A NEW COOLING SYSTEM FOR CRYOCOOLED PERMANENT MAGNET UNDULATORS AT DIAMOND LIGHT SOURCE

E. C. Longhi, A. G. Miller, E. C. M. Rial, A. Rose, J. C. Schouten,
C. Thompson, A. Thomson, J. Williams, Diamond Light Source, Oxfordshire, UK,
Charles Monroe, Monroe Brothers Ltd., Moreton-in-Marsh, UK

Abstract

In this paper we report about the first test results of a new system to cool the magnet girders of a Cryogenic Permanent Magnet Undulator (CPMU) using a liquid nitrogen thermosiphon to drive the circulation. This has the advantage of absorbing large amounts of heat with very small temperature gradients. By choosing the right pipe diameters and using a combination of variable impedance and heaters the thermosiphon can be set up in such a way that the nitrogen is boiling inside the cooling channels thereby reducing the temperature variation along the girder and minimising the temperature rise for heat loads up to several hundreds of watts.

INTRODUCTION

The first cryocooled undulator installed at Diamond has been operating since 2010 [1]. This CPMU operates at 147 K and is cooled by a weak thermal coupling to a liquid nitrogen circuit which runs at 78 K. The nitrogen is pressurised and circulated by a conventional liquid nitrogen cryocooler which, strictly speaking, is a liquid nitrogen subcooler of the type mostly used for cooling monochromators. Although the system works satisfactorily we have lost the beam a couple of times when the cryo-cooler developed a fault.

A few years ago it was proposed to use a special grade of PrFeB magnets for new CPMUs which has a maximum in the remanence below 80 K. The team at Soleil have successfully used this material in their first CPMU which operates at 78 K [2]. We at Diamond have since also started to develop a new CPMU using this new material which will operate at 78 K. It will be directly cooled by circulating liquid nitrogen through the magnet girders. In order to improve the reliability we decided to develop a new cooling system which is based on a thermosiphon. Thermosiphons are commonly used with liquid helium to cool superconducting magnets but less so for liquid nitrogen cooling. The big advantage is that they can deliver high circulating flow rates with a corresponding high cooling power and small thermal gradients along the girders. It is even possible to set up the flow regime in such a way that the nitrogen is boiling along the full length of the magnet girders and the temperature variations can be made even smaller. The other advantage is that they are maintenance free and reliable in operation. Furthermore, there is a significant cost reduction with the elimination of a cryocooler system for each device constructed.

EXPECTED HEAT LOADS

There are three main sources of heat flowing into the magnet girder: radiation, electron beam heating and conduction through the rf tapers and the supports. The radiation heat load depends strongly on the emissivity of the girders and the inside of the UHV vacuum chamber. In our design it is estimated to be around 50 W to 75 W assuming $\varepsilon = 0.15$ to 0.20 for both the girders and the inside surface of the vacuum chamber. The heat load due to the supports can be minimised in our design to less than 1 W. The total heat load from the rf tapers is estimated to be around 50 W as well.

The estimates for the total electron beam heating vary quite a lot. Measurements from installed superconducting wigglers, CPMU and from the recent COLDDIAG experiment [3], indicate at least a factor of 2 difference. Our current worst case is that it can be as high as 100 W per girder for a 2 meter device. Therefore the total heat load during operation could vary from 100 W with no beam to a sudden increase of 300 W for heating on two girders.

SUSCEPTIBILITY TO TEMPERATURE VARIATION

Our current CPMU uses NdFeB magnets, and the variation of remanence with temperature has a flat peak at around 147 K. Hence small deviations of the temperature due to heat loads do not change the magnetic field. In contrast, the new magnetic material $(Nd_xPr_{1-x})_2Fe_{14}B$ has a remanence curve versus temperature which continues to increase for temperatures below 150 K, which peaks below 80 K, the precise location of which depends on the material composition. This means that the operating temperature of a CPMU using this material can be close to the boiling point of liquid nitrogen. However because the remanence still changes with temperature $(dB/dT = 0.1\%$ per K$)$ it is very important to keep the temperature constant. In addition the temperature gradient along the beam should be kept as low as possible to avoid a build-up of systematic phase error. Target: uniform temperature stability across the magnets beams has to be better than 0.2K.

NEW COOLING SYSTEM

Most conventional liquid nitrogen cryocoolers use a Barber Nichols pump with a capacity of 19 ltr/min (5 US G/min) which provides a maximum cooling power of about 250 W/K per girder. Hence a 150 W heat load will lead to temperature gradients of 0.6 K.

Figure 1 shows the basic flow diagram for the thermosiphon system. The main components are a small reservoir at the highest point of the system, a well insulated cold feed tube which runs from the reservoir to the lowest point, a feed tube up to the magnet girder and a return tube back to the reservoir. The tubes for the upward flow should have a continuous positive gradient to avoid vapour locks. The purpose of the valve and the feed line riser heater will be explained later.
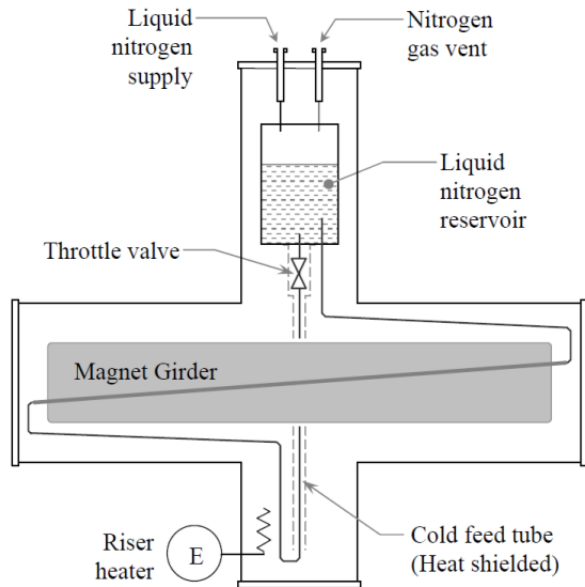

Figure 1: Basic flow diagram for a thermosiphon system.

The performance of the thermosiphon will be compared with the cryocooler on two measures: first, the temperature variation along the length of the girder; and second, the temperature rise of the girder as a result of electron beam heating.

THEORETICAL ANALYSIS

The thermosiphon design was developed using the fluid flow model from Monroe Brothers Ltd. This estimated that the conditions for liquid flow, two phase flow or vapour flow, by dividing a flow circuit into a number of nodes and calculating the pressure change due to friction losses, hydrostatic changes, pipe section changes and through fittings or valves. In addition, the heating to the fluid is used to calculate the change in temperature or vapour quality. The model uses the "RefProps" [4] property estimation package from NIST which includes nitrogen in the fluids database.

A thermosiphon uses the difference in buoyancy between the low density return path compared to the colder and the denser feed path to balance the pressure drop due to friction losses, section changes and bends etc. Therefore the flow model includes a convergence routine to adjust the inlet flow rate so that the total pressure change around the circuit is zero.

The first results, illustrated in figure 2 by the "diamond" data points labelled "Nitrogen – Valve open", showed an unexpected rise in the nitrogen temperature

and then a plateau. Closer examination of the calculated data revealed that the liquid head from the nitrogen in the reservoir, which is approximately 0.9 m above the girder, was suppressing the boiling through the cooling channels. Therefore the heat loads are absorbed by heating the liquid until the temperature has risen to the point where boiling starts. Evaluating the numbers, 0.9 m of liquid head is equivalent to a pressure of 0.07 bar and a corresponding rise in the boiling temperature of 0.5 K. This is comparable to the temperature rise on the chart which is 0.36 K: the discrepancy being attributed to the heat loads on the feed pipe and the pressure drop along the pipe.

In order to eliminate this temperature rise, two design changes were made: heaters were attached to the riser pipe before the girder and a throttle valve was introduced in the feed pipe of the thermosiphon circuit. The heater power can be adjusted to superheat the liquid nitrogen until it is on the point of boiling and the throttle valve will introduce a pressure drop and flash gas. Both of these features encourage the nitrogen to boil along the length of the girder and the improvement is illustrated in figure 2 by the "diagonal cross" data points labelled "Nitrogen – Valve restricted".
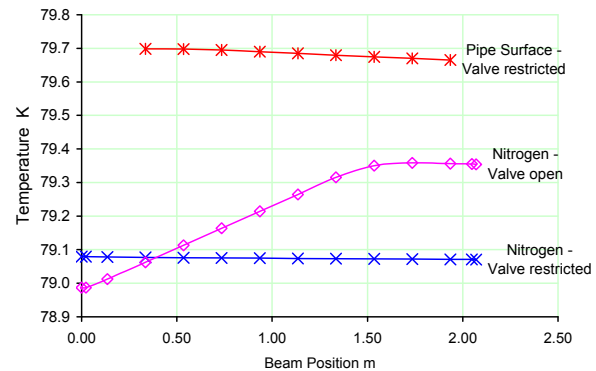

Figure 2: Beam temperature profile.

Also shown on this figure 2 profile is the pipe surface temperature by the "triple cross" data points labelled "Pipe Surface – Valve restricted", which includes the temperature drop due to heat transfer. The pipe surface shows a theoretical 0.03 K temperature drop along the length of the girder due to the change in heat transfer coefficient as the vapour quality increases.

EXPERIMENTAL SET-UP

To test this new cooling system we have designed and built a dedicated vacuum vessel which can accommodate a two meter long trial magnet girder.

The vessel has been made out of a 600 mm diameter tube with a top and bottom turret of the same size welded in the centre of the (X) long vessel. The top turret houses the small reservoir, feed valve and the liquid fill and exhaust connections. The vessel has been fitted with windows in both end flanges to allow optical measurements of any bending of the magnet girder.

Great care was taken to ensure we have a positive upwards slope along the internal tubes from the lowest point to the magnet girder and from the girder to the reservoir. Also the cooling tubes gun drilled through the girder have a small positive slope. Another objective of the tests was to measure temporary or permanent deformation of the magnet girder when cooled to 77 K and after a few thermal cycles. To avoid thermal shocks during cooling there is an extra inlet for pre-cooling below the throttle valve (not shown in figure 1). This allows us to slowly cool the girder with cold nitrogen gas to about 150 K before filling the system with liquid.

Thermometry and Heaters

Inlet and outlet tubes have been fitted with Pt100 temperature sensors while 6 CERNOX sensors are fitted in pairs to the beginning, the middle and the end of the trial magnet girder (one of the pair on the top and the other on the bottom of the girder). Two 100 W heaters are fitted on the lowest point of the feed tube where it starts to go up to the girder. There are also two 100 W heaters fitted on either side of the magnet girder to simulate beam heating plus two 100 W heaters on the top of the girder which allows us to bend the magnet girder and correct the effects of any LN2 cooling.

EXPERIMENTAL RESULTS

The initial experimental work examined the variation in temperature along the length of the girder corresponding to changes in the feed heater power or the inlet valve opening. Only a limited data was obtained for variations in temperature along the girder as a result of changes in the beam heating. One of the inlet sensors was lost and the outlet sensors were both reading high due to the instrumentation wires touching the Outer Vacuum Casing causing a heat leak and a high temperature offset.
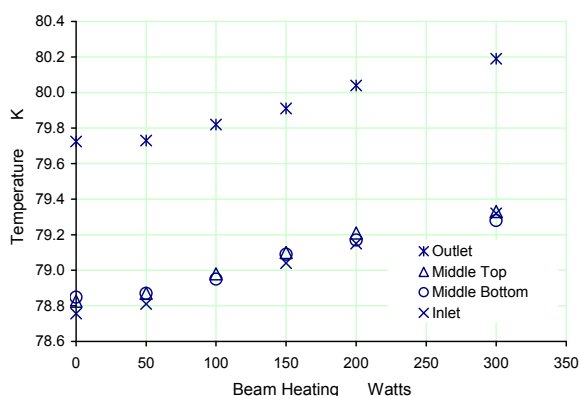

Figure 3: Temperatures versus beam heating.

The temperature variation as a function of heating the girder is shown in figure 3. Based on the inlet and middle temperature sensors, the temperature rise of the whole girder due to heating of 100 W per girder is less than 0.2 K. If the error on the outlet temperature sensor is assumed to be a constant offset due to the ambient heat leak on the wires, then the temperature rise on the outlet

of the girder is comparable. Examining the inlet and the mid sensors the temperature variation along the girder at any heat load is less than 0.1 K and appears to stay the same with increasing heat load. The temperature rise of the girder is due to the increasing temperature difference across the pipe surface and the two phase nitrogen. This is proportional to the power and the inverse of the heat transfer coefficient. The latter is affected by the thermosiphon flow rate and the liquid vapour quality.

The next experimental campaign will improve the accuracy of the instrumentation, the process control of the nitrogen fill and vent system and the data acquisition for more accurate temperature readings over extended periods. This will enable the system to be commissioned with the optimum setting of the feed heaters and the inlet throttle valve in order to minimise the temperature gradient along the girder due to beam heating.

CONCLUSION

The following conclusions are drawn by way of comparison with using a liquid nitrogen cryocooler (subcooler) system.

1. The initial results indicate that the temperature gradient along the girder is less than 0.1 K compared to a cryocooler cooled girder having a temperature gradient of 0.4 K at 100 W of heating per girder.
2. The temperature rise of the whole girder resulting from the beam heating is primarily due to the heat transfer between the pipe wall and the liquid but is better than for a cryocooler system by at least a factor of two.
3. The thermosiphon system will avoid the cost of a cryocooler and associated operating costs of maintenance and power.
4. There is significant ease of operation as after pre-cooling there is only level and pressure control required.
5. The system will be very reliable compared to a cryocooler system as there are no moving parts.

The accuracy of the temperature measurements will be improved and the experimental programme will proceed to obtain long timescale measurements.

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