ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Genova

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PROPOSAL FOR THE DEVELOPMENT OF A TEST COIL FOR ASTROMAG

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ABSTRACT

The preliminary design of a test coil for ASTROMAG is presented. The test coil is designed in order to understand the stability limits of this type of winding . A fully impregnated winding is proposed: the conductor, the restraining structure and the cooling pipes are impregnated at the same time. An anisotropic banding structure is designed in order to reduce the shear stresses at the winding-banding structure border. The quench calculation is performed and an experimental program is also developed.

1.- INTRODUCTION

The ASTROMAG project, aiming to study the particle astrophysics, has a magnetic core, for deflecting the particles to be detected and recognized. The magnetic field is generated by a superconducting magnet, a thin aluminum stabilized solenoid(1,2,3), indirectely cooled by a circulation of superfluid helium (1).

The operation of such a magnet can be critical due to both the mechanical stress in the winding and the stability against disturbances.

This proposal aims for the first design of an ASTROMAG test coil, which allows :

1) to determine the parameters related to the stability i.e. the minimum propagation zone and the minimum energy to quench the magnet.

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2) to better understand the relation between the previous parameters and the strains of the winding during the cool-down and the magnet energization.

We started the design of the test coil taking into consideration the conclusions about the free-flyer aluminum magnet parameters (4) by M.Green. We will refer to these parameters as '*reference design*'.

Though in the following design the main structure of the winding is almost the same of the *reference design,* some changes are made on the cooling system and the support structure in order to have a complete and generally interesting R&D program .

2. - MAIN FEATURES OF THE TEST COIL

2.1.- Dimensions

Our aim is the design of superconducting solenoid , aluminum stabilized and indirectely cooled by LHeII. Since we are mainly interested to the stability of the winding, we chose to design a magnet with the same structure of the real solenoid (the same number of layers and turns) but with a shorter inner diameter. This choice is due to both the high costs of a 1:1 model and the possibility to use existing cryostats to test the coil. From these considerations the inner diameter of the test coil was set to 700 mm.. This dimension is also noticeable considering applications in balloon-borne experiments. The winding is composed by 28 layers of 90 turns wound with the conductor the characteristics of which are listed in Table I. The conductor is a composite NbTi/Cu enclosed by a co-estrusion process into a pure aluminum stabilizer.

TABLE I. Main parameters of the conductor

Dimensions:	2x3 mm^2	(nude)
	2.3x3.3 mm^2	(insulated)
NbTi/Cu/Al ratios	1 : 0.9 : 3.7	
Critical Current :	>900 A	at 4.2K and 8T
	>2480 A	at 4.2k and 5 T

This conductor was chosen(2,5) after a comparison with a copper stabilized conductor and we will not discuss this choice.

In order to solve a critical mechanical probem, the conductor insulation thickness was increased of 200 % with respect the reference design. This feature will be discused next section.

1.2. - Winding structure

A critical point of the winding is, in our opinion, the mechanical connection between the winding and the support structure . In the previous designes of astromag coils(2) or test coils(5) , this structure is an aluminum alloy cylinder. This cylinder, during the cool-down, overcomes a thermal contraction not matching the axial contraction of the winding so that an interface force takes place. This force can produce at any time movements of the winding with respect to the cylinder causing heat releases and quenching. This effect increases on charging the magnet, because the axial forces cause a further axial displacement of the winding, so that the shear stress at the interface is increased.

Using a conductor as defined by the *reference design*,this problem can be solved pre-stressing the cylinder in compressive state with respect the winding, so that on cooling down and on charging the magnet, no relative axial displacements take place. Nevertheless this solution requires heavy containing mechanical structures. A different solution was found and applied by us in designing and constructing an insert of a large bore (400 m) 10 T solenoid(6). This alternative solution is based on the use of an anisotropic banding structure. In the case of the ASTROMAG test coil, the banding structure can be made by winding an aluminum alloy strip onto the conductor winding and then impregnating the whole structure. This type of banding structure can be designed in order to match the thermal contraction of the winding so that the relative stresses due to the cool-down are canceled. A further advantage is that the axial Young modulus is strongly reduced with respect to the cylinder, so that the shear force at the winding-banding structure border is reduced too, lowering the probability that heat releases can occurr. Appendix A shows a comparison between the mechanical behaviour of the support cylinder and of the anisotropic structure.

We want to remark that using the conductor defined by the *reference design*, the axial thermal contraction of the winding would be lower than the contraction of aluminum. Nevertheless a structure with a thermal contraction lower than aluminum can not be carried out in a simple and feasible way; for this reason, we modified the conductor insulation thickness.

1.3.- Cooling channels

The drawback of using an anisotropic banding structure is the reduction of the thermal conductance between the coolant and the winding. This is an important point because the effectiveness of the coolant to remove the heat generared by some disturbance could be reduced.

This problem can be solved putting directely the cooling channels inside the winding and impegnating the structure composed by winding, banding structure and cooling channels (aluminum alloy pipes). Pure aluminum strips can be placed between some layers to improve the axial thermal conductance. Some of these layers can be used for quench back.

This test coil is then characterized to be a fully impregnated magnet with two electrical ends an two hydraulic ends. A cross sectional wiev of part of the magnet is shown in Fig.1.

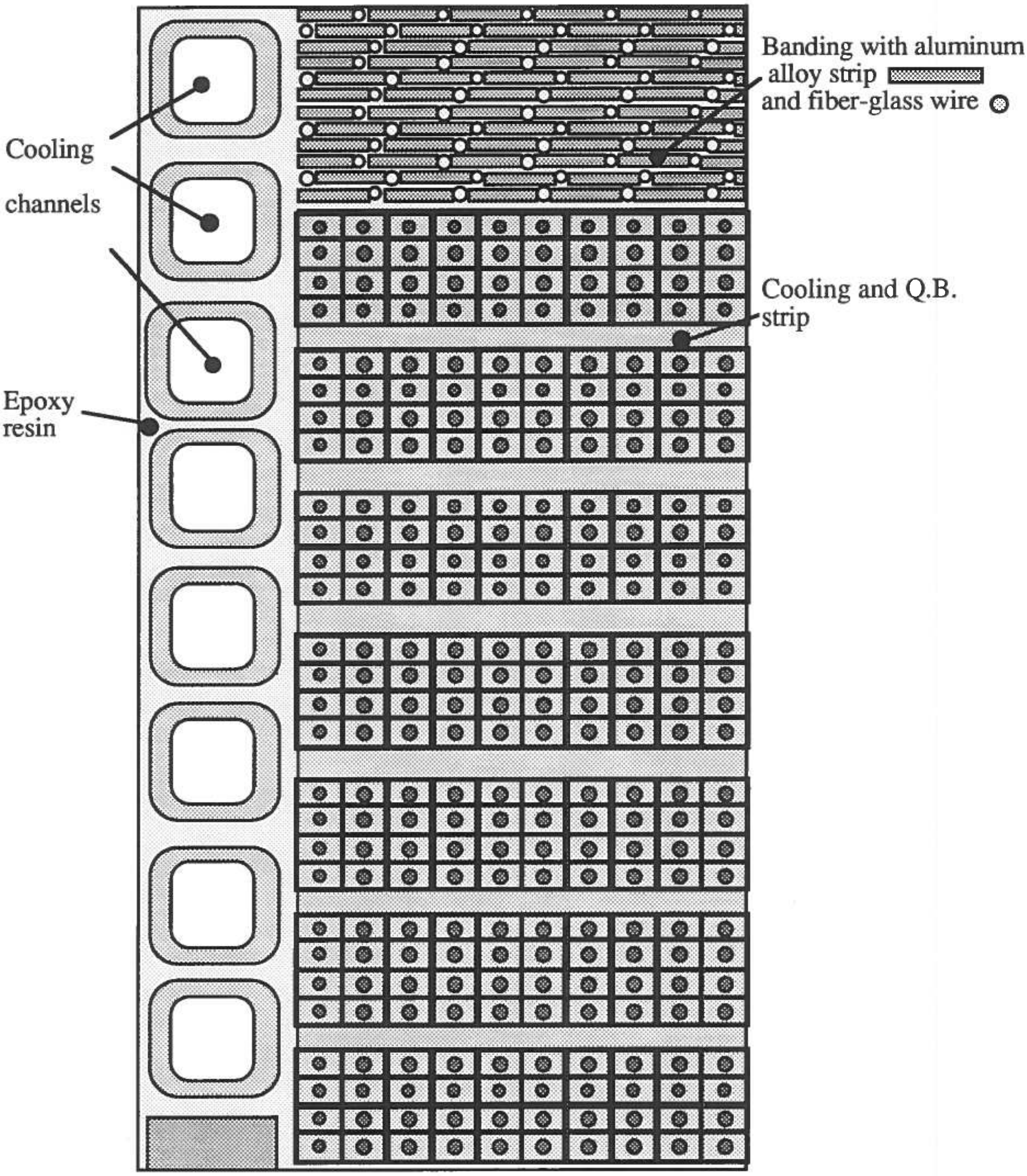

Fig.1 - A cross section of the designed test coil

In Table II the test coil parameters are listed. Fig.2 shows the load lines with the critical curves $I_c=I_c(B)$. at 4.2 K and 2 K.

TABLE II- Test coil parameters

Dimensions:

Inner diameter	700.0	mm	(Winding)
Outer diameter	843.2	mm	(Winding)
Outer diameter	873.0	mm	(Banding)
Lenght	297.0	mm	(Winding
Lenght	330.0	mm	(Overall)
No. of turns	90 x 28		

Electrical param:

Nominal current	800.00	A	
Central field	3.10	T	at R=0,Z=0
Peak field	5.20	T	at the winding
Inductance	4.87	H	
Stored Energy	1.56	MJ	at 800 A
Critical current	1150.00	A	at 4.2K
Critical current	1500.00	A	at 2.0K

Other parameters:

Cable lenght	6110.00	m	
Total weight	190.00	Kg	cold mass
Cooling	indirect		
Supporting system	anisotropic banding structure		

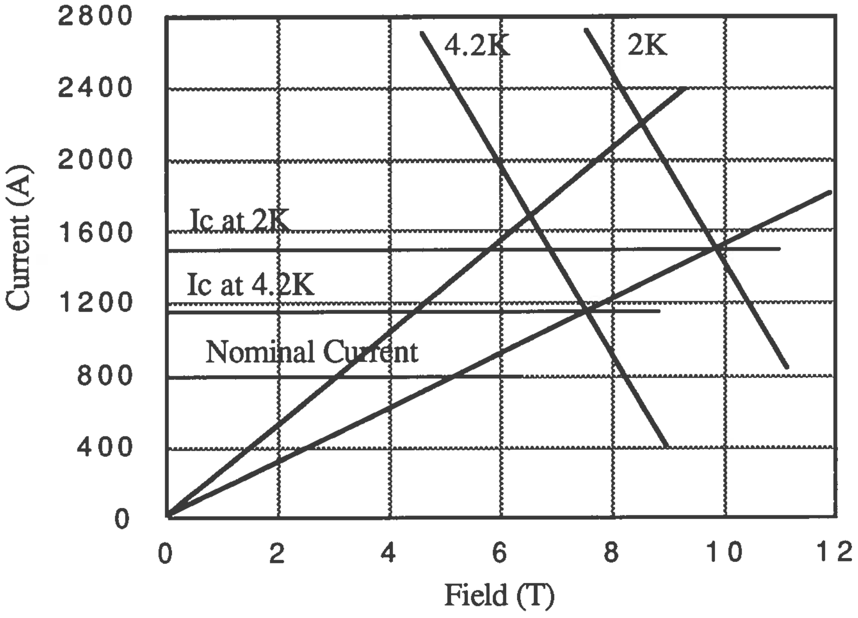

Fig.2 - Critical curves and load lines

3. - STRESS ANALISYS AND WINDING STRUCTURE

In order to calculate the stresses on the winding during the cool-down and the energization, the complete magnet history must be taken into account, because the elastic deformations due to the winding procedure and to the impregnation play an important role on the stresses of the energized coil. In this section we will follow an ideal magnet construction evaluating at any time the stresses in the winding.

The main problem, on performing such analisys, is due to the low yield strenght of pure aluminum; our experience and literature data give a value of $\sigma = 2.0$ Kgf/mm2 . The researchers of KEK(5), who developed a coil of the same kind, used a pure aluminum with $\sigma = 4.5$ Kgf/mm2 . The calculated stresses, as we will show, have values greater than these limits. This means that a stress analisys using only the elastic properties of pure aluminum can be wrong. A further indication is that the aluminum matrix is stressed beyond the elastic limit some times during the construction and every time the coil is cooled-down or energized. This last point will require a more accurate discussion, which will be reported in next sections.

3.1. - The model for stress calculation

The stress analisys is performed using a mono-dimensional shell model. The winding is considered as set of contrentric shells, each one being defined by an inner and an outer radius, a Young modulus E(T) and a thermal contraction coefficient $\alpha(T)$. Two neighbouring shells are mechanically coupled. In our case the winding was subdivided into 58 shells; a detail of the winding model is shown in fig.3. Since the analisys is carried out in the pure elastic limit, a critical discussion is made in some peculiar cases.

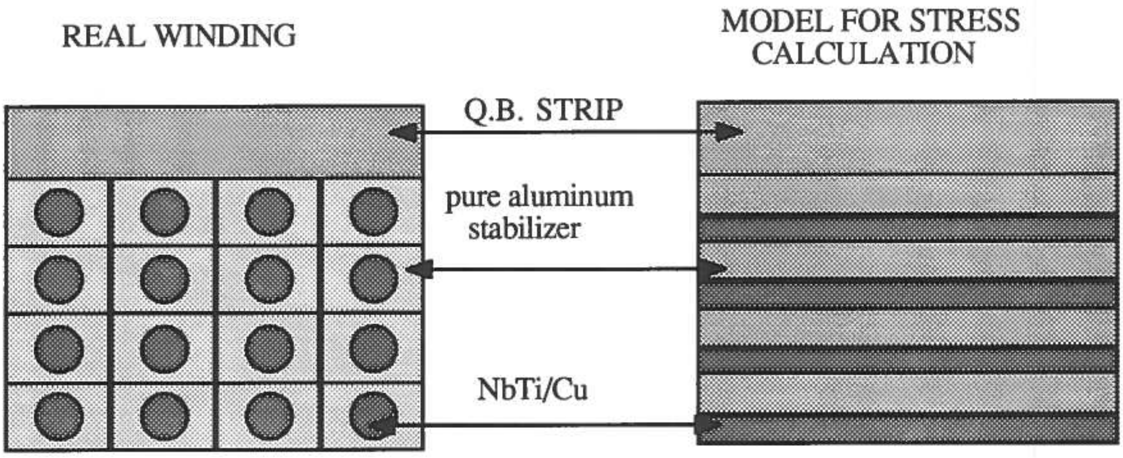

Fig.3 - The model for stress calculation

3.2. - Winding

The conductor is wound onto a dismountable aluminum alloy mandrel having a thickness of 25 mm. During the winding the conductor is kept in tension with a pressure of 2 Kgf/mm^2. After the conductor is wound, the aluminum alloy strip 5x1 mm^2 is wound onto the conductor winding (see APPENDIX A). The tension of the strip must be 5 Kgf/mm^2.

Fig.4 shows the calculated stress on the pure aluminum and the NbTi/Cu composite. The pure aluminum of the inner conductor layer is put into compression of -1.66 Kgf/mm2 while the pure aluminum of the outer layer is stressed in tension of 1.47 Kgf/mm^2. The NbTi/Cu composite is stressed of -1.81 Kgf/mm^2 at inner layer and 0.25 Kgf/mm^2 at the outer layer. The average tension of the banding structure is lowered to about 4.4 Kgf/mm^2. The mandrel is put in compression of 0.7 Kgf/mm^2.

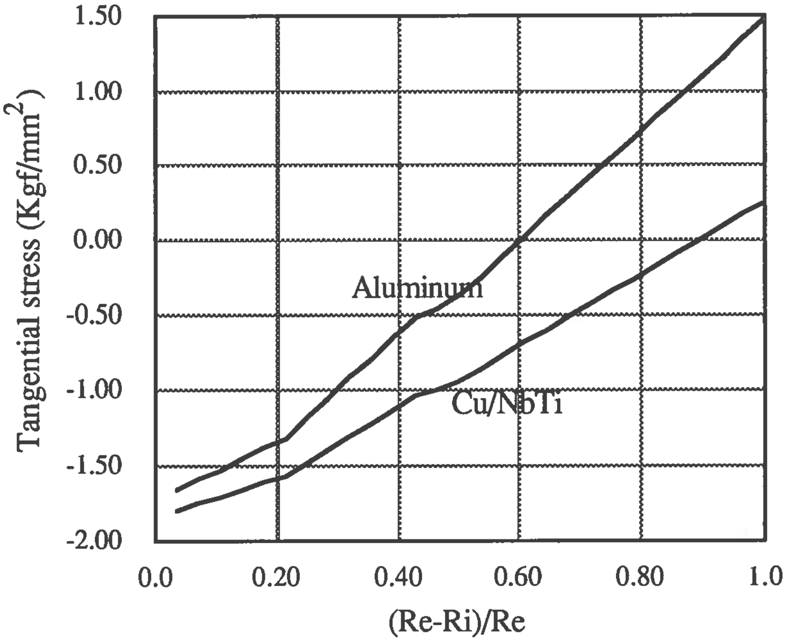

Fig.4 - Winding stress at room temperature

The cooling pipe can be wind on separate mandrel and then impregnated so that we have a disk-like structure. The disk can be coupled to the coil before the winding, using it as containing flange. It will be impregnated again at the same time of the winding.impregnation.

3- Impregnation and mandrel removal

The impregnation must be performed with an epoxy resin (ARALDIT with two components) mixed at a pressure of few mbars. The impregnated winding must be react. If the reaction is carried out at a temperature of 120 ^{o}C, the winding is stressed as shown in Fig.5. The pure aluminum of the conductor is stresses into compression up to -3.61 Kgf/mm^2 i.e. beyond or very close to the elastic limit of this material. In the framework of this proposal we will suppose, for simplicity, that the pure aluminum can be stressed up to 4.00 Kgf/mm^2 , but the final design must take into account the inelastic effects.

Removing the mandrel after the thermal reaction, the winding contracts, causing a stress release as shown in Fig.6.

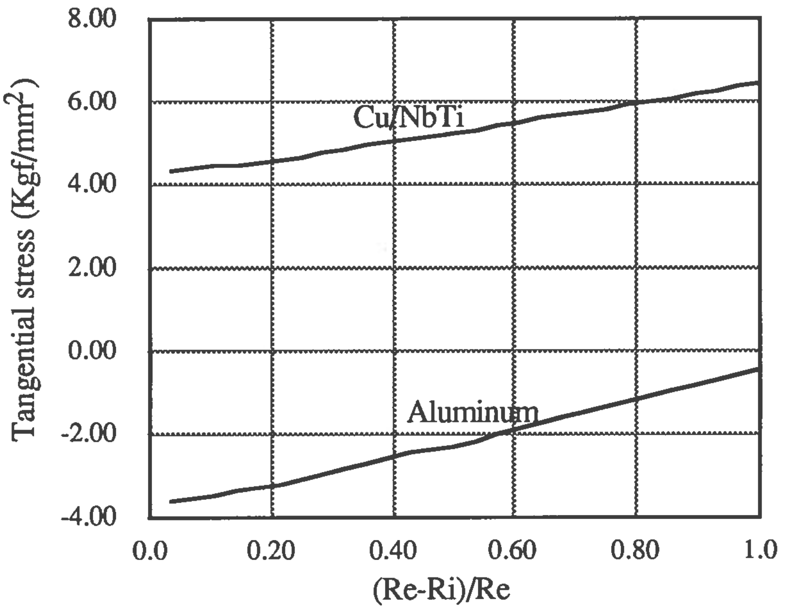

Fig.5 - Stress at the winding at 120 ºC during the thermal reaction

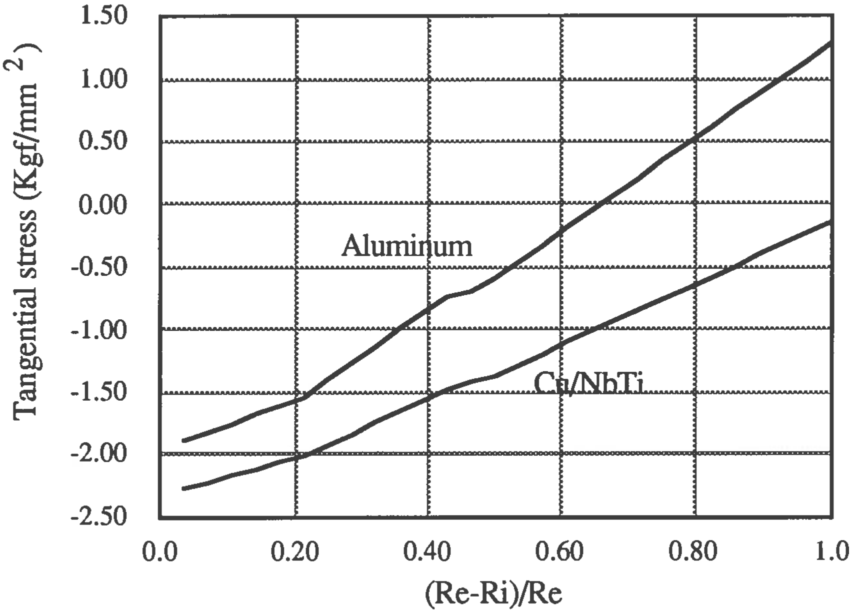

Fig.6 - Stress after the mandrel removal

3.4. - Cool down

The cool down causes an high stress of both Cu/NbTi (up to 9.81 Kgf/mm^2 of compressive stress) and of pure aluminum (up to 5.15 Kgf/mm^2 of tensile stress).

In this case the stresses of aluminum are quite higher than the elastic limits.. We have made a rought evaluation of the real stresses supposing that ,beyong a value of 4 Kgf/mm2 , the aluminum is no more stressed. The results are shown in Fig.7.

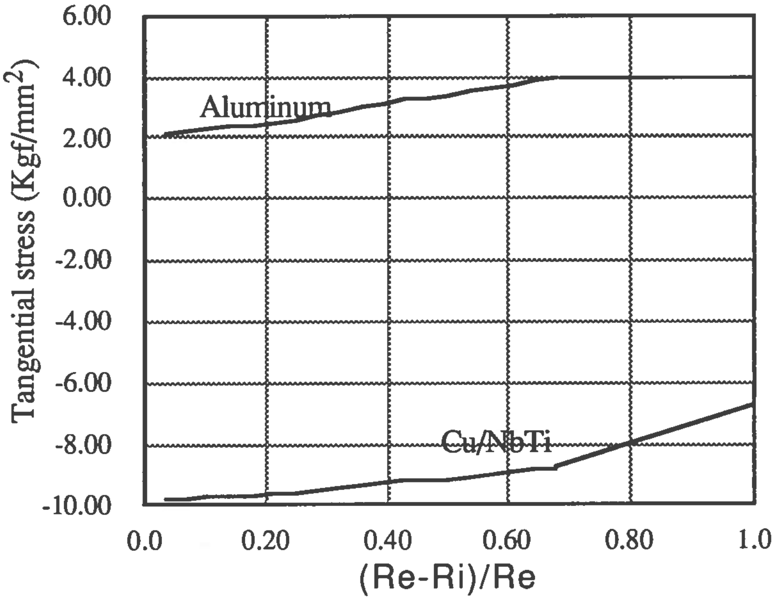

Fig.7 - Stresses due to the cool down

The outer banding structure is stressed up to 11 Kgf/mm^2.

3.5 - Energization

Energizing the magnet to the nominal curent the pure aluminum of the winding would be stressed much more the elastic limit. Also in this case we evaluated the real stress putting a limit stress on pure aluminum of 4 Kgf/mm^2. Fig.8 shows the calculation in both elastic and inelastic limits.No problems are for the Cu/nbTi , which is stressed well above its limits. The banding structure is put in tensile stress of 16 Kgf/mm^2; this means that the aluminum alloy strip are stressed up to 20 Kgf/mm^2. This last value is very close to the elastic limit of aluminum. The final design must take into consideration this point.

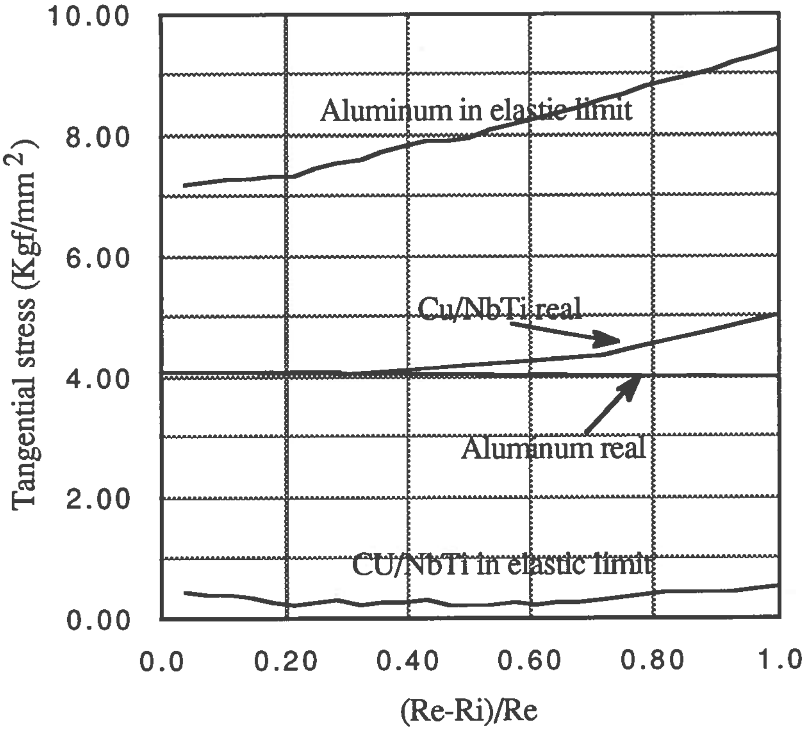

Fig.8 - Stresses of energized winding

3.6 - Further considerations

As pointed out on beggining this discussion about the mechanical problems, the pure aluminum of the conductor is several times stressed above its elastic limits. There are no problems for the winding because the forces are held by the banding structure and by the Cu/NbTi part of the conductor. The problems are related to the electrical properties of the pure aluminum. The stresses cause an hardening of this material with the consequent increasing of the electrical resistivity . Furthermore the plastic relative movement of the aluminum with respect the Cu/NbTi can affect the transverse resistance. Both these effects affect the stability of the winding, lowering the minimum energy to quench the magnet.

4. - THERMAL STABILITY

The thermal stability of the winding is determined by two parameters: the Minimum Propagating Zone and the Minimum Energy to Quench the magnet. These parameters should be measured directly. Nevertheless it is very important to develop a model for accurate previsions, because the real ASTROMAG magnet can have a different structure so that a checked model can be very usefull. The model can be only numerical and based on experimental tests performed on short samples of the conductor (It can be very interesting the transfer lenght measurements) We want to point out that the actual design has tried to remove the causes of heat generation inside the winding (See the reasons for using an anisotropic banding structure). Nevertheless we have also remarked the problem of the high stresses on pure aluminum, which can move with respect the Cu/NbTi . The elastic energy is then converted to heat . There is no way to understand these problems different from the experimenal observations.

5 - QUENCHING

The designed winding should not have any problem at the quenching. We have made the quench calcuation using the code QUENCH developed by M.Wilson. No protection resistance is included. The quench back ,due to the pure aluminum strips, is included through an high axial velocity. The quench propagation velocity was calculated to be 60 m/sec; for safety reasons the quench calculation was carried out using a velocity of 10 times lower.

The results for the temperature increasing of the hottest point, the current decay and the internal voltage are shown in fig.9

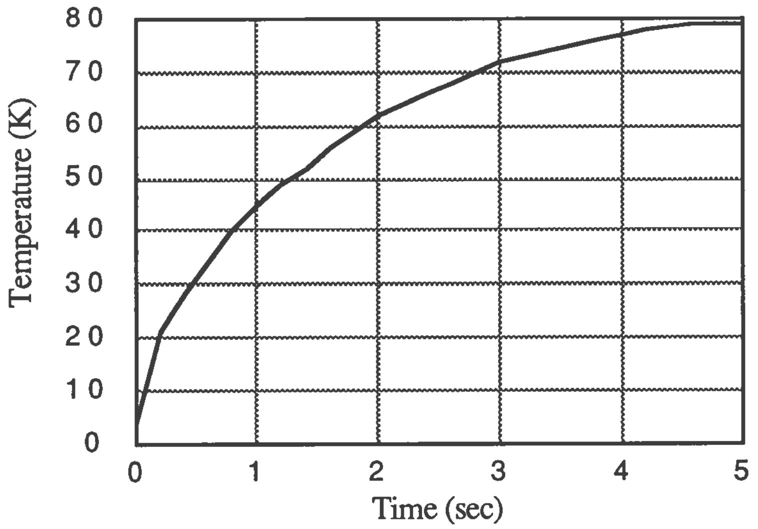

Fig.9.a - Temperature of the hottest point

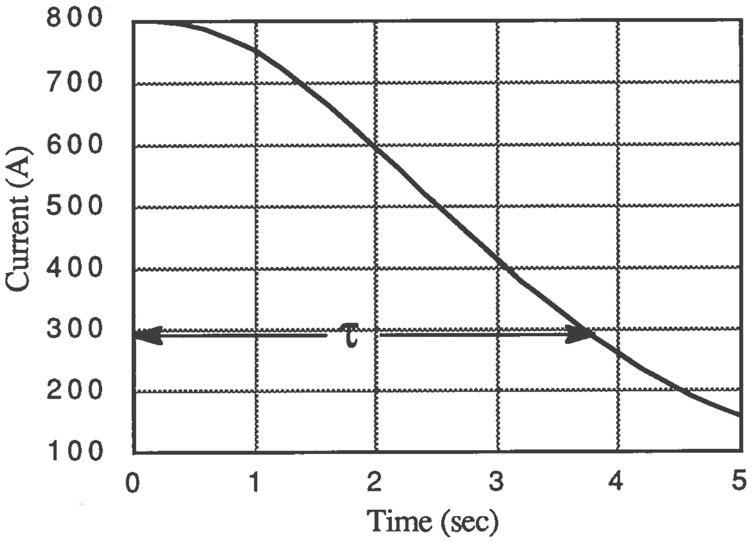

Fig.9.b - Current decay

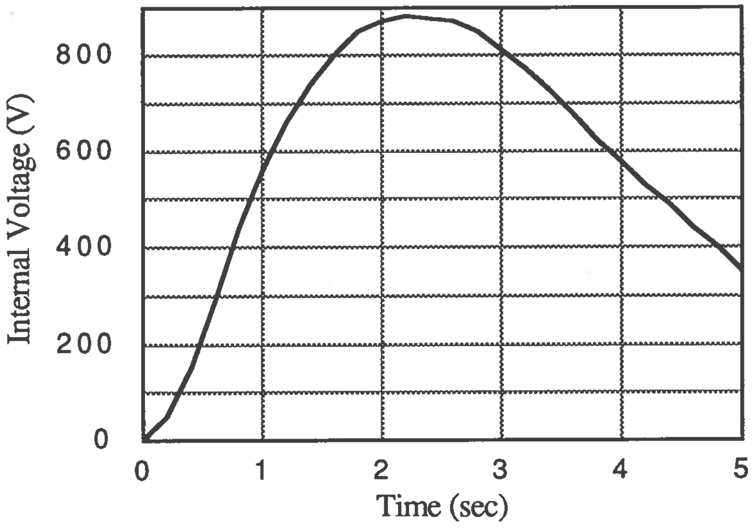

Fig.9.c - Internal voltage during the quench

6 - TEST PROGRAM

6.1 Sensors

The main purpose of the test coil is to check the stability properties i.e. the Minimum Propagating Zone and the Minimum energy to quench the coil. Heaters of different shapes must be put inside the winding at several positions of the inner layer. For each heater several voltage taps occur. It would be better to also use thermometers (Carbon glass sensors) placed close to the heaters. This type of instrumentation would allow to perform significant stability measurements

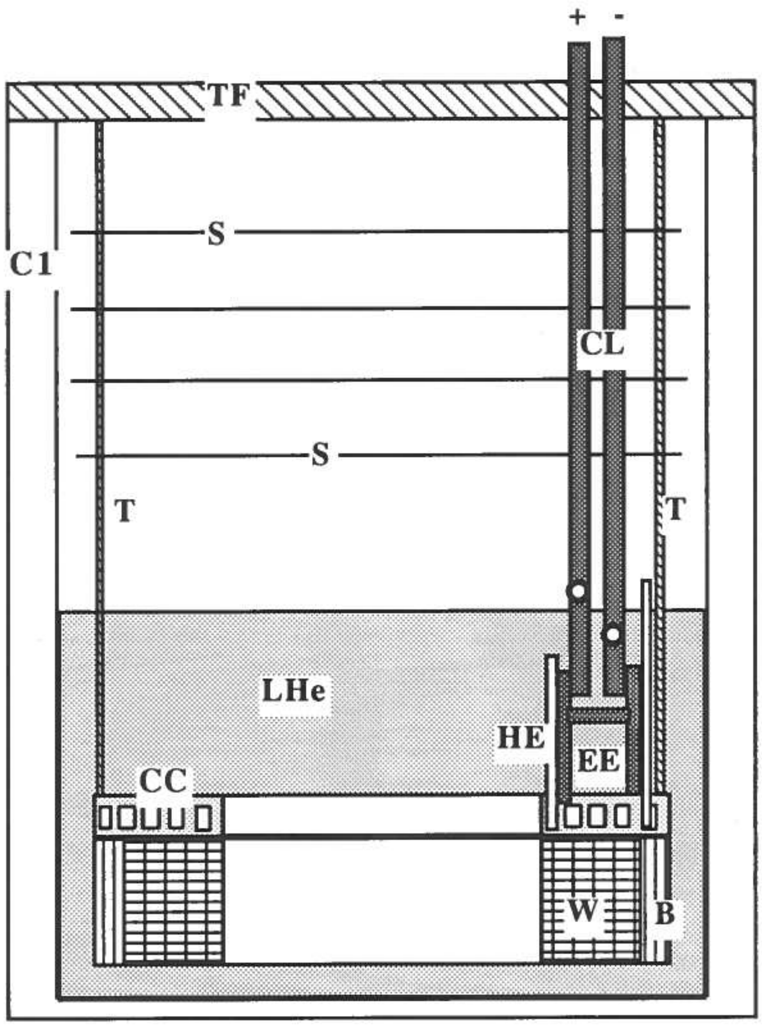

Fig. 10 - Setup for 4.2 K measurements : TF - top flange; C1 - vertical cryostat; S - thermal shields; CL - current leads; T - tie rods; HE - hydralic ends; EE - electric ends; CC - cooling channels; W - winding; B - banding structure

6.2 - Measurements at 4.2 K

It is advisable to perform the first tests at 4.2 K. This can be simply made putting the coil into a vertical cryostat filled with liquid helium. Fig.10 shows the set-up . The nominal current and the possible training can be check. The stability measurements can be also performed. Other interesting tests like the operation in persistent mode can be also carried out.

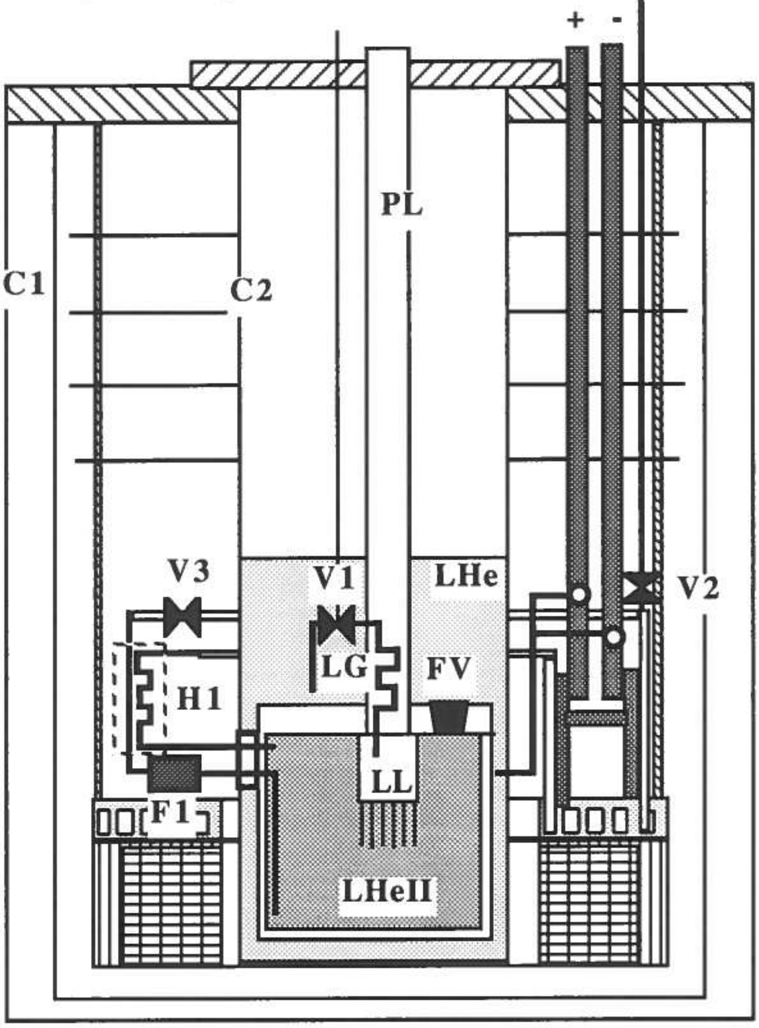

FIG 11 - Set up for 2K measurements: C1- Vacuum tank; C2 - LHe I&II vessel; PL He pumping line; V1- saturate LHe II flow controling valve; LG - saturate LHeII liquid-gas exchanger; LL - saturate LHeII liquid-subcooled LHeII liquid exchanger; FV - filling valve; F1 - porous element; H1 - fountain effect pump heat exchanger ; V3 - Circulation controlling valve; V2 - Cooldown controling valve

6.2 - Measurements at 2 K

The more complex and complete test at 2 K can be carried out in the same cryostat with a setup shown in fig.11. This test requires a LHeII circulation, which can be obtained by using a fountain effect pump. The cryostat C1 is now used as a vacuum tank containing the magnet and the LHe vessel C1. This vessel contains an insulated chamber filled by subcooled LHeII cooled by pumping the LHe bath through the heat exchangers LG and LL. The subcooled helium is then circulated by a fountain effect pump driven by the heat released by the magnet. The current leads are cooled by a gas flux starting from the LHe bath. The subcooled LHeII bath is in thermal contact with the the LHe bath through a leak in the filling valve FV.

7. - CONCLUSIONS

The aim of this study, far to be complete, was to give the guidelines for the development of a test coil for ASTROMAG. The dimensions of test coil were determined. A winding with some new ideas was proposed and the feasibility checked by a simple mechanical analysis. We think that this work can be followed by an engineering design carried out with the collaboration of an industrial partnership. Several problems must be solved: 1- The mechanical behaviour is to be checked testing the properties of the available pure aluminum and using a finite element analysis (ANSYS CODE) for the stress calculations; 2- The cooling and Q.B. strips require a more accurate design taking into considerations the thermal effects during the magnetic field variations; 3- The setup for 2 K measurements is only preliminary and verifies are needed. 4- The codes for stability calculation must be developed and tested by an experimental activity on aluminum stabilized conductor prototype.

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APPENDIX A

CONTAINING CYLINDER AND ANISOTROPIC BANDING STRUCTURE

In this appendix we will show the advantages of using an anisotropic banding structure with respect a containing cylinder.

For simplicity let we consider two coupled structures of parallelepipedal shape as shown in fig 12. The structure "m" is the coil and the ones called "c" is the outer cylinder or banding structure.

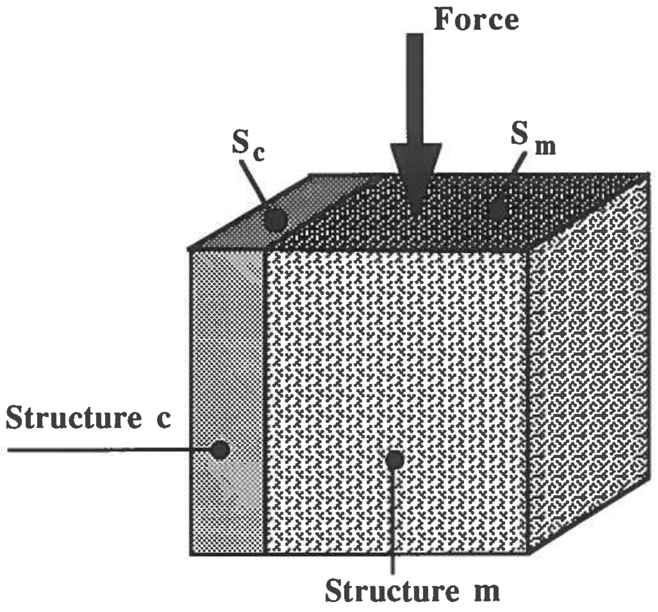

Fig.12 - Model for axial stress calculation

Case 1 -outer cylinder

Let be E_m and E_c the Young moduli (in this case E_c(at T=4.2)=8000 Kgf/mm^2 and E_m=6400 Kgf/mm^2) α_c and α_m the relative thermal contractions from 300 to 4.2K : α_c =0.0042 and $\alpha_m = 0.0038$ in the case of *reference design*. The thermal contraction of the two coupled structures is:

$$\alpha=(S_cE_c\alpha_c+S_mE_m\alpha_m)/(S_cE_c+S_mE_m) \qquad \text{(A.1)}$$

Where S_c and S_m are the cross sections, as shown in fig 12.

From A.1 we find $\alpha=0.0039$, so that the cylinder goes in compressive state with a strain of $\varepsilon=0.0039-0.0042=-0.0003$ while the coil is in tension of $\varepsilon=0.0039-0.0038=0.0001$. Using the stress -strain relation

$$\sigma=E\varepsilon \qquad \text{(A.2)}$$

We find an axial stress of 2.4 Kgf/mm^2 on the outer cylinder, corresponding to a shear force of 95 tons at the cylinder-coil border.

Case 2 - anisotropic banding structure

The shear force at the border , due to the cool-down, could be completely canceled if the outer containing structure had the same thermal contraction of the winding. Nevertheless there is no practical way to reduce the axial contraction of the outer structure. It is easier to modify the winding, by increasing the conductor insulation thickness, because the insulation material can have very high thermal contraction. Though this solution allows to design a winding with the same axial thermal contraction of aluminum, we propose to design a winding with a thermal contraction higher than aluminum, so that we have however to modify the outer structure. The reason of this choice is the following:

Let we suppose to insulate the conductor using Polyvinyl formal with a thickness of 0.09 mm. The axial thermal contraction of the banding structure is just 0.0043.

During the energization of the magnet, an axial force F_m , inward directed, takes place. This force of strenght 4 MN causes an axial deformation of the magnet structure (banding structure + winding) Δ r=0.142 mm. Nevertheless being the force applied only to the winding, we have again an axial shear force F_s at the border winding-banding structure . The shear force can be calculated as:

$$F_s=F_m\,(E_cS_c/E_cS_c+E_mS_m)=1\ \text{MN} \qquad \text{(A.3)}$$

Though it is not possible to avoid that the force F_s occurs, we can reduce it, if the banding structure Young modulus in the axial direction is lowered as possible with respect to the winding Young modulus.

This can be made if the conductor insulation thickness is increased to 0.15 mm. In this case the axial thermal contraction is about 0.0046. Using a banding structure as shown in fig. 1, by winding an aluminum alloy strip with glass spacers onto the coil, the thermal contraction matches the new one of the coil so that no shear force takes place during the cool-down During the energization, being the axial Young modulus 3700 Kgf/mm^2(a value of 53% lower than the aluminum cylinder Young modulus) the force F_s is lowered of 30%.

The mechanical properties of this banding structure along the circumferential direction are changed with respect to the cylinder: the elastic Young modulus is lowered from 8000 to 6600 Kgf/mm^2 and the yield strenght is lowered from 24 to 19 Kgf/mm^2 .

APPENDIX B

MECHANICAL PROPERTIES OF MATERIALS

Material or structure	E (Young) at 300 K Kgf/mm^2	E (Young) at 4.2 K Kgf/mm^2	Thermal contraction 300->4.2	Yield strenght at 4.2 K Kgf/mm^2
Pure Aluminum	6800	7500	0.0042	2.0-4.0
Aluminum alloy (5456-0)	7000	8000	0.0043	25
Cu/NbTi	11400	12800	0.0025	50
Conductor (circ.)	8500	9600	0.0033	
Conduct insulation	700	800	0.0160	
Conductor (axial)	8200	9300	0.0038	