AUTOMATIC SYSTEM FOR THE MAPPING OF THE VINCY CYCLOTRON MAGNETIC FIELD

by

Aleksandar DOBROSAVLJEVIĆ[1], Saša T. ĆIRKOVIĆ[1], Djordje KOŠUTIĆ[1], Ljubiša VUKOSAVLJEVIĆ[1], and Dragan VRANIĆ[2]

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The VINCY Cyclotron is the main part of the TESLA Accelerator Installation at the VINČA Institute of Nuclear Sciences in Belgrade. It is an isochronous cyclotron for the acceleration of both light and heavy ions. The pole of its magnet has the diameter of 2000 mm; its bending limit is 134 MeV, while its focusing limit is 73 MeV. This paper describes the magnetic field measurement system that has been used for the shimming of the VINCY Cyclotron magnet, *i. e.*, for precise shaping of its sectors and plugs. It is an automatic measurement system based on the Hall-probe that moves in the median plane, between the poles of the magnet. We have used this system to obtain precise maps of the magnetic field for different operating regimes of the cyclotron, needed in the process of shimming. The overall measurement uncertainty was estimated to be in the range of 0.02%.

Key words: accelerator, cyclotron, magnetic field measurement, magnet shimming

INTRODUCTION

The TESLA Accelerator Installation is a multipurpose facility for the acceleration of heavy and light ions. It consists of an isochronous cyclotron (VINCY), a heavy ion source (mVINIS), a light ion source (pVINIS), and several experimental channels [1]. The construction of this facility is in its final stage at the VINČA Institute of Nuclear Sciences, Belgrade.

Measurements of the magnetic field represent one of the most important phases in the construction of an isochronous cyclotron [2]. Magnetic field measurements are an integral part of the magnet shimming campaign. This procedure involves small corrections of the shape of the magnet sectors and plugs that produce local changes in the magnetic field, so that the isochronism can be achieved in the whole operating range of the cyclotron. The shimming procedure is performed trough several iterations, each comprising:

(a) measurements of the magnetic field in the median plane of the cyclotron magnet (central plane between the poles of the magnet where the trajectories of accelerated ions are located),

(b) comparison of the measured magnetic field maps with theoretical ones obtained from the magnetic field simulation program [3],

(c) defining how to change the shape of the sectors and plugs in order to reduce the differences between the real and the ideal magnetic field maps, and

(d) precise machining of the sectors and plugs.

The main goal of magnet shimming is to obtain the isochronous magnetic field for the nominal (usually the most frequently used) working regime of the cyclotron with the contribution of main coils only. The next step is obtaining detailed maps of the magnetic field for the other important operating regimes (accelerated ion species and energies), taking into account the contributions of the main coils, as well as those of the trim coils [4]. As the magnetic field mapping is performed once in a lifetime of the

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Authors' addresses:
[1] VINČA Institute of Nuclear Sciences,
Laboratory of Physics
P. O. Box 522, 11001 Belgrade
Serbia
[2] Mikro Kontrol
30, Vase Pelagića, 11000 Belgrade
Serbia

E-mail address of corresponding author:
alexd@vin.bg.ac.yu (A. Dobrosavljević)

cyclotron (hopefully), the acquired data form a permanent basis for the cyclotron control system. Moreover, this database serves for the future development of the installation, in particular for the simulation of the injection [5], acceleration and extraction [6] of different ion beams that may be planned for future experimental programs.

It is obvious that the magnetic field measurement system has to be reliable, accurate and flexible, because it plays an important role in the course of the construction of a modern multipurpose cyclotron.

CONCEPT OF THE MAGNETIC FIELD MEASUREMENT SYSTEM

The magnetic structure of the VINCY Cyclotron consists of ferromagnetic elements (yoke, poles, sectors, plugs), main coils, trim coils, and harmonic coils. The simplified scheme of the magnetic structure is shown in fig. 1.

The pole diameter is 2000 mm. There are four straight sectors per pole, having an angular span of 42 (sectors S1, S2, S3, S4 on the lower pole and corresponding sectors S5, S6, S7, S8 on the upper pole). The axial gap between the sectors is 36 mm. There are 10 circular trim coils per pole and they are placed between the poles and sectors. Also, there are eight quasi-trapezoidal harmonic coils per pole – four of them in the central region and four of them in the extraction region. The maximal current applied to the main coils is 1000 A, producing a magnetic induction of 2.6 T at certain points between the sectors (in the ion beam extraction region). The corresponding upper and lower pole trim coils are serially connected to 10 independent DC power supplies delivering maximal 300 A. Together with the main coils, trim coils provide the isochronous magnetic field for different operating regimes of the cyclotron. Harmonic coils are used for the fine adjustment of the ion beam orbits in the central or in the extraction region.

To a great extent, the shape of the cyclotron magnet defines the construction of the measurement system. The cylindrical shape of the poles, the radial symmetry of the magnetic field in the median plane between the poles and the trajectory of the accelerated particles, impose a cylindrical coordinate system: the z-axes coincide with the axis of the axial channel going trough the center of the poles, while the R- plane coincides with the median plane. The main goal of the measurement system is to enable the mapping of the magnetic field in the median plane between the poles of the magnet. These measurements take place during the shimming or, later on, during the mapping campaign. In order to cover the whole circular surface with a fine mesh of measurement points, it is necessary to choose the appropriate step of the measurement probe in the radial direction, covering the range from $R = 0$ to 1000 mm, and in the azimuthal direction, covering the range from $\theta = 0$ to 360 .

The operating principle of our magnetic field measurement system is described in fig. 2. It is based on the positioning of the measurement arm in the median plane across the whole diameter of the pole. The arm is supported at three points: one at the center of the magnet where it is fixed to the vertical shaft in the axial channel and two points at the circumference of the supporting ring, by means of supporting wheels. The supporting ring is mounted to the lower pole with several supporting legs. The measurement probe travels along the measurement arm, scanning the magnetic field from one to the other side of the pole (from $R = +1000$ to –1000 mm). When the probe reaches the end position, the measurement arm moves in the azimuthal direction for one step and measurements are repeated once more. In this manner, rotating the measurement arm in the azi-

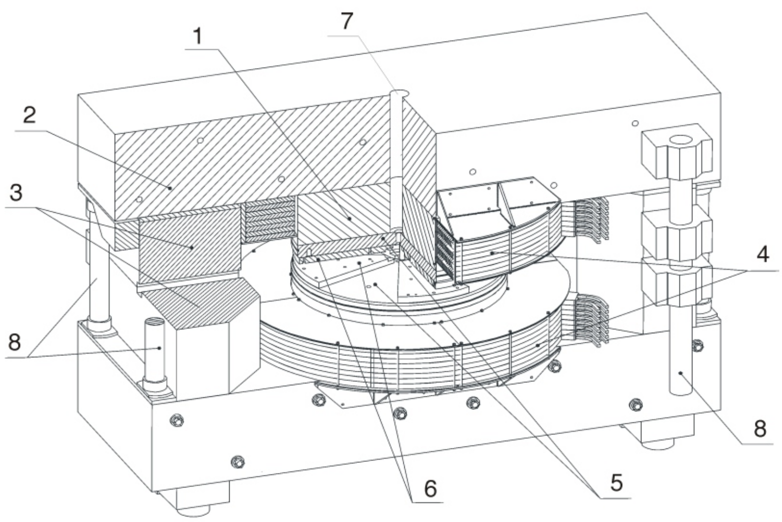

Figure 1. Ferromagnetic structure of the VINCY Cyclotron
1 – pole,
2, 3 – yoke,
4 – main coils,
5 – median pole plates,
6 – sectors,
7 – upper axial channel,
8 – elevation system

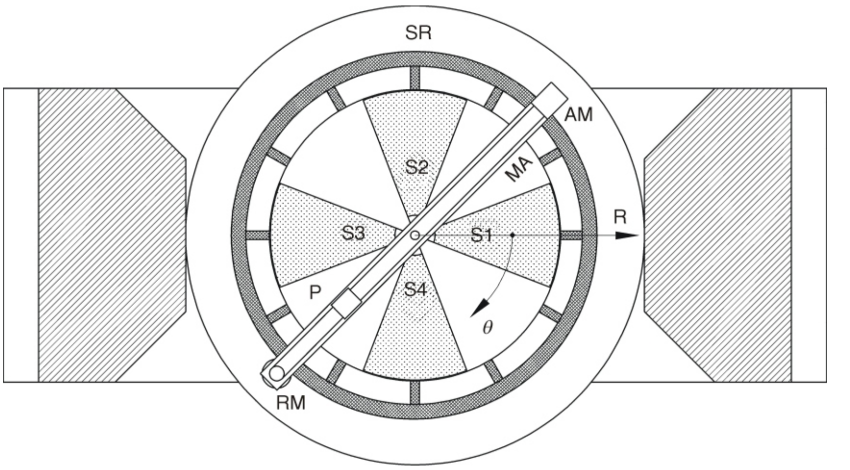

Figure 2. Principle scheme of the magnetic field measurement system
MA – measurement arm,
RM – motor for radial positioning of the probe,
AM – motor for azimuthal positioning of the measurement arm,
P – measurement probe on the cart,
SR – supporting ring,
S1, S2, S3. S4 – sectors,
R, θ – coordinate system axes

muthal direction for 180 , we cover the whole surface in the median plane and obtain a complete map of the magnetic field. The two servo motors installed at the opposite ends of the measurement arm are used for the radial positioning of the probe along the measurement arm and azimuthal positioning of the measurement arm, respectively.

BASIC MEASUREMENT REQUIREMENTS

The following geometrical parameters of the magnet strongly influenced the design of the magnetic field measurement system:

pole diameter of 2000 mm (defines the range for the radial positioning of the probe),

minimal gap between the poles of the magnet of 36 mm (defines the space where the measurement arm should be installed),

diameter of the lover axial channel inside the magnet plug of 20 mm, 180 mm below the plug (defining the space for the axial shaft and absolute encoder for the azimuthal positioning of the arm), and

distance between the magnet pillars of 3120 mm (defines the clearance for the turning of the measurement arm between the pillars).

The basic requirements that the measurement system should fulfill are the following:

ion beam dynamics calculations require that the relative accuracy of the magnetic field measurements should be 0.01% (*e. g.* accuracy of 0.2 mT on a 2 T field level),

flexible radial positioning of the measurement probe along the measurement arm (*e. g.* radial step of 5, 10, or 20 mm),

flexible azimuthal positioning of the measurement arm (*e. g.* azimuthal step of 1 or 2),

the accuracy of radial and azimuthal positioning of the measurement probe should be better than 0.1 mm in order to achieve the required measurement accuracy (defined by high magnetic field gradients at certain locations),

simple and precise installation and removal of the system from the cyclotron magnet (several times during the shimming campaign, the mapping system has to be mounted at the magnet for measurement purposes and afterwards removed, in order to remove and machine the sectors and plugs),

parts of the measurement system, located in the measurement region, are subject to a high magnetic field (B_{max}= 2.6 T); therefore, they have to be fabricated of nonmagnetic materials in order to enable their movement and avoid their influence on measurement accuracy,

movable parts of the measurement system exposed to high gradients of the magnetic field have to be made of nonmagnetic materials with low electrical conductivity in order to reduce the effect of induced eddy currents that may affect measurements (*e. g.* measurement arm made of titanium instead of aluminum), and

obtaining a detailed map of the magnetic field in a relatively short time (3-4 hours) requires the use of the automatic measurement system.

REALIZATION OF THE MAGNETIC FIELD MEASUREMENT SYSTEM

The scheme of the realized magnetic field measurement system is shown in fig. 3. It consists of the following subsystems: the mechanical structure, control unit, and measurement instrumentation.

Mechanical structure

The mechanical structure serves to move and position the measurement probe in the median plane with high precision and repeatability. It consists of:

measurement arm,

supporting ring,

driving mechanism for azimuthal positioning of the measurement arm, and

driving mechanism for radial positioning of the measurement probe along the measurement arm.

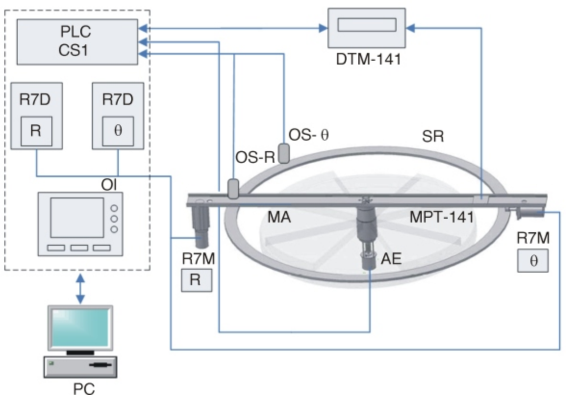

Figure 3. The scheme of the realized magnetic field measurement system
MA - measurement arm,
SR supporting ring,
AE absolute encoder,
MPT-141 miniature Hall probe,
R7M OMRON servomotors for radial (R) and azimuthal (θ) positioning,
OS optical switches for radial (R) and azimuthal (θ) origin point,
DTM-141 Digital Hall-Effect Teslameter,
PLC CS1 OMRON servo drivers,
OI operator interface panel,
PC computer with programs and archive of magnetic field maps

The measurement arm made of titanium is light, firm and ensures minimal side effects in the presence of a strong magnetic field (nonmagnetic material, poor electrical conductor). Its maximal thickness is 27 mm, total length 2860 mm, and width 160 mm. All elements of the measurement arm are made of titanium or plastic materials. The measuring probe is installed on the cart traveling along the measurement arm.

The supporting ring is made of aluminum. Its inner diameter is 2300 mm, width 95 mm and it is fixed to the lower median pole plate with 12 supporting legs made of aluminum. Each leg has an adjusting screw, enabling the precise positioning of the supporting ring in the horizontal plane.

The OMRON R7, 400 W servomotor [7] with an optical incremental encoder of 8000 pulses/rev, performs the azimuthal positioning of the measurement arm. It is mounted at one end of the measurement arm. The motor driving wheel covered with rubber travels along the supporting ring achieving movement of the arm by friction. The optical absolute encoder Allen-Bradley 845G with a 15-bit resolution is attached to the axial shaft of the measurement arm, below the plug, and it supervises the azimuthal positioning of the arm. The theoretical precision of azimuthal positioning of the measurement arm is 1.7 , while the accuracy of the absolute encoder readout is 40 .

The driving mechanism for the radial positioning of the probe along the measurement arm consists of an OMRON R7, 200 W servomotor with an optical incremental encoder of 8000 pulses/rev, mounted at the end of the measurement arm, reduction gear with zero clearance and gear reduction ratio 1:29, toothed belt gear made of Kevlar and the cart carrying the measurement probe. The theoretical precision of radial positioning of the measurement probe is 0.6   m.

Control unit

The control unit consists of a PC computer, OMRON CS-1 programmable logic controller with an operator interface panel, two OMRON R7D servo drivers, two optical switches defining the radial and azimuthal origin point and limiting switches for the measurement probe and measurement arm.

The measurement system can work in several operating regimes. Its programming is performed *via* the operator interface panel (OI) and a PC computer.

The manual regime is used during the initial adjustments of the measurement system and for bringing its mechanical structure into the referent coordinate system of the cyclotron. Fine adjustments of the radial and azimuthal offset values are used to achieve the precise positioning of the measurement probe, bringing its active sensor area into the coordinate system of the machine.

The user s program (program for a specific measurement) is used to define the input parameters for a specific measurement: radial and azimuthal steps, starting and ending positions of the measurement probe and measurement arm. Usually, we choose 5, 10, or 20 mm for the radial step and 1 or 2 for the azimuthal step, but they could equal anything, down to the theoretical limit of probe positioning. In addition, we can define regions with different steps, taking for example smaller steps in the region of special interest or where the field gradients are large (*e. g.* taking a 5 mm radial step in the central region R = +200 to   200, while the rest of the median plane map is obtained with a 20 mm step).

The automatic regime is used for performing automatic measurements. Starting this regime, we initiate the previously generated user s program. During the measurement, all acquired data are graphically presented on the screen.

Measurement instrumentation

The measurement instrumentation consists of a Digital Hall-Effect Teslameter and the NMR Teslameter. The Digital Hall-Effect Teslameter, DTM-141, made by Group3 Company, can measure the magnetic field of up to 3.0 T. Together with the miniature Hall probe MPT-141, it can perform magnetic field measurements with relative accuracy of 0.01% [8]. A temperature sensor is included in the probe, allowing the microprocessor inside the instrument to compute temperature corrections and, virtually, eliminate all temperature dependent effects of the Hall probe [9]. The MPT-141 probe has a small physical size (14   5   2 mm), while its small sensitive area of 1   0.5 mm enables precise measurements of the local magnetic field. The DTM-141 Teslameter is connected to the PLC *via* RS-232C port, sending measured field values in tesla or gauss. The MPT-141 probe is installed on the moving cart on the measurement arm. This instrument is an integral part of the magnetic field measurement system, enabling maximal 10 readings per second.

The METROLAB PT 2025 is a high precision microprocessor, controlled and fully programmable NMR Teslameter [10]. It can perform measurements with $10^{\ 7}$ T resolution and absolute accuracy better than   5 ppm. Five different measuring probes cover the range from 0.09 to 3.4 T. The active measuring volume inside the probe is a cylinder 8 mm in diameter and 4.5 mm long. It requires a relatively homogeneous field for the measurement (200-1300 ppm/cm, depending on the probe range). That is why the NMR Teslameter is used only as a referent instrument for the calibration of the Hall probes and for certain precise measurements of the magnetic field inside the cyclotron magnet.

Figure 4 shows the magnetic field measurement system installed at the VINCY Cyclotron.

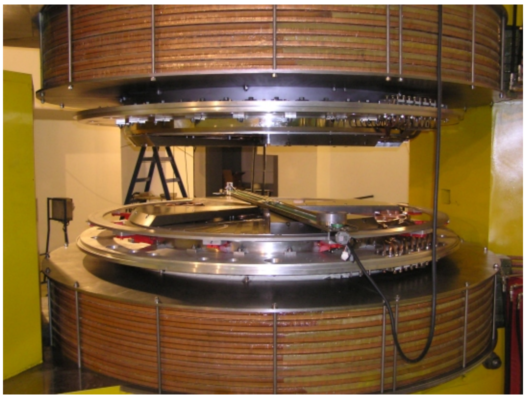

Figure 4. Magnetic field measurement system mounted at the VINCY Cyclotron (upper pole elevated)

MEASUREMENT PROCEDURE

Before the mapping of the magnetic field, the system has to be calibrated and brought into the coordinate system of the cyclotron magnet.

First, we had to calibrate the Hall probe using the NMR Teslameter. The Hall probe had initially been calibrated by the producer, but only up to the maximal field of 2.2 T. Since the maximal field in the cyclotron magnet was higher, we performed a complete calibration again, this time reaching the maximal field value of 2.6 T.

We also performed the calibration of the radial positioning of the probe using the HP 5528A laser interferometer system. The calibration took into account all imperfections in the machining of the elements of the measurement arm, elasticity of the toothed belt gear, *etc*.

The fine adjustment of the measurement system comprised bringing the active measurement area of the Hall probe, as precise as possible, into the coordinate system of the magnet. That adjustment had to be performed each time the system was mounted at the cyclotron magnet. The technique of adjustment is described in fig. 5. The first step comprised the mechanical adjustment of the measurement system and a rough defining of the radial and axial origin points. The radial origin point (R = +1000) was defined by shifting the cart until the marker point on the probe was positioned against the edge of the pole. At that point, the movable cart carrying the probe should trigger the optical switch that is installed at the measurement arm. The azimuthal origin point (θ = 0) was defined using the axel-pin installed on the lower pole plate at θ = 56 . Fine adjustments were performed using the high field gradients at the edges of the sectors. Here, we presumed field gradients between corresponding sector pairs. Since all crucial ferromagnetic elements (poles, sectors, plugs) were machined and assembled with high accuracy (better than 50   m), we presumed that the corresponding magnetic field was symmetric enough to be used for precise adjustment of the probe position (*i. e*. positioning of the active measurement area of 1   0.5 mm that is located inside the measurement probe). Fine azimuthal positioning was performed using field gradients at the edges of sectors S4-S8 (for R = 900 mm and θ_1 = 69 and $_2$ = 111), while fine radial positioning was performed using field gradients in the center of the magnet (where the axial channel produces a depression in the field), and at the edges of sectors S1-S5 and S3-S7 (arm positioned at θ = 0 , and R = +900, 0,   900 mm). The fine adjustment of the radial and azimuthal offset within the control unit was used to obtain almost identical (as close as possible) values of the magnetic field at the symmetrical edge points of the sectors. This is explained in fig. 5. Values marked with crosses were obtained after the mechanical adjustment of the system, while those marked with circles were obtained after the fine adjustment of offsets. If we suspected that the arm was not centered well, we could check the probe radial positioning again, but that time for θ = 90 or 180 .

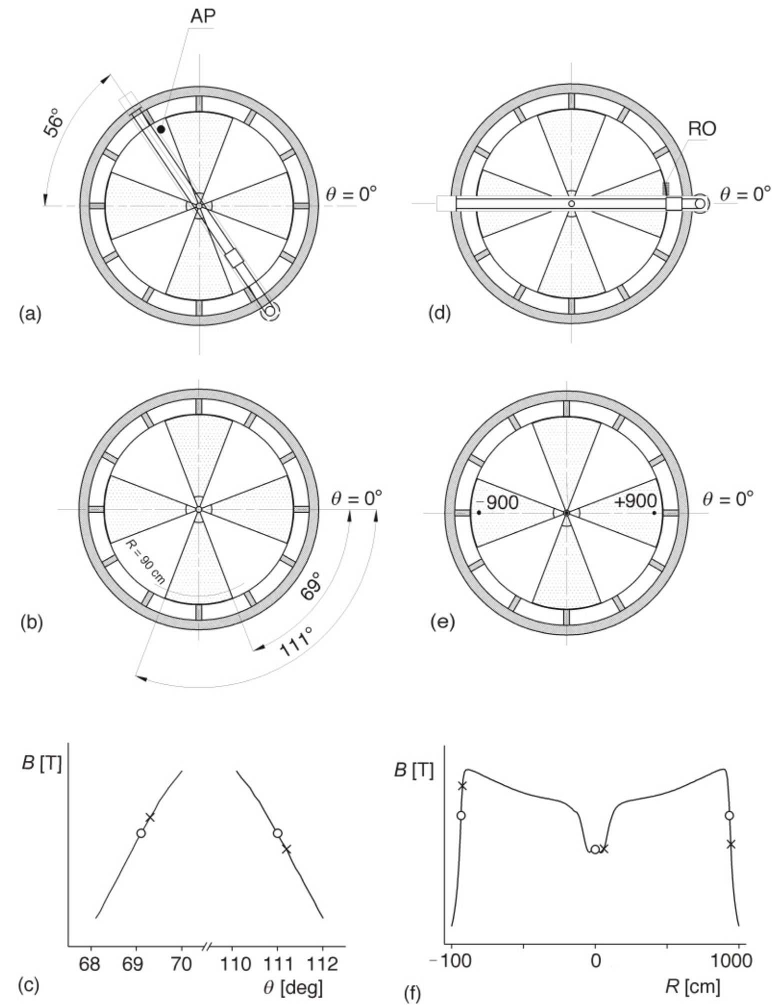

Figure 5. Adjustment of the magnetic field measurement system to the coordinate system of the cyclotron
(a) mechanical adjustment of the azimuthal position of the measurement arm against the axel-pin (AP),
(b) fine adjustment of the azimuthal position against the sector 4 edges at θ = 69° and θ = 111°,
(c) initial values obtained after mechanical adjustment (crosses) are corrected by the offset value (circles),
(d) mechanical positioning of the probe against the radial origin optical switch (RO),
(e) fine adjustment of radial position against the edges of sector 1 and 3 (for θ = 0°) and center of the axial channel (R = +900, 0, 900),
(f) initial values obtained after mechanical positioning (crosses) are corrected by the radial offset value (circles)

A typical magnetic field mapping procedure is based on a 20 mm radial step and a 2 azimuthal step, producing a map of 9191 measurement points. Measurements along the measurement arm were performed in steps and always in one direction, from R = +1000 to R = 1000 mm. When the probe reached R = 1000 mm, a measurement sequence was completed and the measurement arm moved in the azimuthal direction for 2 . Afterwards, the probe returned back to R = +1005 mm and than went back again to the starting position at R = +1000 mm, thus eliminating the overall backlash; the measurement sequence was then repeated again. In this manner, a complete map of the magnetic field can be obtained in less than 3 hours. The duration of the measurement may be reduced by changing the measurement procedure, by introducing measurements along the measurement arm in both directions or by increasing the speed of the radial probe movement. This would cause a somewhat higher imprecision in the positioning of the probe. In any case, the major limiting factor is the maximal measurement rate of DTM-141 Digital Teslameter of 10 readings per second.

MEASUREMENT RESULTS

The described magnetic field measurement system has been used during the course of the magnet shimming campaign. As an illustration, we have used a magnetic field map that corresponds to the regime for the acceleration of H_2^+ ions to 30 MeV energy (the 30 MeV proton beam is obtained after the ion beam extraction by stripping foil). The corresponding 3D magnetic field map presented in fig. 6 was obtained for the main coils current I_m=711 A. One can notice local depressions in the sectors, caused by improperly machined screws, errors being below 0.2 mm. This illustrates the sensitivity of magnetic field measurements, as well as the required high precision of machining of all ferromagnetic elements. Another way of presenting the same magnetic field map (2D plot) is shown in fig. 7. Finally, fig. 8 shows the difference between the measured average magnetic induction (obtained from the previous map, averaged over θ) and the calculated average isochronous magnetic induction, showing significant discrepancy in the central region. This "bump" was removed during the shimming pro-

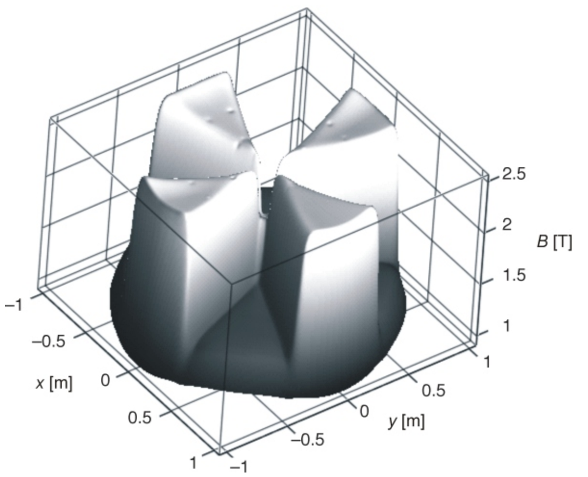

Figure 6. Magnetic field map obtained during the magnet shimming procedure for I_m = 711 A. This regime corresponds to the acceleration of H_2^+ ions to 30 MeV energy

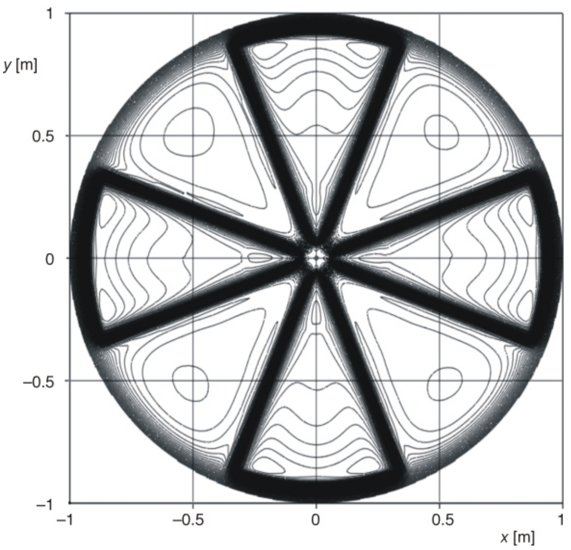

Figure 7. A 2D presentation of the magnetic field map for I_m = 711 A

cedure by the appropriate machining of the magnetic plug.

We have finished the magnet shimming successfully [11] and are now engaged in mapping the magnetic field. This procedure comprises acquiring numerous magnetic field maps for different operating regimes, taking into account contributions of the main, trim, and harmonic coils.

In the course of these measurements, we have been able to analyze the measurement procedure and estimate the measurement accuracy, as well as the overall measurement uncertainty. We

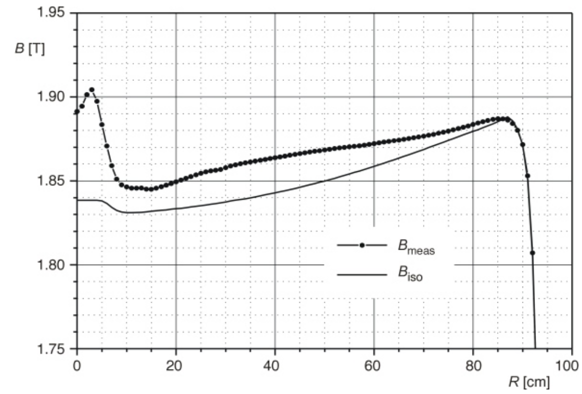

Figure 8. Measured average magnetic induction (B_{meas}) obtained for I_m = 711 A compared to the calculated isochronous magnetic induction for the same regime (B_{iso}), showing how to correct the profile of magnet plugs and sectors

are confident that the accuracy in probe positioning in the median plane is better than 50 m, leading to the overall uncertainty of 0.1 mm. The relative accuracy of the magnetic field measurements by the calibrated MPT-141 Hall probe is 0.01%. Taking into account the combined errors caused by the imperfect positioning of the probe in the median plane and by the limited measurement accuracy of the probe itself, we have estimated that the overall uncertainty of the magnetic field measurements is 0.02% (*e. g.* 0.5 mT at the field level of 2.5 T), which satisfies the basic requirements for the shimming and mapping of the VINCY Cyclotron.

CONCLUSION

The system for the mapping of the VINCY Cyclotron magnetic field is a completely automatic measurement system with high flexibility, repeatability, and accuracy. It enables the flexible positioning of the measurement probe, with arbitrary steps in the radial and azimuthal direction. The measurement system is constructed to enable simple assembling and disassembling from the cyclotron magnet, providing at the same time high measurement repeatability. Analysis of the measured maps has shown that the relative accuracy of magnetic filed measurements is quite good, taking into account successful simulations of the beams in these fields. The system was used during the shimming procedure that has been successfully finished, by means of which the final shape of the sectors and plugs and the nominal isochronous field have been achieved.

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Александар ДОБРОСАВЉЕВИЋ, Саша Т. ЋИРКОВИЋ, Ђорђе КОШУТИЋ
Љубиша ВУКОСАВЉЕВИЋ, Драган ВРАНИЋ

АУТОМАТСКИ СИСТЕМ ЗА МЕРЕЊЕ МАГНЕТСКОГ ПОЉА ЦИКЛОТРОНА ВИНСИ

Циклотрон ВИНСИ је главни део Акцелераторске инсталације ТЕСЛА која се гради у Институту за нуклеарне науке „Винча" у Београду. То је изохрони циклотрон за убрзавање како лаких тако и тешких јона. Пречник пола магнета је 2000 mm; магнетска крутост снопа је 134 MeV, док је константа фокусирања 73 MeV. У овом раду описан је систем за мерење магнетског поља који се користи за добијање коначног облика сектора Циклотрона ВИНСИ у једном итеративном поступку: прорачун поља помоћу 3D симулације магнетске структуре, машинска обрада сектора и мерење магнетског поља. Аутоматски систем за мерење поља заснован је на Холовој сонди која се креће у медијалној равни између полова магнета. Прецизне мапе магнетског поља за различите радне режиме циклотрона, неопходне у процесу обликовања сектора, добијају се користећи поменути систем. Општа мерна несигурност процењена је у опсегу од 0,02%.

Кључне речи: акцелератор, циклотрон, мерење магнетског поља, обликовање сектора