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STATUS OF THE FIELD MAPPING SYSTEM DESIGN FOR THE C400 CYCLOTRON

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Abstract

NHa and IBA are collaborating to develop a new cyclotron dedicated to hadron therapy. The manufacturing of the magnet is in an advanced stage. In parallel, extensive studies are carried out to develop an accurate field mapping system. It is required to perform the high precision magnetic field measurement (75 ppm) that will provide the final isochronous field after the shimming procedure.

In this article, the topic focuses on the modelling of the search coil response as a function of its geometrical form factor, as well the status of the new mechanical system providing the probe motion will be presented. The aim is to evaluate and manage the potential errors induced by the measurement of such averaged flux over the coil inner volume in case of very inhomogeneous fields.

INTRODUCTION

In isochronous cyclotrons like the C400 [1], isochronism is obtained by trimming the average magnetic field on the particle's trajectories using shims and modifications of the pole edges geometry. In addition, tuning is made to avoid harmful resonances. These modifications are based on accurate measurements of the magnetic field in a median plan map. Due to the large radius of the acceleration plane of the C400 (1.8 m) and the combination of both high magnetic field level (up to 4.5 T) and high precision measurement required (0.1 mm position accuracy, 75 ppm magnetic field precision), using only a Hall probe would prove insufficient to fulfill both the requested precision and acceptable mapping duration (<48 hours). Therefore, a new mapping system is currently being designed specifically for the C400. The design of the mechanical system ensuring the high precision movement accuracy and repeatability is finished (see Fig.1). The setup will be assembled and tested in the following months at the IBA assembly hall. It will enable both radial and azimuthal movement at a max radial (resp. azimuthal) speed of ~0.5 m/s (resp. 5 RPM, translating to ~0.95 m/s at max radius) and with a 50 µm read back resolution. In parallel, a measurement technique making use of a dual search coil probe is being developed to enable fast and high precision field measurement, profiting from past IBA experience [2] and existing literature about isochronous cyclotron field mapping with this kind of sensor [3]. Numerical tools are being developed to model precisely the response function of such search coils, especially in the high gradient area where high precision is critical to correctly evaluate the impact of the shimming process. This paper presents the preliminary results of these studies that are still under progress: validation of the coil geometries and benchmarking of the calculation approximations and optimizations. The full scope of these studies will include the validation of the full chain of data acquisition, preparation of the measurement campaigns for the coil calibration and evaluation/control of the systematic effects during the actual cyclotron field mapping.

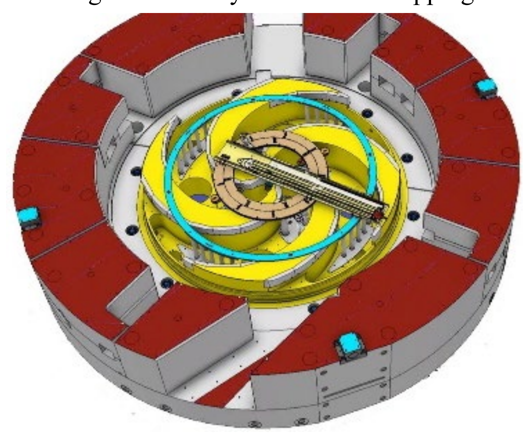

Figure 1: 3D View of the Mapping Wheel Set Up in the C400.

DESIGN CONTRAINTS OF THE SEARCH COIL

Induction Coil as Magnetic Field Sensor

Using small and tightly packed conductive wire turns to measure magnetic field with high speed and high precision has a long history and well-studied shortcomings and point of attention [4]. Among them are the intrinsically averaged field measurement due to the not local sensitive volume. In the case of a cylindrical coil, the height-to-diameter ratio (L/D) of the coil is known to induce potential measurement errors, especially in area with large higher order derivatives of the field. Such area is commonly found in the fringe field of dipole but is also present in isochronous cyclotron, typically at the hill-to-valley crossings and close to the pole edges.

Search Coils for The C400 Cyclotron

The C400 magnetic field has been precisely modelled with OPERA 3D (Fig. 2) and it was readily observed that some particle trajectories were passing very close (< 5mm) to area with strong field gradient (>500 G/mm) both at max radius, close to poles edges and tails, and few millimetres above the median plane.

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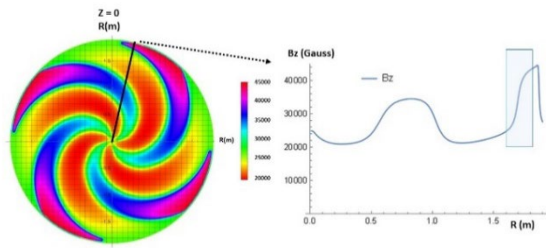

Figure 2: Left: 2D Magnetic Field of The C400 Cyclotron At Z=0 Mm. Right: Magnetic Field Profile Along Cyclotron Radius and at 20° Azimuthal Angle. The Selected Area Around R=1.7 M Corresponds to the one Where the Search Coil Responses were Computed for This Study.

To comply with such field characteristics, a very small coil geometry, labelled 'SC_S', has been defined: $\{L,D,d_w\}=\{2.6,3.8,19\}$ (height L and diameter D given in mm, wire diameter including insulation d_w given in µm). Such a small geometry limits strongly the number of turns (<8000 assuming a packing factor of 0.85) and thus the probe signal level, which may cause issue to measure small field gradients. Therefore, a larger coil 'SC_L' $\{L,D,d_w\}=\{5,7.4,26\}$ will be installed next to the small one on a dual probe holder and the mapping system will feature the possibility to switch between them depending on the field characteristics to measure. Since search coils are only sensitive to flux variation, an NMR probe will also be present to provide the absolute field value reference.

MODELLING THE SEARCH COIL RESPONSE

Scope of the Study

The aim of this study is to numerically reproduce the voltage response of the search coil (SC) while probing a high precision 3D modelling of the C400 magnetic field. Interpolating the latter, elementary flux variations calculated through the surface defined by each wire turn (or 'spire') are computed numerically (Eq. 1) and summed to provide the total flux variation seen by the coil and generating the voltage output signal (Eq.2). Knowing the effective surface of the coil, its displacement velocity and having an absolute reference provided by the NMR probe, the magnetic field can be numerically reconstructed (Eq.3) along the probe trajectory and compared to its 'true simulated value', the local field at the centre of the probe.

$$\phi = \sum_{i=0}^{n} \iint_S B_z dS_i \quad (1)$$
$$V = -\frac{d\phi}{dt} = -S_{eff}\frac{dBz}{dt} = -(S_{eff}.v)\frac{dBz}{dx} \quad (2)$$
$$B_z^{SC} = \frac{1}{S_{eff}.v}\int_{x_{ini}}^{x_{end}} V(x)dx + B_0 \quad (3)$$

ϕ is the total flux passing through the coil for a magnetic field having a B_z component along the normal vector of the surfaces dS_i formed by the n wire turns.

V is the voltage produced at the terminal of a SC having a S_{eff} effective surface and moving at a speed v. S_{eff} is a scalar equal to the sum of the elementary surfaces.

B_z^{SC}, the magnetic field profile as measured by the SC is given by the integration of the coil signal combined to the absolute field reference B_0 measured somewhere along the probe trajectory with an independent absolute sensor (i.e. NMR probe).

With this method, any high order derivative of the field that may significantly bias the global coil response is intrinsically considered and the theoretical field precision achievable with the chosen coil design can be precisely estimated. Furthermore, all the variables that could impact the final measurement can be studied: displacement velocity, tilt of the probe, high vertical field gradient area, etc. The following sections explain the technical implementations of this numerical tool and the preliminary results obtained with it: computing time optimization and validation of the coil response.

Technical Implementations

The software used is Mathematica from the Wolfram company. The numerical interpolation and calculation can be performed both in polar and cartesian coordinates, depending on which are better suited to solve the problem at hand. The results presented in this paper were all obtained from a polar geometry corresponding to the median plane of the cyclotron. To simulate the measurement by SC of the magnetic field profiles along the cyclotron radius, called 'radial track' thereafter, the $B_z(r,\theta,z)$ field map extracted from OPERA3D data is interpolated using spline method of order 5 in both directions. Even with parallel computing, a single and partial (the 230 mm long portion around R~1.7 m shown in fig.2) radial track takes about 14.5 hours on Intel Xeon W-2225 CPU@4.1GHz 4 cores if all the spire fluxes are computed. This drawback could be suppressed by calculation optimization presented in the next section.

PRELIMINARY RESULTS OF THE NUMERICAL STUDY

Calculation Time Optimization

To be able to scale the use of this calculation tool to the full C400 mapping, the following optimizations were performed, carefully checking their impact on the probe response: making use of existing symmetry when possible (for example, only half a coil calculated when located on the median plane and when the top-bottom symmetry is verified) and, less straightforward, an adaptative calculation step algorithm in both radial and vertical directions depending on the local gradient amplitude. In the vertical direction, the wire diameter was virtually increased keeping the total coil height constant, thereby reducing drastically the number of turns to calculate. Benchmark tests were executed by arbitrarily enlarging the vertical field gradient $\frac{dBz}{dz}$ to compute the figure of merit of such approximations.

In the radial direction, a similar study was performed simply by varying the distance between two consecutive numerical calculations ('radial step').

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Fig. 3 shows the difference between the true simulated field B_z^{OP3D} and B_z^{SC}, obtained from the computed response of the search coils with respect to the chosen constant radial step, still using the same partial track as before. This numerical error was computed at three different locations along the track: where the coil voltage signal variation is a) maximal – at this point the maximal numerical error is obtained, b) equals to half the maximum and c) equals to one seventh of the maximum. From this figure, one can see for example that if an absolute error below 5 G is requested, the step size must be reduced to at least 5 mm around the max signal variation region for this radial track but can be made larger elsewhere.

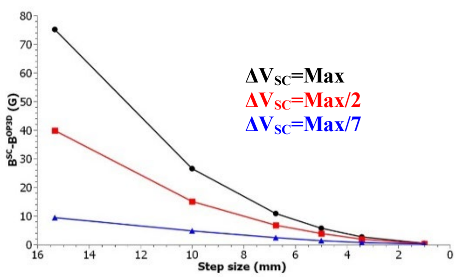

Figure 3: Numerical Errors with Respect to The Radial Step Distance at Radial Track Positions Where the Coil Voltage Is Maximal (black), Half of The Maximum (red) and One Seventh Of The Maximum (blue).

Finally, these optimizations permitted to reduce the computing time by a factor ~20 while keeping the numerical error under control, i.e. significantly below the errors produced by the coil size effects.

Validation of the Search Coil Response

Discussion in the literature concluded that the optimal height-to-diameter ratio, i.e. the one minimizing the error induced by the finite SC volume, is L/D=0.67 in theory [5]. However, the actual best value depends on the field profile shape itself. Since the C400 field is very complex and present various profiles, it was decided to keep L/D=0.67 for both small and larger coils as a design guideline and to use the numerical tool presented here to compensate for potential bias during the full mapping. To validate that the modelling tool is indeed reproducing the expected error related to this shape factor, other coil geometries morphed from the real ones were tested. The morphing was done at effective surface constant and moving the L/D factor from 0.67 to 2.2 (thin & long coil) on one side and 0.06 (flat & large coil) on the other side. Those values were chosen to check that the distortion visible on Fig.1 of [6] was correctly reproduced. As visible on Fig. 4, it is indeed the case: a very large & flat coil will tend to overestimate the true field in the first half of positive field gradient, then will underestimate it in the second half. The effect is vice versa for the thin & long coil. Also from fig. 4, we can deduce that the actual best shape ratio for the tested profile is located somewhere between L/D=0.67 and 2.2.

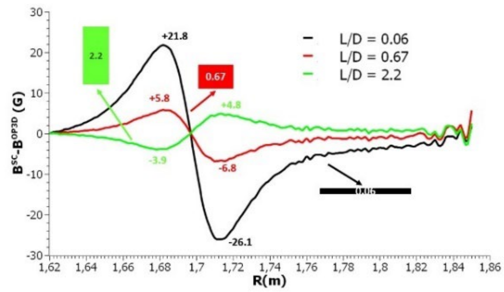

Figure 4: Field Measurement Error of SC_S (L/D=0.67, red) and its Morphed Shape Variations (L/D=2.2, green and L/D=0.06, black) Along the Radial Track at R~1.7 m and θ=20° Azimuthal Angle. (Simulation parameters: radial step=5 mm, probe speed=0.5 m/s).

Finally, it is known that the coil height L can also have a dramatic impact on the measurement error, especially if a non-negligible vertical field gradient is present. Fig. 5 investigates this point by showing how the computed error grows with respect to the field gradient along the vertical axis for both SC_S and SC_L. This was obtained by artificially multiplying the OPERA field map with a set of increasing factor numbers. As expected, SC_L, taller by 2.4 mm (almost +100% relative to SC_s), is much more impacted by an increasing gradient and it seems the error grows faster than linearly with L in accordance with what is predicted in [5].

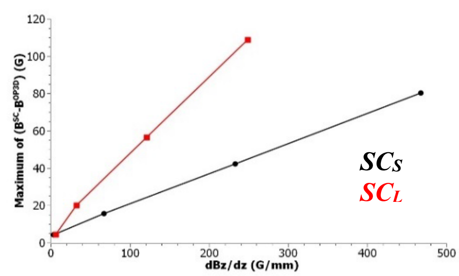

Figure 5: Computed Error as a Function of the Vertical Field Gradient for Both SC Geometries.

Realistic vertical gradient in the C400 is in the order of $\frac{dBz}{dz} \sim 4$ G/mm and at this value, the calculations show that the error induced by the coil size should remain below the absolute precision requirement, which tends to confirm the coil design choices.

CONCLUSION

A simulation tool is being developed to model precisely the response of the search coils that will have the task the perform the field mapping of the new C400, both the cyclotron and the mapping system being in an advanced stage of development. The results obtained so far are promising and tends to confirm the search coil geometry design choice. These studies will continue, and the tool developed will serve to prepare both the coil calibration process and the final C400 field mapping strategy, ensuring the best possible precision will be achieved.

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