Validation Test of the Forced-Flow Cooling Concept for the Superconducting Magnet of AMIT Cyclotron

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***Abstract*—Advanced Molecular Imaging Techniques cyclotron is a compact device aimed to produce radioisotopes for medical imaging. A uniform 4-T field is created by means of two NbTi coils in a Helmholtz arrangement. Both coils are embedded in a stainless steel casing that holds the Lorentz forces. The cooling scheme is based on a low-pressure forced internal flow of two-phase liquid–vapor helium through a narrow channel machined in the casing. Preliminary thermohydraulic analysis showed that this concept is capable of cooling the coils, removing a heat load of up to 1 W with just a small amount of mass flow (about 0.1 g/s). In the final application, cold helium will be provided by a cryogenic supply system (CSS), which basically consists of a closed circuit recondenser using a single cryocooler. Previous heat loads are inside the CSS specifications. This paper will present the results of a scaled mock-up of the coils, cooled by a controlled flow of helium provided from a helium Dewar, tested to check the thermal loads, quench training, fluid–solid interaction, and the necessary control system to handle the helium mass flow. It will prove the viability of the concept while advising the potential problems that could arise in the real system.**

***Index Terms*—Accelerator magnets, cryogenics, fluid dynamics, heat exchanger, helium, two-phase flow.**

I. INTRODUCTION

AMIT cyclotron includes two low-temperature superconducting coils that must be cooled while accomplishing restrictive boundary conditions [1]. These include a very compact design for the whole magnet, which relies in a challenging design for cooling (heat exchange concept) and insulation. Magnet provides a uniform 4 T field by means of two NbTi coils in a Helmholtz arrangement and warm iron. These coils are fit using an aluminum shrinkage to withstand magnetic pressure. Also, they are supported by a stainless steel casing to withstand repulsive force between them. A helicoidal path is provided in it for liquid helium (LHe) flow. As the whole casing is at helium temperature, it is surrounded by a thermal shield cooled by helium gas at about 60 K to be used as thermal shield. Finally, glass fiber rods are responsible for handling net magnetic forces and positioning the coils inside the casing in a low heat losses approach.

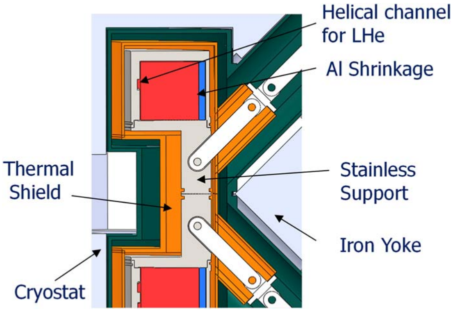

Fig. 1. Cross sectional view of magnet design.

Magnet design included studies on several physics: mechanical, thermal, fluid dynamics and magnetic calculations at several operational scenarios have been evaluated. A schematic view of the design is shown (Fig. 1).

Another request from the AMIT project is the key point of being an autonomous system from the cooling and fluids point of view. To achieve this goal while optimizing magnet size, a single cryocooler is used to liquefy the helium, so this helium cools the magnet while flowing inside the cyclotron in a closed loop pipe connected to the cryocooler by means of the Cryogenic Supply System (CSS). To take advantage of the two stages of the cryocooler, LHe cools the coils, and then it is used as helium gas to cool the shield prior to the reliquefaction in the CSS developed at CERN.

Nominal cooling power supplied by the available cryocooler is 1.5 W at 4.2 K. Latent heat of liquid helium (1.3 bar nominal pressure) is about 19 J/g, so a nominal mass flow of 0,1 g/s will be considered for first rough design of the system. Liquid helium flows in close contact to the coils through a helical channel (10 mm by 5 mm). As liquid helium absorbs heat from the coil, it boils. Thus, a mixture of vapor and liquid helium (two-phase flow) is the actual cooling fluid. Literature can be found about tests and models of two-phase flow of helium inside a channel, for example [3]. Calculations based in these empirical relations or fluid models are not expected to be really accurate because the geometry of this system is very complex. It includes a lot of sectional changes very close to one another and abrupt directional changes of the path, so the flow is not fully developed in most of the path. Anyway, overall and quantitative real performance should be evaluated in advance during design stage to ensure a successful magnet.

Manuscript received September 7, 2015; accepted January 29, 2016. Date of publication February 11, 2016; date of current version February 29, 2016. This work was supported by the Spanish Ministry of Economy and Competitiveness under Projects CEN-20101014 and FPA2013-47883-C2-2-P.

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Digital Object Identifier 10.1109/TASC.2016.2528682

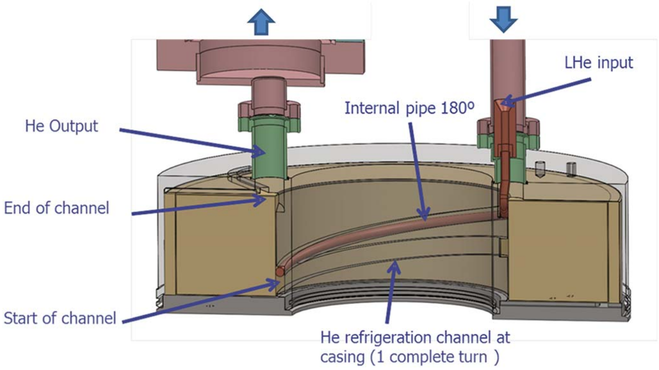

Fig. 2. Detailed view of coil and casing for the mock-up set-up.

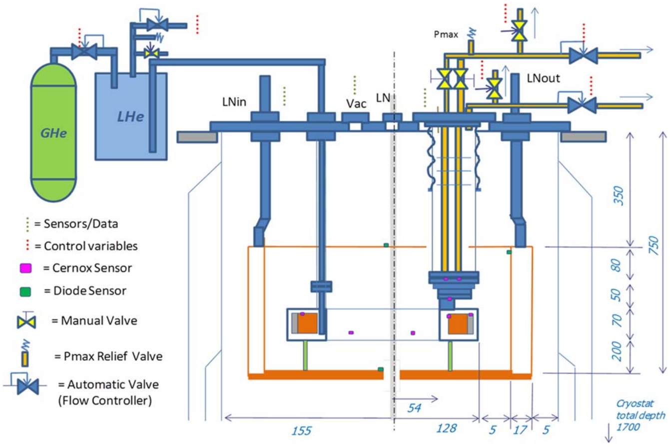

Fig. 3. Test setup including valves and sensors in the cryostat.

II. TEST CONCEPT AND DESIGN

To prove the feasibility of the solution adopted to cool the cyclotron, some tests were carried out in a mock-up system (Fig. 2).

A coil of the same cross sectional area, number of turns and wire was manufactured. About half external diameter was used to accommodate it in the available cryostat. Materials to be used are the same as in the real cyclotron. Non-ferromagnetic stainless steel is mandatory to avoid magnetic forces, heating and undesirable effects on the magnetic field created for the particles. Cernox sensors are used for temperature measurement to provide reliability at 4 K for a range of magnetic field up to 4 T.

Fig. 3 shows the conceptual design of the test. It includes a LHe Dewar as reservoir of cryogen instead of the CSS system and electronically controlled valves to regulate and measure the flow. Pressurization is achieved by means of a helium gas high pressure bottle controlled by a flow controller equipped with a forward pressure gauge. Instead of having a thermal shield cooled by helium gas, radiation shielding is provided by a liquid nitrogen reservoir.

Helium mass flow rate is measured at the outlet at two points by the mass flow controllers. One of them measures the helium flow inside the current leads and the other measures the helium flowing out at the cryostat upper flange. Mass flow rate is measured for gas at ambient temperature by the flow controllers shown at Fig. 3.

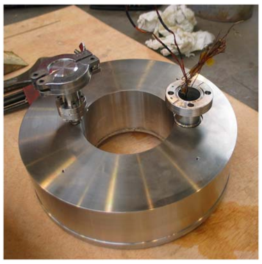

Fig. 4. Manufactured casing ready for testing.

Fig. 5. Complete insert ready to be installed in cryostat.

Coils and parts have been manufactured by ANTECSA and CIEMAT. Assembly of the system includes some difficult welding operations. These have been intentionally kept in the design in order to be in the same challenging boundary conditions to overcome in the AMIT cyclotron. Welding preparations are physically quite close to the coil and temperature sensors, so special welding techniques have been used and validated for sensors and magnet safety. Fig. 4 shows casing ready for installation while Fig. 5 shows the whole insert including the casing, the thermal shield and the inner pipes for the helium flow.

III. PHYSICAL MODELS

Analytical calculation of stresses and temperature distribution in the coil considering some simplifications is possible [2], but in order to include in the model the mechanical and thermal anisotropy of the coil, FEM models were performed using ANSYS coupled with Ansoft Maxwell (Fig. 6). Results provide complete information on temperature distribution and the effect of the aluminum shrinkage, which are important to ensure superconductor state at every possible operational condition. Expected heat losses summary is shown in Table I. About 1,5 W are expected for this setup, while the real cyclotron needs just 1 W.

Calculations and models can be compared even if the real conditions are different. Main reasons for this discrepancy are the inlet and outlet helium pipes inside the cryostat and the helium cooled resistive current leads. Real cyclotron includes optimized transfer line design by CERN and superconducting current leads to achieve the 1 W loss goal. Also, thermal shield

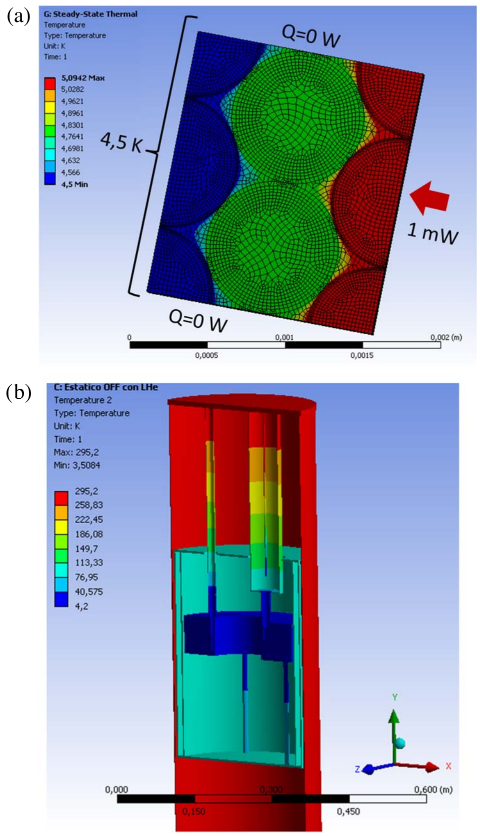

Fig. 6. Thermal calculations: a) Equivalent conductivity of the coil; b) the temperature distribution during tests.

TABLE I
STEADY STATE THERMAL LOSSES CALCULATIONS

Heat contribution	Main parameters [a]	Value (W at 4,2 K)
Conduction (Rods)	$K_{0\text{-}77K} = 18$ W/m	0,028
Conduction (Inlet)	$K_{0\text{-}77K} = 3000$ W/m	0,42
Conduction (Outlet)	$K_{0\text{-}77K} = 3000$ W/m	0,08
Conduction (GHe In)	$K_{0\text{-}300K} = 27$ W/m	0,027
Conduction (GHe Out)	$K_{0\text{-}300K} = 27$ W/m	0,3
Radiation to casing	Cold Surface 0,16 m^2	0,57
Current Leads	100 A (nominal)	0,1
Conduction Vacuum	0,07 W/m^2	0,012
TOTAL		1,54

[a] K is the integral thermal conductivity.

temperature for this setup is 77 K for convenience instead of 60 K for the real cyclotron.

Fig. 6 (a) shows the calculation of coil thermal conductivity. Real raw material properties are included (Cu, superconducting wires, insulation and epoxy) to compute the net conductivity of the coil at each direction.

Fig. 6 (b) shows temperature distribution of the cryostat and main components of the mock-up test. Thermal shield cooled by liquid nitrogen protects the casing from the outer radiation. Liquid helium flows inside the casing so the cryostat itself is kept at high vacuum level.

Fluid behavior was modelled using empirical relations according to [5]. In order to model heat transfer and pressure drop due to the two-phase helium flow, homogeneous model was chosen. Then, each phase is evaluated according to its mean fluid properties and frictional pressure drop is evaluated according to the typical Darcy-Weisbach factor. Convective contribution is evaluated according the homogeneous model, while the boiling contribution using Kutateladze correlation [5].

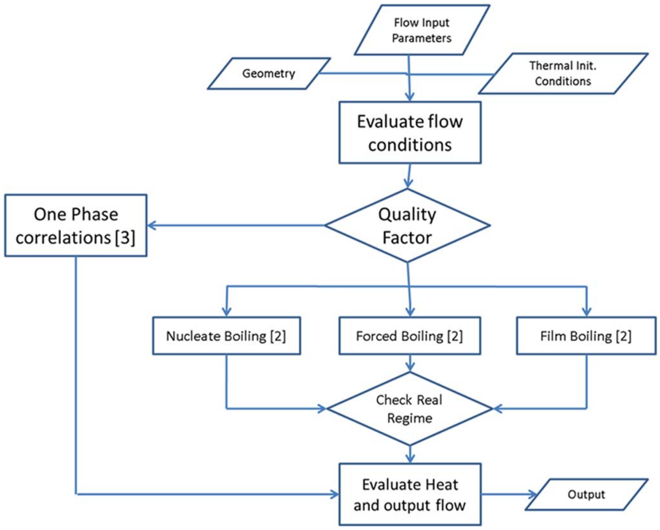

Fig. 7. Schematic of FEM model for transient calculations.

Transient calculations were made for the cool down process. As cryogen is actually helium gas during most of the cool-down time, usual heat transfer correlations for forced inner one-phase flow were used [3].

To calculate these empirical correlations for a transient or a general chain of elements (inlet geometry, path inside the casing, outlet geometry), a custom-made FEM code was developed in Matlab (Fig. 7).

It considers just one kind of unidimensional element, with parametric thermal and geometrical properties: heat input, initial temperature, specific heat, mass, sectional area, perimeter, length and surface roughness. In this model, the heat input over the coil is distributed homogeneously along coil surface and the properties of each element are evaluated as a compound value from the materials in contact with the fluid at that element.

Program parameters include time step and input file path with geometry and starting parameters of the system.

Then, for each time step, the program evaluates in sequence the temperature change of each element taking as input fluid properties the output fluid properties of the previous.

Heat input is manually adjusted as function of temperature from ANSYS thermal models, while materials and fluid properties are from NIST cryogenics web.[1]

Such a model does not take into account all the involved fluid physics, but it has been proved that good match was found. First of all, it uses the homogeneous model which is not a really accurate model for medium quality factors. Moreover, a unidimensional model cannot take into account lateral effects on stratifications or waves in the liquid part. Buoyancy effects are not included either for this simplified mock-up, while

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[1] NIST web. http://www.cryogenics.nist.gov/

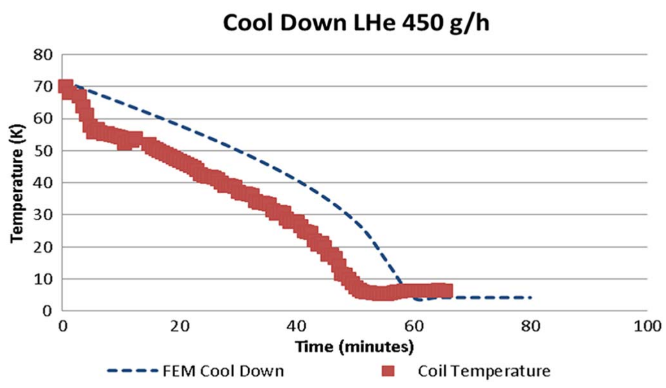

Fig. 8. Coil temperature during cool down.

for the real cyclotron model they could be relevant because flow changes direction and elevation several times along the complete cryogen closed path.

IV. RESULTS

The temperature evolution of the coil was measured at a constant LHe flow input to check accuracy of heat load measurements and flow model (Fig. 8). Temperature sensors were placed in the upper wall of the coil, near the outlet of the casing, while calculated temperature of the coil is the mean temperature.

Cool down was about 15% faster than expected. Heat transfer calculation of the two-phase flow should be improved for future designs and AMIT cyclotron simulations. Also some assumptions for the heat inputs could be slightly conservative, but for this test the cooling down results can be considered as a success. Moreover, as the temperature is measured at the outer surface of the coil, values are lower than the calculated ones for the mean temperature of the coil cross-section during the cool down transient.

On the other hand, real final temperature of the coil is not 4,2 K as expected for this 450 g/h LHe flow. This can be explained as the effect of an important heat loss (about 4 W) at the LHe transfer line connecting Dewar and cryostat. No information about performance was available for this transfer line. For that reason, a second test was performed.

In addition, an unexpected fast cool down was found at the beginning of the process. The whole casing was cooled using liquid nitrogen which was then evacuated prior to the liquid helium flow. Then, Fig. 8 shows just this helium process starting at about 70 K.

The second test was made to check the real influence of the transfer line. Vaporization rate of LHe inside the casing without transfer line was measured. The found value was 220 g/h, corresponding to 1,3 W.

For the third test, equilibrium temperature of the coil as a function of LHe mass flow was measured. Results can be found in Fig. 9. Calculated values include the extra heat losses coming from the inlet transfer line. Best correlation with experiment data was found for high mass flow if including 5 W as shown. The difference between heat losses with and without transfer line confirms a real heat loss of 4,5 ± 0,5 W at 4,2 K in the transfer line.

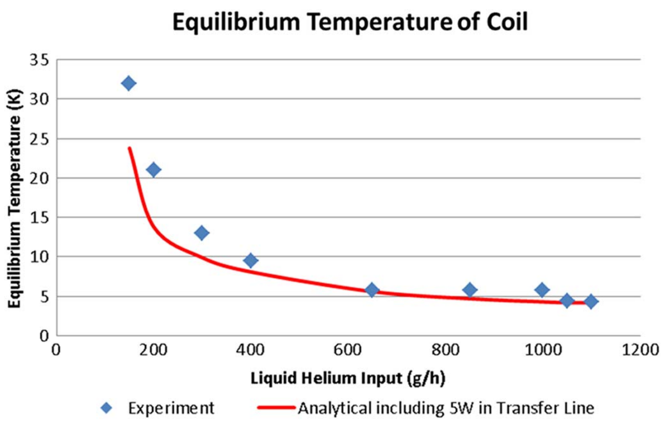

Fig. 9. Equilibrium temperature of coil as a function of LHe mass flow.

Finally, electrical tests were carried out, including critical current for superconducting state, quench behavior, training and voltage drop on the current leads.

Measured critical current was according to specifications as designed, and no degradation or problematic effects were found during these tests. Superconducting state was found up to nominal critical current considering the load line of the wires, magnetic field and temperature (169 A) at the first quench. Second quench reached the same value.

V. CONCLUSION

This test has proved that cooling scheme for AMIT cyclotron is sufficient to evacuate about 1 W of heat at 4.2 K in a compact space. Moreover, it has been proved that models and assumptions used for AMIT cyclotron cooling studies are valid.

Potential risks come from the efficiency of the transfer line and possible mechanical overpressures when quenching inside the cyclotron, where pipes are longer than in this setup.

Fluid dynamics modelled from empirical relations according to non-dimensional parameters procedure are good enough to roughly describe the potential of the system, but it fails when explaining finer details or some specific properties of helium. Important presence of non-completely developed flow is probably one of the most limiting assumptions in the model developed for the calculations shown in this paper.

Electromagnetic design of the coil and manufacturing procedure have been proved to be adequate in terms of superconductive state of the coils, so real size cyclotron coils will be designed and manufactured according to the same techniques.

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