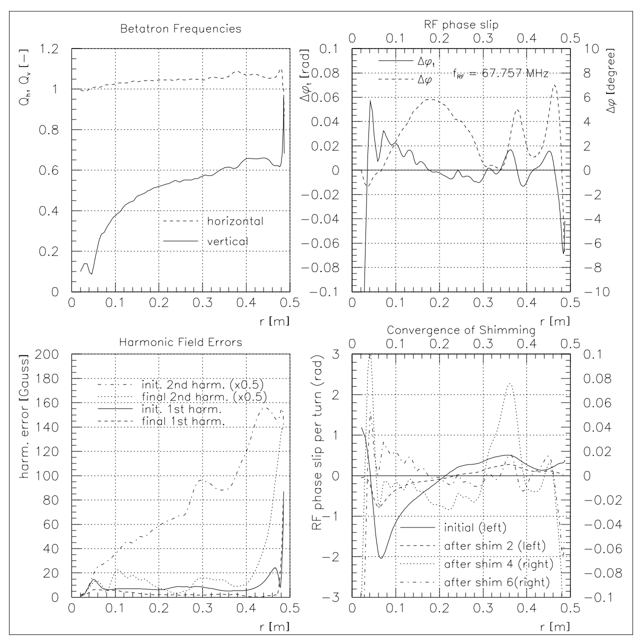

Figure 7: Final magnetic field properties

7 REFERENCES

[1] W. Kleeven, S. Lucas, S. Zaremba, W. Beeckman, D. Vandeplassche, M. Abs, Y. Jongen, *The Self-Extracting Cyclotron*, these proceedings.

[2] H.L. Hagedoorn and N.F. Verster, *Orbits in an AVF Cyclotron*, Nucl. Intstr. Meth. **18,19** (1962)201-228

[3] W. Kleeven, *Shimming Scheme of the Self–Extraction Cyclotron*, IBA internal document 88.25.02.020-A, 2000.