Cold Krypton system for the Phase III Upgrade of the LHC

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Presentation outlines

- Necessity to go colder with the future upgrade of the LHC (HL-LHC plan)
- **Issues:** temperatures unattainable by current CO_2 cooling technology

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- Definition of a new cooling cycle using Krypton
- Definition of the different transient modes encountered during gradual cooldown
- Design principles to base future design
- Dynamic modelling and control logic
- Prototype to test cooling concept

Current 2PACL system (CO_2)

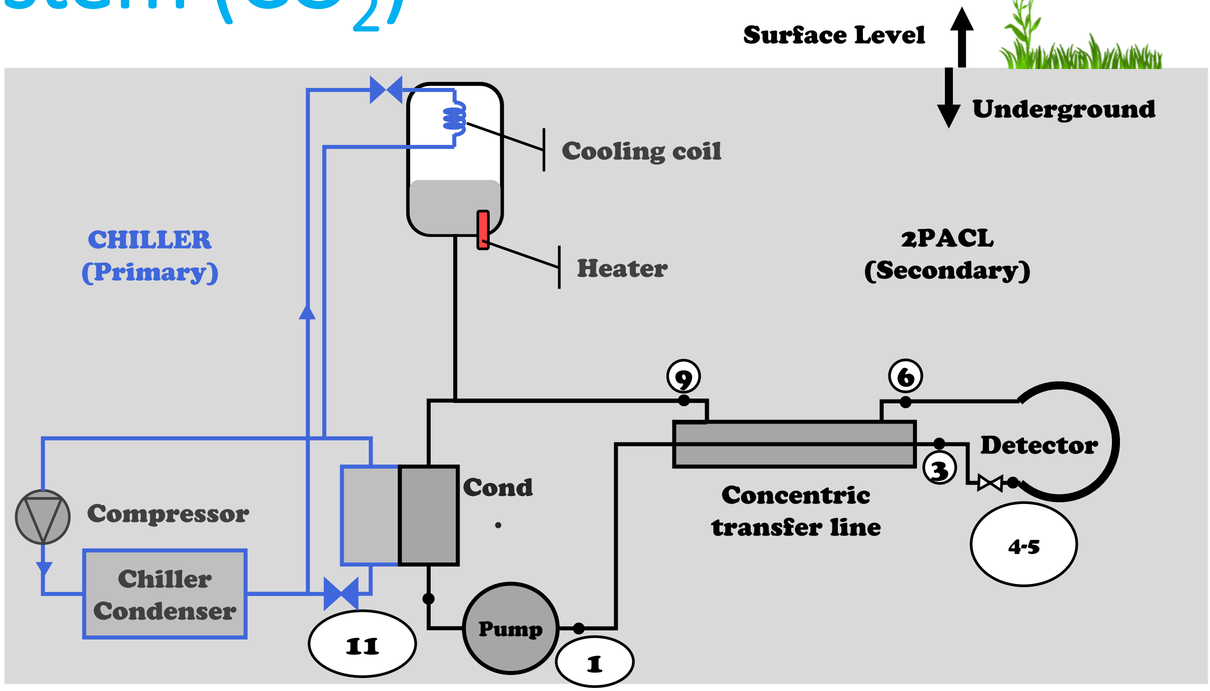
- Liquid / two-phase pumped loop system
- Use of dependency temperature-pressure in the two-phase area for monitoring of the detector

Advantages such as:

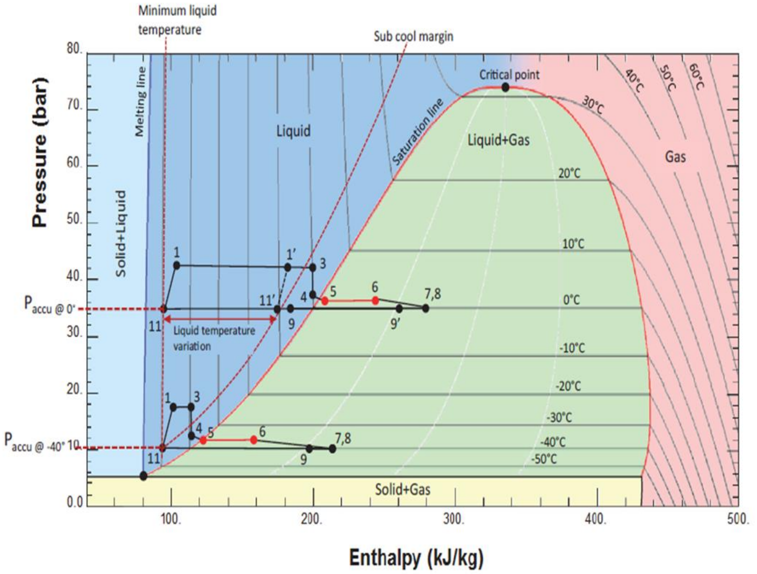
- Remote control through accumulator (heating and cooling)
- “Easy” startup in liquid phase, no risk to damage the detector by pressurization of the system

But:

- CO_2 triple point ≈ -56 degC
- Starts becoming less performant at very low pressure (ΔP induces much larger ΔT → uneven cooling)
- Pump needs subcooling at the entrance to avoid risk of cavitation → min temperature in the detector ≈ -40 degC



Viren Bhanot, **Dynamic simulations of Phase 2 detector cooling system**, Forum on Tracking Detector Mechanics 2022, Frascati.



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Aim of the study

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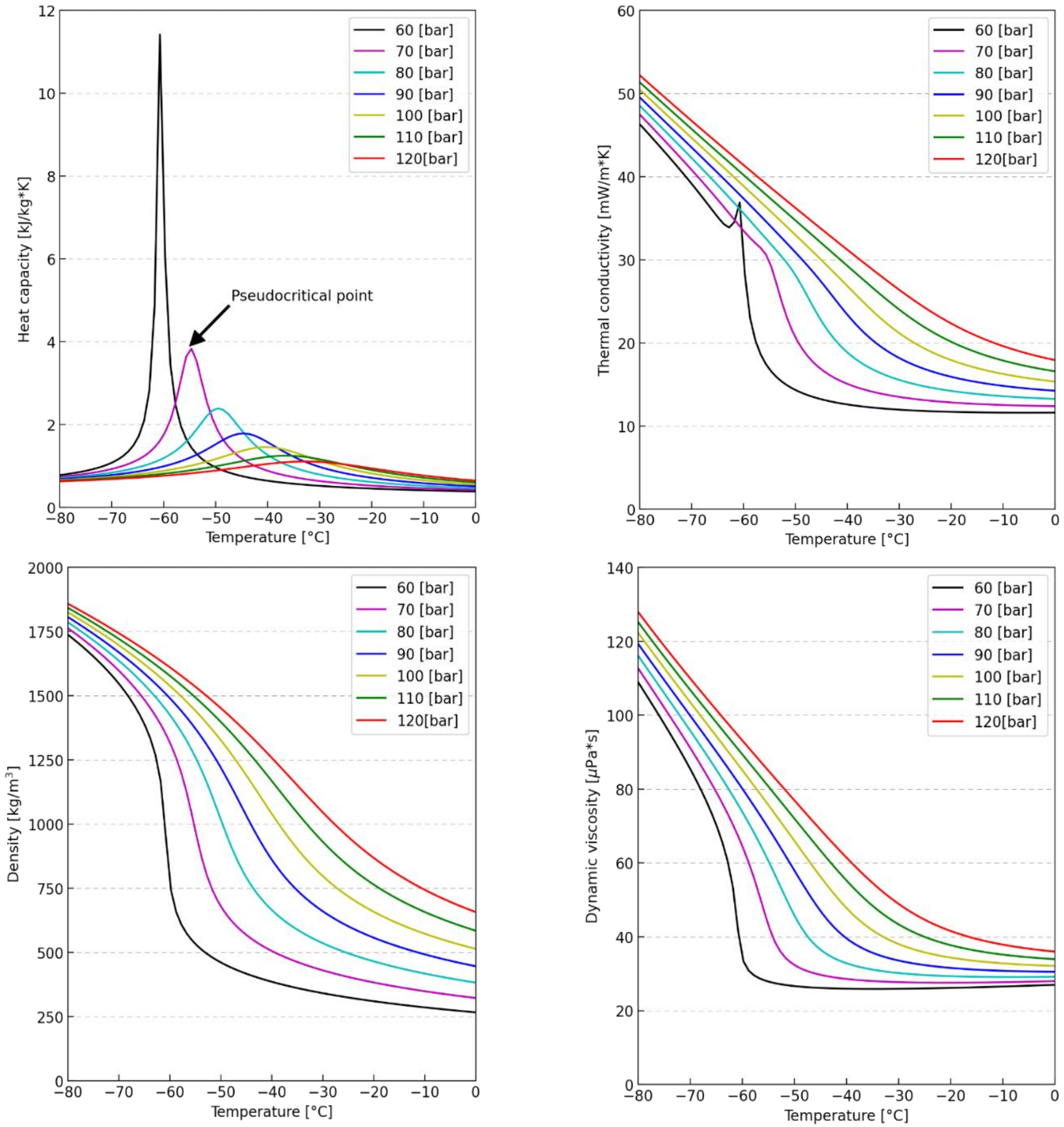
- Design of a new completely technology for cooling of the detector trackers targeting temperature ≈ - 60°C
- Investigation of the supercritical area, because:

✓ Mono-phase area (neither liquid or vapor)
✓ Low viscosity, high specific heat and thermal conductivity close to the critical point
✓ Easier distribution through multiple cooling channel compared to a two-phase system

<u>BUT completely different dynamics compared to a two-phase system</u>

Krypton physical properties
(T_{crit} ≈ -64°C, p_{crit} ≈ 55 bar)



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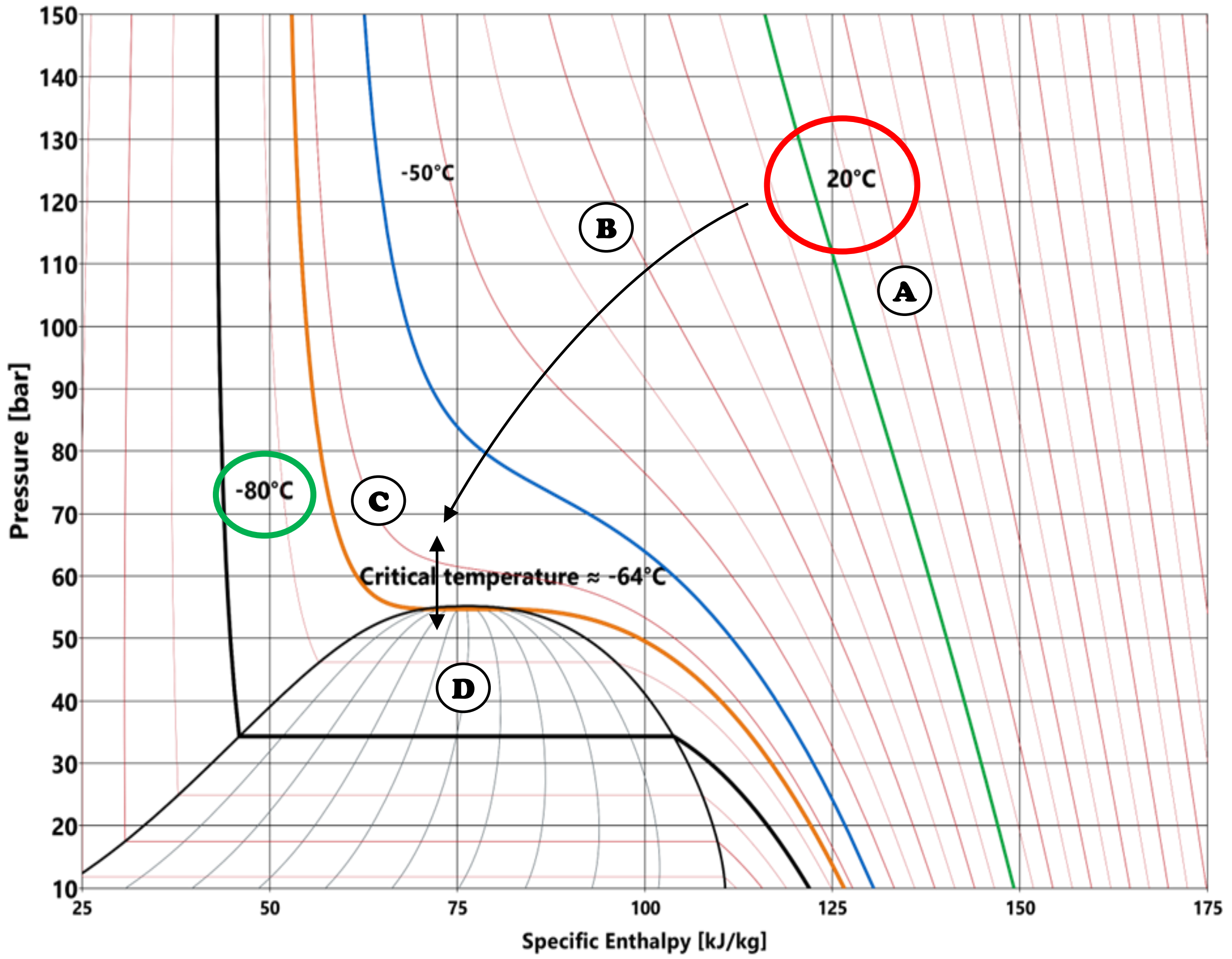
New colder fluid Krypton



- Pressure-wise similar to CO_2
- Much denser and colder fluid (critical temperature ≈ -64 degC vs 31.1 for CO_2)
- Starting temperature (20 degC) in gas phase

Four different scenarios to be investigated:

- Startup (A)
- Supercritical cooldown (B)
- Transition supercritical to subcritical (C)
- Transcritical operation (D)

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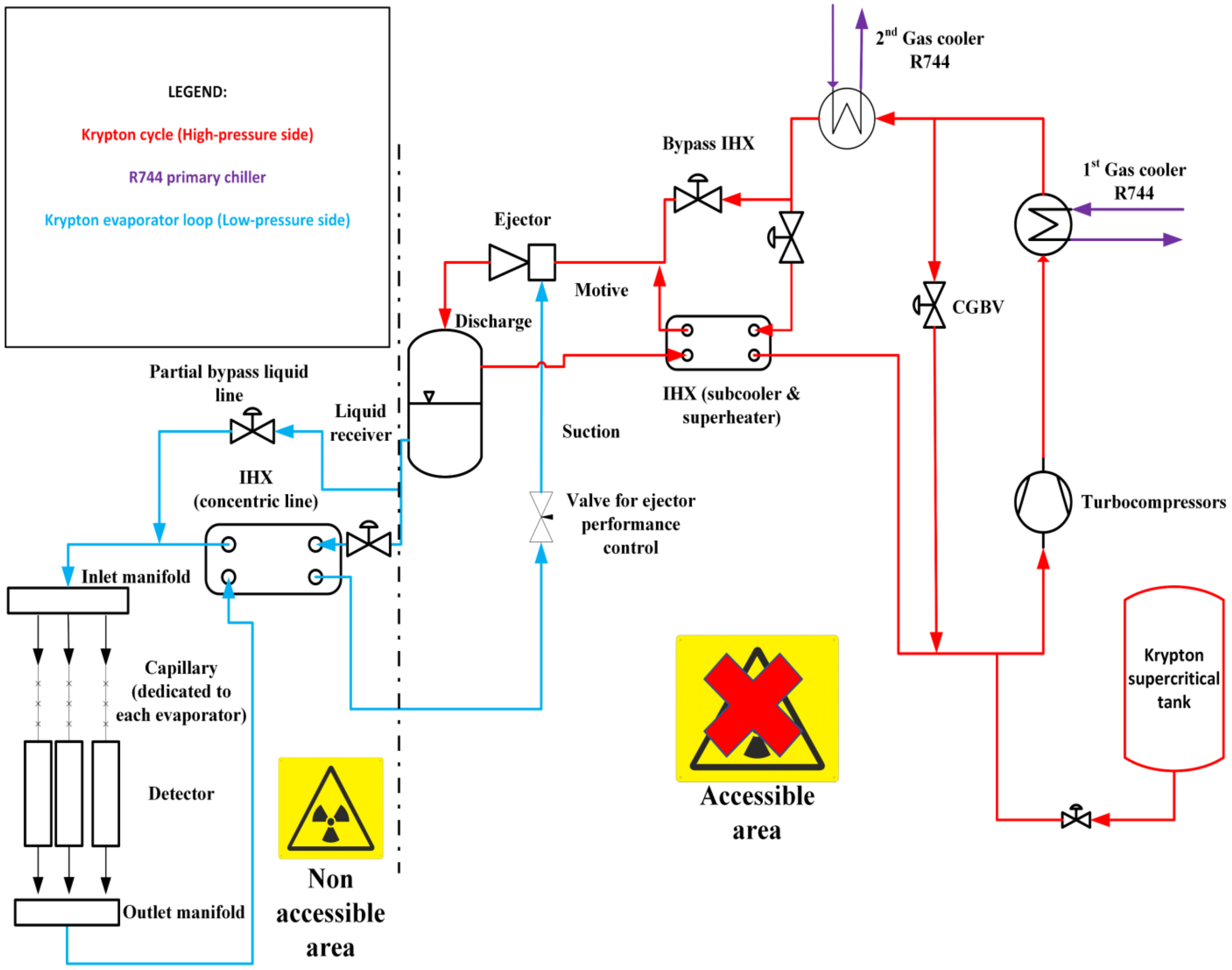
Colder cooling system with Krypton

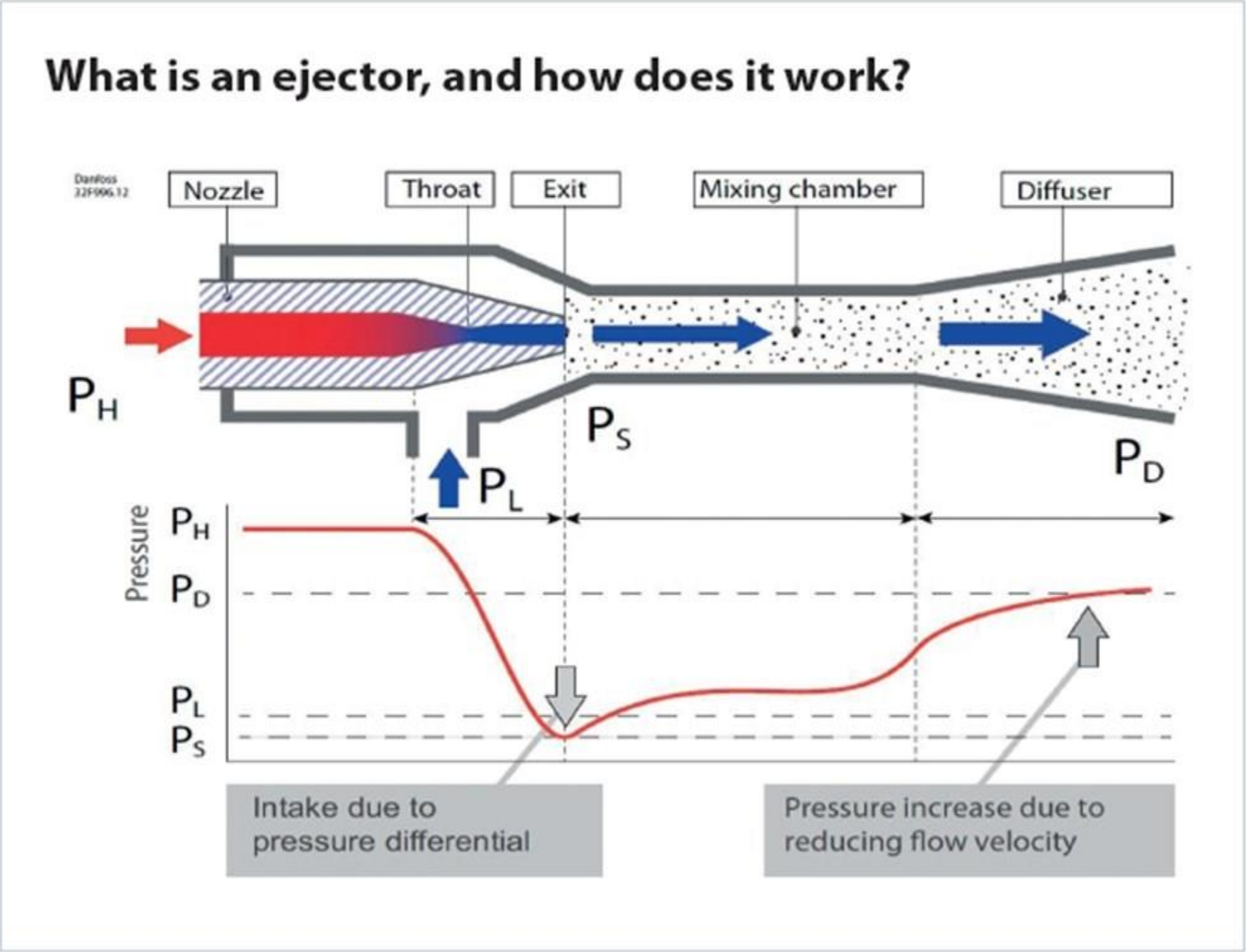


- New ejector-supported cycle <u>with feature of being able to operate either in supercritical or transcritical state</u>
- Still fulfilling detector requirements such as “passive” expansion upstream detectors, etc..
- <u>Ejector becomes the main regulator for detector operation</u>

Reliability as main concern, so:

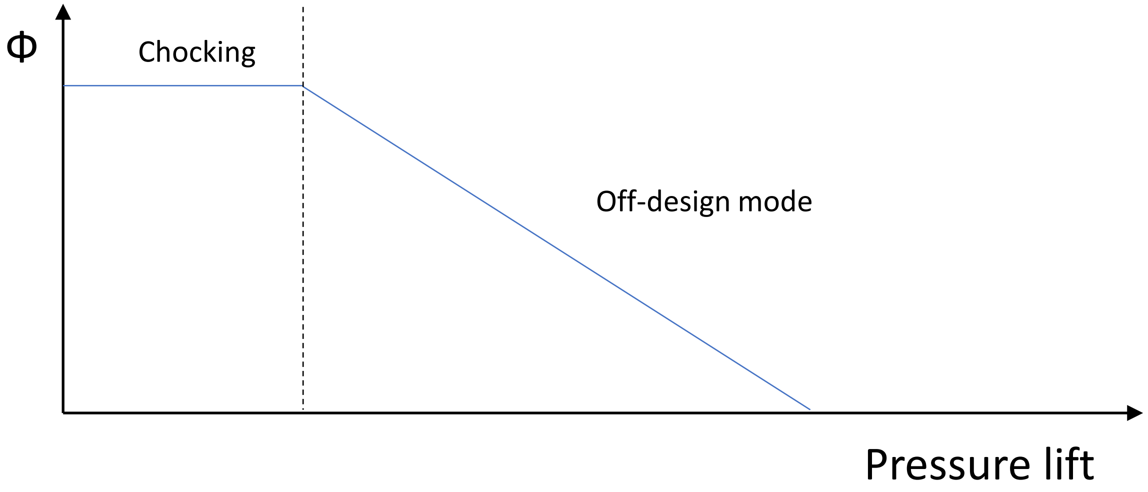
- Compression stage oversized to gain additional degree of freedom
- Additional valve upstream suction nozzle of the ejector for performance regulation

Ejector working principle



https://www.danfoss.com/en/service-and-support/case-stories/dcs/the-danfoss-multi-ejector-range-for-co2-refrigeration/

- Device using energy from a high-pressure stream to entrain and pre-compress a low-pressure stream
- Ejector characteristic curve:



Entrainment and pressure lift cannot be high at the same time

- If a large flow is entrained from low side, only small jump in pressure
- Little amount of flow can be lifted up to 12 bar
- Extremely dipendent on geometry and refrigerant properties

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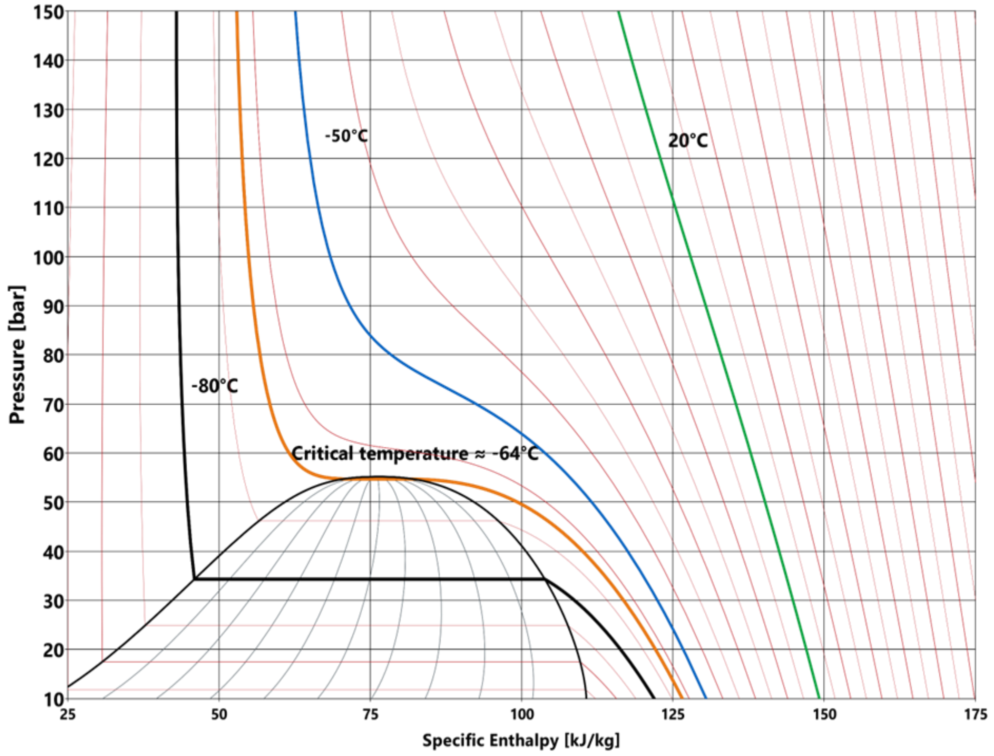
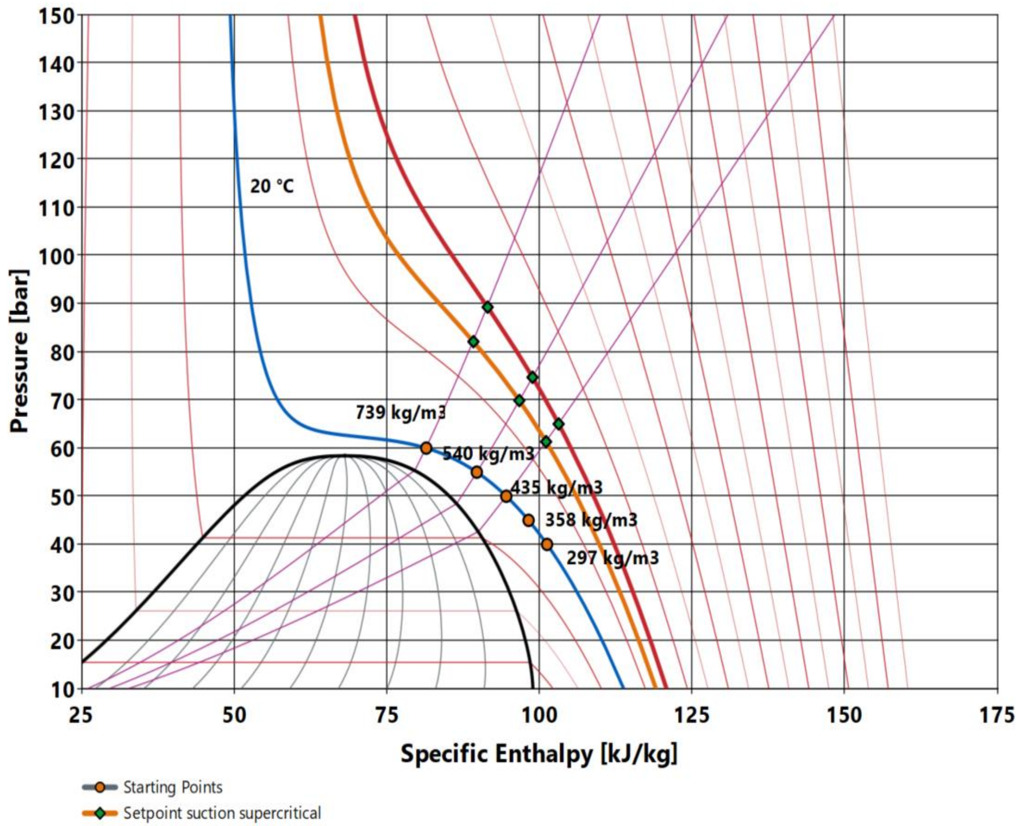
Xenon demonstrator for the Krypton cycle

- Use of Krypton problematic due to very cold temperatures (T_{crit} ≈ -64°C)
- Xenon proposed thanks to its warmer critical temperature (≈ 17degC)
- Required to precondition the unit to start in supercritical phase

Krypton

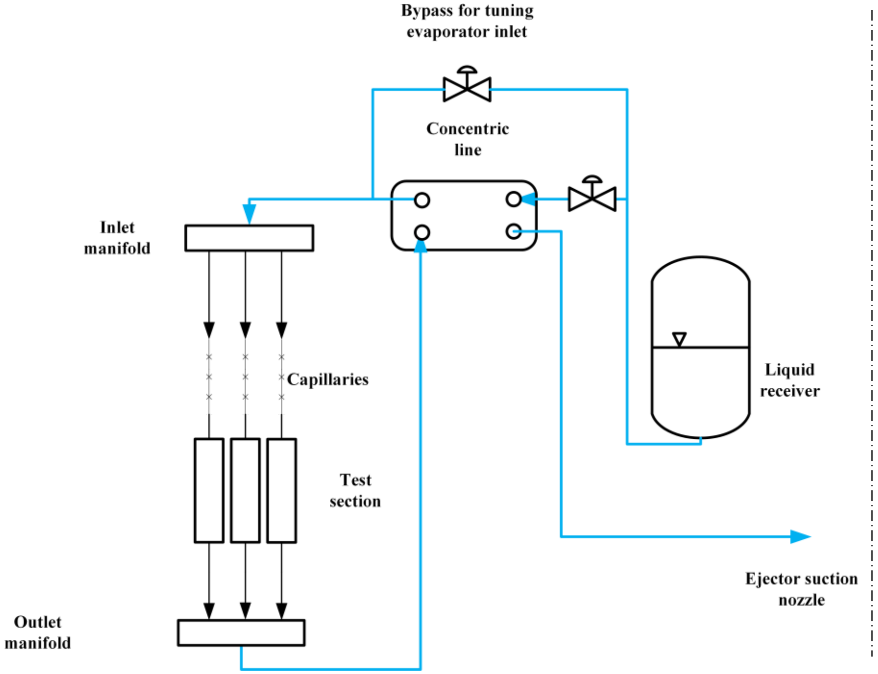


Xenon



Design principles of the Xenon test-rig

- Supercritical state unknow, design based on two-phase area
- Design follow ejector's nature
- Two-phase area interesting only at high reduced pressure
- In the same manner of the 2PACL, all starts from the detector section (gas heating/evaporator)



Estimation flow and pressure drop in the evaporator (VQ limit 35%)

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Hydraulic balance of multiple lines require $\Delta P_{cap} = 4/5 * \Delta P_{evap}$

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Estimation of the ejector pressure lift

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Design concentric line such to have low ΔP on both sides → Controlling the pressure lift means accurate control detector outlet pressure

Ejector strategy control through different setpoints

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Constant pressure lift

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Cycle simulation (system operation curve)

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Optimum ejector geometry from crossing of system-ejector curve

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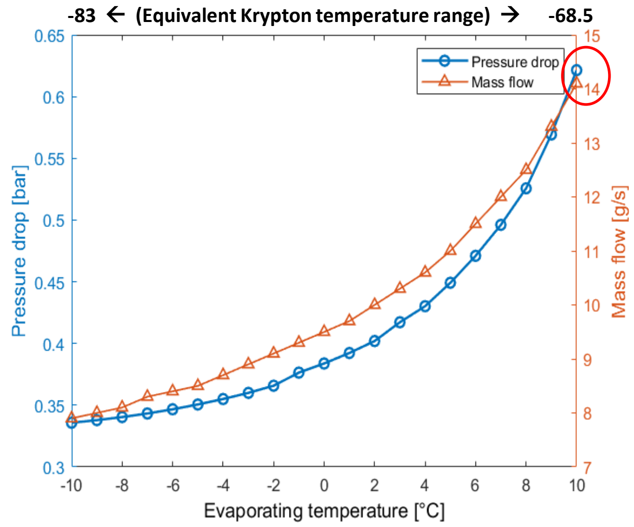
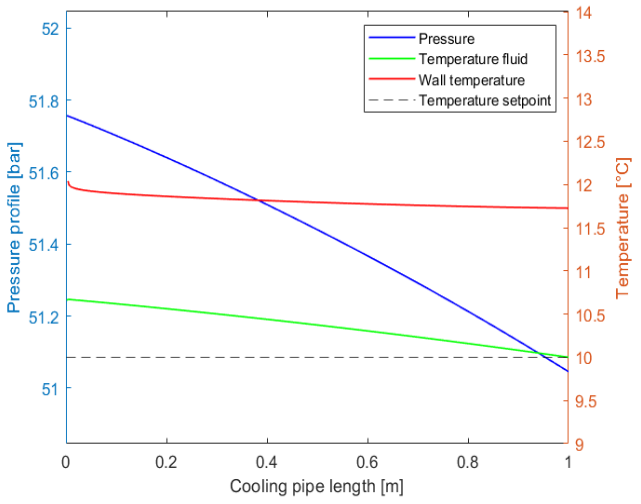
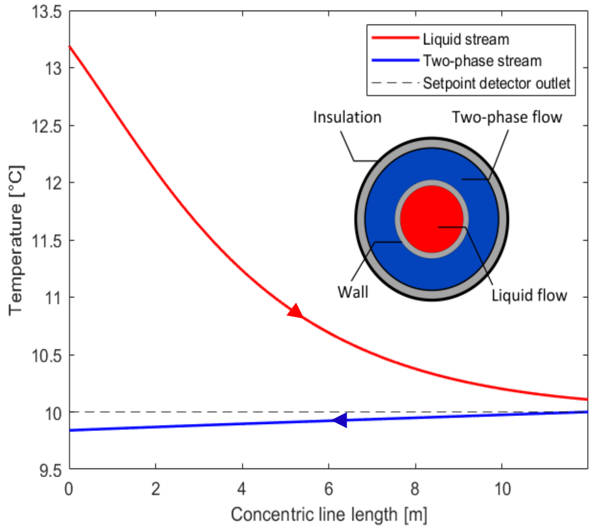
Design evaporator & concentric line

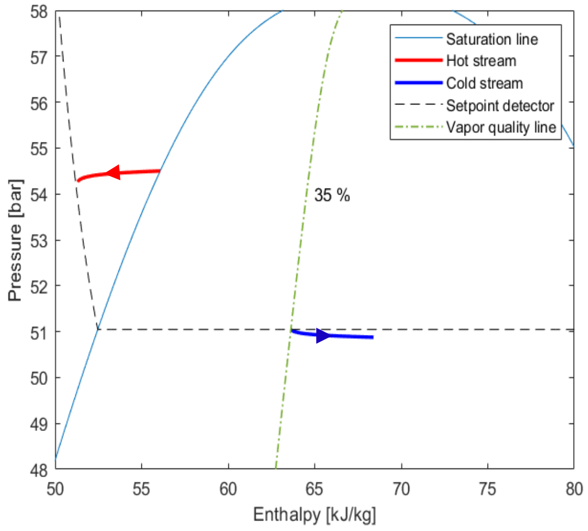




- Noble gas high molecular weight → low latent heat
- Close to critical point latent heat tends to zero
- Case at 10 degC design case (highest flow)
- Capillary sized according to flow expected

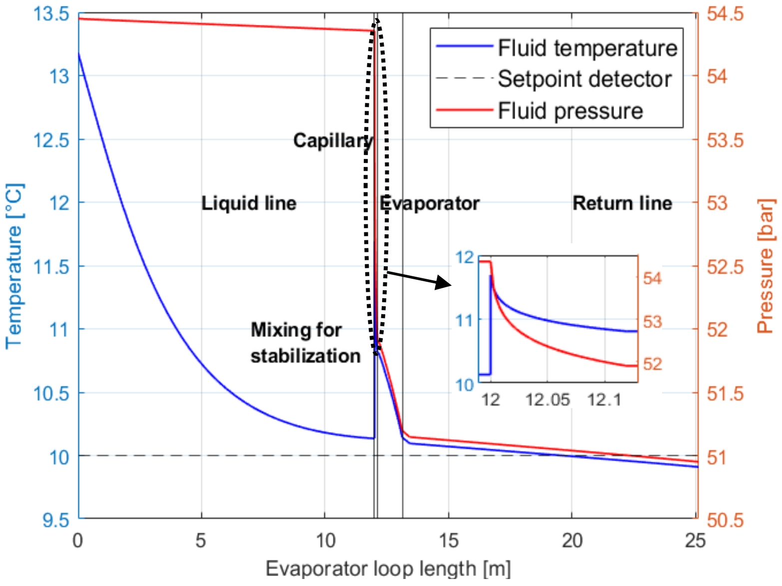
- Constant pressure lift strategy → overflow through the detector for lower reduced pressures

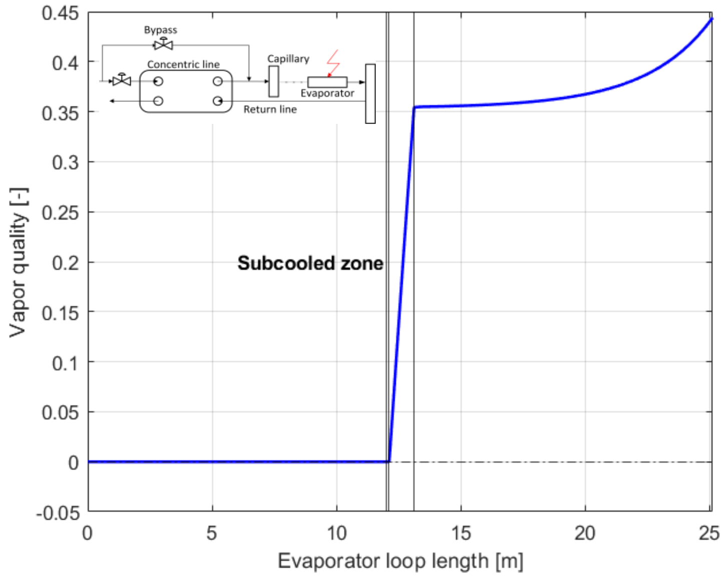




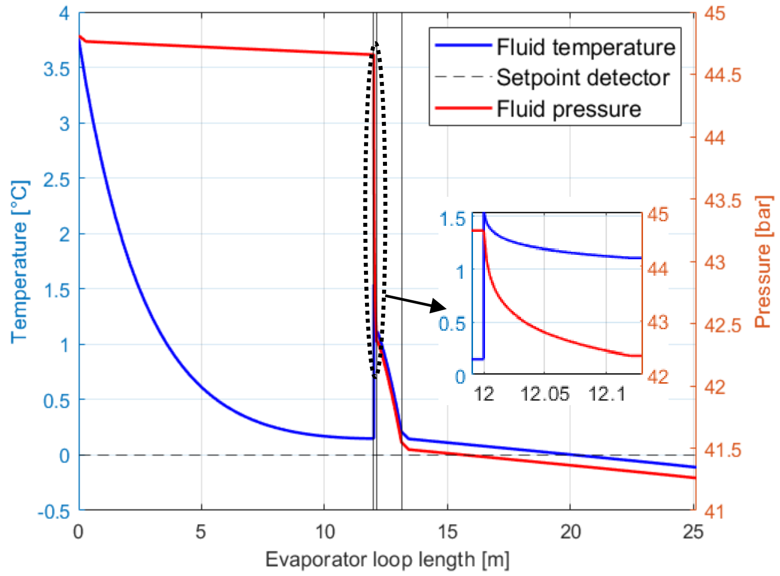
- Concentric line designed such to potentially cool down the liquid to same temperature detector outlet (same principle in 2PACL)
- At high-reduced pressures fluid compressible → bypass needed to trigger boiling at the evaporator entrance

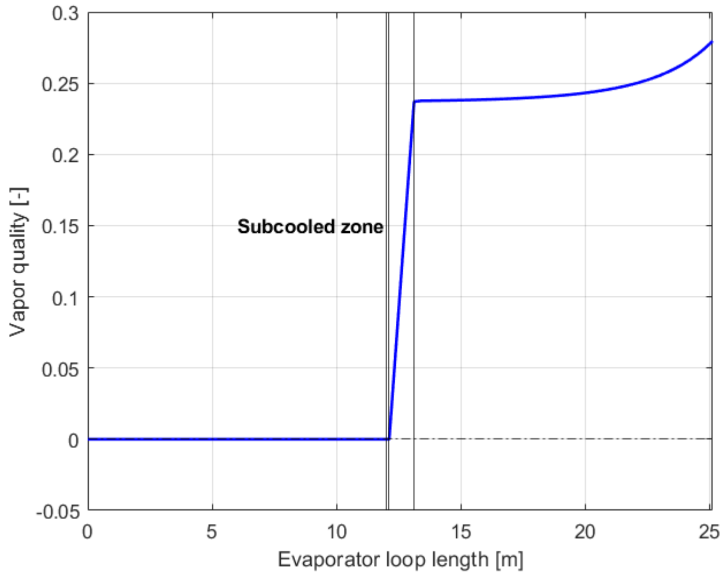
Cooling branch





- Detector setpoint = 10 degC
- Bypass to promote boiling at the entrance





- Detector setpoint = 0 degC
- Overflow ← ejector control strategy
- Pressure lift = f(mass flow)
- Capillary producing main ΔP in the loop → almost constant flow

- Side-effect → larger Δ T inlet-outlet evap

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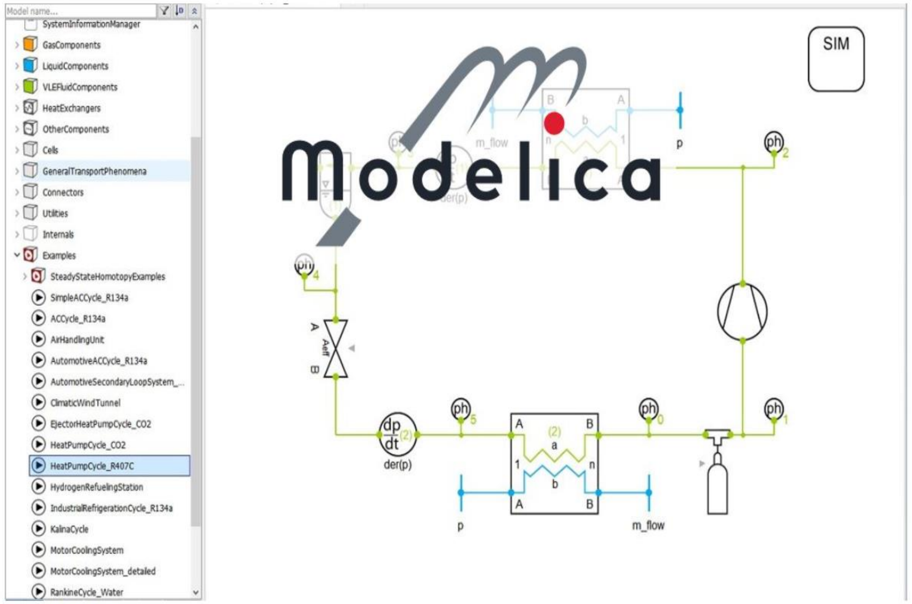
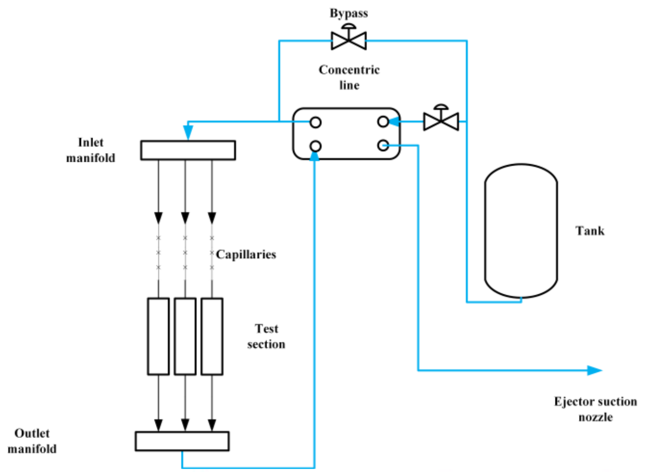
Dynamic modelling : startup

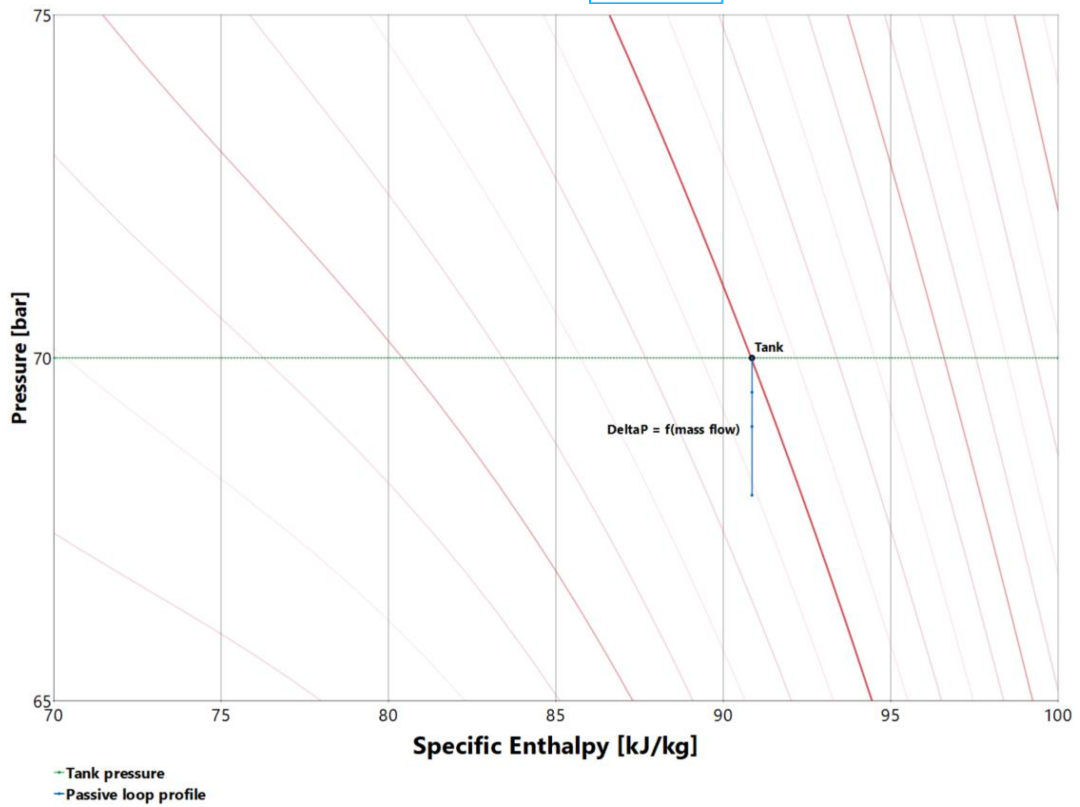
- Geometric parameters detector loop + real size components (receiver, compressor, gas coolers all CO_2 high-pressure rated) with the aim to keep the system volume (charge) as low as possible
- Supercritical state → pressure-temperature independent on each other, <u>receiver does not act as buffer tank</u>
- <u>Only injection-withdrawn of refrigerant mass controls the pressure</u>
- Cooling power unknown → <u>controlling inlet temperature to the detector to avoid thermal shocks</u>
- Dymola used as tool for simulation of complex systems



Dymola Screenshot / TLK Energy

Startup without thermal shocks





Implications of the supercritical cycle:

- Once the compressor start the pressure will fall → temperature drops and possible thermal shock
- Excessive cooling through HP gas cooler → thermal shock
- Detector loop passive → flow distribution ditactes pressure-temperature profile

How to develop a suitable control strategy?

- First, understand how cooling/heating influence mass distribution in the system
- Relationship density – pressure
- Understand the ejector working principle

In few words, what should be controlled?

- Tank pressure-temperature (remember independency of those two properties)
- Flow through the detector → Ejector regulation

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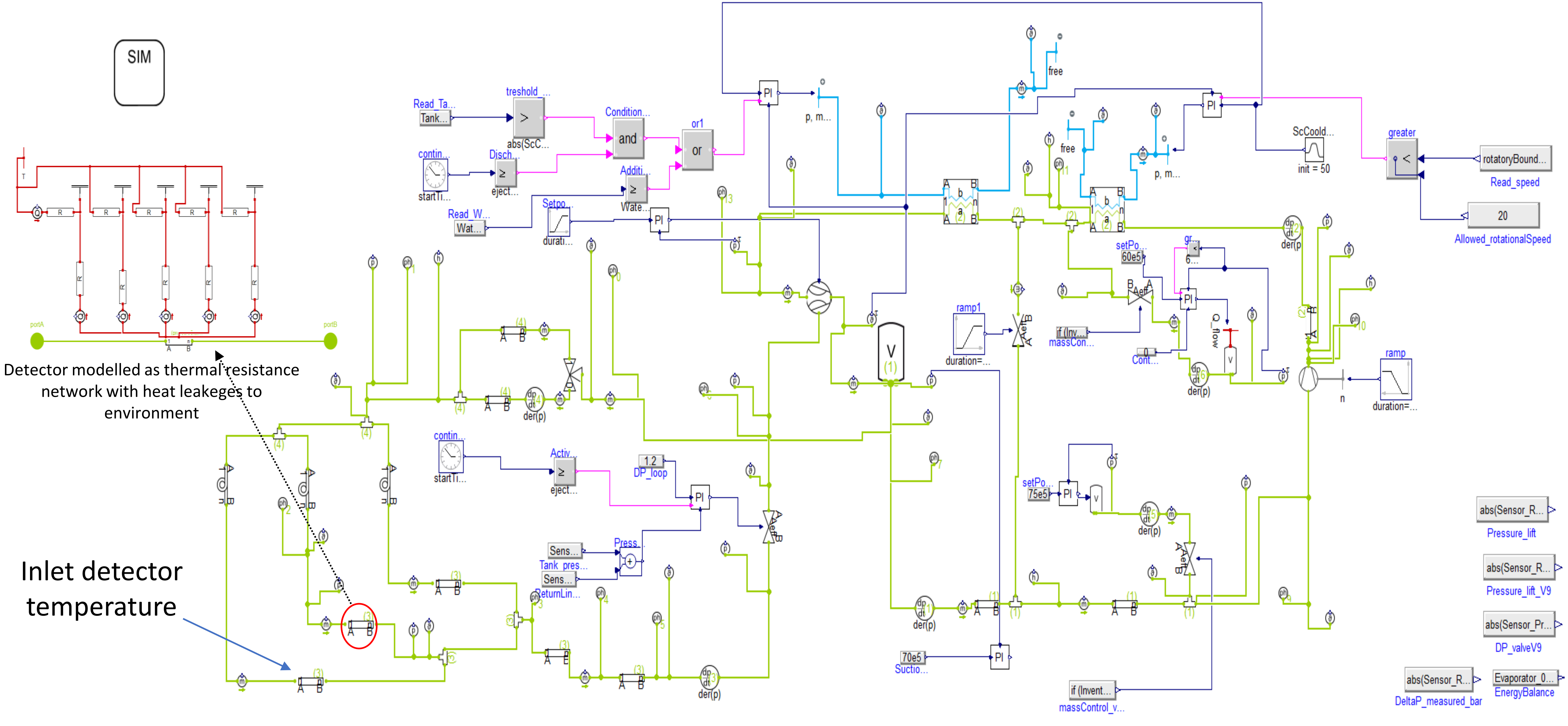
Dymola model: startup (T = 50 °C, p = 70 bar)



Dynamic modelling : startup

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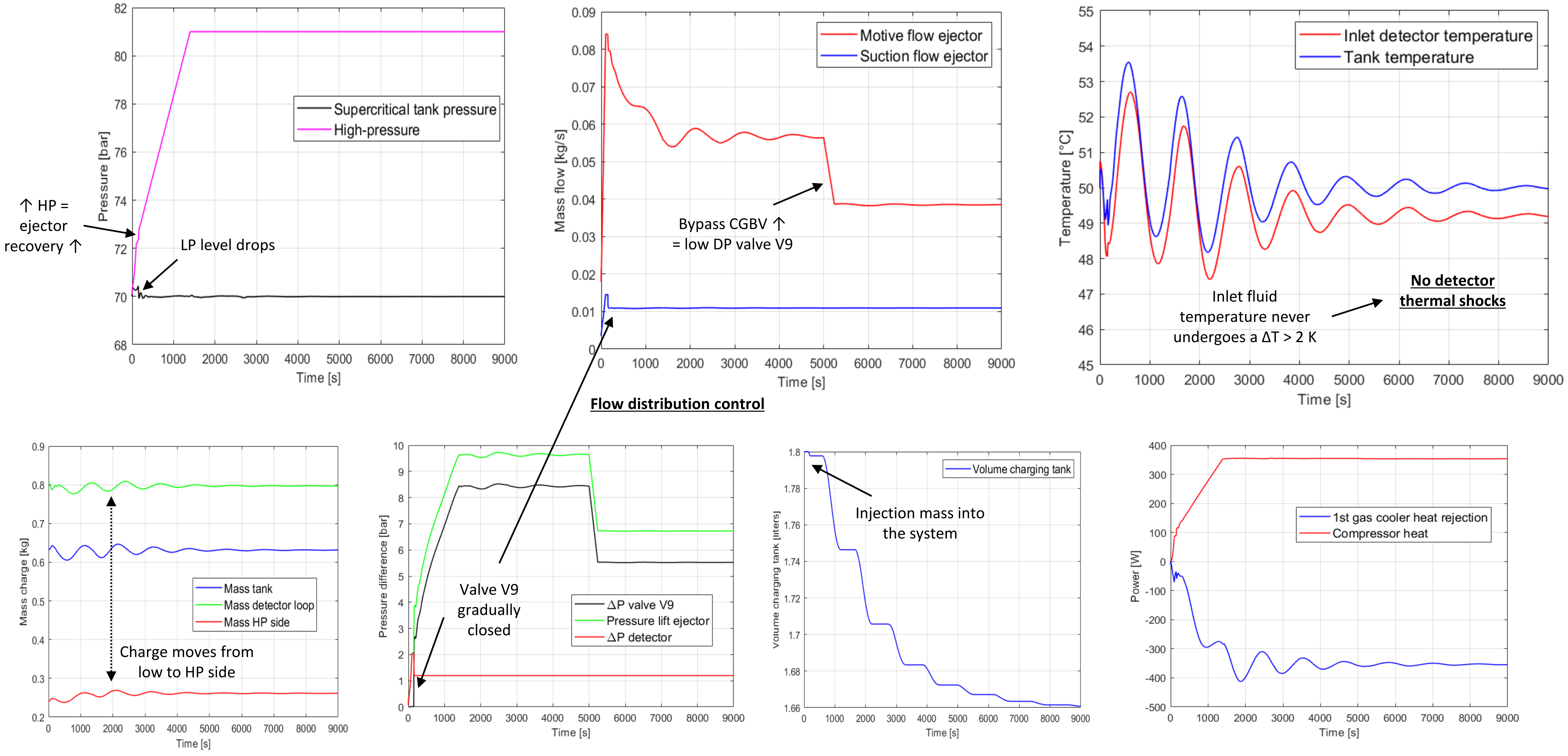
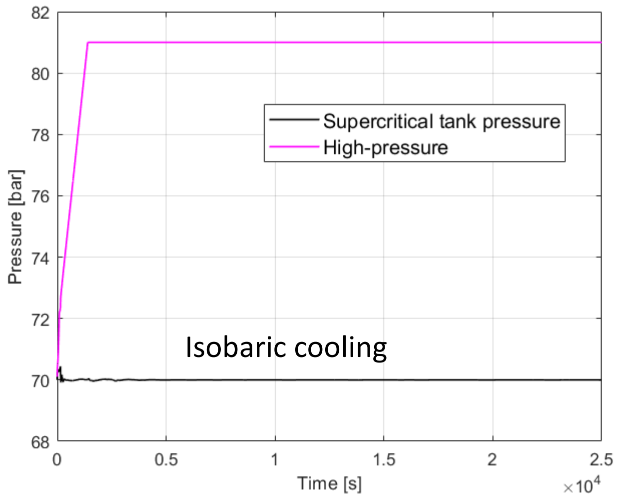
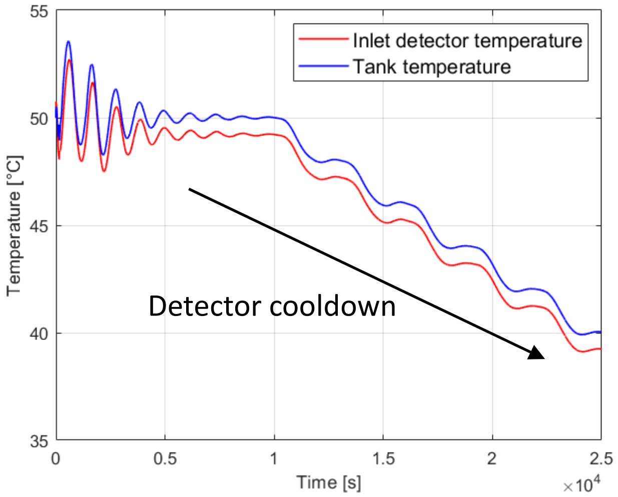
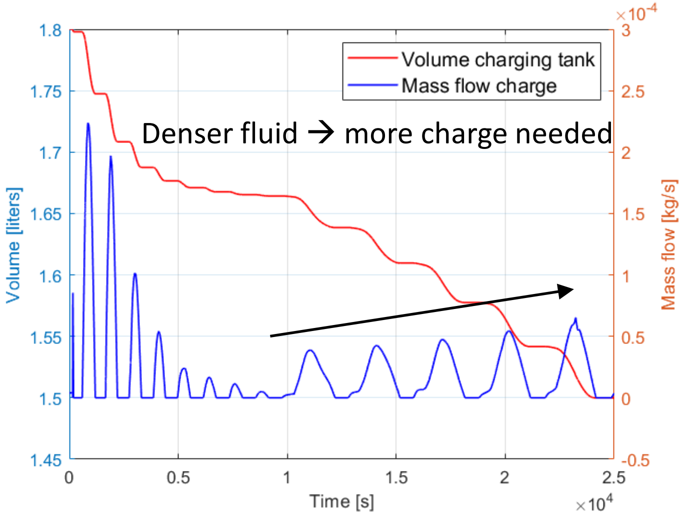
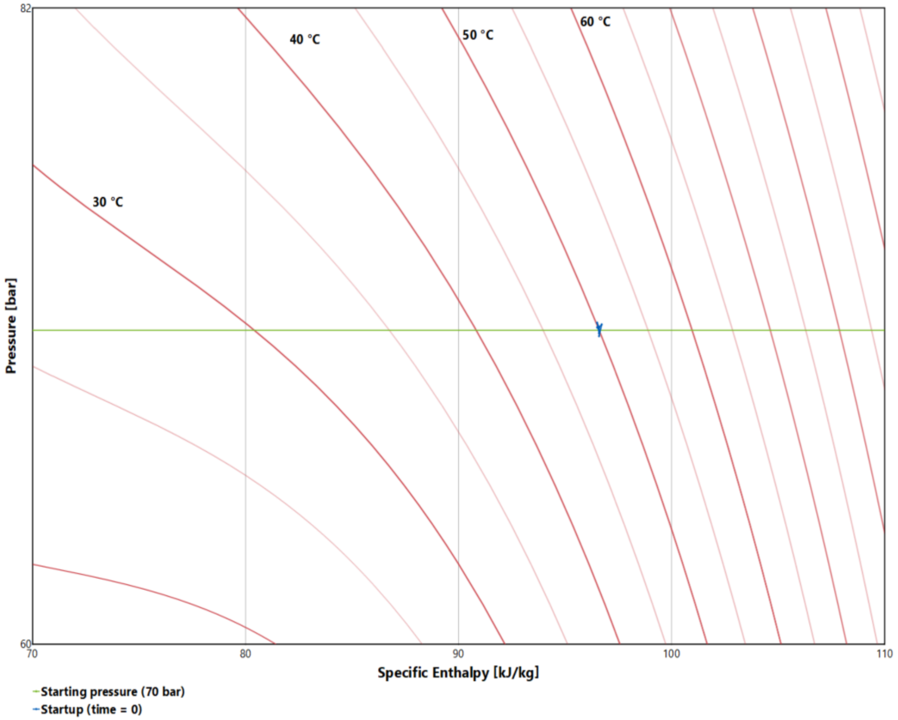


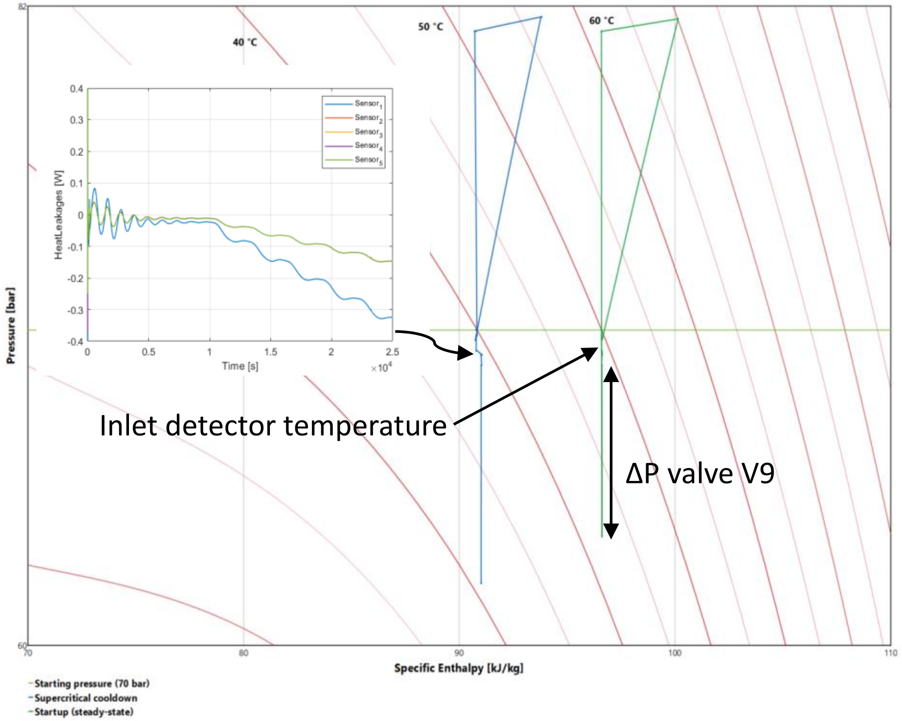
Dynamic modelling : supercritical cooldown



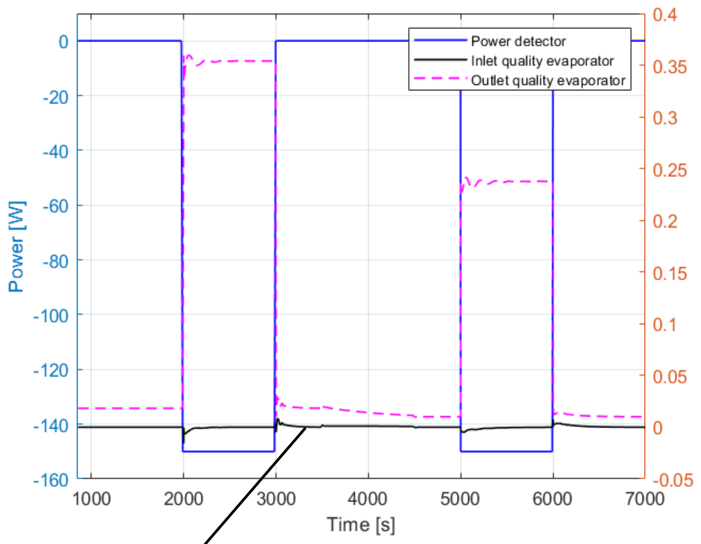


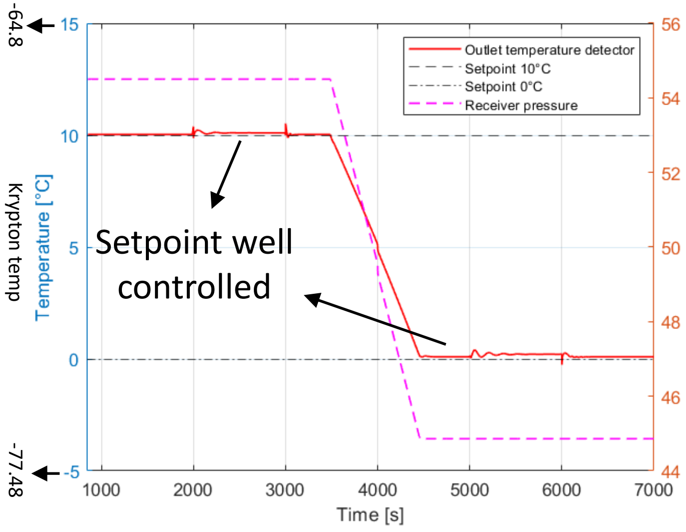






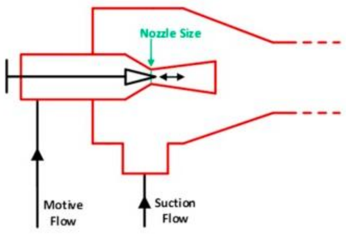
Going colder : transcritical mode



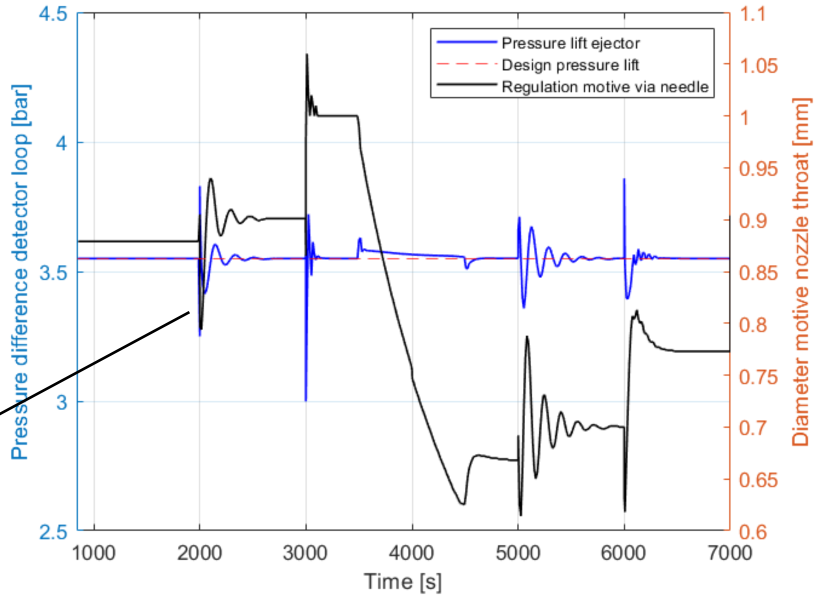


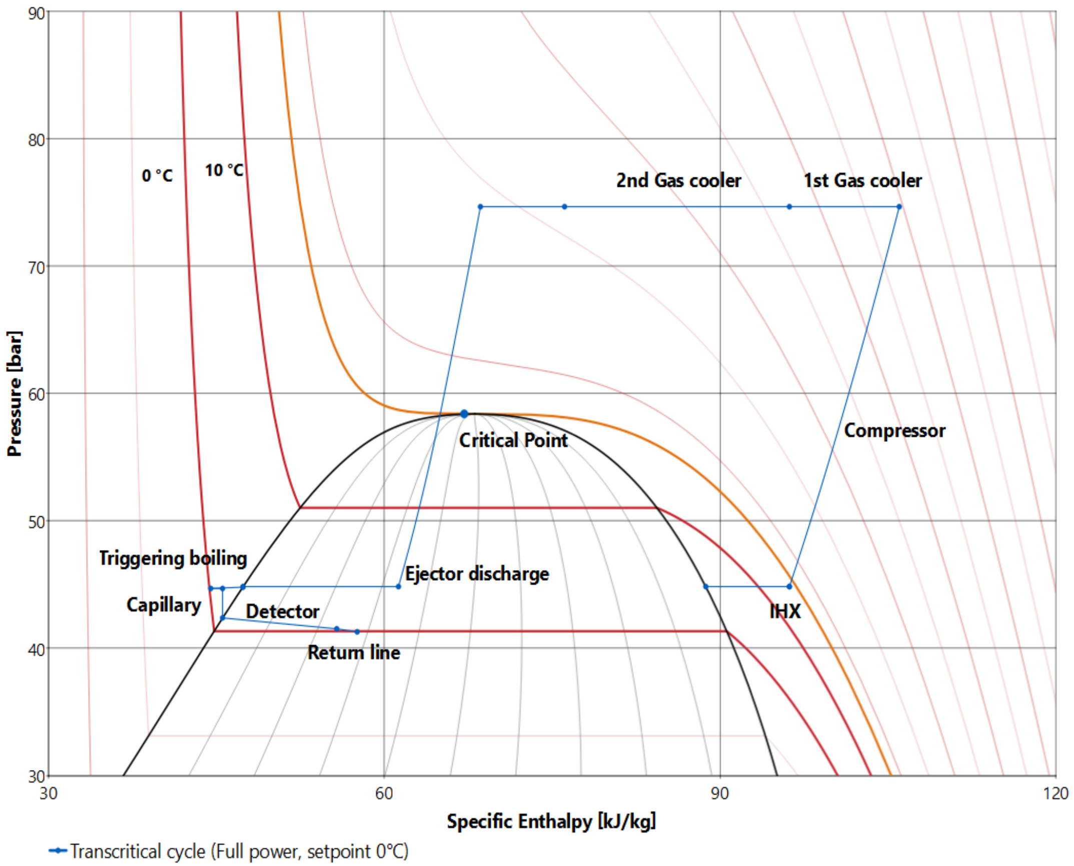
Setpoint well controlled

Bypass trigger boiling at the entrance



Needle to accurate control discharge pressure





Similar to traditional CO_2 ejector supported system except for particular requirements in the evaporator

3D model Xenon test-rig

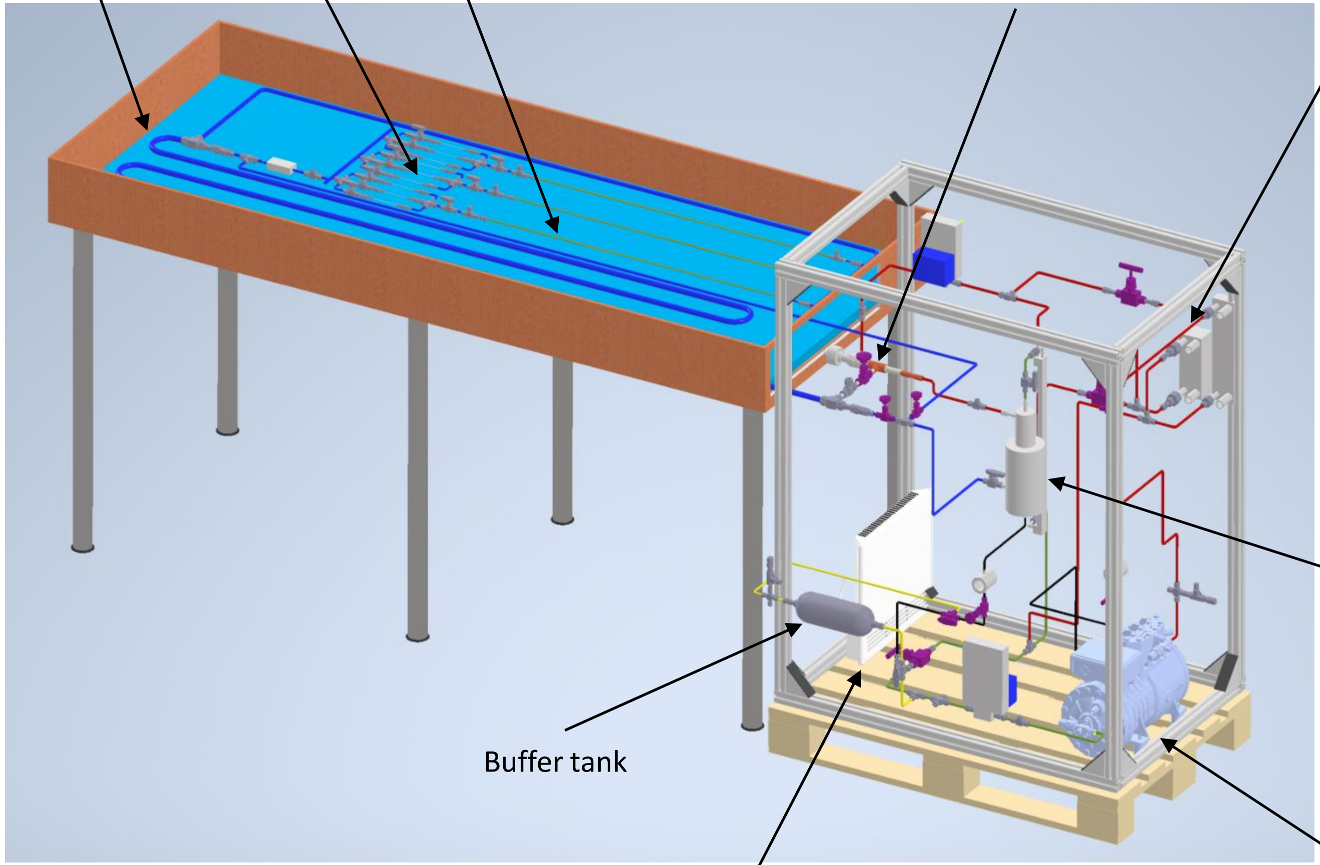
Charging & discharging tanks not present in the drawing but <u>necessary for the supercritical phase</u>

Concentric line

Capillaries

Test section

Controllable-ejector geometry



Buffer tank

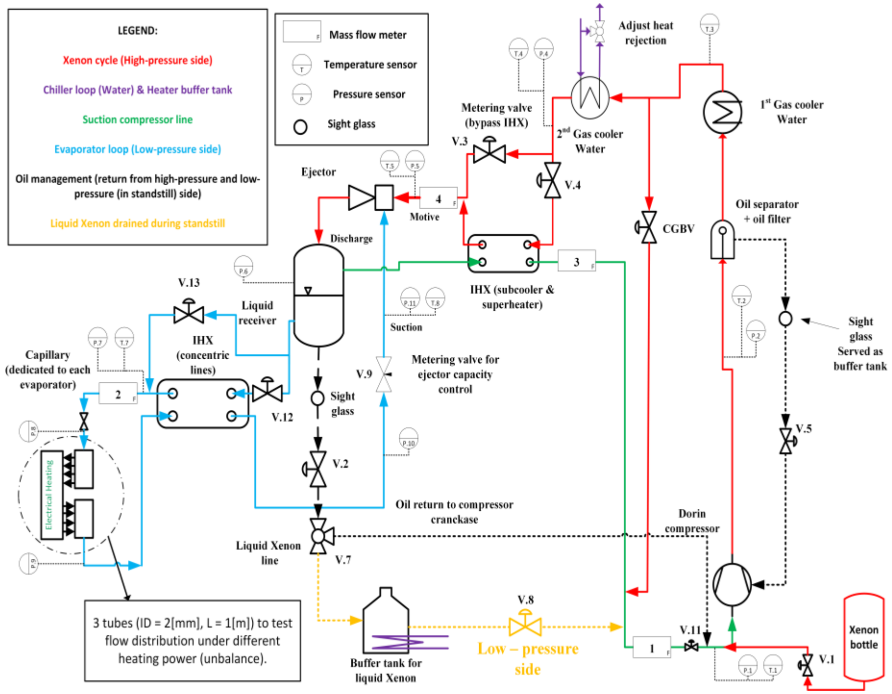
Heater to emulate Krypton starting conditions (Supercritical state)

Gas coolers

Separator / tank

Compressor

Simplified PI&D Xenon system with instrumentation



Thanks for your attention!

Questions?