# UAr Cryogenics Status

Forti Committee Meeting – Breakout Session

24 June 2024

Guillaume Plante, for the UAr Cryogenics WG

# UAr Cryogenics: Overall Progress

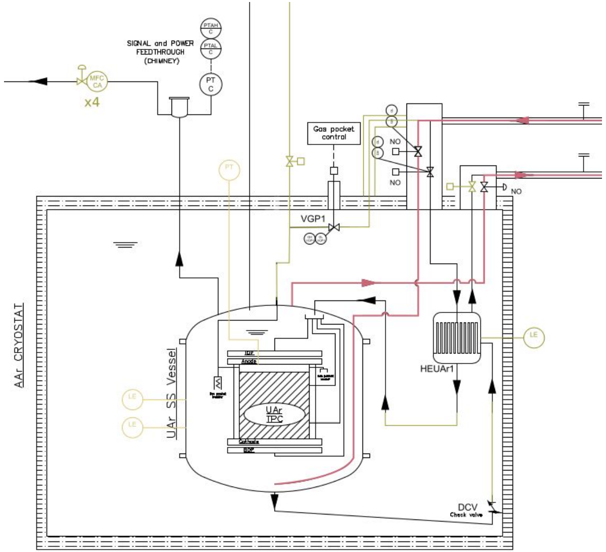
- Advances since the last review meeting
  - Continued progress in reviewing and finalizing the UAr cryogenics P&ID
  - Work on detailed analyses of the main operating modes (recovery)
    - A few modifications to the P&ID from the analysis of the recovery operation mode
    - Greater confidence in system achieving intended functionality, reduction of potential technical risks
  - Work on interplay between AAr and UAr systems during cool down, filling, and recovery
    - Developed a combined description of the main procedural steps, which system sets pace when, alarms, interlocks
    - Defined interfaces (exchanged process variables) and required functional logic based on this combined description
  - Theoretical calculations to validate existing components or guide the sizing / detailed design
    - Heat transfer in two-phase vertical tube banks heat exchangers
  - Mockup
    - Successful completion of cryogenics test runs (talk by Kevin Thieme)
  - Radon trap
    - Two test benches built: one to measure radon dynamic adsorption coefficient as a function of temperature and flow; one to measure the flow resistance properties of the candidate charcoal adsorbents
  - Slow control
    - Started describing the interfaces between the DS-20k Detector Control System, Detector Safety System and the UAr cryogenics basic control system
  - Procurement
    - Ready to place order for some long lead-time items: getter gas purifier, UHP valves

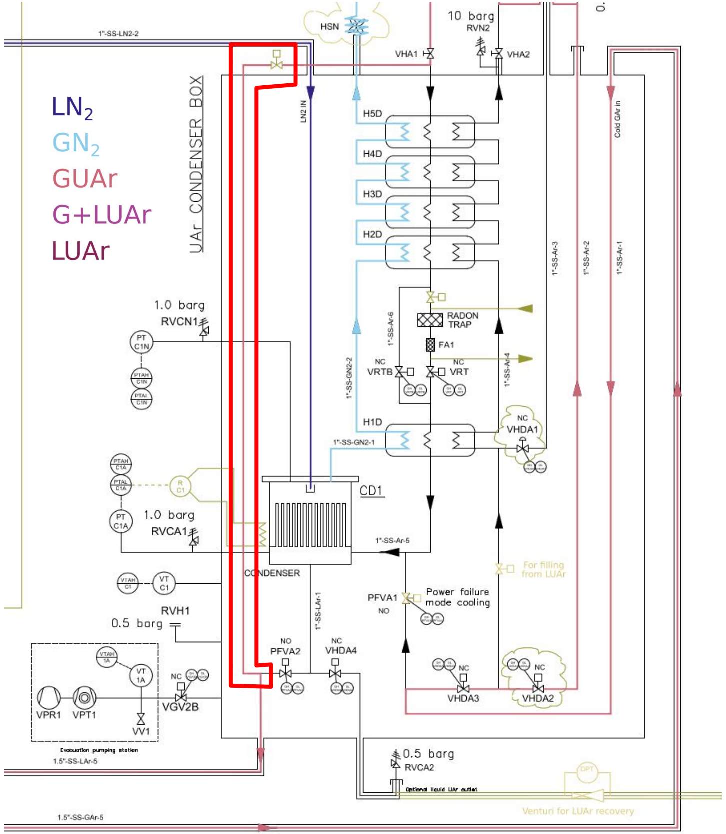
# UAr Cryogenics: P&ID Updates

- P&ID revision in the final stages of release
- Modifications in this revision
  - Update of tags according to ANSI/ISA S5.1 and ISO 14617-6 standards
  - Addition of a pressure control valve in parallel to VMFN2 with a flow coefficient sized for lower cooling power operation (e.g. photoelectronics off). Also, addition of a manual PCV for a last resort manual control.
  - Addition of an electrical heater on condenser to eliminate technical risk of cooling at zero N2 flow (and as an emergency defrost)
  - Added an on/off valve between the LUAr source flow control valve VHDA1 and the GUAr flow out of the UAr vessel
  - Added an on/off valve and line bypassing CD1 to provide heat to the UAr volume during recovery
  - Added level transmitters to the UAr vessel and to the HEUAr1 heat exchanger
  - Other minor piping modifications/simplifications
    - Addition of an on/off valve on the GUAr outlet of HEUAr1
    - Moved S2 gas pocket flow control valve VGP1 inlet to the GUAr volume of the line from CD1
    - Reverted PFVA1 to an on/off valve
    - Removal of gas pump QDC1 on the chimney GUAr outlets
    - Substitution of flow meter MFMCE with three mass flow controllers
    - Change LN2 supply valves VPLNS1/2 to proportional valves
    - Modifications to the calibration sources injection piping

# UAr Cryogenics: P&ID Updates

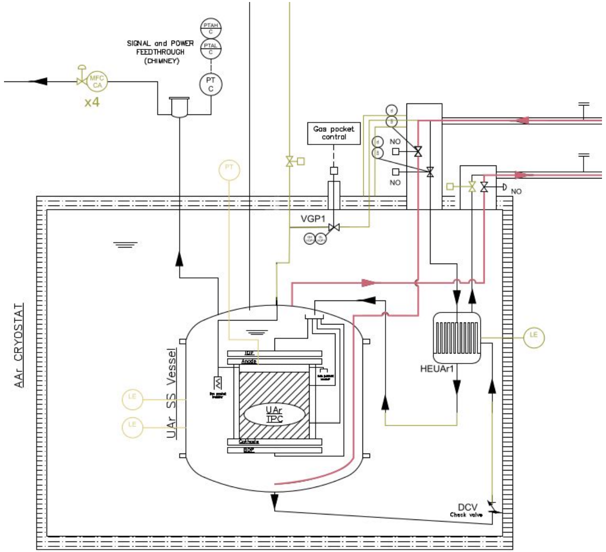
- Recovery mode, GUAr to storage
  - Previous revision had not been analyzed thoroughly yet
  - Bring heat to the LUAr volume of the UAr vessel by injecting warm GUAr through the “filling” tube at the bottom
- Changes
  - Added valve and line bypassing CD1

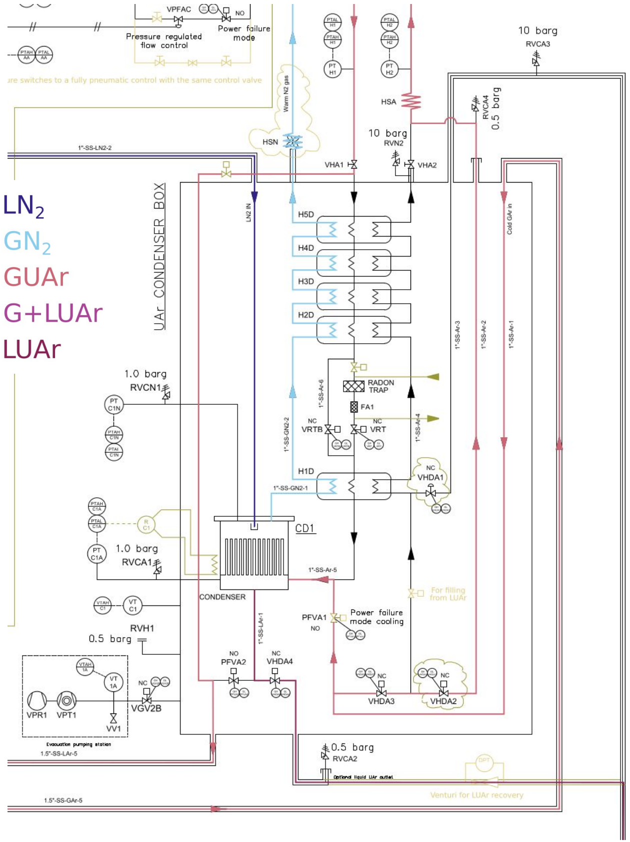


# UAr Cryogenics: P&ID Updates

- Recovery mode, LUAr to storage, start
  - New mode where the cooling power of CD1 is used to condense the GUAr extracted from the UAr vessel and route the LUAr to storage.
  - Bring heat to the LUAr volume of the UAr vessel by injecting warm GUAr through the “filling” tube at the bottom



# UAr Cryogenics: UAr / AAr Coordination During Filling

- At a high level, the overall filling operation can be thought of being composed of the phases:

| Phase | AAr | UAr | Notes |
|---|---|---|---|
| Preparation | GAAr Purge | 1. Evacuate<br>2. Fill GUAr<br>3. Recirculate GUAr | Delay purge operation |
| Cool Down | Cool Down | Slow GUAr cool down | UAr limits AAr cool down rate |
| Filling 1 | Fill LAAr until height H0 of SS vessel | Fill minimal LUAr quantity | LAAr availability sets pace |
| Filling 2 | Semi-synchronous LAAr/LUAr filling until height H1 of SS vessel | Semi-synchronous LAAr/LUAr filling until height H1 of SS vessel | Maintain differential height below limit |
| Filling 3 | Complete LAAr filling | Normal operation | |

# UAr Cryogenics: UAr / AAr Coordination During Filling

- Started defining list of alarms and interlocks that are always active and relevant to cryogenic operations

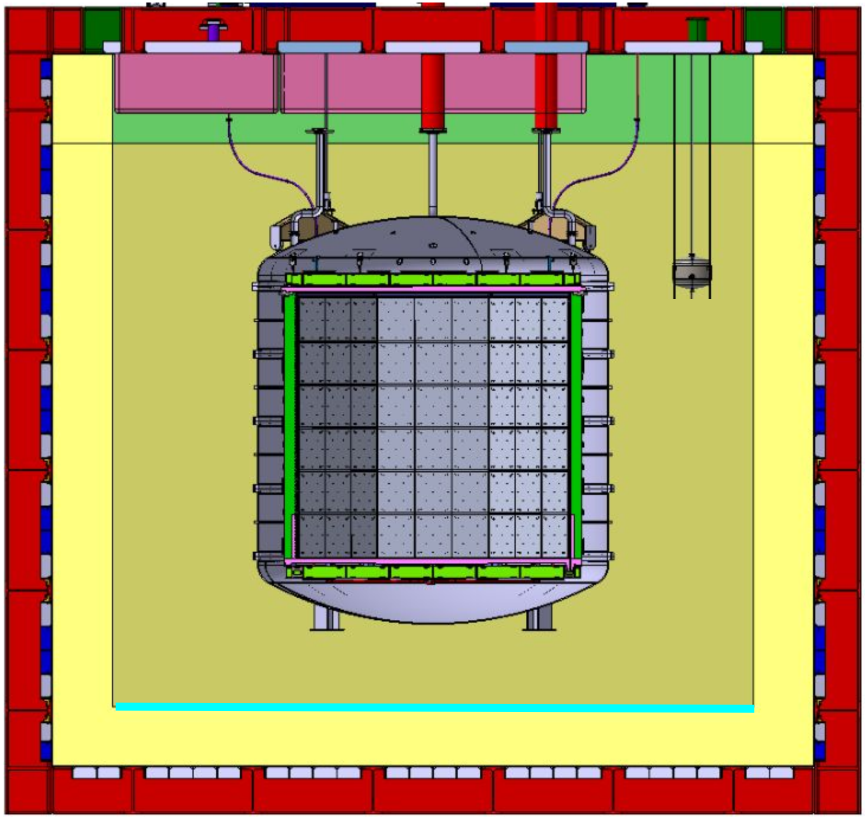
Table 2: Alarms and Interlocks Always Active

| Name | P&ID Tags | Description | Notes |
|---|---|---|---|
| UAR_PRESSURE_H | PTAA, PTAB | High alarm on the UAr SS vessel pressure, interlock that activates the UAr system no-power mechanical pressure control system | Warns the operator of a potential UAr vessel overpressure scenario |
| UAR_PRESSURE_HH | PTAA, PTAB | High high alarm on the UAr SS vessel pressure, interlock that stop heat flows into UAr SS vessel, e.g., stops gas circulation pumps | Warns the operator of a potential UAr vessel overpressure scenario, attempts to limit further pressure increases |
| UAR_PRESSURE_L | PTC1A | Low alarm on the UAr cryogenic system condenser pressure, interlock that activates the condenser heater system | Warns the operator of a potential UAr cryogenic system condenser overcooling scenario |
| UAR_RD1_H | PT1A | High alarm on the UAr SS vessel pressure relief safety vent pressure | Warns operator that pressure relief safety device RD1A is either malfunctioning or has burst |
| LN2_MASS_L | TBD | Low alarm on the $LN_2$ mass available in storage | Warns operator, e.g., that the $LN_2$ consumption has been in excess of re-liquefaction capacity |
| LN2_PRESSURE_L | TBD | Low alarm on the $LN_2$ storage supply pressure | Warns operator of, e.g., potential malfunction in the $LN_2$ supply system |
| UAR_VESSEL_LOAD_H | TBD | High alarm on the downward force on the UAr SS vessel support system | Warns operator of, e.g., a filled mass in the UAr SS vessel approaching its limit |
| UAR_VESSEL_LOAD_L | TBD | Low alarm on the downward force on the UAr SS vessel support system | Warns operator of, e.g., a buoyancy force on the UAr SS vessel approaching its limit |

# UAr Cryogenics: UAr / AAr Coordination During Filling

- Cool down
  - GUAr slow cool down
  - As fast as the most fragile component allows
  - Monitor T gradients
- Alarms

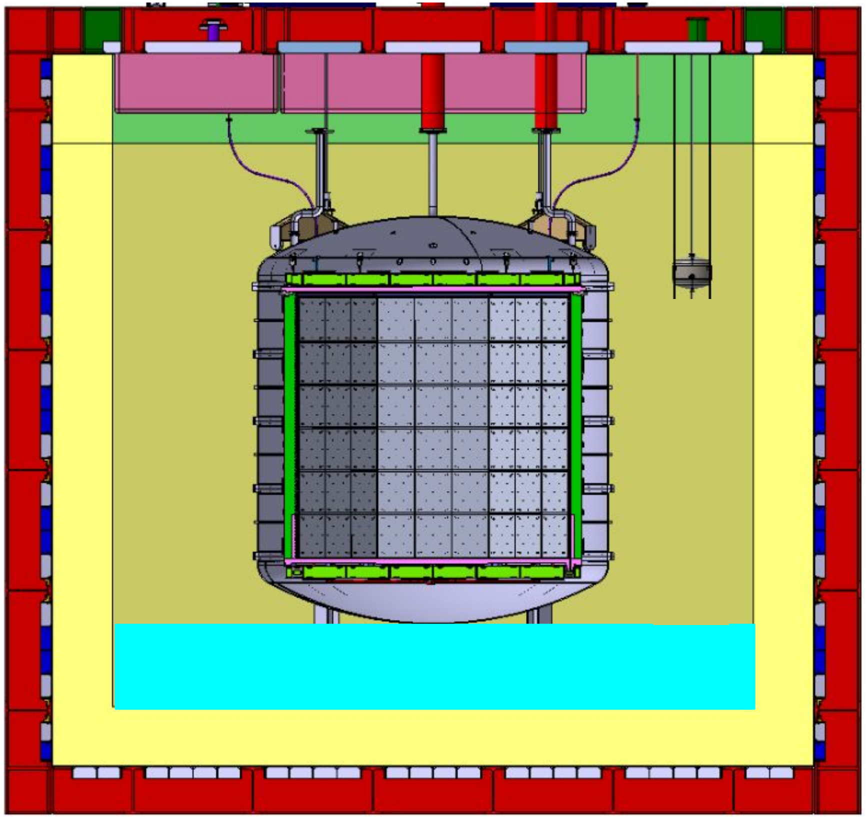
| Table 3: Alarms and Interlocks Active During the Cool Down Phase | | | |
|---|---|---|---|
| Name | P&ID Tags | Description | Notes |
| UAR_COOLING_RATE_H | TBD | High alarm on the cooling rate of the gaseous UAr inside the SS vessel | Warns operator if the cooling rate achieved is larger than desired |
| VESSEL_COOLING_RATE_H | TBD | High alarm on the UAr SS vessel cooling rate | Warns operator that the UAr SS vessel cooling rate is faster than desired, operator should reduce the AAr cryostat cool down |
| TPC_DTDX1_H | TBD | Generic high alarm on a spatial temperature gradient | Warns operator if a temperature gradient across a critical component or components is approaching the limit |
| TPC_DTDX1_HH | TBD | Generic high high alarm on a spatial temperature gradient, interlock that stops or reduces the cooling | Ensures that a temperature gradient across a critical component or components stops increasing |



# UAr Cryogenics: UAr / AAr Coordination During Filling

- Filling 1
  - Fill LAAr until height H0 of SS vessel
  - H0 such that we can fill a minimal amount of LUAr in the SS vessel
  - Pace set by the availability of LAAr trucks
- Alarms

| Table 4: Alarms and Interlocks Active During the Filling 1 Phase | | | |
|---|---|---|---|
| Name | P&ID Tags | Description | Notes |
| AAR_UAR_DELTAP_H | PTAA, PT4910 | High alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., of excess cooling power on the UAr volume or insufficient cooling power on the AAr volume |
| AAR_UAR_DELTAP_L | PTAA, PT4910 | Low alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator of the reverse situation as above |
| AAR_UAR_DELTAL_H | PDT4915, TBD | High alarm on liquid level difference between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., that the AAr filling speed is faster than desired |
| AAR_LEVEL_H0_H | PDT4915 | High alarm on AAr cryostat liquid level | Warns operator that the desired AAr liquid level ($H_{\text{vessel}} + H_0$) has been reached and that the Filling 1 phase has been completed |

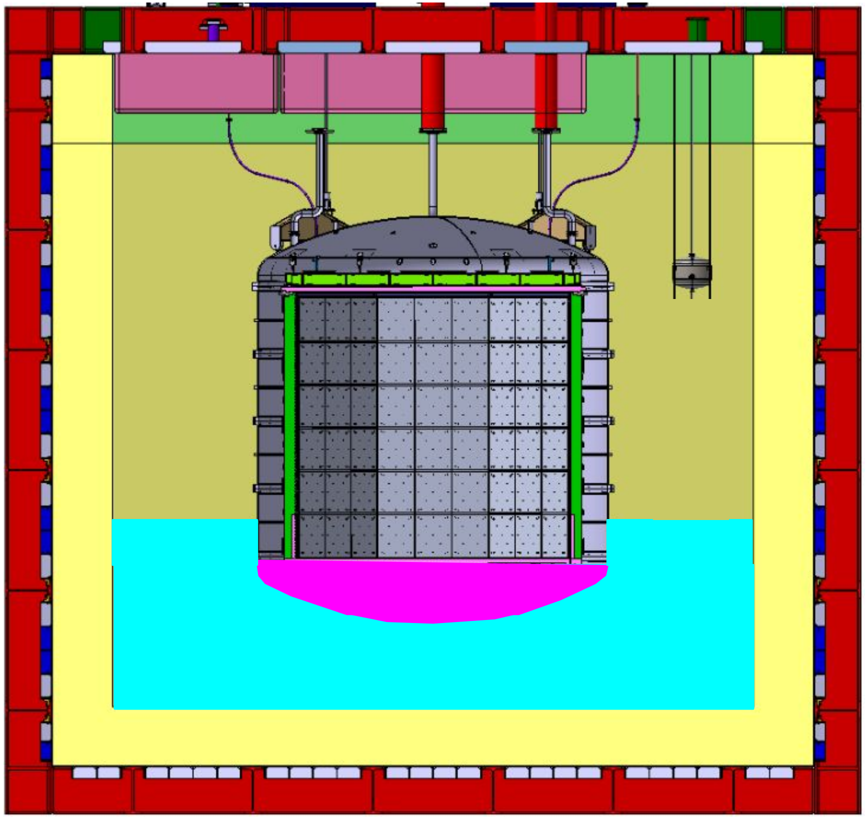


# UAr Cryogenics: UAr / AAr Coordination During Filling

- Filling 2
  - Semi-synchronous LAAr/LUAr filling until height H1 of SS vessel
  - Filling rate limited by UAr cryogenics
- Alarms

Table 5: Alarms and Interlocks Active During the Filling 2 Phase

| Name | P&ID Tags | Description | Notes |
|---|---|---|---|
| AAR_UAR_DELTAP_H | PTAA, PT4910 | High alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., of excess cooling power on the UAr volume or insufficient cooling power on the AAr volume |
| AAR_UAR_DELTAP_L | PTAA, PT4910 | Low alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator of the reverse situation as above |
| AAR_UAR_DELTAL_H | PDT4915, TBD | High alarm on liquid level difference between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., that the AAr (UAr) filling speed is faster (slower) than desired |
| AAR_UAR_DELTAL_L | PDT4915, TBD | Low alarm on liquid level difference between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., that the AAr (UAr) filling speed is slower (faster) than desired |
| LN2_DMDT_H | TBD | High alarm on the $LN_2$ consumption rate | Warns operator, e.g., that the current $LN_2$ consumption rate might not be sustainable for a long period, that the AAr and/or the UAr filling speeds should be reduced, etc |
| UAR_LEVEL_H1_H | TBD | High alarm on UAr SS vessel liquid level | Warns operator, e.g., that the desired UAr liquid level ($H_1$) has been reached and that the Filling 2 phase has been completed |

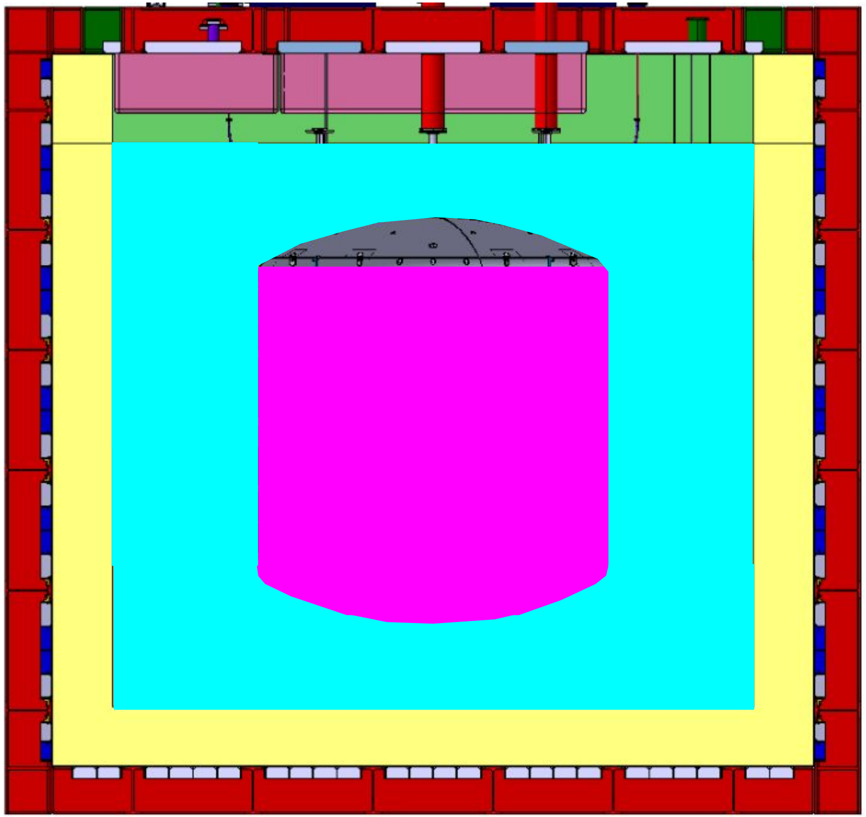


# UAr Cryogenics: UAr / AAr Coordination During Filling

- Filling 3
  - Complete LAAr filling
  - UAr cryogenic system can be put in normal operation mode
- Alarms

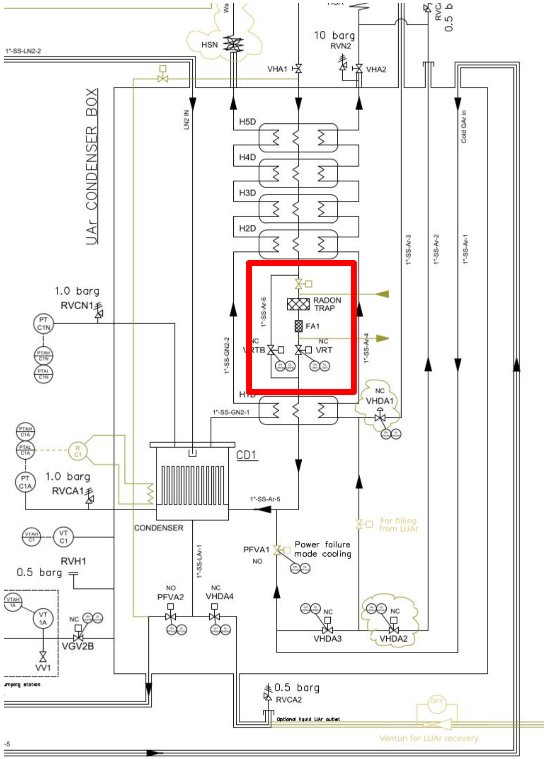
Table 6: Alarms and Interlocks Active During the Filling 3 Phase

| Name | P&ID Tags | Description | Notes |
|---|---|---|---|
| AAR_UAR_DELTAP_H | PTAA, PT4910 | High alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator, e.g., of excess cooling power on the UAr volume or insufficient cooling power on the AAr volume |
| AAR_UAR_DELTAP_L | PTAA, PT4910 | Low alarm on differential pressure between the AAr cryostat and the UAr SS vessel | Warns operator of the reverse situation as above |
| AAR_LEVEL_H2_H | PT4910 | High alarm on AAr cryostat liquid level | Warns operator, e.g., that the desired AAr liquid level ($H_2$) has been reached and that the Filling 3 phase has been completed |

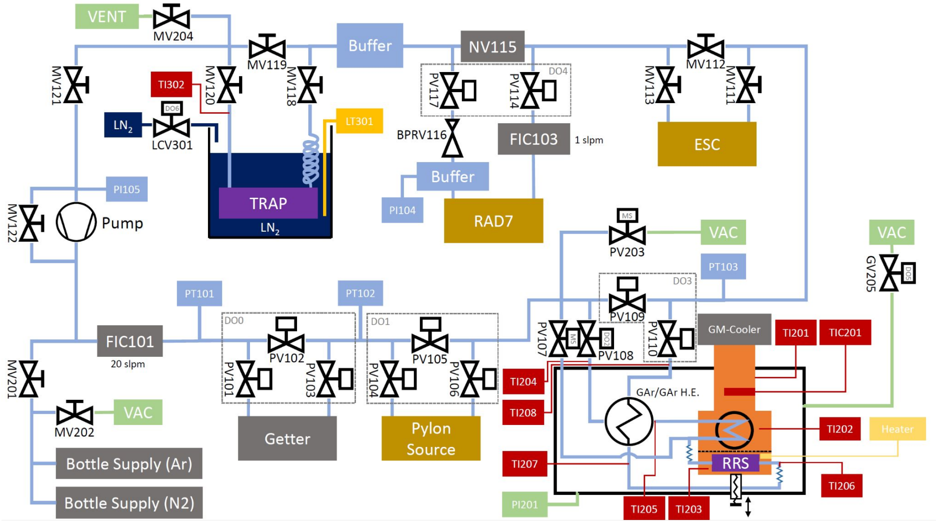


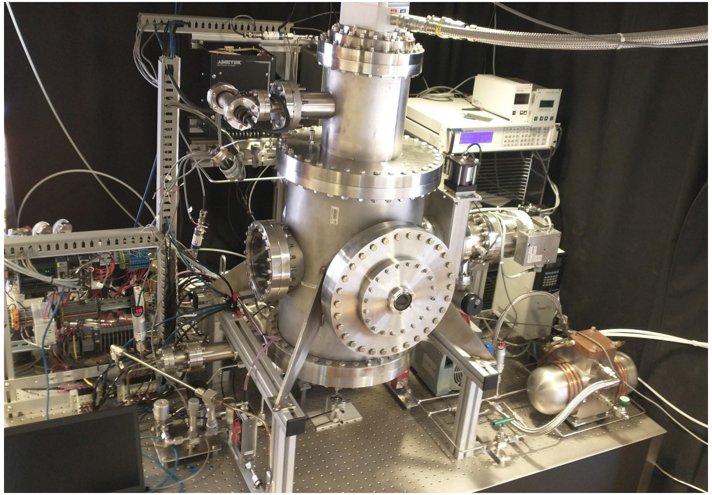
# UAr Cryogenics: Radon Trap

- Planned to be in the UAr purification loop return path the TPC
  - Installed between GUAr/GUAr heat exchangers H2D and H1D
  - Temperature of operation ≈100 K
  - Particulate filter installed downstream
- We want a predictable performance both in terms of radon removal and flow resistance.
- Activated charcoal suitability/QA tests
  - Specific activity of an adsorbent mBq/kg (relying on other collaboration facilities).
  - Radon dynamic adsorption coefficient and its temperature dependence.
  - Flow resistance tests to construct an adequate model of the pressure drop versus flow for a given radon trap geometry.
- Built two test benches:
  - Radon trap test bench to measure the radon dynamic adsorption coefficient as a function of temperature and flow
  - Flow resistance test bench to measure the pressure drop across various cylindrical trap geometries with different adsorbents

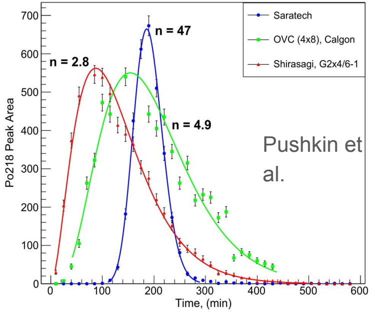


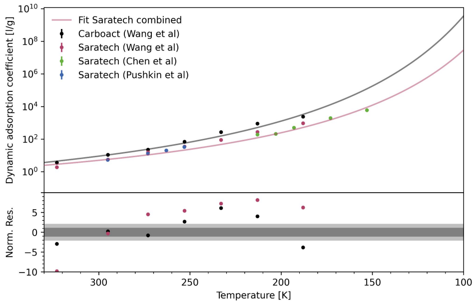
# UAr Cryo Updates: Radon Trap



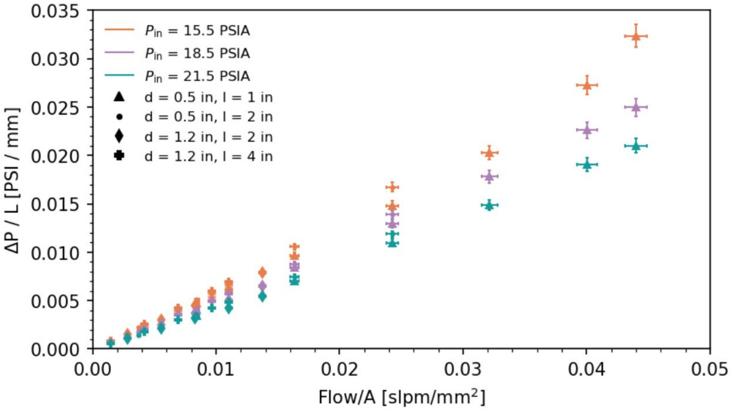
- Strategy:
  - Measure charcoal radon dynamic adsorption coefficient with Ar carrier gas at different T
  - Design a trap with a (statistically) known radon removal performance and as low as reasonably achievable pressure drop



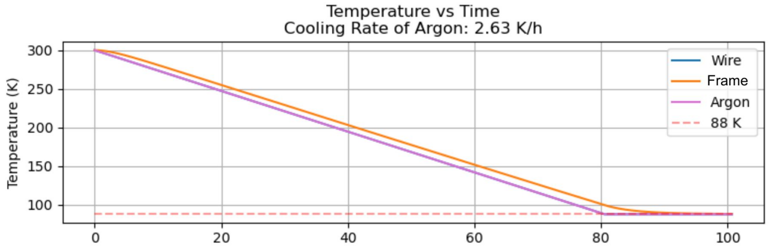
# UAr Cryogenics: Radon Trap

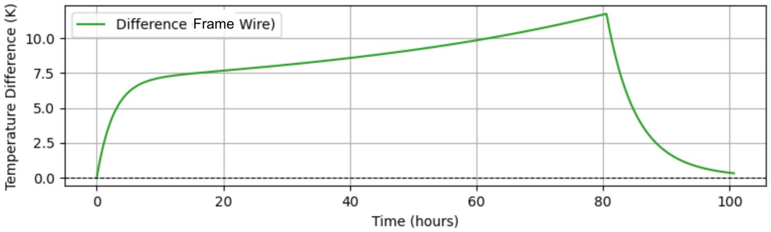
- Procurement
  - Charcoal adsorbents sample from CarboAct for QA testing in hand
  - Charcoal adsorbents from Talamon GmbH for QA testing in hand
    - More than enough for tests and for the production trap
- Flow resistance test bench
  - Completed tests for the Talamon (ϕ = 0.4 mm) adsorbent.
  - Parameters extracted allow us to reliably predict the maximum pressure drop of a given radon trap geometry.
- DS-20k trap design
  - Algorithm elaborated for sizing and detailed design.
    - Takes as input key DS-20k specifications, results of QA tests; prescribes a trap geometry that fulfills the radon reduction while satisfying pressure drop requirement.
- Status
  - Talamon (ϕ = 0.4 mm) adsorbent sample shipped for radon emanation measurement
  - Start measuring dynamic radon adsorption coefficients this summer
  - Finalize trap design and start fabrication Q4-24



# UAr Cryogenics: Cool Down Estimates

- Work on estimating temperature gradients in different cooling scenarios
  - Work in a simplified geometry, assumptions on boundary conditions (insulated, HTC, etc)
  - Use HTC correlations appropriate for the problem
  - Calculate temperature gradients as a function of the GUAr cooling rate
- Goal: have the means to determine a cooling rate that satisfies ΔT constraints (with safety margin)
- Examples:
  - Mockup: ΔT between grid wire and frame
    - Natural convection HTC for cylinder in gas at fixed temperature
    - Linearly decreasing GUAr volume temperature
  - Mockup: ΔT within PMMA panels
    - Natural convection HTC for vertical slab in gas at fixed temperature



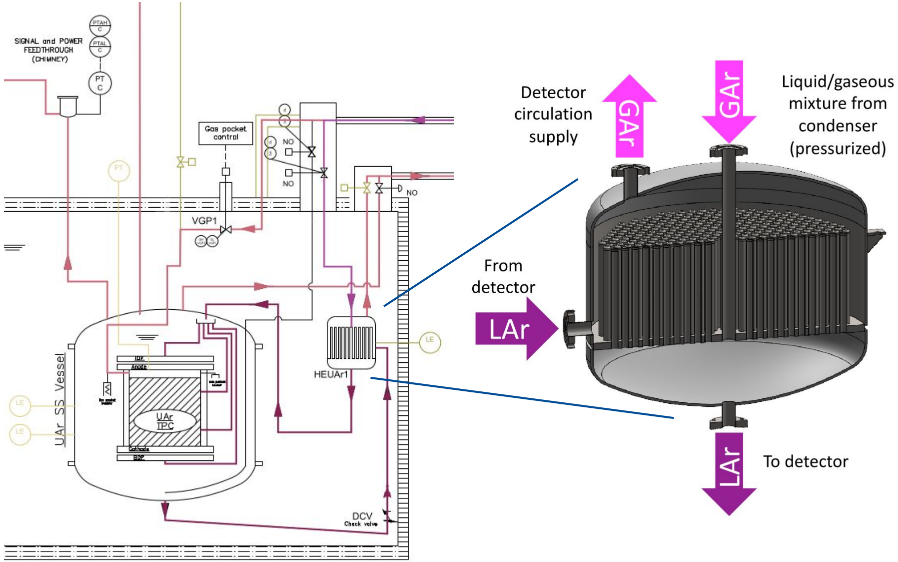

**Wire**: L = 0.68 m and d = 0.15 mm. **Frame**: L = 2.63 m and d = 13 mm

$$\frac{dT}{dt} = -h(T,t) \times A \times \frac{T - T_{\mathrm{Ar}}(t)}{m \times c}$$

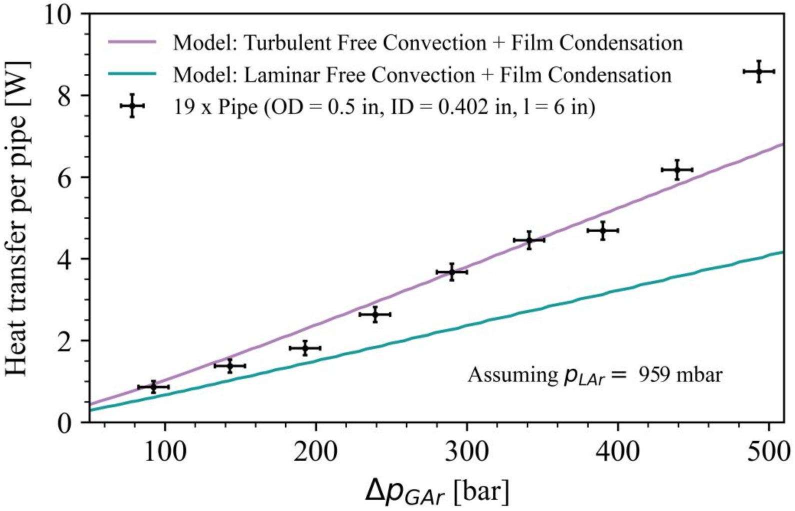
$$h(T,t) = \left(\frac{k_{\mathrm{Ar}}(t)}{d}\right) \times \left(0.6 + \frac{0.387 \times (\mathrm{Ra}(T,t))^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{(\mathrm{Pr}(t))^{\frac{9}{16}}}\right)^{\frac{8}{27}}\right)^{2}}\right)$$

# UAr Cryogenics: Two-Phase HE Modeling/Design

- Progress on modelling the heat transfer inside the two-phase HE of the proposed design
- Very good agreement with data if we assume:
  - HTC correlation for film condensation on a vertical wall
  - HTC correlation for turbulent free convection in the liquid

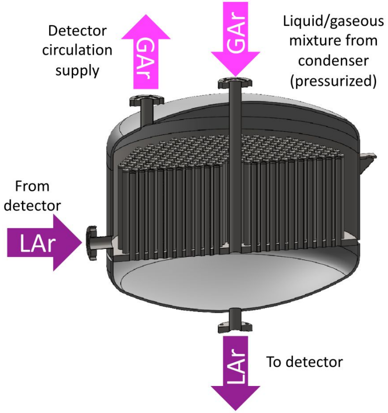



Compare Model to Data from 19 pipe measurements at CERN

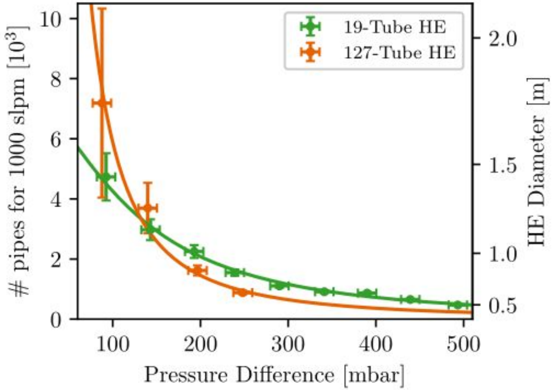


# UAr Cryogenics: Two-Phase HE Modeling/Design

- Conditions that have to be fulfilled for the purification loop to function established
- In a good position to dimension and position HE appropriately, choose reliable safety margins




Mockup Cryo Tests

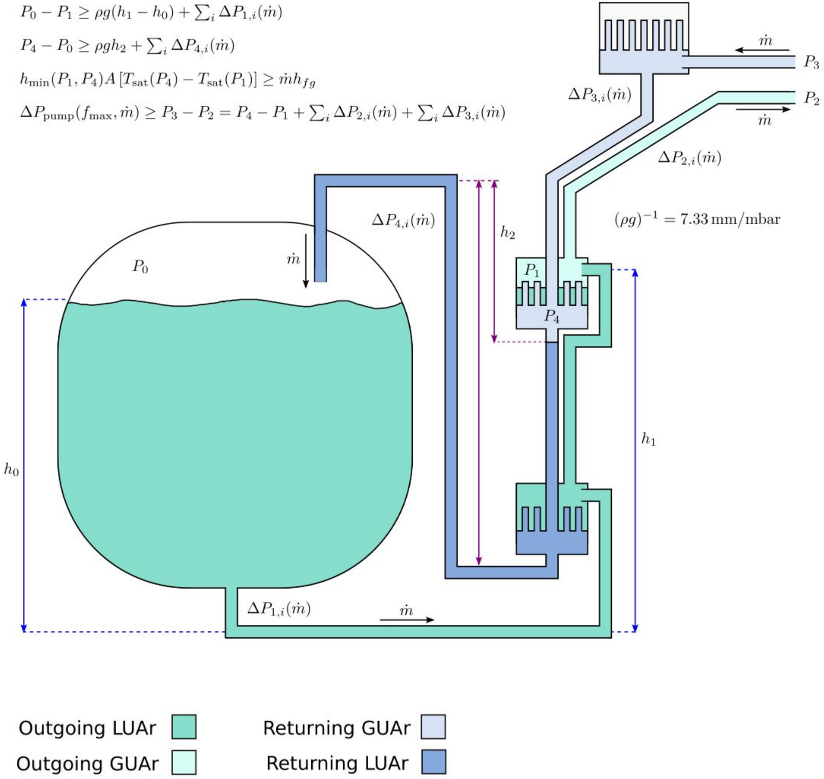



$$P_0 - P_1 \geq \rho g(h_1 - h_0) + \sum_i \Delta P_{1,i}(\dot{m})$$

$$P_4 - P_0 \geq \rho g h_2 + \sum_i \Delta P_{4,i}(\dot{m})$$

$$h_{\min}(P_1, P_4) A \left[T_{\text{sat}}(P_4) - T_{\text{sat}}(P_1)\right] \geq \dot{m} h_{fg}$$

$$\Delta P_{\text{pump}}(f_{\max}, \dot{m}) \geq P_3 - P_2 = P_4 - P_1 + \sum_i \Delta P_{2,i}(\dot{m}) + \sum_i \Delta P_{3,i}(\dot{m})$$



# UAr Cryogenics: Upcoming Activities

- Basic design
  - Complete a final cycle of analyses of system operational modes
  - Expect only minor P&ID modifications at this stage (e.g. additional sensors, etc).
- Detailed design
  - UAr continuous purification loop, two-phase heat exchangers, cryostat top valve box, etc
  - UAr condenser box modifications (radon trap, and anything else, as informed by mockup cryo tests)
  - Review of functional logic description for the basic control system
- Procurement
  - Place orders on long lead items (gas purifier, high-flow valves, etc)
  - Followed up by fabrication materials for UAr continuous purification loop
  - RFQs for gas circulation pumps
  - RFQs for fabrication of other main system components (two-phase HEs, LN2 supply, etc)
- Schedule
  - On track for delivery of UAr cryogenics major components to LNGS without affecting the critical path

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