A LARGE 100 MW PULSED MAGNETIC COIL FOR FUSION RESEARCH

M. Huguet, P. H. Rebut, and A. Torossian
ASSOCIATION EURATOM-CEA SUR LA FUSION
Département de Physique du Plasma et de la Fusion Contrôlée
Centre d'Etudes Nucléaires
Boîte Postale No. 6, 92 FONTENAY-AUX-ROSES (France)

M. Meier
Société OERLIKON

Abstract

The main toroidal magnet for the TFR fusion device which is now being assembled at Fontenay-aux-Roses is described. The magnet consists of a 98 cm major radius and 30 cm minor radius torus. It is composed of 24 oil-cooled Bitter-type coils. Each coil consists of 35 turns of full-hard copper insulated with kapton The total weight of the 24 coils is about 20 tons. A center-line field of 60 kG is generated with a current of 35 000 A. The field corrugations along the center line do not exceed 0.5%. With a peak power input of 120 MW and for a mean pulse length of 1.5 sec, the energy delivered to the magnet during one pulse is 150 MJ, and the magnetic energy stored is 40 MJ. The repetition rate is one pulse every 4 minutes.

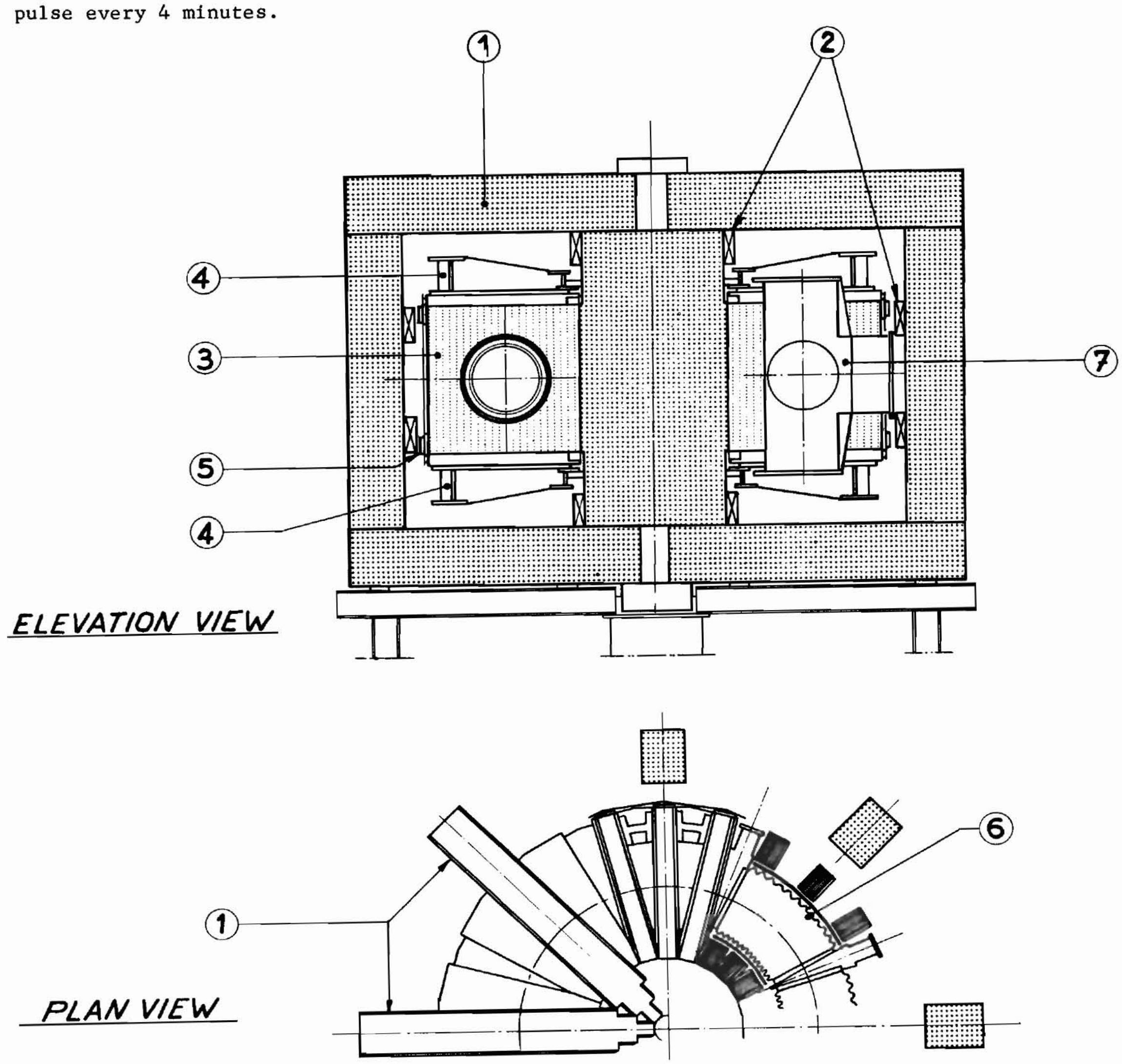

Fig. 1. Plan and elevation view of TFR. Legend: 1: Magnetic circuit; 2: Poloidal coils; 3: Toroidal coils; 4: Positioning plates: 5: Precompression hoops; 6: Vacuum vessel; 7: Observation ports.

I. Description of the TFR Device

The TFR fusion device which is now being assembled at Fontenay-aux-Roses belongs to the Tokamak family. Tokamak devices have been developed in the USSR and have produced the closest approach until now to parameters needed for a controlled thermonuclear reaction.

A general view of the TFR device is shown on Fig. 1. TFR is a transformer, the secondary of which is the plasma. Primary coils (B_θ coils) initiate the gaseous discharge in the toroidal vacuum chamber, and induce a large current in the plasma. By ohmic heating, the temperature of the plasma rises, and by pinch effect, the plasma is confined. However the confinement is unstable and a strong toroidal magnetic field is required to counteract the instabilities. TFR is mainly composed of:

- a vacuum system (toroidal chamber; observation port and pumps),
- a transformer (poloidal coils; a magnetic circuit is used to improve the coupling between the poloidal coils and the plasma),
- a toroidal winding for stabilization.

This paper describes the stabilizing winding.

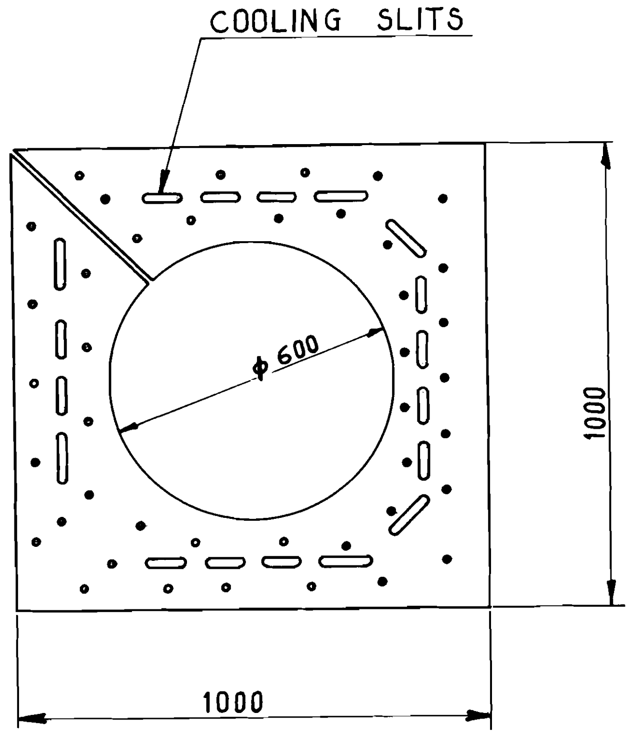

Fig. 2. Plate of copper.

TABLE I. Basic parameters of the TFR device

Plasma major radius	0.98 m
Plasma minor radius	0.20 m
Maximum expected current in the plasma	400 kA
Maximum duration of the plasma current pulse	0.5 sec
Expected mean plasma temperature	1 keV
Total weight of the magnetic circuit	48 tons
Toroidal field	60 kG

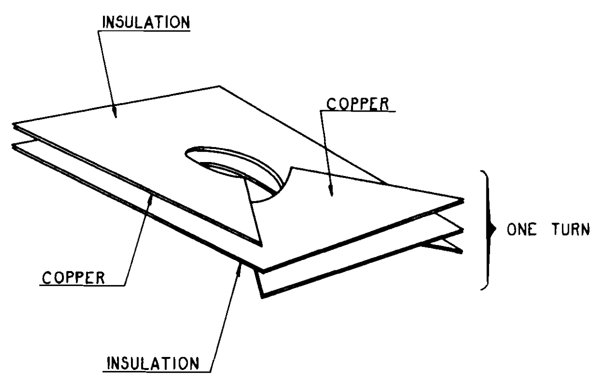

Fig. 3. Stacking mode for one turn.

II. Description of the 60 kG Toroidal Magnet

The magnet consists of a 98 cm major radius and 30 cm minor radius torus. It is composed of 24 oil-cooled Bitter-type coils. Each coil consists of 35 turns of full hard copper containing 0.07% silver. The yield limit for full hard copper is 28 kg/mm^2. The presence of silver raises the tempering temperature of copper. Each turn is insulated with polyimide sheets. A turn utilizes two copper plates and two insulator sheets stacked to form a double copper helix and a double insulator helix. The stacking mode is shown on Fig. 3. Each coil is clamped between two high resistance aluminum alloy plates, by means of insulated bolts and spring washers. The spring washers are necessary if the insulators continue to yield slightly throughout the life of the coil. The clamping pressure is about 60 atmospheres.

TABLE II. Construction parameters of the magnet

External dimensions of one coil	$(1 \times 1)\ m^2$
Inner diameter of one coil	0.6 m
Weight of one coil	800 kg
Copper thickness per turn	2.8 mm
Insulator thickness per turn	0.3 mm

Before manufacturing, a great number of tests have been done with models.

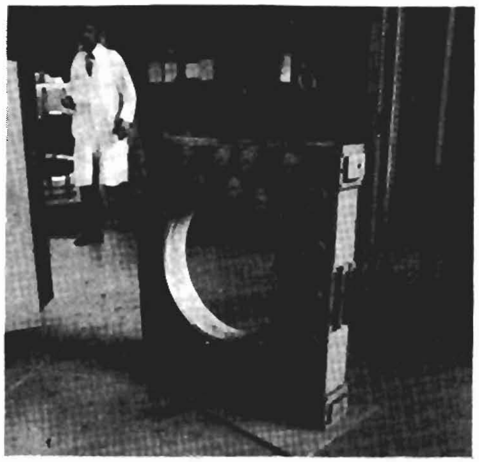

Fig. 4. One TFR coil

The mechanical resistance of the coils has been verified with a scale 1/3 coil model. During this test a pulsed 500 atmospheres hydraulic pressure has been applied along the inner diameter of the coil model. The stresses in the copper reached 13 kg/mm^2. No damage was found after 10 000 cycles.

The more interesting tests have been done with the co-operation of the Magnet Laboratory at Cambridge. The model coil has been powered with the pulsed power generator of the laboratory. The test conditions were severe:

- mean current density 3.5 times higher than in the TFR coils,
- adiabatic temperature rise of more than 200°C.

The coils have been ordered from the CEM (Compagnie Electro-Mécanique) and manufactured by the Société Oerlikon. One of the main problems during the stacking of the coils was that of cleanliness, because the polyimide sheets are very easily perforated by small metallic particles.

III. Electrical Operation Parameters

The magnet operates in a pulsed regime and is energized by an alternator coupled to a flywheel. The waveforms of the voltage and current delivered by the rectifiers are shown on Fig. 5. The repetition rate is one pulse every 4 minutes.

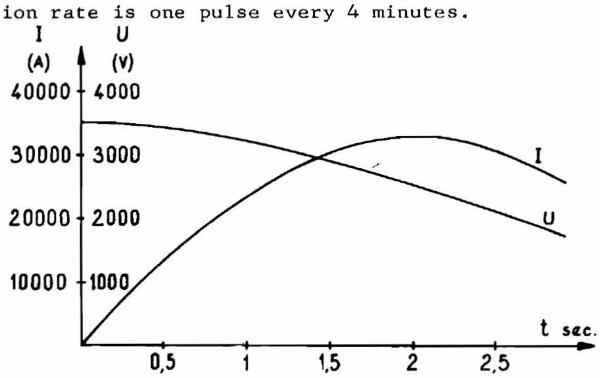

Fig. 5. Voltage and current in the magnet.

TABLE III. Electrical parameters

Nominal current	35 000 A
Nominal voltage	3500 V
Peak voltage	4500 V
Peak power	120 MW
Energy dissipated in the magnet per pulse	150 MJ
Resistance of the magnet	0.07 Ω
Inductance	0.063 H
Peak voltage per turn	5.4 V

IV. Toroidal Magnetic Field

With a magnet current of 35 000 A a 60 kG field is generated along a circumference of 98 cm radius. The maximum field, along a 70 cm radius circumference is 80 kG. The magnetic energy stored in the magnet is 40 MJ.

Resulting from the gaps between the coils the field intensity along a field line is not constant. The field corrugations are shown in Fig. 6. This figure shows the cross sections of the surfaces where $\Delta B/B$ is constant.

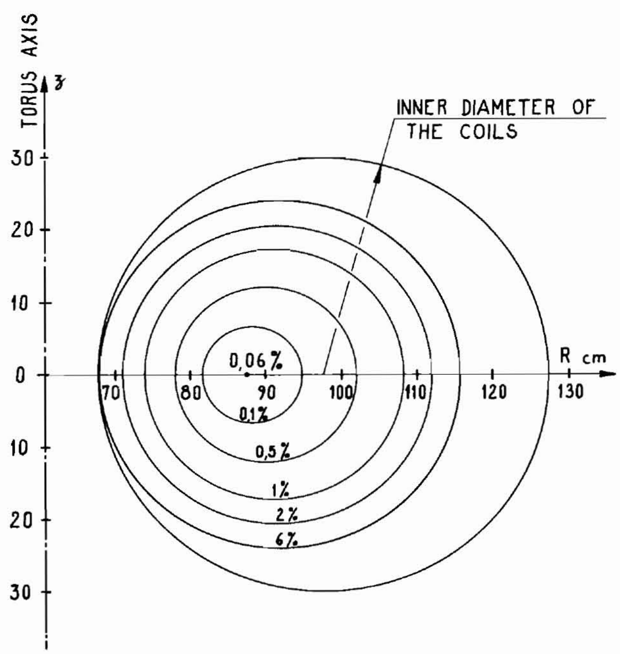

Fig. 6. Toroidal field corrugations.

B is the field mean value along a closed field line.

ΔB is the variations of B along a closed field line.

$\Delta B = B_{max} - B_{min}$ where B_{max} is the value of B in the midplane of a coil, and B_{min} the value of B between two coils.

The 24 coils are all connected in series and they produce a spurious field component parallel to the torus axis. This component is almost cancelled by the return current which flows in a conductor placed just at the outer surface of the coils. However a correction is necessary because at the beginning of the plasma discharge when the breakdown occurs it is very important for the toroidal field lines to be closed. The B_θ coils and their power supplies have been designed in order to cancel this spurious field.

V. Cooling System

The thermal parameters of the magnet are given in the following table.

TABLE IV. Thermal parameters

Mean power dissipated (nominal repetition rate)	600 kW
Mean adiabatic temperature rise per pulse	25°C
Peak adiabatic temperature rise (inner diameter of the coils)	60°C
Peak temperature in the coils (inner diameter)	about 110°C

The specific power of the magnet is not very high. Moreover, during the time interval between two pulses, the heat diffuses through the copper. Consequently, a great number of cooling holes as for Bitter-type coils is not required. Figure 2 shows the cooling slits. The coolant flows parallel to the copper plates and a great surface is available for heat exchange.

Demineralized water was first chosen as a cooling fluid. But in spite of the clamping pressure water infiltrates between the copper plates and loses its high resistivity. Consequently the insulators between turns are slowly destroyed by leakage currents. That is probably the reason why Bitter coils must be periodically disassembled and new insulators provided. As the TFR device cannot be easily disassembled it was decided to use a dielectric fluid. We have selected "pyralène" which is a nonflammable transformer insulating fluid. To prevent the trickling of pyralène the coils are enclosed in tight 1 mm thick stainless steel casings (Fig. 7).

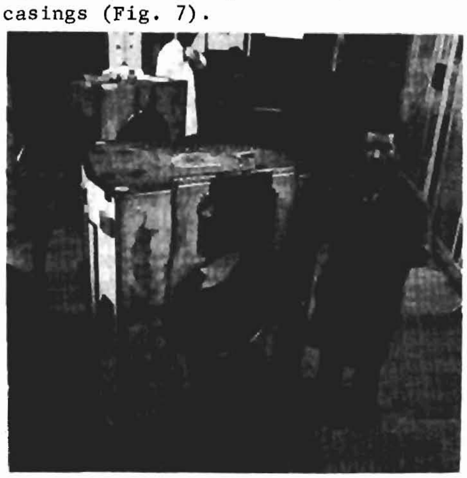

Fig. 7. Stainless steel casing for three coils.

The efficiency of the cooling system depends to a large extent on the physical properties of the coolant. By assuming that the heat transfer coefficient from the copper of the coils to the turbulent pyralène flow is described by the classical relation

$$N_u = 0.023 \; P_r^{0.4} \; R_e^{0.8} \; ,$$

where N_u, P_r and R_e are the dimensionless Nusselt, Prandtl and Reynolds numbers.

We find that the temperature difference between copper and coolant is

$$\Delta T = P \; A \; B$$

where P is the power removed by the coolant,
A is a function of the dimensions of the cooling slits alone,
B is a function of the physical properties of the coolant alone.

$$B = \left(\frac{\mu}{C_p \rho^2 k^{3/2}} \right)^{0.4}$$

μ viscosity
C_p specific heat
ρ density
k heat conductivity.

The comparison of water with pyralène, shows that pyralène is about 7 or 8 times less efficient than water. Calculations and model experiments have shown that the heat-transfer coefficient from copper to pyralène should be about 0.1 W/cm^2·°C for a coolant flow velocity of 1 m/sec.

The coolant is pumped in a closed loop which contains 1.5 m^3 of fluid; a heat exchanger transfers the heat to water in the primary circuit. The pressure drop through one coil does not exceed 2 atmospheres. All the coils are fed in parallel; the flow-rate and the temperature are monitored at the outlet of each coil. The resistivity of pyralène is also continuously monitored.

VI. Mechanical Stresses

1. Forces resulting from the toroidal field

The magnetic pressure tends to increase the diameter of each coil. The stresses in the copper reach 10 kg/mm^2. The safety factor is almost 3.

Resulting from the toroidal shape, each coil is submitted to a centripetal force of 170 tons when the field is 60 kG.

Forces are shown in Fig. 8.

2. Forces resulting from external fields

As any current carrying conductor, the plasma torus tends to increase its inductance by increasing its major radius. This tendency of the major radius to expand is reinforced by the plasma internal pressure. To counteract the expansion

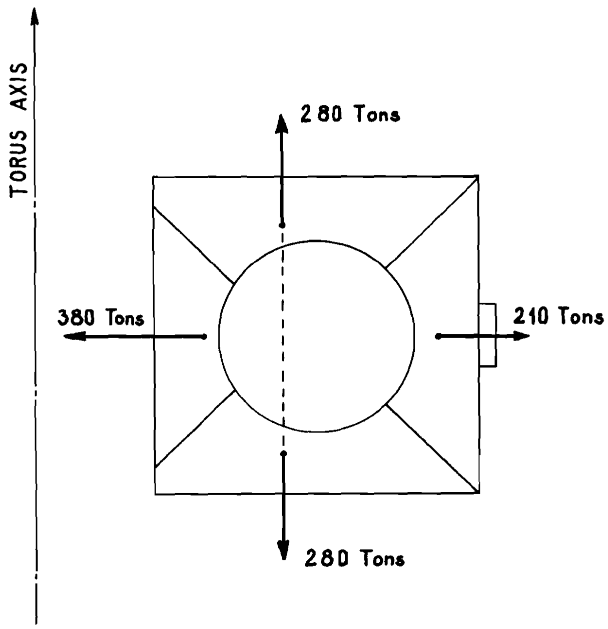

Fig. 8. Dynamic loading of one coil.

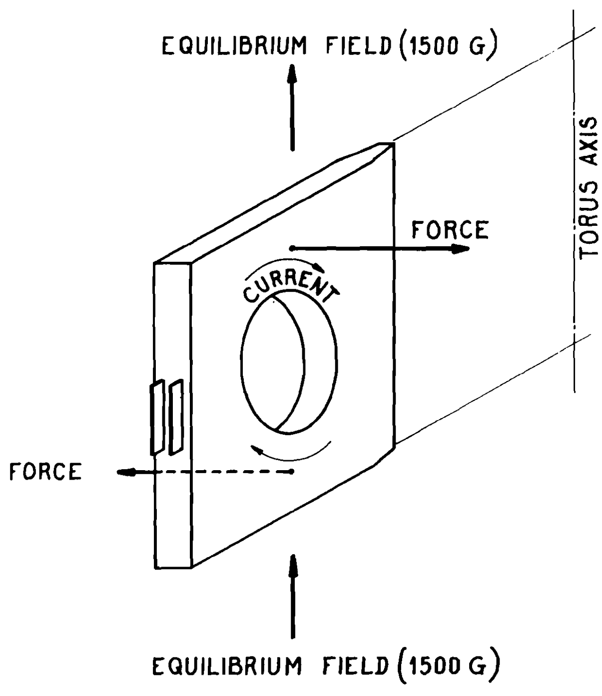

Fig. 9. Equilibrium field torque.

forces, a magnetic field whose lines of force are parallel to the torus axis is required. For the TFR devices, the "equilibrium field" of 1500 G is produced by the B_θ coils. This field tends to rotate each coil of the toroidal magnet with a torque of 7.5 tons meter (Fig. 9).

3. Forces arising in the case of an electrical failure

The most dangerous failure is the short circuit of one coil. In this case, the coils adjacent to the failing ones are pushed apart by very large forces.

If the short circuit occurs at the beginning of the current pulse, the current in the short circuited coil flows in the direction opposite to the main current, but the time constant of the failing coil is long and the current cannot reach an appreciable value. Moreover the control system (see Section VIII) can detect the failure and the power supply is switched off.

If the short circuit occurs when the current reaches its maximum value, the forces can be pessimistically evaluated by assuming that no current flows in the failing coil. In this case, the distribution of forces is shown in Fig. 10.

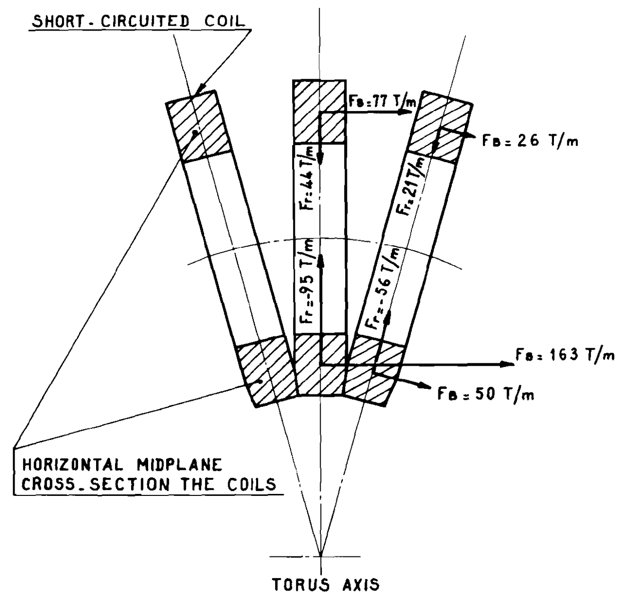

Fig. 10. Additional forces arising in case of a short circuit of one coil. The forces are given in tons per meter.

VII. Mechanical Structure

The problem is to withstand every force while maintaining an accurate alignment of the coils.

The toroidal centering force of 170 tons on each coil is supported by the cylindrical core of the magnetic circuit. The core has been specially designed in order to sustain the pressure of the coils. It is composed of magnetic sheets, stacked radially and bounded with epoxy resin. A filament-wound fiberglass sheath encloses the magnetic sheets. Flat surfaces have been machined in front of each coil, in order to ensure a good support. A pre-compression of all the coils against the core is accomplished by two steel hoops, and a system of wedges between the hoops and the outer surfaces of the coils. Due to the temperature rise and mechanical stresses, the expansion of the diameters of the coils is about 1.5 mm during a pulse. The supports have been designed in order to offer a minimum friction to radial displacements.

Forces resulting from an electrical failure are held by wedges placed between the coils in such a way as to form a closed arch. The wedges cross over some observation holes of the vacuum chamber.

For the positioning of the coils, two large circular aluminum plates have been machined with a great precision. The winding is clamped between the lower and the upper plate by a great number of high resistance steel tie-rods. The two plates are able to stand the torques resulting from the equilibrium field.

VIII. Detection of the Electrical Failures

Two cases of electrical failure have been considered: arcing to ground and short circuit of one or several turns.

In every case, the circuit breaker between the alternator and the rectifiers is automatically opened.

1. Detection of arcing to ground

The mid-point of the winding is connected to the ground through a 100 Ω resistor. During normal operation no current flows through this resistor. A possible arcing to ground is detected by measuring the current flowing in the resistor.

2. Detection of the short circuit of one or several turns

If a short circuit of one or several turns occurs, the resistance and especially the inductance of the failing coil decreases. Consequently, the failure can be detected by continuously controlling the voltage of each coil.

The method used is to compare the voltages of two coils. The problem is complicated by the induced currents which can flow through metallic structures (such as the observation ports of the metallic vacuum chamber). The inductance of one coil is indeed a function of the inductive coupling between the coil and these structures. Consequently the coils have been associated symmetrically with respect to the currents induced in the structures.

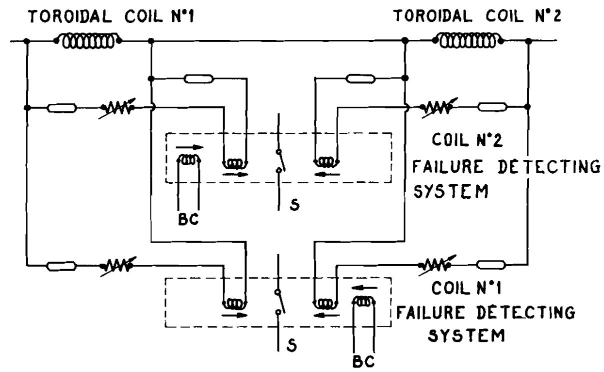

Fig. 11. Short-circuited turn detection system.
Legend: S ferromagnetic switch
BC biasing coil.
The field directions are shown by the arrows.

The system is shown in Fig. 11. Small co-axial coils produce fields in opposite directions. In case of a failure, the resulting field closes the ferromagnetic switch. The sensitivity is improved by biasing the switch with an auxiliary coil. Two systems with opposite biasings are necessary. The sensitivity is adjusted by means of the bias current. The system is able to detect a variation of 1% in the voltage of one coil.