A DESIGN STUDY FOR A SUPERCONDUCTING EXTRACTION ELEMENT FOR AGOR

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SUMMARY

In this paper a feasability study is presented for a superconducting electromagnetic channel that is part of the AGOR extraction system. Specific boundary conditions and constraints on the cryogenic design are discussed. The proposed lay out of the coils and their mandrels is reviewed as well as the operation of the cooling system that has to be implemented in the overall AGOR cryogenic system.

GENERAL INTRODUCTION

The AGOR cyclotron, a joint undertaken of the Dutch Organisation for Fundamental Research on Matter (FOM) and the French Institut de Physique Nucléaire et de Physique des Particules (IN2P3), has now entered the production stage. Almost all subsystems have been subcontracted to industrial partners. A general description of the AGOR cyclotron is given by Gales[1] and the present status is discussed by Schreuder[2]. In this paper we will focus on a design study that has to prove the feasability of using superconducting elements in the AGOR extraction system. The general lay-out of this extraction system and its electromagnetic behaviour is discussed by Gustafson[3].

BOUNDARY CONDITIONS

The AGOR extraction system basically consists of four elements. The Electrostatic Deflector (ESD), two Electromagnetic Channels (EMC1 and EMC2) and two quadropoles (Q1 and Q2). They are positioned in the mid-plane of the cyclotron as indicated in figure 1. Out of these four elements EMC2 and the quadropoles are possible candidates to be produced as superconducting elements. In this paper we will discuss the basic design of EMC2 with respect to geometrical and cryogenic constraints. As a consequence of the split cryostat design that was adopted for this cyclotron[4] to facilitate an easy mounting and demounting of several elements in the mid-plane, EMC2 cannot be implemented inside the main cyrostat, but will be positioned in between the two sections of the cryostat. Its cooling system however has to be implemented in the refrigeration cycle of the main cryostat. The available space in between the two parts of the cryostat is limited to 80 mm in vertical direction.

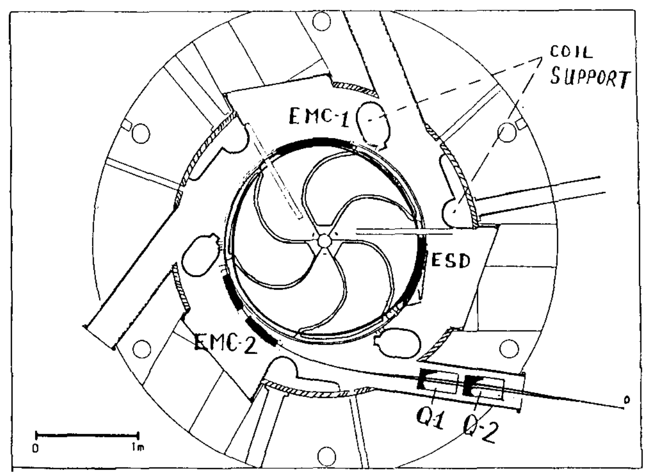

Figure 1: mid-plane position of the extraction elements

Another important boundary conditon is given by the expected beam loss inside this electro magnetic channel. The cooling system of this channel should therefore be designed to withstand a beam loss of up to 20W contineously at the inner bore for a 200 MeV proton beam.

BASIC COIL DESIGN

The second electromagnetic channel consists of two almost identical sections, each having three independent coil systems: the main field coils, the gradient coils and the correction coils. The two sections are electrically connected in series. Each section has an angular extension of 20 degrees, which equals about 400mm (see also fig.1). The optimum geometry of the different coils has been calculated by Gustafson taking into account the space limitations and the requirements for cooling. The final coil dimensions are given in figure 2. due to the very limited space between the coils they can only be cooled by conduction from cooling channels that have to be integrated in the supporting structure for the coils. Each coil will have its own winding mandrel, precisely machined out of high conductivity copper. After winding and impregnation of each separate coil

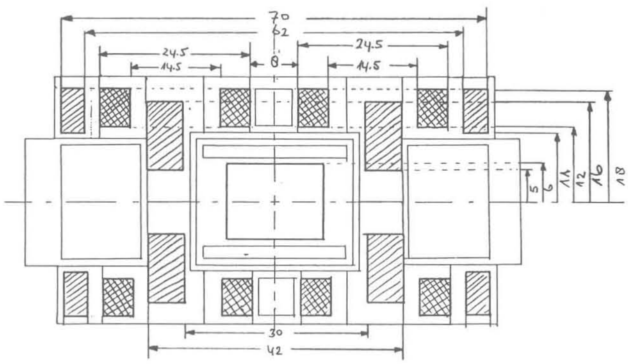

Figure 2: geometry of the EMC2 coil system

the coil system will be assembled thus forming a rigid structure. A general view of this assembly including the integrated cooling channels is given in figure 3. As high conductivity copper is used as a structural material for the EMC2 coil system with a maximum Tensile Yield stress of about 60 N/mm^2 an analysis has to be made to see whether the mechanical stress level in the system is acceptable. For the main coil the maximum radial force rates about 7 tonns per meter length. A finite element analysis using the three dimensional computer program PATRAN showed that the maximum combined or Von Mises stress will be 27 N/mm^2 on the supporting structure. In this calculation it was assumed that a stainless steel outer cover is used to enclose the different mandrels and cooling channels. The use of high conductivity Copper is then acceptable in terms of mechanical stability.

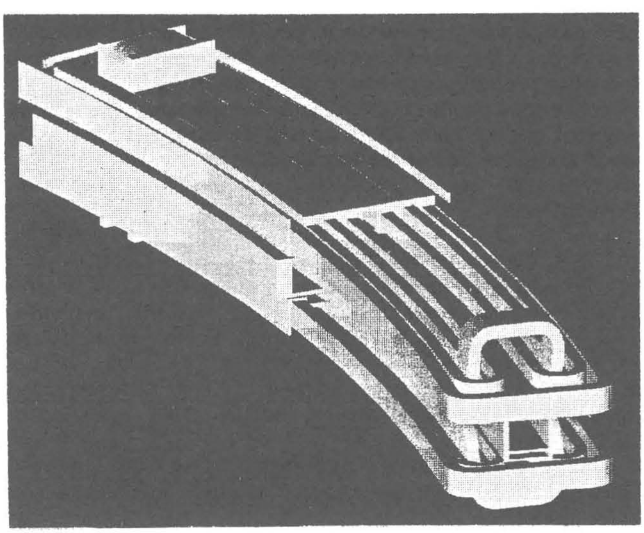

Figure 3: the proposed configuration for EMC2

CONDUCTOR SPECIFICATION

With the coil geometry as given in fig. 2 the maximum current density in the coils will be 250 A/mm^2 to obtain the required field profiles for extraction. To reduce current lead losses a standard multifilamentary NbTi conductor is proposed with a diameter of 0.5 mm and a Copper to superconductor ratio of 1.8 and a critical current of 168A at 5T. Operating this conductor at less than 40% of its critical current will give a temperature margin of 1.5K to absorb small amounts of internal dissipation. The coils will be intrinsically stable with maximium quench temperatures well below 50K. The total conductor length needed for the two sections of EMC2 is about 2.5 km with a minimum single lenght of 1150m. The EMC2 consists of 16 subcoils, each wound on a seperate mandrel. The soldered joints between the sub coils, 13 in total, will introduce a heat load of less than 1 mW.

CRYOGENIC DESIGN

Expected Heat Loads

One of the most challenging aspects of the cryogenic design of this electromagnetic channel has been to find a solution for the dissipation due to the beam losses at the inner bore of the channel. We estimated the maximum contineous loss for the most powerful beam (5 A, 200 MeV protons) at 20W. Such a load cannot be absorbed by the coil mandrels, that are only indirectly cooled, without an increase in temperature above the critical conductor temperature. For that reason it has been necessary to implement a shield inside the inner bore of the channel. Following the results of calculations by Schapira[5] the wall thickness of such a shield should be 3.5 mm to prevent that beam losses would be dissipated inside the coil system. To increase its efficiency gold could be used at its inner radius. In order to avoid high thermal gradients over the shield it has to be actively cooled. As indicated before the elctromagnetic channel should be installed inside the median plane gap of the main cryostat having a maximum clearance of 80 mm in height. At the position of the crossovers of the main coils the overall height of the coil system is 65 mm. This indicates that a seperate vacuum chamber for this superconducting channel cannot be used and that it will thus be operated in the beam vacuum. To reduce the radiation heat load at 4K an outer radiation shield has to be installed, operating at about 80K. Although normally superinsulation would be applied to such a shield this is not possible as it would seriously reduce the quality of the beam vacuum. The estimated radiative heat load in this shield is 10W, including the support structure. Heat loads at 4K level are mainly determinated by the current lead losses. The three coils of each section of the channel will be connected in series. As it is requred to operate them independently 6 current leads are needed with a maximum total rated current of 360 A. Including the support systems between 80K and 4K the heat loads at 4K are estimated at 2W.

Lay-Out Of The Cryogenic System

The AGOR cryogenic system is based on a multipurpose refrigeration system. A Sulzer TCF50 refrigerator/liquefier is used to provide the cooling for the main coils and their 80K radiation shield as well as for the superconducting elecromagnetic channel. Its general specifications and operating modes are described elsewhere[6]. Here we will discuss only the specific cooling system for the EMC2. A flow chart of this part of the cryogenic system is given in figure 4. It is connected to the main refrigeration system at the level of a distribution box that is installed close to the cyclotron. Here a small massflow is taken from the main 4K and 80K cooling circuits and transported to the median plane

A: main transferline
B: distributionbox
C: cryogenic part of EMC2
D: main cryostat
E: Helium supply/return lines main coils
F: precooling connection
G: Nitrogen recondensation system
H: inner shield
K: EMC2 coil system
M: outer shield
N: heat exchanger
P: current leads.

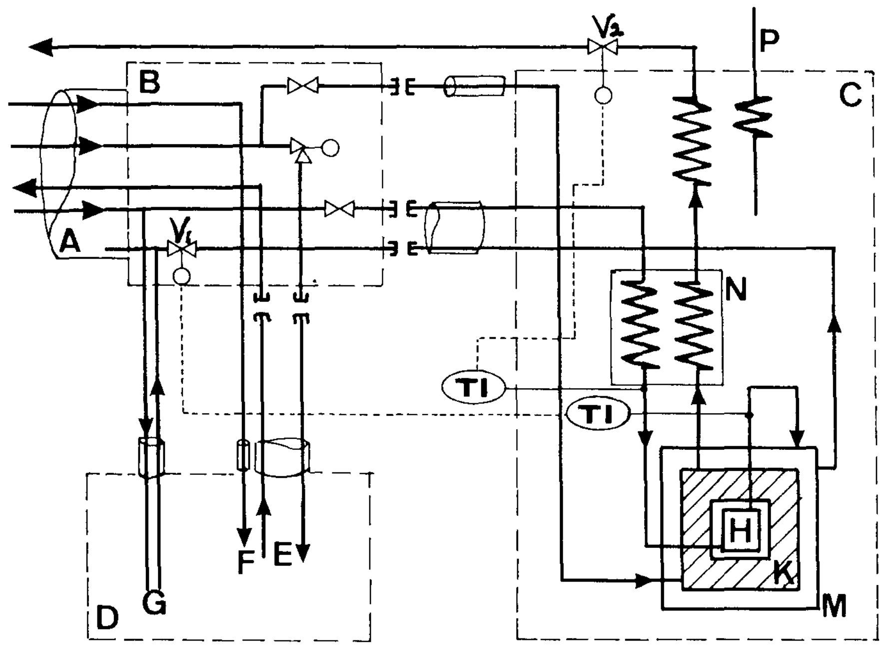

Figure 4: flow chart of the EMC2 cooling system

area where the EMC2 is installed, by means of two flexible transfer lines.

The EMC2 cooling circuit is based on maximum contineous heat loads of 20W on the inner shield, 2W on the superconducting coils and 10W on the outer radiation shield. Its general operation is as follows: a massflow of about 0.1 g/s is taken from the liquid Helium supply line of the main coils and fed into the integrated 4K cooling channels of the EMC2. The two sections will be cooled in parallel. The enthalpy of the evaporated Helium gas is than partly used inside an heat exchanger to precool the incoming 80K flow for the shields that has been taken from the main 80K circuit, cooling it down to a temperature of about 10K. The remaining enthalpy of the evaporated Helium between 80K and 300K is than used to cool the current leads and the supports and finally fed into the suction side of the system compressor. The precooled shield flow is circulated through the inner shield where its temperature will be raised to some intermediate temperature level depending on the actual heat load generated by the beam loss. It is than fed into the outer shield and is returned at approximately 80K to the 80K circuit of the main cryostat.

The actual heat loads on the coils and the shields depend on the current setting of the coils and the intensity of the extracted beam. Therefore it should be possible to regulate the mass flows of the two EMC2 cooling circuits to create an optimum performance under all circumstances. This is realised by the two regulating valves V1 and V2 in figure 4 which will be controlled by temperature sensors installed in the EMC2 cooling circuits. In this way a dynamic cooling systems can be realised that is automatically adjusted to the requested heat loads of the channel and is only limited by the capacity of the system refrigerator.

PRESENT STATUS

Development is still in progress on the implementation of the EMC2 in the median plane of the cyclotron. To comply with the multiple trajectories of extracted beams, ranging from protons to heavy ions, a positioning system is needed to move the electromagnetic channel in tangential and radial direction. This mechanism will be connected to the EMC2 at 80K level where the heat loads can be absorbed in an efficient way. Soon a principle decision will be taken on the production of a prototype to study the stability of the system under simulated heat loads and the dynamic operating range of the refrigeration system to absorb both contineous and peak losses of the beam.

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