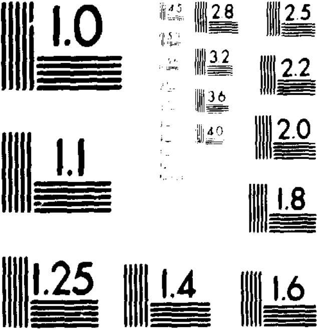

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ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC-86/14
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CONSTRUCTION AND ASSEMBLING OF THE TRIM COILS FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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SUMMARY

This paper presents the main characteristics of the trim coils realized for the heavy ions superconducting cyclotron under construction at the Milan University.

The guidelines in the choice of the conductor size, of the insulation and cooling parameters are discussed in some details. The main operations in the coils construction, as winding, impregnation, electrical tests and assembling, are described.

1) INTRODUCTION

The magnetic field isochronism requirements, for different accelerated ions, in the superconducting cyclotron under construction at the Milan University, are achieved with indipendent excitation of two sections of the main superconducting coils and with conventional coils (trim coils) which gives a trimming of a few hundred Gauss.

Detailed reports on magnetic field produced by the trim coils, their configuration and forces acting on them have been published elsewhere (1,2).

For sake of clarity we will give a short description of the coils. They are wound on the hills, close to the median plane of the machine and following the spiral profile of the hills. The figs. 1,2,3 give an idea about the place where are installed the trim coils and their particular shape.

The cooling and current supply of the coils are achieved with leads which are adherent to the hill walls and cross the yoke of the magnet in the upper and lower pole caps.

The trim coils, on each hill, are twenty, divided in five groups, separated by radial spacers which are able to withstand the magnetic forces acting on the coils.

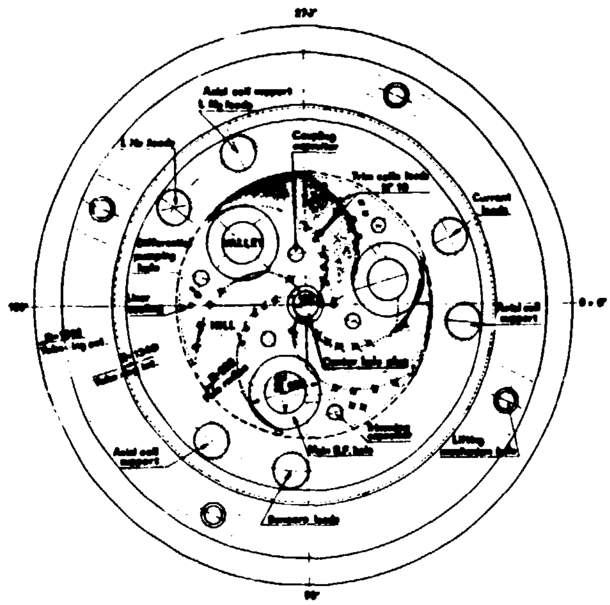

FIG. 1 - Top view of the magnet.

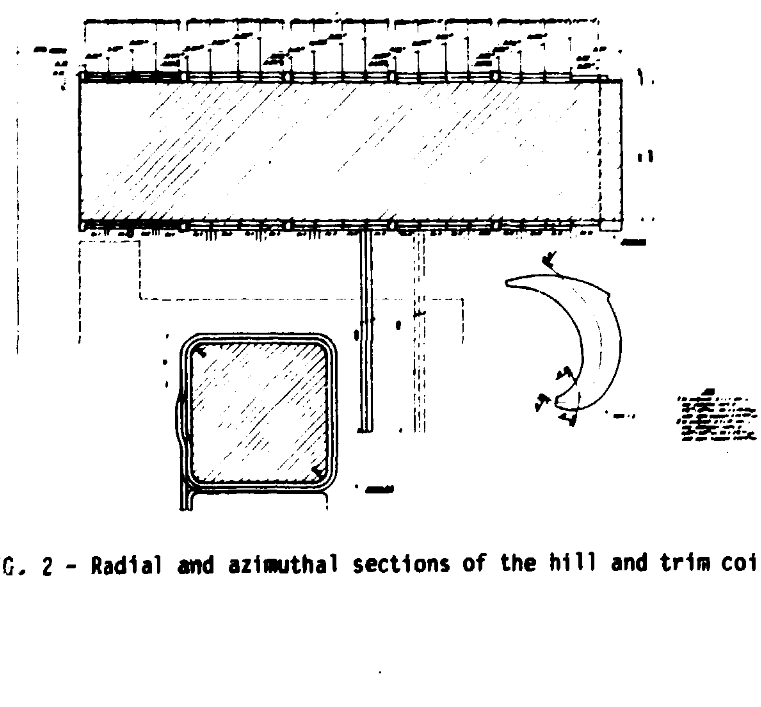

FIG. 2 - Radial and azimuthal sections of the hill and trim coils.

The fig 4 and 5 give some typical field contributions and current settings of the trim coils necessary for the isochronous acceleration of different ions.

The solutions are consistent with a double layer trim coils winding in order to achieve the maximum field correction.

This paper is particularly devoted to the technical solutions concerning the design of the components and the operations for the coils construction as:

- Conductor, insulation and cooling design
- Winding procedure
- Coils impregnation, moulding and assembly
- Vacuum tight current feedtrough
- Coils supply and thermal protection

Fig. 3 - Top view of the trim coils on the hill.

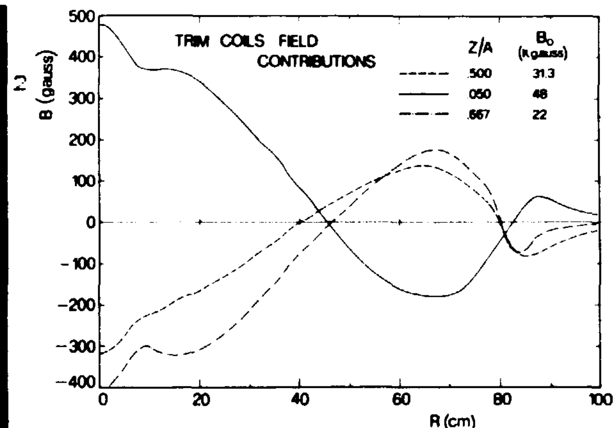

FIG. 4 - Trim coils field contributions to achieve the isochronous magnetic fields for the indicated ions.

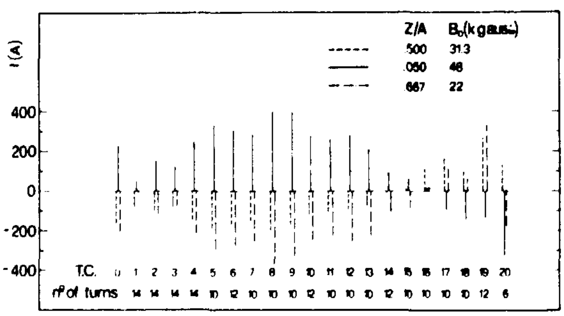

FIG. 5 - Trim coils currents setting for the indicated ions.

2) CONDUCTOR

In the choice of the conductor in terms of size, insulation and cooling system we take into account the following requirements:

- Maximum magnetomotive force 4000 At.
- Maximum vertical coils thickness 15 mm.
- Maximum radial coils dimension 35 mm.
- Azimuthal coils thickness as small as possible
- Epoxy impregnation of the coils

Moreover the coils must work in a differential vacuum chamber with a pressure of about 10^{-3} mbar.

The possibility to utilize conductors of different materials instead of copper (i.e. Aluminium) has been investigated. The construction procedure and the adopted cooling system are consistent only with the "copper solution".

2.1) Cooling

The total power dissipated in the coils must be removed with a fluid forced flow ; therefore we have decided to utilize a demineralized water cooling network available in the laboratory with a temperature of about 20 ^{0}C and a pressure of 5 bar.

The conductor overall dimensions are largely determined by the maximum magnetomotive force, the available space and the cooling requirements. The square size presents the highest filling factor and the useful dimensions are in the range 4x4 mm square and 7x7 mm square. The choice of the dimensions and the hole diameter has been determined by the following criteria:

i) minimum temperature increase in the conductor

ii) pressure drop of the cooling water limited to 4 bar.

A computing program based on the classical relationships:

$$Re = \frac{Do \quad Go}{\mu} \qquad (1)$$

$$Pr = \frac{Cp \quad \mu}{K} \qquad (2)$$

$$Fc = 1.4 \quad 10^{-3} + 0.125(Re)^{-0.3} \qquad (3)$$

$$Pd = \frac{2 \quad Fc \quad Go^2 \; L}{\varrho \; g \quad Do} \qquad (4)$$

$$\alpha = 0.0023 \quad \frac{K}{Do} \quad (Re)^{0.8} \quad (Pr)^{0.4} \qquad (5)$$

Where :

- Rc Reynolds number
- Pr Prandtl number
- Fc Friction coefficient
- Pd Pressure drop (gr/cm^2)
- α Coefficient of thermal exchange copper/cooling fluid
- Do Ponderal diameter (cm)
- Go Ponderal speed (gr/ (cm^2 sec))
- μ Cooling fluid viscosity (gr/cm sec)
- Cp Specific heat (J/gr ^{0}K) of the cooling fluid
- K Thermal conductivity (W/cm ^{0}K) of the cooling fluid
- g Acceleration of gravity (cm /sec^2)
- L Conductor lenght (cm)
- ϱ Fluid density (gr/cm^3)

has been developed. It uses as inputs the following data:
- Square conductor external dimensions
- Hole diameter
- Conductor current
- Temperature increase in the conductor

and gives these outputs:
- Copper/hole section ratio
- Cooling fluid pressure drop
- Cooling fluid ponderal speed
- Temperature coefficient of copper/water thermal exchange

The specific pressure drop, the specific temperature increase, the coefficient of copper/water thermal exchange and water ponderal speed are plotted as a function of the hole diameter for different conductor dimensions in the fig. 6.

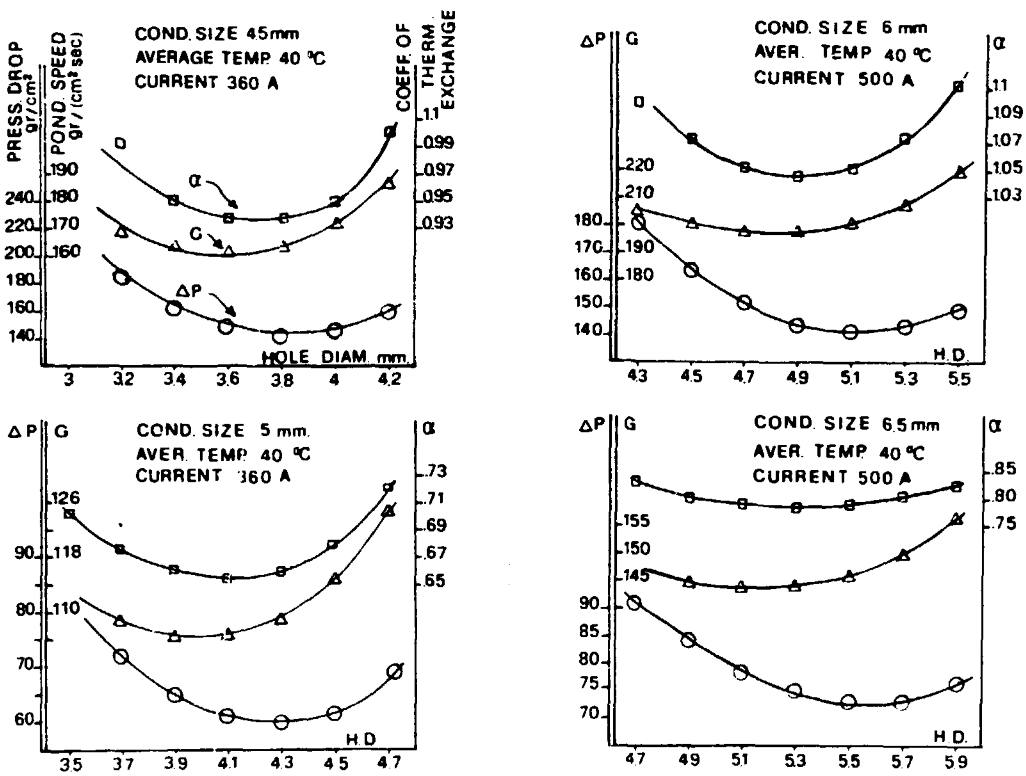

FIG. 6 - Cooling circuit parameters as a function of the hole diameter for different conductor sizes.

The choice of a copper/hole section ratio of about 0.9 may be a good compromise for conductors with external side greater than 6 mm. For conductors of lower dimensions it is better to increase the ratio for mechanical reasons. The Table I presents two possible solutions for the trim coils conductors. in the same Table the expected pressure drop and the temperature increase for unit lenght of the conductor are presented.

TABLE I - Characteristics of the proposed conductors

SQUARE CONDUC. SIDE (mm.)	HOLE DIAMETER (mm.)	RADIUS ON CORNER (mm.)	DIMENS. TOLERANC. (mm.)	PRESS. DROP x Mt (gr/cm2)	TEMP INCR. xMt (0C)	RATED CURR. (A)	NOTES
6.5	5.2	.5	+/-.1	76	1.75	500	
4.5	3.6	.5	+/-.1	112	3.5	360	coils in the centr.reg.

Considered that the suppliers do not make a little production (about 600 Kg.) of special size conductors which fulfil our needs we have examined the commercial available products. The conductors which approach our requirements are reported in Table II; with the expected pressure drop and temperature increase for length unit.

TABLE II- Conductor characteristics.

SQUARE CONDUC SIDE (mm.)	HOLE DIAMETER (mm.)	RADIUS ON CORNER (mm.)	DIMENS. TOLER. (mm.)	PRESS. DROP x MT. (gr/cm^2)	TEMP. INCR. x MT. (°C)	RATED CURR. (A)	NOTES
6.25	4.77	.5	+/-.1	113	1.75	500	OFHC Copper
4.77	3.2	.5	+/-.1	155	3.5	360	Minimum Lenght 100 Mt.

2.2) Conductor insulation

Turn to turn and turn to ground insulation requirements for the trim coils can be guaranteed with an adequate conductor insulation.

It should be an easy problem to solve for the low voltage, but the relatively high current that supplies the coils is able to produce a welding point on the coils in the event of a spark.

Different materials have been taken in account for the insulation of the conductor:
- Nomex ribbon
- Epoxy enamel
- Fiberglass ribbon
- Fiberglass thread
- Daglas thread

The main properties required for a good conductor insulation are:
- Low hygroscopicity
- Low thickness
- High roughness
- High adhesion with the conductor
- High cut and friction mechanical resistance
- High fitting at low bending radii

The table III makes a comparison of these properties for different insulating materials.

TABLE III - Properties of some insulating materials.

I T E M	HYGROS.	THICK.	ROUGH.	ADHES.	MECH.RES.	FITT.
Nomex rib.	high	low	low	low	high	low
Epoxy enam.	low	low	low	high	high	high
Fiberg.rib.	high	high	high	low	high	low
Fiberg.thr.	high	low	high	low	high	high
Daglas.thr.	med.*	low	high	high	high	high

* Daglas hygroscopicity is reduced after thermal process.

It appears evident that Epoxy enamel and Daglas thread solutions score all the other. The good experience in this field furnished by the Pirelli Co. (MILAN) allowed us to choose the second solution.

The insulating curing could be this one:

- The conductor well cleaned pass through a series of reels with the Daglas thread wound up.
- These ones turn on clockwise and counterclockwise directions around the conductor providing a double spiral Daglas coating.
- Then, the insulated conductor, reaches a sufficent heating in order to fuse the polyesther component of the Daglas which give a very good adherence between copper and insulator.

The electrical tests performed on some samples of conductor insulated with double Daglas thickness of 0.25 mm gave us a turn to turn and a turn to ground sparking voltage higher than 500 Vdc.

After the construction of a prototype set of 1 to 1 scale of twenty trim coils the thickness of the conductor insulation was increased at a double Daglas thickness of 0.35 mm. for safety reasons.

3) VACUUM TIGHT - CURRENT FEEDTHROUGH

The prototype of the vacuum tight current feedtrough for the trim coils was developed first because it is one of the crucial components in the trim coils system.

In its design we have taken into account the possibility to reduce the number of the holes in the pole caps. This philosophy is quite different from that adopted at the MSU where each current leads crosses the magnet with an indipendent hole.

In their design we have taken into account:

- Casting technique for the vacuum tightness
- Holes in the magnet, less than possible
- Electrical connections between coils and terminal board
- Cooling connections

3.1) Vacuum tight

In the final solution, for the vacuum tight current feedthrough, presented in fig. 7, particular care was taken in the choice of the epoxy compound, casting technique and neverthless the tests to try on the prototypes.

We can say that good results should be warranted only following these suggestions:

- Proper resin choice, depending on working conditions
- Compound age less than 1 year
- Exact mixing of the components
- Proper surfaces treatment (cleaning,sanding,etc..)
- Proper thermal cycles
- Resin deaerating before and after mixing
- Vibration during and after the injection of the resin

The prototype of vacuum tight current feedthrough has been made with different factories products. We have tried various thermal cycles, surfaces treatments and resins injection techniques: at last we have chosen the 3M Scotchcast type 281 which has a vacuum leak lower than :

$$1 \cdot 10^{-8}\ \text{Torr lt./sec.}$$

after hundred thermal cicles from 120 °C to 20 °C.

Sticking with epoxy resins of copper and stainless steel is not very easy expecially if we want a perfect vacuum tight. We think therefore justified to write something about the procedure that we have developed.

- The internal side of the stainless steel tubes is properly wrinkled with sanding and coated with primer Scotchcast 265.
- The conductors from which the insulation is removed, are wrinkled

with glass-paper and coated with primer too.

- Epoxy compound, mixed, deaerated and warmed, is slowly injected in the tube with a syringe and, the vacuum feed through, is put on vibration. The trapped air during resin injection must be removed only with vibration. (3)

We want to recall your attention on the fact that, in the epoxy compound, there are volatile elements essential for the flexibility. Therefore in the figure 8 are shown curves concerning the pressure/temperature limits, in the deaereating process of some 3M compound.

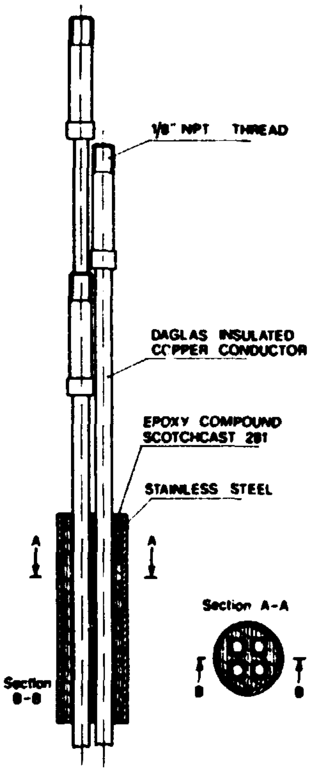

FIG. 7 - Vertical and horizontal cross sections of the vacuum tight current feedtrough.

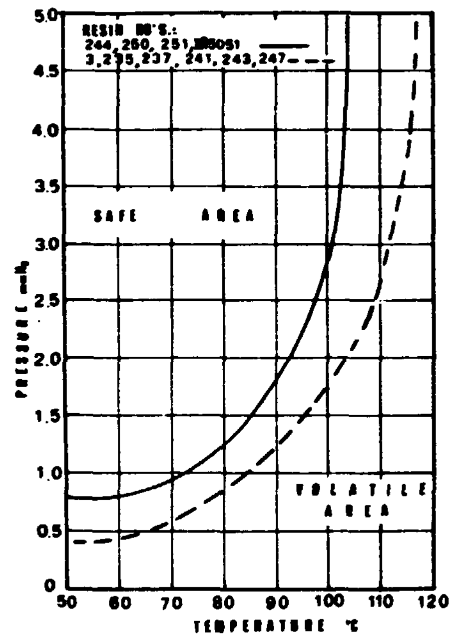

FIG. 8 - Vacuum/Temperature limits for deaerating procedure.

3.2) Supply and cooling connections

The square section of the conductor is not suitable for the electrical and cooling connections therefore cylindrical termination has been welded. A 1/8 inch thread on these terminations allows the cooling water connection, see fig. 9. A particular copper-chrome alloy with low resistivity and very good mechanical properties was preferred in the construction of the cylindrical ends of the coils.

The shape of the ends and their electrical connections were achieved after the realisation of a few different prototypes. They are silver coated and the maximum voltage drop is 1 mV at 500 A.

The horizontal cross section of the current feed through shows that it is not possible to have the four cylindrical ends at the same level. We have adopted a three levels solution which makes easier the connections from coil to coil and from the coils to the terminal board on the upper and lower pole caps of the magnet.

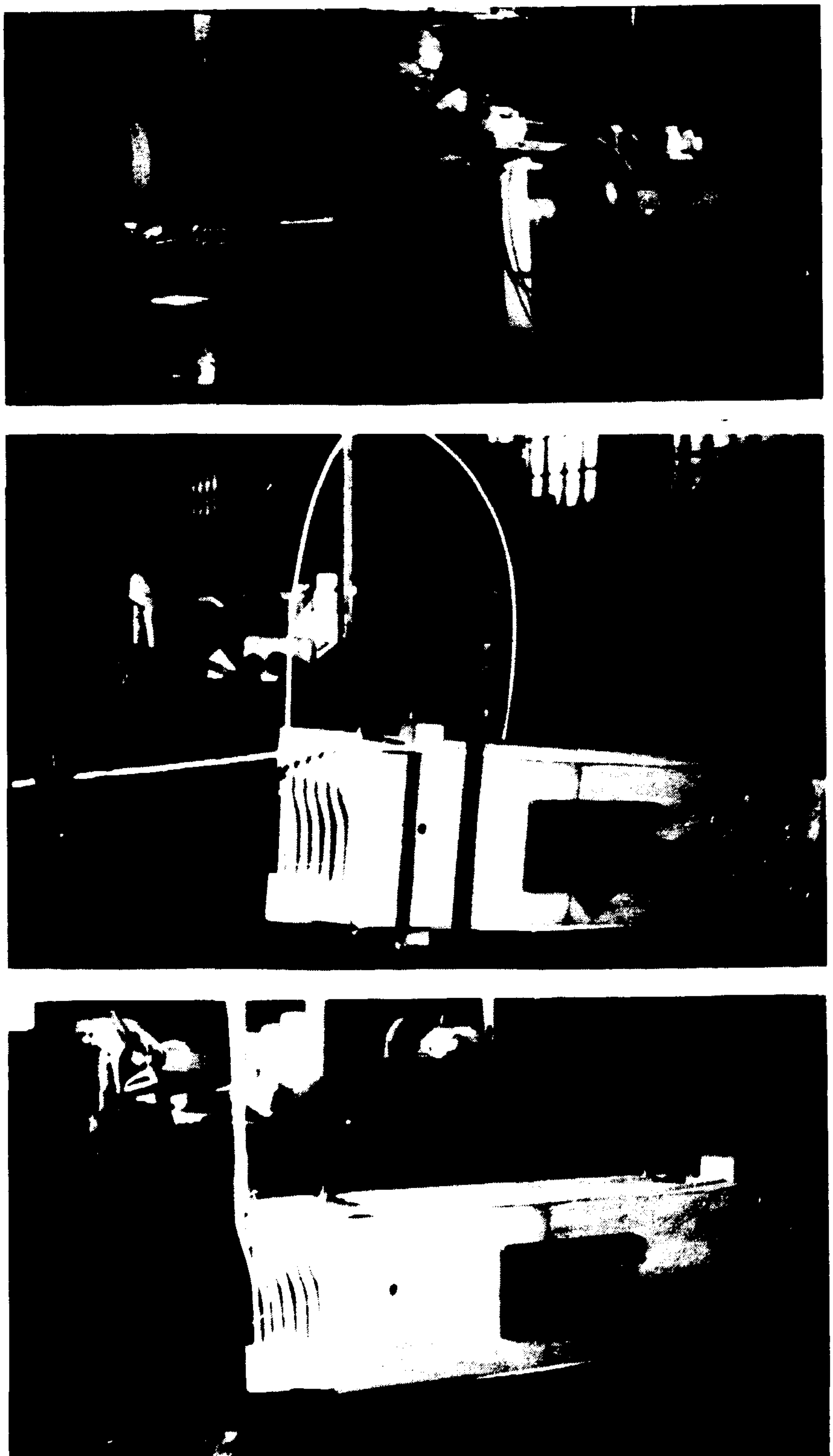

FIG. 9 - Phases of the trim coils winding.

4) COILS WINDING

The complex shape of the coils was the main reason for our troubles to find a company intereste in their construction. Among the companies asked for a tender only the OCEM Company (MI) had given a positive replay .

The large experience of the OCEM in the construction of the medium power electrical transformers was very important for the good results obtained.

4.1) Winding technique

As mentioned in paragraph 2, it is very important to get an azimuthal thickness very low in the proximity of the median plane of the machine, in order to have an accelerating angle as close as possible to 60°. The layer change shown in fig. 2 is achieved at a minimum distance of 70 mm. from the top, median plane side, of the coils. Moreover it is very important, in order to reduce the magnetic field harmonics, to have a regular radial distribution of the coils.

A full scale aluminium prototype of two sectors and valley has been made, in order to check out the machining procedures and to allow the assembling of a full set of twenty trim coils on the hill

At the same time a prototype set of the trim coils were wound with Daglas insulated copper conductor on suitable wood models.

This allwoved us :

- to check the precision of mechanical assembling of the trim coils on the hill.
- to increase the number of turns of some trim coils.
- to minimize the trim coil azimuthal thickness.
- to take in place a proper arrangement of the coils for the impregnation.

Some phases of trim coils' winding are shown in the pictures of fig. 10. The final trim coils winding begun in November 1982 and was completed in April 1983.

The Table IV summarizes the geometrical and electrical characteristics of the trim coils. The control of the first harmonic in the central region and at the extraction is reached respectively with the coils 1,2 or 3,4 and the coils 19,20.

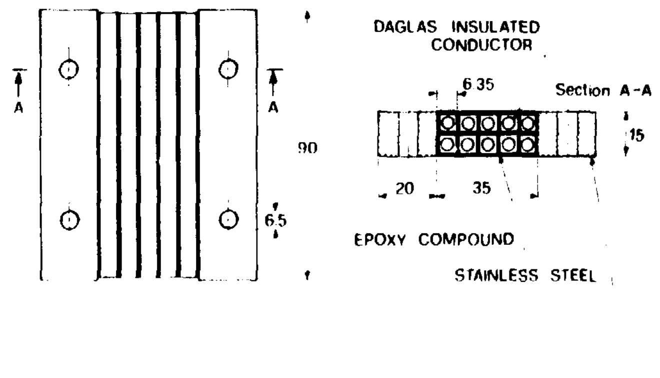

FIG. 10 - Sample for the mechanical tests on the resins. Dim. in mm.

TABLE IV - Trim coils mechanical and electrical characteristics.

TC n.	RAV (cm)	Ri (cm)	Rf (cm)	Df (deg)	TN	Imax (A)	Res (m)	Ind (uH)	NOTES
1	11.59	9.58	13.38	42.1	14	360	15.5	39.0	Harmonic
2	13.17	13.38	16.95	44.3	14	360	16.8	46.0	Coils
3	18.74	16.95	20.53	45.6	14	360	17.7	55.0	Conductor
4	22.32	20.53	24.11	46.5	14	360	18.9	61.0	4.77 mm.
		24.11	25.41						Spacer 1
5	27.08	25.41	28.76	48.0	10	500	10.4	36.5	Conductor
6	30.77	28.76	32.77	48.3	12	500	12.9	54.0	6.25 mm.
7	34.45	32.77	36.12	48.5	10	500	11.7	43.5	"
8	37.80	36.12	39.47	48.5	10	500	12.5	45.5	"
		39.47	40.77						Spacer 2
9	42.46	40.77	44.14	48.4	10	500	12.8	49.5	Conductor
10	46.16	44.14	48.19	49.2	12	500	15.6	72.0	6.25 mm.
11	49.87	48.19	51.56	48.1	10	500	13.9	56.0	"
12	53.24	51.56	54.93	48.1	10	500	14.5	60.0	"
		54.93	56.23						Spacer 3
13	57.92	56.23	59.60	48.0	10	500	15.2	62.5	Conductor
14	61.62	59.60	63.65	47.9	12	500	18.5	89.0	6.25 mm.
15	65.33	63.65	67.02	47.9	10	500	16.5	70.0	"
16	68.70	67.02	70.39	48.0	10	500	17.1	73.5	"
		70.39	71.69						Spacer 4
17	73.38	71.69	75.08	48.1	10	500	17.5	76.0	Conductor
18	76.77	75.08	78.47	48.5	10	500	18.2	81.0	6.25 mm.
19	80.50	78.47	82.53	49.7	12	500	22.4	120.0	Harm. coil
20	84.57	82.53	86.60	51.1	6	500	14.9	36.0	Harm.1 layer
		86.60	87.90						Spacer 5

TC Trim coil number
RAV Average radius of the trim coil
Ri,Rf Initial and final trim coil radii
Df Average azimuthal width of the trim coil
TN Number of turns of the trim coil
Imax Maximum excitation current (trimming and harmonic excitation)
Res Resistance of the trim coil and leads at 40 °C
Ind Self inductance of the trim coil

5) IMPREGNATION

The trim coils structure is absolutely not adequate to withstand the magnetic forces due to the high magnetic field in which they operate. The main forces are in radial and vertical direction; a precise computation of these forces has been made. (3)

Mechanical coils' rigidity and a good sticking with the spacers may be satisfied by the epoxy resins impregnation of the coil.

We remember that the coil's set have to be removable in order to allow the shimming of the hills or to change the damaged coils. In this part we will illustrate the criteria of the resins choices, tests on the cured compound and impregnation procedure.

5.1) Epoxy resins

A lot of epoxy compound are commercially available,the problem is to find the more adequate at our need. It is always advisable to make specific tests on the resins, in fact the allowable technical data supplied from the Companies are not guaranteed.

Our experience in construction and maintenance of magnets for nuclear research allows us to prepare a list of the main characteristics that would be compared in the compounds' selection and the tests to be tried. They are in particular:

- Class of insulation
- Hygroscopicity
- Loss of weight under vacuum
- Thermal conductivity
- Sharing strenght
- Thermal shock resistance
- Coefficient of thermal expansion
- Viscosity
- Hardness
- Radiation damage

The more suitable solution seems that with warm curing liquid resins; their electrical and mechanical performances justify the major complexity in handling in comparison with the cold curing one. We can't forget moreover that is not possible to find the class "F" thermal performaces in the field of the cold curing resins. The familiarity with the warm curing compounds, supplied from different companies, acquired during the construction of the vacuum tight current feedtrough, allowed us to make the test for the impregnation of the trim coils at a restricted number of 3M compounds.

A sample which reproduces the trim coils and spacers structure, see fig.10, was developed in order to perform the thermo mechanical tests and to take in place a good impregnation technique.

The tensile resistance of the samples was verified depending from:

- Thermal shock
- Radiation damage (20 MRad with 40 Mev protons)
- Spacer surface treatment
- Thermal curing schedules
- Deaerating with vacuum and vibration of the resin during casting

All the informations collected can be resumed with few statements:

- The most important damage for an epoxy resin is the thermal shock in particular for rigid types.
- Tensile strenght decreases until 30-40 % after thermal shock
- Tensile strenght decreases about 10-20 % after radiation damage
- Tensile strenght increases about 20 % with suitable choices of surfaces treatment, curing schedule, and so on.

5.2) Trim coils assembing on the hill

The trim coils, even if very well manifactured, require a mechanical fitting on the hills. During this operation we must take care do not damage the conductor insulation. When the fitting is completed the coils are disassembled and the hill is completely covered with a thin mylar sheet. This will allow to disassemble the coils from the hills for shimming or reparing if damaged, moreover we have an increase of the ground insulation.

Before the final assembling of the coils on the hills we perform a first series of electrical tests on the coils in order to verify their resistance and turn to turn insulation, fig.11 show the instrumentation for electrical tests.

The preliminary electrical tests sequence is this one:

1) With a particular transformer an a.c. voltage of the order of 20 volt, 50 Hz, is induced in the coil in order to verify turn to turn insulation.
2) The coil resistance is measured at a d.c. supply current of 50 A, with an accuracy of the order of 1%, and recorded.
3) The room temperature is measured at the beginning and at the end of the tests.

This procedure allow to check the coil resistance during assembly phases and verify the turn to turn insulation with a sensitivity larger than 50 mVolt.

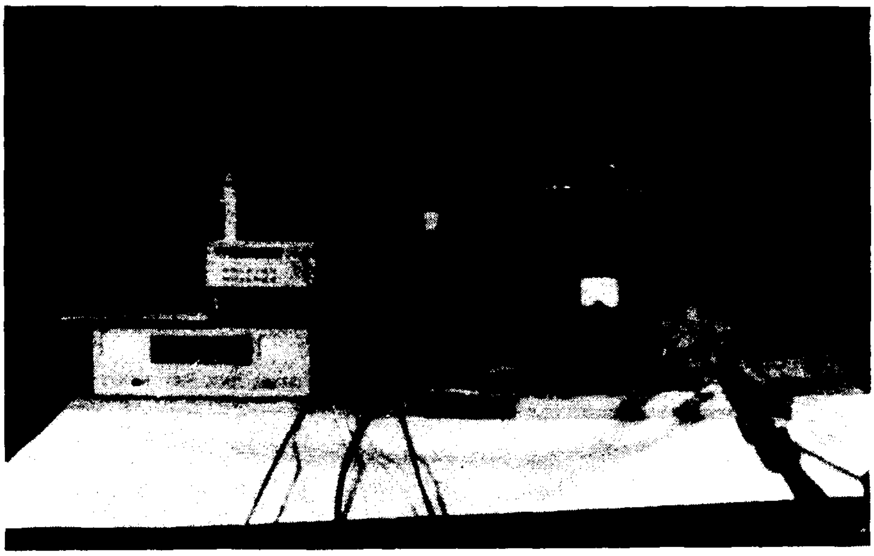

FIG. 11 - Equipment for the electrical tests.

After a careful cleaning, the coils are finally assembled on the hill. During the assembling, the electrical lead terminations are welded and, the vacuum tight current feedthrough are made.

A new series of electrical tests are performed, in order to verify: turn to turn, coil to coil and coils to ground insulation; then the coils are ready for the epoxy casting.

5.3) Moulding

The hill, with the trim coils assembled is removed from its stand and placed on a strong steel plate coated with PTFE enamel. This is the bottom side of the moulding box, mechanical references allow a proper positioning of the hill on the plate. The position of the vertical walls of the box is lightly variable in order to optimize the azimuthal thickness of the resin. These also PTFE coated are six pieces, which with screws, are fixed together and at the bottom side of the box.

The coupling between upper and lower hill is guaranteed by a proper aluminium plate, fixed on the spacers, even if, this makes worse resins deaerating of the upper coils side.

Accurately sealed the moulding box is ready for the introduction in the vacuum chamber.

The vacuum chamber overall dimensions are just a little greater than the moulding box, from the vacuum chamber's cover to the vacuum current feedthrough we have ten aluminium tubes with vacuum tight at their ends.

The working pressure of 5 - 10 mbar is achievied with a mechanical vacuum pump. The coils are heated at 70 - 80 °C, with a supply current of 50 - 100 A. We perform a continuous monitoring of the temperature in ten different coils'positions during all impregnation phases. Data are printed at time intervals of 5 - 10 minutes.

At the same time the procedure for the mixing begins following this scheme :

- Heating at 60 °C of the separated components
- Careful and repeated blending of the components until their density become homogeneous
- Mixing of the two components
- Deaerating under vacuum of the resin.

The resin ready for impregnation is contained in an heated chamber with four valves, and with a very low filling rate, put on the hot coils, under vacuum.

The total weight of the resin introduced is about 15 Kg.

The vacuum chamber is maintained in vibration during the injection procedure and moreafter.

Following this statements put on place during prototypes construction we have had good results from both functional and aesthetical points of view. Some of the mentioned operations are shown in fig. 12.

6) THERMAL PROTECTION

The magnet thermal protection has to be very well designed, our experience teaches us that it is better to have two or three indipendent safety systems. So we have considered needful a double indipendent thermal protection system for the trim-coils. The first, is a particular control circuit, in the power supply, which reads the coils' resistance and switches off the power supply for overtemperature.

The second one is composed of 120 thermometers, stuck on the hot spot of the coils. Their signals are monitored and processed in a particular unit which provides:

- Thermometer supply
- Signal linearisation and conversion to °C
- Power supplies switching off for coils' overtemperature
- Local and remote reading of the coils' temperature

A very reliable control of the water flow, was taken in account but considered too much expensive for the high number of flow switches involved.

7) POWER SUPPLY - COILS CONNECTIONS

To supply the trim coils we need at last 28 power supply, their output characteristics are rated at the coils' size. Another power supply is foreseen for the trim coil "zero" on the central plug of the machine.

The current stability on the order of 10^{-3} of full scale, a good efficiency for all the load conditions,low voltage ripple, low conducted and radiated noise and very little dimensions are the most important requirements of our specifications.

The power supplies manifactured by Elind Co.(MI) are grouped for 6 in 5 cubicles 1 mt depht, 2 mt large and 2.2 mt high. The regulating unit of each power supply, can be easily extracted from the cabinet as a plug on wheels for maintenance or repairing. In the cubicle take place also the local module of the computer control system for the six power supplies, this allows the remote control of the power supply and diagnosis of failure.

The electrical connections, among the coils on the upper and lower magnet pole caps are achieved with a multi layers copper bars system. Several months have been necessary for the interconnecting system design and to find a company able to manifacture it.

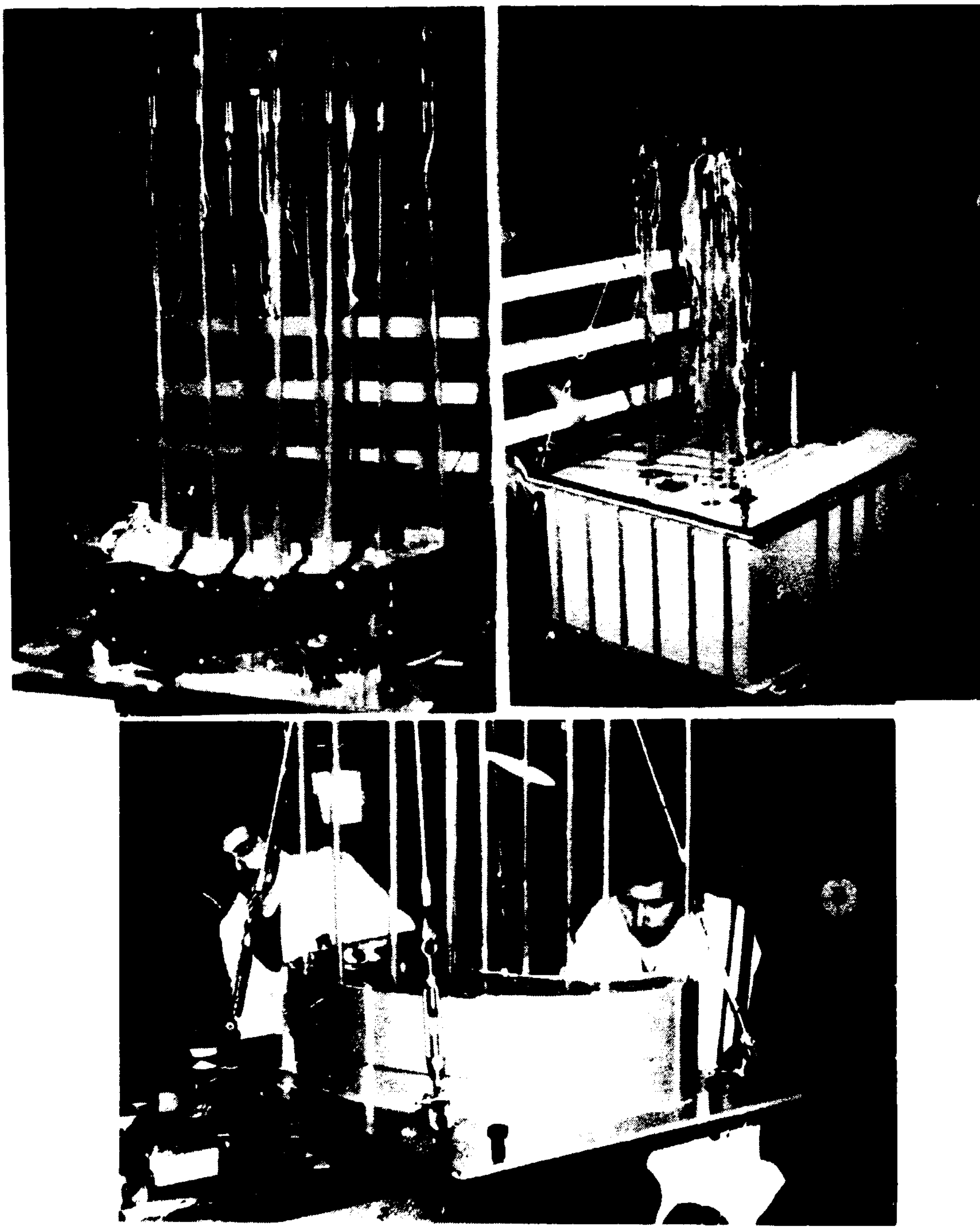

FIG. 12 - Trim coils moulding.

The interconnecting system was made by VEI Electric System Co. (MI). The figs. 13,14 pictures show a power supplies' cabinet and the interconnecting system under construction.

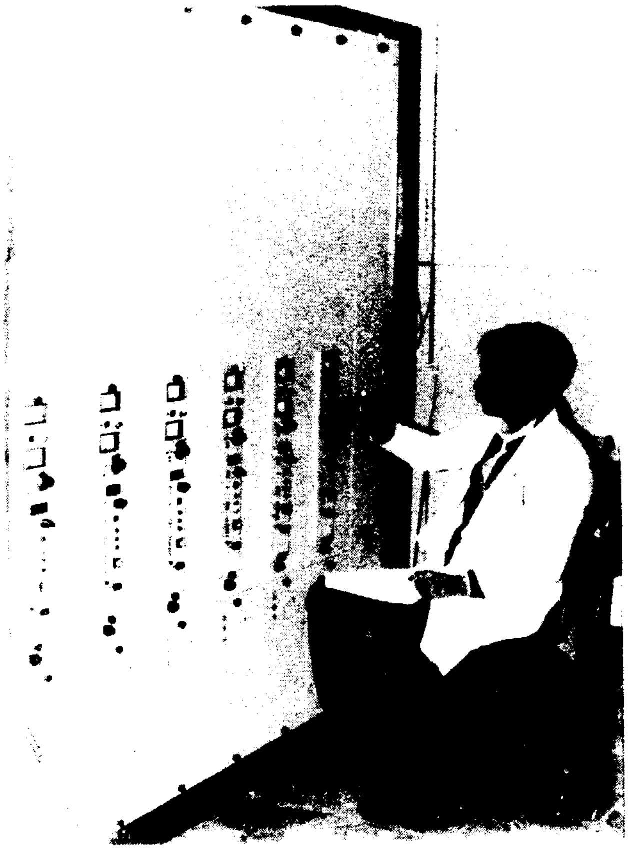

FIG. 13 - Trim coils power supplies.

FIG. 14 - Trim coils interconnecting system under construction.

8) CONCLUSIONS

We can say that the troubles in the trim coils' assembling and construction are overcome.

In the next months trim coils' work will be completed by:

- Impregnation of the trim coils on the upper hills
- Assembling of the trim coils on the magnet
- Assembling of the interconnecting systems on the magnet
- Set up of the power supplies

Authors are persuaded that the improved know how of the staff, with the construction and assembling of the trim coils is very important for the staff itself and, in the future, for the construction of epoxy impregnated magnets.

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