Results from the UAr Cryogenics Testbed at LNGS

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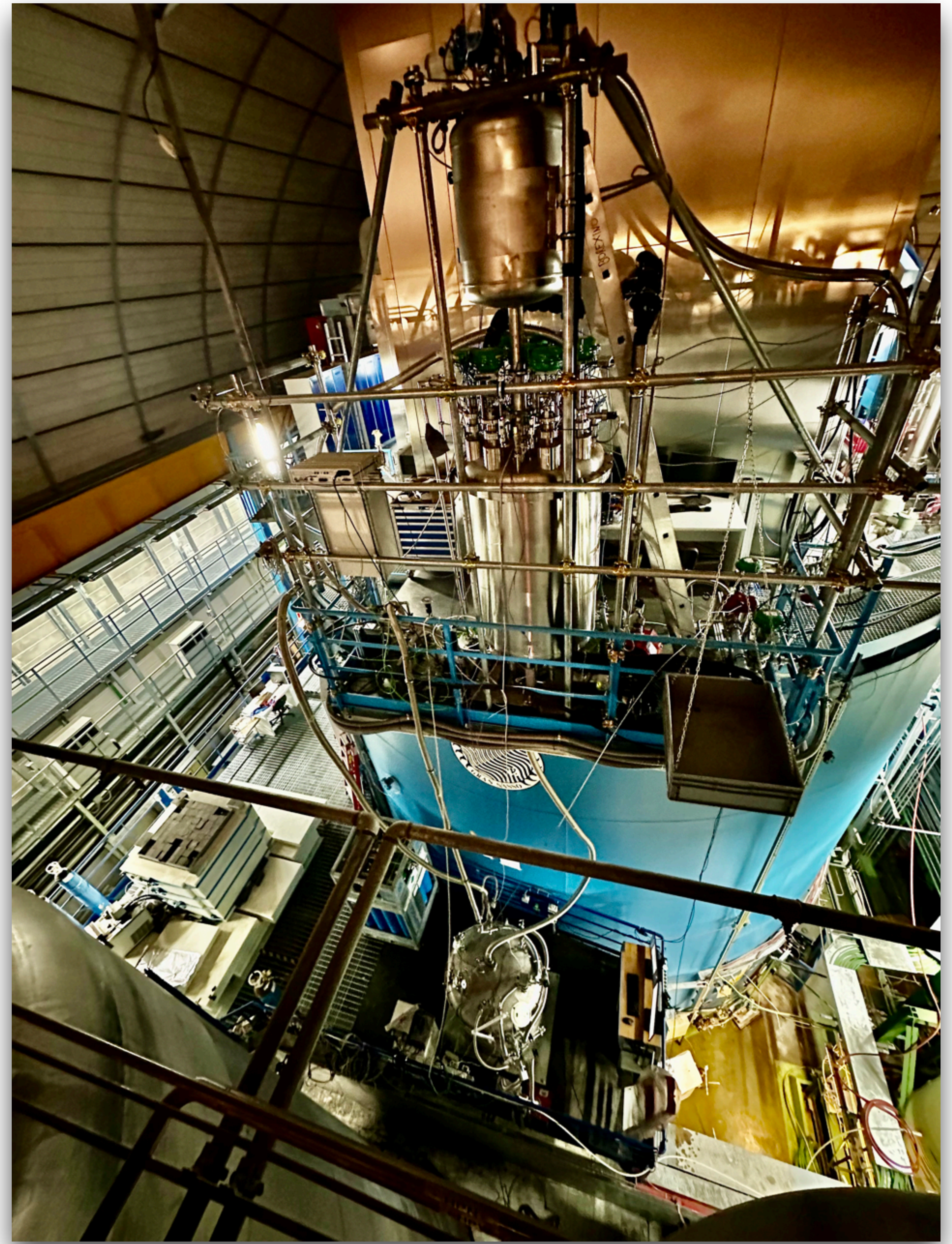
on behalf of the Mockup Team and the UAr Cryogenics Working Group

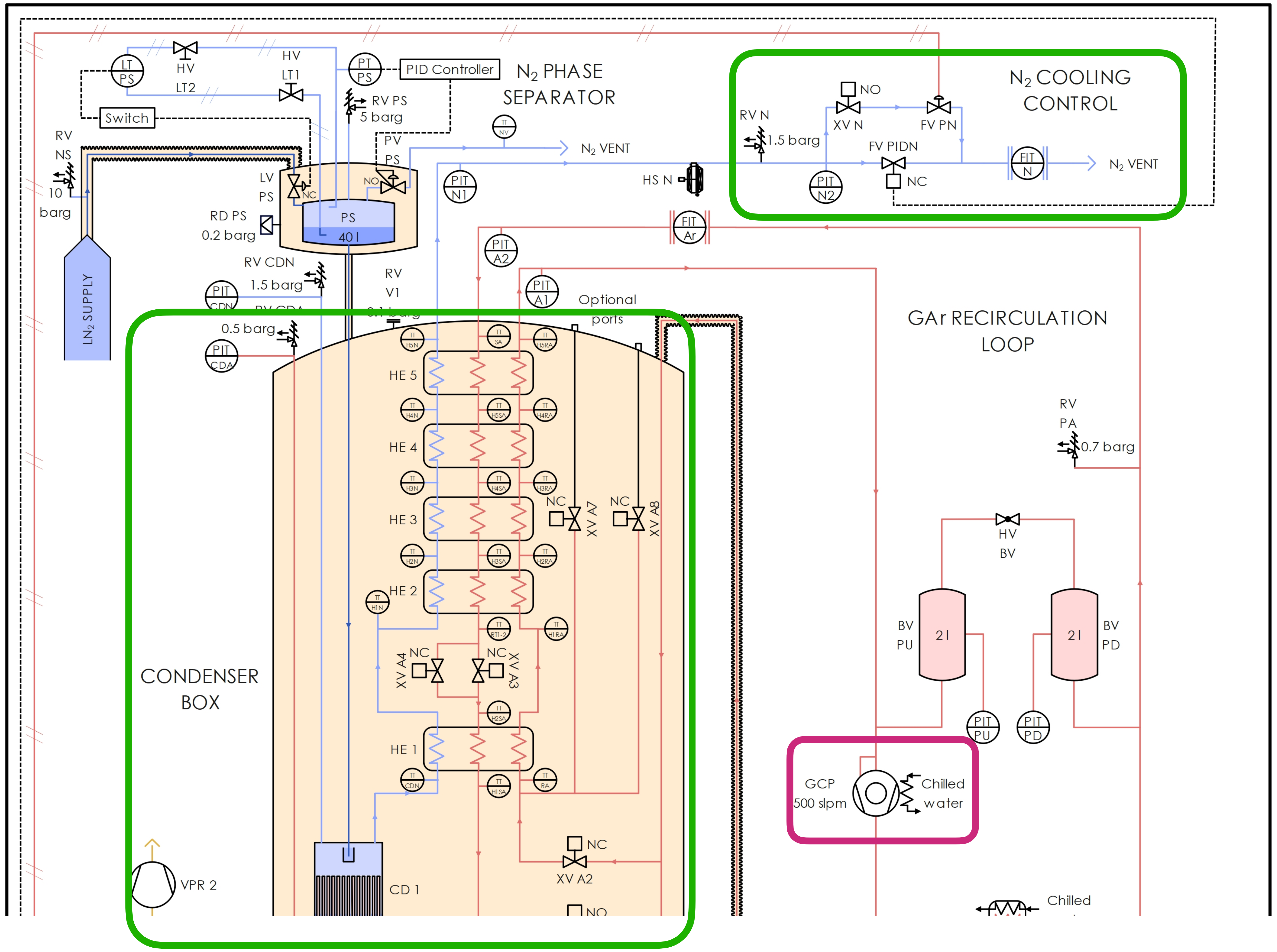
UAr CRYOGENICS TESTBED IN HALL C

- Thorough benchmarking of integral components of the DS-20k UAr Cryogenics System
- Inform finalisation of design by testing candidate components
- Prepare service operation for DS-20k Mockup detector
- 2 runs: mid Oct. – end Dec. 2023 & Feb. 2024
- Cooling for DS-20k Mockup detector

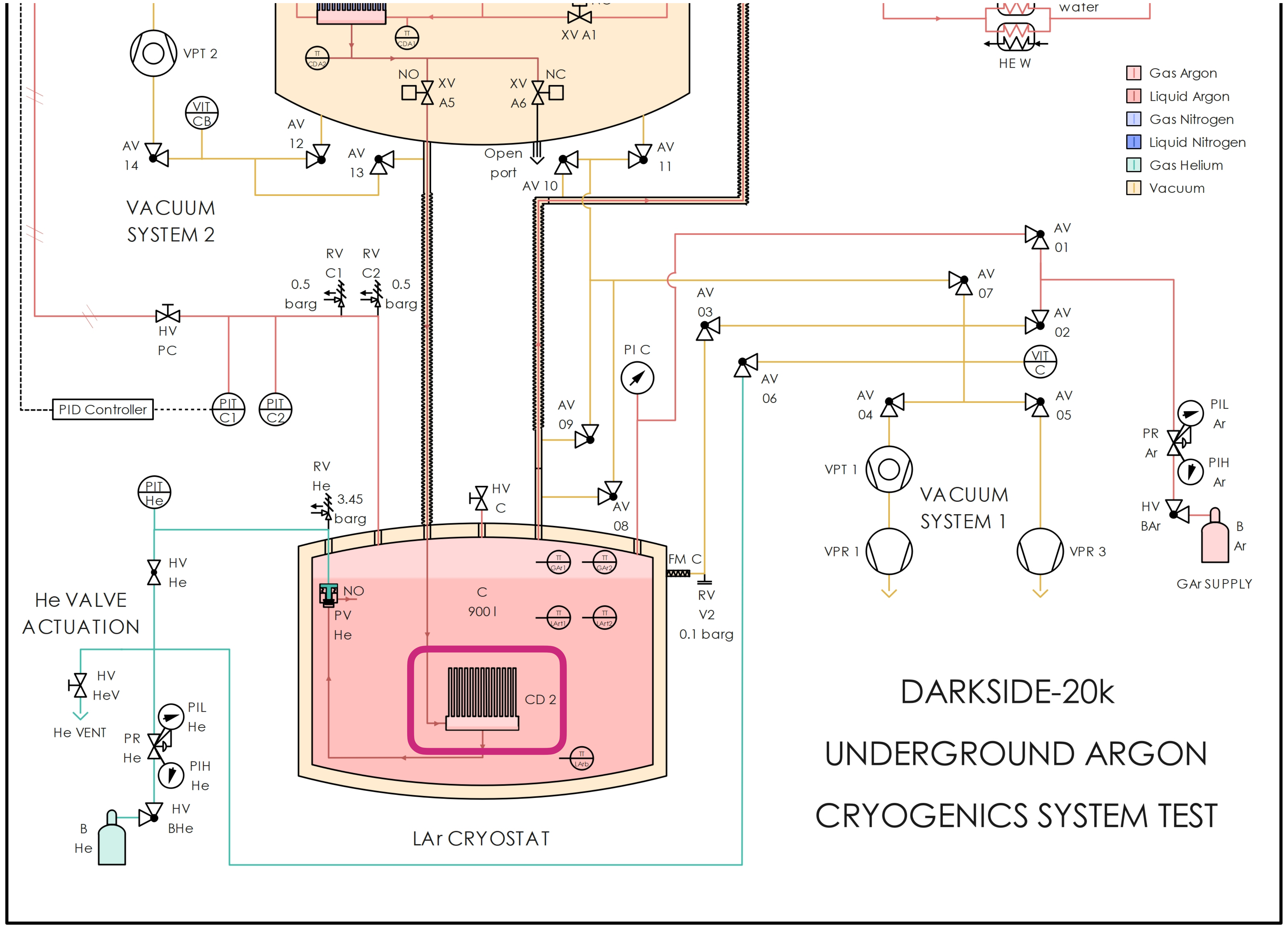


For results from Run 1 see talk at January meeting or backup slides of this talk.

THE TEST BED



- Cooling-power based on cryostat pressure
- Controlled through adjusting GN2 outflow of condenser with independent flow-control valves: Pneumatically-actuated PID-controlled proportional valve & Passive bellow valve (requires no power)

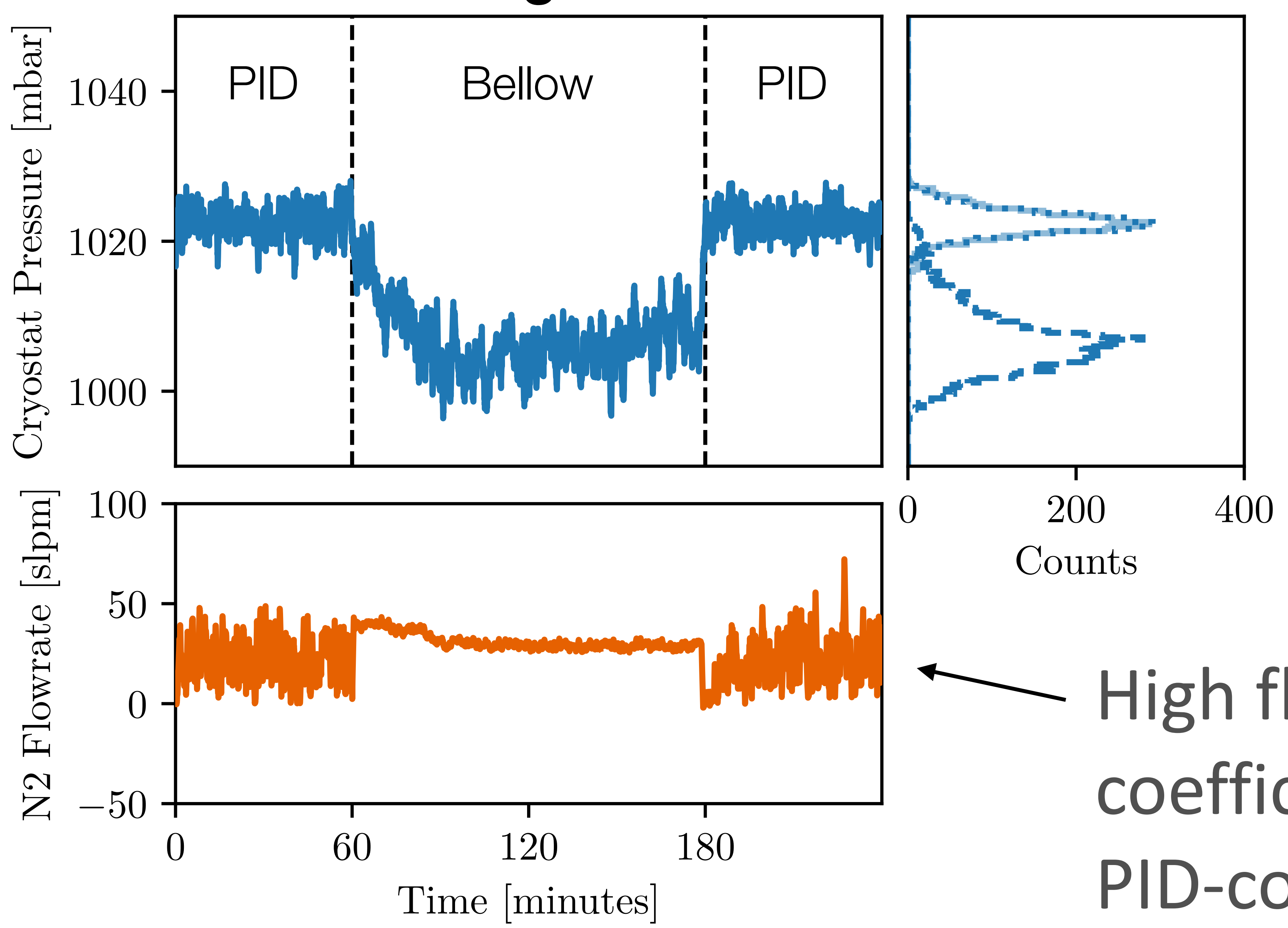


- Tube condenser with chicken feeder
- 5 dual-circuit plate heat exchangers

COOLING PERFORMANCE AND PRESSURE STABILITY I

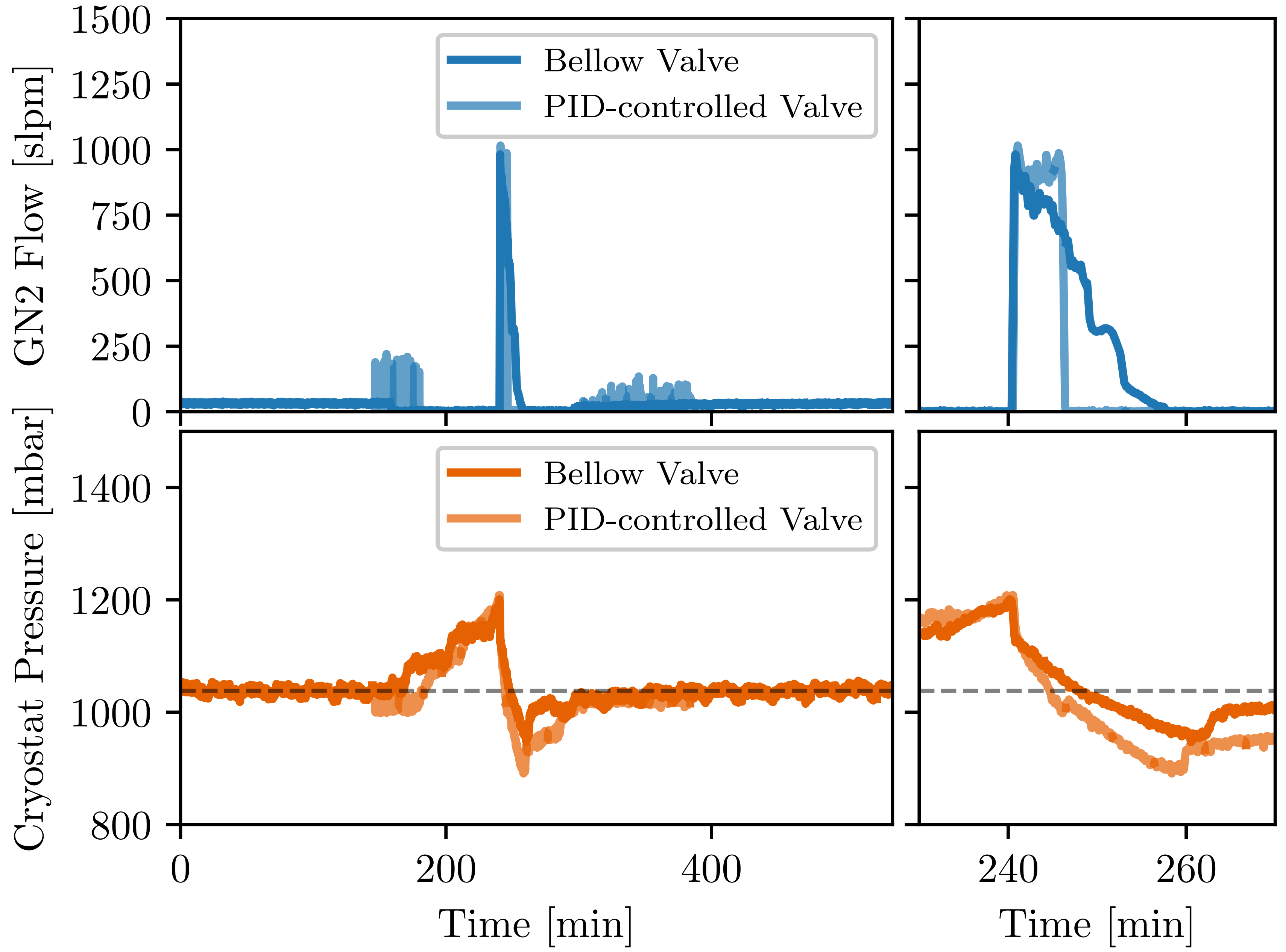
- Operated at various N2 pressures in the range 1.2–2.0 bara
  - Cooling control and cryostat pressure with both valves stable at all N2 pressures
  - LAr temperature from condenser with variations of O(0.1 K) around nominal 84.4 K at 1.5 bara N2
  - Expect percent-level changes of required GN2 flow (cannot be observed at O(10 slpm) flows with deployed flow meter)
- Tested switching between bellow and PID valve and response to sudden pressure increases

Switching between valves



High flow coefficient of the PID-controlled valve

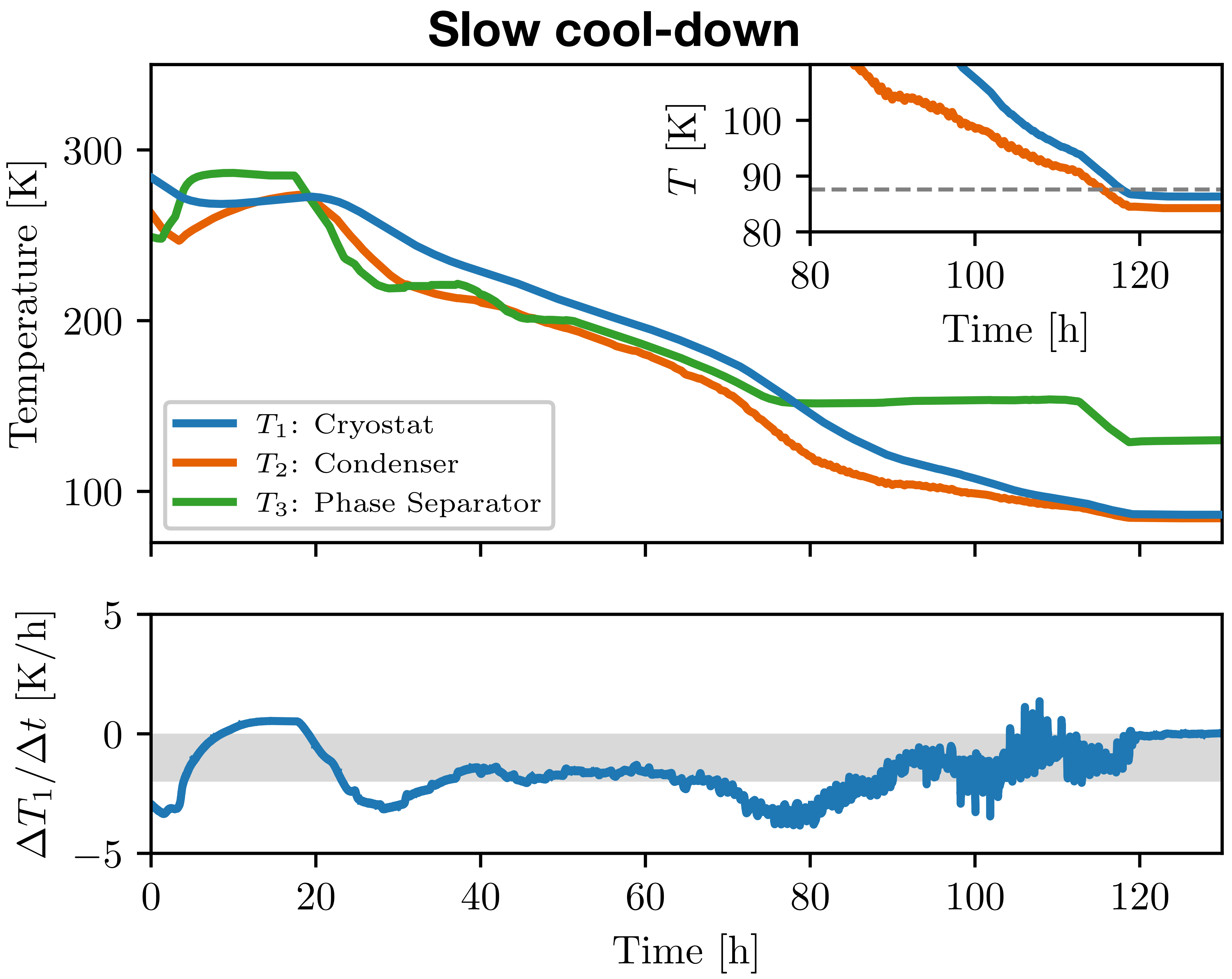
Response to pressure increase

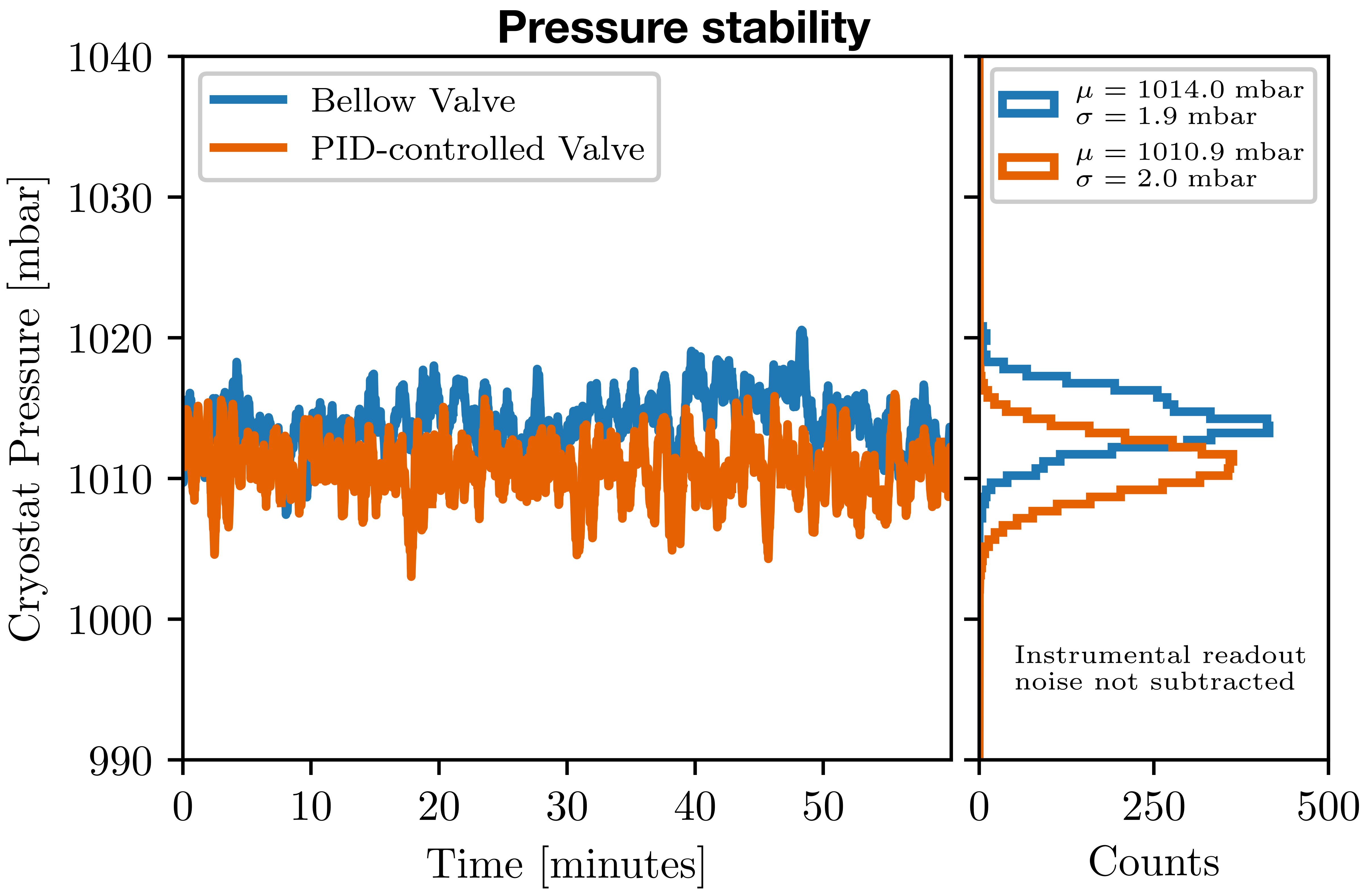


Recovery within 40 min

COOLING PERFORMANCE AND PRESSURE STABILITY I

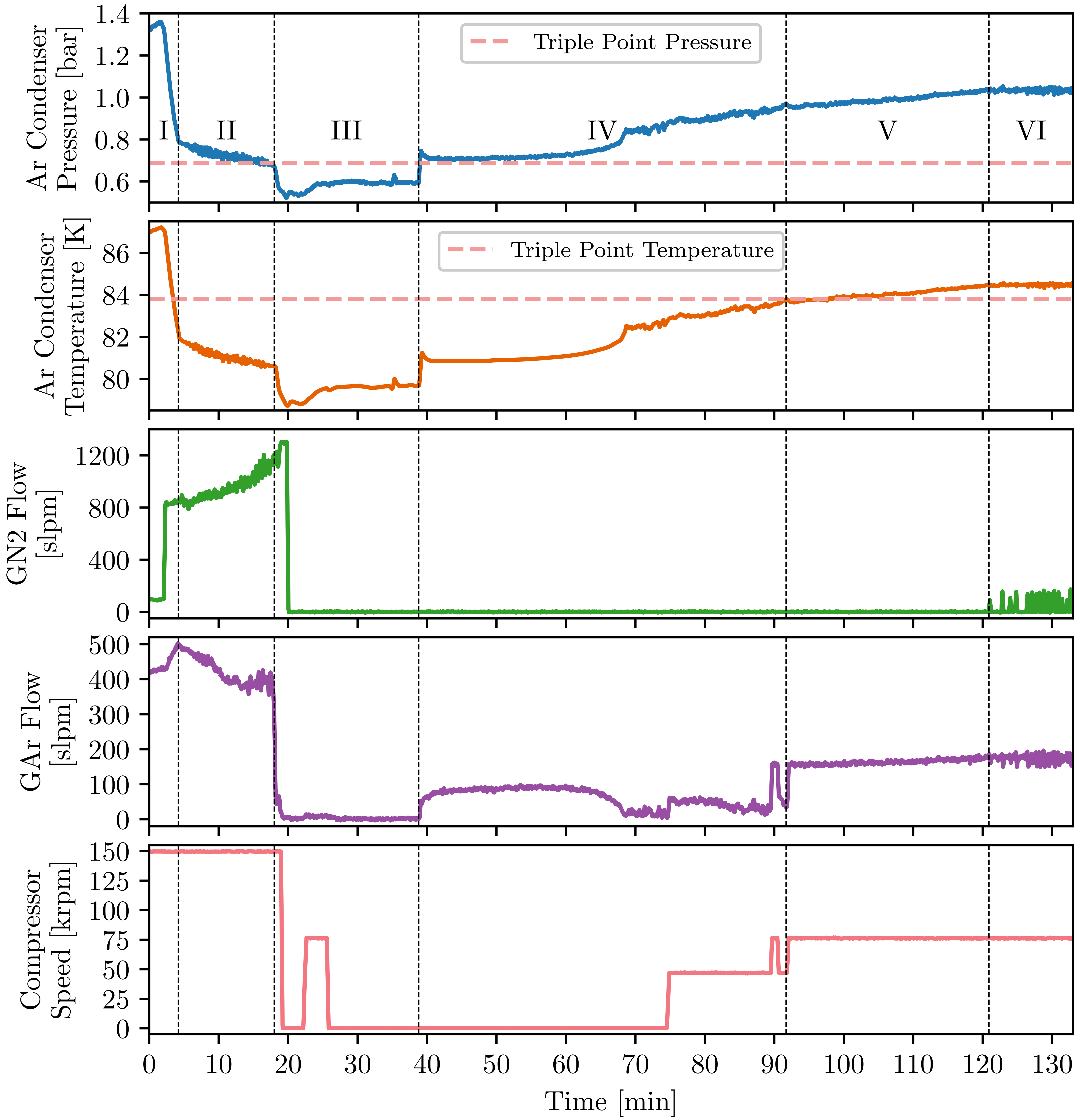
- Slow cool-down test for TPC phase and DS-20k with empty cryostat (low heat capacity): stayed within -2 K/h for most of the time
- Using GAr in the cryostat almost until the end -> no temperature step
- Remove electronic noise based on noise-only (vacuum) datasets (σ=1.8 mbar) with principal component analysis
- Yields pressure stability within 0.1 mbar (bellow valve) and 0.2 mbar (PID valve) RMS



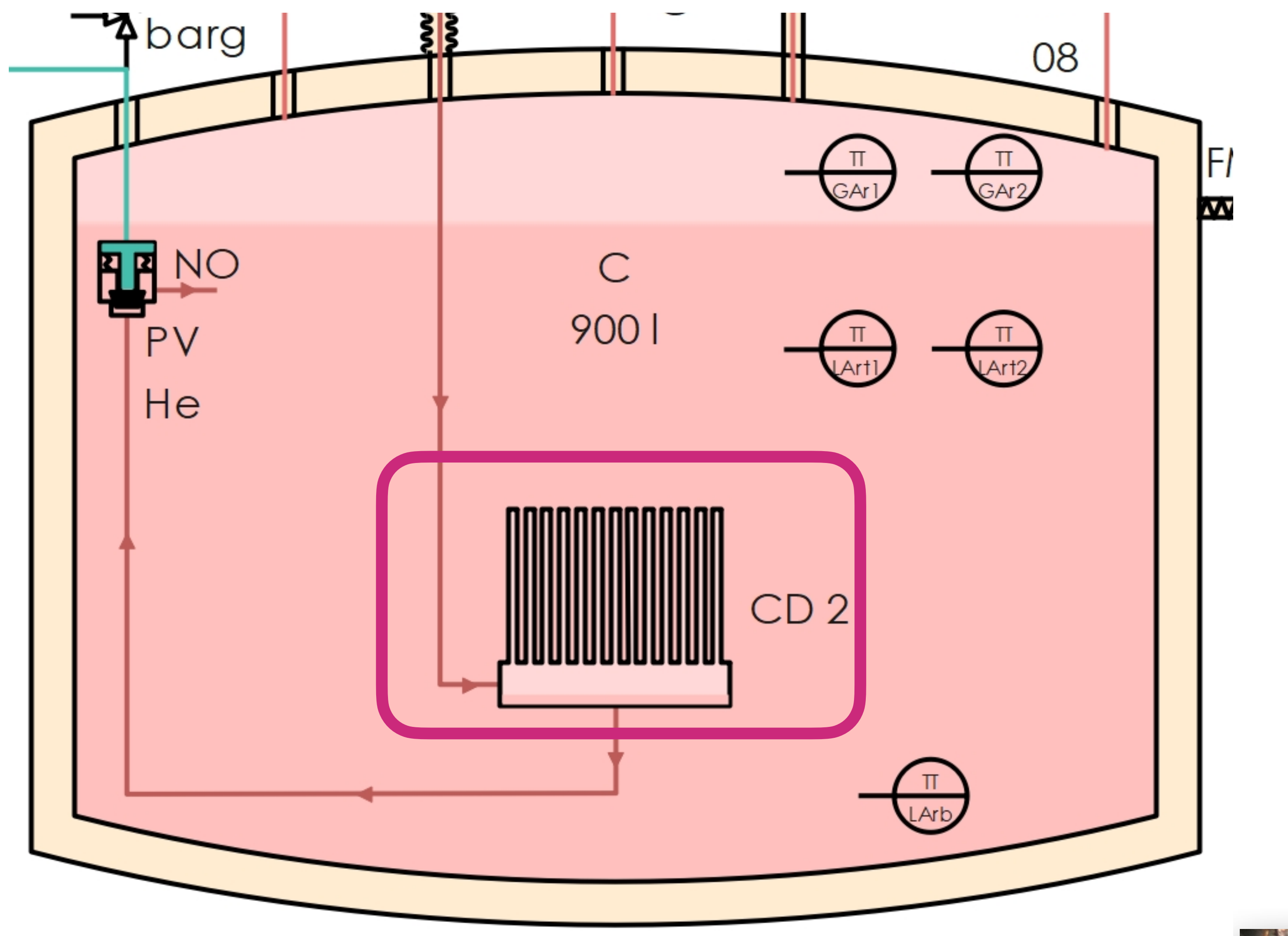


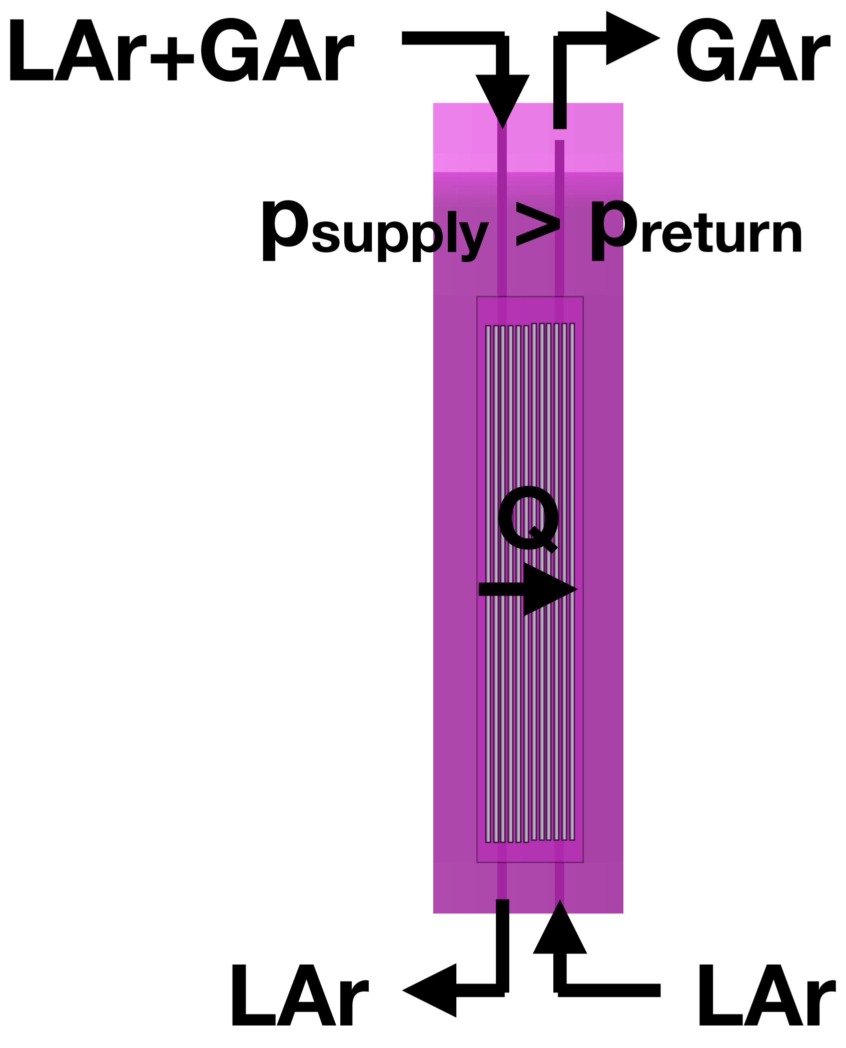
INTENTIONAL CONDENSER ICING TEST

- LN2 only slightly pressurised to drive the flow (typically 1.5 bara with 80.8 K at saturation) -> below melting point of argon
- Chicken feeder doses LN2 on an as-needed basis in such a way that argon does not freeze in normal operations
- Intentional freezing by requiring a large sudden cooling power through a setpoint change of 0.6 bar
- System behaves predictably and recovers safely to normal state without operator's intervention, data is understood
- All parameters stayed within working range and no safety relief valve opened
- Condenser inlet and outlet clogged by SAr
- 101 min for complete recovery



TWO-PHASE ARGON HEAT EXCHANGERS IN CRYOSTAT

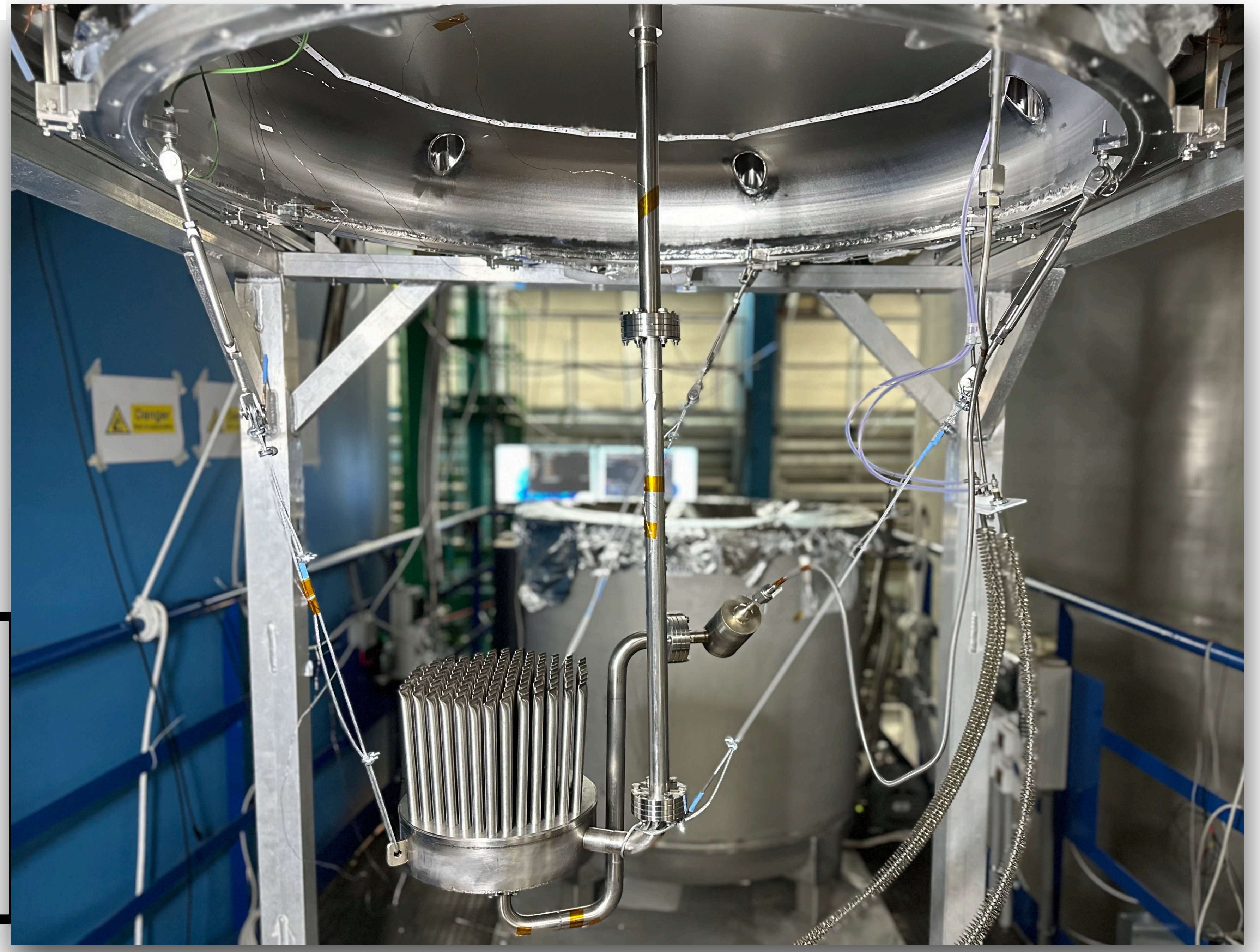




- Produce efficiently boil-off gas for recirculation
- Make design choice for DS-20k

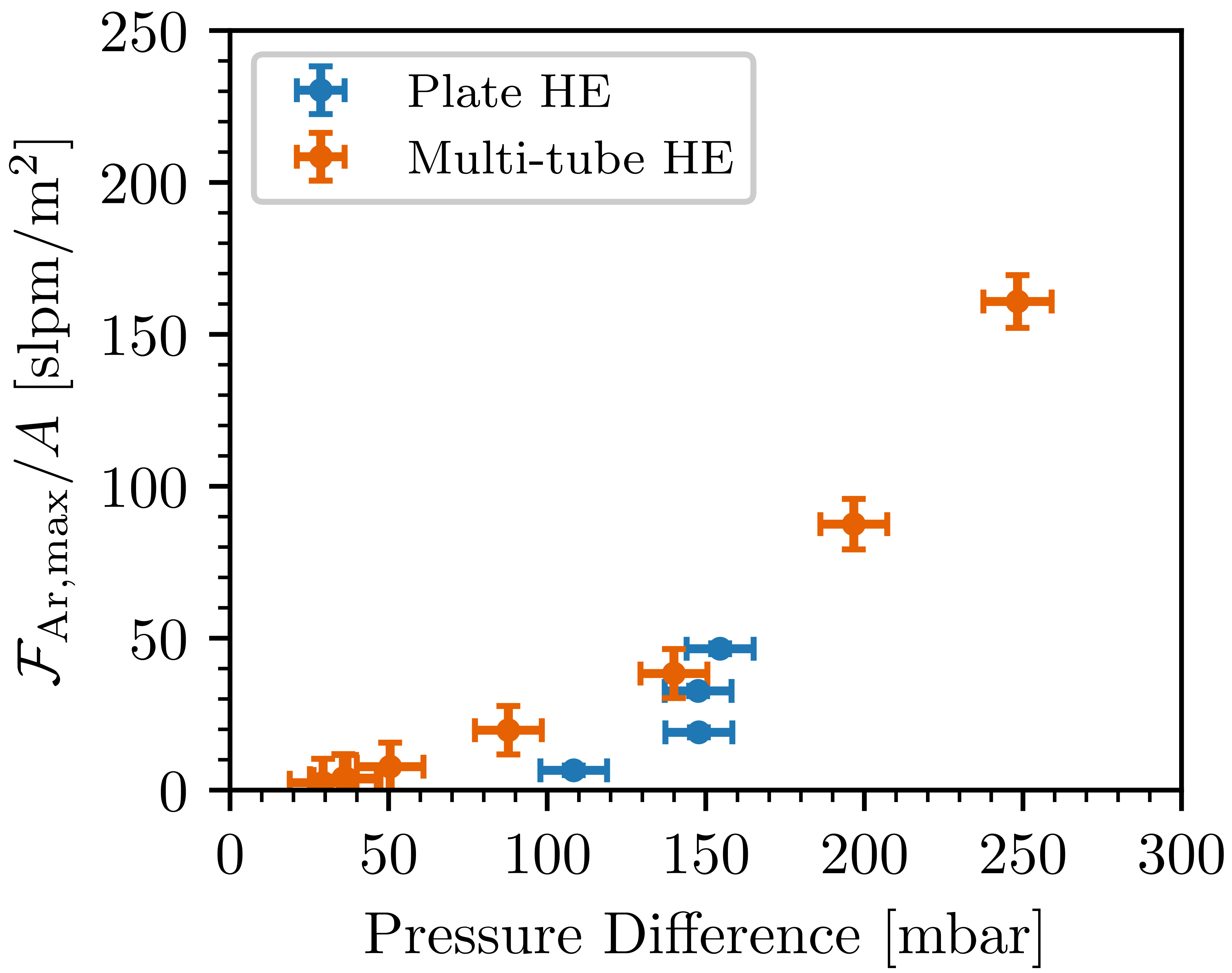
- 2 parallel plate heat exchangers
- Total surface: 4.84 m2

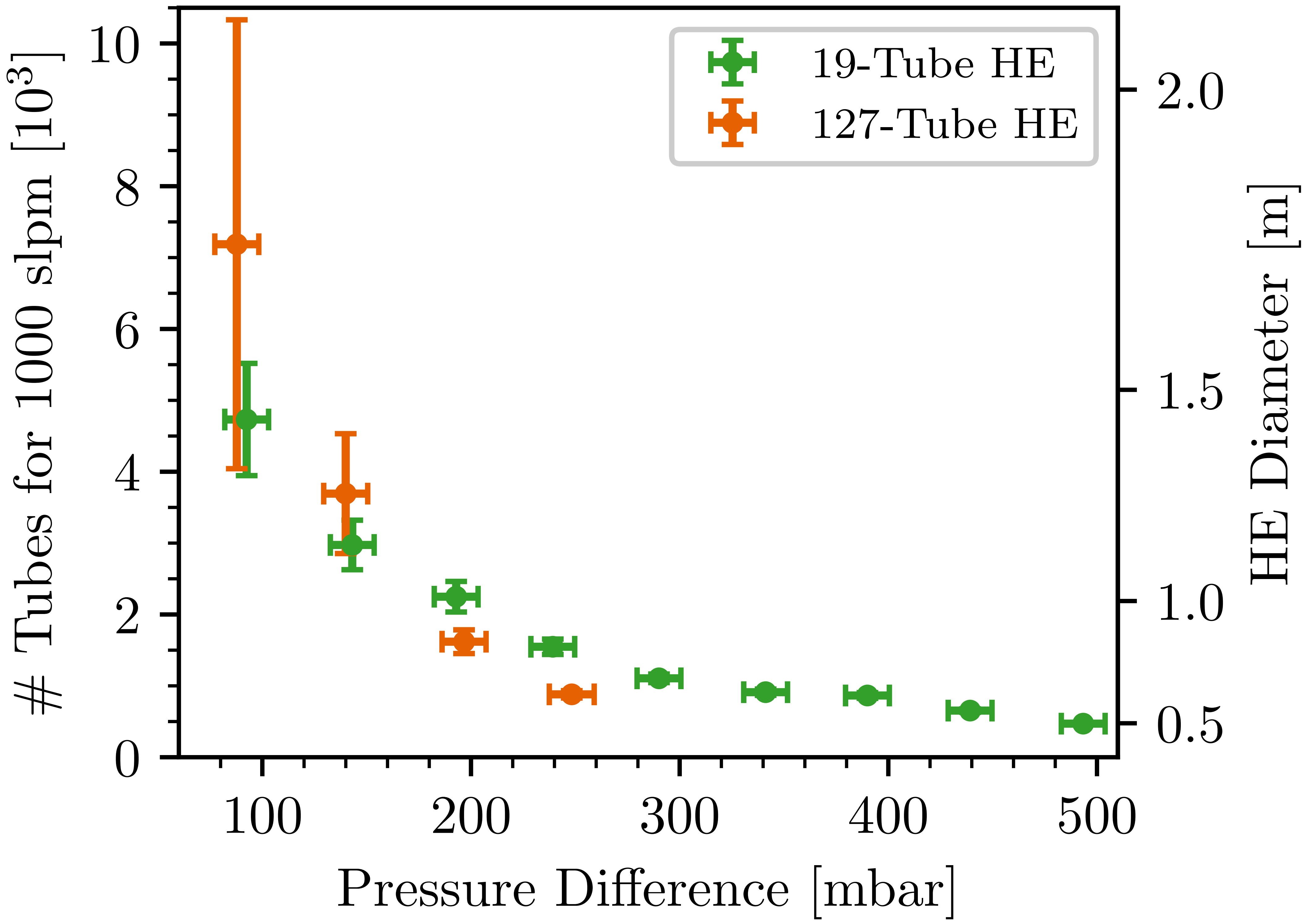
- 127 (1/2“ x 7“) pipes, closely packed at 3/4“ pitch
- Total surface: 0.9 m2



MAXIMUM ARGON FLOW RATE

- Measure maximum heat transfer capability of both heat exchanger configurations as a function of pressure difference
- Achievable pressure difference limited by compressor performance
- Small inter-plate distance of plate heat exchanger not designed for phase change
- Non-linear scaling of tube heat exchanger at high pressure differences (enhanced convection in the centre)





IMPLICATIONS OF THE TESTS FOR DS-20k I

- Heat exchanger cascade:
  - Pressure drop too high (~400 mbar at 300 slpm at room temperature)
  - Will be replaced while maintaining high efficiency
  - HE1 will be dimensioned to allow for phase change during LAr filling
- Condenser:
  - Add electric heater to condenser body to enable the operator to actively de-ice and possibly integrate into the functional logic
  - Create interlock that reduces cooling power in case of condenser icing and send alarm to operator
- Cooling control:
  - Performed as expected
  - 2 additional bypasses will be installed: control-valve with smaller flow coefficient for 0–100 slpm regime and manual bypass
  - Bellow-valve will be upgraded with double containment and metal gaskets

IMPLICATIONS OF THE TESTS FOR DS-20k II

- Two-phase heat exchanger:
  - Data and modelling are the basis for design with target operating point of 300 mbard -> 1200 pipes and ⌀ 750 mm
- Celeroton CT-1000 Ar compressor:
  - Performs to specifications and is satisfactory for the test stand requirements
  - Compression ratio of 1.6 at 500 slpm insufficient for DS-20k (requirement is 2.0 at 1000 slpm)

CONCLUSION

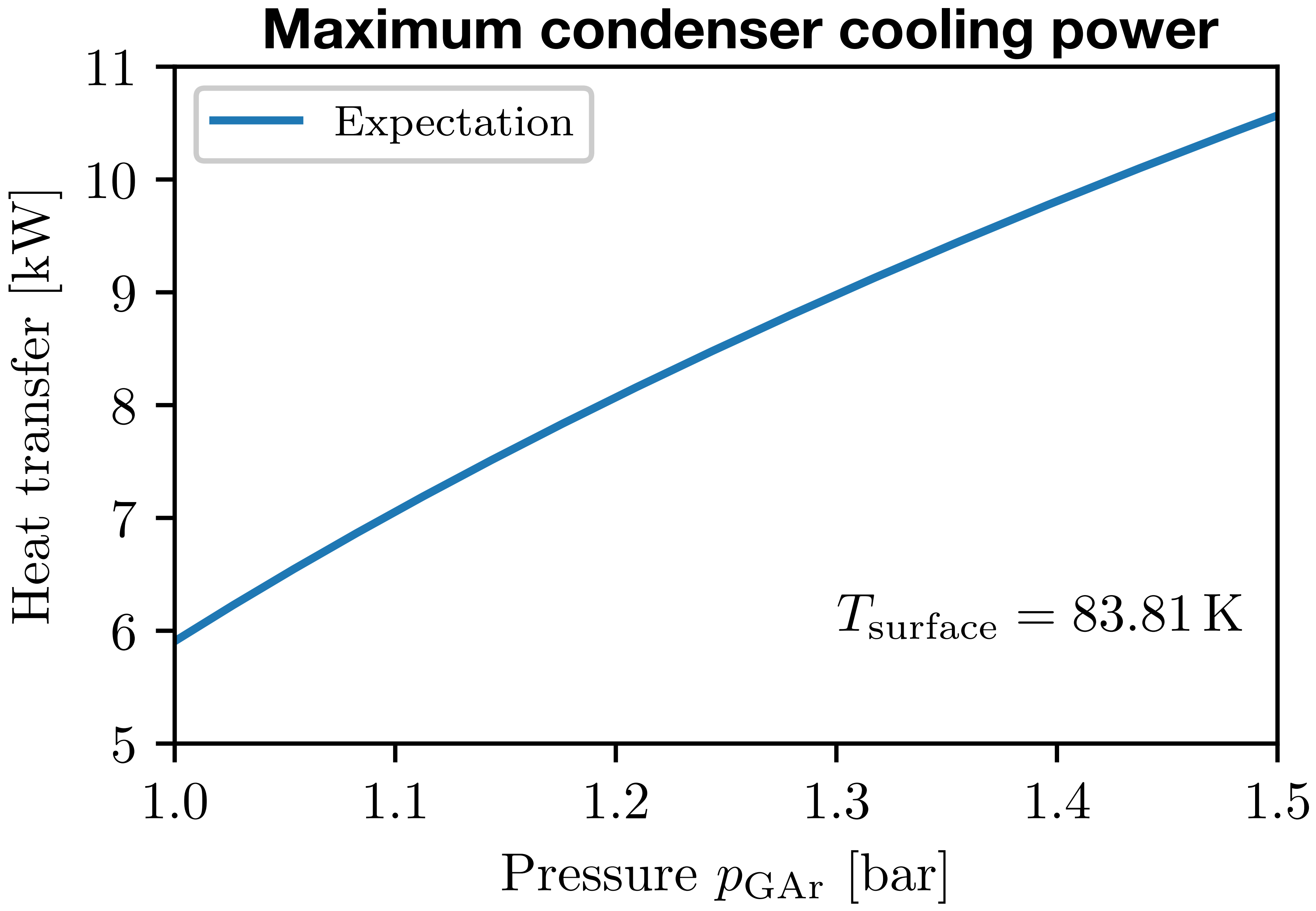
- Core components successfully benchmarked
- Necessary modifications for DS-20k are understood
- Currently installed heat exchanger cascade has dynamic heat load recovery efficiency of 95 %
- Pressure-based cooling control with self-regulating dosing works fine and allows for stable operations of the system
- 0.1– 0.2 mbar RMS pressure stability; further improvements for DS-20k —> will use 2 N_2 phase separators in alternating manner, larger gas ullage and use of control valve with appropriately-sized flow coefficient (depending on flow-regime)

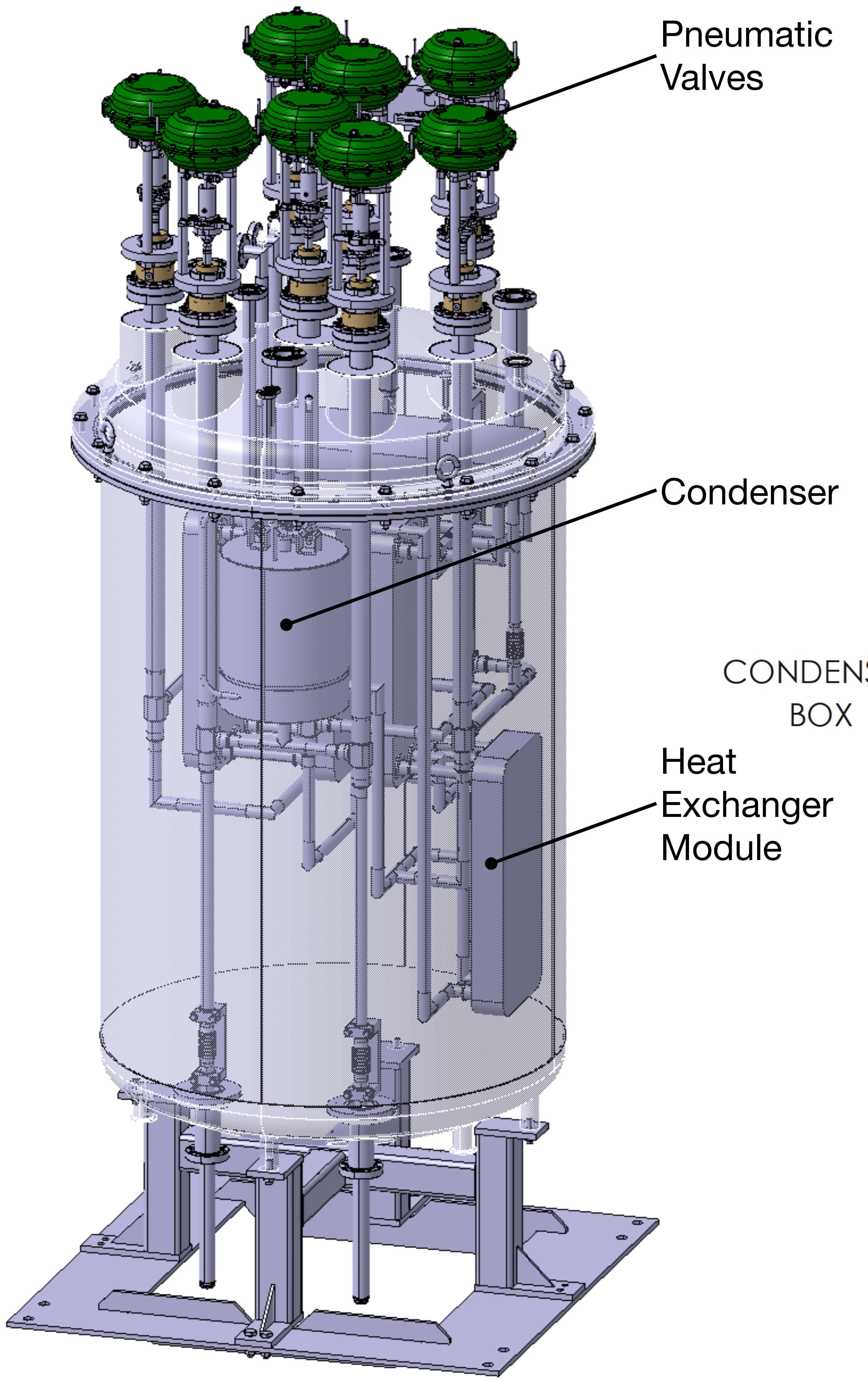
THE END

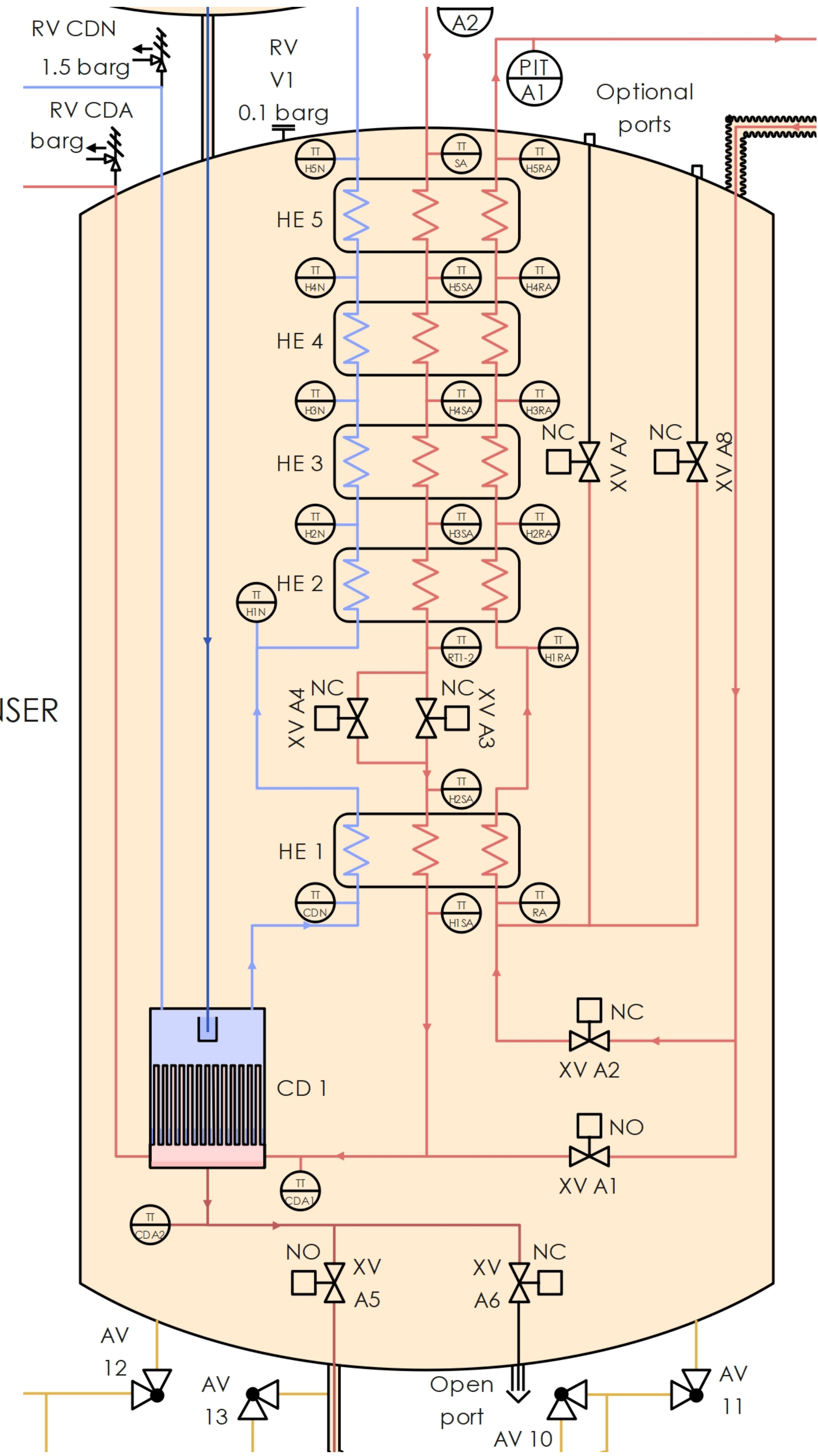
BACKUP

CONDENSER BOX

- Tube condenser with chicken feeder
- 5 dual-circuit plate heat exchangers
- Radon trap (not installed for the tests)
- 8 pneumatically-actuated cryogenic valves
- 8 kW total* cooling power at 1000 slpm GN2 flow

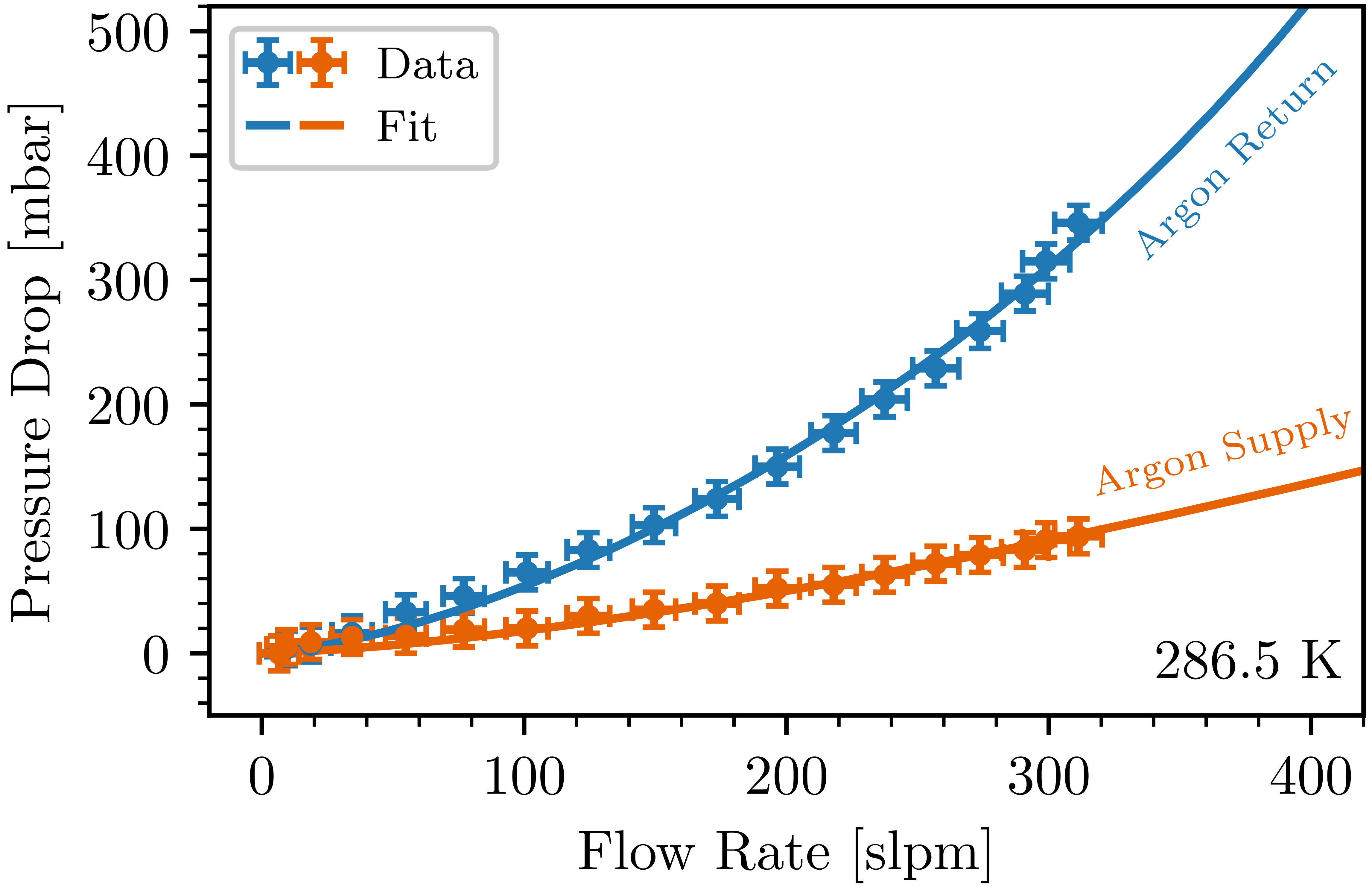


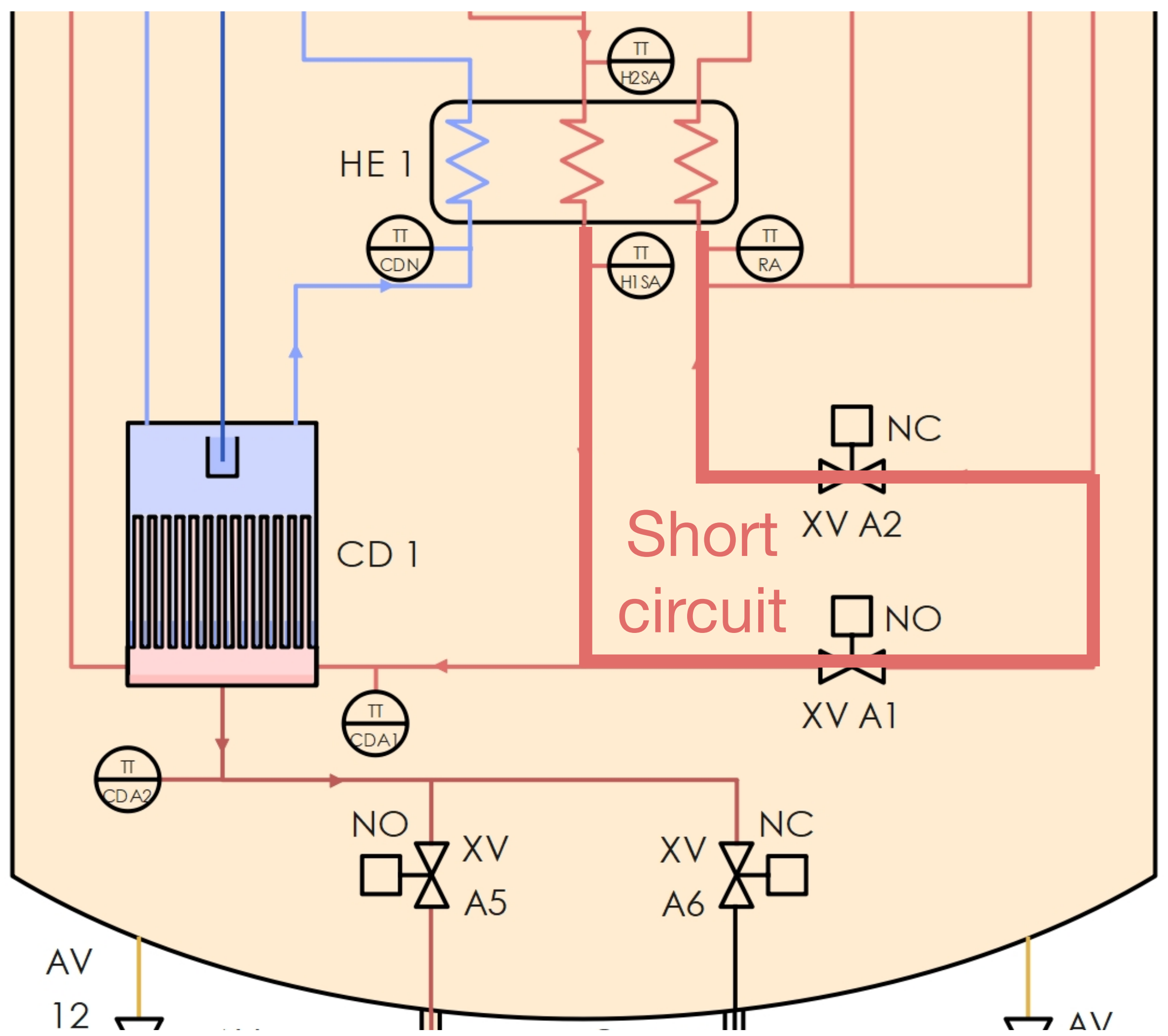


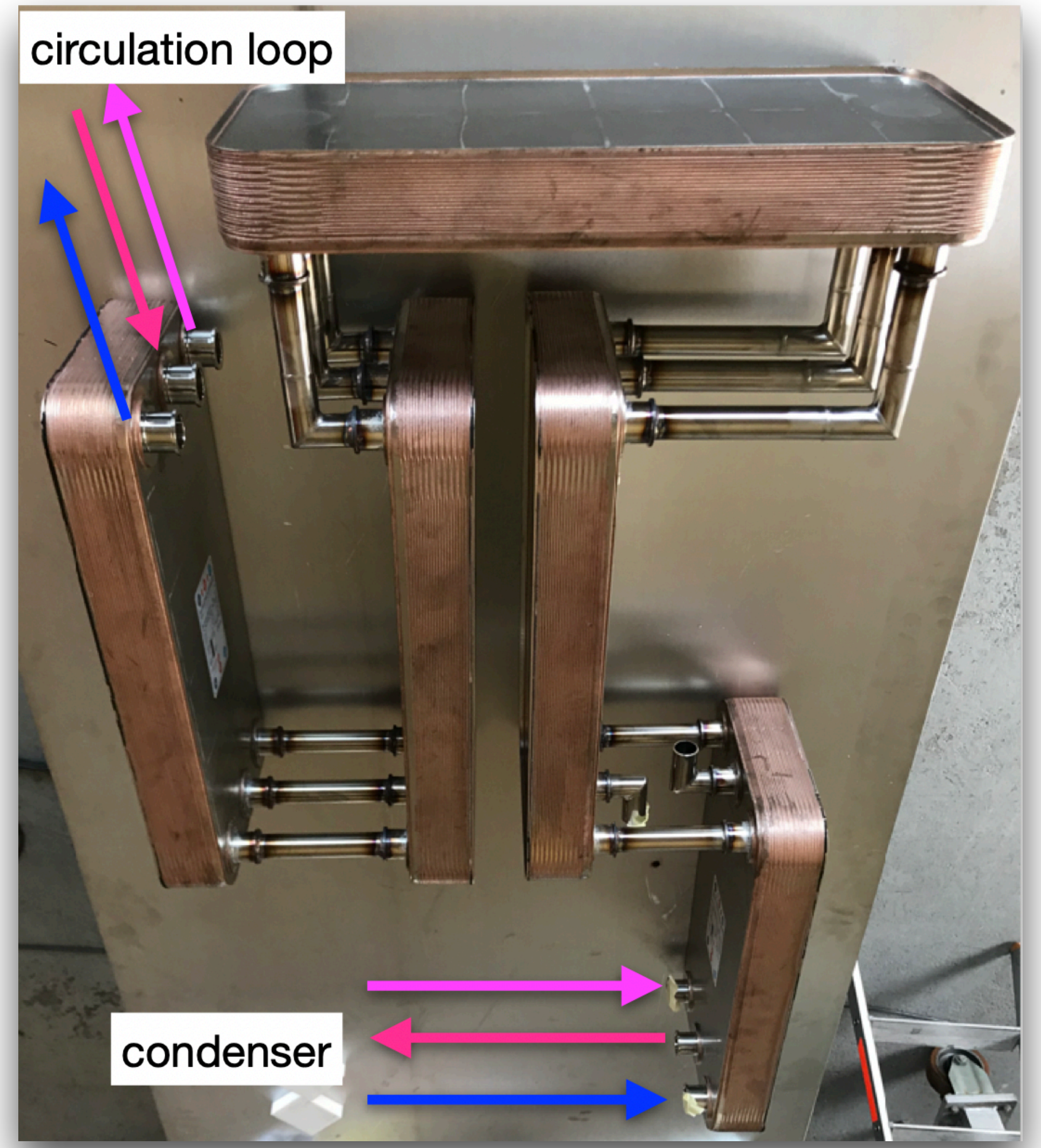


*condenser (latent heat) + heat exchangers (gas-gas)

CIRCUIT RESISTANCE







- Circuit resistance dominated by pressure drop over heat exchanger cascade (dual-circuit type with twice as many channels on the supply side)
- Acquired pressure data in flow range [5,311] slpm at 286.5 K
- Argon-side of condenser at 1065 mbar
- Modelled with Darcy-Weisbach equation and Muley friction factor

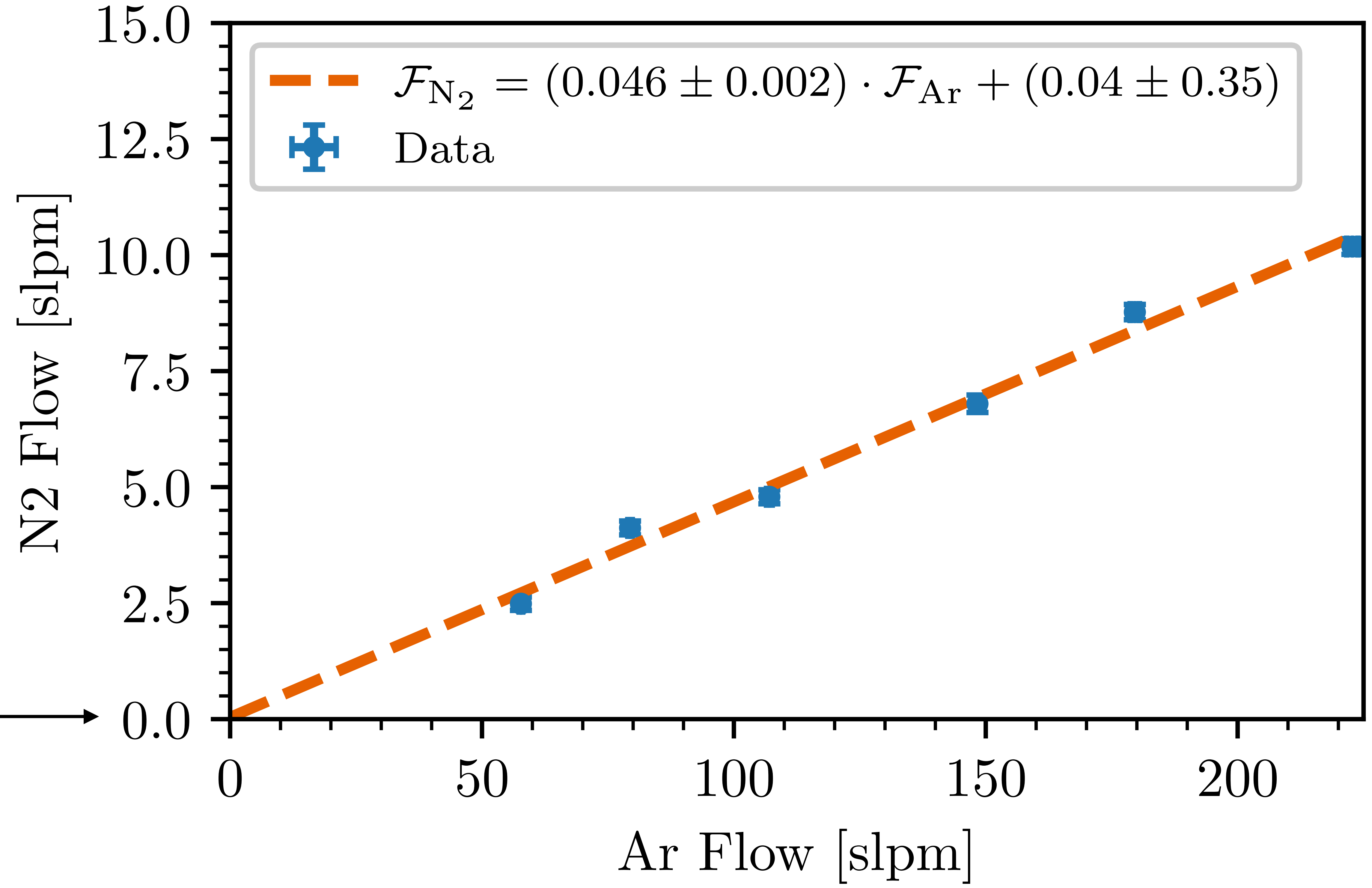
$$\Delta p_{\mathrm{ch}} = 4f\frac{\rho u^2}{2}\frac{L}{D_{\mathrm{h}}}$$

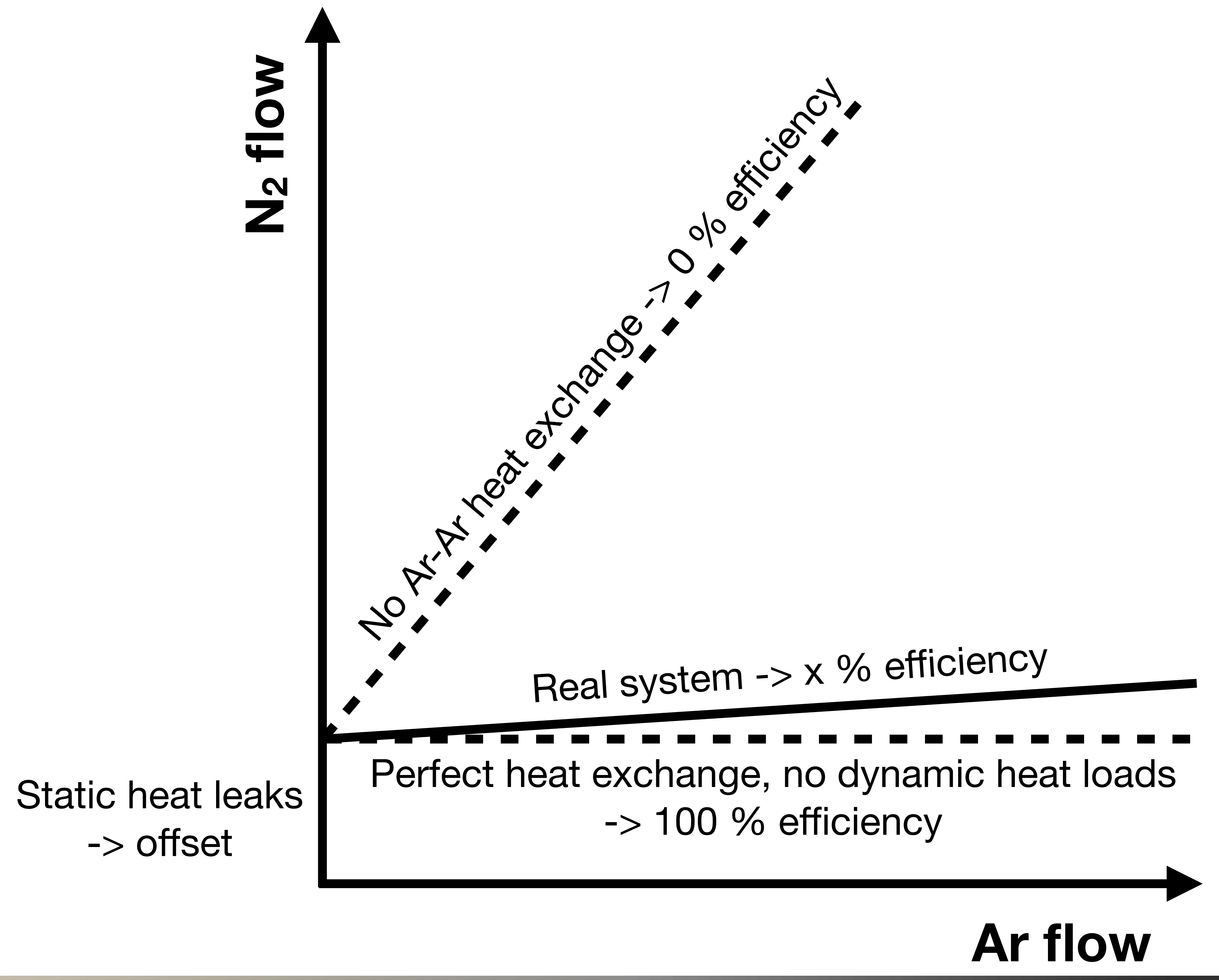
$$f = \left(\frac{\alpha}{30}\right)^{0.83}\left[\left(\frac{30.2}{\mathrm{Re}}\right)^5 + \left(\frac{6.28}{\mathrm{Re}^{0.5}}\right)^5\right]^{0.2}$$

SYSTEM EFFICIENCY

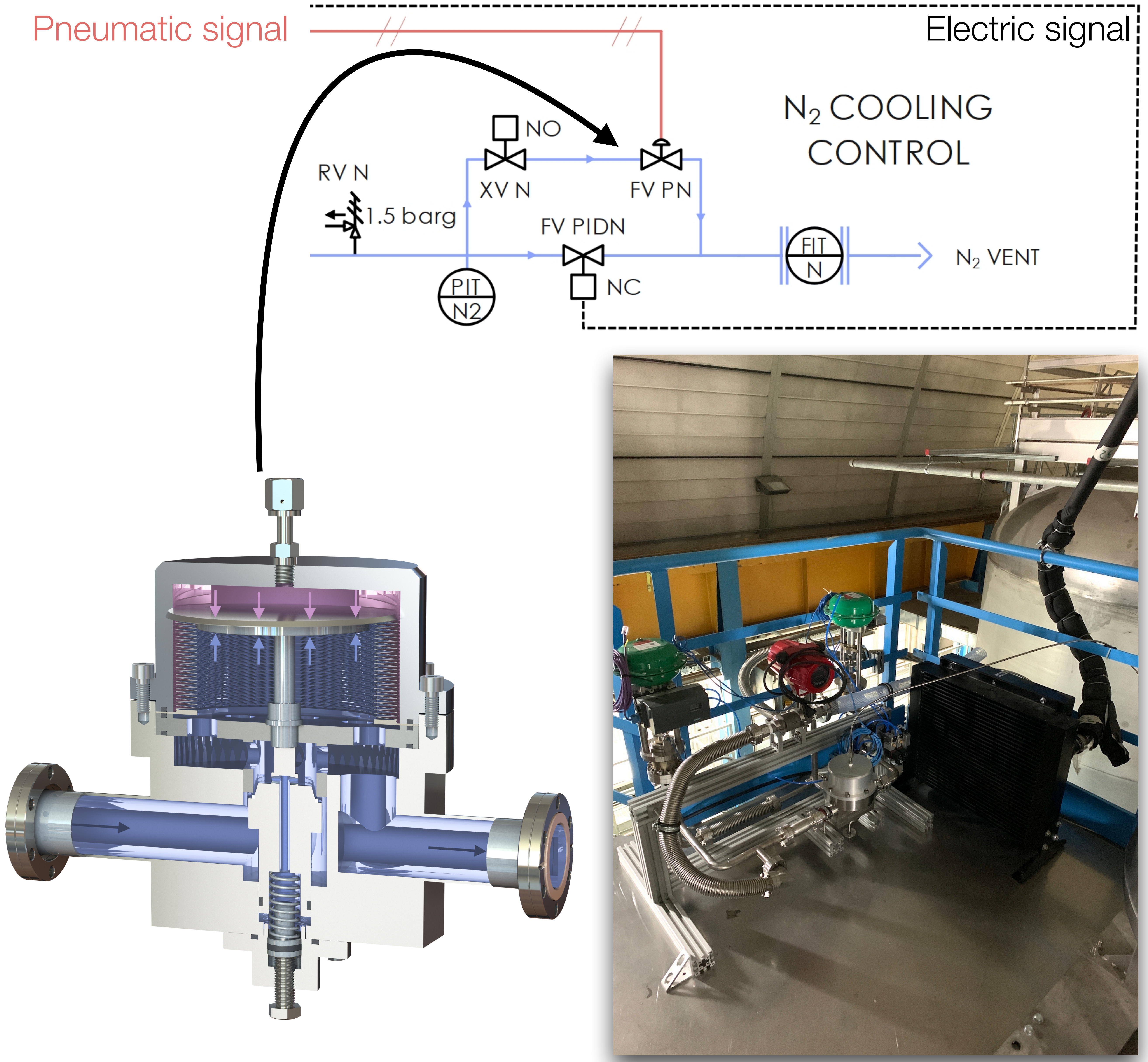
- Measure GN2 and GAr flow at various pump speeds in equilibrium conditions
- Define heat recovery efficiency during gas recirculation as: $\eta = 1 - \frac{\rho_{N_2}}{\rho_{Ar}} \left| \frac{\Delta h_{N_2}}{\Delta h_{Ar}} \right| \frac{d\mathscr{F}_{N_2}}{d\mathscr{F}_{Ar}}$
- Includes any dynamic heat loads
- Obtain $\eta = 95\ \%$, need less than 50 slpm GN2 @ 1000 slpm GAr if linearity is preserved up to 1000 slpm GAr

Measured static heat load subtracted





COOLING CONTROL

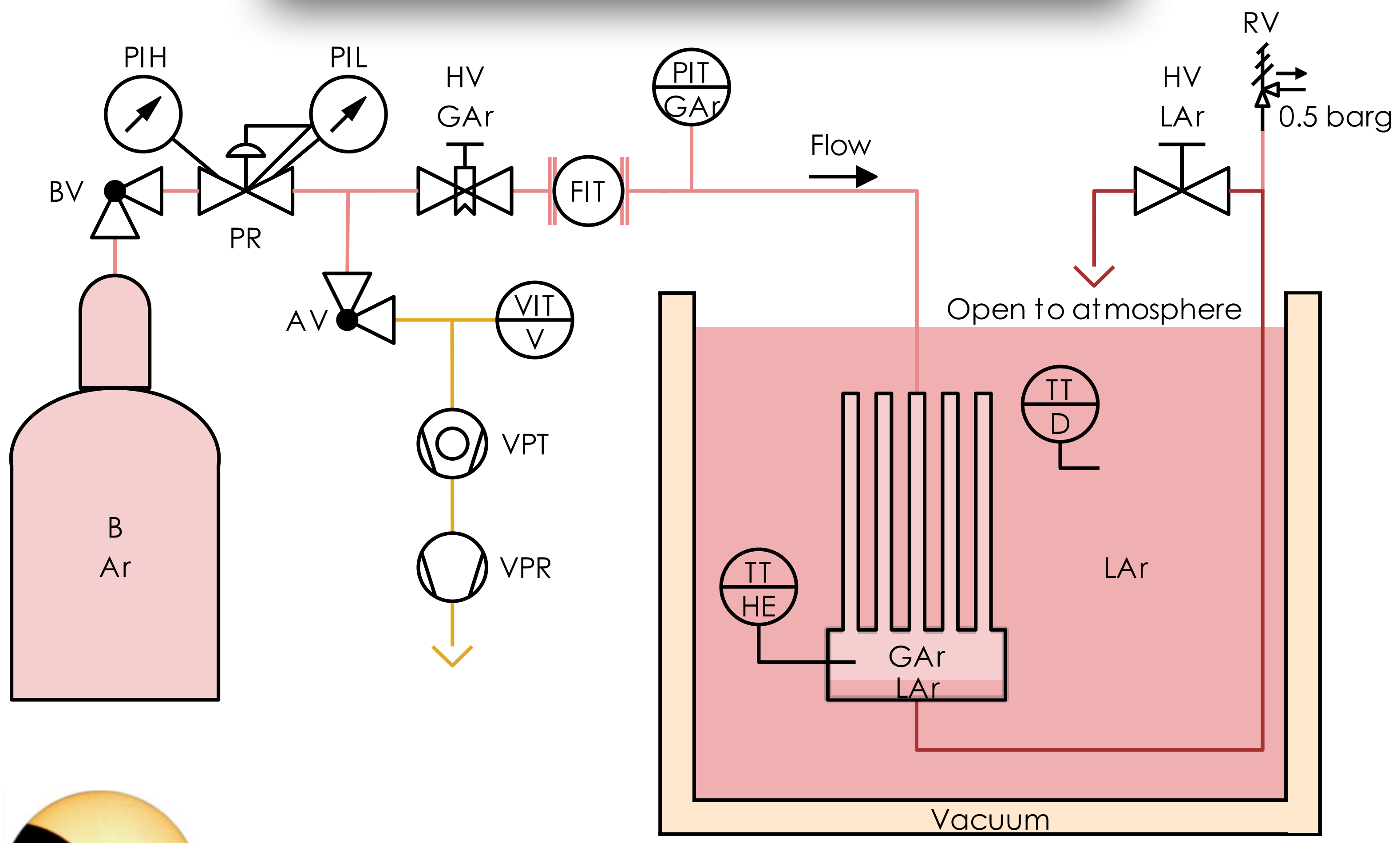


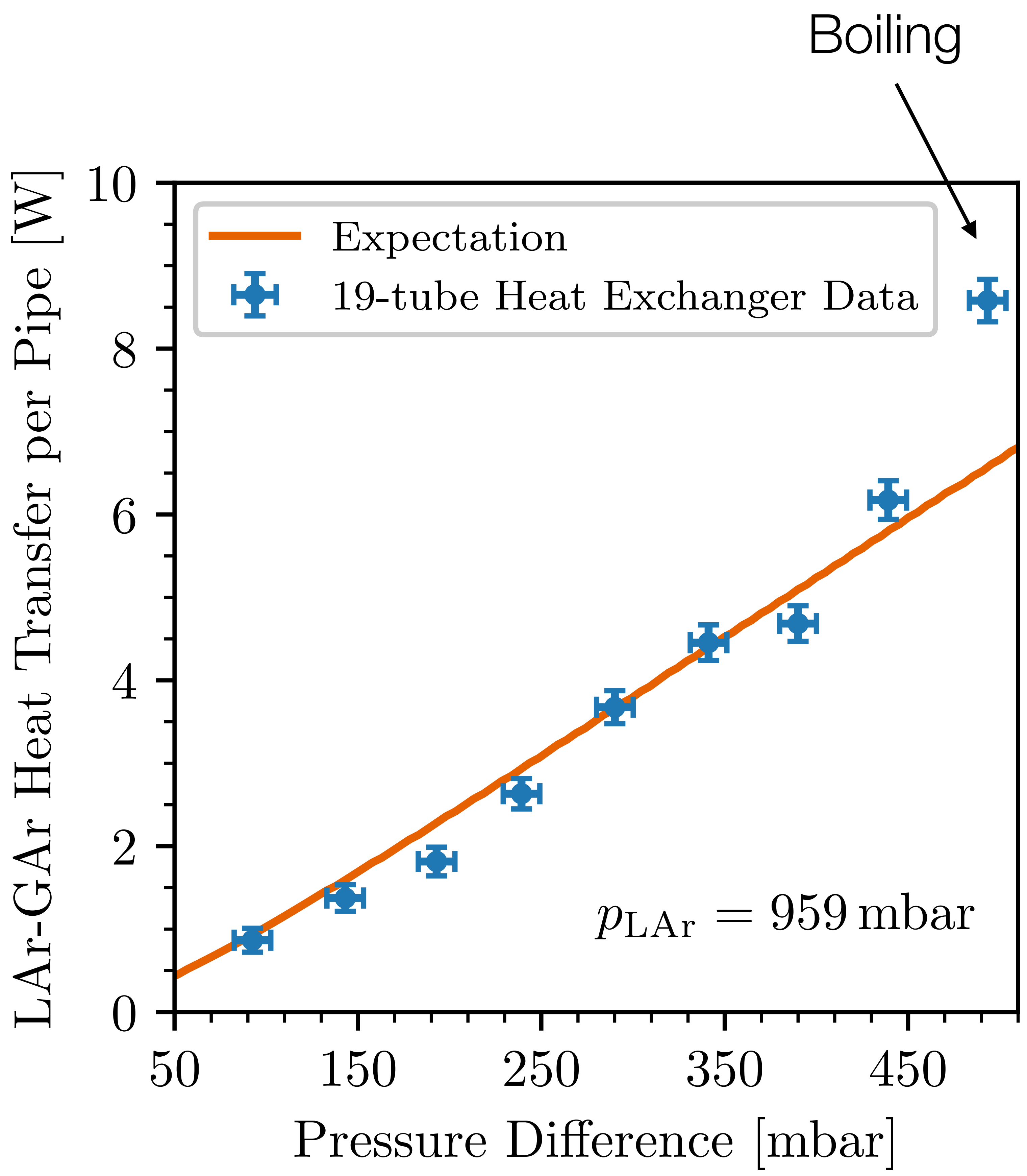
- Cooling-power based on cryostat pressure
- Controlled through adjusting GN2 outflow of condenser
- Two independent flow-control valves:
  - Pneumatically-actuated PID-controlled proportional valve
  - Passive bellow valve (requires no power)

PHASE CHANGE IN TUBE HEAT EXCHANGER

- Nitrogen-argon (condenser) & argon-argon (cryostat)
- Goal: obtain heat transfer for maximum cooling power estimation & heat exchanger dimensioning for DS-20k

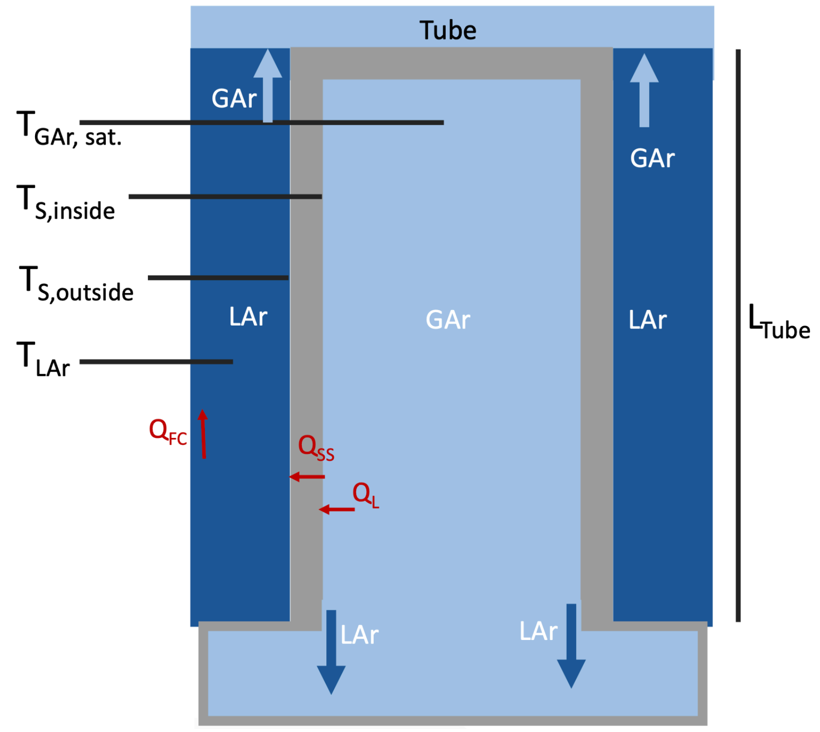
Measurement





Expectation

$$Q_{\mathrm{GAr-SS}} = Q_{\mathrm{SS}} = Q_{\mathrm{LAr-SS}}$$



Turbulent free convection outside:

$$h_{\text{LAr-SS}} = \frac{k_{\text{LAr}}}{L}\left(0.825 + \frac{0.387 Ra_{\text{LAr}}^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right)^2$$

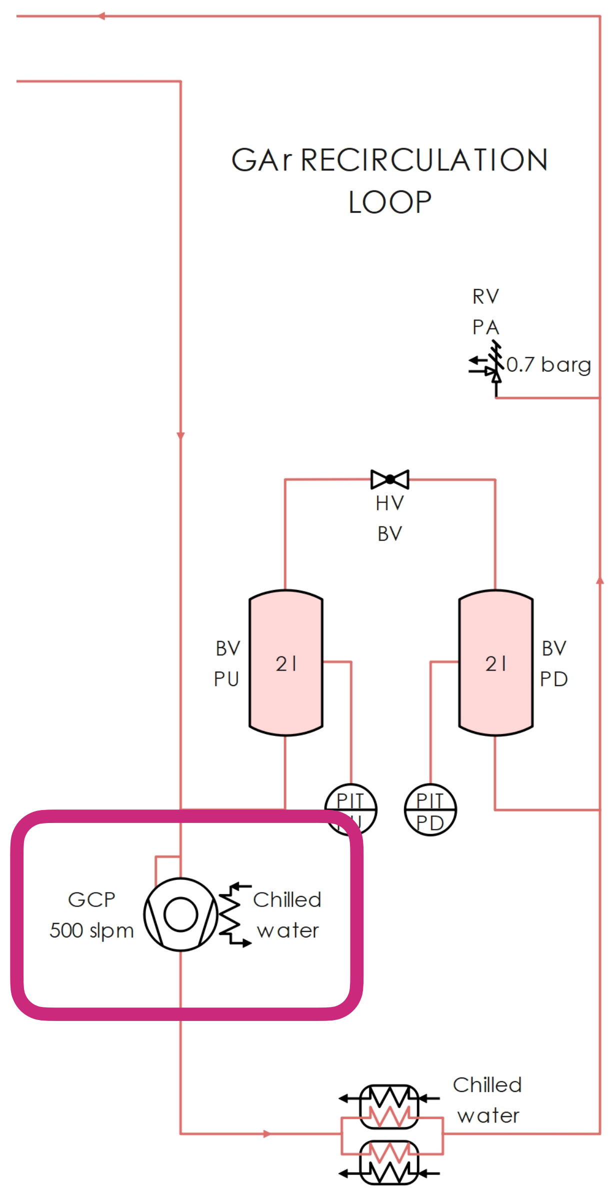
Conduction through tube: $h_{\text{SS}} = \dfrac{\lambda_{\text{SS}}}{d_{\text{Wall}}}$

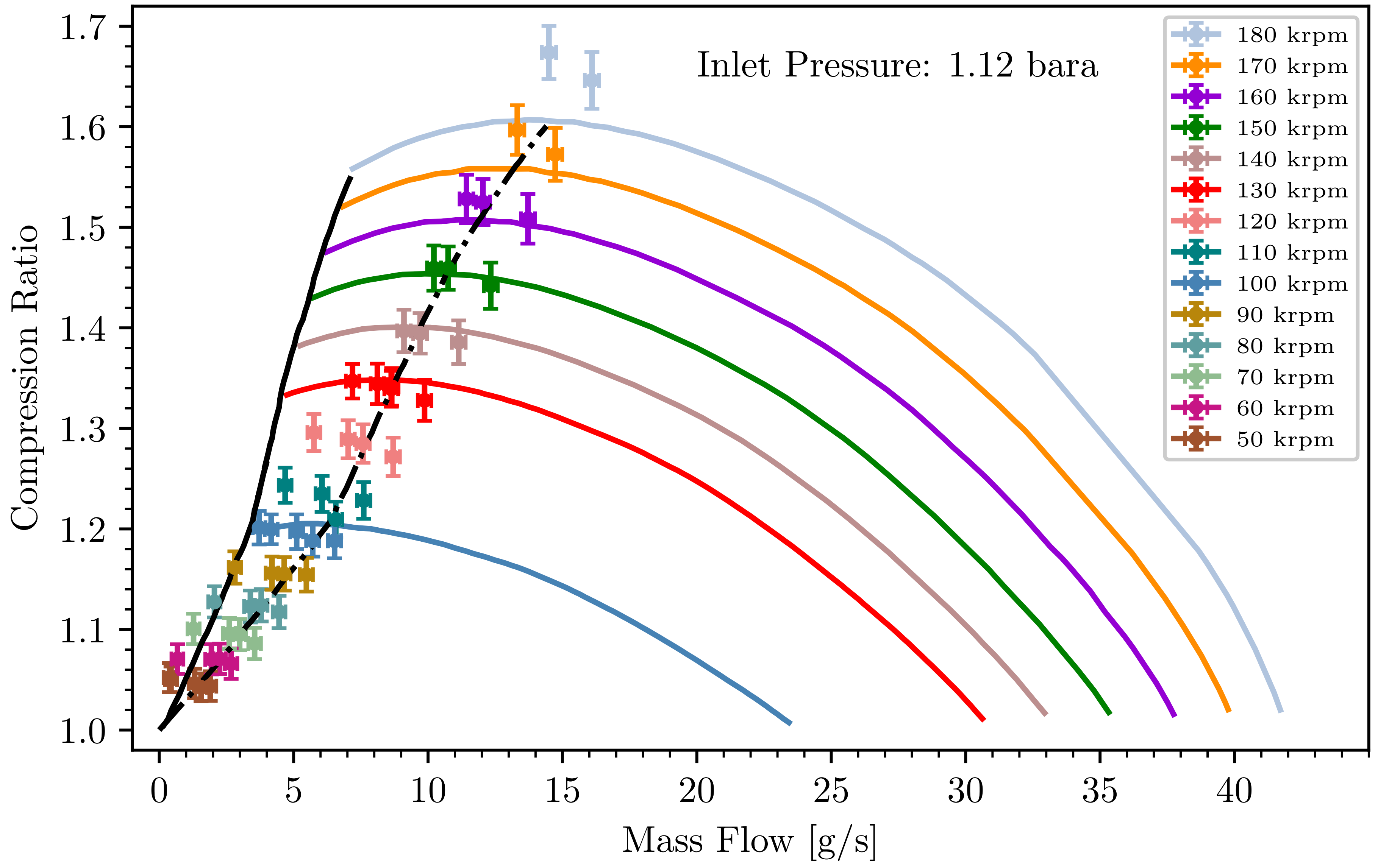
Thin film condensation inside:

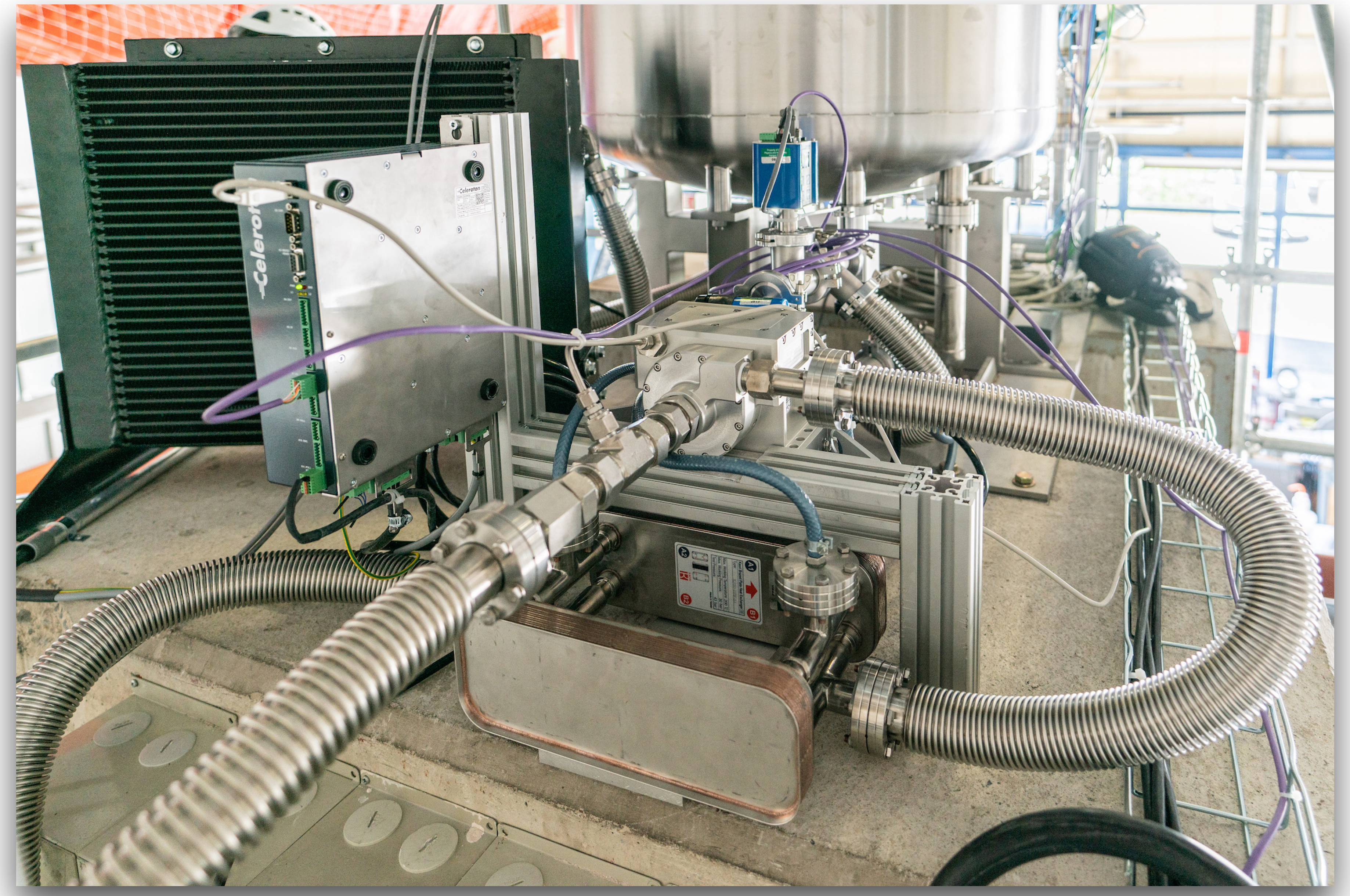
$$h_{\mathrm{GAr-SS}} = 0.943\left(\frac{g \cdot \rho_{\mathrm{LAr}}(\rho_{\mathrm{LAr}} - \rho_{\mathrm{GAr}})k_{\mathrm{LAr}}^3 \cdot \Delta H_{\text{vap}}^{\mathrm{Ar}}}{\mu_{\mathrm{LAr}} \cdot (T_{\mathrm{GAr,sat}} - T_{\mathrm{S,in}}) \cdot L}\right)^{1/4}$$

RECIRCULATION PUMP PERFORMANCE

- Celeroton pump (radial-turbo compressor with gas-bearing)
- Recorded performance curve (Differential pressure vs. flow)
  - Acquired data at 1.06 and 1.2 bara system pressure at 10–180 krpm speed with various impedances at 286.5 K
  - Compression ratio for fixed speed and configuration constant
  - Mass flow vs. inlet pressure linearly extrapolated
- Good agreement with manufacturer's specifications around maximum compression line, compressor surge occurs earlier at higher speeds







SYSTEM REQUIREMENTS

DS-20k science goals

> 10 years lifetime

High S2 yield and good resolution

Enable all operating modes

Power failure immunity

Redundancy, reliability and maintain-ability

40 days turnover

1000 slpm filling & circulation

High heat recovery efficiency

< 0.06 ppb oxygen-equivalent impurity level

≥ 8 kW cooling power

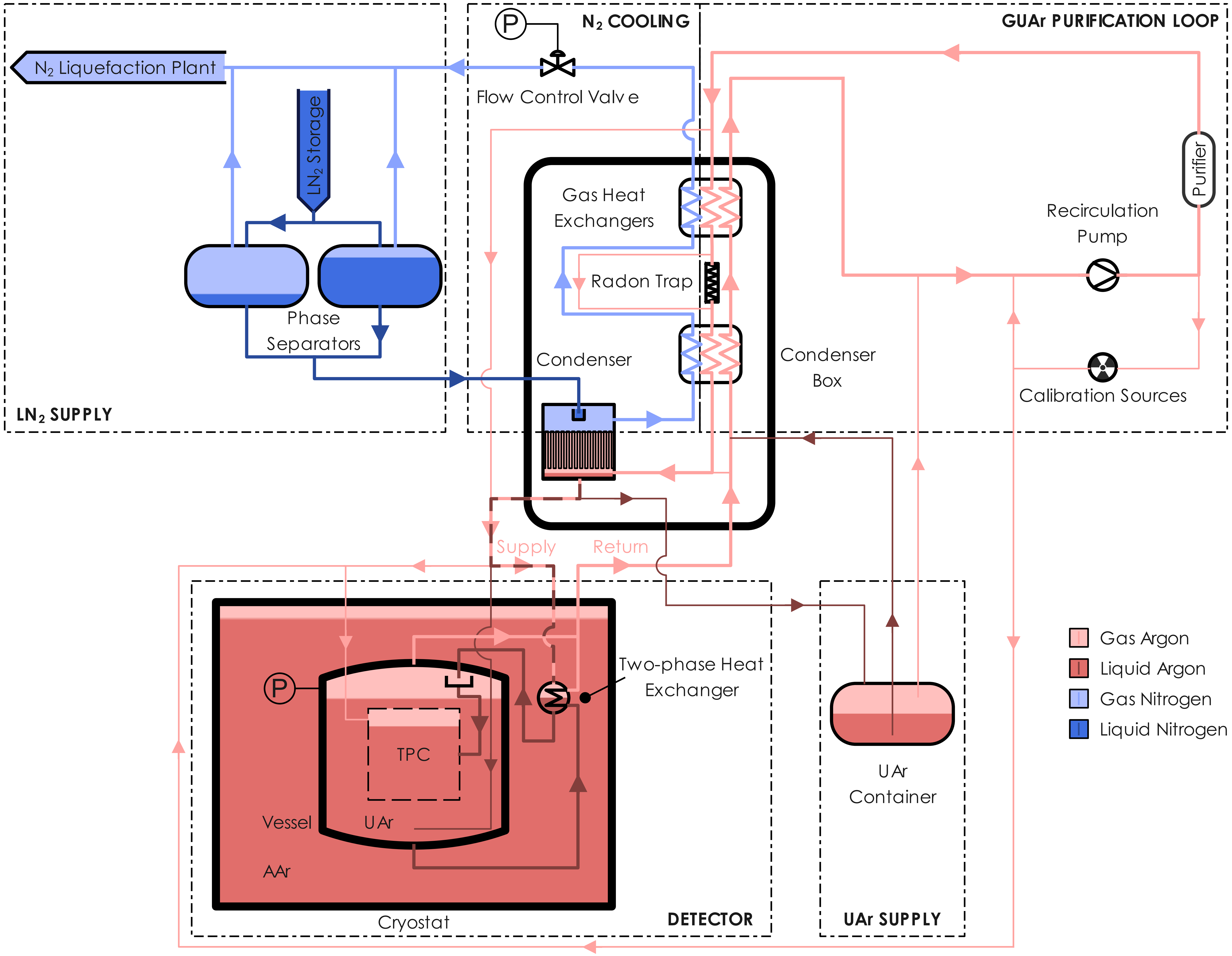
< 1e-8 mbar l / s He leak-tightness

1 mbar RMS vessel pressure stability

Underground Argon

Cryogenics System

CONCEPTUAL DESIGN



HEAT LOAD ONTO AAr

- Heat load from shell of upper HE and non-insulated pipes
- Heat transfer to AAr depends on size of the shell -> on the number of tubes -> on the allowed pressure differential
- But it depends even stronger on the pressure differential to the AA
- Plot is upper limit