MAPPING OF THE NEW IBA SUPERCONDUCTING SYNCHROCYCLOTRON (S2C2) FOR PROTON THERAPY

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Abstract

The magnetic field in the Superconducting Synchrocyclotron (S2C2) has been measured with a newly developed mapping system during the commissioning of the machine at IBA. The major difference with other mapping systems at IBA is the usage of a search coil, which provides high linearity over a large magnetic field range and the possibility to measure in a more time efficient way. The first mapping results of the S2C2 were compared with OPERA3D calculations. The average field, the tune functions and the first harmonic were the main quantities which were compared with calculations. The horizontal position of the main coil was found to be a crucial parameter to get a good agreement between calculation and measurement. The vertical position of the main coil was optimized based on measured vertical forces on the main coil.

INTRODUCTION

The newly developed superconducting synchrocyclotron (S2C2) is the first non-isochronous and superconducting cyclotron build at IBA. It's compact size (2.5 m diameter) is crucial to reduce the footprint and overall cost of existing proton therapy solutions. The compact single room proton therapy system called ProteusONE® aims at making proton therapy available to more people at a reduced cost and with less impact on building and infrastructure.

THE MAPPING SYSTEM

The mapping system is shown in Figure 1 and consists of a search coil (MagnetPhysik, FS 2800 W), a Hall probe (Arepoc s.r.o., LHP-NP) and a NMR probe (Metrolab) which are all mounted on a wheel which covers 360 degrees azimuthally and has a radial range of about 50 cm. The NMR probe can be positioned in the centre of the S2C2, where the field homogeneity is good enough to measure the 5.72 Tesla field with high precision. This NMR measurement is the starting value for the relative measurement with the search coil, which moves from the centre to a maximum radius with a speed of 6 cm/s. The voltage induced in the search coil is integrated with a Metrolab PDI5025. The integration intervals are defined by an optical ruler along the track of the search coil which has a radial pitch of 50 μm. The radial resolution chosen for the mapping of the S2C2 is 1 mm. The magnetic field at radius r is given by :

$$B(r) = B_0 + \int_{t_1}^{t_2} \frac{V(t) - V_{offset}}{A_{eff}} dt$$

where B_0 is the field measured in the centre with the NMR probe, t_1 and t_2 are the trigger interval time limits defined by the optical ruler, V_{offset} is the measured voltage offset on the integrator input and A_{eff} is the effective surface of the search coil. The latter was calibrated separately in a calibration magnet [1]. The Hall probe present on the mapping wheel was used to compare the field profiles measured with Hall probe and search coil at different main coil currents. In this way, the effective surface calibration of the search coil was checked. The dimensions of the search coil were chosen carefully in order to minimize the influence from the finite size of the search coil [2]. Prior to each radial track with the search coil, the voltage offset on the integrator input is measured. It was found that this offset varies about 25 μV over the full mapping time (maximum 24 hours). With a total measurement time of about 10 seconds for each radial track, an offset of 25 μV would contribute about 8 Gauss of "artificial" field at the end of the track. Figure 2 shows the measured field map at nominal current (652 A) in color scale. The regions indicated in Figure 2 are (1) the regenerator region, (2) the region between azimuth 180° and 270° where the radial range of the search coil is limited due to the presence of the septum in the median plane, (3) the region where the beam enters the extraction channel.

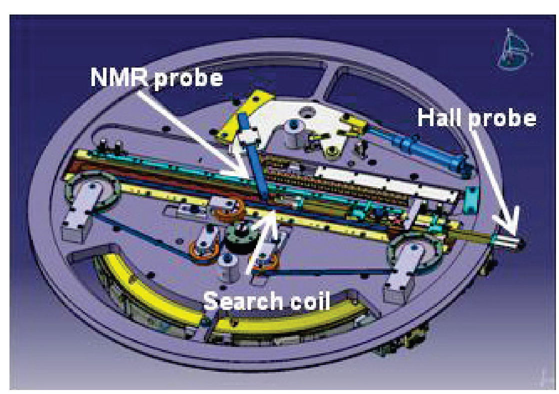

Figure 1: Layout of the mapping wheel.

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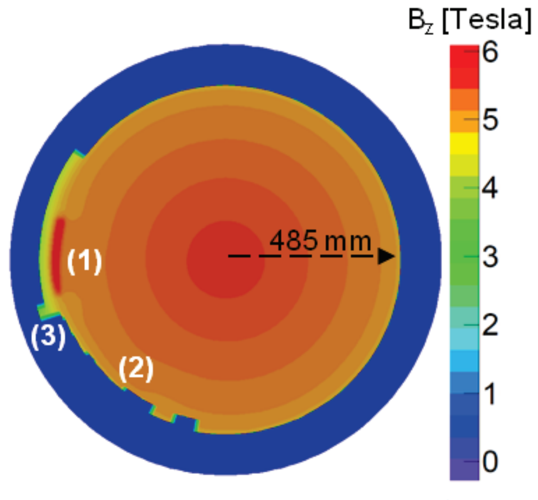

Figure 2: Full measured field map of the S2C2 at nominal current. (1) = the regenerator region, (2) = limited radial range due to presence of the septum in the median plane and (3) entrance of the extraction channel.

MAPPING RESULTS

Central and Average Field

The field in the centre of the S2C2 was measured with the NMR probe and an agreement at the 0.2 % level between the measured and predicted fields, at various main coil currents, was obtained. This was achieved thanks to careful measurement of the various S2C2 steels magnetization curves.

The measured average field inside the S2C2 is shown in Figure 3 with the red line. The dashed black line is the average field as calculated in OPERA3D and the green dotted line represents the pure coil field. The deviation between the measured and the calculated average field is given in the right scale and is below 0.3%. At the extraction radius of about 50 cm, the coil contributes

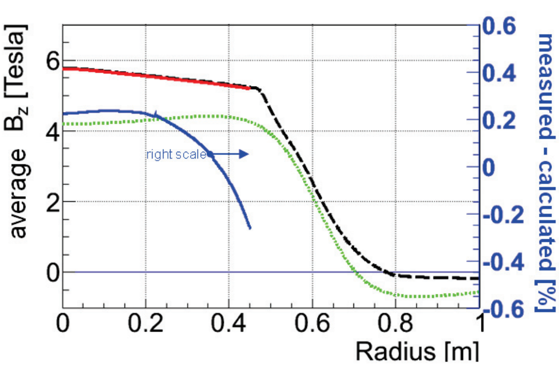

Figure 3 : Average field in the S2C2. Red full line= measured, black dashed line= calculated with OPERA3D, green dotted line= calculated pure coil field, blue full line (right scale)= deviation between measured and calculated average field.

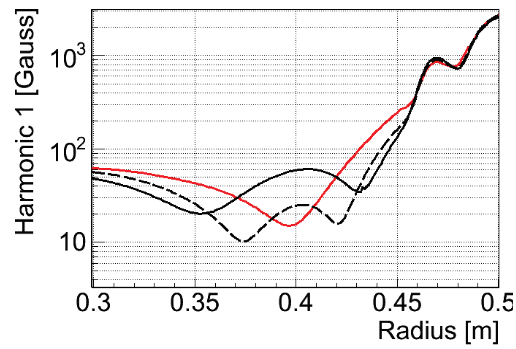

Figure 4: First harmonic component in the field map: red full line= measured with a slightly horizontally displaced main coil, black full line= measured with a horizontally centered main coil, black dashed line= calculated first harmonic from the OPERA3D field map.

about 80% of the total vertical magnetic field in the median plane. The influence of the horizontal main coil position will be illustrated in the next section.

First Harmonic Components and Tune Functions

The first harmonic component is plotted in Figure 4. The full red line is the first harmonic measured with a main coil which was slightly displaced in the horizontal direction. The corresponding tune functions for this configuration are plotted in Figure 5 (red lines). It can be seen that in this configuration, the Walkinshaw resonance at $Q_H=2Q_V$ is crossed. Its harmful effect was confirmed by tracking protons in this field, indicating major vertical losses and horizontal losses on the accelerator structure. By shifting the main coil by about 3 mm the first harmonic and tune functions shown in Figure 4 and 5 (resp.) with the full black line were obtained. The first harmonic corresponds better to the calculated first harmonic, which is shown with the dashed line in Figure 4. At the same time the resonance is avoided and the tune functions correspond better to the design tune functions (dashed lines in Figure 5). Tracking of protons in this field map augmented the calculated extraction efficiency

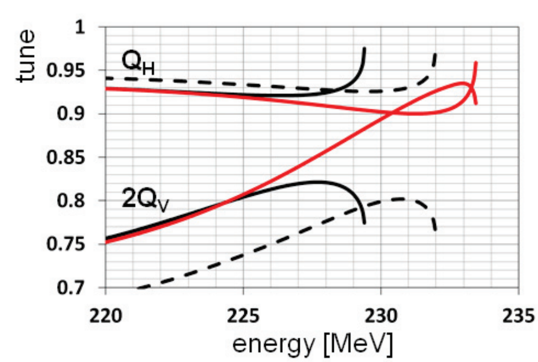

Figure 5: Tune functions. Red full line= measured with slightly horizontally displaced coil, black full line= measured with horizontally centered coil, black dashed line = design tune functions.

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to the design value of about 50%. This illustrates the importance of the main coil position and its influence on beam extraction and dynamics.

SHIMMING AND FORCES

Radial fields in the median plane (median plane errors) are extremely difficult to measure directly. Two major sources for median plane errors were identified in OPERA3D: the iron asymmetries around the machine and the vertical position of the main coil. The former can be corrected for by applying shims on the return yoke of the S2C2. Calculated radial fields are shown in Figure 6 (top) with and without shims on the top yoke. The shims as they have been implemented in OPERA3D and on the S2C2 are shown in Figure 7. In Figure 6 (bottom), the vertical force on the main coil is shown as a function of main coil current for the same configurations (with and without shims). This shows that minimization of the total force at nominal current reduces at the same time the average radial fields in the median plane to less than 1 Gauss.

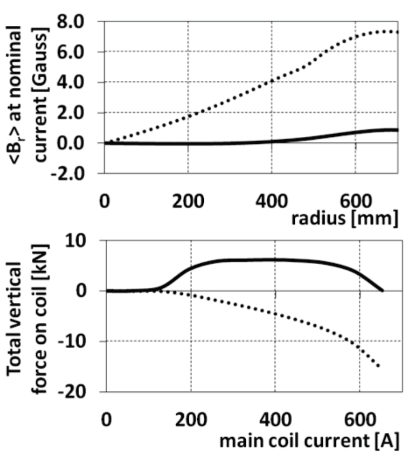

Figure 6: (top) calculated average radial fields in the S2C2 with (full line) and without (dotted line) shims on the top yoke. (bottom) calculated total vertical force on the main coil with and without shims.

Figure 8 shows the evolution of the total vertical force on the main coil as it was measured during commissioning of the machine. The dotted line is the initial vertical force at first rampup of the coil. The dashed line is the total force after the coil has been moved by 2 mm and the full line is the total force after full shimming of the S2C2. This shows that the total force has been reduced to almost zero at nominal current by applying shims on the S2C2 and by accurate vertical positioning of the main coil.

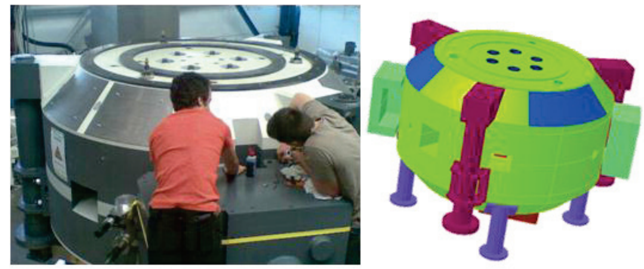

Figure 7: (left) shims applied on the S2C2 (may 2013) (right) OPERA3D model of the S2C2 with all shims included on the top yoke.

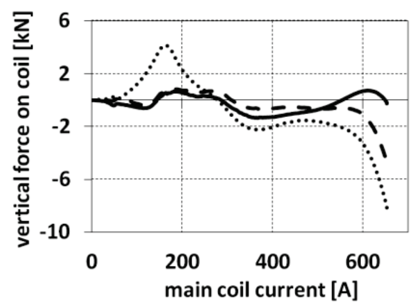

Figure 8: Measured total vertical force on the main coil. Dotted line= during the initial ramp-up, dashed line= after vertical positioning of the main coil and full line= after application of all shims on the top yoke.

CONCLUSIONS

The mapping of the S2C2 has been successfully finalized at IBA. The horizontal position of the main coil, was a crucial parameter to reproduce the design tune functions and the first harmonics. The vertical positioning of the main coil was done by minimizing the total vertical force on the main coil at nominal current. Shimming of the S2C2 was performed as well to eliminate radial fields in the median plane. In the coming months, beam tests will be performed with the S2C2.

REFERENCES

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[2] M.D. Thomason, Cylindrical Point Coils for Magnetic Field Mapping; Los Alamos Informal Report LA-5304-M, 1973