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A thin gold coated hydrogen heat pipe-cryogenic target for external experiments at COSY

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ABSTRACT

A gravity assisted Gold coated heat pipe (GCHP) with 5-mm diameter has been developed and tested to cool a liquid hydrogen target for external beam experiments at COSY. The need for a narrow target diameter leads us to study the effect of reducing the heat pipe diameter to 5 mm instead of 7 mm, to study the effect of coating the external surface of the heat pipe by a shiny gold layer (to decrease the radiation heat load), and to study the effect of using the heat pipe without using 20 layers of' super-insulation around it (aluminized Mylar foil) to keep the target diameter as small as possible. The developed gold coated heat pipe was tested with 20 layers of super-insulation (WI) and without super-insulation (WOI). The operating characteristics for both conditions were compared to show the advantages and disadvantages.

1. Introduction

Nuclear reactions take place between accelerated particles and target materials. At the COoler SYnchrotron (COSY) [1] interactions of protons in the GeV energy range with target nuclei are studied. The target materials in our experiments are liquefied hydrogen and deuterium. To liquefy them, a standard cooling machine (RGD 210 Leybold AG) is used [2] and the target is built on the 2nd stage of this cooling machine as shown in Fig. 1. Earlier target versions used different heat conductors (Cu, Ag, Al) between the cooling machine and the target [3]. The longer and narrower heat link between the target and the cooler is needed for two reasons. Firstly, the cooler has to be as far as possible from the reaction point to avoid secondary interactions. Secondly, shadowing of the measuring detectors needs to be avoided. The shortest cooling down and heating up times were obtained with aluminum (the best heat conductor compared with Cu, Ag). A large improvement has been achieved by changing from metallic conduction to heat transfer by convection in heat pipes. Evaporation and condensation of a working fluid at opposite ends of a tube is used to transfer a large amount of heat [4–7]. A 16 mm diameter heat pipe was developed and tested [8]. Other improvements in the target performance were achieved by using aluminum condenser instead of copper, and a 7 mm-diameter heat pipe instead of 16 mm [9]. Further development is using a gold coated aluminum heat shield around the cold parts of the cold head and a 5 mm gold coated heat pipe [10]. After the success of these developments and due to the need for narrower diameter targets there was a question about the value of the lower limit of the heat pipe diameter which still allows stable operation. To answer this question, the diameter of the heat pipe has been reduced from 7 mm to 5 mm and the external surface has been coated by a very thin gold layer. The internal plastic tube for the liquid flow from the condenser to the evaporator was kept at the same diameter of 3 mm. The reduction in the heat pipe diameter thus only affects the cross-sectional area of the vapor flow from the evaporator to the condenser (12.56 mm^2 compared to 31.4 mm^2 for the 7 mm diameter heat pipe). The target liquid material is contained in a cylindrically shaped thin copper cell (wall thickness 30 μm) with 6 mm diameter and 4 mm length fabricated by galvanization. The beam entrance and exit apertures are closed by a 0.9 μm Mylar foil [3]. The hydrogen gas filling inside the heat pipe–bellow system has a pressure of 205 mbar at room temperature. This low pressure is stabilized during the operation to higher and stable values than the hydrogen triple point (70 mbar, 13.9 K) by a pressure stabilization system [12] to prevent solidification of hydrogen that stops the heat pipe operation. The study will concentrate on measuring the 5 mm diameter gold coated liquid hydrogen heat pipe characteristics in two cases:

1. Heat pipe isolated with 20 layers super-insulation (WI) Table 1.
2. Heat pipe without super-insulation (WOI).

The measurements were done with the heat pipe inclined at 40° with respect to the horizontal plane. For both conditions, the cool down time to liquefy the hydrogen has been measured (Section 3).

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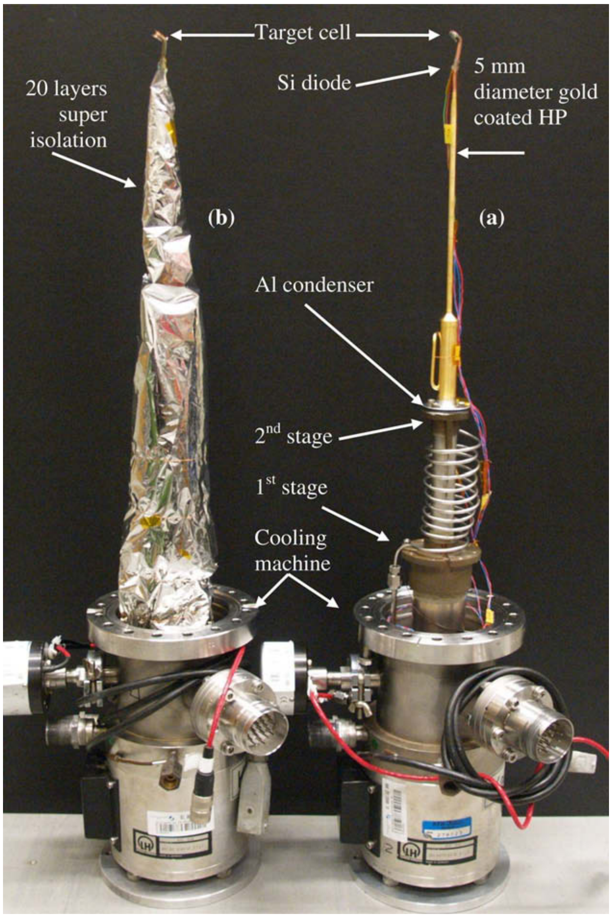

Fig. 1. Standard cooling machine RGD 210 Leybold AG with target built on the 2nd stage, (a) 5 mm diameter gold coated heat pipe target, (b) 5 mm diameter gold coated heat pipe target with 20 layers super-insulation.

Table 1
Characteristic of the aluminized Mylar foil (one side is Mylar, the 2nd side is shiny aluminum) [8].

		Mylar	Aluminum
Total thickness	30 μm		
Thermal conductivity (W/cm K)		1.3 E−3	3.0
Chemical structure		$C_5H_4O_2$	Pure aluminum
Density (g/cm^3)		1.395	2.7

The temperature difference between the condenser and the evaporator of the heat pipe has been measured and compared (Section 4). The effective thermal conductivity (Section 5) and the liquid hydrogen mass (Section 6) have been estimated. The characteristics of the 16 mm, the 7 mm, and the 5 mm diameter heat pipes have been compared (Section 7).

2. Heat pipe dimensions and design

A 5 mm diameter, 32 cm long with 0.1 mm wall thickness stainless steel heat pipe coated with ≈0.1 μm thickness shiny gold layer was fabricated. The material, the surface area, the steady state heat load due to radiation, and the heat capacity have been reduced compared to the previously used 16 mm and 7 mm diameter heat pipes [8,9]. An aluminum condenser with a control heater was used in the upper part. Also a gold coated target appendix with very thin copper walls was used in the lower part as the evaporator. A small resistor (160 Ω) attached to the target appendix is used to simulate an additional heat load in addition to thermal radiation to be applied to the target (applied heat load). A 3-mm diameter plastic tube with 0.1 mm wall thickness was used in the center of the heat pipe for liquid transportation between the condenser and the evaporator. Fig. 2 shows a longitudinal section for the heat pipe with the target appendix, the internal tube, and the aluminum condenser. Table 2 summarizes the parameters of this developed target version.

3. Cool down time with LH_2

Hydrogen is used as the fluid material in the heat pipe and at the same time as the target material. The cool down time to fill the LH_2 target cell with the gold coated heat pipe in cases WI and WOI has been measured. The time dependence of the condenser and evaporator temperatures at the filling condition (205 mbar, 6.13 l) is shown in Fig. 3. The condensation of hydrogen around the aluminum condenser started 39 min after switching on the cooling machine. The total cool down time from starting the cooling until the LH_2 reaches the target cell is 44 and 48 min for case WI and WOI, respectively. Thus, 5 and 9 min, respectively are required for the liquid to proceed down and reach the evaporator section. During that time the liquid must cool down the internal plastic tube over its full length. Afterwards, the LH_2 starts to accumulate in the target cell. Thereafter, only a couple of seconds are needed to fill the target cell with LH_2 because all the heat pipe parts became cold, therefore, no thermal resistance prevents the liquid hydrogen flow downwards to the target cell. Finally, the system has a steady rate of condensation on the condenser and flow of liquid down in the inner tube, vaporization in the evaporator and flow of vapor upwards in the space between the inner tube and the heat pipe. The cool down time for the WOI system is longer because of the thermal radiation contribution from the surroundings. This additional heat load can be estimated from black body radiation formula,

$$P = \sigma A \varepsilon (T^4_{outside} - T^4_{surface}), \quad (1)$$

where σ is the Stefan–Boltzmann constant = (5.7×10^{-8} W m^{-2} K^{-4}), A is the surface area of the 5 mm heat pipe (7.4 E−3 m^2), ε is the emissivity of the surface (polished gold = *0.018*), $T_{surface}$ = 15 K, $T_{outside}$ = 300 K.

The contribution of the radiation heat load to the polished gold coated 5 mm heat pipe target system for WOI is 61.0 mW and for WI is 7.6 mW [11]. The reduction of the thermal heat load for the WI system is due to the temperature profile along the 20 layers super-insulation. The temperature of the layer beside the heat pipe is ≈140 K [11]. So the liquid needs shorter time to reach the target cell in case of WI. In case of using one layer of super-insulation the temperature beside the heat pipe is ≈252 K and the resulting radiation heat load on the heat pipe is 30.6 mW instead of 7.6 mW in case of 20 layers.

4. Temperature difference between the ends of the heat pipe

The temperature difference ΔT between the external surfaces of the evaporator and the condenser of the heat pipe–target system is measured as a function of the applied heat load to the evaporator at different condenser temperatures. A small ΔT allows us to operate the cold head at a higher temperature where higher cooling power is available [11]. Fig. 4 shows the measured ΔT for different applied heat loads at the evaporator for different condenser temperatures in steady state operating conditions for WI and WOI. ΔT increases when the applied heat loads are increased at the same condenser temperature level, and ΔT increases at increasing con-