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Applying krypton as refrigerant for cooling of future particle detector trackers at CERN

Luca CONTIERO*[a,b], Bart VERLAAT[a], Armin HAFNER[b], Krzysztof BANASIAK[b], Yosr ALLOUCHE[b], Paolo PETAGNA[b]

[a] European Organization for Nuclear Research, Geneva, 1211, Switzerland,* luca.contiero@cern.ch

[b] Norwegian University of Science and Technology, Trondheim, 7491, Norway

ABSTRACT

Future silicon-based particle detectors at CERN's Large Hadron Collider will be exposed to higher radiation levels, requiring the silicon sensors to be kept at lower temperatures than the ones provided by the current cooling systems, using CO_2. Aiming to approach temperature levels unattainable by CO_2 and ranging between -60 to -80°C while maintaining the system environmentally friendly, the use of Krypton appears promising for the thermal management of future high energy physics detectors. Although studies about using noble gases for refrigeration purposes outside of deep cryogenic applications are extremely rare, the thermodynamic and transport properties of Krypton suggest its great potential as a coolant in detector applications. Since silicon detectors are characterized by ultra-light and fragile structures requiring a controlled cooldown to avoid thermal shocks, a new cooling system was developed. This work presents the concept and the strategies to be implemented to fulfill the harsh requirements imposed by detector cooling.

Keywords: Carbon Dioxide, Krypton, Ejector, Detectors, Supercritical

1 INTRODUCTION

Silicon detectors are used for detection and measurement of ionizing radiation caused by interaction with charged particles and photons. The ionization of the charged particles in the insulating layers of the sensors produce a surface damage (Lutz and Klanner, 2020). The different defects created have several consequences for the detectors, especially the risk of thermal runaway (Beck and Viehhauser, 2010) of the sensors which represent their major limitation in harsh radiation environment of high-luminosity colliders like the CERN LHC. At higher radiation doses compared to what experience nowadays, colder temperatures will be required pushing the need of a new cooling agent in the range -60 to -80°C (ECFA Detector R&D Roadmap Process Group, 2020). Since 2008, CO_2 emerged as excellent cooling fluid (Verlaat, 2008) for particle detector trackers thanks to its thermal performance which allow the use of very small pipes, feature appreciated in low-mass detector where every material produces noise to the measurements and thus need to be minimized. The advantage of two-phase cooling to extract the heat isothermally (temperature does change only due to pressure drops) spread all over the different experiments at CERN the CO_2 cooling concept. Because of the fluid triple point (≈ -56°C), colder temperatures are unattainable. Following the same approach that led to the adoption of CO_2 in particle detectors, a new high pressure and environmental-friendly fluid is needed. Among different candidates, krypton appears to be promising for thermal management of future highly irradiated detectors. As a fluid with a low critical temperature is necessary to maximize the thermal performance, the system architecture needs to be completely revised as a pumped loop cycle cannot longer be used due to the initial gas state of the fluid at standstill. In order to provide cooling in the temperature domain required for future detectors while preserving their integrity during the slow and controlled cooldown process, a new ejector-supported cycle is proposed. The common points with the existing CO_2 system are also analyzed and discussed, as the guidelines developed for the current system can partially be extended to the future cycle using krypton.

2 SELECTION OF A PROMISING COOLING AGENT IN HEP EXPERIMENTS

The requirements normally encountered in a traditional refrigeration system differ from what is demanded in physic experiments (Petagna, 2018). The experimental area is strongly irradiated thus all the instrumentation of the cooling system needs to be placed far away. Any active components nearby the detectors must be replaced with passive components (i.e. capillary as expansion device). To minimize disturbances to the measurements, small cooling lines are utilized to reduce the cooling hardware within the detectors. The use of two-phase cooling requires additional safety measures during the design phase of the system to avoid risk of dry out along the cooling line with consequent risk of electrical breakdown of the sensors. As a rule of thumb, cooling lines are designed such to never exceed vapor qualities around 35-40%. Boiling should be induced at the entrance of the detector, avoiding low heat transfer coefficients typically associated to the subcooled liquid state. Efficient cooling in small pipe diameters is merely a characteristic of the fluid used in the temperature range of interest. To address a meaningful comparison among different candidates, a modified version of the heat transfer coefficient will be introduced: the volumetric heat transfer coefficient.

As the power dissipation of the sensors is sensitive to the temperature (Beck and Viehhauser, 2010), having a homogeneous temperature distribution across the detector is extremely important to guarantee optimum working conditions of the sensors. The thermal efficiency of the cooling agent is normally quantified within the detector community via a parameter called Thermal Figure of Merit (TFM) (Viehhauser, 2015). It describes the thermal efficiency of the convective (fluid-dependent) and conductive (dependent on the structure embedding the cooling pipe) heat transfer processes along the chain fluid-sensors. The parameter is defined as Eq. (1), representing the inverse of the thermal impedance.

$$TFM = \frac{\Delta T_{fluid-sensor}}{Surface\ power\ density} \qquad \text{Eq. (1)}$$

The minimization of this parameter requires optimization of both the cooling fluid as well as the use of materials with high thermal conductivity and low density, so to minimize the shielding effect to the particle crossing. In this paper, only the convective contribution is discussed.

2.1 Natural cooling fluids

Natural alternatives to CO_2 in the ultra-low temperature range below -50°C (American Society of Heating, 2018) are very limited and comprise the following fluids: hydrocarbons ethane and ethylene, nitrous oxide and noble gases xenon and krypton. Each of them present different peculiarities such as risk of flammability, explosion (N_2O) (Kauffeld., 2020) or asphyxiation in high concentration which need to be consider during the design phase. However, from the thermodynamic point of view, a quick comparison can be assessed by looking at their critical temperature and pressure. In a detector application is important to minimize the temperature drops along the cooling pipe such to limit the temperature gradient with the sensors. In Figure 1 the temperature drops associated to an arbitrary pressure drop of 1 bar is illustrated as a function of the reduced pressure for the different fluids.

CO_2 and the perfluorocarbon C_3F_8 are also reported in the graph to compare the new and the old cooling philosophy at CERN. Historically, C_3F_8 was selected because of its radiation hardness (Battistin, 2015) and the operation at low temperature (≈-25°C) with thinner tubing, due to the low operating pressure. This choice turned out in using larger pipe size to maintain at acceptable levels the temperature gradients caused by the pressure drops, which are more pronounced at low reduced pressure. As result, hardware minimization inside the detector was not achieved meanwhile heat transfer performance were relatively poor. The primary indicators of such low performance were the high critical temperature of C_3F_8 (≈ 71°C) and the operating pressure in the range of interest (≈ 1.4 bars at -30°C).

In contrast, CO_2 demonstrated significantly better performance, with the temperature losses nearly three times smaller. Each fluid is more performant in terms of temperature drops close to the critical point due to the vapor density approaching the liquid phase density. At lower pressures the saturation temperature is more affected by pressure changes pointing out the importance of working in proximity of the critical point.

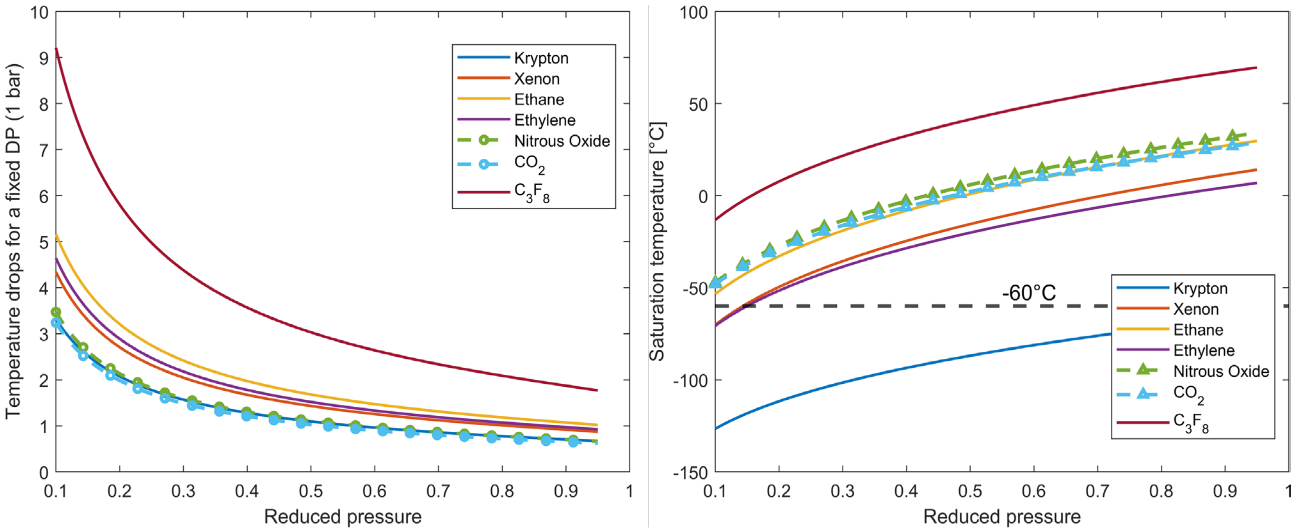

Figure 1: Saturated temperature drops for an arbitrary pressure drop(a) and saturated temperature (b) as a function of the reduced pressure for different fluids.

If the future temperature level spans around -60/-80°C, a fluid with low critical temperature is needed to maximize its thermal performance. Closer to the critical point is also possible to exploit the high fluid operating pressure which results in a volume reduction of the cooling line thanks to a more compressed gas phase (low specific volume). A high-pressure fluid is less sensitive to temperature drops and larger pressure losses can be accepted at the expense of a larger pumping power. In a detector cooling application where mass minimization is crucial, reducing pipe size to leverage higher fluid velocity and heat transfer coefficient becomes imperative.

2.2 Fluid study comparison

The simplest approach that can aid in a more comprehensive evaluation among different candidates is to use a non-conventional parameter called the volumetric heat transfer coefficient (Petagna, 2018). This parameter is defined as in Eq. (2) and it does not assess the fluid performance at a local level but rather gives an overall indication of its heat removal capability. During flow boiling the warmest spot is normally located at the entrance of the cooling pipe where the fluid pressure is the highest.

$$VHTC = \frac{Q}{Volume*(\Delta T(\Delta p) + \Delta T(HTC))} \qquad \text{Eq. (2)}$$

This parameter combines the most important requirements that a fluid should have to be considered for thermal management of detectors. A high value of the VHTC means an optimization of the different aspects involved to achieve an efficient cooling:

- Reduced volume of the cooling line
- Low saturated temperature losses, described via ΔT(Δp)
- Low temperature difference between the bulk fluid and the wall due to high fluid heat transfer coefficients, described via ΔT(HTC).

The VHTC has been calculated using MATLAB (The MathWorks Inc., 2022) , where correlations of heat transfer and pressure drop (Kandlikar (Kandlikar, 1990) and Friedel (Friedel, 1979)) have been implemented. Outlet conditions in terms of saturated pressure and outlet vapor quality are fixed, thus requiring an iterative procedure to converge and find the mass flow rate entering the detector under saturated conditions. Figure 2 (a) illustrates graphically the procedure involved in the estimation of the VHTC: the optimum tube size is calculated as a trade-off procedure. Larger pipe sizes help to minimize the temperature losses but they deteriorate the heat transfer coefficient, while pipe's volume also increases. Conversely, using a smaller pipe size impacts less the detector performance but the larger pressure drops cause a greater longitudinal gradient in the saturated temperature. However, due to the increased flow speeds the heat transfer coefficient will increase, reducing the transversal gradient fluid-wall despite the larger drop in the fluid temperature.

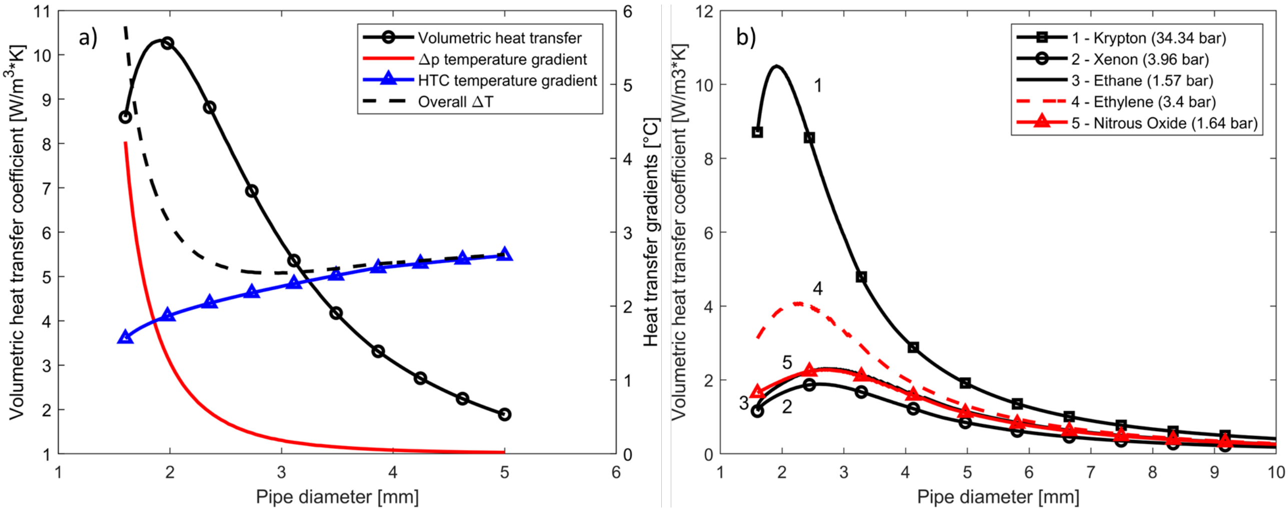

Figure 2: Graphical representation (a) of the volumetric heat transfer coefficient considering krypton and a standard detector (length = 1 [m], heat load = 200 [W]). In (b) the optimization is carried out for different fluids under the same detector boundary conditions.

Krypton shows a peak in VHTC (Figure 2(b)) that is much higher than that of all the other fluids, while the tube diameter remains in the range of mini channels (≈ 2 mm), similar to what is currently used with CO_2.All the other fluids are extremely sensitive to pressure drops due to the much lower operating pressure.

2.3 Challenges with krypton cooling

The estimation of the thermal performance of krypton is the first step towards the design of the future cooling system. Silicon detectors need to be cautiously cooldown starting from room temperature down to cold temperatures. This cooldown process must occur without any thermal shocks that could potentially harm their integrity and efficiency. Figure 3 gives an indication of the different starting conditions while using CO_2 or krypton, which require to approach the cycle design differently. There are also indicated the main transients that the krypton system undergoes during its lifetime: startup (A), supercritical cooldown (B), supercritical (C) and transcritical operation (D).

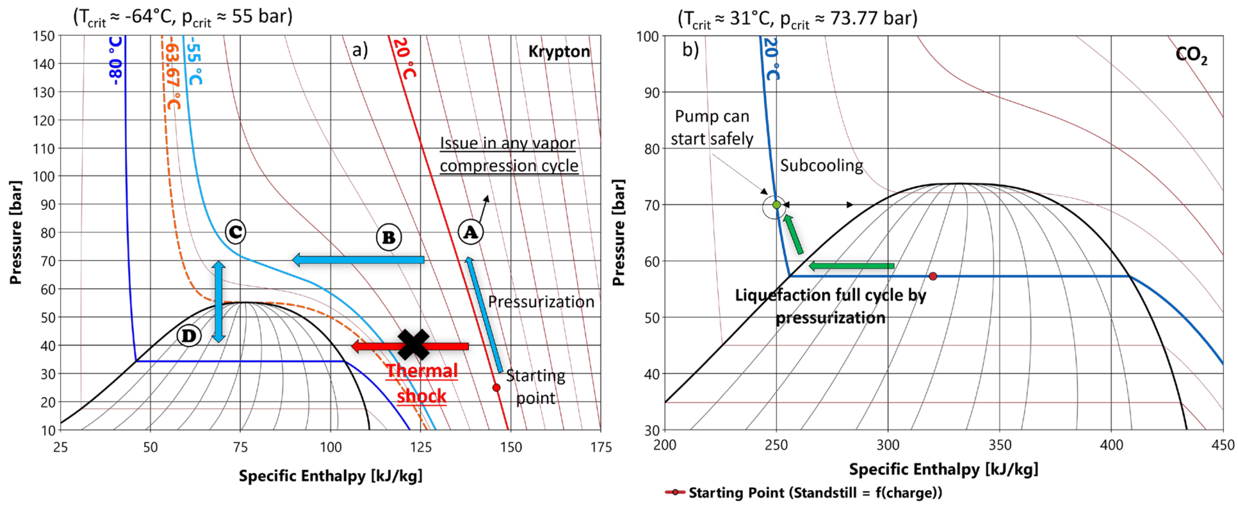

Figure 3: Starting conditions of krypton (a) and CO_2 (b) when the system is in standstill

During standstill, CO_2 is in gas, liquid or two-phase state according to the system's charge. Very briefly, the CO_2 system called 2PACL (Verlaat, 2007) is a pumped loop system where a remote temperature control of the sensors is achieved via pressure control of a two-phase accumulator, guaranteeing a remote precise modulation of the detector operating temperature. Considering the necessary subcooling for the pump to avoid cavitation, all system is fully liquefied by means of pressurization via an external high pressure charging tank. This allows to start safely the pump once enough subcooling is reached and then the accumulator takes control of the detector operating temperature. The 2PACL technology has proven to be highly reliable and stable over different years of operation but due to the initial gas state of krypton this cycle technology cannot longer be used. The starting condition with krypton imposes to use a vapor compression cycle. Oil free machines are required due to the impossibility of having oil circulation in the detector because the oil could decompose in dangerous substances under strong irradiation. Additionally, a thermal shock typically occurs during the startup of the compressor: a sudden depletion of refrigerant mass upstream the compressor causes the pressure and temperature to drop. This dynamic is unacceptable in a detector application and must be addressed via a specific startup procedure to ensure minimal thermal excursion of the sensors. From Figure 3 it is possible notice the pressure similarities between the two fluids indicating that similar cooling construction can be used with krypton.

2.4 New cold krypton ejector-supported cycle

A new cooling technology needs to be developed to handle the different transients encountered in Figure 3 (a). The system is first pressurized up to high pressure (≈70 bars) before starting. Operation at high pressures where the isothermal lines are nearly vertical gives extra protection against a fast overcooling of the sensors. After the startup, the system undergoes a supercritical cooldown process before reaching the working area of interest, spanning above and close the critical point of the fluid. Another issue during cold subcritical operation is the two-phase exhaust flow at the detector outlet reaching the compressor. To overcome these challenges while providing many benefits to the cycle, the use of an ejector is proposed. Ejectors are passive device used for expansion work recovery that enables flow circulation of a low-pressure stream via expansion of a high-pressure fluid (Elbel, 2011). Ejectors can be either static or controlled, where two different approaches are commercially available: multi-ejector blocks consisting in static ejectors of different capacity operating in parallel or controllable ejectors via insertion-removal of a needle in front of the motive throat. In a static ejector the entrainment potential cannot be actively controlled under off-design conditions, compromising the amount of secondary flow entrained. In a multi-ejector or controllable needle-ejector is possible to follow the load demands under different operating conditions at both motive and suction nozzle ports. Considering the peculiarities of detector cooling where a precise flow and temperature control is required, the authors decided to integrate a needle-controlled ejector in the system.

The cycle designed here presented (Figure 4) is like a traditional low-pressure receiver cycle where the ejector is used for flow circulation through the evaporator (Contiero, 2024). The system rejects heat to a primary CO_2 chiller maintaining partially unchanged the whole layout. Compared to the current cascade configuration CO_2-CO_2, the low temperature circuit 2PACL is replaced with the krypton unit, leaving the cascade system fully environmentally friendly.

Main difference compared to a standard architecture lies on the complex layout of the detector loop (blue loop) which remains almost unchanged with respect to the current CO_2 system. The bypass valve downstream the compressor called cold gas bypass valve (CGBV) is preferred to a variable speed drive compressor to perform not only capacity control but also to take advantage of the combined operation with the needle-controlled ejector, especially during the startup mode. In this case, the compressor is oversized to consistently deliver the required cooling capacity at the detector level through the ejector which acts as a pumping device. Additional valves are also installed in the detector loop to offer extra protection against a fast overcooling: valve V.10 acts as a bypass while valve V.9 serves to reduce the entrained flow by the ejector via a reduction of the opening degree of the valve. The latter valve would be active whenever V.10 reaches the maximum capacity and the flow circulating through the detector exceeds the required setpoint unless the adjustment of the cooling capacity is carried out by further inserting the needle into the ejector with a consequent decrease in the annular flow area and in the primary mass flow. For single-phase operation in gas/supercritical state, the system is connected to a pressurized gas tank for pressure control. In single phase state the temperature and pressure are independent on each other: if one pressure level is controlled the other one is a result of the mass distribution within the system, dictated by section's volume and density of the fluid locally. To achieve an isobaric supercritical cooldown process, the tank injects krypton mass into the system to avoid a fall of the system's pressure with a consequent thermal shock.

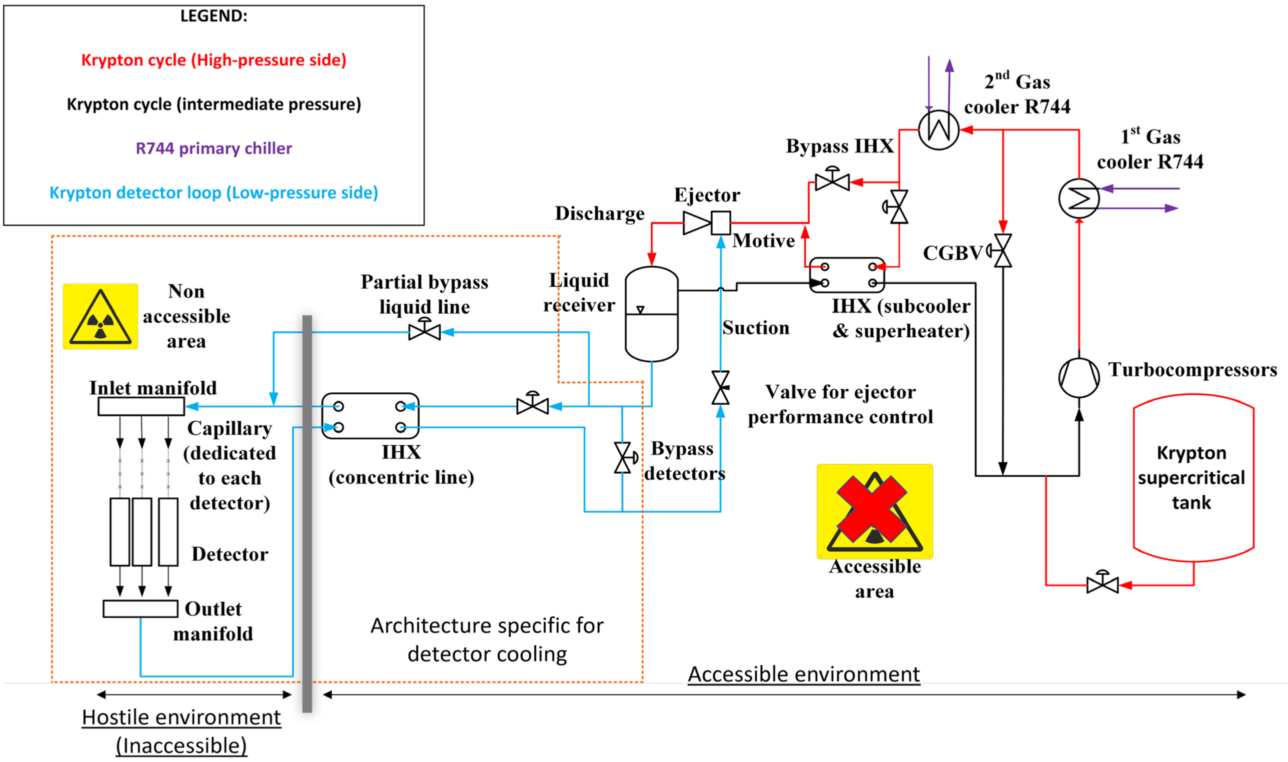

Figure 4: Simplified piping and instrumentation diagram (P&ID) of the krypton cooling unit

3 CONTROL STRATEGIES OF THE SYSTEM

The cooling system undergoes various operational states throughout its lifespan, including both gas, supercritical and two-phase. A key distinction lies in transient processes such as the cooldown of the sensors and the area characterized by low temperatures (< -55°C) where physic experiments are conducted and the detectors are powered. Detectors are light weight components, extremely sensitive to sudden temperature excursion. Controlling the fluid condition entering the detectors is therefore the best approach to avoid any thermal breakdown of the sensors, since they align with the fluid temperature. This strategy of controlling the fluid temperature is adopted throughout the supercritical cooldown, including the system startup.

For cold operations, the system can be tailored to operate with continuity delivering at the detector either supercritical cold conditions or in subcritical conditions in subcooled state to ensure that in this latter case boiling initiates at the entrance of the evaporator. The main priorities of the cycle are controlled and slow cooldown of the sensors, a precise and stable control of the evaporating-gas heating temperature of the fluid during sudden cooling power and setpoint changes which are governed by the experiments.

3.1 Startup and supercritical cooldown

The startup of the system represents a challenge for a vapor compression cycle connected to the detectors: the sudden drop in pressure after the compressor turns on will sudden create cold fluid in the upstream section where normally the evaporator section is located. To overcome this challenge, a specific startup procedure was developed (Figure 5). The combined use of a needle-controlled ejector together with the bypass valve downstream the compressor enables to protect the detector loop from pressure oscillations induced by the compressor over the time needed for its thermal stabilization. Fast pressurization of the detector loop consequent the mass movement generated by the startup of the compressor will produce a temperature increase or decrease in case of depressurization, and to damp those temperature fluctuations a smooth and slow increase of the discharge pressure is of primary importance. During Phase I the needle is fully inserted, producing no entrainment effect and therefore no flow circulation in the detector loop. Meanwhile the triangle cycle comprising compressor-1st gas cooler-CGBV can be stabilize. Any tiny flow in the detector loop is solely determined by the mass distribution induced by pressure oscillations on the vapor compression cycle. The high-pressure tank connected to the suction of the compressor helps to make smoother and tiny those pressure oscillations propagated to the detectors, by holding the pressure in between the tank and the compressor. After the latter attains thermal stability, the needle is slowly withdrawn to start carrying over some krypton flow in the detectors. During this initial phase where the entrainment potential increases with a nonlinear profile, the use of valve V.10 is beneficial for additional flow control.

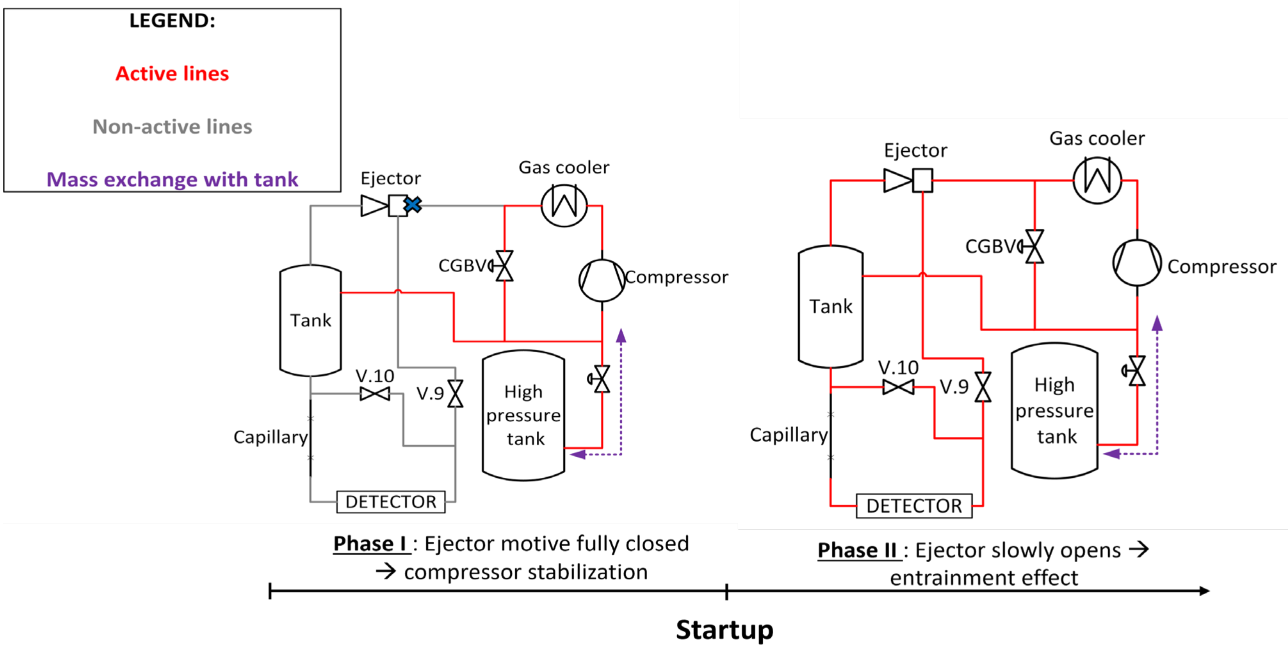

Figure 5: Simplified sketch of the startup procedure developed which comprises two distinct phases.

When the required flow circulation at the detector level is reached (Figure 6), the system is ready to undergo the cooldown process. During the startup and cooldown phase there is no power dissipated by the sensors and only the first gas cooler is active to reject the heat produced by the compression. Throughout the cooldown process, the high-pressure tank keeps injecting mass into the system to sustain the pressure. Conversely to the strategy adopted in the 2PACL system where the two-phase accumulator is used for setpoint changes, in the krypton system the cooldown is governed by the primary CO_2 chiller. By further cooling down the high-pressure side, colder conditions are reached at the compressor suction port as well as at the motive throat of the ejector.

This approach gives a very precise and safe control on the cooldown speed of the cycle. The cooldown of the compressor suction conditions occurs faster than at the detector level due to the thermal inertia and volume of the section. The colder conditions at the motive nozzle generate slightly colder fluid discharged into the accumulator, which represents the entering conditions to the detectors. A chasing-like process will see the detector loop interested by temperatures always above the setpoint imposed at the compressor suction, guaranteeing a very slow controlled process. During the cooldown modulation of the opening degree of the ejector together with the valve V.10 will provide the necessary flow conditions to the detector such to maintain thermal excursion always below 1 K/min, which is normally used as a rule of thumb in HEP experiments (Petagna, 2018).

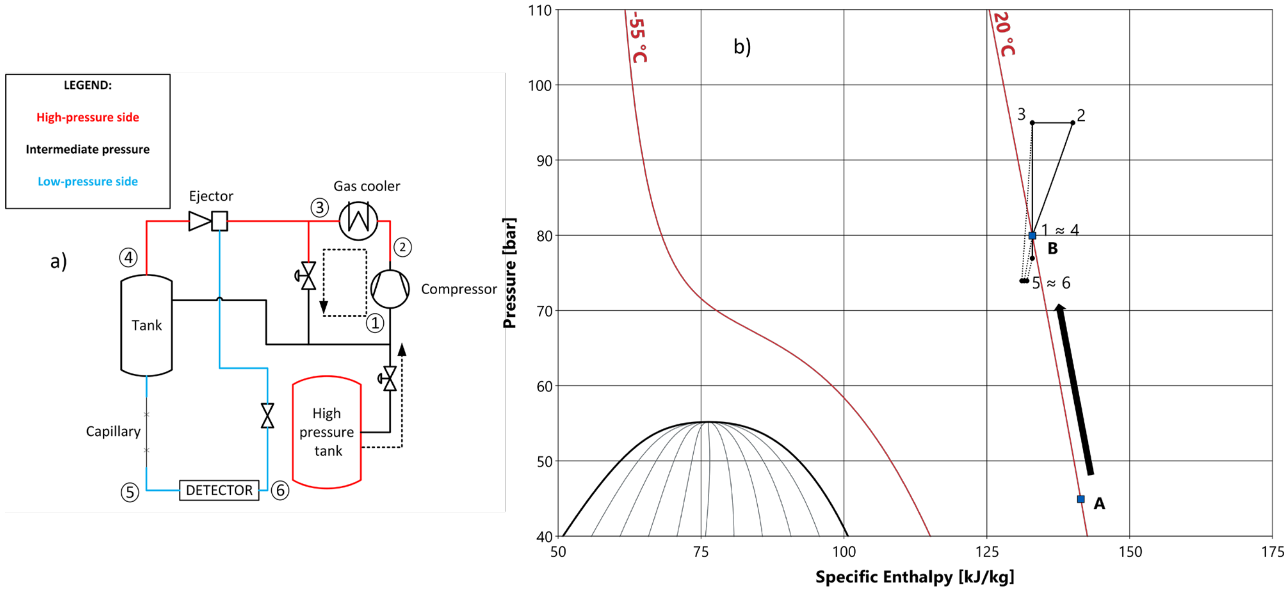

Figure 6 : Simplified scheme of the cycle during startup and transcritical cooldown (a) and its representation in the p-h diagram (b)

3.2 Supercritical operation

At temperatures levels around -55°C, the detector is ready to be powered. In this case the second gas cooler will be activated to achieve thermal stability to avoid a runaway towards the gas area (Figure 7).

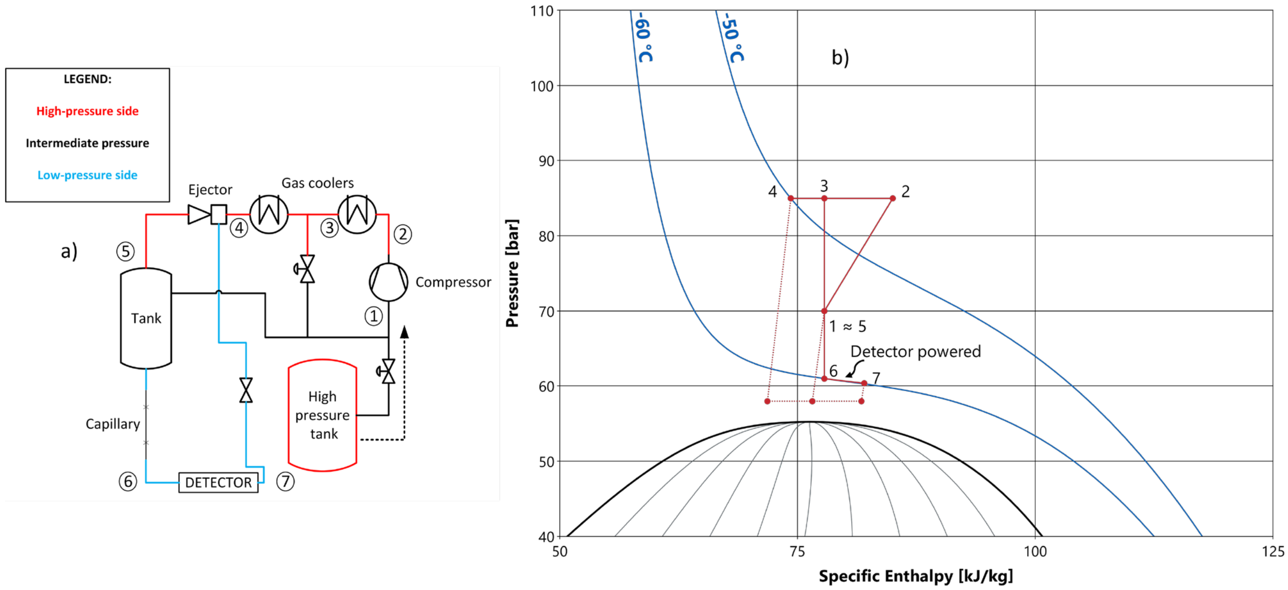

Figure 7: Simplified scheme of the cycle during supercritical operation (a) with detector powered and its representation in the p-h diagram (b)

Given the characteristics of the gas heating process in the supercritical state, the ejector will start pumping before powering the detectors to promptly mitigate the temperature rise at the exhaust supercritical flow at the detector outlet. This process would occur in the same manner during two-phase operation to eliminate the risk of dry out. High temperature difference among inlet-outlet leads to a non-homogeneous temperature along the sensors. The supercritical state offers several advantages compared to two-phase flow system as a weaker dependency on the heating power applied when dealing with flow distribution of multi cooling branch in parallel. Even though around the pseudocritical point sharp changes of thermophysical properties as viscosity and density are observed, the fluid does not undergo the same property changes as occur in two-phase, especially at low pressures.

In supercritical state two factors need to be considered: temperature distribution of the fluid along the long cooling lines and heat transfer deterioration while moving away from the area characterized by peaks of heat transfer properties, such as the specific heat. Pressure drops in supercritical state are welcome to follow an isothermal bulk fluid profile, conversely to flow boiling operation. Regarding heat transfer performance, several studies have been conducted over the years to analyze heat transfer enhancement and deterioration of supercritical fluids around the pseudocritical points. Entering conditions to the detectors is of primary importance to exploit high heat transfer coefficients avoiding poor performance typical of single-phase liquid-like cooling, exactly in the same manner of two-phase cooling where subcooled liquid entering the detectors must be avoided.

Supercritical cycles present additional challenges due to the independency of temperature on pressure. The high-pressure is still controlled via the CGBV while the ejector is modulated such to initially overflow the detectors while they are still unpowered. If excessive cold temperatures are created at the detector inlet due to the fixed fluid resistance given by the capillaries, valve V.9 can be used to reduce the entrained flow. This valve is modulated to provide a fast response to a steep increase of the cooling load, up to its maximum capacity. When the detector is powered, if the temperature increase of the fluid at the exit of the detector is excessive, the ejector increases its suction potential through either an increase in flow rate or pressure. The pressure increase has consequences in terms of the refrigerant mass that must be supplied. For this reason, it would be preferable to work under constant motive pressures. In case of excessive large variation of the cooling load, a battery of ejectors can be installed to satisfy the required flow rates which differ greatly depending on the working area of the fluid.

3.3 Transcritical operation

The coldest operation is provided via a transcritical configuration. Flow boiling in this case is achieved at detector level for any setpoint around or below -70°C. Considering that supercritical systems are far from being well-known as the two-phase system, the design should be based on the subcritical operation achieved at the detector level, which represents the core of the cycle. The almost-passive loop surrounding the detector is sized to provide the necessary entering flow conditions under different setpoints and accordingly the ejector too. Predominant pressure drops upstream the detector is supplied by the capillary such to suppress parallel boiling channel flow instabilities due to the different cooling powers imposed by the experiments. Figure 8 illustrates the similarities between the 2PACL technology and the ejector-supported system in terms of flow conditions provided to the detector. In red, the 2PACL process is illustrated: the subcooled liquid is pumped through a concentric line, conditioning the fluid entering the capillaries before being expanded to low vapor qualities. The CO_2 is then partially vaporized in the detector before being condensed and subcooled prior entering the pump.

The ejector in the new system replaces the pump of the 2PACL. The vapor compression cycle provides the necessary flow conditions (motive) for the functionality of the ejector. The expansion of the motive flow generates a secondary flow, which undergoes the same processes as in the 2PACL cycle. The main difference lies on the exhaust two-phase flow at the detector outlet which is now mixed inside the ejector and compressed back to the liquid separator, where liquid and vapor are separated by gravity.

The detector experiences sudden power changes and setpoint changes at any time. The system must always react to any perturbation by prioritizing the detectors, maintaining their temperature nearly stable while eliminating the risk of dry out inception. With respect to this, a dedicated control logic must be implemented. The design of the ejector is linked to the geometry and flow requirements through the detector loop. Although with more complex dynamics involved, the cycle’s regulation can partially be drawn from a traditional low pressure receiver cycle.

The receiver pressure is controlled via heat rejection in the second gas cooler: if the detector load suddenly drops, the liquid level in the separator increases and the associated drop in pressure of the latter would cause excessive cold temperatures of the fluid entering the detector. To counteract the drop in pressure, warmer gas is expanded through the motive nozzle via a reduction of the heat rejection in the second gas cooler. Meanwhile, the valve V.9 installed upstream the suction nozzle is modulated such to waste part of the expansion work recovered gained by the warmer motive conditions ensuring a nearly constant suction flow. Conversely, if the cooling power suddenly increases, the system reacts to ensure enough liquid flow through the detector. The supercritical krypton entering the motive nozzle is now colder, balancing the increase in the separator pressure consequent the vapor formed by vaporization in the detector. In this case valve V9 is again used for fast manipulation (deterioration) of the total flow entrained.

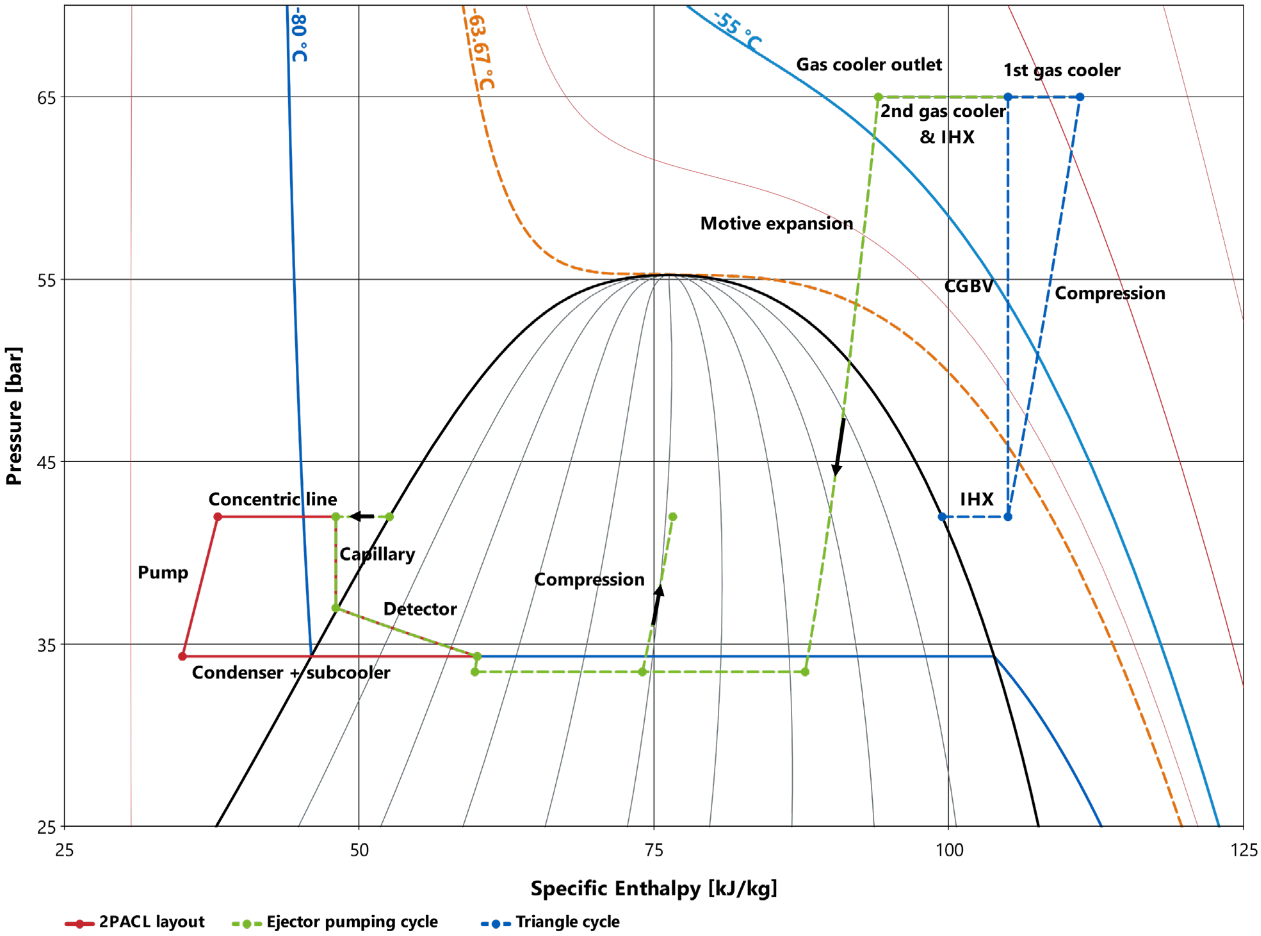

Figure 8: Graphical representation depicts how the ejector system supplies the necessary flow conditions to the detectors in an equal manner to the 2PACL system.

4 CONCLUSIONS

In this work, the challenges arising from a future upgrade of the LHC are discussed. A new fluid able to attain colder temperatures than CO_2 is necessary to keep the sensor thermally safe from the risk of electrical breakdown. Based on a fluid study comparison in the temperature range of interest spanning around -60 down to -80°C, krypton stands out as a promising cooling agent for thermal management of future detectors. Its thermophysical properties impose a new cooling technology starting from warm gas condition. An ejector-supported cycle with a dedicated system architecture was developed providing all the necessary features to the cycle to ensure a slow and controlled cooldown of the sensors throughout the main transients. Parallel modulation of the ejector, heat rejection and the bypass valve for capacity control is of primary importance for temperature stability of the sensors. For both supercritical and subcritical scenarios where the detectors are powered, dedicated control logics are discussed to handle sudden changes in setpoint and heat loads which are driven by the physics experiments and to which the cooling system must quickly respond.

ACKNOWLEDGEMENTS

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NOMENCLATURE

HTC	Heat transfer coefficient [W/m^2*K]	*ΔT*	Temperature drops [K]
Δp	Pressure drops [bar]	*Q*	Heat load [W]
TFM	Thermal Figure of Merit [-]	*VHTC*	Volumetric heat transfer coefficient [W/m^3*K]

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