Commissioning of an Autonomous Cooling System for a Compact Superconducting Cyclotron Devoted to Radioisotope Production

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***Abstract*—A 4 Tesla superconducting magnet has been developed by CIEMAT for a compact cyclotron for radioisotope production in the framework of AMIT project (Advanced Molecular Imaging Techniques) in collaboration with other Spanish companies. First power tests were performed using liquid helium transferred from dewars. An autonomous cooling system has been developed in collaboration with CERN, where the system was characterized with a dummy load. Some improvements have been implemented to reduce the cooling time before connecting the cyclotron magnet. A new low-thermal-loss transfer line has been developed to overcome the problems detected in the first cooling tests connecting the magnet.**

***Index Terms*—Superconducting cyclotron, remote cryogenics, radioisotopes production.**

I. Introduction

THE AMIT cyclotron is a classical superconducting cyclotron [1]. Its main characteristic is its compactness, while producing a 4T field for 8.5 MeV as nominal energy. It was developed for providing radioisotopes for on-demand production of radiopharmaceuticals. The magnet consists in two NbTi coils in a Helmholtz configuration and a warm iron yoke. In order to keep the dimensions as small as possible, the distance between the coils and the yoke was minimized. The supporting structure of the cold mass is based on 8 fiberglass rods which are attached to the outer surface of the iron. These rods can be adjusted to move the coils (which are hermetically covered by a stainless steel casing) and the holding forces can be measured by strain gages attached to them. Regarding the refrigeration, a remote and autonomous cooling concept using Helium as the cryogen to transport the heat generated in the cyclotron was selected as explained in [2].

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Fig. 1. AMIT superconducting cyclotron and the cryogenic supply system (CSS).

The first cold test done on this cyclotron was reported in [3]. There, the cyclotron was precooled with liquid Nitrogen and then liquid Helium from a Dewar was injected. The steady-state conditions were achieved when the coils were completely immersed with the liquid Helium. Around 75 liters of liquid Helium and 90 liters of liquid Nitrogen were needed in total to reach nominal conditions before the magnetic measurements could be started.

The autonomous cooling system (Cryogenic Supply System CSS) was developed [4] in order to avoid liquid cryogens for both the cooling stage and the nominal operation, as reported in [5]. There is a commercial cryocooler from Sumitomo [6] installed and the CSS is able to provide two lines of Helium at the temperature of the two stages of the cryocooler. The CSS is connected to the cyclotron by a custom transfer line including both the input and the return lines of Helium (Fig. 2). These lines are connected in series and therefore the ambient temperature Helium gas is first cooled with the first stage and then it goes to the cyclotron to refrigerate the intermediate temperature parts. The helium returns to the CSS and it cooled again with the first stage of the cold head before being cooled by the second stage of the cryocooler. The helium is then finally sent to the cyclotron coils. Three heat exchangers are included inside the CSS for

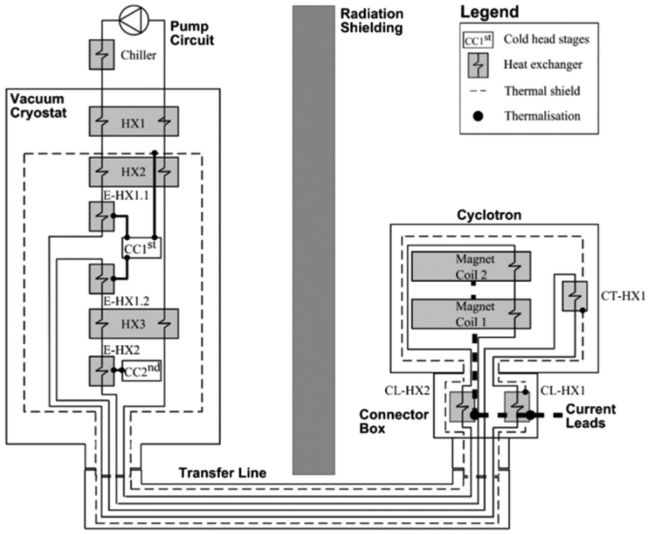

Fig. 2. AMIT superconducting cyclotron (right) and the cryogenic supply system *CSS* (left). (Figure from [4]).

Fig. 3. Assembly of the new transfer line.

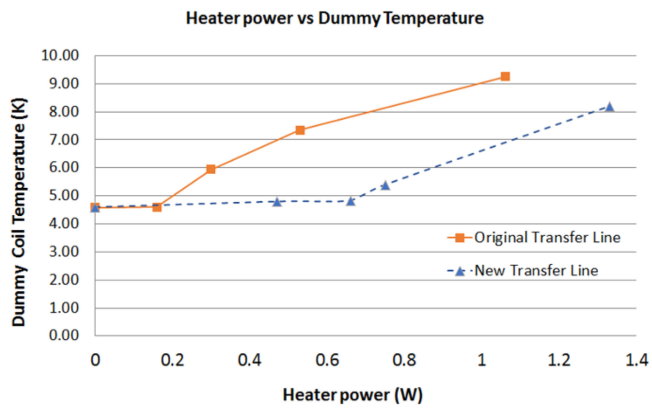

Fig. 4. Commissioning results for the CSS when cooling a dummy load connected to the original transfer line and the new one.

precooling the input helium using the returned Helium enthalpy. The AMIT cyclotron current leads are made of high-temperature superconductor [7] and their warm and colds ends are cooled by the first and second stage circuit respectively. The first operation of the CSS system integrated with the cyclotron was not able to reduce the temperature of the coils further than 11 K, while the critical temperature of the cyclotron is slightly above 6K.

Additional analysis, including stand-alone testing of the CSS and the transfer line, yield to the conclusion of higher heat losses than expected in the transfer line. Cernox sensors were installed in both ends of the transfer line and the mass flow was also measured to evaluate these losses. It was impossible to perform a non-destructive check on it due to its construction based on welded concentric parts. Thus, a new transfer line was designed and manufactured.

II. Cryogenic Transfer Line Commissioning

The new transfer line was designed for achieving low thermal losses while providing the capability of being dismantled in case of need and a new concept for managing the thermal contractions was included (Fig. 3). Both the CSS and the cyclotron are fixed to ground; therefore the contraction of the cold pipes inside the transfer line has to be considered. Moreover, there are in total four pipes at different temperatures (two cooling circuits being two pipes each one for Helium go and return). Sliding supports made of glass fiber composite were designed to hold the pipes and the thermal shield inside the transfer line. A thermal shield, which is refrigerated by one of the pipes of the first stage circuit of Helium, was defined to reduce the radiation losses to the coldest pipes. This thermal shield is made of three parts to avoid thermal stresses, but soldered to the pipe to enhance thermal conductivity. The pipes are bent at the ends to minimize the thermal stresses.

The results of the stand-alone operation of the CSS and the transfer line are shown in Fig. 4. A dummy load of Copper and a heater were attached to each circuit to check the cooling capabilities and temperatures. When low heat power is applied, the Helium is liquefied and therefore the coil temperature is almost the same of the cryocooler 2nd stage.

At certain power level, the cooling power is not enough to liquefy the Helium, there is no phase change and therefore the temperature increment between the cryocooler and the dummy coil increases. The maximum heat for liquid Helium in the dummy load is increased from 0.15 W to 0.6 W with the new transfer line compared to the original. The available cooling power to refrigerate the cyclotron up to the critical temperature (6 K) was found to be more than 0.9 W in a stand-alone test of the CSS. The CSS and the new transfer line can refrigerate at least 0.6 W with liquefied Helium to a device which is 2.5 m apart from the cryocooler.

III. CSS Commissioning

Once the CSS and the transfer line were able to provide enough cooling power at the cyclotron operational temperature, they were connected to it for a cooling test.

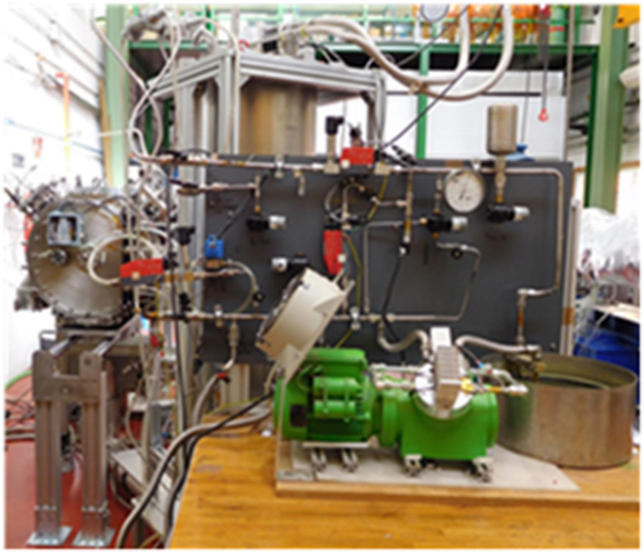

Fig. 5. Helium pumping circuit for the CSS.

It took 5 days to reach the steady-state temperature (Fig. 4). No additional cryogens and/or cooling power were used except the CSS. Fig. 5 shows the warm side circuit being the pump, mass flow controllers and buffers the main components. Helium gas at ambient temperature is injected as needed to keep the pressure level while the cyclotron is cooled down. Both manual and automatic safety components were included in parallel, so it can operate automatically according to the pressure and mass flow setpoints. The pressure is controlled by electronic valves and the mass flow can be adjusted by using a mass flow controller which is connecting both sides of the circulation pump. Safety valves and rupture disks were added for redundant safety.

The vacuum system can be also monitored and controlled automatically. A pneumatic normally-closed gate valve was included between the vacuum pump and the cryostat for safety reasons.

There is a bypass valve inside the CSS to short-circuit the main heat exchanger. Using this bypass the cooling down time is reduced about 20%. The main reason for this improvement is the lower pressure drop in the system, and therefore higher pressure and mass flow can be pumped. A higher mass flow yields in a lower temperature difference between the CSS and cyclotron. Thus, the cooling power (based on the temperature of the CSS) applied to the cyclotron (at coil temperature) is optimized because the cooling power of the CSS is lower at lower temperatures. The bypass valve is initially opened and it is closed when the helium gas returning to the CSS reached a colder temperature than the first stage of the cryocooler. At this moment, the third heat exchanger (HX3) is needed to cool down as much as possible the Helium before getting the second stage of the cryocooler to reach lower temperatures.

During this test (after the cool down transient), a problem occurred in the water chiller of the cryocooler compressor, so a new one was installed. With this new chiller, the water for the cryocooler compressor refrigeration was improved from 400 l/h

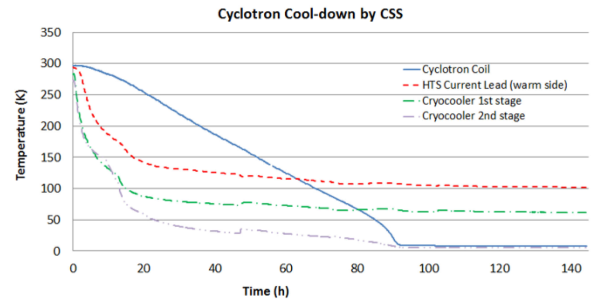

Fig. 6. Cool down of AMIT cyclotron with CSS.

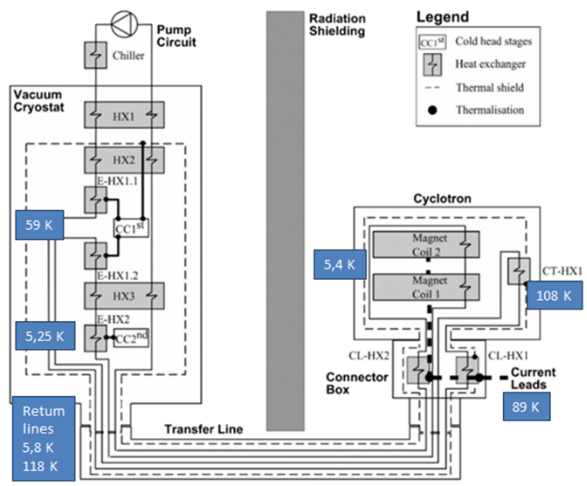

Fig. 7. Schematic view of the system including selected temperature values at steady state.

at 12 C to 450 l/h at 8 °C. In both cases the water is well inside the specifications from the supplier. Additionally, the power supply to this compressor was modified to operate at 60 Hz instead of the 50 Hz of the European standard. The available power at the first stage of the cryocooler is increased according to the manufacturer specifications (35 W at 50 K for 50 Hz, 45 at 50 K for 60 Hz)., but it was not reported any improvement in the second stage capabilities according to the supplier datasheet.

IV. Cyclotron Thermal Commissioning Results

A selection of some relevant temperatures of the system is shown at Fig. 7. These are the values for the steady-state. The mass flow of Helium being circulated through the circuit was 7.6 g/min and the minimum value of the pressure 2.4 bar. There is no liquid Helium in any part of the circuit.

The minimum achievable temperature at the coils is strongly affected by the operational pressure (Fig. 8). This is the result of two main effects. The first of them is similar to bypassing the heat exchanger: higher pressure and mass flow results in lower temperature difference between CSS and the cyclotron while the minimum temperature in the CSS is related to its cooling power. Secondly, the diaphragm pump cannot provide higher volumetric flow but if the inlet pressure is increased, a higher mass flow is pumped into the CSS.

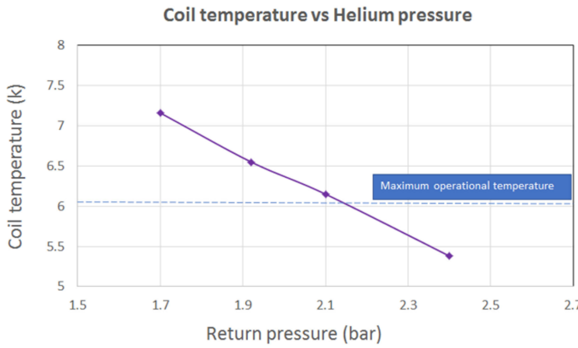

Fig. 8. Achievable coil temperature as a function of the Helium pressure in the CSS.

Some additional important results are related to the operational variables. The effect of the power supply frequency was measured: The steady-state temperature of the coils was 0.2 K lower when the cryocooler was working at 60 Hz compared to the 50 Hz supply. On the other hand, no relevant effects on the CSS capabilities were detected because of the improvement of the refrigeration water of the compressor when tested again at 50 Hz operation for comparison.

V. Conclusion

The commissioning of the cryogenic system of the AMIT cyclotron has been presented.

Both the coils and the current leads reached their operational temperatures by using just one cryocooler installed two meters away from the cyclotron. The achieved cooling allows for operation of the magnet coils up to full working current. It takes about 5 days to reach the nominal conditions starting at ambient temperature once that the vacuum inside the cyclotron and CSS cryostat is ready (two days more if the cryostat was recently closed).

The cryogenic system can refrigerate a remote load of 0.6 W up to liquid Helium temperature. For a higher load, this system can remotely refrigerate it by using Helium gas: for example 1 W at 6.5 K.

At this moment, the alignment of the coils is being performed. The magnetic forces are being measured and they are used as the driving parameter for the tuning of the rods. It is expected that this procedure will result in a near-zero net force in the casing as it is holding both coils and therefore the magnetic forces will compensate in the perfectly aligned position.

Once that the coils are aligned, a magnetic measurements campaign will start. Additional work could be needed for reaching the magnetic field quality in case it does not meet the specifications. Because of this, the iron yoke was specifically designed to include detachable poles without opening the cryostat for the shimming process.

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