AGOR CRYOGENICS: A STATUS REPORT

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SUMMARY

In cooperation with the manufacturers of the superconducting coils and their cryostat and the refrigeration system for the AGOR cyclotron the design of the AGOR cryogenic system has been almost completed. The most important aspects of this design are discussed especially with respect to the lay-out of the superconducting coil system and the operation of the refrigeration system. Several parts of the cryogenic system are presently in production.

GENERAL INTRODUCTION

AGOR, the joint project of the Dutch organisation FOM and the French organisation IN2P3 is now in the stage of production of the different subsystems. As far as the AGOR cryogenic system is concerned the production of the coils, radiations shields and cryostat has been granted to Ansaldo Componenti SpA, Genoa, Italy in July 1988. At Ansaldo the final productions drawings are at present (May 1989) almost completed. The orginal AGOR design has been modified slightly to comply with the manufacturers production techniques and experience. Recently the drawings of the cryostat have been approved by AGOR for production. Coil winding will start in July 1989 and the complete system is expected to be ready for domestic tests in May 1990. Delivery of the system to the IPN in Orsay is scheduled for August 1990.
The order for the production of the system refrigerator and transferlines has been given to Sulzer Winterthur, Switzerland in December 1988. Several parts of this system are already in production. Partial delevery of the different subsystems to Orsay will start in October 1989 and installation should be completed by the end of January 1990. The system will than be commisioned by using a test cryostat presently under development at the IPN, that can simulate the different operating conditions of the cyclotron. Since the last papers presented on the AGOR cyrogenic system [1,2] a number of modifications has been adopted basically to improve the mechanical stability of the coil system and the performance of the cooling system. These modifications and the actual design are described in this paper.

SPECIFICATIONS OF THE SUPERCONDUCTOR

The three main parameters, defining the specification of the superconductor are the maximum field strength at the conductor, the maximum current and the temperature. To provide a reasonable temperature margin the superconductor will be used at only 40% of its critical current. Therefore the superconductor can absorb small amounts of dissipation without becoming normal. This is especially important for boundary cooled vacuum impregnated coils. We defined the cross section of the conductors as being; coils 1: 5.2 x 2.9 mm² and coils 2: 8.5 x 5.4 mm². The short sample values for the conductors are 2150 A at 3.7 T and 4.6 K for the coils 1 and 4500 A at 4.8 T and 4.6 K for the coils 2. The total conductor length will be 7.1 km for one coil 1 and 10.4 km for one coil 2. A standard round wire from Asea Brown Boveri (type S66) will be used as the basic conductor. It has a bare diameter of 0.77 mm, with a Copper to superconductor ratio of 1.3. To reach the required critical current, a round cable with a diameter of 1.6 mm, consisting of four basic conductors will be produced for coil 1. For coil 2 a rectangular shaped cable with a dimension of 1.2 x 4 mm² will be produced out of eleven basic conductors. Finally, these cables will be soldered into their respective copper substrates. the final conductor for coil pair 1 will be produced in five lengths for each coil and for coil 2 in seven lengths. As a consequence a total of 20 joints has to be made during the production of the coils. At present about 400 km of the basic conductor is being produced and will be finished in June 1989. Delivery of the different batches of the final conductor to Ansaldo will start in July 1989.

PRODUCTION OF THE MAIN COILS

The final geometry for the AGOR main coils is given in figure 1. The tolerances on the field profile are tight in both the acceleration plane and in the area where the extraction elements are placed. As the field gradient is very steep in the extraction region and the performance of those elements is related to the field strength of the main coils, the dimensions indicated in figure 1 should be realised at the operating temperature (4.5 K) of the system within a tolerance of 0.5 mm. This requires amongst others a precise calculation of the coil dimensions at room-temperature. The thermal expansion coef-

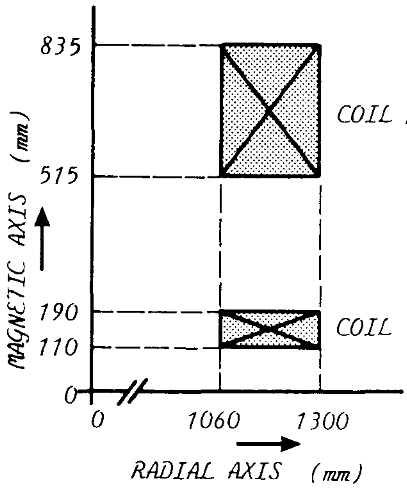

Figure 1: Final geometry of the AGOR coils.

ficents are different in tangential, radial and axial direction of the coils and depend on the relative Copper/glass-epoxy factions in the winding package. With respect to the production two fundamental aspects of the AGOR coils are: 1) the AGOR coils are not adhered to their coil casings to avoid the risk of epoxy cracking at the boundary between coils and casings, and 2) the liquid Helium is in contact with all outer surfaces of the winding packages to improve the thermal stability. As a consequence these coils can not be wound and impregnated in the same casings. This has to be done in a temporary (re-usable) winding mandrel. The winding itself will be realised as follows: the composite conductor will be wound in layers and insulated by two layers of glass tape with an effective thickness after winding of 0.125mm. Between each layer one extra glass-cloth layer will be applied. So called R-glass, that is free from Boron, has to be used to avoid the risk that the glass epoxy is activated due to irradiation, thus reducing the mechanical strength of the epoxy.
The coils 2 will consist of 40 layers each having 36 turns and the coils 1 will have 70 layers with 14 turns each. The joints, six for each coil 2 and four for each coil 1, will be brought to the side flange and have a soldered length of 200 mm each.
After the winding is completed, the AGOR coils will be vacuum impregnated in special made moulds inside an autoclave. After impregnation the magnetic field profile of each coil will be measured and the outer surfaces of the coils will be machined in such a way that the magnetic tolerances are fulfilled. The next step concerns the mounting of an outer banding cylinder, that was introduced to reduce the hoop stress in the coil system well below 100 N/mm^2. After that, another field measurement will be done and reference points will be made on all banding cylinders. These reference points will be used in the final assembly of the coil system, in order to meet the mechanical tolerances as required. There after the side flanges, facing the median plane, will be prepared. Copper plates to be mounted onto these flanges, provide a path of low thermal resistance to the Helium, hence friction heat, produced when the coil moves radially due to the Lorentz force, is transfered to the liquid Helium instead of to the conductor.

The other side flanges will be equipped with a special spring type stainless steel plate that is used to cope with the axial load on the coils so that their position inside the casing is firmly fixed. Finally, the coils will be put inside their stainless steel (316 LN) casings which will be closed by welding the side flanges under an axial preload of about 400 tonns.

LAY-OUT OF COIL CASINGS

The final evaluation of the stresses in the supports of the coil system across the median plane, the construction of the coil casings and the supports between the coils 1 and 2 has been done using the three-dimensional finite-element computer program CASTEM from CISI, France. Starting from a preliminary design "O" made for the "AGOR cyclotron design report"[3], an iterative design and calculation process was initiated to obtain lower values for the different stress levels on the coils. In all calculations stainless steel 316L was considered to be the structural material for the mechanical construction while the winding packages were considered as being an an-isotropic medium characterized by the Young's moduli $E_r = E_z = 30$ GPa and $E_\theta = 110$ GPa. The magnetic forces working on the mechanical structure were obtained from the program POISSON. The first modification (design A) was to rotate the twelve inter coil supports by 90 degrees. This resulted in a reduction of about a factor of two in the deflection at the inner circumference of the coils 1. In design B we modified the intercoil support by adding a circumferential wall at the inner and outer diameter combined with six radial supports. In this calculation we also implemented the higher attracting forces between the coils due to a reduction of the height of the iron yoke from 3.8 m to 3.6 m. All this resulted in higher deflections and stress levels in the coils. Only the compressive stress was reduced. In design C we shifted three of the median plane supports towards the inner diameter of the coils again combined with twelve radial supports between the coils resulting in a considerable reduction of deflection and stress levels. Finally, with the geometry "D" we obtained a system that showed acceptable stress levels (and deflections). The geometry D is the basis for a more detailed design presently in progress at ANSALDO Genoa. The mesh for the design D is shown in figure 2.

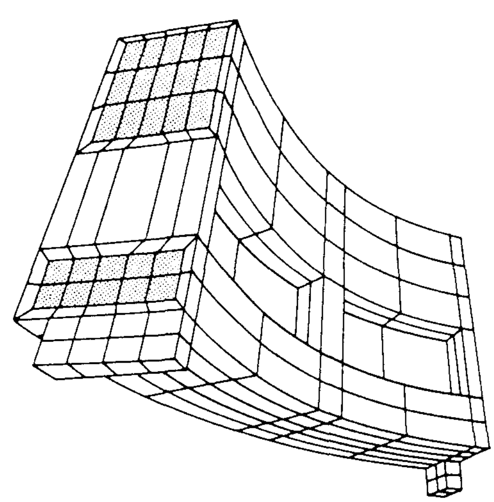

Figure 2: proposed lay-out of coil casing.

The results in terms of the deflections at the inner diameter of the coils 1 of the designs O, A, B, C and D is given in figure 3. Calculations were done for the

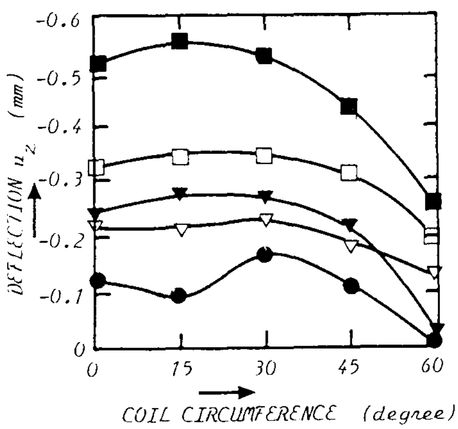

Figure 3: calculated deflections at inner diameter coil 1

operation point B, in which the current settings of the coils give the maximum attracting forces between the coils.
In this operating point the maximum equivalent stress in the mechanical structure is less than 200 N/mm². In the coils we obtained also safe values for the stress levels: the compressive stress will be less than 25 N/mm² and the maximum shear stress will be less than 10 N/mm².

THE AGOR REFRIGERATION PLANT

Based on the guaranteed values of the heat loads on the main coils and expected values for other subsystems like superconducting extraction elements, the maximum cooling capacity for the system refrigerator was specified as 600 W at 80 K, 50 W at 4.5 K and 15 l/h liquid Helium simultaneously in refrigerator mode and 50 l/h of liquid Helium in liquefaction mode. This cooling power will be provided by a Sulzer type TCF 50 coldbox. The refrigeration plant further comprises two 13 bar compressors, a 1000 liter storage dewar, connected to the coldbox by two standard transferlines, a main transferline of about 13 m length with 5 inner lines connecting the coldbox to the distrubution box that will be installed close to the main cryostat and several flexible transferlines between the distribution box and the different cryogenic service ports on top of the cryostat as well as the superconducting extraction elements in the median plane. A flow chart of this system is given in figure 4, in which also the main components are indicated.

OPERATION OF THE REFRIGERATION PLANT

The 4 K System
The liquefier/refrigerator is connected to the storage container by means of a standard coaxial transferline. In normal operation, the liquefier produces into the storage container.
From the storage container two-phase Helium is fed via the coldbox and the main transferline into the buffer volume inside the main cryostat. Part of this flow can be used for cooling of superconducting extraction elements. The mass flow is regulated by the pressure difference between the storage ocntainer and the main

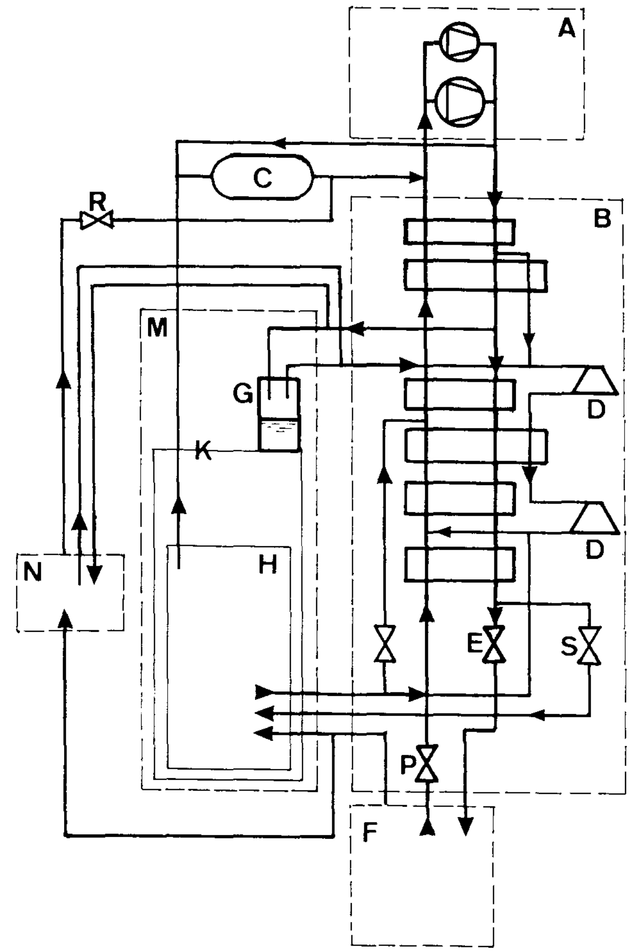

Figure 4: flow chart of the AGOR refrigeration system.
A: compressor group, B: coldbox TCF50
C: 20 m³, 15 bar, 300 K buffer vessel,
D: turbine expanders, E: J-T valve,
F: 1000 liter storage container,
G: Nitrogen recondensor main 77 K shield,
H: main coil system, K: main 77 k shield,
M: main cryostat vacuum chamber,
N: superconducting extraction system,
P: regulation valve main coils cooling,
R: regulation valve extraction cooling.

cryostat. The maximum pressure inside the main cryostat is limited to 1.4 bar absolute.
The liquid Helium that evaporates from the main cryostat can leave the cryostat in two ways:
The first part is fed back at low temperature to the refrigerator via the main transferline and joins inside the coldbox the gas return line of the storage container. Both streams enter the refrigerator at the level of the Joule-Thomson heat exchanger.
A second part leaves the main cryostat while cooling the three current leads of the main coils. The warm Helium gas is than fed back to the suction side of the compressor.
The cooling cycle is completely closed, thus avoiding impurities in the Helium gas.

The refrigerator is also used for a controlled cooldown of the main coils from 300 K to 4 K. The main coils will be fully vacuum impregnated, and thus the cooldown requires special attention to avoid epoxy cracking. Therefore the maximum temperature difference over a coil will be kept below 40 K. The refrigerator will be regulated by a control system using the temperature sensors attached to each of the coils.
In this mode the Helium will bypass the production container and will be connected via the main transfer line to the cooldown circuit of the main coils. The return gas will leave the cryostat through the main transferline and will enter the refrigerator at the appropriate level.
The cooldown time of the system (including initial filling with liquid Helium) will be less than 21 days. In principle, no liquid Nitrogen will be used to boost the refrigerator. After cooldown both the main coils (250 liter) and the storage container (1000 liter) are filled at a rate of 50 l/h.

The 80 K System
An 80 K cold Helium gas circulation system will be used for the recondensation of evaporated Nitrogen from the radiation shield of the main cryostat, for the cooling of the radiation shield inside the main transferline and possibly also to cool the inner and outer radiation shields of a superconducting electromagnetic channel presently under study. The cooling power for the 80 K system is provided by the refrigerator. The 80 K lines will be implemented in the main transferline connecting the refrigerator to a distribution box close to the cyclotron.

The Compressors
Due to the multiple functions and operating modes of the cyclotron, two screw compressors with different capacity (36 g/s and 10 g/s) will be installed. During normal operation the larger one of these compressors should be able to provide the neccesary mass flow for the liquefier. During cooldown and fill-up of the system both compressors are used to obtain the maximum plant capacity. In the shutdown mode, when only the coils have to be kept at a temperature of about 80 K the smaller one of the compressors will be used in order to save on running costs.

REFERENCES

1) K. Pieterman, Proc. 11th Int. Conf. on cyclotrons and their applications, Tokyo 1986, p. 548.
2) C. Commeaux, Proc. 12th Cryogenic Eng. Conf., Southhampton 1988, p. 246.
3) AGOR design report, IPN October 1986.