MEASUREMENT AND SHIMMING OF THE IMPROVED CERN SYNCHRO-CYCLOTRON MAGNET

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Abstract

All magnetic measurements of the CERN SC2 magnet were done with Hall-plates. The principal element of the measuring gear was a 3.5m long bar with 100 Hall-plates mounted on a computer-controlled turn-table. The Hall-voltages were scanned, converted into field values and stored on tape. For special regions other Hall-plate arrangements were used. The field maps were evaluated in terms of mean radius, frequency, n-value, etc. versus energy. The optimum field for capture near the centre, acceleration and transmission through the extraction system was calculated. Shimming was required near the centre and in the channel-regenerator region. The same programs as for the original design were used. The programs used will be briefly described.

Shim Calculation

The reconstruction of the CERN synchro-cyclotron was undertaken to get a considerable increase of the proton beam intensity. The principal changes were a new RF system giving higher Dee voltage and repetition rate and a new hooded arc ion source and central geometry to get efficient capture into a well-defined beam. The axial introduction of the ion source required a 20cm diameter hole to be drilled through the poles. Simultaneously the magnet focusing near the source needed improving. These contradictory requests could only be fulfilled by an intricate shimming. Also the extraction system, that now consists of a regenerator, an electromagnetic septum and three iron channel sections, required shimming to minimize undesired perturbance of the orbits. The shimming was followed by magnetic measurements and reshimming in several cycles.

Capture calculations had given an initial "ideal" field shape and "ideal" frequency curve. The field shape and pole shape should be unchanged outside 25cm radius. To calculate the shimming around the central hole a program called FUNCFLD was used[1][2]. The field in the gap is represented by a number of current loops. Another set of current loops together with a permeability function represent the field in the iron. The desired field in the mid-plane and co-ordinates of a set of known points on the pole surface (in this case outside 25cm radius and in the hole) can be specified. The program attempts to match scalar and vector potentials for gap and iron on a pole surface and give the desired field. At first every attempt failed; the reason was soon found to be that the large hole in the centre contradicted Maxwell's equations for the desired field. Every effort was then made to decrease the hole diameter, particularly near the pole surface (see Fig. 1). The innermost part of

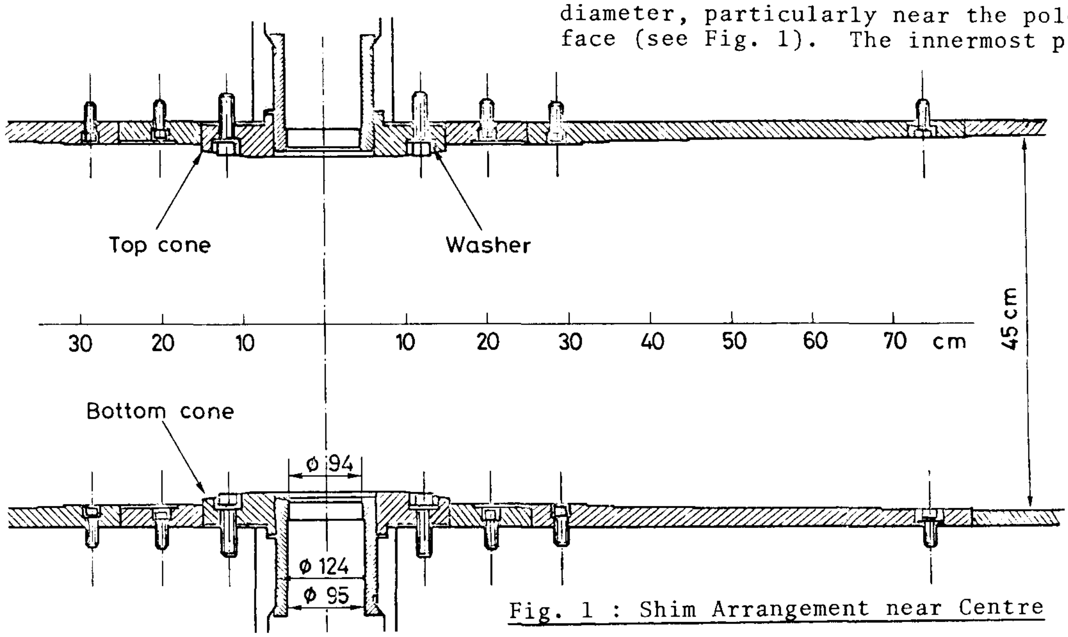

Fig. 1 : Shim Arrangement near Centre

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the shimming had even to go out together with the source. The resulting hole diameter was 94mm and the required pole shape could be calculated.

The regenerator and iron channel shims were calculated by a special program called OPTCHA, under the assumption that the iron walls and the iron bars used for shimming were saturated in the vertical direction and that the effect of the poles, which is relatively small close to the walls of the channel, could be treated as reflections in flat surfaces with a reflection coefficient of 1-1/p, where p is the average permeability in the pole[3]).

Arrangement for Measurement

All measurements were done with Hall-plates. In order to measure the vertical field in the mechanical mid-plane of the magnet 100 Hall-plates (SBV 579 Siemens) were mounted with 3cm spacing on a 3.5m long cast aluminium bar (see Fig. 2). The plates were temperature stabilized to 25 $\pm$ 0.1°C. The bar was mounted on a turntable in the centre of the SC. The angle was controlled by an Electronic Positioning System (accuracy = 0.01 degree, speed = 0.13 degree/sec). At any wanted azimuth up to 100 Hall-voltages were measured with the help of an Analog Scan System (Hewlett Packard Model 2323A with 140 channels and an integrating digital voltmeter, scan speed = 40 channels/sec, absolute accuracy = 3.10^{-4}).

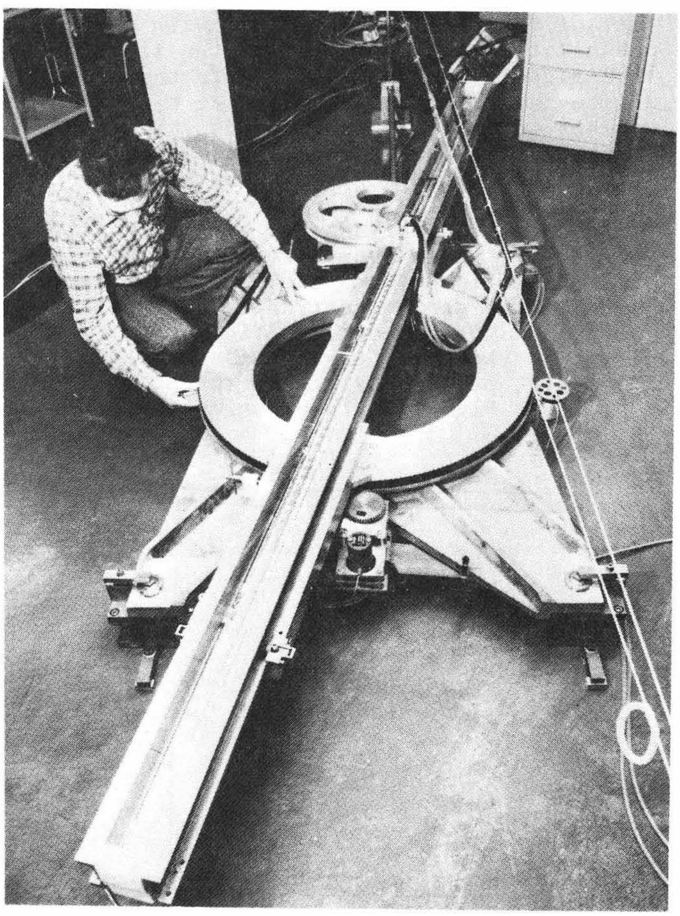

Fig. 2 : Mechanical Measurement Equipment mounted in the CERN Synchro-Cyclotron

Positioning and scanning were controlled by a process control computer (Siemens 301 with 16K core memory, 24 bits word length, 1.6 µs cycle time). After setting up initial conditions and step angle a complete flux map was automatically taken and stored on magnetic tape or, if desired, on punched cards. The Hall-voltages were converted into field values using a polynomial, and other parameters such as SC magnet current were checked and stored. A block diagram of the data flow is shown in Fig. 3.

For special regions of the magnet such as between the walls of the iron channel other Hall-plate supports were used.

A special task was to measure the horizontal field component. To determine the magnetic mid-plane within ± 2mm the horizontal component must be measured with an accuracy of ± 1 Gauss in the presence of a vertical field 20000 times stronger. The measurements were done with Hall-plates (SBV 579 Siemens) fixed on a pendulum, an idea of Abrosimov, Eliseev and Ryabov, "Russian Pendulum"[3]) (see Fig. 4).

The pendulum consists of an Al-plate with a lead weight underneath and hung by a pair of nylon threads from a support. Any misalignment of the Hall-plates may cause a large Hall-voltage. By turning the support 180° and taking the difference the Hall-voltage due to misalignment is eliminated and the true horizontal field component found. By having two Hall-plates with 4cm vertical distance one can by interpolation find where the horizontal component is zero. If this is at the same level for all azimuths this is also the magnetic mid-plane. To minimize the vertical emittance of the beam it is particularly important near the centre that the magnetic and mechanical mid-planes coincide. A correction was possible by shifting iron washers from the top cone to the bottom cone.

These same washers could also serve to get the equilibrium orbits well centred horizontally for small radii. Furthermore, when the possibilities of the real RF

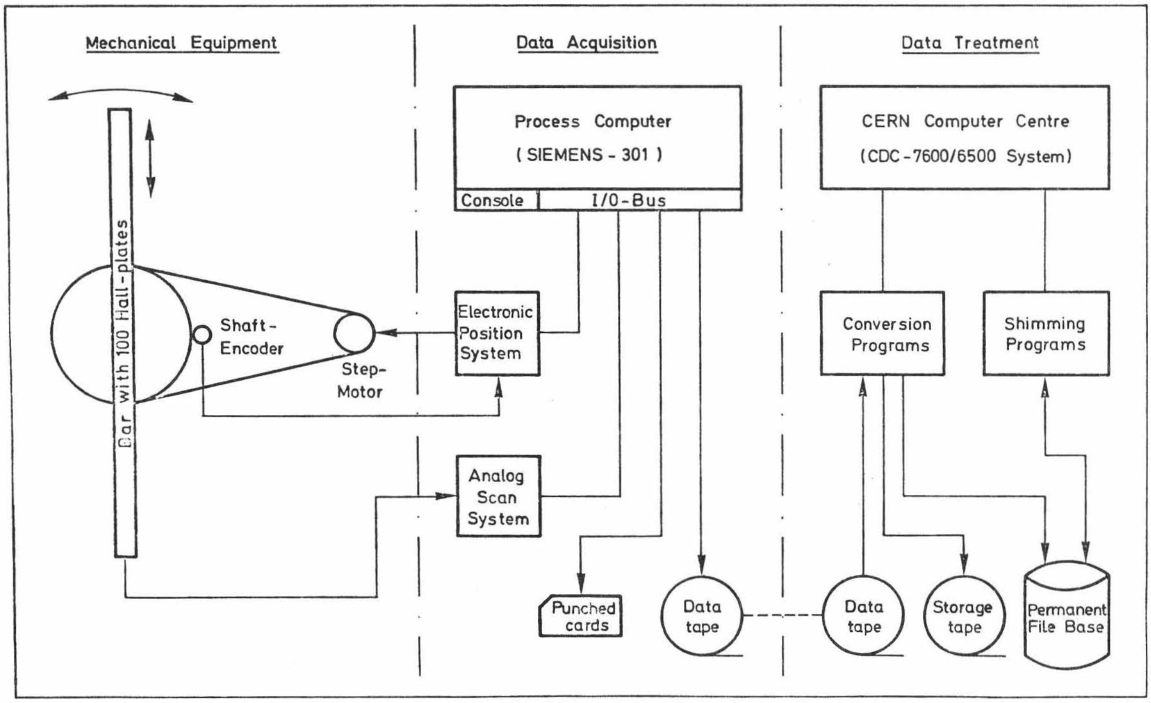

Fig. 3 : Block Diagram for Data Flow

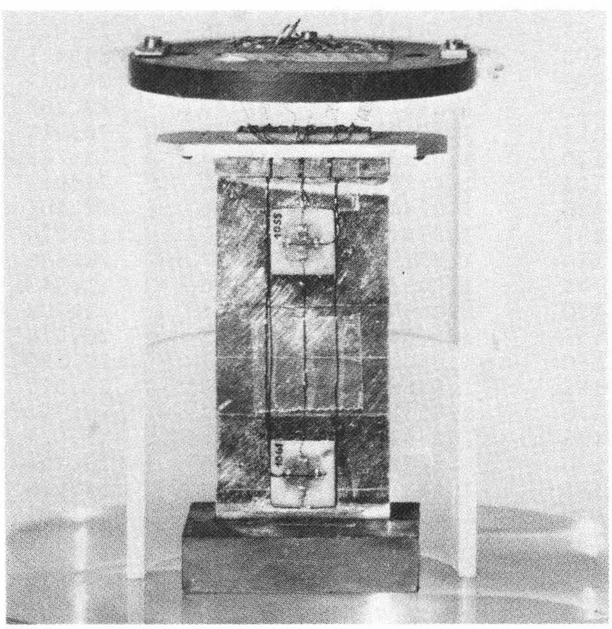

Fig. 4 : "Russian Pendulum"

system became available, calculations indicated that a higher value of

$$K = -\frac{E}{W}\frac{\partial W}{\partial E} \sim 1 - \frac{E_o^{\ 2}}{c^2 B_o^{\ 3}}\frac{d^2B}{dR^2}$$

was desired. This could be achieved by placing shim plates under the cones and increasing the thickness of the washers.

The computational checking of the centring of the measured field was naturally quite complicated since the field gradient dB/dR at the machine axis vanishes. To get sufficient accuracy 5 complete field maps with 4^o angular and 3cm radial steps were measured around the centre, the 100 Hall-plate measuring bar being shifted in 3cm steps between measurements. Since for each complete turn of the bar the field in each point is measured twice, with 5 measurements, the field in each point was measured 10 times with 10 different Hall-plates. By averaging these 10 measurements a sufficient accuracy was obtained to calculate the proton equilibrium orbits close to the centre. With the final shim situation these were concentric within 0.2mm out to 10cm radius.

Considerable data handling was required to find the required shimming. For each radius the average flux density, the amplitude and phase angle of the first harmonic and also n- and K-values were calculated. In the extraction region the effect of each channel section was found by deducting the field at the same radius at opposite direction and performing a co-ordinate transformation to a polar system corresponding to the curvature at the channel. It was then possible to separate the effects of each section and compare with calculated values. The size of the new shims was then found by program OPTCHA, by setting the "desired field" = previous calculated field - error found. The convergence was good except that a rather big first harmonic some 10cm inside the extraction radius grew up. This could be understood by the higher saturation of the poles produced and could be eliminated by harmonic shims fixed to the pole surface.

The Hall-plates were calibrated against an NMR-probe before and after the measurement. The drift over an 18-month period was found to be small. The principal causes of errors were therefore uncertainty of the last digit of the DVM and fluctuations of magnet current, steering current and temperature, resulting in an absolute accuracy of ± 2 G. By proper averaging and using a reference Hall-plate in a fixed position in the gap during the measurement the relative accuracy was further improved.

Mean B versus Mean R at 1820 Amp, Reg. Pos. + 3mm

(R) (cm)	(B) (T)	E (MeV)	F (MHz)
0	1.97606	0.00	30.127
5	1.97490	.47	30.095
10	1.97056	1.86	29.984
15	1.96304	4.14	29.797
20	1.95456	7.29	29.570
25	1.94725	11.28	29.335
30	1.94121	16.11	29.096
35	1.93565	21.73	28.843
40	1.93028	28.13	28.573
45	1.92528	35.29	28.289
50	1.92086	43.19	27.997
55	1.91708	51.82	27.698
60	1.91361	61.15	27.390
65	1.91018	71.14	27.070
70	1.90669	81.76	26.740
75	1.90330	92.99	26.401
80	1.90021	104.83	26.059
85	1.89747	117.27	25.715
90	1.89504	130.28	25.369
95	1.89282	143.85	25.022
100	1.89068	157.93	24.673
105	1.88851	172.48	24.321
110	1.88619	187.46	23.968
115	1.88377	202.85	23.615
120	1.88131	218.64	23.262
125	1.87888	234.81	22.911
130	1.87649	251.36	22.564
135	1.87412	268.25	22.220
140	1.87176	285.47	21.880
145	1.86927	302.96	21.543
150	1.86653	320.66	21.209
155	1.86345	338.52	20.878
160	1.86010	356.51	20.550
165	1.85662	374.68	20.228
170	1.85311	393.03	19.912
175	1.84956	411.54	19.601
180	1.84589	430.16	19.296
185	1.84211	448.89	18.996
190	1.83833	467.74	18.703
195	1.83477	486.82	18.417
200	1.83179	506.27	18.139
205	1.82888	525.88	17.868
210	1.82507	545.18	17.599
215	1.82118	564.51	17.336
220	1.81806	584.30	17.081
225	1.81511	604.28	16.832

References

1) B. Hedin, Three-Dimensional Potential Functions for Magnet Design, Proc. Int. Symp. on Magnet Technology, Stanford 1965, p.89.

2) M. W. Garrett, An Elliptic Integral Computer Package, ORNL-3575, 1965

3) B. Hedin, Design of CERN Synchro-Cyclotron Magnet, CERN 55-3, p.15

4) N. K. Abrosimov, V. A. Eliseev and G. A. Ryabov, Leningrad, 1967, Device for the Measurement of the Median Plane Position, CERN Trans. 71-5