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CONSTRUCTION OF THE EXCITATION WINDINGS FOR THE INTERSECTING STORAGE RINGS

by

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1. INTRODUCTION

The requirements of reliability put on the excitation windings for the Intersecting Storage Rings magnets are even more stringent than those for classical accelerators. This is clear if one considers that any breakdown in the magnets will immediately lead to a loss of the stored beam which, apart from the loss in time for restacking, may cause permanent damage to machine components and prohibitive levels of induced activity. The main effort was, therefore, concentrated on combining the demands dictated by design considerations with manufacturing techniques which would guarantee trouble free operation.

Preliminary test samples had been required because of various contingencies, in order to select the components; then models and prototypes had to be made to refine the mass production methods and verify that they are satisfactory.

Otherwise, the high fabrication rate (1104 coils in 12 months), has required important means, for fabrication as well as for control.

2. DESIGN PARAMETERS

2.1 General data

The excitation windings are wound with hollow copper conductor, having a cross section of 1570 mm^2, to form flat pancakes with 8 turns of 3162 mm length for the short magnet units and 5752 mm length for the long units. Cooling water enters at 13°C on the outside and leaves at 33°C on the inside, the temperature of the surroundings being 20°C. The excitation current is 3750 A, the maximum voltage to earth 1875 V.

2.2 Mechanical stresses in the insulation

a) Hooping effect

The cooling water flow from outside to inside of the coil sets up a positive temperature gradient in this direction. The expansion of each turn is constrained by its neighbour and compressive stresses build up in the curved parts of the coil.

Considering two adjacent turns (Fig. 1), we note that the increase in radius

$$\Delta R = \alpha R \Delta T$$

is constrained by the internal pressure on the outer and the external pressure on the inner conductor.

For the maximum shearing stress occuring at the inner surface of the outer conductor we have*

$$\tau_{max} = E \alpha \Delta T \frac{r_2^2 (R^2 - r_1^2)}{2R^2 (r_2^2 - r_1^2)}$$

with

$\alpha = 1.7\ 10^{-5}$

$E = 1.25\ 10^4\ kg/mm^2$

$\Delta T = 2.5^oC$

$r_1 = 60$ mm

$R = 92$ mm

$r_2 = 124$ mm

$\tau_{max} = 0.18\ kg/mm^2$

b) Extremity effect

To determine the limits of stress conditions under cyclic temperature variations, a test was prescribed in which 3 parallel conductor bars of 5 m length, insulated in the proposed way, were subject to alternating expansions, by heating respectively first the inner and then the two outer bars up to a 30°C temperature difference. This cycle was repeated 1000 times and the differential expansion was monitored and recorded. Throughout this test, the difference in elongation of the hot and the cold bar never exceed 75µ at each end whereas free expansion would give 1.3 mm.

A simplified formula (see Appendix) gives for the value of the maximum shear stress in insulation at extremity:

For the girder : $\tau = \alpha \Delta T \sqrt{\frac{WEG}{3d}}$

For the coil : $\tau' = 1.20\ \alpha \Delta T' \sqrt{\frac{WEG}{3d}}$

with:

ΔT : hot water - cold water temperature variation

$\Delta T'$: inlet - outlet temperature variation

W : copper thickness 32 mm

d : insulation thickness 1.3 mm

G : insulation shear modulus.

With $\Delta T = 30$ and $\Delta T' = 20$, the girder is subjected to 20 % more stress as compared with that found in the coil in normal operation that is to say respectively 0.5 kg/mm^2 in the girder, and 0.42 kg/mm^2 in the coil.

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*Timoshenko, strength of materials part II, page 211

A first girder insulated with mica tape and polyester felt tape has not successfully withstood the stress.

The second girder, insulated with mica glass tape only, was very satisfactory: constant differential expansion from beginning to end of the cycles; good final dielectric strength between conductor and ground at 20 kV - 50 Hz during 20 mn.

c) Prototype

4 short prototype coils have been made and were immersed in water for a week, subjected to 1000 thermal cycles then immersed again for a week. Insulation resistance was measured after every immersion, at 2500 V.

The thermal shocks were obtained by exciting the coils at 3500 A with reduced water flow, then by switching off the current and sending the maximum water flow when the variation of temperature between water inlet and outlet reached 40°C.

Such a test gives thermal stresses theoretically twice the normal stresses.

Insulation to ground was found to loosen, especially in the curved parts on the 4 first coils. Several causes are possible: utilization of different mica glass tapes in the extremities and in the straight parts. Poor distribution of heat between inlet and outlet (because of the accelerating of the processing cycle) led to theoretical stresses $2\frac{1}{2}$ times normal stresses. Insufficient textile reinforcement of outer connections.

The second series of 4 prototypes, taking into account this lesson, has perfectly resisted.

2.3 Dielectric stress and humidity resistance

A good understanding of the dielectric behaviour after thermal cycling and immersion is given by the previous tests.

Moreover, the insulation resistance of 3 insulated conductor samples, of 1 meter length, has been measured after a week of immersion in water.

The resistivity of the insulation at 10 kV DC is from 10^{13} to 10^{14} ohm.m. Samples have resisted to a dielectric test of 20 kV r.m.s. during 20 mn.

The breakdown voltage was from 58 to 79 kV.

The results obtained showed the excellent resistance to water absorbtion of the insulation.

2.4 Mechanical tolerances

To ensure compatibility with all components during assembly of the magnet units and to eliminate influence on the magnetic field gradient from errors in coil positioning, the tolerances imposed were:

on the thickness	± 1mm
on the width	+ 2 mm - 1 mm
on the length	± 5mmm

2.5 Mechanical stresses in the conductor

Almost exclusively from thermal origin, the stresses in the conductor are relatively low: 2 kg/mm^2 in normal working conditions, therefore, greatly lower than the elastic limit of annealed copper.

As always, the weak point is constituted by the brazed joints.

So we have tried to obtain a brazing method as reproducible as possible and well suited to mass production, the test being brazes resisting to a tension of at least 16 kg/mm^2 (25 T for 1570 mm^2).

Previously we have made a certain number of tests, with or without alignment bushing, with joints at right-angle or inclined from 30° to 45°, with brazing media fed from inside, from outside or from a small auxiliary hole (Gargamelle technique). These tests have not been conclusive as to a preferable method.

For the ISR, we have finally adopted the alignment bushing, the joint at right angle, the brazing solder fed from inside with a complement from the outside.

In view of the requirements of reliable and reproducible brazes, a high frequency induction method was retained, as this process lends itself best to semi-automation (Fig. 3). Two water-cooled solenoïds, of unequal length placed symmetrically with respect to the joint, are powered by a rotating generator. A pyrometer, aimed at the joint, controls through an amplifier the excitation of this generator. The pre-set brazing temperature is thus maintained through on-off switching of the excitation. A temperature of 780°C is reached in 2 minutes, the total operation lasts only 3 minutes. The brazing material Silfos is present in the form of a spiral located in the bore, in the position of the smaller solenoïd. The high temperature, caused by the more powerful solenoïd, draws the solder to the other side. When the solder appears at the joint interface, some material is added by hand. Throughout the operation of heating, soldering and cooling down a constant pressure is applied with small pneumatic cylinders, attached to one of the two bars, the other being rigidly clamped. Unconstrained thermal expansion and contraction is thus provided. Nitrogen gas is flowing under a small overpressure through the bore.

To check for change in the brazing set up one joint per day is made, during which the temperature cycle is recorded. This joint is then tested for tensile strength. The average value of 285 tests performed over a period of 10 months has been 20.7 kg/mm^2.

The number of joints has been limited as much as possible by using elementary conductors of maximum length (14 m - 200 kg).

Very few bad joints have been detected later on: a few out of about 5000.

The brazes for the external connecting lugs, outside the insulation, have been made with a torch.

2.6 Radiation resistance

The absorbed radiation dose, over a period of 10 years, estimated from dose measurements around the CERN Proton Synchrotron, was set at 10^9 rad.

In practice, the flexural strength of pure resin, submitted to 10^9 rad., has to be not less than 50 % of the flexural strength before irradiation.

On the other hand, such a radiation rate made it mandatory to use tapes and fillers exclusively made from mineral products: glass tape for mechanical strength, glass and micapaper tape for dielectric strength, mineral fillers in the resin.

A study done at CERN on the resistance of epoxy resins to radiation resulted in certain recommended components, whereas others are to be avoided [1].

Also, the maker had to use a product with low viscosity in order to ensure thorough impregnation, with an extended pot life to allow for a prolonged impregnation operation, since penetration into mica is always difficult. In addition, the product had to be plastic enough to prevent cracking and it had to be harmless to handle.

Therefore, considering CERN's conclusions and after performing various radiation tests on several formulae, we modified our general purpose resin to the following formula [2] which satisfies all these requirements:

- a bisphenol type resin, very pure, to reduce the viscosity,
- a novolaque type resin to ensure good resistance to radiation,
- a small quantity of plasticizer,
- an anhydride hardener mix resulting in a product without tendency to cracking,
- small amounts of zirconium oxide filler.

Reactive diluents have been eliminated.

3. MANUFACTURING PROCESS AND TESTS DURING PRODUCTION

The rate of 4 coils per day required important production means located in a workshop of 2500 m^2.

The copper is supplied and stored as straight bars, approximately 14 meters in length. This length has been determined to be the best compromise for the various practical requirements. The bars are brought to a mechanical feeder which dispenses them one by one to the preparation area.

This preparation includes machining of the end face so that proper mating of the surface is ensured; boring of the central hole to the dimension required for the sleeve; mechanical and chemical cleaning of all machined surfaces.

Then brazing by induction is performed.

Immediately after brazing and cooling, the joint is stressed to 3.5 kg/mm^2 with hydraulic jacks.

The complete length of brazed conductor for 4 short coils or 2 long coils is stored on a drum of 8 m diameter (Fig. 4).

The conductor is then carried from the drum to the brazed joint test stand with a special handling fixture.

The following tests are being performed on the joints:

a) Hot water (90°C) circulates through the bore, the outside of the joint is sprayed every other minute with cold water. This cycle is repeated 25 times.

b) Water is pumped at 100 atm. for 10 minutes in the bore. A hygroscopic paint is sprayed on the outside of the joint. Moreover, we check that the pressure does not fall.

c) The bore is dried and vacuum pumped. Helium is then pumped into the conductor under 1 atm. overpressure. All joints are sniffed with a leak detector having a sensitivity of 10^{-10} Torr. l/sec.

Then the special handling fixture carries the conductor to the reel for the winding operation.

Conductor insulation is made during winding (Fig. 6).

The application of the interturn insulation is done automatically, immediately after sandblasting and varnishing of the conductor. During this operation, the positions of the joints are marked on the insulation to facilitate leak testing at a later stage. The first three turns of the coils are, however, wound uninsulated, as the small radius of curvature might damage the tape.

The winding method adopted differs basically from the method indicated in the specification for tenders. The original idea was for a continuous brazing and winding process, i.e. the brazes would be made and tested each time the coil winding has reached the end of a conductor bar. It was, however, agreed that this process does not allow a continuous and thus economic flow of the production line. The winding machine especially would have to be stopped regularly during the brazing and testing sequences. With the adopted process, the brazing and winding operations were decoupled, using the intermediate stage of the storage drum for testing.

Equally suggested in the specification was the application of the interturn insulation after winding the coil, by opening the coil in a spiral. This would permit an easy access of all joints after winding. For the same arguments of production flow this process was abandoned in favour of the application of the insulation before winding, except for the first three turns, where the copper has to be machined due to keystoning.

The experience showed that precisely the spiralling of the finished coil for applying the insulation on these three turns and the subsequent closing proved to be very delicate and lead to frequent damaging of the insulation. In future constructions it will be desirable to study a way of overcoming these difficulties by applying all the insulation before winding.

The insulation consists of 2 layers, half overlapped, 0.16 mm glass-samica-glass tape.

The conductor length is cut to size, the external connecting lugs are brazed and the coil is opened in a spiral for applying manually the insulation on the first 3 turns. To stress the brazes on the connecting lugs, and to verify that no joints have been damaged during the winding operation, a hydraulic pressure test followed by a helium leak test is performed.

The ground insulation is applied by hand in the curved parts of the coil. Tapered cut tape is used in this operation to prevent excessive build up of insulation thickness on the inner radii. The ground insulation is applied by machine on the straight parts.

At this stage an impulse voltage test (25 kV 1/50) is performed to detect any short circuits between winding which would lead to rejection of the coil after complete impregnation.

For the impregnation closed moulds are used which take up 4 coils at a time. Two moulds for the long and three for the short coils are needed to cope with the production schedule. The moulds can be heated by externally applied heating elements (30 kW for the short moulds and 70 kW for the long ones) and are thermally insulated. Twelve hours are required for heating and pumping down to the final vacuum of about 1 mm Hg. at 65°C. The pre-heated and degassed resin mixture is introduced in about 1 hour, when the resin appears in the overflow, the inlet valve is shut and the vacuum on the top of the resin in the overflow broken, to improve filling of the mould under atmospheric pressure. Vacuum is again pumped and the inlet opened. This cycle is repeated 7 to 8 times in 7 hours. A last filling with a slightly charged resin is performed to mechanically strengthen the outer contours of the coil. Polymerisation is completed in 12 hours, during which the temperature rises from 60°C to 115°C and cooling down requires 5 hours. The cycle is automatically controlled (Fig. 7).

As the central core of the mould is made of aluminium which contracts faster than the steel mould, the coils can be easily lifted using suction devices.

After the dimensional checks, a one week ageing follows. The coils are then thermally cycled by adjusting current and cooling to obtain a 40°C temperature rise between inlet and outlet, which is done 10 times. After a 24 hours water immersion the dielectric tests: 7 kV, 50 per. for 20 min., 25 kV 1/10 5 times and insulation resistance $> 10^9\ \Omega$ at 2.5 kV are performed. Ohmic resistance is measured and recorded. After a final visual inspection for fissures, cracks, etc., the coils are ready for delivery.

Lastly, to make sure of a continuous quality level, further controls have been performed during production:

- one braze per day submitted to a tensile test,
- one verification per week of the brazing temperature, comparing the pyrometer preset temperature with the temperature of a bar element equipped with a thermocouple,
- 3 sets of samples taken from each batch of casting resin were tested for resistance to radiation.

To obtain the production rate of 4 coils per day for 6 days per week the production line occupied 60 people in two shifts.

REFERENCES

[1] G. Pluym and M.H. Van de Voorde - Radiation damages of epoxy resins, Oxford 1967

[2] J. Carlier et J. Goyer - Conception et isolation des grandes bobines d'électro-aimants, octobre 1969.

APPENDIX

The layout of the 3-bar test is shown in Fig. 2. Assuming the central bar is heated and the two outer ones are cold, y is taken equal to the difference in elongation between the warm and cold bars.

On the symmetry axis x = 0 we suppose y = 0

Considering an element of the bars dx at a distance x from the symmetry axis, we have

for the warm bar a compressive force

$$F_1 = \frac{A}{2} E \left(\alpha \Delta T - \frac{\partial u_1}{\partial x}\right) \tag{1}$$

for the cold bar a tensile force

$$F_2 = AE \frac{\partial u_2}{\partial x} \tag{2}$$

The forces arising from the elongation of the element of insulation dx are neglected, because $E_{ins} << E_{cu}$.
The force due to the shearing of the insulation over a distance y is

$$F_3 = h \int_x^l \frac{y}{d} G \, dx \qquad (h = \text{conductor height}) \tag{3}$$

From the equilibrium conditions we have

$$F_1 - F_3 = 0 \text{ and } F_3 - F_2 = 0, \text{ so } F_1 = F_2 = F_3 \tag{4}$$

with

$$y = u_1 - u_2, \text{ we have } \frac{\partial y}{\partial x} = \frac{\partial u_1}{\partial x} - \frac{\partial u_2}{\partial x} \tag{5}$$

Substituting (4) and (5) in (1), (2) and (3), we obtain

$$\frac{hG}{d} \int_x^l y dx = \frac{1}{3} A E \alpha \Delta T - \frac{1}{3} AE \frac{\partial y}{\partial x} \tag{6}$$

Noting that $\int_x^l = \int_o^l - \int_o^x$ and differentiating (6) gives

$$\frac{hG}{d} y = \frac{1}{3} AEy'' \tag{7}$$

or

$$y'' - \lambda^2 y = o \text{ with } \lambda^2 = \frac{3hG}{dAE} = \frac{3G}{dwE} \tag{8}$$

with the boundary conditions $x = o \quad y = o$
and from (6) $x = \ell \quad y' = \alpha \Delta T$

the solution for $x = \ell$ becomes

$$y = \frac{\alpha \Delta T}{\lambda} \tanh \lambda\ell \qquad \tau_{max} = y \frac{G}{d} = \alpha \Delta T \sqrt{\frac{WEG}{3d}} \tanh\lambda\ell \tag{9}$$

using the data

$\ell = 2.5\ 10^{3}$ mm
$\Delta T = 30^{o}$
$w = 32$ mm
$d = 1.3$ mm
$E = 1.25\ 10^{4}$ kg/mm^{2}
$y = 75\ 10^{-3}$ mm
$\tanh\lambda\ell \approx 1$
$\tau_{max} = \alpha \Delta T \sqrt{\frac{WEG}{3d}}$

we find $G = 8$ kg/mm^{2} which indicates that plastic deformation has set in. Under these conditions $\tau_{max} = 0.5$ kg/mm^{2}.

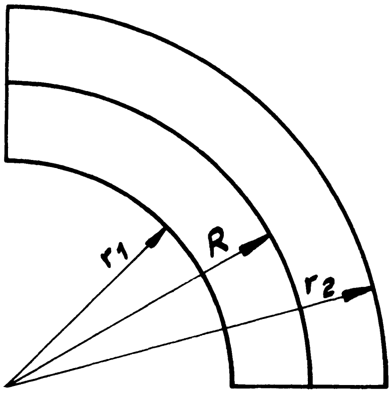

r1
R
r2

FIG. 1

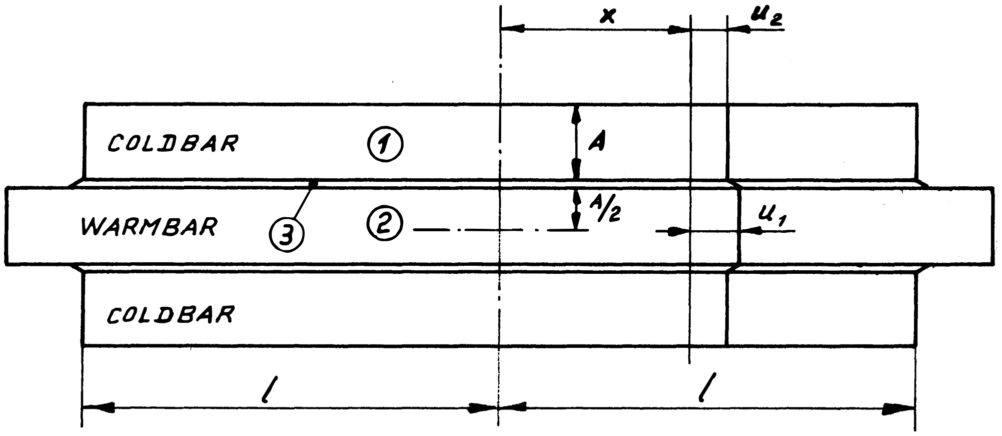
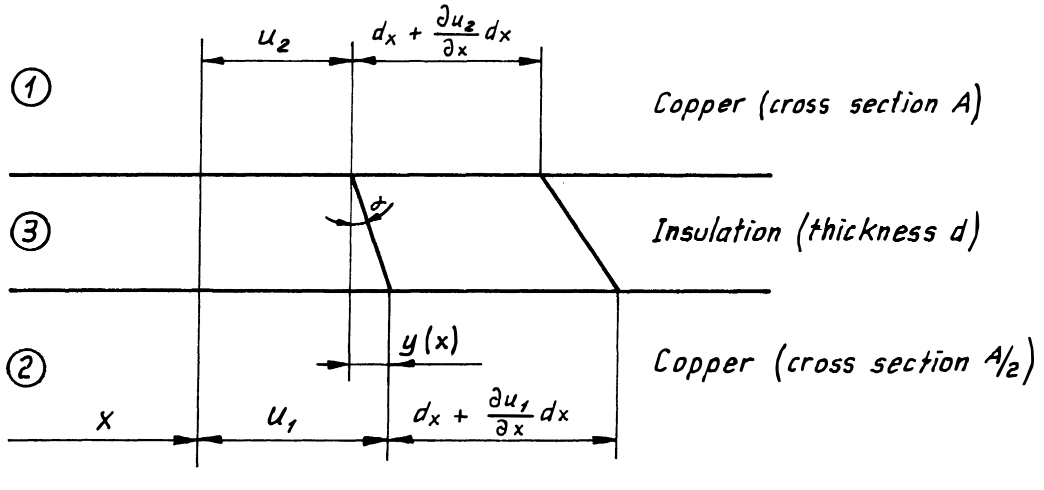
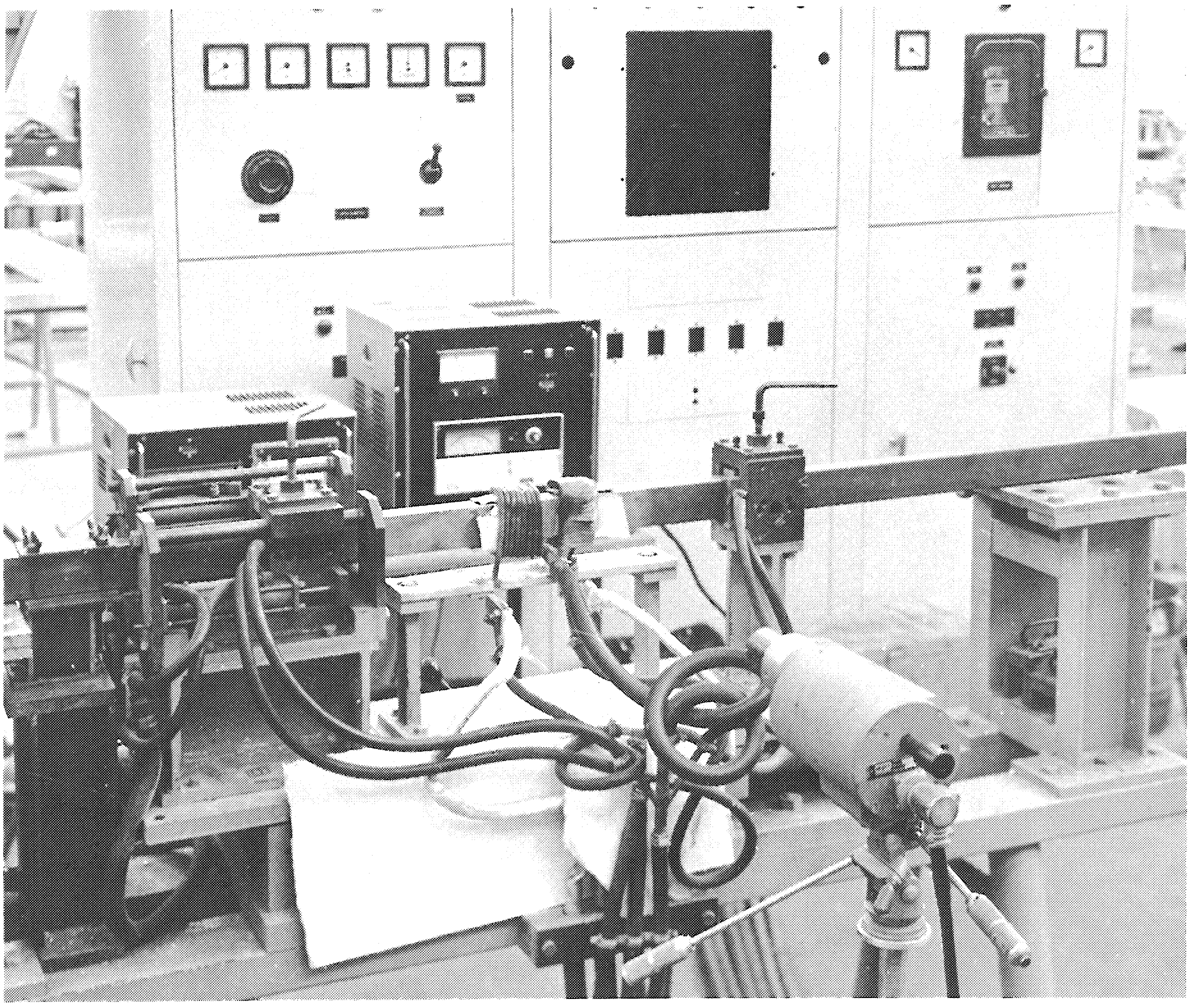

x
u2
COLDBAR
①
A
WARMBAR
③
②
A/2
u1
COLDBAR
l
l

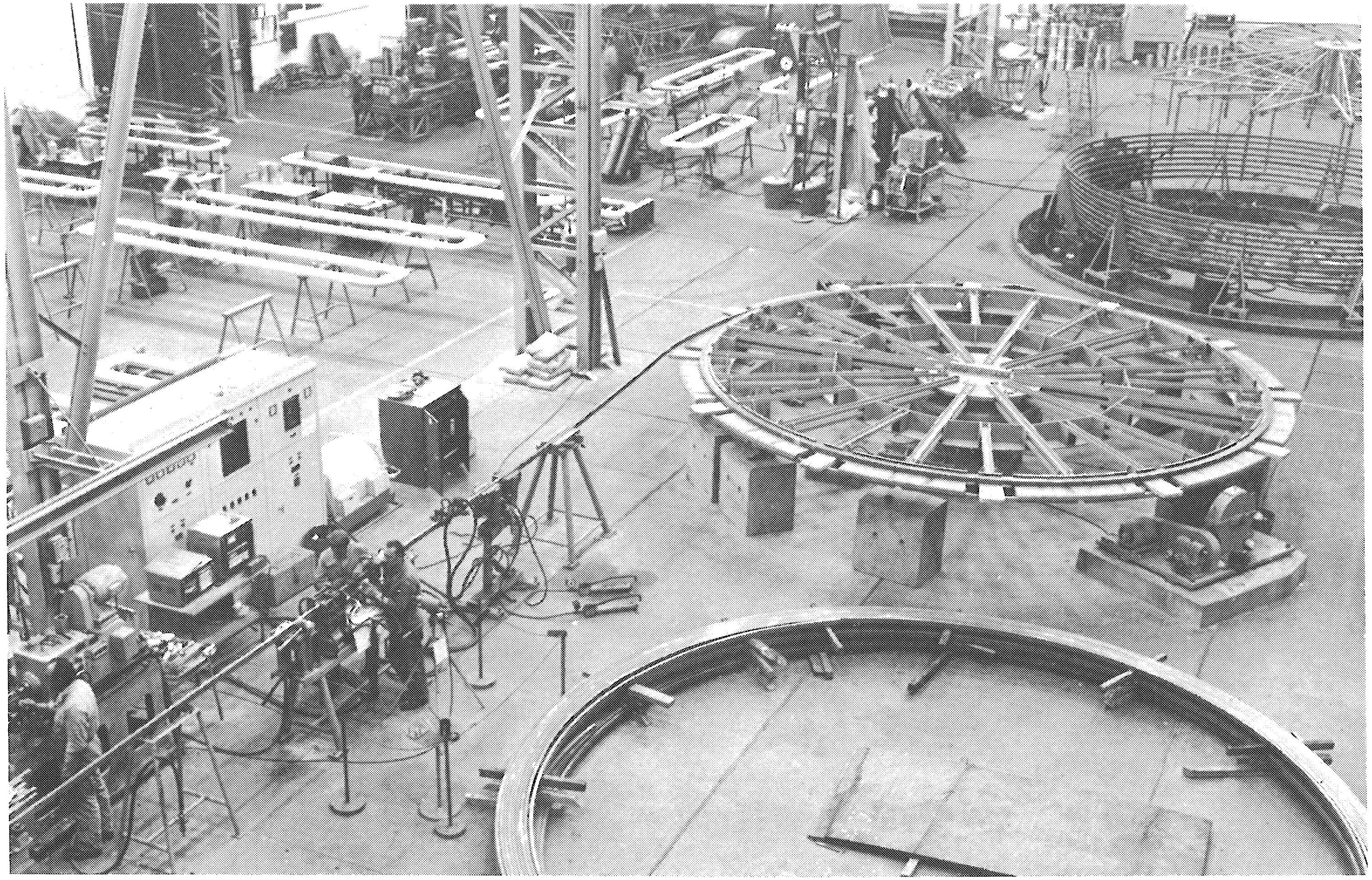
FIG. 2


①
③
②
u2
dx + ∂u2/∂x dx
α
y(x)
x
u1
dx + ∂u1/∂x dx
Copper (cross section A)
Insulation (thickness d)
Copper (cross section A/2)



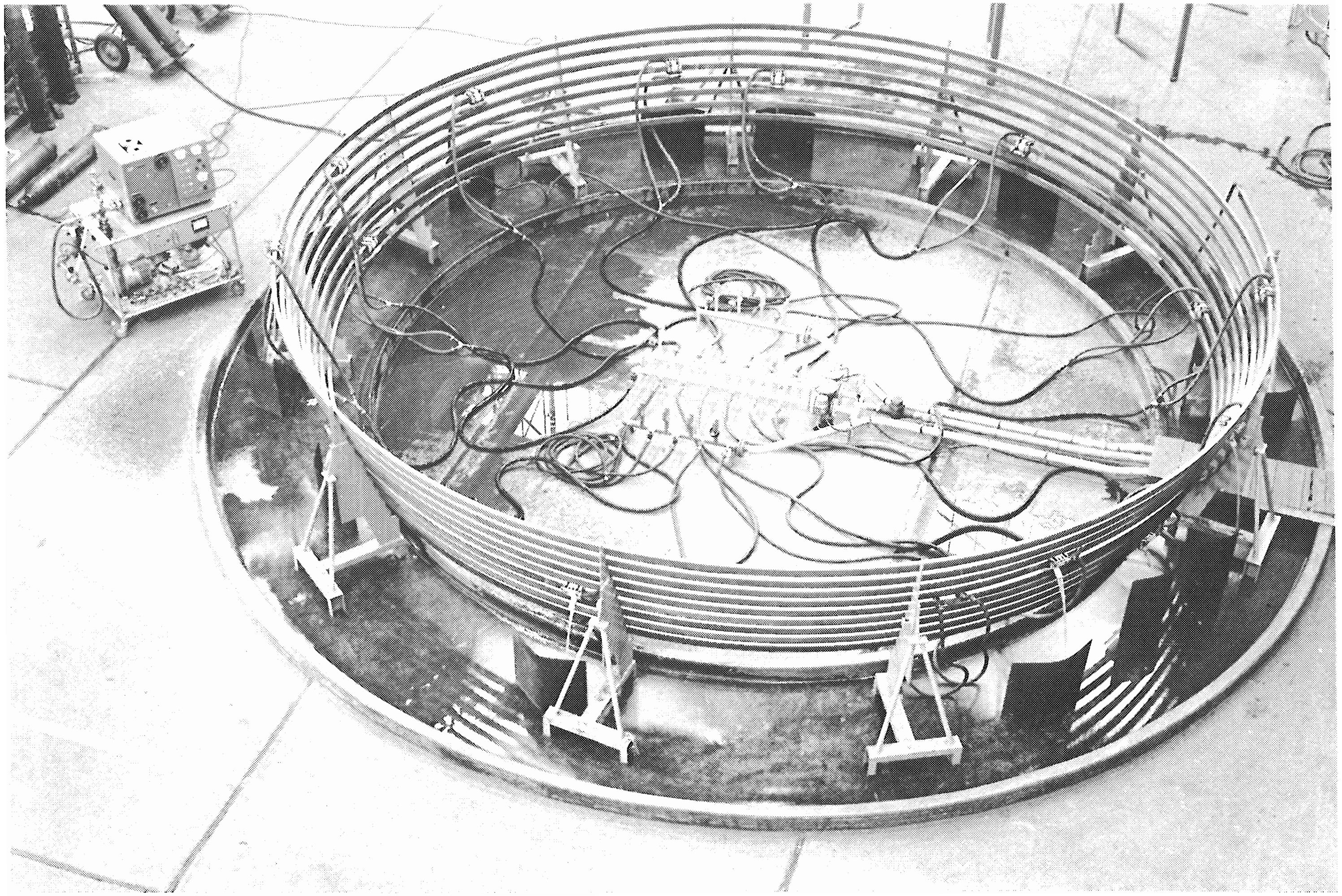
C-1582 - ALSTHOM
CERN à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3.200 m - 496 bobines de 5.700 m
Poste de brasage haute frequence

Fig 3



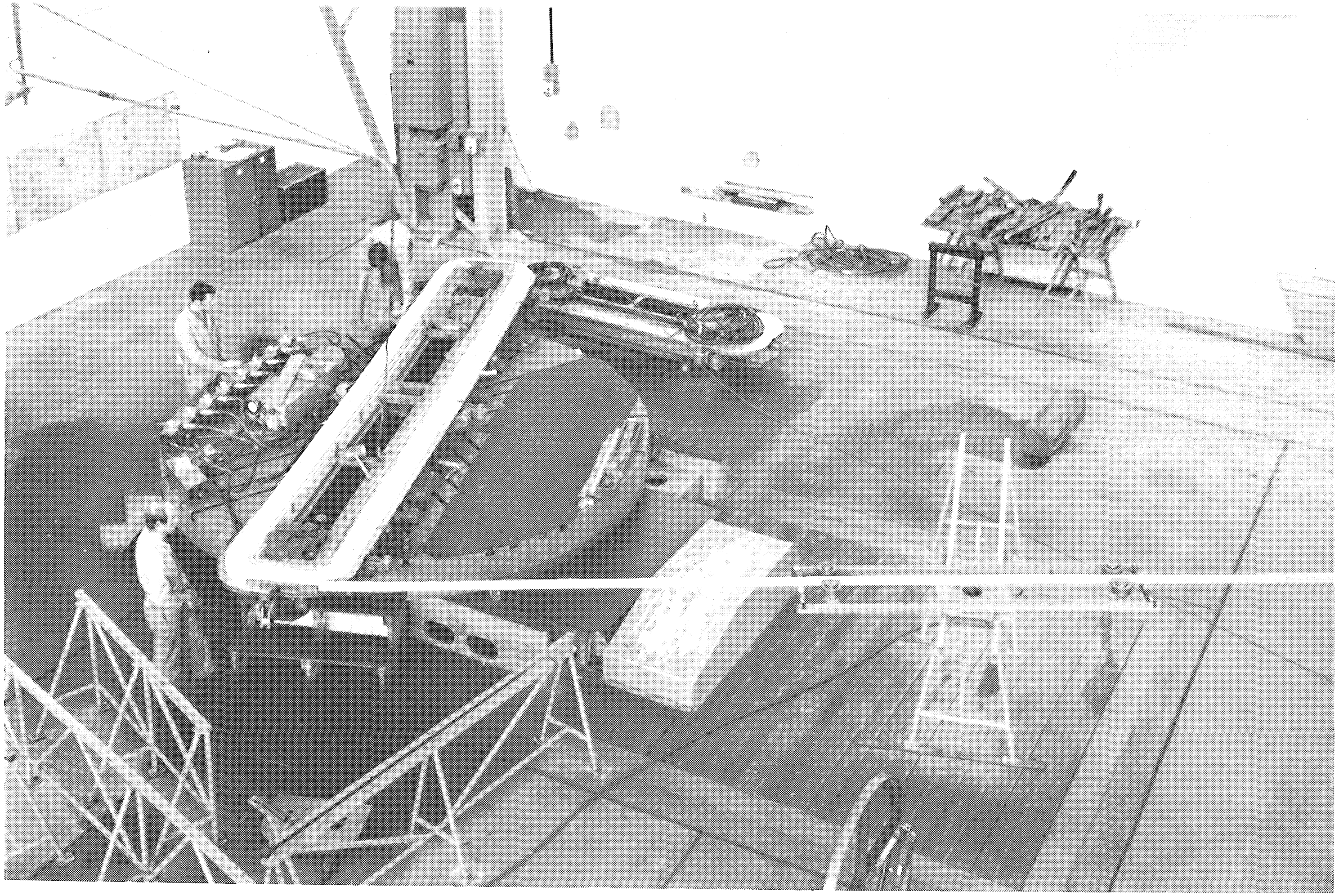
C-1637 - ALSTHOM
C E R N à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3,200 m - 496 bobines de 5,700 m
Brasure et roulage sur tambour intermédiaire

Fig. 4



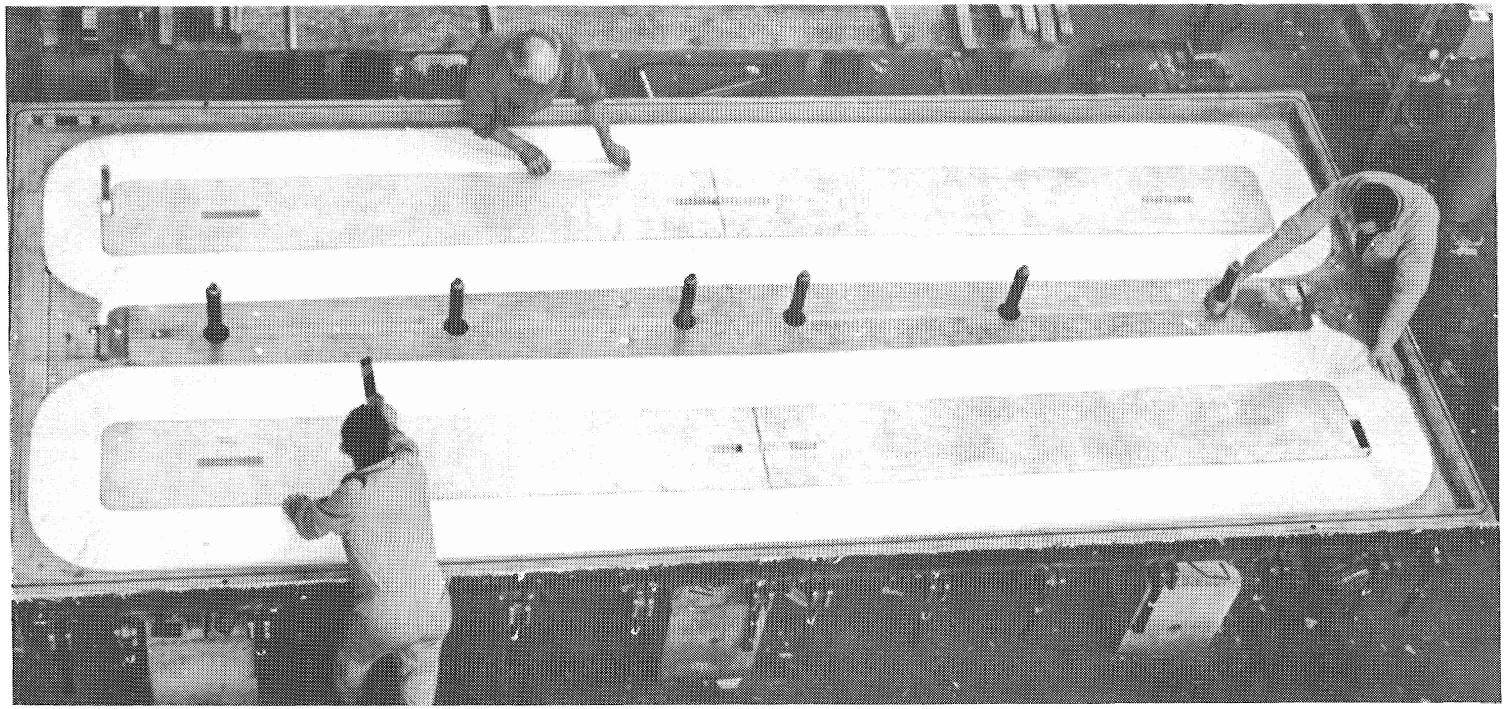
C-1638 - ALSTHOM
CERN à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3,200 m - 496 bobines de 5,700 m
Essais des brasures

Fig. 5



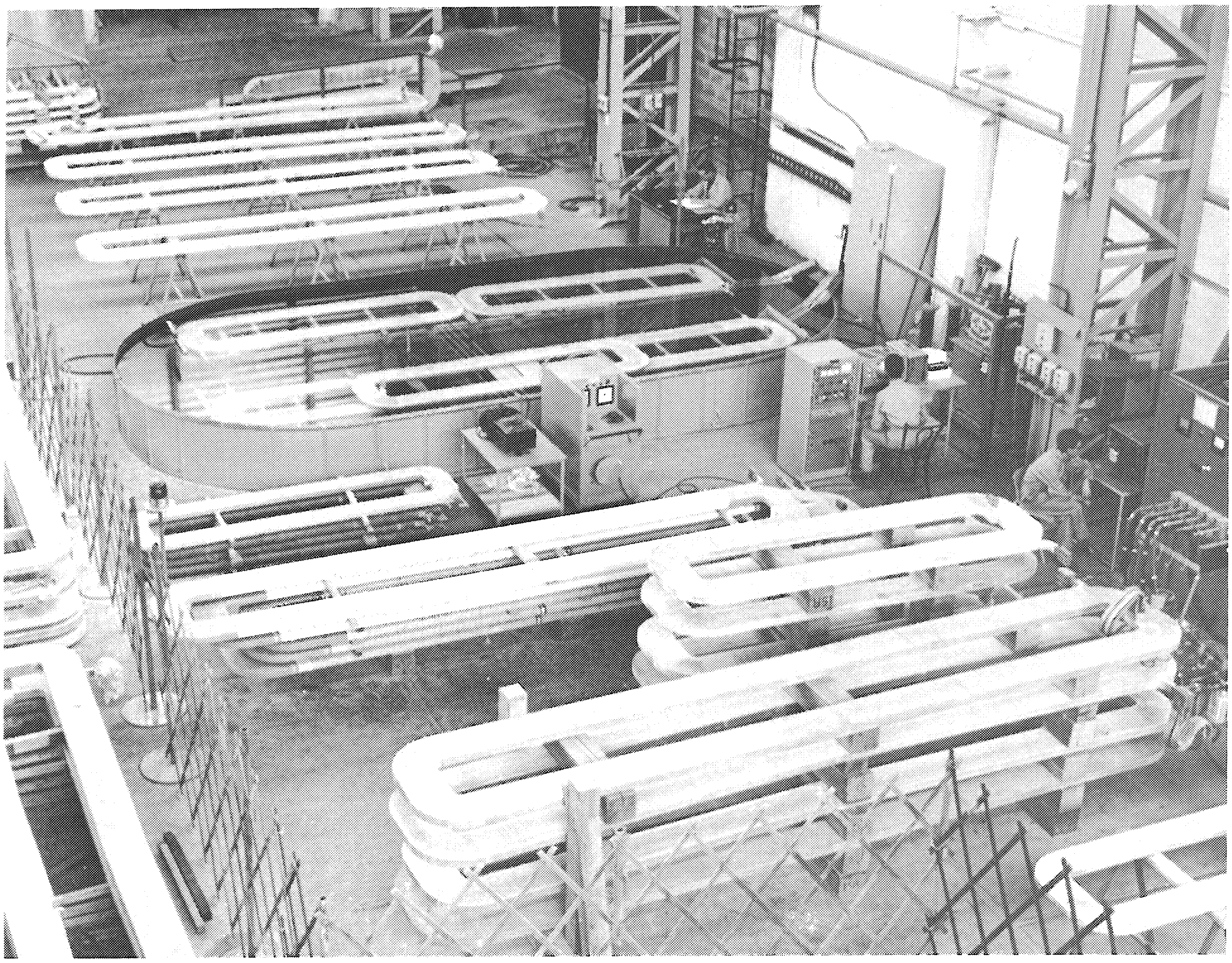
C-1636 - ALSTHOM
CERN à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3,200 m - 496 bobines de 5,700 m
Roulage d'une bobine longue

Fig. 6



C-1639 - ALSTHOM
CERN à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3,200 m - 496 bobines de 5,700 m
Mise en moule de bobines longues

Fig. 7



C-1641 - ALSTHOM
C E R N à GENEVE
Bobines principales des Anneaux de Stockage et d'Intersection
608 bobines de 3,200 m - 496 bobines de 5,700 m
Plateforme d'essais

Fig. 8