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CO2 cooling tests and pre-heater characterisation for the CMS Phase II Outer Tracker TB2S

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The cooling system for the CMS Tracker is currently being designed within the scope of the Phase II upgrade. In order to limit radiation damage to silicon modules, and ensure detector performance for its expected lifetime, the silicon must be kept as cold as possible. Evaporative CO2 cooling is chosen because it is possible to keep a fairly constant cold temperature throughout the detector, with the addition of heat only causing the evaporation of liquid rather than an increase in bulk fluid temperature. This allows for the use of smaller mass flows and hence small pipes in a region where the material budget is to be minimised.
To evaluate the performance of the two-phase cooling system, tests have been performed on geometry representative of the Outer Tracker TB2S ladders down to -24℃ over a range of operating conditions. The obtained results can be compared to simulations using tools like CoBra to contribute to our understanding of detector cooling performance and design.
The effect of superheating has been observed in previous detector applications with CO2 cooling (particularly in ATLAS). Superheating is when the liquid CO2 passes the saturation point without evaporation occurring, the fluid continues to heat up as its enthalpy increases, obviously counterproductive to keeping the silicon modules as cold as possible. Superheating appears to be unstable, and at a certain point (distance along the pipe, or in time) the superheated fluid boils and drops in temperature to the "normal"two-phase curve. The use of a heating device clamped to the outside of the pipe ("pre-heater") to trigger bubble nucleation upstream of the modules has been explored.
Pre-heaters seem to be effective at dispelling superheating within the test setup representing a single TB2S detector cooling loop. The main parameters affecting the power required to trigger nucleation are shown to be: pre-heater length, pipe inner and outer diameters, CO2 temperature, mass flow rate and the amount of sub-cooling of the liquid.
A semi-empirical model for the pre-heater design is also proposed: starting from a few experimental data points, the model characterises a pipe made of a specific material and production process, giving the possibility to design the pre-heater for that type of pipe while changing any boundary condition (flow, power, length). The model is based on the onset conditions of nucleate boiling: for nucleation to occur on a pipe wall, the entire liquid-vapour interface of a bubble should be at a temperature above the minimum liquid superheat requirement for the bubble itself. Since the temperature in the liquid reduces farther away from the pipe surface, the lowest temperature in the liquid is experienced in the tip of the growing bubble. A simple condition is thus derived when the liquid temperature at the tip exceeds the minimum required temperature to sustain the vapour bubble, with the liquid temperature profile derived from duct turbulent flow analysis. This gives the definitions of a minimum and a maximum radius of active cavities that allow the onset of nucleate boiling. As it is generally difficult to assess what is the microscopic structure of pipes, in order to understand if the pipe surface contains cavities that are suitable to generate nucleate bubbles, experimental data is needed in order to obtain the cavity radii range for the surface of the pipe under investigation. The model itself seems to correctly predict the impact of changing the design of the pre-heaters, catching the expected variations of their nominal power with respect to some of the parameters involved, such as the pre-heater length, the liquid CO2 temperature and its mass flow rate. A more extensive validation campaign is needed, to analyse the model behaviour when other influential variables are changed: pipe diameter, subcooling level, and pipe roughness.

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