AN ELECTROMAGNETIC SEPTUM MAGNET FOR THE INJECTION/ EJECTION SCHEME OF THE CELSIUS RING

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1. INTRODUCTION

The Swedish National Accelerator Centre, Uppsala, is presently reconstructing the Synchro-cyclotron machine. At the same time a new storage ring, CELSIUS, is being built for protons and heavy ions with internal targets and electron cooling. Once the rebuilding phase is completed the cyclotron will be used for fixed target physics and also as the injector to the new storage ring [1].

Amongst the partners in the CELSIUS project are the Tandem Accelerator Laboratory and the Gustaf Werner Institute of Uppsala University, the Dept. of Accelerator Technology of the Royal Institute of Technology, Stockholm and the Studsvik Science Research Laboratory. There is also a formal collaboration agreement between CERN and the University of Uppsala.

This agreement extends from using the former ICE bending magnets to collaboration in a number of other disciplines, amongst these being the construction of an electromagnetic septum magnet for the injection-ejection scheme. Because of very similar aperture and bending strength requirements the thin magnetic septum magnet SMH 11 from the CERN LEAR machine has been chosen for this task. This note describes the magnet and gives the important para-meters for both injection and ejection operating modes.

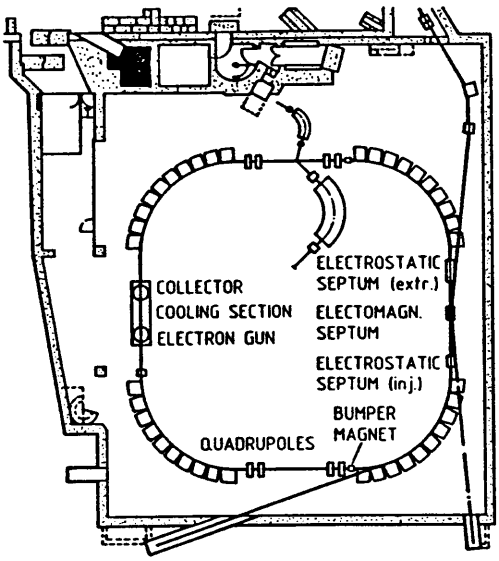


Fig. 1.

2. DESIGN REQUIREMENTS

A scheme has been adopted 2) which combines one magnetic septum with two electrostatic septa, all placed in the same straight section, for both injection and ejection (Figure 1). The magnetic septum, positioned between the electrostatic septa, has an effective length of 85.2 cm. The injection electrostatic septum has a length of 72 cm and the ejection electrostatic septum 150 cm. The maximum particle momentum will be 1.874 GeV/c (ejection) with a corresponding maximum magnetic rigidity of 6.25 Tm. For the required deflection angles in the magnetic septum of 7° (injection) and 3.5° (ejection), magnetic fields of 0.307 T and 0.448 T are needed. In addition a minimum horizontal aperture of 90 mm is necessary at injection.

These design parameters including aperture dimensions, are summarised below in Table 1.

PARAMETER		INJECTION	EJECTION
Maximum particle momentum	GeV/c	0.644	1.874
Magnetic rigidity	Tm	2.148	6.25
Magnetic septum bending angle	degrees	7	3.61
Magnetic field	T	0.307	0.4616
Nominal Magnetic length	mm	852	852
Vertical aperture	mm	54.7	54.7
Horizontal aperture	mm	155	155

Table 1.

3. MAGNET CONSTRUCTION

a) Magnet Core

The magnet core is constructed from laminated steel 1.5 mm thick (Cockerill-type Magnetil BC). The permeability curve is plotted in Figure 2. The magnet core is made in two halves which bolt together through the rear part of the core. This technique enables the magnet to be more easily assembled and permits its removal from the beam line without having to dismantle the vacuum chamber.

During the fabrication the semi-finished half laminations are pressed at 10 Kg/cm^2 whilst the holding and support plates are seam welded on. The final mechanical tolerances are then obtained by machining each of the assembled half cores.

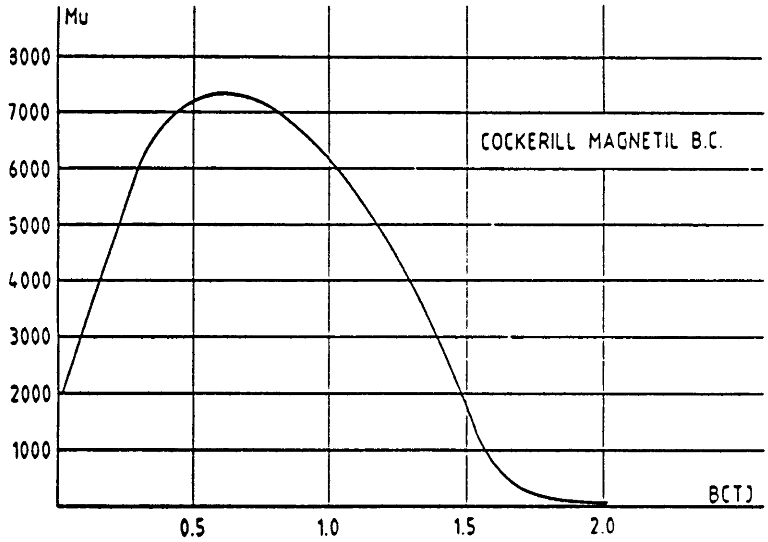


Fig. 2.

The magnet vertical aperture is 54.7 mm giving a half core vertical gap height of 27.35 mm. The manufacturing dimension and tolerance requested is $27.35^{+0.05}_{-0.0}$ mm. After fabrication the measured vertical gap height on the two finished half cores was found to be well within tolerance at 27.38 mm.

b) Magnet Coil

The 10 turn magnet coil is made up from two 5 turn half coils which are connected electrically in series. Copper (OFHC) tubes are used in its construction, the cross-section being as shown in Figure 3. To reduce the overall power loss the electrical resistance of the return conductors is reduced by brazing a solid copper bar to either side of the tube. Figure 4 shows this feature together with the cooled connection point where the two half coils are joined in series.

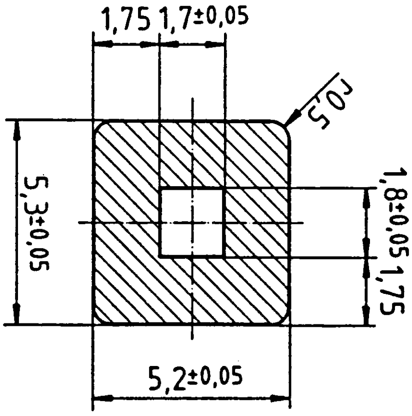


Fig. 3.

A traditional insulation for the individual turns is used. Vetronite strips of 0.2 mm thickness are placed between turns to obtain good positional accuracy. The total half coil is then wrapped with 0.15 mm thick fibre glass tape and placed in a hot vacuum mould for about 12 hours. An Araldite mixture at a temperature of 90°C is injected under vacuum. The half coil and the mould is then kept under vacuum at a temperature of 95° C for about 8 hours after which the temperature is increased to 120°C for 24 hours. The mould with half coil is then removed from the oven and allowed to cool down naturally before opening. This technique [3]) has been developed for the manufacture of multi-turn septum coils which operate outside of vacuum. The accurate dimensions of the inside of the mould ensure a correctly dimensioned, insulated, half coil. The final width obtained for the fully insulated septum blade of the coil is 5.9 mm. Two complete coil sets have been manufactured for this magnet using this procedure.

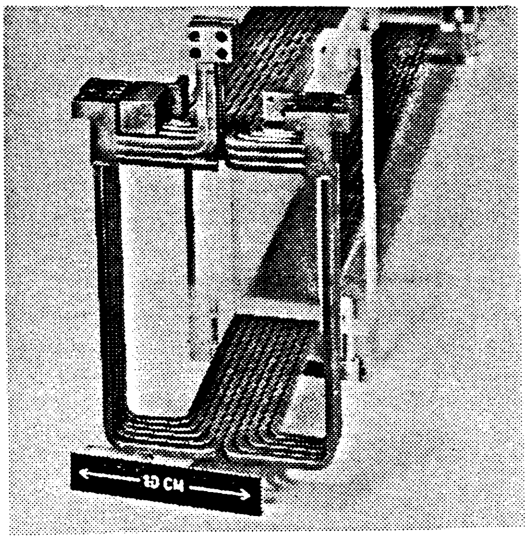


Fig. 4

4. COOLING

Deminereralised water is passed through the central cooling channel in each conductor at high pressure. The cooling uses two parallel paths in each half coil as shown in Figure 5. Water enters at one manifold and splits into the return conductor and septum paths. The output connection is made at the second manifold where the two paths rejoin at the other end of the half coil. The average hydraulic length is about 120 cm.

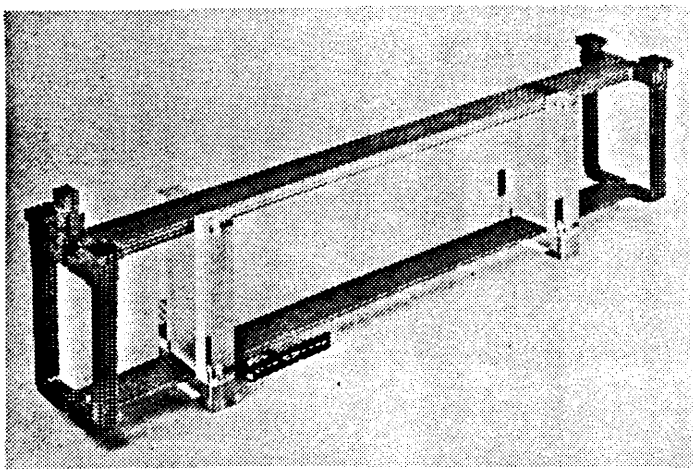


Fig. 5.

During the electrical testing of the assembled magnet the data in Table 2 was taken. The test conditions were with a total water flow of 37 ℓ/min. which was divided between the two half coils in the following manner :

Top half coil 18.2 ℓ/min.

Bottom half coil 18.8 ℓ/min.

The measured pressure drop between the coil ends was 17.4 bars.

I (Amps)	V (Volts)	R (mΩ)	P (kW)
200	2.4	12	0.48
1000	12.1	12.1	12.1
1500	18.5	12.33	27.75
1950	24.8	12.72	48.36
1970	25.1	12.74	49.45

Table 2.

The effect of various differential pressures on water flow in both half coils has been investigated. Changes in ΔP were made from 5.5 to 16.5 bars and the corresponding water flow noted. The results shown in Figure 6 are for both coils Nos. 1 and 2.

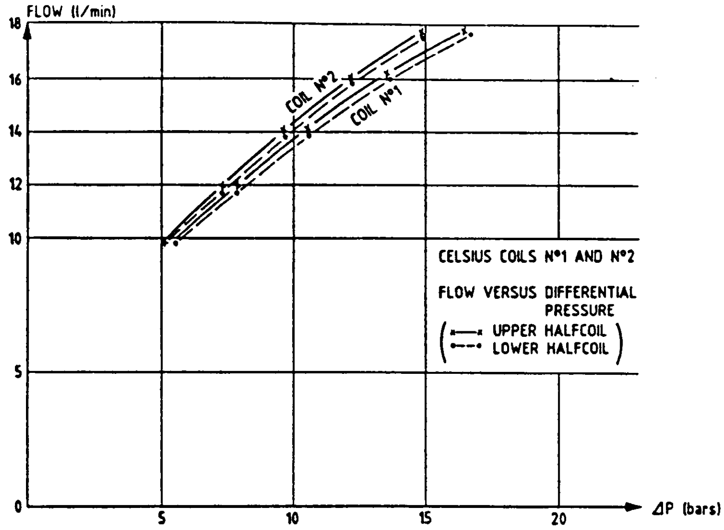


Fig. 6.

Cooling tests were conducted for both coils using a nominal differential water pressure ΔP of 12.5 bars. The results of these tests are given below in Table 3.

TEST PARAMETER		COIL 1	COIL 2
Coil current	Amps	1950	1940
Input water temp.	°C	22.5	23
Top half coil water ΔT	°C	19.5	15
Bottom half coil water ΔT	°C	19.5	15
Top half coil water flow	ℓ/min.	15.4	16.4
Bottom half coil water flow	ℓ/min.	15.7	16.0
Ambient temp.	°C	21	21.5
Magnet core temp. (after 2 hrs.)	°C	35	33
Connection terminal temp.	°C	36.5	37
Upper coil terminal bar temp.	°C	42	46
Lower coil terminal bar temp.	°C	56	50
Interconnection block temp.	°C	44	27
Max. coil copper temp.	°C	51	52
Min. coil copper temp.	°C	28	26

Table 3.

5. ELECTRICAL DATA

Shown below in Table 4 are the important parameters which have been calculated for the septum magnet in both injection and ejection modes.

PARAMETER		INJECTION	EJECTION
Maximum particle momentum	GeV/c	0.644	1.874
Deflection angle	mrad	122.17	63.0
Magnetic field	T	0.307	0.462
Coil current	Amps	1336.6	2009
Septum conductor current density	A/mm^2	54.55	82.02
Input water temp.	°C	20	20
Differential water temp. ΔT	°C	20	20
Nominal water flow	ℓ/min.	16.2	36.5
Magnet dc power	kW	22.5	50.9
Maximum copper temp.	°C	55.1	51.5
Minimum copper temp.	°C	28.4	28.7

Table 4

The measured inductance of the assembled magnet was found to be L = 263 μH at 1 KHz.

The calculated temperature gradient over a 120 cm cooled septum conductor with a current of 2009 Amps is shown in Figure 7 and is to be compared with the measured values in Table 3.

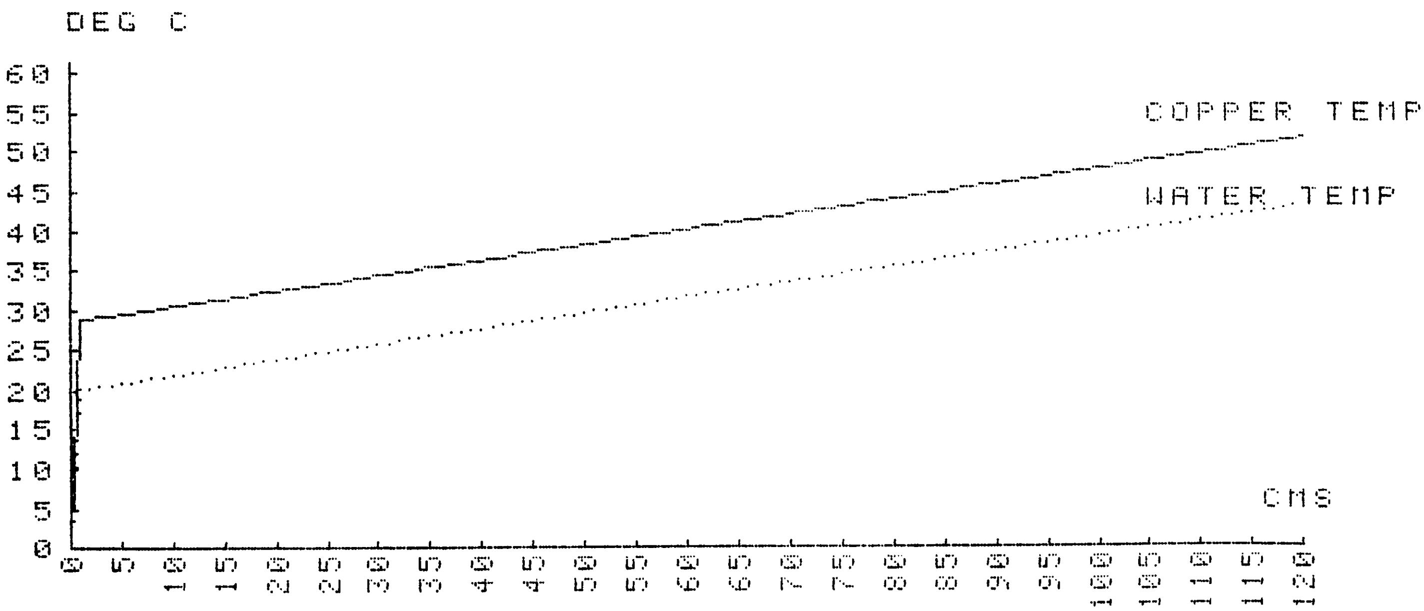


Fig. 7.

6. MAGNET PROTECTION

This is the thermal protection built onto the magnet coil and does not include the external, and necessary, water flow detection and measurement.

Each turn of the coil has fitted at the water output end, two calibrated and sealed thermoswitches which protect the septum and return conductor tubes. These switches are in thermal contact with the copper and open when their body temperature reaches 80°C. The twenty thermoswitch contacts, Figure 8, are connected via in-line sockets to a 48 pin Burndy socket on the magnet plexiglass cover.

The normally closed contacts are series connected and used as an interlock for the dc power supply. Tests have been made on each coil to check the correct functioning of these thermoswitches. The test conditions for coil No. 2 were the following :

Magnet current 1750 A

Copper temp. T = 50°C

Water $\Delta P \approx$ 10 bars

Flow = 15 ℓ/min.

The thermoswitches operated when the flow was reduced to 11 ℓ/min.

In addition to the temperature protection there is installed, integral with the plexiglass rear cover, a water leak detector. Any water leaking out of the cooling distributor blocks or water cooled power cables is trapped in the bottom of the detector and activates a switch contact. This contact is also connected via the Burndy socket to the interlock equipment of the power supply and to the electromagnetic inlet cooling water valve.

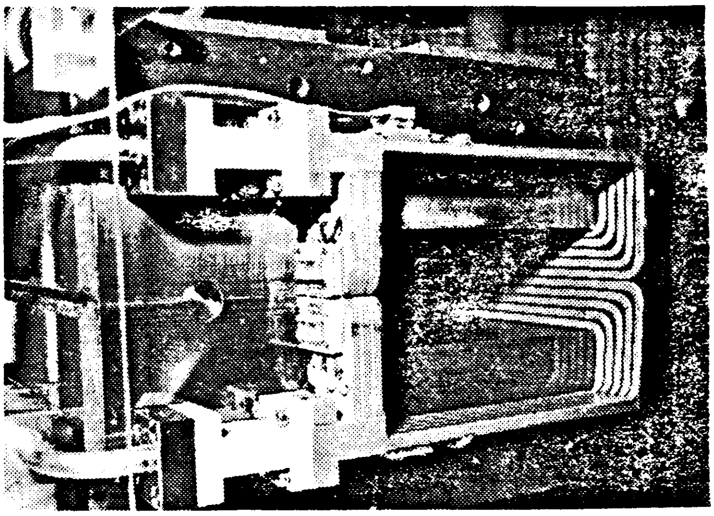


Fig. 8.

7. MAGNETIC MEASUREMENTS

All measurements were made on the median plane of the magnet using either a gaussmeter with a Hall probe or an integrating voltmeter and two 1.3 m long coils.

The two coils were mounted on a support frame with mechanically coupled drive spindles so as to obtain simultaneous rotation of 180°. The distance between their central axes was 17 mm, and their total surface areas (known from a previous calibration to a precision of 10^{-4}) were 2.5785 and 2.5674 m^2.

The coils were connected in series opposition to a PREMA 5055 integrating voltmeter. The radial field variation ΔB_x, at increments of 17 mm on the horizontal median plane, was measured (see annexe 1).

Using a single 1.3 m long coil, the integrated value of the stray field on the median plane outside the magnet gap was measured and compared to the integrated field on the gap centre axis. In both cases, the integration was made over a total lênqth of 1300 mm, sufficient to fully include the end effects of the 900 mm long magnet. The precision of measurement for the absolute field values was of the order of $\pm 2.10^{-3}$ whilst for the relative measurements $< 10^{-4}$ was obtained. The spot values obtained with the gaussmeter and Hall probe were accurate to within 10^{-2} for the absolute values and $< 10^{-3}$ for the relative value measurements.

Because of the similarity between the CELSIUS and the original LEAR SM 11 magnets only control measurements of important parameters were made. These were compared to the original measurements (4) and are reproduced in Figures 10 to 13. The measured field values at the nominal operating current of 1940 Amps, (for ejection at a maximum particle momentum of 1.874 GeV/c), are given in Table 5. The stray field measurement was made with the mu-metal screen (1.5 mm) in position.

PARAMETER		VALUE
Magnet current	A	1940
Field at gap centre Bo	T	0.4590
Integrated stray field at 25 mm	‰	1.03
Magnetic length	m	0.8472
Bending strength	T.m	0.3846
Deflection constant	mrad/A	0.0313

Table 5

8. SUMMARY

A complete magnet, including spare coil, has been made, tested and measured in CERN for the CELSIUS ring at Uppsala. The finished magnet is shown in Figure 9 below. The installation date for the magnet at the Swedish National Accelerator Centre will be September 1986. This date coincides with the availability of the dc power supply and water cooled cables together with magnet support frame and vacuum chamber supplied by the CELSIUS team directly.

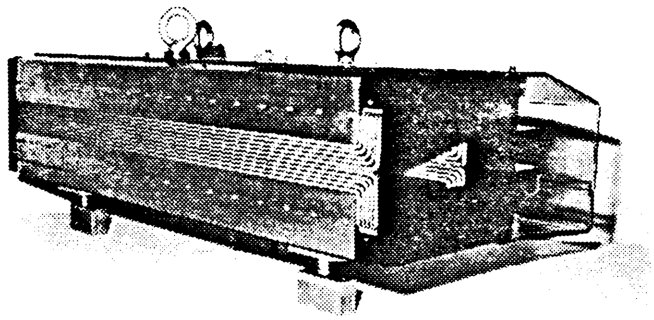


Fig. 9.

REFERENCES

1. Status of CELSIUS, A Johansson, D. Reistad, Celsius Note 84-42.

2. Private communication, D. Reistad.

3. Technique de la construction des bobines multi-spires pour les aimants à septum EPA, G. Berardi, PS/BT/Note 84-12.

4. Measures magnétiques des aimants à septum Lear SM11 et SM12, B. Boileau, PS/BT/Note 82-10.

Distribution :

Celsius Team
BT Group
R. Billinge

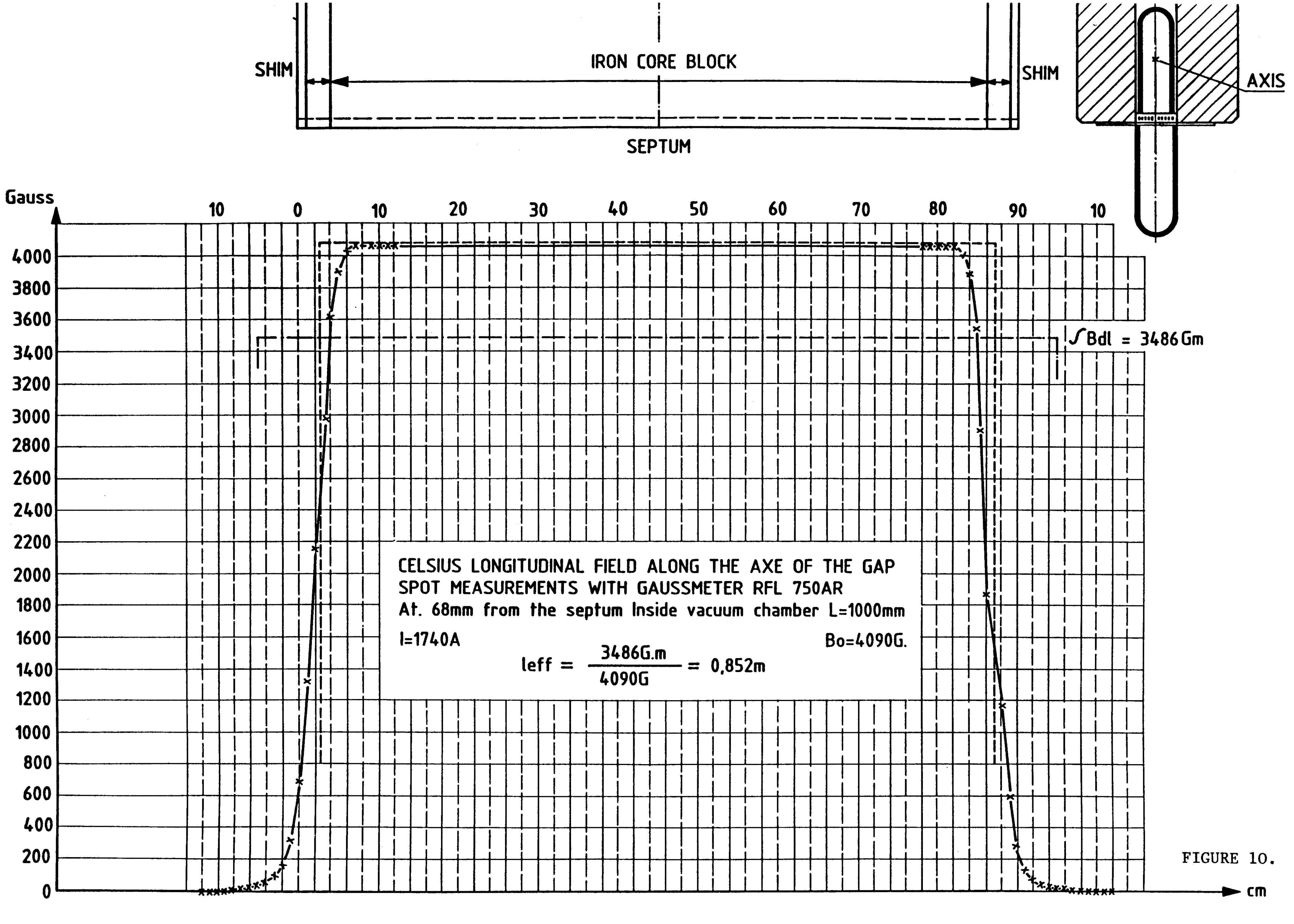
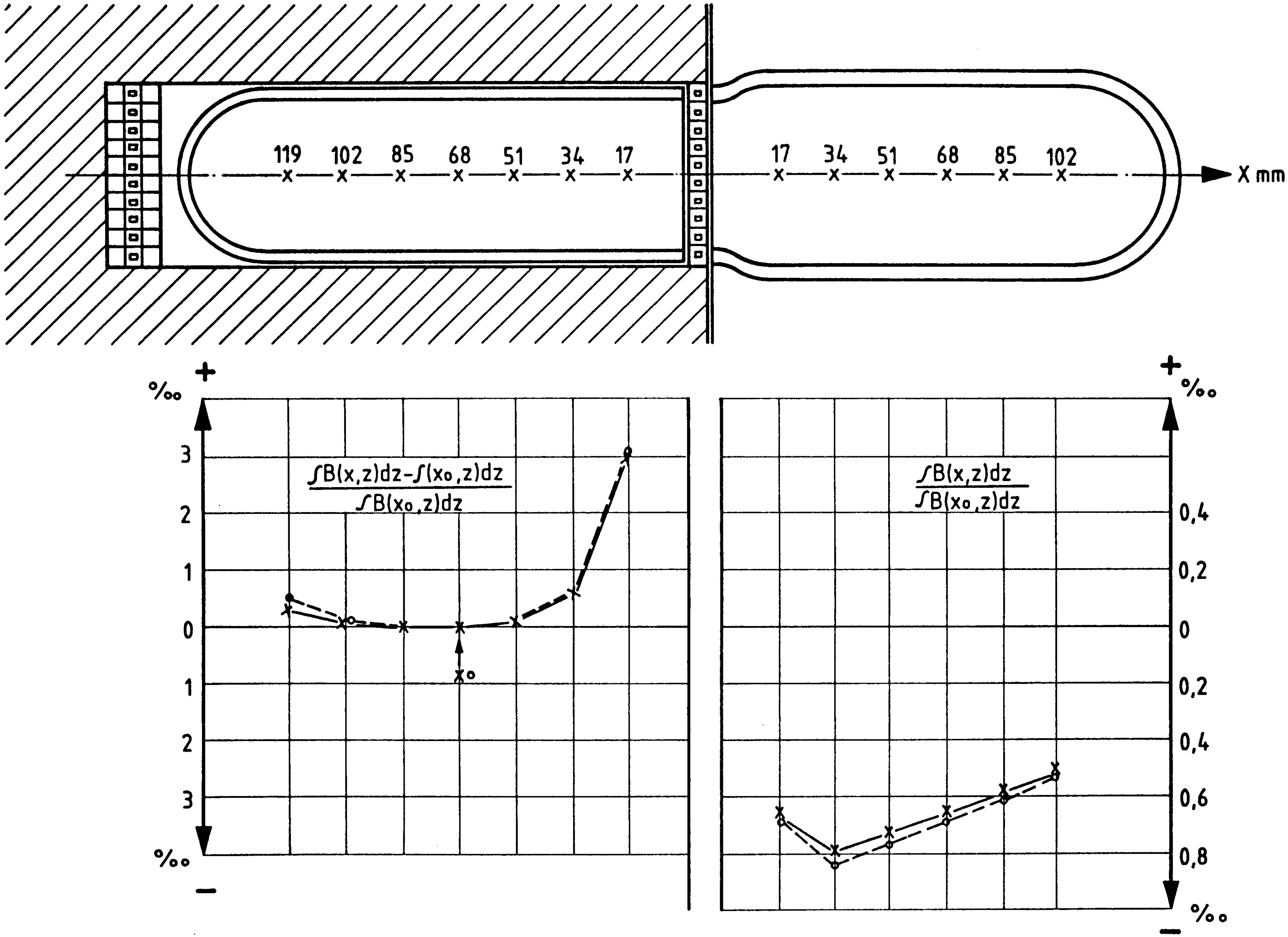

SHIM
IRON CORE BLOCK
SHIM
AXIS
SEPTUM
Gauss
cm
10
0
10
20
30
40
50
60
70
80
90
10
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
∫Bdl = 3486 Gm
CELSIUS LONGITUDINAL FIELD ALONG THE AXE OF THE GAP
SPOT MEASUREMENTS WITH GAUSSMETER RFL 750AR
At. 68mm from the septum Inside vacuum chamber L=1000mm
I=1740A
Bo=4090G.
leff = 3486G.m / 4090G = 0,852m

FIGURE 10.



CELSIUS - TRANSVERSAL VARIATION OF INTEGRATED FIELD I=1740A Bo=4090G

MEASURED WITH COILS L=1300mm Inside vacuum chamber L=1000mm

FIGURE 11.

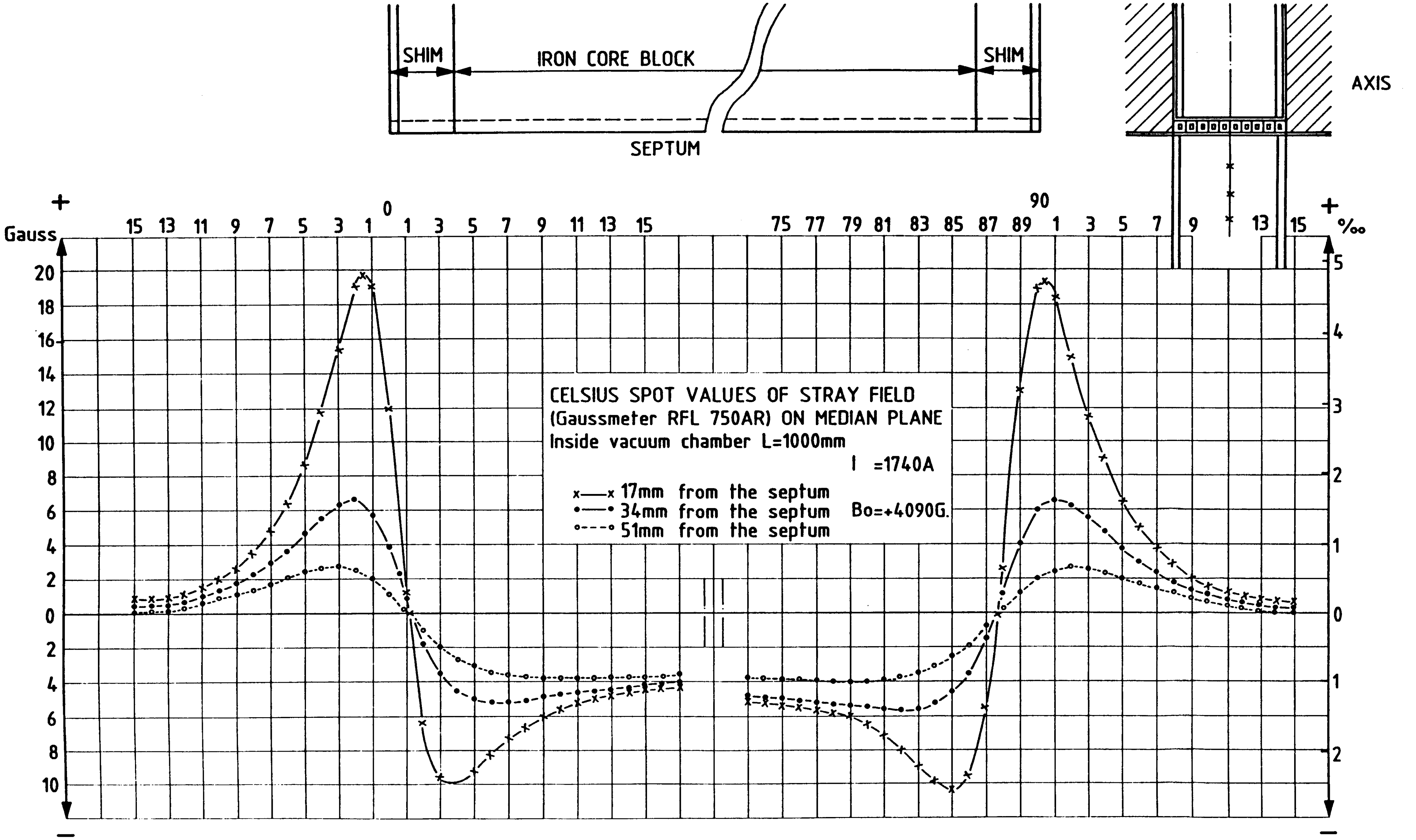

SHIM
IRON CORE BLOCK
SHIM
SEPTUM
AXIS
CELSIUS SPOT VALUES OF STRAY FIELD
(Gaussmeter RFL 750AR) ON MEDIAN PLANE
Inside vacuum chamber L=1000mm
I =1740A
17mm from the septum
34mm from the septum
51mm from the septum
Bo=+4090G.
Gauss
‰
0
90
15 13 11 9 7 5 3 1 1 3 5 7 9 11 13 15
75 77 79 81 83 85 87 89 1 3 5 7 9 13 15
20 18 16 14 12 10 8 6 4 2 0 2 4 6 8 10
5 4 3 2 1 0 1 2
+
−

FIGURE 12.

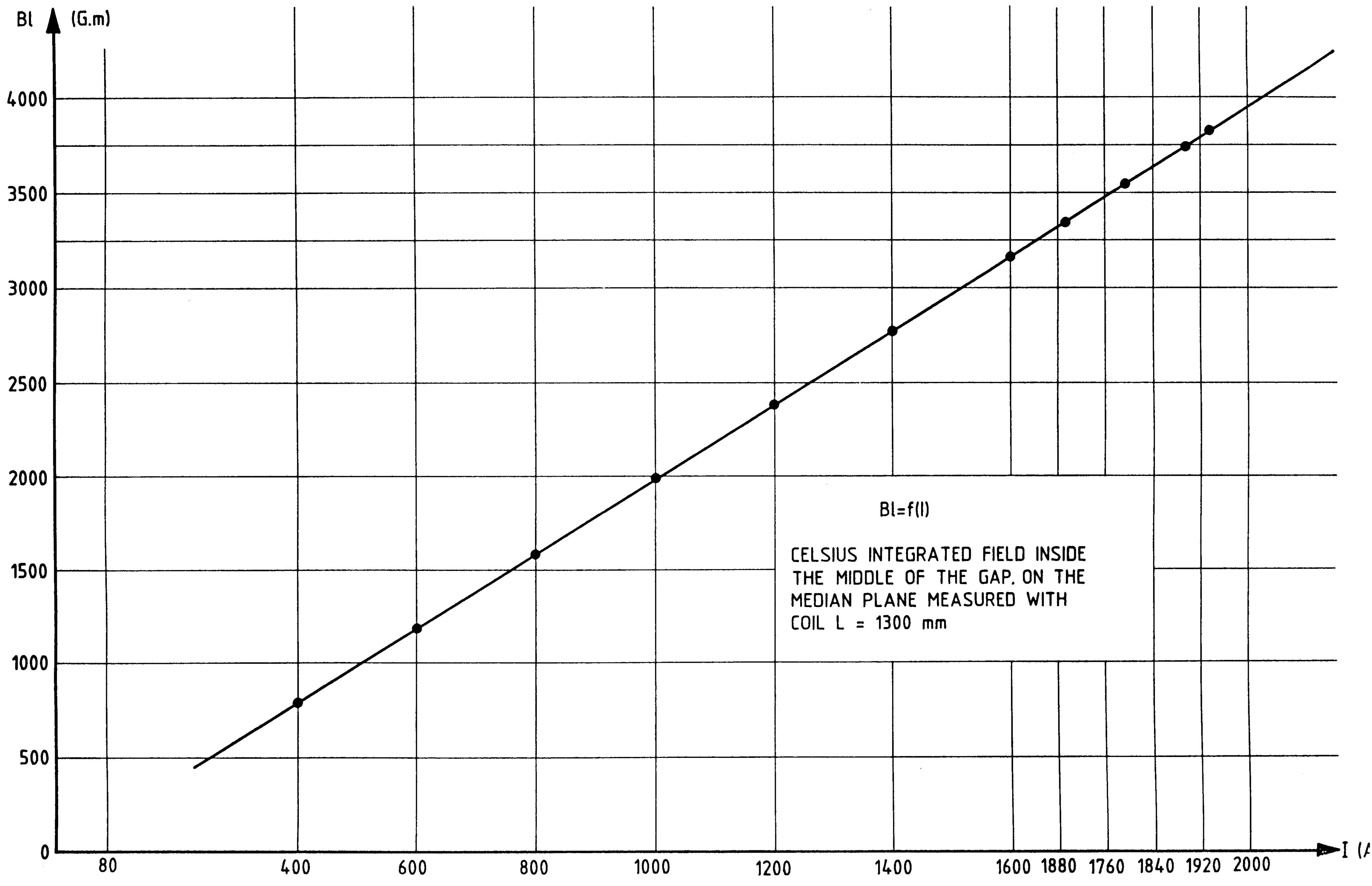
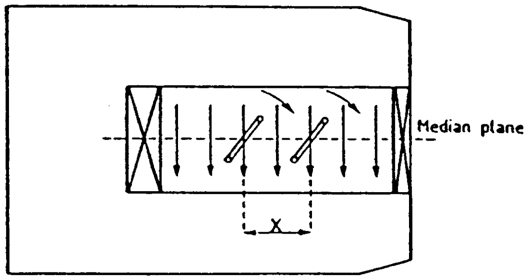

Bl (G.m)
4000
3500
3000
2500
2000
1500
1000
500
0
80
400
600
800
1000
1200
1400
1600
1880
1760
1840
1920
2000
I (A
Bl=f(I)
CELSIUS INTEGRATED FIELD INSIDE
THE MIDDLE OF THE GAP, ON THE
MEDIAN PLANE MEASURED WITH
COIL L = 1300 mm

FIGURE 13.

ANNEX 1

The use of two mechanically coupled long coils for measuring the radial gradient field of a dc powered magnet is fairly common. The total surface area of both coils must be known to a certain precision as well as the distance between the axes of the coils.



S_1 and S_2 = surface areas of the two coils

and $S_1 = A_1 N_1$

$S_2 = A_2 N_2$ where A = area of one turn

N = number of turns per coil

Then on turning the coils through 180° in a magnetic field of flux density B a voltage will be induced in each coil.

$$\int_0^{\pi} e\,dt = N \int_{-\phi}^{\phi} d\phi$$

Since ϕ = BA then $\int edt$ = 2 BS and the gradient field over the distance X mm = ΔB_X derived from the two coil signals connected in series opposition.

$$\Delta B_X = \tfrac{1}{2} \int \frac{e_1}{S_1} - \frac{e_2}{S_2} \quad dt$$

For practical reasons both coils are made with very similar surface areas, so that $S_1 = S_2 = S$ and $\Delta B_X = \frac{1}{2S} \int (e_1 - e_2)\,dt$. The resulting signal is measured directly with an integrating voltmeter.

The accuracy of measurement is not affected by the speed of rotation of the coupled coil assembly, however the integrating voltmeter must be capable of following.