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System design challenges for CO_2 evaporative cooling in tracking detectors

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CO_2 evaporative cooling has become one of the most popular thermal management technologies for silicon detectors to be operated at low temperature. At LHC, this solution is already in use on the LHCb Velo, the ATLAS IBL and the CMS Phase I Pixel. The LHCb Velo upgrade and the UT detectors will be cooled in the same way as of 2019, as well as ATLAS and CMS upgraded tracking and vertexing detectors for the HL-LHC (2025). In order to fully exploit the heat removal capacity which can be achieved with carbon dioxide in evaporative mode, the cooling system needs a very careful design, combining the process, the transfer lines and the on-detector evaporators. This work discusses the challenges for the design of an optimised CO_2 cooling system, including the mechanics, the thermal interfaces and the process instrumentation for controls and monitoring. Examples of presently adopted solutions are given, together with their limits and the needed further development in order to achieve reliable systems of much higher cooling power as in HL-LHC detectors.

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1. Introduction

In the last 10 years, evaporative CO_2 cooling has been introduced in particle physics and, thanks to the excellent performances, reached a general consensus as the best technological choice for the future upgrades of the CMS and ATLAS experiments at HL-LHC ([1], [2], [3]). The reasons are several: evaporative cooling allows for higher heat transfer coefficients than mono-phase systems, thus reducing the mass of the needed pipework to distribute the coolant inside the detector volume, particularly appreciated for lightweight vertexing and tracking detector; CO_2 has a much lower environmental impact and cost than all other fluids available for detector cooling in the same operating range (typically perfluorocarbons) and it has, as well, excellent radiation resistance; the system design can be based on fully passive components in the non-reachable detector environment. Today, the requirements for the cooling of the HL-LHC ATLAS and CMS upgrades push the CO_2 cooling technology beyond the limits of the present applications: unprecedented powers (up to 1 MW as total cooling capacity demand from ATLAS and CMS), temperatures as low as -40°C at the detector and thousands of parallel evaporators ask for a well thought system, which should guarantee stable operation to several detectors all along the experiment lifetime [4].

2. The challenges in the design of an evaporative system

In order for evaporative CO_2 cooling to perform at best of its capacity, strict design rules shall apply to the full system: the on-detector evaporators and local distribution, the main distribution, the on-detector and main transfer lines and, finally, the CO_2 cooling plant itself, as schematically illustrated in Figure 1. Changes in the design of one part of the system (pipe size, flow rate, thermal contact) would dramatically influence the performances of the rest, as detailed further below.

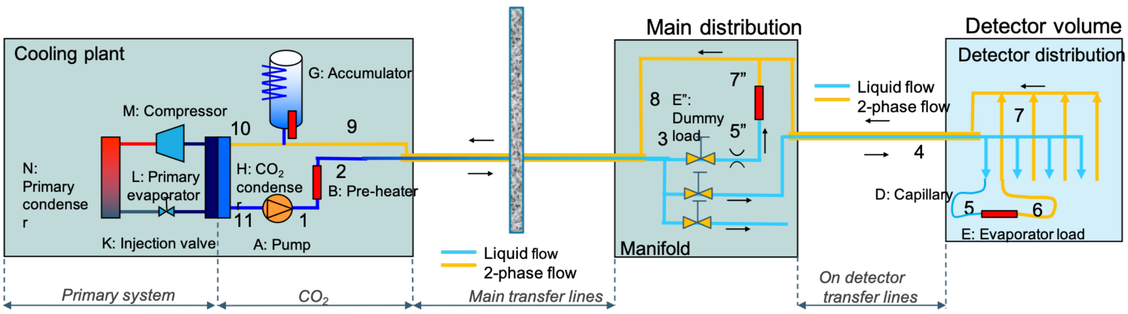

Figure 1: The CO_2 evaporative cooling system schematic.

2.1 The 2PACL cooling system

The CO_2 evaporative cooling cycle used on all particle physics detector applications is the so-called 2PACL (2 phase accumulator controlled loop) [5]. In figure 2, the cycle is represented on the pressure-enthalpy diagram. Liquid CO_2 is pumped (10-1) and transferred (1-3) up to the distribution manifolds, as close as possible to the detector evaporators. There, sub-cooled CO_2 is further distributed and expanded in ad-hoc restrictions (4-5) before entering the active area of the detector. The heat load inside the detector volume (5-6) partially evaporate the CO_2, which returns in a two-phase mixture up to the cooling plant (6-10). At the plant, CO_2 is condensed and sub-cooled by means of a primary refrigeration cycle before being pumped back to the detector. A liquid/gas collector positioned on the return line at the CO_2 plant, called accumulator, is used to control the evaporation temperature inside the detector. The pressure at the accumulator can be varied by means of heating or cooling actions. The system has several advantages for detector cooling applications: the saturation temperature in the detector is set by controlling the fluid properties far away from the evaporators, thus avoiding the installation of active components inside the non-accessible experimental areas; the liquid CO_2 is clean and non-sensible to radiation, because of the oil free pumps which can be employed; the stability in temperature regulation is very high, and almost independent from the heat load applied.

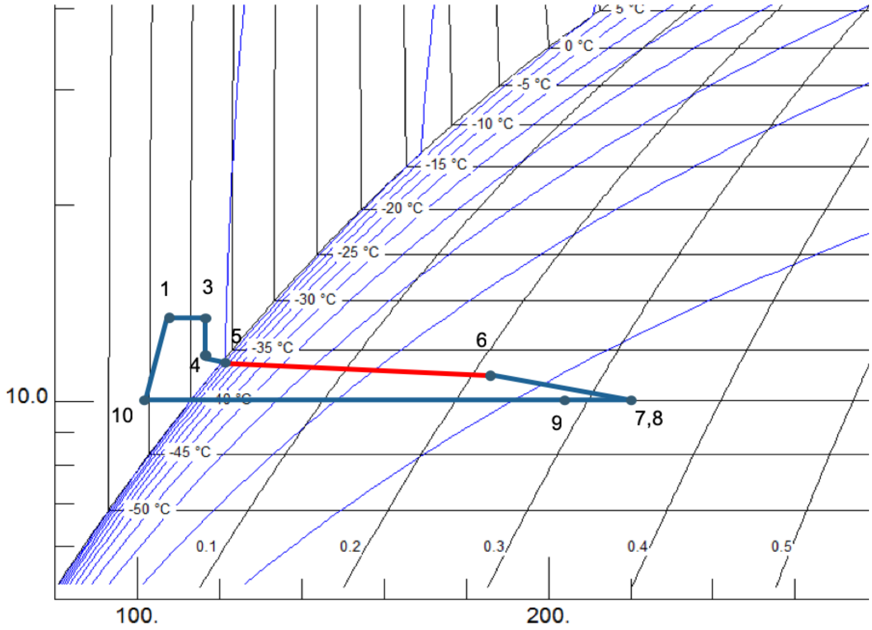

Figure 2: The 2PACL thermodynamic cycle.

3. The design chain

The design chain shall start from the on-detector requirements: the temperature on the detector modules will depend on the coolant temperature in the evaporators, the heat transfer coefficient and the integrated thermal resistance between the pipe and the module. The challenges in the design of a proper thermal contact (choice of mounting technologies, materials, glues, etc.) are described in detail, for example, in [6] and in [7].

3.1 Temperature profile - on detector evaporators

When designing the on-detector evaporators, one should start from an analysis of the detector layout and the choice of the needed granularity, which are dictated by physics performance and failure analysis. Once the detector module heat load on each evaporator is determined, the coolant mass flow rate can be easily chosen, following standardised design rules. A CO_2 mass flow of 1 g/s will guarantee to cool down about 100 W at -35°C, with the coolant reaching 0.33 vapor quality at the exit of the evaporator. During commissioning and installation phase, detectors may need to operate at temperatures above ambient dew point (typically 15°C for the LHC experiments). In these conditions, the same mass flow rate will deliver the same cooling power when reaching a vapor quality of 0.66. This vapor quality is somehow set as a limit for detector applications, in order to guarantee the heat transfer performances of the evaporators. From literature data about the evaporative behavior of CO_2, one can see that the dry-out phenomenon appears, in the range of pipes commonly used for detector applications, when vapor quality is above 0.7-0.8. When this happens, the heat transfer coefficient of the 2-phase mixture suddenly drops, and this may lead to fast detector overheating [8].

For a given evaporator length and mass flow, the choice of the pipe diameter will determine the total thermal gradient from the coolant to the detector through two effects: the pressure drops along the evaporator have an impact on the axial (along the evaporator length) thermal gradient, the heat transfer coefficient has an impact on the transverse thermal gradient (from fluid to pipe wall). The pressure drops effect is increasing with a smaller pipe diameter. The heat transfer coefficient contribution decreases for a smaller pipe diameter. In order to optimise the size of the evaporators, both effects shall be considered, and it is common to define a "combined" temperature gradient to be minimised, as schematically represented in figure 3 [8]. In figure 4, one can see an example of calculations for the optimal range of pipe diameter for a specific case. There, a temperature gradient range is taken as design parameter (2.5 to 3 °C). The curves plotted against the ranges of possible pipe inner diameters, for a range of mass flows, represent the calculated temperature gradient due to the pressure drop (bottom curves) and the temperature gradient for the combined effect pressure drops/heat transfer coefficient variation (top curves). The region enclosed by the intersection of the perpendicular lines represents the range of operational possibilities where to chose the pipe diameter in order to maintain the desired temperature gradient. In order to compute two-phase pressure drops, mathematical tools like the "CoBra" code [9], implementing the most reliable empirical models available in literature [10] are currently used. Nevertheless, such models feature errors in the prediction of pressure drops in the order of 25% or more and testing of any detector evaporator design is mandatory to validate it.

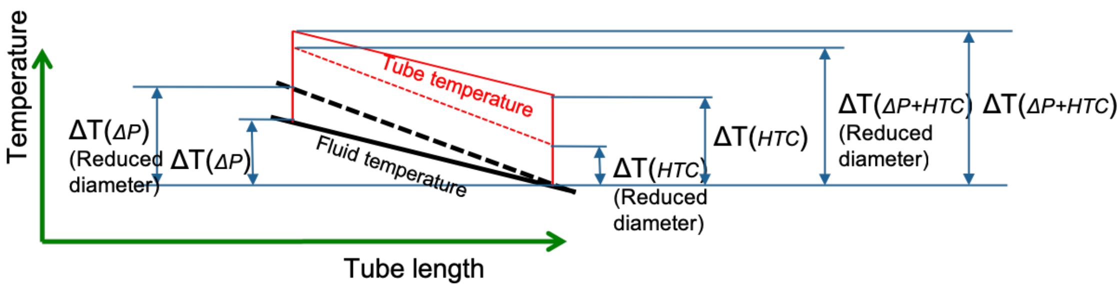

Figure 3: The on-detector evaporator design optimization: effect of temperature variation along the detector due to pipe size and heat transfer coefficient variations

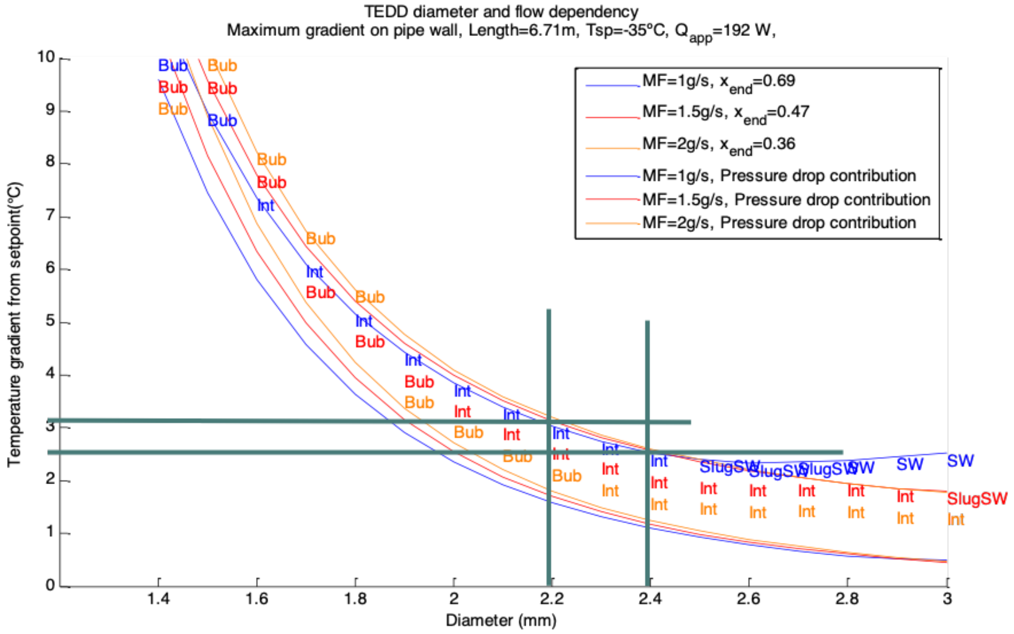

Figure 4: Optimization of pipe diameter choice for a given evaporator length and load

3.2 Temperature profile - transfer lines

The temperature gradient along the detector is determined by the design of the evaporator itself. The gradient between the detector exit and the accumulator, where the temperature is controlled, is determined by the pressure drops along the return transfer lines. In 2PACL systems, concentric transfer lines are used for connecting the plant and main manifolds to the detector volume, with the liquid supply circulating in the inner pipe and a mixture of gas and liquid being returned to the cooling plant on the outermost pipe. This design has a double effect:

1. The liquid coolant is shielded from the environment by the return two-phase mixture, which takes the heat pickup due to non-perfect insulation by further evaporating the mixture

2. The liquid coolant temperature at the detector inlet is equal to the evaporation temperature at the detector exit, thus controlled

In order to minimise the pressure drops on the return lines, the return duct cross section shall be optimised. Also in this case, the empirical methods for prediction of CO_2 two-phase pressure drops [10] are used, with two additional caveats: the models are applied to annular cross sections but are validated for circular ones, and they do not take into account any gravitational effect. For this reason, accurate testing of vertical flow in concentric transfer lines is now on-going on several setups at CERN, in order to validate the design for the phase II upgrade CO_2 cooling systems of ATLAS and CMS.

4. Detector operation with CO_2 cooling

In the cooling system design phase, it is important to consider the operational aspects at the different expected operation ranges, in particular focusing on:

1. ensuring that all parallel detector loops can operate in all conditions, no matter the powering or cooling status of the others
2. ensuring that evaporation happens where the detector heat load is applied, not before or after the detector volume
3. defining the proper information exchange between the CO_2 cooling process and the detector

4.1 Parallel loops

A typical feature of detector cooling system is the high number of parallel cooling circuits feeding the detector volume. In table 1 the typical baseline numbers for the CMS phase II upgrade sub-detectors are shown. There, up to a maximum of 19 parallel evaporators are fed by the same transfer line, which ends in the close vicinity of the detector volume in an appropriate manifold. The flow rate to be distributed to each parallel branch is directly proportional to the heat load removed trough that evaporator, as seen previously. As in mono-phase systems, balancing of parallel loops can be obtained by introducing adequate pressure drops on top of the single loop ones. The difficulty with evaporative systems lays in the fact that the evaporator pressure drop characteristic during operation varies when the coolant is liquid (no detector power) or two-phases (detector is powered on): the ratio between pressure drops in liquid or in two-phase for a single evaporator can go up to a factor 7. This implies that the balancing tools shall cope with the full range of operational pressure drops of each evaporator, guaranteeing that each of them is fed by the good amount of coolant when the corresponding modules are switched on, even in case all the other parallel circuits are off and thus their impedance is much lower. A ratio of 4 between the nominal pressure drop in two-phase of the evaporator and the pressure drop provided by the balancing tool is calculated to be appropriate. Given the limited space in the detector volume and the harsh environment (radiation and magnetic field in all LHC experiments) only passive components can be used to distribute the flow. Two choices have been implemented on existing detectors so far and are in the baseline for future HL-LHC detectors: capillaries or calibrated orifices. The calibrated orifice solution, employed, for example, on the LHCb Upstream Tracker [11], has the advantage of being extremely compact. Moreover, the calibrated orifice size can be easily exchanged with no major impact on the integration, in case the orifice holder is accessible. On the other hand, the capillary solution has two main advantages: the pipe inner diameter can be kept above 500 μm, thus reducing the clogging risk, and the capillary can be used as part of the circuitry, reducing the total length of the bigger pipes which have a major impact of the total mass inside the detector volume.

4.2 Boiling triggering

In an evaporative cooling system, the main advantage with respect to pure liquid cooling is given by the high values of heat transfer coefficient reached during evaporation. In order to exploit this at best, one need to ensure that the part of the circuit where evaporation happens is the one inside the active detector area. Thanks to the heat exchanged along the concentric transfer lines, CO_2 evaporative cooling provides sub-cooled liquid at the inlet of the detector, just before the last

Detector	Transfer lines	Evaporators	Max evap. per transfer line
Inner Tracker	24	168	8
Outer Tracker	48	476	12
Barrel Timing Layer	12	72	11
Endcap Timing Layer	8	144	18
Calorimeter Endcap	48	912	19

Table 1: The CMS phase II upgrade detector evaporators and transfer lines.

distribution manifold feeding the on-detector evaporators. At this stage, the system shall be designed such that the CO_2 can be warmed up to saturation temperature and that evaporation can start before the first detector module, without super heating occurring. The latter is the phenomenon for which a substance can be heated above the temperature at which a change of state would ordinarily take place, without such a change of state occurring, for example, the heating of a liquid above its boiling point, without boiling taking place; this results in a meta-stable state. Models exist in literature [12], defining the maximum temperature liquid CO_2 can reach without boiling and the experimental values obtained from testing of sample detector structures [13] are compatible with such models. Nonetheless, existing models do not allow for precise design of adequate tools which can be used on detector applications in order to avoid the super-heating phenomenon. Different solutions have been applied so far. in the CMS phase I Pixel upgrade [14], the pipe section between the capillaries and the first detector modules runs along the supply tube, cooling the dc-dc converters and the electronics port-cards which are installed in that region. The heat dissipated by these is enough to warm up the sub-cooled CO_2 and allow for evaporation to start in close vicinity of the first detector modules. For the phase II upgrade of the CMS CO_2 cooled detectors, a concentrated heat source called "pre-heater" will be installed upstream of each detector evaporator. The system consist in a small bloc, with a concentrated electrical heat source in contact with the pipe. In figure 5, the effect of different power applied to the pre-heater bloc is measured for a dummy CMS Tracker evaporator, running with CO_2 at -24°C. The liquid superheating effect is remarkable on the temperature-distance plots which correspond to the pure distributed detector load (0 W pre-heater) up to the 4.5 W pre-heater case. In the range above 5 W of pre-heat applied to the detector evaporator, the temperature profile follows the expected curve: a limited heating (2 °C) is followed by the evaporation start, and the temperature decrease down to the exit of the evaporator.

In the ATLAS phase II upgrade, the super-heating effect will be avoided by use of co-current heat exchangers, installed in close vicinity to the detector evaporators. A parallel branch of CO_2 coolant, maintained at at a warmer temperature than the detector one by means of back pressure regulators, will bring fluid to the heat exchanger to heat up the sub-cooled CO_2 up to the boiling temperature. Work is presently on-going in the ATLAS community to test the prototypes of 3D printed heat exchangers [15].

4.3 System operation

During system design, the appropriate sensors to monitor the cooling performances in operation shall be selected and foreseen. A set of critical temperature measurement points is shown in figure6, where the temperature profile for a typical detector cooling loop is schematized. The

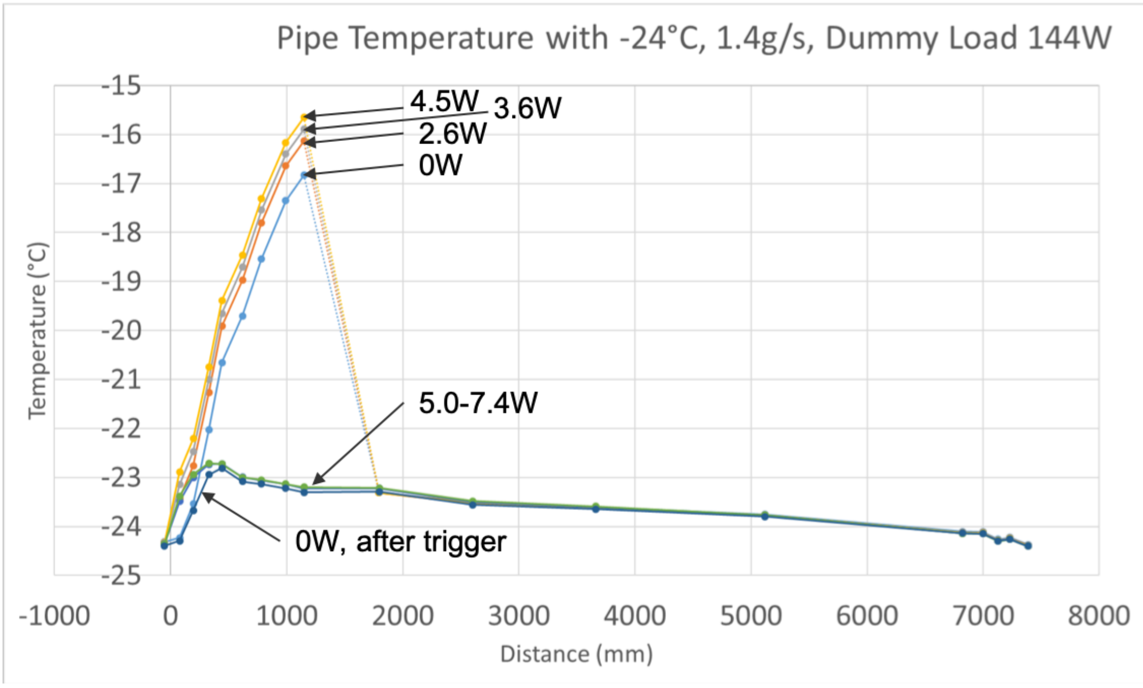

Figure 5: The effect of varying pre-heater loads on the evaporator temperature profile

temperature variation between the inlet manifold and the capillary outlet would show a positive trend in case the CO_2 is still liquid, as it should, up to the inlet of the evaporator. From there, the temperature shall decrease, for the combined effect of evaporation and pressure decay. With increasing number of parallel cooling loops on each detector, it is suggested to equip at least one or two parallel loops per each detector manifold, in order to maintain a wide overview of the system performances during operation.

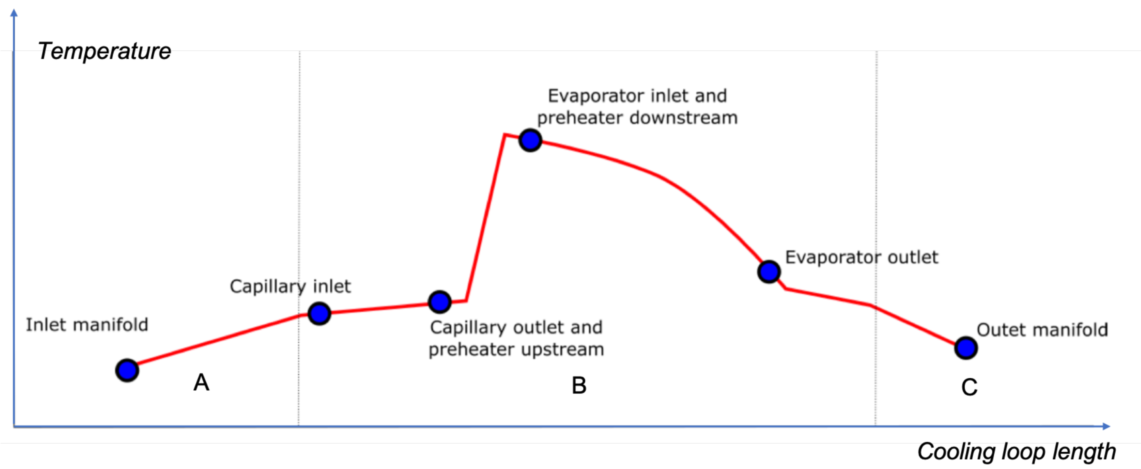

Figure 6: Cooling loop temperature profile and suggested measuring points

5. Conclusion

CO_2 evaporative cooling has been chosen by several experiments as the most promising technology for the future generation of tracking detectors at HL-LHC. The design phase of the cooling system is deeply connected to the one of the detector, given the complexity and interdependence of the system parts. The evaluation of the on-detector and off-detector requirements and constraints needs to be done in parallel, in order to anticipate changes that may put the performances at risk. Empirical models used in the simulations for the CO_2 cooling system design are extremely complex: testing of all substructures and careful choice of the monitoring tools to be put on the final systems are mandatory.

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