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PCB coil array for measuring curved accelerator dipoles: two case studies on the MedAustron accelerator

G. Golluccio[1], A. Beaumont[1], M. Buzio[2], O. Dunkel[2], M. Stockner[1], T. Zickler[2]

[1] EBG MedAustron GmbH, Marie Curie-Straße 5A-2700 Wiener Neustadt, giancarlo.golluccio@cern.ch, anthony.beaumont@cern.ch, markus.stockner@medaustorn.at
[2] CERN European Organization for Nuclear Research, CH-1211 Geneva 23, marco.buzio@cern.ch, olaf.dunkel@cern.ch, thomas.zickler@cern.ch

Abstract –
Printed Circuit Boards (PCB) are largely used as measurement devices. Recently they have found applications in magnetic field measurements of accelerator magnets, in particular in rotating coil system, thanks to the quality that can be achieved in terms of coil area and winding distribution.
In this paper the application of such technology to produce an array of coils for measuring the integral field homogeneity inside curved accelerator dipole magnets is presented. A set of static coils measuring the flux variations during a current pulse, which are installed on parallel paths of the particle trajectory, is the so-called "fluxmeter". After an introduction to the challenges to face in measuring large curved dipoles, we describe the measurement requirements and constraints, required by the MedAustron accelerators synchrotron and high energy transfer line dipoles. In the second part, the design and technical details of the PCB and the whole fluxmeter structure are reported. The last section is dedicated to the method used for the relative calibration of the coils and the results.

I. INTRODUCTION

Single curved coils, translated longitudinally or transversally, have been used in the past to measure curved dipole magnets, e.g., the curved dipoles of the SIS (Heavy Ion Synchrotron) at GSI [1]. Another measurement method and system to evaluate the field quality of curved dipoles has been developed at CERN to measure the dipoles of the CNAO (Centro Nazionale Adronterapia Oncologica) accelerator [2].

The method is based on an array of several coils shaped to follow the theoretical path of a particle passing through a hard edged magnet [3] (in the following we indicate the path as L). The field homogeneity is obtained by compensating the flux measured by the central coil (x=0), during a field pulse, with the flux measured by an adjacent coil displaced on the x-axis. Such kind of measurement systems are the so-called "fluxmeters". The first version CNAO fluxmeter was made by a set of 12+1 coils wound on a flexible core of 2.75 m and then shaped on a wooden support. In addition a 14th coil was used as reference on an adapted support. The disadvantages of such system were the weight of the complete structure (~70 kg) and the weakness in maintaining the trajectory shape, resulting in a frequent relative calibration.

To overcome these drawbacks, the CERN magnetic measurement team, in collaboration with MedAustron, has developed a new fluxmeter concept based on printed circuit board mounted on a composite sandwich plate. The use of Printed Circuit Board (in the following PCB) technologies has the following advantages:

- the local relative position between coils is known at the micron scale and well defined (a negligible drift of the order of a few tenths of a millimeter can accumulate over distances of 2 meters);
- the weight of the complete structure is drastically reduced (~5 kg), which makes the handling required for measurements and calibration easier;
- technically, it would be possible to measure the field integral along the theoretical particle trajectory (obtained by numerical simulation) taking into account the actual longitudinal field profile;
- the dimensional stability over a long period (at least 1 year for a series of 16 magnets) is guaranteed;
- the ease of adapting such kind of design and implementation to different magnets having different lengths and pole width.

The only disadvantage of such approach is the difficulty to find PCB manufacturers able to produce multilayer boards (up to 20/30 layers) of large dimensions (up to 200 mm width and 1 to 2.5 m length) guaranteeing an accuracy of the conductive path within 0.1 millimeter. This problem has been solved by constructing the fluxmeter using two symmetric multilayer PCBs having half of the required length (1.163 m for the synchrotron dipole fluxmeter and 1.347 m for the high energy transfer line dipoles). In the following chapters after a description

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of the requirements of the magnets and the measurement system, we report the details of the design and implementation of the fluxmeters. The last chapter shows the measurement results obtained with the fluxmeter in measuring and adjusting the field quality of the synchrotron dipoles and its measurement performance.

II. MEASUREMENT REQUIREMENTS OF THE CASE STUDIES

A. Magnetic parameter requirements

The MedAustron accelerator facility is based on a synchrotron accelerator composed of 16 dipoles (named in the following as MBH-C) generating field levels from 90 mT to 1.5 T [4] to deflect proton and ion beams up to 400 MeV/n. The accelerated beams are then delivered to the treatment rooms through a transfer line (HEBT) composed of 12 high energy curved dipoles (MBH-Es in the following).The PCB fluxmeter has been developed essentially to measure the integral field homogeneity along the central trajectory, $B_L = \int_L B_y(0,0)dl$, and the variation of such quantity all along the good field region:

$$\Delta B_L(x,y) = \frac{B_L(x,y) - B_L(0,0)}{B_L(0,0)} \qquad (1)$$

of two types of curved magnets. The MBH-Cs are H-type magnets with a bending radius of 4.231 m and have a deflection angle of 22°. The design and the optimization of the pole profile have been presented in [5]. The 16 MBH-Cs are connected in series and pulsed to the nominal integrated field of 2.5 Tm in 0.5 sec. For this reason one of the requirement is that the difference of their integral field should be within $\pm 1.2 \times 10^{-3}$. The MBH-Es are instead C-type magnets [6] with a larger radius (5.078 m) and the same deflection angle as the synchrotron dipoles. For those, the series connection is between two magnets at the time and the integral field difference between them should be the same within $\pm 2 \times 10^{-3}$. Both magnets have been designed with the possibility to adjust (shim) the iron length in order to fulfill those requirements. Both magnet types should respect another strict requirement concerning the integral field homogeneity along the particles trajectory. The homogeneity should be within $\pm 2 \times 10^{-4}$ over a GFR of 120 × 56 mm and over a GFR of 60 × 20 mm from the minimum beam injection to the maximum beam extraction field levels, respectively for the MBH-Cs and MBH-Es. The magnets have been designed with five removable blocks for the fine adjustment of the field homogeneity and, if needed, to compensate for faults during the magnet production that could reduce the field quality.

B. Fluxmeter requirements

The fluxmeters (fig.1) have been designed in order to verify the quality of the magnet production and to identify mechanical defects. The measurements also provide a valid description of the magnetic field in the magnet to the beam physicists with the aim to optimize the tuning of the machine. The system is used as a reference for the magnet to magnet comparison and to support with the measurements the iterative process of magnetic field adjustment. For these reasons the fluxmeters should provide:

- magnetic measurements of the integral field homogeneity inside the GFR with uncertainties one order of magnitude below the $\pm 2 \times 10^{-4}$;
- a good approximation of the field profile along the GFR border, in particular the minimum number of coils in the array along the *x* axis is given by the maximum order of the polynomial function approximating the field, used in the particle tracking software from the beam optics;
- a long term stability in order to be able to measure all the series magnets with minimal recalibrations;
- ease of handling, due to the many displacement steps that have to be taken for the iterative shimming procedure in short time.

Fig. 1. MBH-E fluxmeter in the magnet

III. THE PCB FLUXMETERS

We designed the fluxmeter in PCB in order to satisfy the requirement of measuring the field along the theoretical particle path on the entire GFR with higher spatial resolution. A second requirement was to provide a system able to verify the uniformity between magnets by measuring several magnetic parameters as the fringe field, the field levels and the field homogeneity.

These requirements have to be fulfilled considering the following constrains: a) output voltage of the coil; b) the

PCB printing dimensions limitations; c) the mechanical behavior of the PCB support and its alignment with respect to the magnet.

In a first design phase we defined the shape and the number of copper tracks (turns) per layers, number of layers in order to satisfy the requirements considering the constraints at the points a) and b).

The copper tracks, laid out with CAD software from the theoretical particle trajectory, are composed by 2 straight parts at the end and a curved path, which the arc length corresponds to the theoretical magnetic length. The straight part is tangent to the arc and their length is chosen in order to get the 90% of the stray field. In Table 1 the parameters for the MBH-C and MBH-E PCB coils are summarized.

Fig. 2 shows the drawing of a PCB fluxmeter.

The turns (i.e. the PCB tracks) composing each coil are concentric as the internal and external edge of each track. This is necessary to avoid that the equivalent width of the coil and the width of each track are not constant along the coil length. At the same time, as shown in fig. 3, the concentricity of the tracks keeps the windings of the coil equally spaced in the curved part. Having the edges and the coil turns parallel would make the coil not uniform along the trajectory (fig.3 left side). On the other hand, the coils in the array are parallel to each other (fig.2).

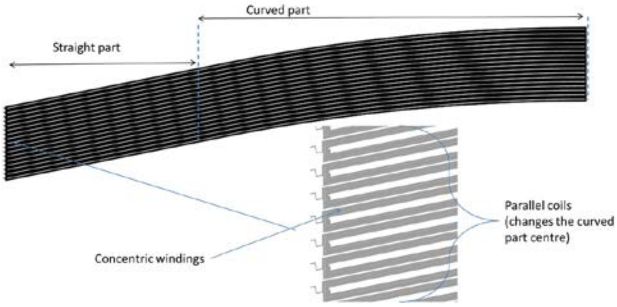

Fig. 2. PCB fluxmeter drawing

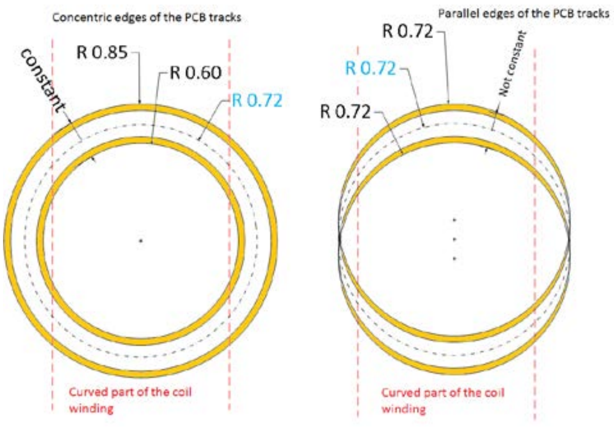

Fig. 3. PCB tracks design

In this way, keeping the length of the tangent to the curve (the straight part) the same for all the turns, they will end at the same longitudinal position. The coils in the array will be parallel to each other by keeping the gap between winding turns constant (0.2 mm). This aspect is quite relevant in magnetic measurements because it improves the coil surface homogeneity along the longitudinal path, one of the main issues in coil manufacturing [7]. The coil designed in such a way, is then replicated at N horizontal positions just by off-centering the curved path by a fixed step. The value of N and the step are chosen in order to cover the GFR width and to fulfill the resolution requirements.

A second design phase is dedicated to the definition of the electrical layout, the layer interconnections and the reference target marks. These serve to position the array with respect to the mechanical structure holding the PCBs and then to the magnet body and the method for align the stack of layers. This last point has a particular importance because it directly affects the measurement accuracy. The correctness of the alignment between layers is checked with longitudinal and lateral controls tracks, representing the coil tracks cross-section. Before the fluxmeter assembly, the control tracks are cut and the metallography allows to detect and measure the alignment errors (the fig. 4 shows an example of the tracks). These tracks, referring to the central coil of the array, are printed on the board side at three longitudinal positions, corresponding to the level of the winding ends and to the junction between the curved and the straight part (fig. 5 shows an example of the marks on the left side of the coil). The mechanical targets on the PCB stack, for the mechanical positioning, are drilled at the average position value of all the layers following the control tracks alignment stacking error.

Table 1. PCB coils parameters.

Parameters	MBH-C	MBH-E
number of PCB per fluxmeter	2	2
longitudinal magnetic gap between the PCB [mm]	2.5	4
coil bending part length (arc length) [mm]	823.4	987.7
bending radius [mm]	4231	5078
bending angle [deg]	11.25	11.25
coil straight part length [mm]	502.7	362.8
PCB length [mm]	1336.9	1355.6
PCB width [mm]	189	121
number of layers/number of turn per layer/total number of turns	8/8/64	2/13/26
copper tracks width/ gap width/thickness [mm]	0.2/0.2/0.035	0.2/0.2/0.035
maximum positioning error of the layer [mm]	0.1	0.1
equivalent coil width [mm]	6	6
equivalent surface [m^2]	0.509	0.211
number of coil per PCB	17	7

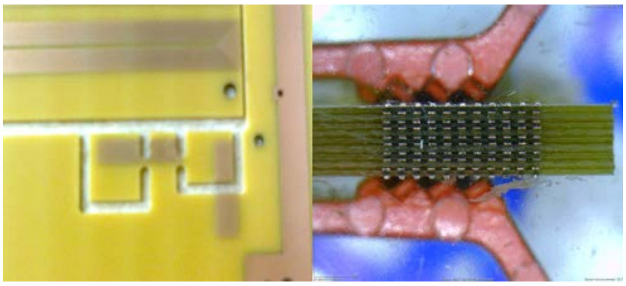

Fig. 4. Control tracks cut (right) and metallography (left) of the board

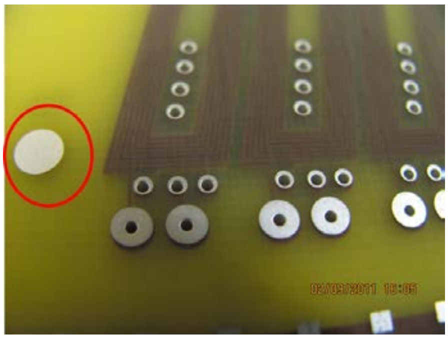

Fig. 5. Reference target marks from MBH-C PCB coils

The third design phase defines the mechanical support structure and dimensions, alignment tolerances for the PCB board installation and the positioning system for the installation in the magnet. Table 2 summarizes the parameters for the MBH-C and MBH-E fluxmeters.

A second set of reference target holes drilled at the two ends of each coil are needed to guarantee the correct positioning of the fluxmeters (measurement and reference) during the in-situ calibration procedure described in the next section. In order to lose weight and gain in rigidity, the fluxmeters were realized as a sandwich structure composed of different materials (fig. 6 shows the fluxmeter cross-section) selected with two criteria: no magnetic influence and easy machining Table 3 summarizes the material used for the MBH-C and MBH-E fluxmeters.

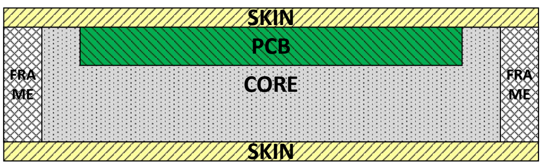

Fig. 6. Fluxmeter cross-section

Table 2. Fluxmeter parameters.

Parameters	MBH-C	MBH-E
overall length [mm]	2800	2850
overall width [mm]	405.6	323
width [mm]	210	140
height [mm]	10	10
reference target holes tolerance	3H7 and 4H7	3H7 and 4H7
relative positioning error between the two PCB coil arry [mm]	0.02	0.02
planarity of the PCB support [mm]	0.05	0.06

Table 3. Fluxmeter material.

parts	material	reference
skin	oriented fiberglass high flexion resistant with epoxy resin	special product
core	rigid foam	Rohacell 51 IG-F
frame	cotton fibers with epoxy resin	Flox-epoxy
inserts for calibration or positioning parts	oriented fiberglass with epoxy resin	EP GC 203
PCB	oriented fiberglass with epoxy resin special for PCB	FR4

The assembly of the whole structure is performed only after a careful control of the PCB production quality. Before and after the stacking process, it is necessary to check for open or short circuits of each layer in order to take corrective action during the production. A second sorting, based on the measurement of the coil surfaces, is needed to select the PCB boards to install in the same support in order to reduce coil differences and misalignments.

IV. CALIBRATION AND MEASUREMENT METHODS

The fluxmeters are used to measure two main parameters of the magnet: the field quality and the integrated field reproducibility from magnet to magnet (in the following defined as "tracking" measurements). Both types of measurements are relative measurements, in the first case we compare the B_L in the position (x_i,y_j) (the index i corresponds to one of the coil in the array, while the index j is the vertical position in the magnet aperture) with the B_L in (0,0). In the second case, the measurement of the B_L^{ref} (the integral field in a magnet chosen as reference), is compared with the one generated from the magnet under measurements (B_L^{mes}).

In particular, during a magnet power cycle, the fluxmeter measures the flux difference between two different coils [6].

$$\frac{\Delta B_L(x_i, y_j)}{B_L} = \frac{\Phi_{i,j}}{\Phi_0}\frac{w_0^{eff}}{w_j^{eff}} - 1 \quad (2)$$

With Φ_0 we indicate the flux variation in the central coil when the fluxmeter is in the mid-plane of the magnet aperture, and $\Phi_{i,j}$ is the flux measured by the i^{th} coil when it is placed in the j position. The flux differences are weighted by the difference in the equivalent coil surfaces (w^{eff}_j and w^{eff}_0).

The same approach can be applied to the tracking measurements. In this case there are two fluxmeters in two different magnets:

$$\frac{B_L^{mes} - B_L^{ref}}{B_L^{ref}} = \frac{\Phi_0}{\Phi_{ref}} \frac{w_{ref}^{eff}}{w_0^{eff}} - 1 \quad (3)$$

w^{eff}_{ref} indicates the surface of the central coil of the fluxmeter in the reference magnet. The equivalent surfaces, designed to be identical in the same fluxmeter and between fluxmeters, in the reality have small variations due to two main reasons: the precision in printing large circuit and the alignment of the circuit layers in the stacks.

The relations (2) and (3) show that for those kind of measurements it is important to know the relative differences between coils rather than the absolute value of their surfaces.

The absolute value of the coil equivalent surfaces can be measured in a reference magnet, but the accuracy of such calibration is reduced due to the difficulty to find a reference magnet with an homogeneous field in the 10 ppm order over a large dimension to cover the entire fluxmeter. In the specific case of the fluxmeters for the MBH-E and MBH-C, they are made of two PCB boards. The two boards are, longitudinally, installed one in front of the other and at the contact edge there is a gap that mechanically is well defined. Moreover, the missing field in that region needs to be magnetically estimated. Such gap is in the order of one millimeter corresponding to around 100 ppm of integral field. A special calibration magnet is under development at CERN to overcome those problems.

Currently, the calibration of the relative difference between coils can be obtained “in-situ”, that is in the magnet under measurement. The reference and calibrated coils are placed symmetrically with respect to the aperture mid-plane (fig. 7). In this region they intercept the same field, since the field profile is symmetrical with respect to the mid-plane, irrespective of power converter instability and magnetic history [8]. The reference (the red in fig. 7) and the measurement coil (in blue in fig. 7) are connected in series opposition, during a current pulse. The generated voltage, integrated corresponds to the remaining flux variation due to the difference in surface between the two coils. The reference coil is then systematically displaced directly above each coil of the measurement fluxmeter.

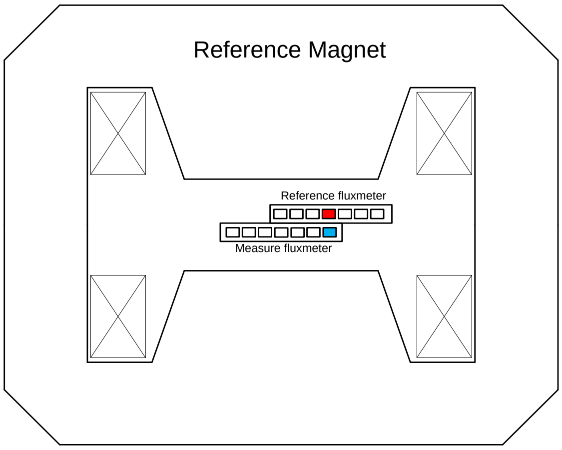

Fig. 7. Calibration example of the Coil # 7 with repect to the reference coil.

V. MEASUREMENT SYSTEM PERFORMANCE

The fluxmeters developed for measuring the MBH-Cs and MBH-Es have been calibrated in situ according to the procedure described above. The in-situ calibration has shown a maximum difference with respect to the coil on the central trajectory of the MBH-C fluxmeter of 2 × 10-4 (fig. 8). Such difference decreases to 0.5 × 10^{-5} (for the coils at -80 mm). Even if the accuracy in producing a single layer printed circuit board can be of the order of 1 micron, the accuracy of a stack of PCB layers is reduced due to the difficulty in aligning horizontally the stacks. In the specific case of the MBH-C fluxmeter such alignment has been measured to be 100 µm (worst case) corresponding to half of the PCB track width [9].

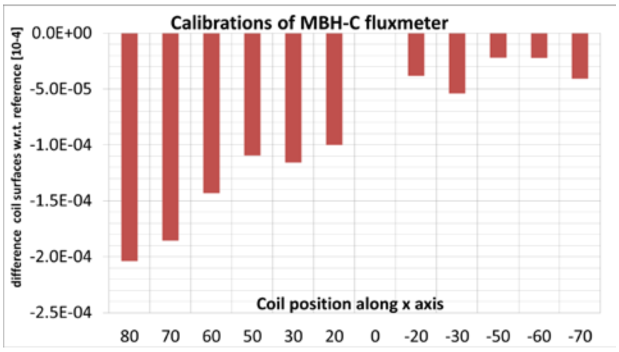

Fig. 8. MBH-C fluxmeter relative calibration

The same measurement performed on the MBH-E fluxmeter has shown a maximum difference below 0.4 × 10^{-4} (Fig. 9). This fluxmeter is made only by one double layer board instead of 8 as for the MBH-C, with coil windings on both layers; this improves by a factor of 2 the quality of the fluxmeter but to the detriment of number of coil turns and spatial resolution of the measurements. The calibration has been repeated in the same reference magnet monthly over a period of 9 months (for the MBH-C fluxmeter, measurement for the MBH-E is still ongoing) to assess the long term stability and thermal stability. Despite of seasonal and daily thermal fluctuations of ± 6 °C in the measurement workshop, the calibration results have shown variations below 0.2×10^{-4}.

At the moment a special calibration magnet powered in AC is under development at CERN. This magnet should be able to provide an accurate absolute calibration of the coil surfaces and the possibility to make a longitudinal scan of the coils in order to verify local deformation of the coil's width. Precise measurement of the "magnetic" gap between the two halves of the fluxmeters can also be obtained.

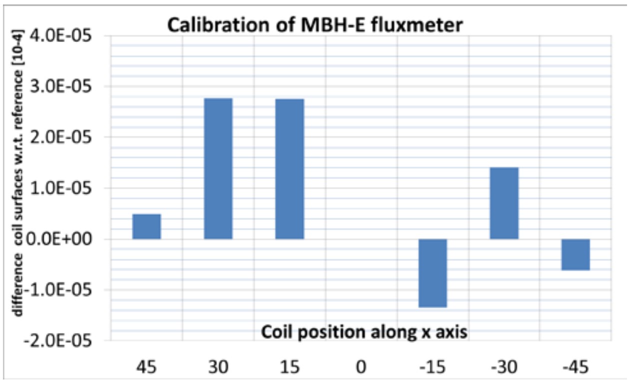

Fig. 9. MBH-E fluxmeter relative calibration

VI. CONCLUSION

In this paper we present the design details and development of a coil array based on printed circuit board technology to measure the integral field homogeneity of curved dipoles.

The design of a PCB fluxmeter has been adapted to develop two measurement coil arrays for measuring the synchrotron and the high energy transfer line dipoles of the MedAustron accelerator. The PCB technology chosen mainly to allow the measurement of the integral field along a curved path, has two other advantages: precision of the coil winding and the long term stability in despite of a smaller winding density with respect to standard manufactured coils used in for magnetic measurements. The precision of the winding results in relative difference between coils below the 10^{-4} that improves drastically the quality of the compensation and, as consequence, the overall accuracy. The long term stability has reduced the time dedicated to the calibration and considerably reduced the overall measurement time.

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REFERENCES

[1] G. Moritz, F. Klos, B. Langenbeck, Q. Youlun, K. Zweig, "Measurements of the SIS magnets", IEEE Trans. on Magnetics, vol. 24, no. 2 (MT-10) (1988) 942-945.

[2] C. Priano, G. Bazzano, D. Bianculli, E. Bressi, M. Pullia, L. Vuffray, I. DeCesaris, M. Buzio, D. Cornuet, R. Chritin, J. Dutour, C. Sanelli, E. Froidefond, "Magnetic Modeling Measurements and Sorting of the CNAO Synchotron dipoles and quadrupoles". Proc, of IPAC'10, 2010, pp. MOBEP004.

[3] S. Russenshuck, "Field Computation for Accelerator Magnets" 2004, publ. Wiley-vch, pp. 388.

[4] M. Benedikt, J. Gutleber, M. Palm,W. Pirkl, U. Dorda, A. Fabich, "Overview of the MedAustron design and thechnology choises", Proc, of IPAC'10, 2010, pp. 109-111.

[5] B. Langenbeck, C. Siedler, M. Stockner, T. Zickler, "Design and optimization of the MedAustron synchrotron main dipoles", Proc, of IPAC'11, 2011, pp. WEPO001.

[6] J. T. Tanabe, "Iron Dominated Electromagnets Design, fabrication, assembly". 2005, publ. World Scientific.

[7] G. Golluccio, A. Beaumont, M. Buzio, R. Chritin, M. Stockner, A. Vorozhtsov, T. Zickler, "Overview of the magnetic measurements status for the MedAustron project", International Workshop Magnetic Measurement (IMMW18), Brookhaven, 2013.

[8] P. Arpaia, M. Buzio, G. Golluccio, L. Walckiers "In situ calibration of rotating sensor coils for magnet testing",Rev Sci Instrum, 2012, pp. 83.

[9] A. Beaumont, M Buzio, R. De Oliveira, O. Dunkel, M. Stockner, T. Zickler, "Printed Circuit Fluxmeter to Measure the Bending Magnets of the MedAustron Synchrotron", International Workshop Magnetic Measurement (IMMW17), Terrassa-Barcelona, 2011.