THE CRYOGENIC SYSTEM FOR THE AGOR SUPERCONDUCTING CYCLOTRON

K. Pieterman, C. Commeaux^{+}, J.A.M. Dam^{++}, A. Kollen^{++}, G. Levy^{+}, H. Postma^{++}.
Kernfysisch Versneller Instituut
Zernikelaan 25, 9747 AA Groningen, The Netherlands
$^{+}$ Institut de Physique Nucléaire
P.O. Box 1, 91406 Orsay Cedex, France
$^{++}$ Dept of Applied Physics, Delft University of Technology
P.O. Box 5046, 2600 GA Delft, The Netherlands

Summary

The AGOR project is a close cooperation between the Dutch Kernfysisch Versneller Instituut (KVI) and the French Institut de Physique Nucléaire (IPN). The purpose of the project is to install a superconducting cyclotron at the KVI in 1992, that will be able to accelerate both light and heavy ions at central field strengths ranging from 1.7 T to 4.07 T. This field is generated by a set of four fully vacuum impregnated superconducting coils, cooled by liquid helium at the total outer perimeter.They will be housed in a split cryostat in which roomtemperature access is provided to most of the mid-plane. In the design of the cooling system much effort has been given to enhance the overall efficiency.

Introduction

In most of the superconducting cyclotrons that are today in operation or under construction, the superconducting coils are cooled by pool boiling of liquid helium. Spacers between the winding layers or between the pancakes provide a cooling path for the liquid helium inside the winding package. The advantage of a winding technique like this is obvious: most of the outer surface of the actual conductor is in direct contact with the coolant, so eventual heat losses in the conductor can be absorbed by the liquid helium.However there is also a severe problem that these superconducting coils have in common: the risk of electrical shorts. Most of the existing cyclotrons have experienced this problem during or after winding$^{1-3}$. The repair of these shorts can take months as in Chalk River, where metal particles were penetrated inside the coils.Moreover with a pancake type of winding there is the problem of exact positioning of the different pancakes relative to each other. It must be done within close tolerances to get the actual field profile of the system accurate enough for proper operation. To overcome these problems an alternative coil lay-out is proposed for the superconducting coils for the AGOR facility. The coils will be layer wound with an insulated conductor on a well machined mandril and will be fully vacuum impregnated after winding. In this way it is possible to produce rigid coils with excellent electrical insulation. For the design of the cryostat the most complicated part is the mid-plane section. Since there is only a narrow gap between the coils just above and below the mid-plane the realisation of the feedthroughs for the extraction elements and the diagnostic probes is complicated, and often leads to considerable heat load on the cryogenic system. If afterwards a change is necessary in the position or the number of the mid-plane feedthroughs, the cryostat has to be dismantled completely. Therefore a split cryostat is proposed for the AGOR cyclotron in which free roomtemperature access is provided to most of the midplane. In this paper we will focus on the design of the superconducting magnet and cooling system for the AGOR cyclotron. An overview of this cyclotron will be given in another paper^{4}.

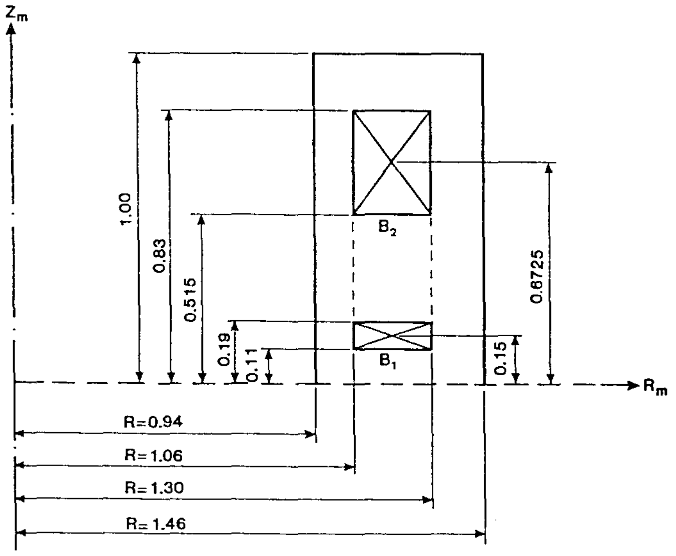

Fig. 1: Geometry of the superconducting coils.

The superconducting coils

Geometry and current density

The coil system consists of a pair of outer coils positioned close to the upper and lower part of the yoke, generating a flat field profile and a second pair of inner coils positioned near the mid-plane that generates the necessary radial field profile. In fig. 1 the final geometry of the coils and their position relative to the yoke and the mid plane is indicated. At the moment 24 ions are specified to be accelerated by the AGOR cyclotron, ranging from H^{+} to $^{187}Au^{19+}$. The current densities in the two coil pairs are given in fig. 2 for the various design points. From this diagram it can be seen that the maximum current density for coil 1 rates 4.27 x 10^{7} A/m² (at point O) and 3.27 x 10^{7} A/m² for coil 2 (point B).

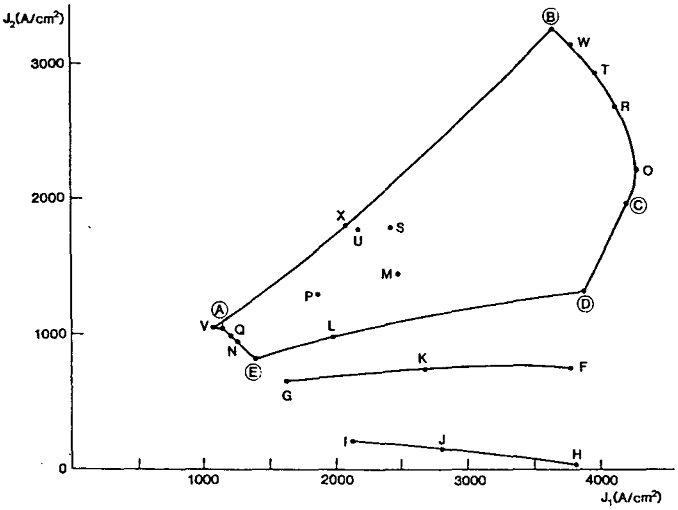

Fig. 2: Current densities in various design points.

At point B we have a maximum field strength on the conductor in the outer coils of 4.74 T and in the inner coils of 3.64 T. These numbers already indicate that a NbTi based superconductor can be used for this cyclotron.

Design of the conductor

For the design of the actual conductor we used the well known hot spot temperature criterion[5]:

$$I \geq \frac{J^2(0)W}{U_d F(\theta_m)} \frac{1}{\lambda^2}$$

where J(0) is the current density at t = 0 s, W is the stored energy, U_d is the voltage over the external dump resistor, $F(\theta_m)$ describes the physical parameters of the matrix material and λ is the filling factor of the coil. Since the internal stresses inside the coil due to the Lorentz forces are high (see fig. 3) half hard copper must be used for the conductor matrix with a residual resistivity ratio of only 30. To exclude damage of the coil by thermal stresses caused by the different expansion coefficients of the construction materials we took a maximum value for θ_m of 80 K. Furthermore, to reduce the heatlosses on the cryogenic system, minimising the nominal transport current was another design criterion. In table 1 the characteristic parameters of the superconducting coils and the actual conductor are summarized as they are proposed for the AGOR coil system.

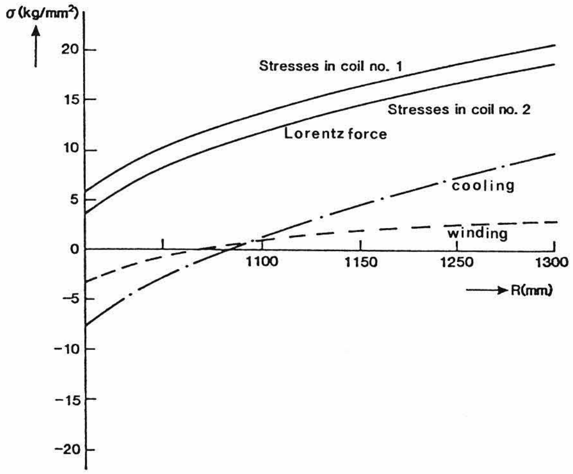

Fig. 3: Stresses inside the coils.

Stability

The main difference between other superconducting coils for cyclotron facilities and the coils presently proposed for the AGOR facility is that the latter are not cryogenically stable. This means that there is a maximum quench energy density for the coils. Any disturbance producing an energy release higher than 4.4 x 10^3 J/m³ for coil 1 and 2.9 x 10^3 J/m³ for coil 2 will cause the magnet system to quench completely. Energy release due to intrinsic disturbances such as flux jumping and AC losses will be reduced by using very small (typically 15 μm) filaments in the actual superconductor. By impregnating the coils with a glass filled epoxy energy release due to mechanical disturbances like conductor motion and cracking of the epoxy will be avoided.

Quench behaviour

To verify the safety of the coil design quench calculations were carried out to see whether the coils could withstand a quench safely also in case of calamities. In normal operation the voltage over each coil will be measured by a bridge detector. As soon as a transition to the normal state occurs somewhere in the superconductor this will unbalance the bridge and the dump switches will be opened in which way a dump resistor is put in series with the coils. Than most of the stored energy of the system (56,2 MJ at point B) will be dissipated in the dump resistor. In this case the hot spot temperature will increase to 55 K for coil 1 at point O and 64 K for coil 2 in point B (see also fig. 4) The maximum hot spot temperature is found in the case that the dump switches fail to open and all energy is dissipated in one coil only. In that case we find a maximum hot spot temperature of 102 K for coil 2 (point B) and 90 K for coil 1 (point O). However these temperatures will not lead to destruction of the coils. Moreover, to reduce the risk of a failure in the dump switches it is considered to use a double set.

Table 1: Characteristics of the superconducting coils.

coil 1:	inner radius	1.06 m
	outer radius	1.30 m
	width	0.08 m
	max. overall current density	42.71 MA/m²
	max. field strength	3.64 T
	conductor cross section (bare)	3.03x5.31 mm²
	(insulated)	3.53x5.71 mm²
	Cu:sc ratio	19
	superconductor	NbTi, rutherfordcable coppersubstrate
	nominal transport current (O)	861 A
	critical current (3.64 T, 4.6 K)	1435 A
	critical temperature	7.5 K
	conductor length (per coil)	7.1 km
	conductor mass (per coil)	1200 kg
coil 2:	inner radius	1.06 m
	outer radius	1.30 m
	width	0.315 m
	max. overall current density	32.65 MA/m²
	max. field strength	4.74 T
	conductor cross section (bare)	5.5x8.6 mm²
	(insulated)	6.0x9.0 mm²
	Cu:sc ratio	26
	superconductor	NbTi, rutherfordcable coppersubstrate
	nominal transport current (B)	1763 A
	critical current (4.74 T, 4.6 K)	2963 A
	critical temperature	6.5 K
	total conductor length (per coil)	11.4 km
	total conductor mass	5700 kg

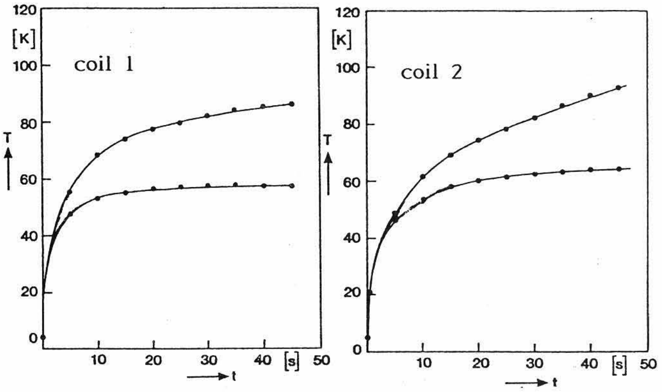

Fig. 4: Temperature rise of the coils in case of a quench.

Lorentz forces

We calculated the Lorentz forces on the system using the computer code POISSON. A summary of the results is given in fig. 5. As can be seen from this figure the maximum attracting force rates 3.5 MN in point B and the maximum repelling force is 0.8 MN in point A. Therefore the mid-plane axial support between the coils should be able to withstand these forces. We found that with six supports in the midplane the maximum deflection of the coil system is 0.25 mm and the maximum stress 213 MPa. These numbers indicate that such a support construction is acceptable, which makes the split cryostat with relatively free mid-plane a real option.

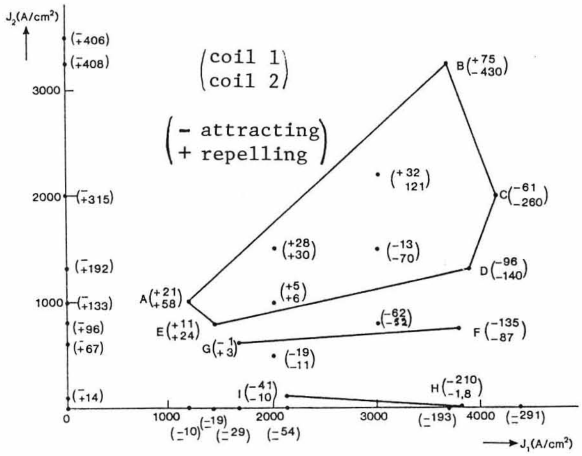

Fig. 5: Axial Lorentz forces on the coils.

The cryostat

Vacuum wall

As we mentioned afore a split cryostat is proposed, which provides roomtemperature access to most of the mid-plane. A general view of the cryostat is given in fig 6. The cryostat will be build in two parts which are connected at only six positions in the mid-plane. (see fig. 7). The main concern in the design of the cryostat vacuum wall was to minimise its deflection in the mid-plane. Since the extraction elements that will be installed in between the cryostat wall in the mid-plane are 79.5 mm high, this deflection should be less than 0.5 mm. From extensive calculations we learned that this was only possible if the weight of the superconducting coils (30 tonnes) was supported by the iron yoke instead of by the cryostat itself. By doing this the (calculated) deflection will be 0.17 mm. During transport and installation of the cryostat when the weight of the coils has to be supported by the cryostat the deflection is 1.75 mm.

Radiation shield

To reduce the heat load on the superconducting coils a radiation shield will be mounted inside the cryostat vacuum wall. This shield will be cooled at 80 K level. Since one of the design criteria for the cryogenic system is that no liquid nitrogen will be used, cooling will be provided by using a special refrigerator and a transfer system that circulates cold helium gas through the shields. The radiation shield is (electrically) coupled to the superconducting coils by mutual inductance. Therefore in case of a quench of the magnet, eddy currents will be generated in the 80 K shield. The absolute value of this current depends strongly on the resistivity of the construction material of the shield, and the current decay time of the magnet system in case of a quench. To reduce these eddy currents and thus the forces that act on the shield, it is proposed to use a stainless steel shield of the 'panel coil' type in which the cooling tubes for the helium gas are integrated.

Assembley of the coils

Each coil will have its own seperate stainless steel housing in which liquid helium is provided in contact with the total outer perimeter of the winding package. The coils 1 and 2 will be connected by twelve supports of 100 x 200 mm². In the mid-plane, there will be only six connecting supports between the two magnet halves. In normal operation the coils will be connected in parallel to the buffer vessel on top of the cryostat. In this way it is avoided that evaporated helium gas from one coil passes through the other coils. In case of precooling however the coils should be connected in series, to avoid temperature differences between the coils. Therefore an extra precooling line is provided (see fig. 8).

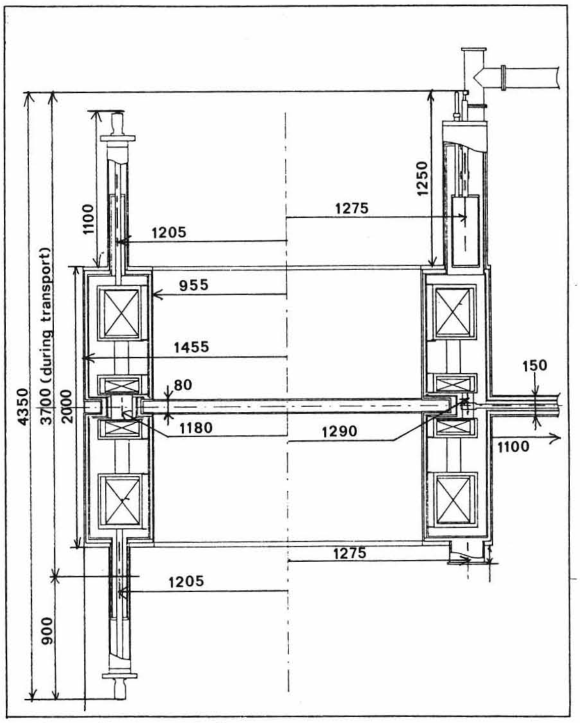

Fig. 6: Overall view of the cryostat.

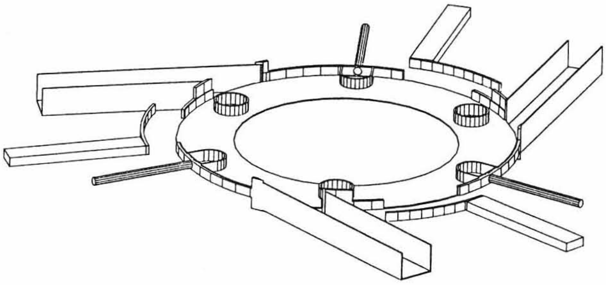

Fig. 7: Schematic view of the mid-plane section.

The cryogenic system

Basic design principles

The design of the cryogenic system for the AGOR superconducting cyclotron has been guided by the following main principles:

1) The enthalpy of the evaporated helium gas from the main coil system will be used completely to enhance the cooling power of the system liquefier.
2) The cooling power that is necessary on different temperature levels will be produced by seperate refrigeration systems.
3) No liquid nitrogen will be used.
4) Operation of the cyclotron should be possible temporarily if a liquefier breakdown occurs.
5) If the liquefier is out of operation for a longer period of time, the coil temperature should not rise above 80 K.
6) The total volume of liquid helium inside the cryostat, that will evaporate in case of a quench of the magnet system, should be minimized.

One of the most important consequences of these design principles is that there will be no cold helium gas available to cool the current leads of the superconducting coil system. It is our feeling however that current lead cooling can be done safely without boil-off gas cooling by using a special purpose refrigerator system. Since there is no helium gas at room-temperature in connection with the leads, the risk of

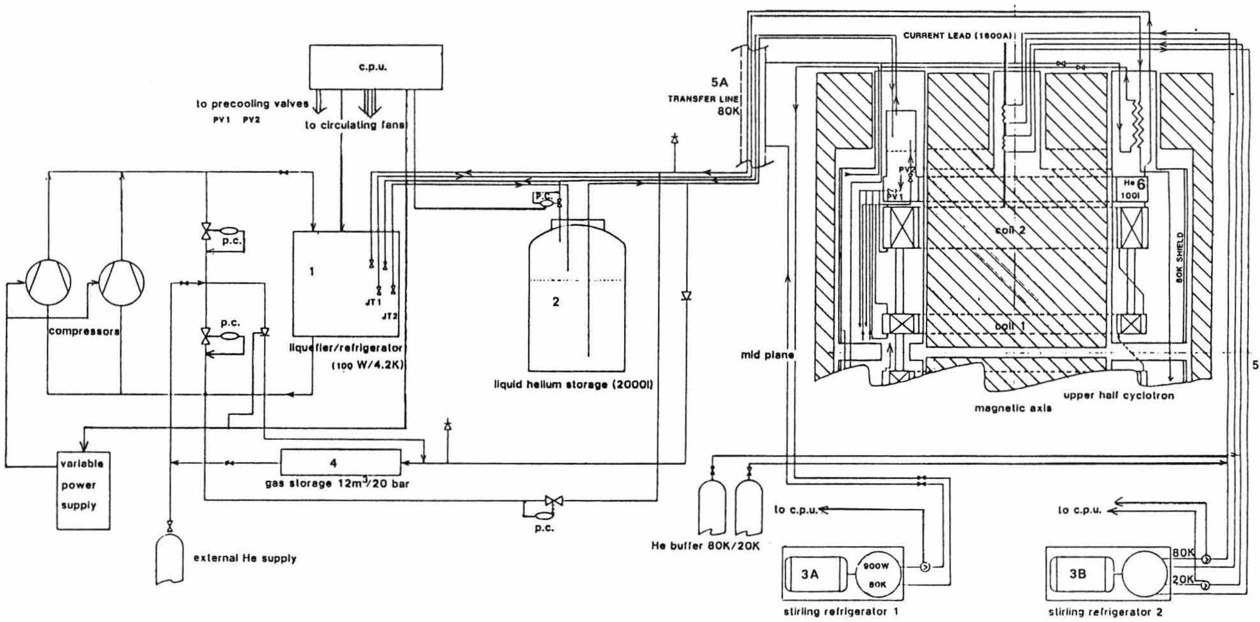

Fig. 8 : Cryogenic system for the AGOR cyclotron.

an electrical breakdown in case of calamities will be reduced. A prototype of these current leads is presently under study.

General lay-out

The cryogenic system will consist basically of five different items:
1) a system liquefier with compressors
2) a production container
3a) a refrigeration system for 80 K level
3b) a refrigeration system for 80 K and 20 K level simultaniously
4) a medium pressure gaseous helium storage system at ambient temperature
5) several cryogenic transfer lines.

Fig. 8 represents a schematic view of the system. The general operation of this cryogenic system will be as follows: (numbers according to fig. 8). Via compressor(s), gaseous helium is compressed from atmospheric pressure to ca. 25 bar and in the liquefier (1), transformed into liquid. This liquid helium is stored in a production container (2). From the production container liquid helium is transferred through a relatively long transfer line (5a) to a small buffer volume (ca. 100 l) (6) inside the cryostat. The helium that has been evaporated due to the heat load on the superconducting magnet system is transferred through the same transfer line directly to the Joule-Thomson section of the liquefier. The vapour thus returns cold to the liquefier, where it is utilised in the heat exchangers of this machine, resulting in an increased cooling power at 4.2 K. Finally, the helium gas, now again at ambient temperature and atmospheric pressure, is returned to the low pressure side of the compressor. If a breakdown of the system liquefier occurs, the system can continue operation for several hours by pressurizing the storage vessel. In that case the boil-off gas will be fed to the medium pressure storage system (4) by means of the compressors. This system will also be used in case of quench of the coil system to preserve the helium gas from the main cryostat. The 80 K refrigerator (3a) will be used to cool the radiation shield inside the transfer lines and the cryostat in a completely closed loop. Its additional cooling power will be used, in case of precooling, to enhance the cooling capacity of the refrigerator. When the liquefier is out of operation for a longer period of time it will be used to maintain the coil temperature below 80 K. The two stage refrigerator (3b) will be used exclusively to cool the current leads of the coil system. It is connected to the cryostat by means of a transfer line (5b). Part of the cooling power at 80 K will be used to cool a radiation shield inside this transfer line. In this way a flexible and reliable cryogenic system can be realised, that has enough built in redundancy to guarantee safe operation also in case of calamities.

Heat load

The total heat load on the cryogenic system is estimated as 500 W at 80 K, 40 W at 20 K and 20 W at 4.2 K. These numbers include the transferlines and the current leads at maximum operating current.

Conclusion

Due to the unique geometry of the coils the axial Lorentz force on the magnet system is low compared to other coil systems for superconducting cyclotrons. Therefore it was possible to support this force only by six rods, equally spaced in the mid-plane. As a consequence a split cryostat could be designed that enables an easy install (and withdrawel) of extraction elements and diagnostic probes in the mid-plane. By using layer wound, fully vacuum impregnated coils, the mechanical stability of the coil system is enhanced and the risk of electrical shorts is reduced. The coils are not cryogenically stable but much attention is given in the design to avoid disturbances in the coils. By using seperate refrigerators for different temperature levels the efficiency of the cryogenic system is improved.

References

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