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STUDIES ON COOLING OF THE TOTEM PARTICLE DETECTOR AT THE LHC

F. Haug

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CERN, Accelerator Technology Department, Geneva Switzerland

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Administrative Secretariat
AT Department
CERN
CH - 1211 Geneva 23

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INTRODUCTION

The Large Hadron Collider (LHC) is CERN’s major project. The commissioning of this 27 km circumference superconducting proton-proton collider with its four large scale experiments ATLAS, CMS, LHC, ALICE is expected for 2007. The fifth experiment TOTEM (1) is particular in its composition with inelastic detectors in the forward region of CMS and with numerous small sub-detectors extending over large distances along the LHC tunnel. Figure 1 gives a principle lay-out of the LHC with its five experiments and figure 2 of the TOTEM experiment. The distant sub-detectors called “roman pot detectors” require cooling. Different cooling methods have been studied and their practicality investigated for the LHC collider environment. The adopted solution is described.

THE TOTEM PARTICLE EXPERIMENT

TOTEM measures the inelastic proton-proton collision rate and the elastic scattered protons up to 220 m downstream of the intersection point 5 (IP5), (Fig. 1). It consists in the very forward of a series of small sub-detectors (“Roman Pots”) placed inside the beam pipe and of ambient temperature tracking telescopes T1 and T2 close to CMS. The Roman Pot stations RP1, RP2, RP3 are installed in the collider tunnel symmetrically from IP5 on either side at 147 m, 180 m and 218 m (Fig. 2). Each station is identically composed of two units being 4 m apart. A unit is made of two Roman Pots that move vertically and one that moves horizontally (Fig. 8), (2).

An individual roman pot consists of an evacuated vessel holding a set of 10 silicon strip detectors close to the thin-walled 0.2 mm thick particle window. The ± 45 degrees strip orientation of the detectors form an x-y coordinate system for two-dimensional resolution (Fig. 3). With a high precision step motor they can be retracted from the beam at injection and then approach the beam to 1 mm in stable run conditions.

The Roman Pots are vacuum sealed from the beam pipe. The dissipated power is approximately 20 W. Detailed cooling requirements and temperatures for the system depend on the final design solution of the silicon detectors. In case the radiation hardness of the detector is an issue operating temperatures of 130 K are required to make use of the Lazarus effect (a phenomenon of natural self repairing of the lattice of the silicon chips disrupted by high-energy particles). In addition low temperatures would reduce parasitic edge surface currents of the edgeless silicon strips. A flexible cooling system able to operate at different temperature is needed.

Figure 1 Lay-out of the LHC experiments

Figure 2 Lay-out of TOTEM

Figure 3 Simplified Roman pot assembly

COOLING SYSTEMS PRINCIPLES

Several cooling principles and schemes have been studied as potential solutions which are discussed.

System with a micro-pump for coolant circulation

The RD39 collaboration at CERN has built a system to cool edge-sensitive silicon detectors of similar type as are the ones of TOTEM. A Gifford McMahon refrigerator cools a secondary closed loop with two-phase argon at 130 K circulated with a cryogenic micro-pump (3), (Fig. 4). The flow is split and distributed to micro cooling tubes of 0.3 mm i.d. attached to the detector mother boards for direct cooling. The high heat transfer obtained due to the evaporative direct cooling are balanced by the requirements for permanent sub-cooling of the suction flow to avoid cavitation in the pump.

System with coolant circulation by compressor flow

A proposal was made with a single, non-condensable fluid (3) (Fig. 5). A central compressor supplies the individual pulse tube refrigerators (one per station). A small by-pass flow is pre-cooled at the cold head before extracting the dissipated heat in the detector. Counter-flow heat exchangers are used. With helium as working fluid the system can operate at different temperatures. Some complication is due to the parallel fluid distribution to the sub-systems which may require valves and process control.

System with J.T. refrigerator

The local cooling stations consists of a counter-flow heat exchanger and a J.T. orifice expansion where part of the fluid is condensed. The two-phase mixture is pushed through the cooling pipes in the roman pot by the compressor flow. The systems advantageous of simple circuitry and two-phase cooling is balanced by the proportionally small condensate quantity produced at expansion and the low efficiency of J.T. refrigerators requiring high pressure ratios and the limited operation temperature range. This could partially be overcome by using fluid mixtures.

Figure 4 System with micro-pump

Figure 5 System with compressor circulation

Figure 6 System with J.T.- refrigerator

Discussion

The described systems apply active circulation of a coolant fluid to extract the dissipated heat of the Roman Pots and a “network” of pipes are needed for coolant distribution requiring instrumentation and process control. For the hostile LHC radiation environment with difficult access and repair options these comparatively complex systems might be vulnerable. The small diameter pipes may be obstructed by solids. Direct circulation of a fluid in the roman pot bears the potential risk of leaks with subsequent contamination of the beam vacuum pipe in case the thin walled particle window brakes. The system based on heat pipes, as shown in figure 7 and described in the following chapter, tries to overcome these limitations. This preferred solution is driven by reliability aspects.

THE PROPOSED COOLING SYSTEM

The design concept is based on passive heat transfer with a minimum of active elements. Each of the 2 x 3 roman pot stations (RP1, RP2, RP3) are identically equipped with a modular cooling system consisting of a central pulse tube refrigerator and six heat pipes connecting to the six roman pots. Figure 7 shows the principle scheme. The dissipated heat in a roman pot is collected by thermal contacts and transferred to the outside by conduction of bulk metal to the evaporator of the connected heat pipe. The 2.5 m long heat pipe transfers the heat to a central cryostat where it is extracted by re-condensation of the working fluid at a heat sink. The cryostat contains the six heat pipe terminals connected to the cold head. The operating temperature is controlled via a film heater attached to the cold head and the excess cooling capacity is dissipated. The refrigerator compressor will be installed in the vicinity in the tunnel. Figure 8 shows the lay-out of a roman pot station with the mechanical devices and the modular cooling system.

As the heat pipe principle is based on a self-sustaining continuous evaporation and condensation process of a working fluid with a very effective thermal conductivity it is well suited to stabilise the temperature of the roman pot connection at a given value even at distance. Operation and transfer of heat starts as soon as a heat source and sink are applied. The heat pipe inner wall is lined with a wick to enhance capillarity and radial heat transfer and the temperature gradient in the fluid phase is expected to 1-2 K over its entire length of 2.5 m. The pulse tube refrigerator used during the current development phase is based on a design for a 165 K application (6). Its cooling capacity is 140 W at 130 K which can be increased with a larger compressor. Helium is the cycle gas and the operating temperature can be varied from below 100 K to 250 K which is useful during the development phase.

Figure 7 System with heat pipes

Figure 8 Cooling system lay-out with heat pipes and a central pulse tube refrigerator for an individual roman pot station

Also the heat pipes can be adapted to different temperatures by selecting the appropriate working fluid. The theoretical temperature limits are between the triple and the critical point of the respective fluid. However, in practice operation close to the triple point should be avoided as heat transfer performances are reduced with potential failures due viscous and sonic limitations of the low density vapour. Close to the critical point the heat of vaporisation becomes smaller and boiling becomes a

limiting factor for the performance. Further limitations are entrainment and capillary pumping. Figure 9 shows the principle performance limitations of a heat pipe as a function of temperature. In Table 1 several low temperature working fluids are listed being potential candidates for this application. Furthermore the overall two-phase cycle pressure drop must be compensated for by the driving capillary and gravitational forces that pump the condensate back to the evaporator. Apart from the fluid properties the geometrical arrangement is of importance. The current design applies longitudinal grooves as wick structure and the outer pipe diameter is 15 mm. The heat pipe has an average inclination of 5% for gravity assist of the condensate return flow.

Figure 9 Limitations to heat transport in heat pipes

Table 1 Heat Pipe Working Fluids proposed

Fluid	Triple point Temp. (K)	Critical point Temp. (K)
Argon	83.8	150.86
Krypton	115.76	209.38
Xenon	161.36	289.74
Methane	90.69	190.55
Ethane	90.35	305.53
Propane	85.47	369.85

To allow the operation of the TOTEM cooling system at different temperature ranges a design feature permits to empty and change the working fluid for adaptation. This is done with valves installed at the pipe appendix after the condenser allowing the evacuation of the fluid and the refill with a different one.

The design principle will be validated with the installation of a prototype Roman Pots detector unit consisting of a pair of vertical pots at the SPS collider beam in the fall of 2004. Two heat pipes and the above described pulse tube refrigerator will be used for this purpose and operation and data acquisition will be done at distance. This permits the verification of the cooling requirements in view of the final installations in 2006. If necessary the refrigerator design may be reviewed for increase of cooling capacity.

SUMMARY

Compared to the rather complex forced flow systems the proposed design mainly applies passive elements for heat extraction and transport with heat pipes and a pulse tube refrigerator. It seems to be particularly suited for the LHC tunnel hostile environment. A prototype will be constructed for tests at the CERN SPS accelerator.

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