THE GANIL MAGNET

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Summary:
Two series of four sector magnets are presently under construction for the SSC1 and SSC2 which are the heart of the GANIL system. Each sector, weighing about 425 tons, is a C yoke magnet with 100 mm gap and 5 square meters pole area.

The last model measurements, the steel quality, the coils design and the technological aspect of the construction are mainly presented.

More than 2,000 tons of steel are already cast, the machining has begun and the first sector will be delivered in February 1979.

1. Introduction

1.1. The GANIL system

See the description in the status report(1).

1.2. Field configuration of the cyclotrons

Each cyclotron has four separated sectors of 52 degrees. The gap is 100 mm. The magnet must keep its properties in the range of 0.65 T to 1.65 T and the average magnetic field along the local isochronous orbit must be proportional to the right γ value in the useful area defined by injection and extraction equivalent radii. (R_i = 857.2 mm; R_S = 3 000 mm). Beyond these values the pole tips have been extended 2.7 and 3 gap-lengths, respectively.

The four sector magnets will receive side shims giving a γ = 1.00 field map for SSC1 and a γ = 1.05 field map for SSC2. To adjust the field for any γ value (from 1.00 up to 1.05 in SSC1 and from 1.05 up to 1.10 or down to 1.00 in SSC2) a set of pole face windings, called trim coils, will be used.

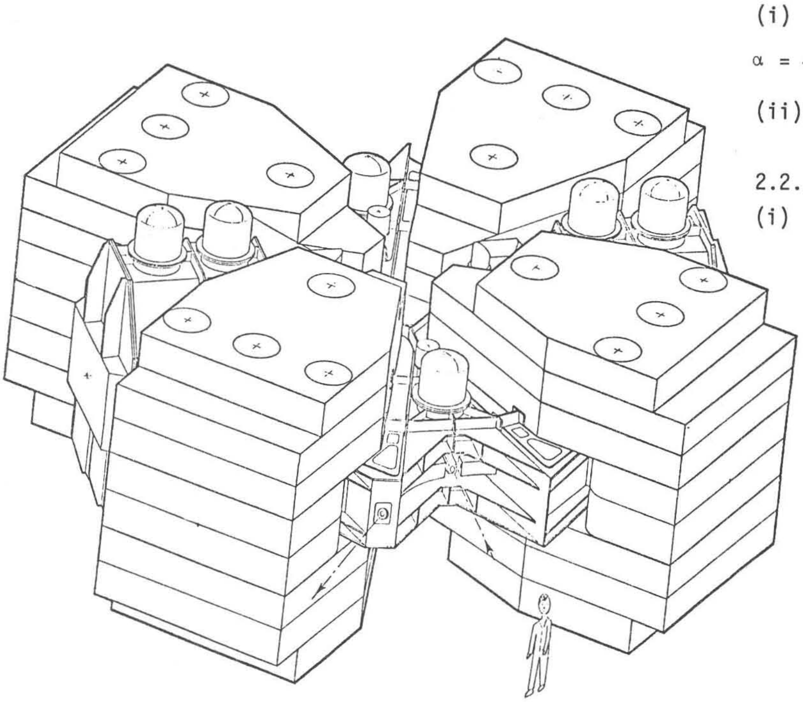

Figure 1. Isometric view of one of the GANIL separated sector cyclotrons: sector magnets and vacuum chamber.

2. Studies

2.1. General

As a result of the magnet cost optimization (steel + coils + 10 years operation), the induction in the iron has been taken equal to its value in the gap:

$$B_f = B_a \quad (1)$$

We have also chosen to make equal the magnetic and mechanical angles of the sectors at any level:

$$\theta_{mag} \simeq \theta_{mech} = 52^o \quad (2)$$

This coincidence avoids additional flux, simplifies the positioning problem and gives to the 3D magnet a behaviour not too far from the cylindrical 2D approximation calculated by the POISSON code.

As a consequence of these two choices (1) and (2), the surface offered to the flux lines is everywhere roughly equal to the pole area (see figure 2).

Although the yoke is not very saturated, the field level and field map are strongly dependent on the iron, due to:

(i) the high value of the ratio:

$$\alpha = \frac{L_f}{e} \quad \frac{\text{path length in the iron}}{\text{gap height}} \quad \frac{10.m}{0.1m} = 100. \quad (3)$$

(ii) the very large pole surface: S = 5.m2 for a gap height of 0.1 m.

2.2. The two effects of iron permeability dispersion

(i) dispersion on field level: this effect, due to the difference of the $\mu(B)$ curves between magnets, has been calculated both with the POISSON code (one material for the whole magnet) and by an analytical method which gives:

$$\frac{\Delta B}{B} = \frac{\alpha}{\mu r} \cdot \frac{1}{1 + \alpha/\mu_r} \cdot \frac{\Delta \mu_r}{\mu_r} \quad (4)$$

(See eq. (3) for definition of α).

From magnet to magnet $\Delta B/B$ is typically 1.10^{-2} at 1.6 T.

(ii) dispersion on field map: this effect is due to the dispersion inside the pieces and has been computed by the POISSON code (different $\mu(B)$ curves in different regions of the magnet).

For a dispersion of $\Delta B = 200.10^{-4}$ T in the poles at H = 12 000 A/m the defect can be $\Delta B/B = 1.5\ 10^{-3}$ in the gap.

So the poles, which are also acting as filters for the yoke defects, need to be very homogeneous and very low dispersed pieces.

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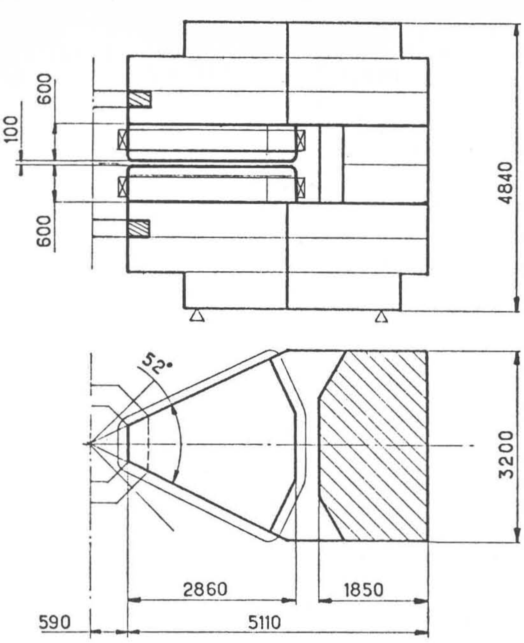

Figure 2. Magnet dimensions.

2.3. Model measurements

2.3.1. Model configuration

A magnetic model of the cyclotron has been set up in Caen. It consists of two 0.25 scale models of the sector and two half-magnets, so-called "noses," which allow simulation of the center (see figure 3).

The field is measured by 25 Hall probes (see figure 4).

The B versus I curve has been measured and the iron saturation at a level of 1.65 T is only 12.8%.

Two rings being necessary to reinforce radially the vacuum chamber, we measured the field with soft iron pieces present in the valleys, just over the coils. The perturbation was only 3.10^{-4} T in the mid plane.

2.3.2. Trim coils measurements

One model has been supplied with 72 trim coils conductors of 2.5 x 6.3 mm2 with a 9.1 mm step. They were wound as coils type B (see figure 10).

We have obtained a "γ = 1.10" field with 10 currents calculated by a 2D code from the following data:

. the measured average field curve
. the conductors' size, positions and connections
. a magnetic efficiency of coils equal to 0.85.

The average field B_{GHE} is calculated along the equivalent Gordon trajectory:

$$B_{GHE} = \frac{1}{S_1 - S_0} \int_{S_0}^{S_1} B(S)\, dS$$

The relative field defect is plotted on figure 5.

In obtaining the experimental result the main difficulty was to adjust the current in the main coil.

2.3.3. Side shims measurements

The model B can receive removable side shims (see figures 3 and 8). We have tested the two configurations foreseen for SSC1 (γ = 1.00) and SSC2 (γ = 1.05) (see figure 6). These shims are flared up in order to compensate the field drop in injection and ejection radii.

The proximity of the HF resonator obliged us to hollow the shim entirely inside the magnet.

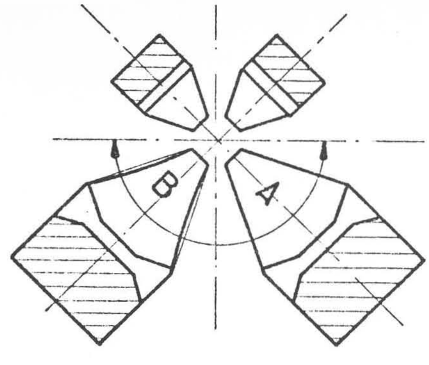

Figure 3. The model configurations: models A, B (with side shims), noses.

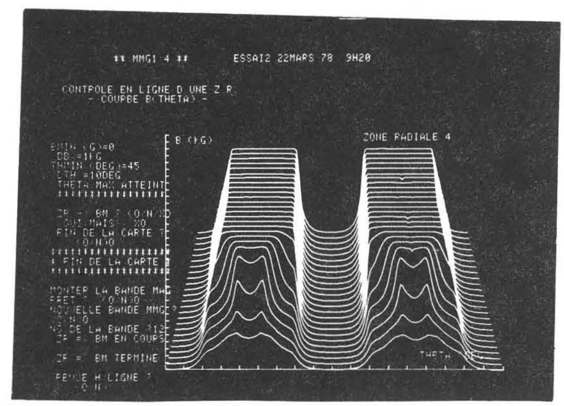

Figure 4. On line visualisation of measurements models A and B.

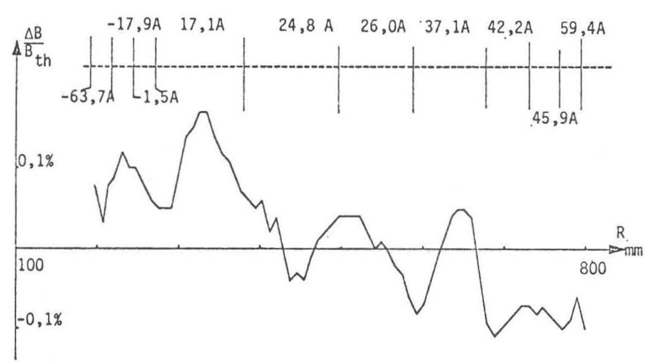

Figure 5. Model measurements with trim coils. 10 currents. Relative field defect in the case of a γ = 1.10 isochronism law.

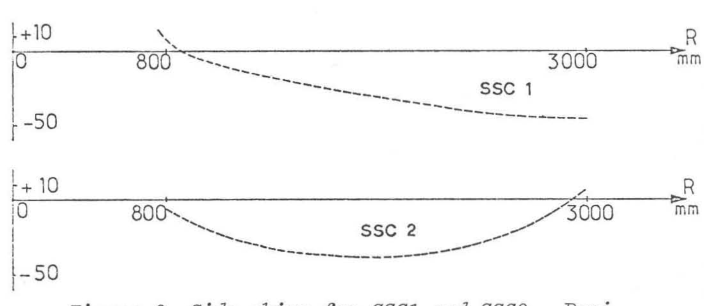

Figure 6. Side shims for SSC1 and SSC2. Position of the shim versus radius (relative to the side of the magnet).

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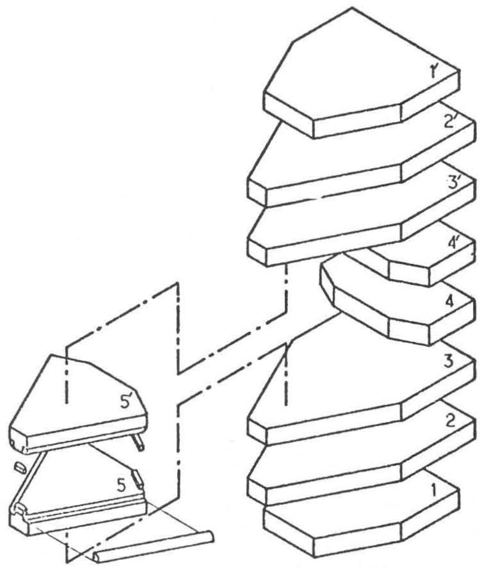

Figure 7. Mechanical structure.

3. Full scale realization

3.1. Cutting of the magnet

Each sector, weighing 425 tons, has been divided into 10 pieces by horizontal cutting (see figure 7).

3.2. Steel quality

3.2.1. The yoke material:

The steel of the different pieces of the yoke is coming from vacuum cast ingots. The ingots are first precrushed with a press and then rolled (average thickness of the pieces 600 mm). The measured characteristics of the first 28 yoke pieces are presented in table 1.

Table 1: Steel of the yokes. Measured characteristics (m: mean value; σ: standard deviation)

Locating (See fig.7)		1-1'	2-2'-3-3'	4-4'	Total
Number of pieces for 8 sectors		8x2	8x2 and 8x2	8x2	64
Already tested		8	12	8	28
Weight of the piece		48 T	57 T	28 T	3040 T
Weight of the ingot		85 T	116 T	67 T	6144 T
Carbon content %	m	0.050	0.053	0.050	0.052
	σ	0.003	0.006	0.009	0.007
B at H = 800 A/m	m	1.3665	1.3442	1.3837	1.3619
	σ	0.0271	0.0201	0.0096	0.0258
B at H = 13,000 A/m	m	1.8897	1.8866	1.8877	1.8878
	σ	0.0017	0.0017	0.0040	0.0027

3.2.2. The poles material

The poles are forged using vacuum cast ingots. The carbon content is 0.015%. We have measured the curve B(H) on 10 ring samples ($\emptyset_i$ = 76 mm, $\emptyset_e$ = 114 mm, e = 15 mm) coming from one pair of poles. See table 2.

Table 2: Steel of the poles. Measured characteristics ($\overline{B}$: mean value; σ_B: standard deviation).

H	240	800	1250	3000	8000	13000	19000
B	1.2848	1.5627	1.6098	1.6922	1.8192	1.9074	1.9878
σB	0.1261	0.0211	0.0096	0.0022	0.0007	0.0005	0.0004

3.3. Mechanical design

The mechanical structure of the magnet is a simple pile of 10 pieces without any bolts between them. The magnet will be assembled just by stacking parts.

A gap of 10 mm is managed between each pole and the corresponding yoke. Through this gap passes a skin which is a part of the vacuum chamber. See figure 8 (1).

At three points of this skin are mechanical devices (see figure 8 (1)) composed of:

- . bellows giving the necessary flexibility between magnets and vacuum chamber;
- . plates transmitting the forces;
- . vertical pins with tightness.

The thickness of the plates will be adjusted to bring the pole complex and the return yoke to exactly the same height.

The useful gap is defined by three spacers cut along the mid plane. The spacer halves are bolted definitely to each pole, the coaxiality between poles will be obtained by horizontal pins between these two halves. See figure 8 (2).

Specified tolerances are 0.05 mm for planarity and 0.1 mm for parallelism of the poles surfaces.

The magnetic forces (attraction between the poles is 600 tons) will induce spacers' compressions: 0.08 mm on front spacer and 0.06 mm on rear ones.

3.4. The main coils and their vacuum-tight boxes

The main coils of the four sectors of one cyclotron are supplied in series, equalizing coils (± 2%) being excited separately:
(the electrical data of the main coil are: number of turns: 56; hollow conductor size: 20 x 20 mm^2; hole: Ø.11 mm; maximum current: 1850 A; power: 120 kW; cooling water flow: 10 m3/h).

The coil is classical but for vacuum reasons, it must be set in a vacuum-tight stainless steel box which will be soldered after impregnation. See figure 8 (1).

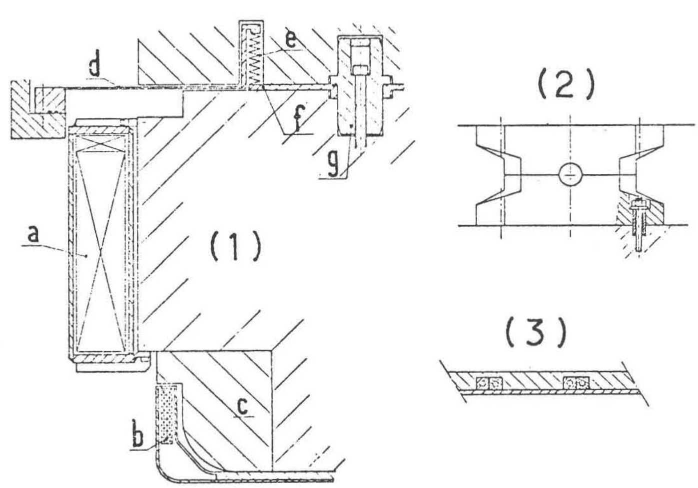

Figure 8. (1) View of the pole showing (a) main coil; (b) trim coils; (c) side shim; (d) skin; (e) bellows; (f) plate; (g) vertical pin; (2) the front spacer with horizontal pin; (3) conductors of trim coils in their casing.

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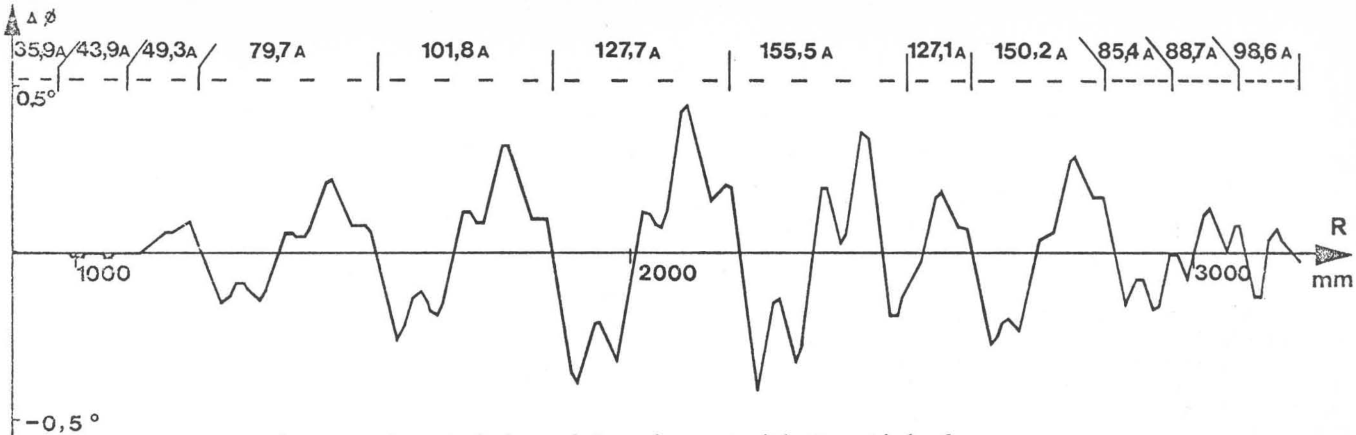

Figure 9. Computed phase defect in SSC2 with 12 optimized currents.

3.5. <u>The trim coils and their vacuum tight casings</u>

Each pole face winding has 32 coils (see figure 10):

. 5 coils, of one turn, type N, for correction of injection defects
. 6 coils of one turn, type B, for correction of sector to sector differences and ejection defects
. 21 coils of two turns, type I, called "isochronism coils" supplied in series from sector to sector and used to adjust the field shape.

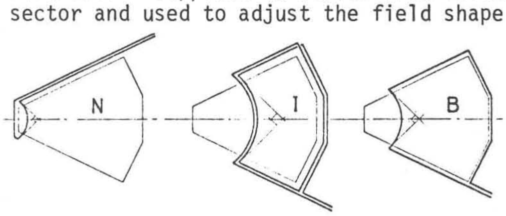

Figure 10. The three types of trim coils.

53 conductors are so taking place in a half gap. They are following the equivalent trajectories "Gordon Hard Edge."

Each coil has electrical inlet and outlet to permit any desired series connection. The maximum intensity is 200 A. For one sector the power consumption is 2 x 12 kW and the average temperature elevation is 10°C.

Each pole face winding uses 565 m of a conductor manufactured by Pyrotenax with the following parameters:

outer dimensions: 8×8 mm central conductor: 6×6 mm²
coating thickness: 0.46 mm cooling hole: 2.5 × 2.5 mm²
insulation thickness: 0.70 mm

After shaping the pole face windings will be enclosed in vacuum tight casings to ensure insulation from the machine vacuum. The casings are subjected to an internal pressure equal to atmospheric pressure. They are made of a plate and of a closing welded upon it. See figure 8 (1) and (3).

3.6. <u>Computed phase defect in SSC2</u>

To illustrate the trim coils design we have plotted the phase defect computed in the SSC2 case:

$$\Delta\phi(R) = 0.05\int_{R_i}^{R} \frac{B(r) - B_{iso}(r)}{B_{iso}(r)}\, r dr \qquad (6)$$

12 currents are supplying the 21 coils, type I, to adjust the field from a perfect γ=1.05 law to a γ=1.10 law. The defect is less than one degree but the case is not realistic.

4. <u>Full scale magnetic measurements apparatus for the SSC</u>

The magnetic field will be measured in the gap mid plane by 90 Hall probes. The device will cover the radial extent from 740 mm to 3220 mm and the azimuthal extent 0° - 360° with a step of one degree.

The Hall probes are Siemens SBV 601-S. They are stabilized at a temperature of 35 ± 0.1°C and preliminarily calibrated (7th order polynomial approximation). The Hall voltage will be measured by a Schlumberger Solartron 7075 voltmeter (time constant: 200 ms).

The measuring arm is mounted on a movable ring displaced, step by step, by a pneumatic device. The position is given by machined groves and read by a pneumatic sensor. See Figure 11.

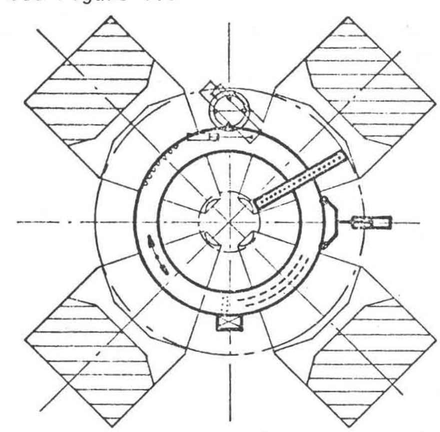

Figure 11. View of the magnetic measurement apparatus.

The whole system (displacement, data acquisition and treatment) will be controlled by a Mitra 125 computer).

5. <u>Time schedule</u>

A contract for the fabrication of 8 magnets including study, steel, maching, main coils, mechanical tests under field and assembling on site was awarded in 1977 to the Société Alsthom Atlantique (Belfort).

The first sector called prototype will permit detailed mechanical tests in the constructor's workshop on January 1979.

The sectors will be delivered in Spring 1979 for first assembling of the machine and magnetic measurements.

<u>Acknowledgements</u>

The authors would like to acknowledge all members of the magnet group for their essential contribution to the presented work.

<u>References</u>

(1) Status Report on GANIL presented by J. Fermé. Same Proceedings.
(2) Internal reports on iron dispersion, trim coils, calculations and model measurements are available.