

# CALIBRATION OF THE SIMULATION MODEL OF THE VINCY CYCLOTRON MAGNET

by

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The MERMAID program will be used to isochronise the nominal magnetic field of the VINCY Cyclotron. This program simulates the response, *i. e.* calculates the magnetic field, of a previously defined model of a magnet. The accuracy of 3D field calculation depends on the density of the grid points in the simulation model grid. The size of the VINCY Cyclotron and the maximum number of grid points in the XY plane limited by MERMAID define the maximum obtainable accuracy of field calculations. Comparisons of the field simulated with maximum obtainable accuracy with the magnetic field measured in the first phase of the VINCY Cyclotron magnetic field measurements campaign has shown that the difference between these two fields is not as small as required. Further decrease of the difference between these fields is obtained by the simulation model calibration, *i. e.* by adjusting the current through the main coils in the simulation model.

*Key words:* cyclotron, magnetic field, 3D calculation, MERMAID

## INTRODUCTION

The VINCY Cyclotron is an isochronous cyclotron with an azimuthally varying magnetic field. It is a multipurpose machine which will be used to accelerate a wide variety of ions whose specific charge ranges from  $\eta = 0.15$  to  $\eta = 1$  [1]. Because isochronous fields corresponding to ions with different specific charges differ, the VINCY Cyclotron will provide a number of isochronous fields. The isochronous field of an ion grants that the rotation frequency of the chosen ion during its acceleration in a cyclotron is constant [2]. In the case of the VINCY Cyclotron, the nominal isochronous magnetic field is the one corresponding to the ion whose specific charge is  $\eta = 0.5$ . The nominal magnetic field should be obtained by exciting the magnetic

structure [3] (Fig. 1.) by the nominal current of the main coils only. All other isochronous fields are created using not only the main coils but also the trim coils [4].

In order to obtain the nominal isochronous magnetic field, the shape of the magnetic structure of the VINCY Cyclotron was adjusted through an iterative procedure. During the first phase of the magnetic field isochronisation [5] each iteration had three steps: two-dimensional (2D) calculation of the magnetic field, magnetic field measurement and sector shimming (Fig. 1.), *i. e.* adjusting the sector shape by taking off a thin layer of ferromagnetic material from a sector side. During the first phase of the field measurement campaign, one set of measurements was performed without sectors, *i. e.* with a medial pole plate, and five sets of measurements carried out with sectors of five different profiles. Analysis of the results of the first phase of the magnetic field measurement campaign [6] showed the disadvantages of 2D calculation of the magnetic field. Namely, that the predicted nominal isochronous field is not achieved and that the difference between predicted and obtained fields is particularly large in the central region of the cyclotron. Therefore, magnetic field isochronisation was subsequently obtained by using MERMAID, the new three-dimensional (3D) magnetic field simulation code [7].

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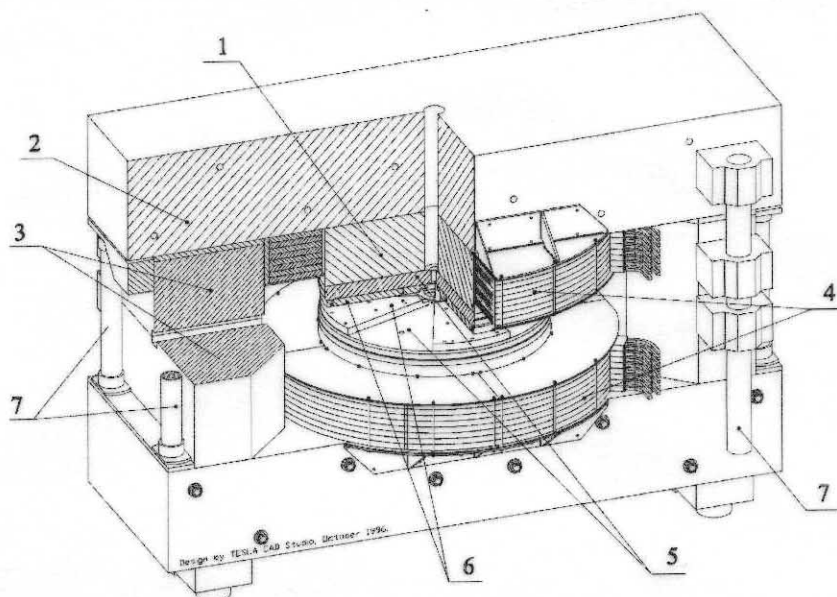


Figure 1. Magnetic structure of the VINCY Cyclotron. 1 – the pole, 2 – the upper part of the yoke, 3 – the side part of the yoke, 4 – the main coil, 5 – the medial pole plates, 6 – the sectors, 7 – the elevation system

The sector shape should be designed by simulating the response to the nominal main coils current of a number of MERMAID models. The simulated field corresponding to the final sector shape is to be compared with the measured magnetic field in the second phase of the field measurement campaign. The measured magnetic fields obtained during the first phase of the field measurements should be used to calibrate the MERMAID simulation model of the VINCY Cyclotron.

### THE FIRST PHASE OF FIELD MEASUREMENTS

Extensive magnetic field measurements are an important step in the construction of a cyclotron. During the first phase of magnetic field measurements of the VINCY Cyclotron, one set of measurements was carried out without sectors and five sets of measurements were performed with sectors of five different profiles. The main coil currents during the measurements without sectors had seven different values ranging from 250 A to 1000 A (Fig. 2). On the other hand, all five sets of measurements with sectors of different profiles were performed for three main coil current values: minimal of 250 A, nominal of 600 A and maximal of 1000 A.

The measured field map of the VINCY Cyclotron magnetic structure without sectors corresponding to the main coil current value of 1000 A is shown in Fig. 3. It was to be expected that the measured maps would reflect the cylindrical symmetry of the pole plates. Analysis of the measured field maps detected an error in the operation of the magnetic field measurement system [8]. The Hall's

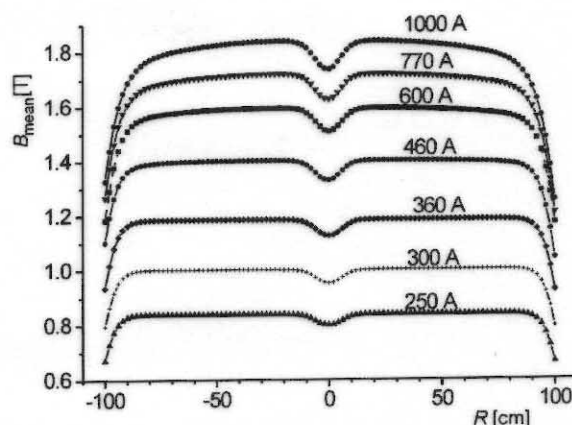


Figure 2. Response of the VINCY Cyclotron magnetic structure without sectors. Figure shows radial dependence of the mean magnetic induction for seven values of the main coils current. The dip around  $R \approx 0$  cm is caused by the axial channel in the magnet poles, while field drops around  $R \approx 100$  cm and  $R \approx -100$  cm are due to the pole edge

probe was not properly positioned at the initial radial position along the measuring arm due to the malfunction of the mechanical switch used for the detection of the initial radial position. The measurement system was subsequently modified by replacing the mechanical with an optical switch and measured maps were corrected numerically [9]. Further on in the text, only the corrected maps are used.

### THE MERMAID CODE

The MERMAID is a product of SIM Limited, Novosibirsk, and is used for two and three-dimen-

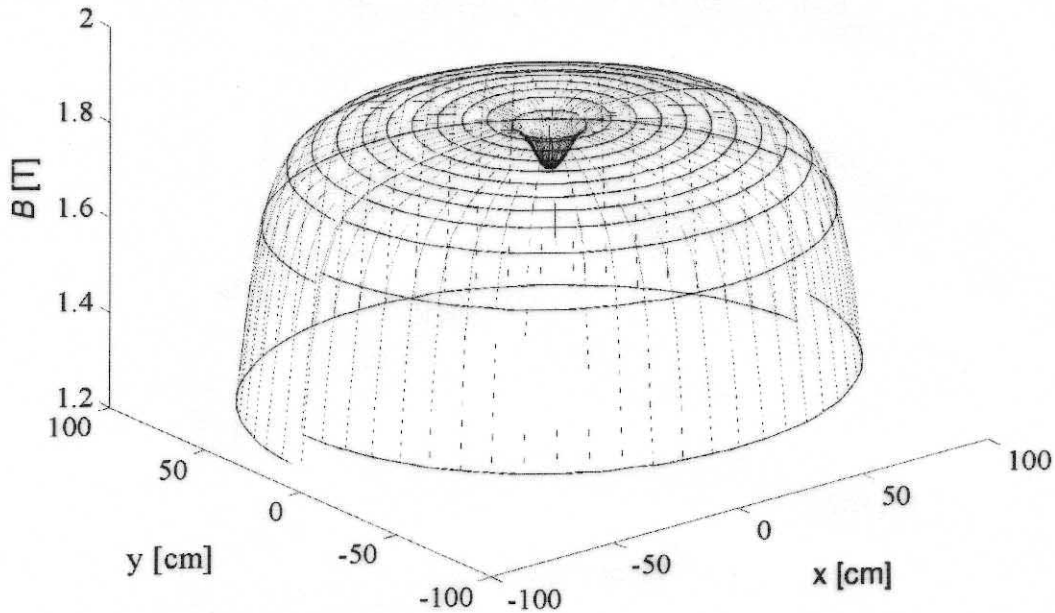


Figure 3. The measured magnetic field map. The measured response of the magnetic structure without sectors to the main coil current of 1000 A is shown. Due to an error in radial positioning of the Hall's probe in the initial point on the measuring arm, the measured magnetic field  $B_{\text{meas}}$  does not have an expected axial symmetry. The measured field values corresponding to two probe positions with the same radius and azimuthal coordinates that are  $180^\circ$  apart differ. This difference is the most visible at azimuthal position  $0^\circ$ , i. e.  $360^\circ$  and  $180^\circ$  where it appears as field discontinuity

sional calculations of static magnetic fields. The MERMAID model of a desired geometry is created by mashing the space of interest by dividing it into regions of constant cell size and then characterising each region as a vacuum, ferromagnetic, coils or a permanent magnet. The magnetic field produced by the created model is calculated using first order finite elements. The accuracy of the solution depends mainly on the number of mesh nodes: the denser the mesh, the more accurate the calculated field is. The maximal number of nodes in the X-Y plane sets the software related limit to simulation accuracy, while the random access memory size of the computer used for calculations determines hardware limitations. The number of Z planes is not limited, but it is usually equal or near to the corresponding parameters of the X and Y planes. The solving procedure will slow down significantly if the mesh size in direction Z is not larger than or at least comparable with the average cell size of the X-Y mesh. The capacity of random access memory also restricts the number of Z planes. All the results shown were obtained with the code and personal computer restrictions of 49729 nodes and 750 MB random access memory, respectively.

Taking into consideration the dimensions of the cyclotron, even the maximal number of nodes in the X-Y plane is not sufficient for creating a high-quality model of the whole cyclotron. Therefore, cyclotron symmetry and proper boundary con-

ditions along the symmetry lines are used to model the smallest possible part of the cyclotron. This method enables the achievement of the highest available accuracy in field calculation.

The two MERMAID models of the VINCY Cyclotron without sectors (see Table 1) were created by using only 1/8 of the machine and a free space of the appropriate size that was necessary for the calculation of the stray field. For the M1 model, the dimensions of the simulated volume in the XYZ coordinate system were  $350 \times 300 \times 300 \text{ cm}^3$  and this volume was covered by  $258 \times 193 \times 159 = 7917246$  mesh nodes. To simulate the magnetic field of a model with this many nodes, MERMAID required 618534 kB of random access memory. For the M2 model, the simulated volume was  $350 \times 250 \times 300 \text{ cm}^3$  and it was covered with  $262 \times 190 \times 190 = 9458200$  nodes. The needed MERMAID random access memory in this case amounted to 738921 kB.

Figure 4 and Table 1 show that a bigger number of nodes does not grant a higher accuracy of the model. The distribution of nodes also significantly affects simulation accuracy. Although the smaller volume was covered with a greater number of nodes in the M2 than in the M1 model, the simulated magnetic field in the median plane of the M1 model was, on the average, 4 mT closer to the measured field than the simulated field of the M2 model in the  $R \leq 86 \text{ cm}$  region. Better accuracy is



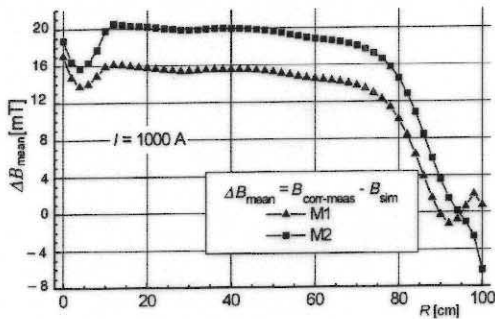


Figure 4. Difference between simulated and measured fields. The radial dependence of azimuthally averaged fields is shown. The two simulated fields are obtained as a response of the two MERMAID models to the main coils current of 1000 A. The response of the model M1 is closer to the measured field than the response of the model M2 for  $R \leq 90$  cm. This is because the mesh of the model M1 is denser for  $R \leq 20$  cm than the mesh of the model M2 (Table 1). The denser mesh near the edge of the pole plate causes the response of the model M2 to be closer to the measured field in this region than the response of the model M1

achieved by a denser mesh in the above mentioned region. The number of nodes in the  $0 \leq R \leq 20$  cm region was three times larger in the M1 model than in the M2 model. On the other hand, the M2 model had denser mesh around the pole plate edge at  $R \approx 100$  cm and consequently gave better results than the M1 model in that region.

Table 1. Grid of the MERMAID model of the VINCY Cyclotron. Density of the model grid depends on the cell size along X and Y-axes. The two MERMAID models of the VINCY Cyclotron are created and used to simulate the magnetic field. The quality of a model depends on how well its simulated magnetic field match the measured field

Range [cm]	Model M1		Model M2		
	$\Delta x$ [cm]	$\Delta y$ [cm]	$\Delta x$ [cm]	$\Delta y$ [cm]	
0 – 9	0.25	0.25	0.5	0.5	
9 – 20			1	1	
20 – 93			1	1	0.5
93 – 98	0.25	0.25			
98 – 100	0.25*	0.25*			
100 – 103	1.5	3*	1	1	
103 – 126	2.021	3.188		2	
126 – 151.5	2.008	10.429		2	5.222
151.5 – 154			10	5	
154 – 156					
156 – 250					
250 – 280					
280 – 300					
300 – 350					

\* A fictitious node had to be introduced in the vicinity of  $Y = 100$  cm in order to enable MERMAID model to describe the VINCY Cyclotron geometry. In the model M1 the fictitious node is at  $Y = 100,1$  cm and for the model M2 it is at  $Y = 100,01$  cm

## MODEL CALIBRATION

A deviation of the accomplished magnetic field from the required isochronous magnetic field causes a phase shift between the orbital frequency of accelerated particles and the frequency of the RF acceleration system. An acceptable phase shift sets the tolerance of the accomplished magnetic field as being not larger than  $\Delta B/B \approx 10^{-4}$ . In the case of the VINCY Cyclotron, the required accuracy of the magnetic field equalled  $\Delta B = 0,5$  mT.

The isochronisation of the nominal magnetic field is performed by adjusting the sector shape in a MERMAID model of a cyclotron until the resulting simulated magnetic field is equal to an error of the required isochronous field. Therefore, the accuracy of the simulated magnetic field should also, at the very least, match the required isochronisation accuracy of 0,5 mT.

In order to achieve the highest available accuracy of the simulated magnetic field of both of the two above mentioned MERMAID models of the VINCY Cyclotron, a maximal number of nodes in the X-Y plane were used. Although the accuracy of the M1 model was improved by better node distribution, the difference between simulated and measured fields of 16 mT (Fig. 4) was much larger than the required isochronisation accuracy. In order to use the MERMAID model of the VINCY Cyclotron for further field isochronisation, the simulated field must resemble the measured field with higher accu-

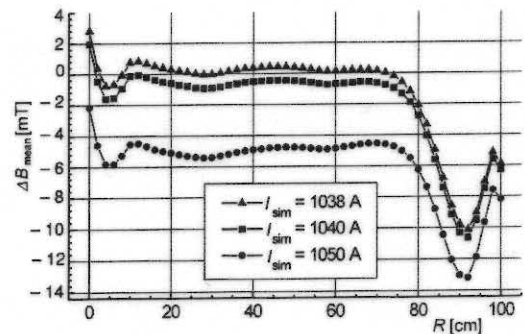


Figure 5. The field difference for the main coil current of 1000 A. The radial dependence of the difference between azimuthally averaged measured and simulated magnetic fields is shown. The measured field is the response of the VINCY Cyclotron magnetic structure without sectors to the main coils current of  $I_{\text{meas}} = 1000$  A. This field is compared to the three simulated fields obtained as a response of the MERMAID model M1 to the main coils currents of 1038 A, 1040 A, and 1050 A. The smallest difference between the simulated and the measured fields is required in the acceleration region to which the flat portions of the curves correspond. The best results are achieved when the simulation model is excited by the main coils current of  $I_{\text{sim}} = 1038$  A

racy than the one achieved in the  $15 \text{ cm} \leq R \leq 86 \text{ cm}$  acceleration region. Since the possibilities to improve simulation accuracy by adjusting the model mesh were thus exhausted, the better of the two models, model M1, was calibrated.

Calibration was performed by adjusting the value of the main coil current used in the simulation until the simulated field was as close as possible to the measured field in the acceleration region.

Figures 5 and 6 show how the current value used in the simulation was calibrated, in respect to main coils current values applied during field measurement of 1000 A and 600 A respectively. A similar procedure was used for all seven measured field maps and the obtained calibration curve is shown in Fig. 7.

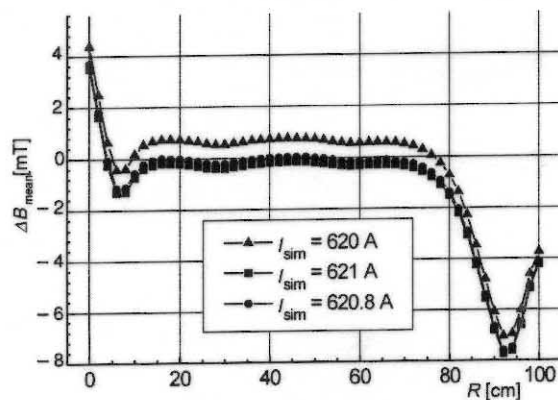


Figure 6. Fine tuning of the simulation current for the nominal field. The nominal main coil current of the real magnet is  $I_{\text{meas}} = 600 \text{ A}$ . The radial dependence of the difference between azimuthally averaged measured and simulated field is shown. The smallest difference in the acceleration region is achieved for  $I_{\text{sim}} = 620.8 \text{ A}$

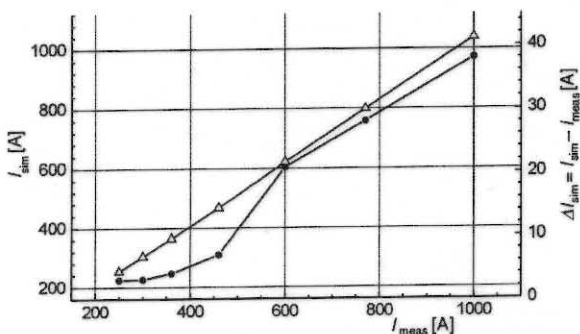


Figure 7. Calibration curve for the VINCY Cyclotron. For each of the seven measured magnetic fields, the values of main coils currents used in the MERMAID model,  $I_{\text{sim}}$ , to obtain the simulated field the closest to the measured field are shown. The measured magnetic fields are responses of the VINCY Cyclotron magnetic structure to the seven values of the main coils currents,  $I_{\text{meas}}$ . Also shown is the difference between the corresponding currents used during simulation and measurements,  $\Delta I = I_{\text{sim}} - I_{\text{meas}}$

As illustrated in Figs. 5 and 6, each calibrated value of the main coils current was obtained through a number of simulations of the MERMAID model response. The data extracted from these simulations and summarized in Figs. 8 and 9 were used to ease and accelerate the calibration process.

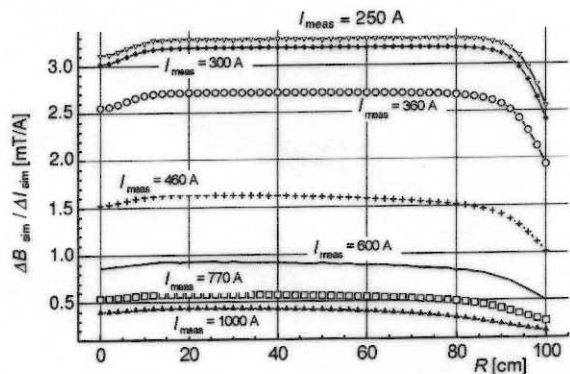


Figure 8. Radial dependence of simulated field sensitivity to simulation current. For each of the measured fields, i. e. main coil current applied to the real magnet,  $I_{\text{meas}}$ , a number of simulations are performed to find the model response that is the best fit to the measured field. Graphs show how the increase in simulation current,  $\Delta I_{\text{sim}}$ , causes the increase in simulated field,  $\Delta B_{\text{sim}}$ . Due to the non-linear response of ferromagnetic elements that the cyclotron magnet is built from, the simulated field is more sensitive to simulation current for smaller values of the real magnet excitation current,  $I_{\text{meas}}$

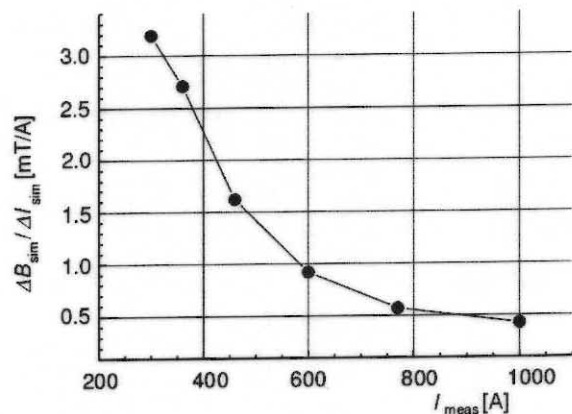


Figure 9. Sensitivity of simulated field to simulation current. The value of the sensitivity of the simulated field to simulation current at  $R = 40 \text{ cm}$  is given for all seven values of real magnet excitation current used during field measurements,  $I_{\text{meas}}$

## CONCLUSION

A 3D magnetic field simulation package, the MERMAID, will be used to finalize the design of the VINCY Cyclotron magnetic structure and isochronise its nominal field. Software and hardware limitations prevent the accuracy of the simulated

magnetic field from reaching the required value. Therefore, the best obtained MERMAID model of the magnetic structure without sectors is calibrated using measured magnetic field maps of the real magnet.

The obtained calibration curves are to be tested by comparing the five measured fields of the real magnet with sectors, and the corresponding five simulated fields of the MERMAID models. During the final design of the sector shape, MERMAID models are to be excited by the adjusted values of the main coil currents obtained from the calibration curve.

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## КАЛИБРАЦИЈА СИМУЛАЦИОНОГ МОДЕЛА МАГНЕТА ЦИКЛОТРОНА ВИНСИ

Номинално магнетско поље Циклотрона ВИНСИ биће изохронизовано уз помоћ програмског пакета MERMAID. Овај програмски пакет, за претходно дефинисан тродимензионални модел и задату побуду, симулира одзив магнета, то јест израчунава магнетско поље. Тачност тродимензионално прорачунаог поља директно зависи од густине чворова симулационог модела. Програмским пакетом ограничен максималан број чворова у X-Y равни и демензије Циклотрона ВИНСИ дефинисали су максималну оствариву тачност прорачунаог поља. Поређење поља симулираног са максималном остваривом тачношћу са магнетским пољем измереним у првој фази мерења магнетског поља Циклотрона ВИНСИ показало је да поклапање ова два поља није остварено са задовољавајућом тачношћу. Даље смањење ове разлике остварује се калибрацијом симулационог модела односно подешавањем магнетопобудне струје главних калемова у симулационом моделу.