GRAAL meeting: MINERVA RF/Cryo modelling

ACCELERATORS and CRYOGENIC SYSTEMS
Parc Orsay Université – 21 rue Jean Rostand
91893 Orsay Cedex

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
IJCLab - UMR9012 - Bât. 100 - 15 rue Georges Clémenceau
91405 Orsay cedex

C. LHOMME

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Outline

- The MYRRHA Project
- The cryogenic simulation tool
- Component model creation: illustration
- Validation of the model
- Conclusion

The MYRRHA Project

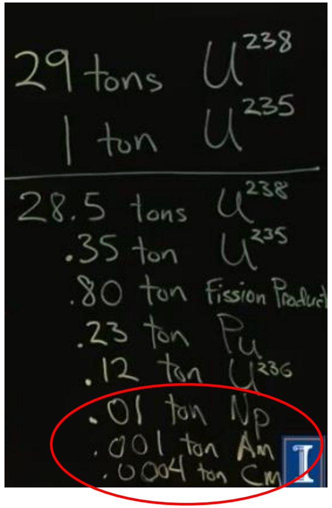
The MYRRHA project

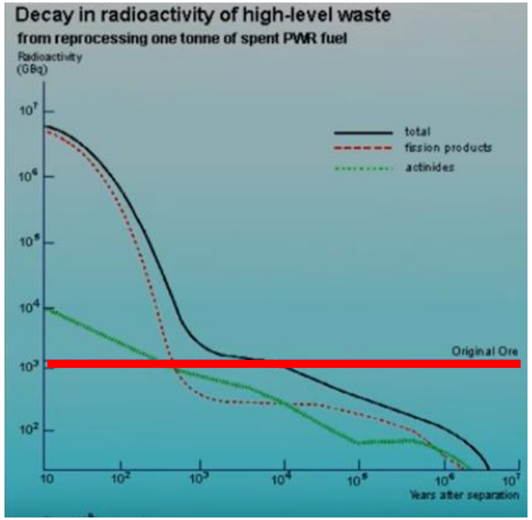
- Transmutation = one way to stabilize the minor actinide (MA) stocks in a multiple-recycling strategy

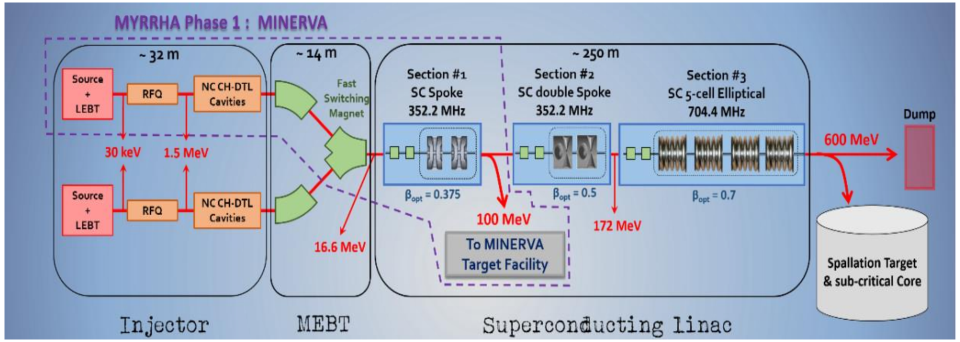
- It is carried out in a fast neutron nuclear reactor, which criticality is driven by external neutrons from an accelerator (ADS)
    - Neutron production by spallation
    - Need for a 600 MeV CW proton beam at 4 mA

- Need for extreme reliability
    - Avoid **long restart procedures** & **stress on the fuel assembly** → no trip longer than 3s
    - No research machine has ever reached this required reliability
    - Parallel and series (“fault tolerance”) redundancy needed

- Timeline
    - In 2018, Belgium committed to build the MYRRHA phase 1 = MINERVA
    - MINERVA = 100 MeV 4mA proton beam, **1st beam in 2027**
    - MINERVA will also supply proton (PTF) and fusion (FTS) targets
        - Overall architecture frozen, main internal floor plan decisions taken
        - PTF design close to level of ACC, FPF catching up
    - **MINERVA must demonstrate the MYRRHA reliability**







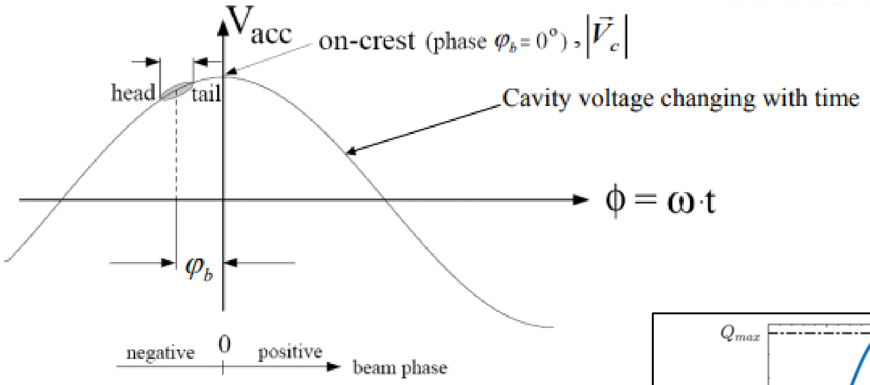
- The LLRF must satisfy ensure stable **amplitude** and **phase** of the electric field → strong requirements from the beam dynamics

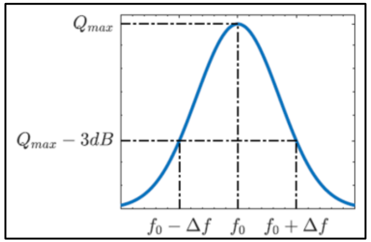
- The LLRF must cope with:
  - A narrow cavity bandpass (≈235 Hz)
  - A **large** yet **limited** amplifier margin + minimize the electrical consumption !
  - → Sets strong requirement on the CTS

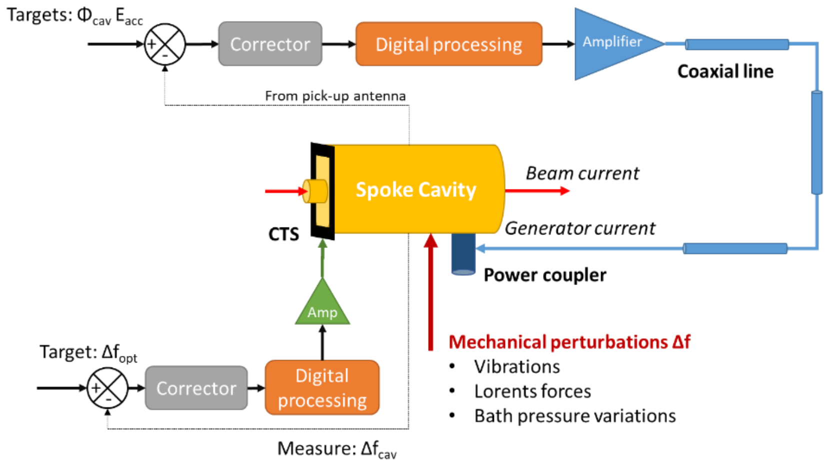
- The CTS (motor and piezo) must cope with:
  - Excitations from vibrations & cryogenic microphonics (limited at 2K - yet existing)
  - Fast tuning-detuning procedures & dynamic Lorenz forces
  - Excitations from cryogenic pressure oscillations → sets requirement on cryogenic feedback loops (level and pressure)

- The cryogenic feedback loops must cope with:
  - High dynamic heat loads = 75% of CM total loads at 2K (**10.6 W)**
  - "Fault tolerance" scenario → changing operating points in < 3s
  - **Many RF operating points: commissioning, nominal, Fault-Tolerance …**
  - **Component discrepancies and drifts**
  - → Cryogenics take hours to recover from failure

Strong coupling of the LLRF, CTS and cryo feedback loops!







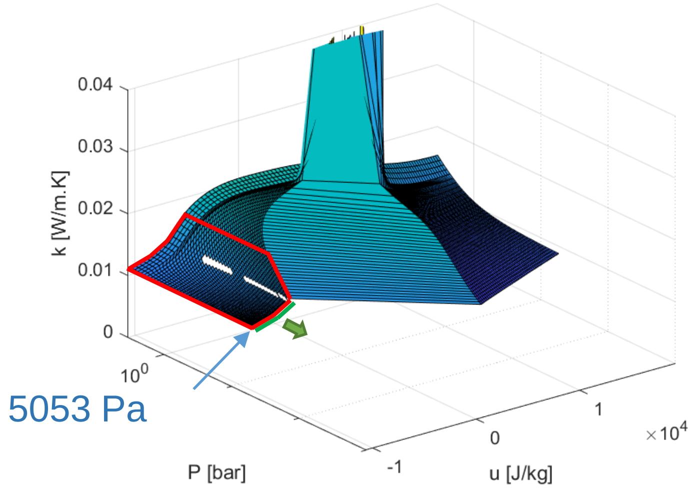
The cryogenic simulation tool

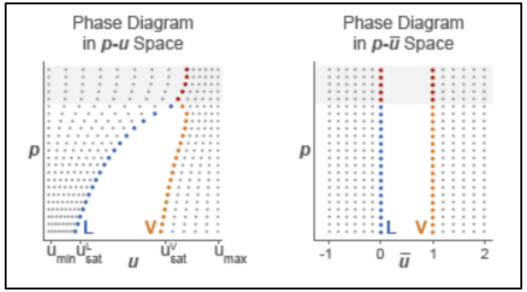
The Simscape environment

- Need for a “dynamic” and multiphysic simulation tool
  - Solving differential and algebraic equations
  - With a carefully chosen level of details (0D, 1D)
  - Target = both **transients** and **steady-states**
- **Step 0**: taking over the existing Simscape multi-physic environment
  - One block = one set of equations
  - Existing thermal and fluid domains
  - **Sufficient for a proof-of-concept but very limited**
- **Step 1** = create databases of Material and Fluid properties 1 – 300 K
  - Read as a function of pressure ***P*** and internal energy ***u***

Need for relevant physics

- Heat loads from conduction & radiation
- Transients: fluids (volumes) and thermal (masses)





Building block creation

- **Step 2**: creating physical building blocks for cryogenic & RF calculations
  - Block list
    - Valves, phase separators, ducts
    - T-dependant thermal mass & conductance
    - Specific RF compounds
  - Identifying the equations to solve
    - Assumptions and simplifications
    - Mass, energy and momentum conservation
  - Implementing the equations in physical building blocks
- **Instantiating a library named *Cryoscape***

Energy conservation

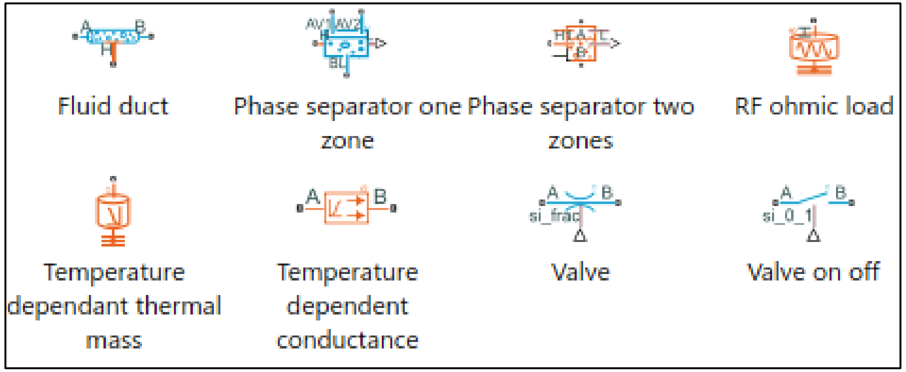
$$M_L \frac{du_L}{dt} + \frac{dM_L}{dt} u_L = \phi_{L,In} - \phi_{L,Out} + \phi_{Con} - \phi_{Vap} + Q_L$$

$$M_V \frac{du_V}{dt} + \frac{dM_V}{dt} u_V = \phi_{V,In} - \phi_{V,Out} - \phi_{Con} + \phi_{Vap} + Q_V$$

Mass conservation

$$\frac{dM_L}{dt} = \dot{m}_{L,In} - \dot{m}_{L,Out} + \dot{m}_{Con} - \dot{m}_{Vap}$$

$$\frac{dM_V}{dt} = \dot{m}_{V,In} - \dot{m}_{V,Out} - \dot{m}_{Con} + \dot{m}_{Vap}$$



Component modelling

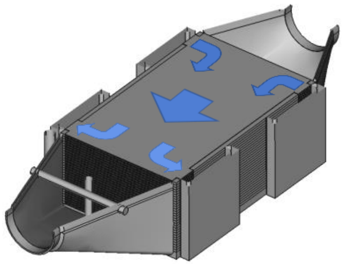
- **Step 3**: assembling the blocks into components
  - Mixing both RF and cryogenic processes
  - Power couplers, cavities, valves, tanks …

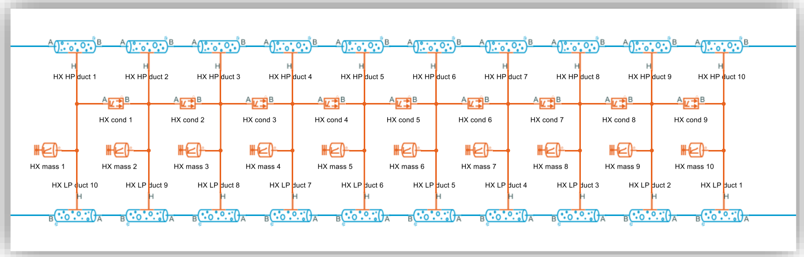
- **Step 4**: parametrizing on the MINERVA VB and CM
  - Taking over the component geometrical and functional data (1D, 3D sim, tests …)
  - **Performing individual component tests**

→ *<u>Challenge 1</u> = knowing what has **really been manufactured***

→ *<u>Challenge 2</u> = **parametrize ≈500 blocks** with **no errors** & and **minimal efforts***

NB: for update from prototype toward series, just need to re-run Step 4 !



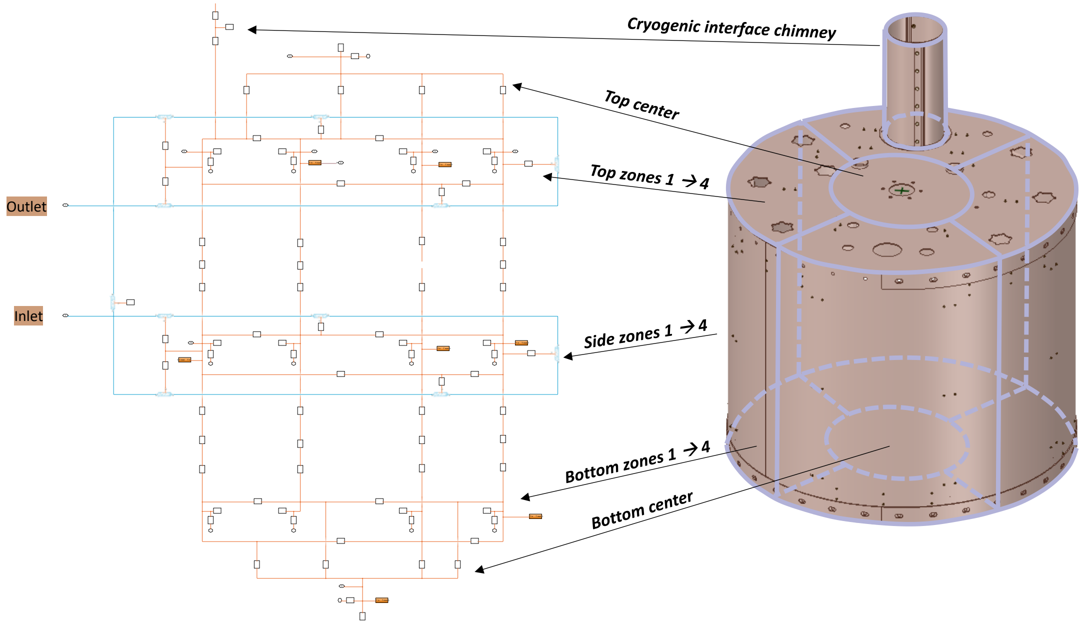


Component model creation: illustration

Illustration on the VB nitrogen thermal screen

- Methodology: discretization in 15 elements
  - Thermal conduction between them
  - Radiation from the vacuum vessel
  - Convection with nitrogen

→ **Keeping on improving the methodology for easier prediction capability**



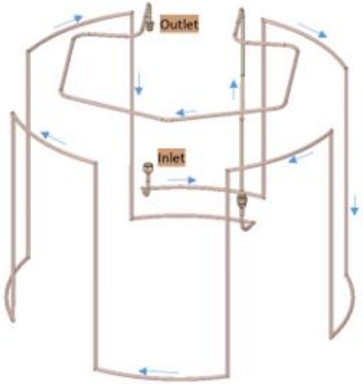
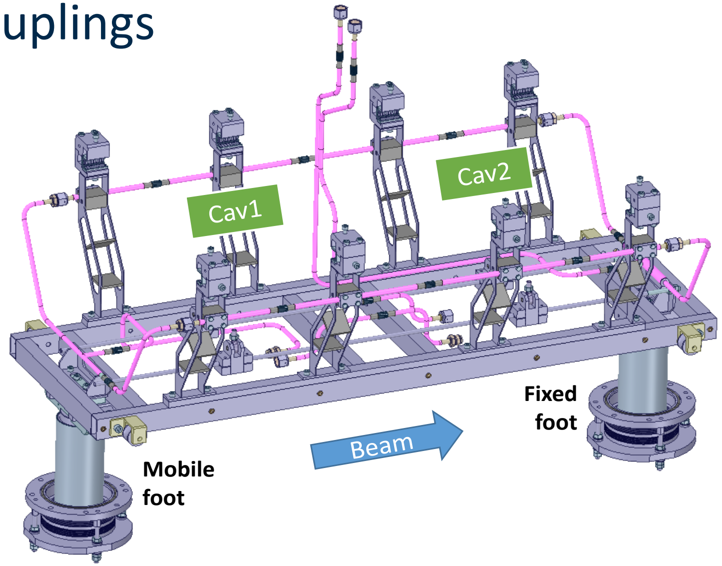


Illustration of component level: « table and arms »

- Stick to ≈ 100 blocks per component
- 1D or 2D
- Focus on order 1 effects
- Thermofluidic couplings



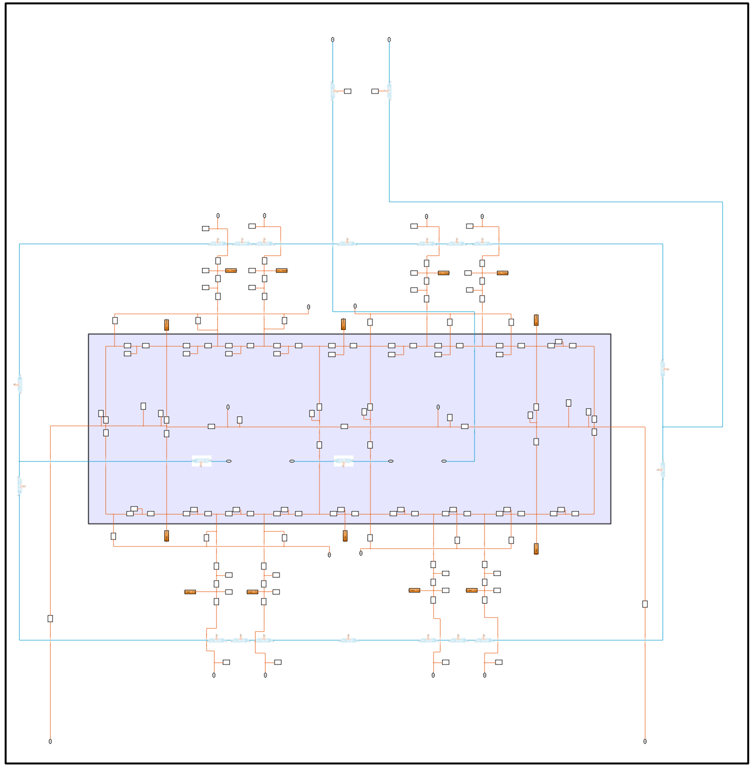
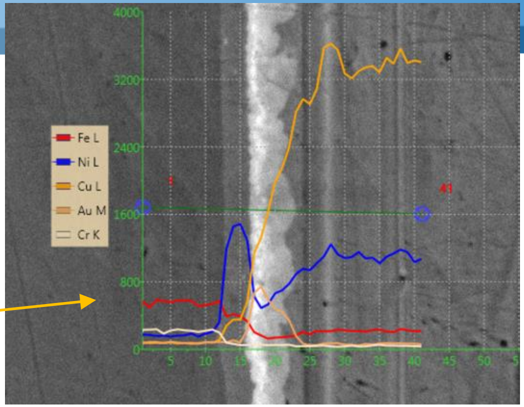
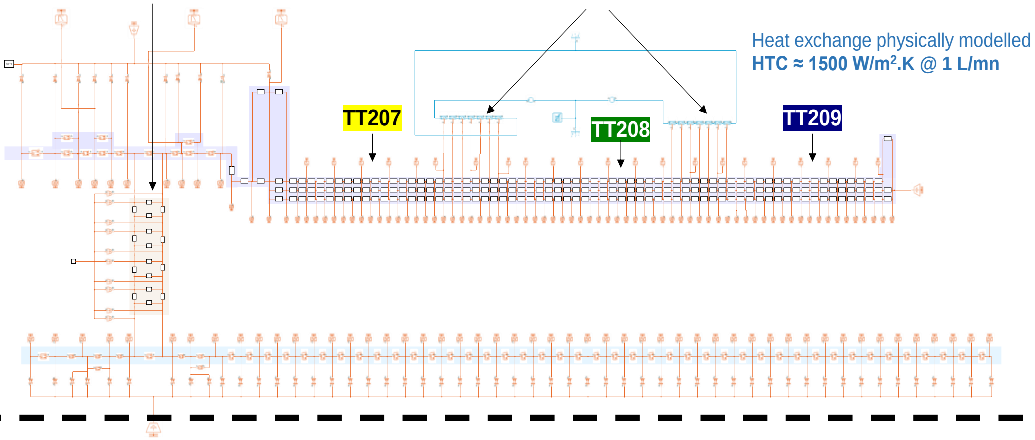


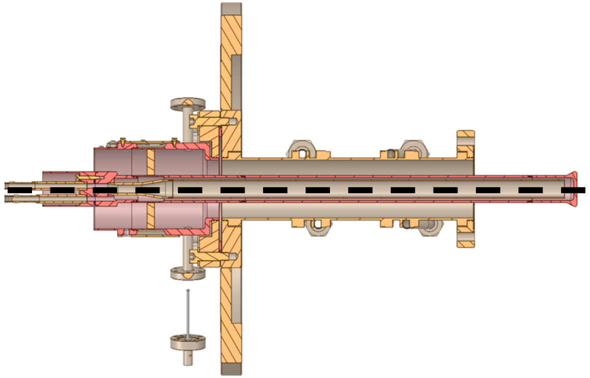
Illustration on the coupler

- 1D axisymetric model full multiphysics
  - Static heat loads from:
    - Representative conductances, masses
    - AND thicknesses !
    - T-dependant material thermal properties
  - Dynamic heat loads from:
    - RF local field
    - T-dependant electrical properties



EDX on SEM picture

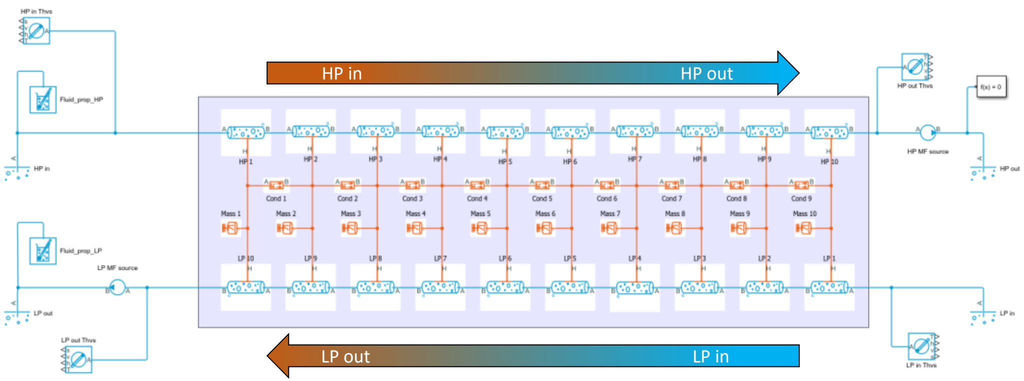


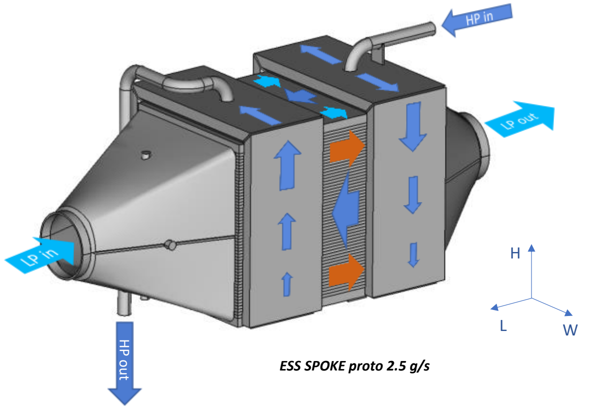


Multipacting heat load can be added !

Illustration on the heat exchanger (HX)

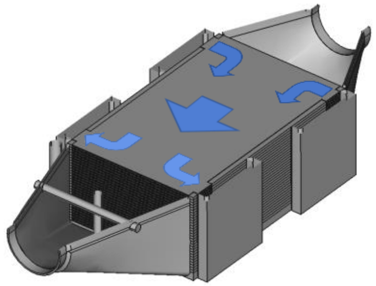
- Plate heat exchanger technology for both ESS and MINERVA
- Thermal performance: modelling approach
  - 0D methods (NTU, LMTD) possible but limited in terms of prediction capacity
  - Decided = 1D discretization 1D
  - Smooth channel assumption
- **+/- 5%** versus DATE simulations and CERN tests
- ΔP : data is inconsistent → Need for a test with RT air





ESS SPOKE proto 2.5 g/s

HP channel flow pattern



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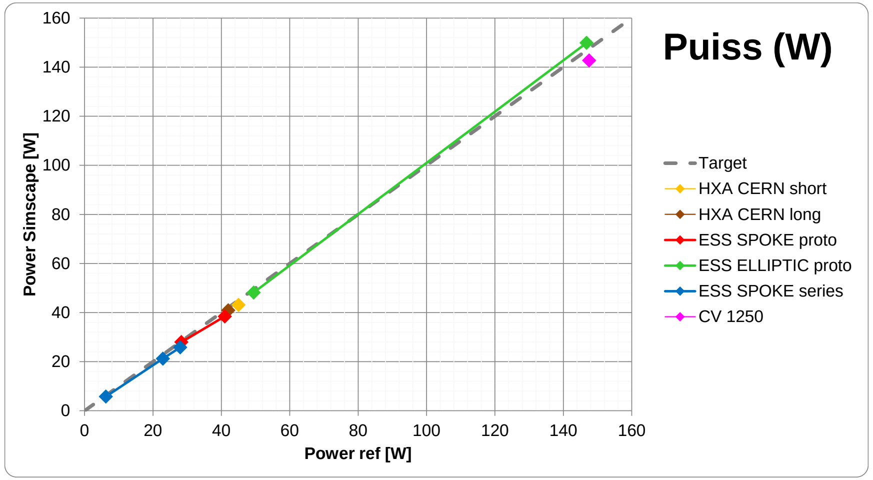
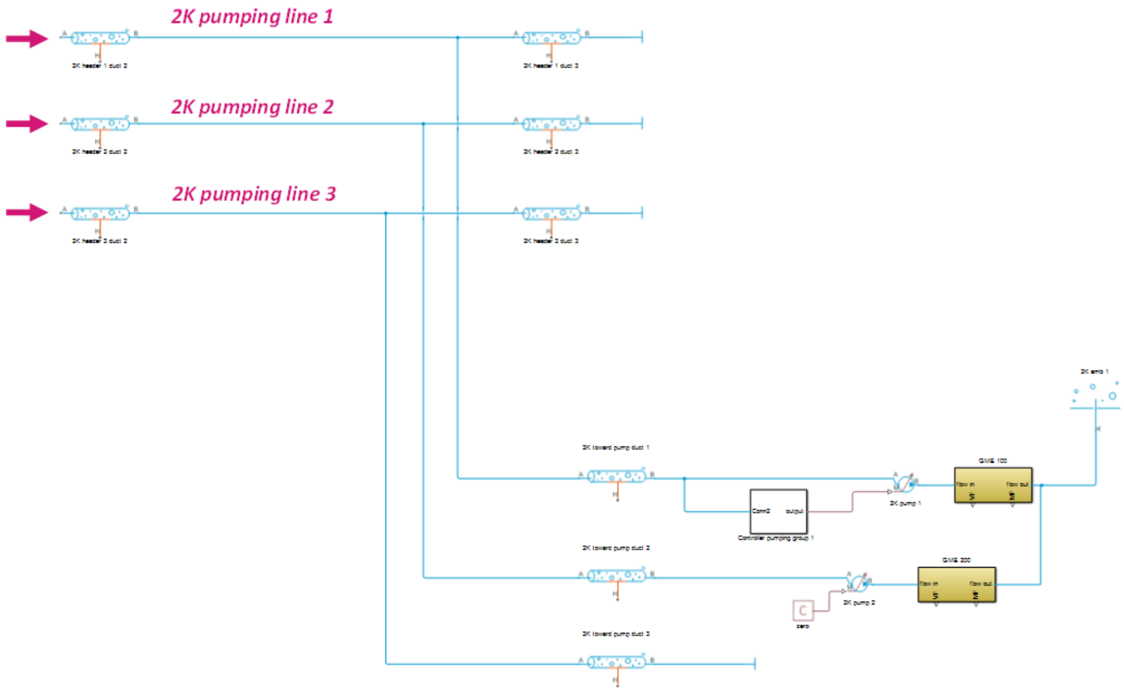
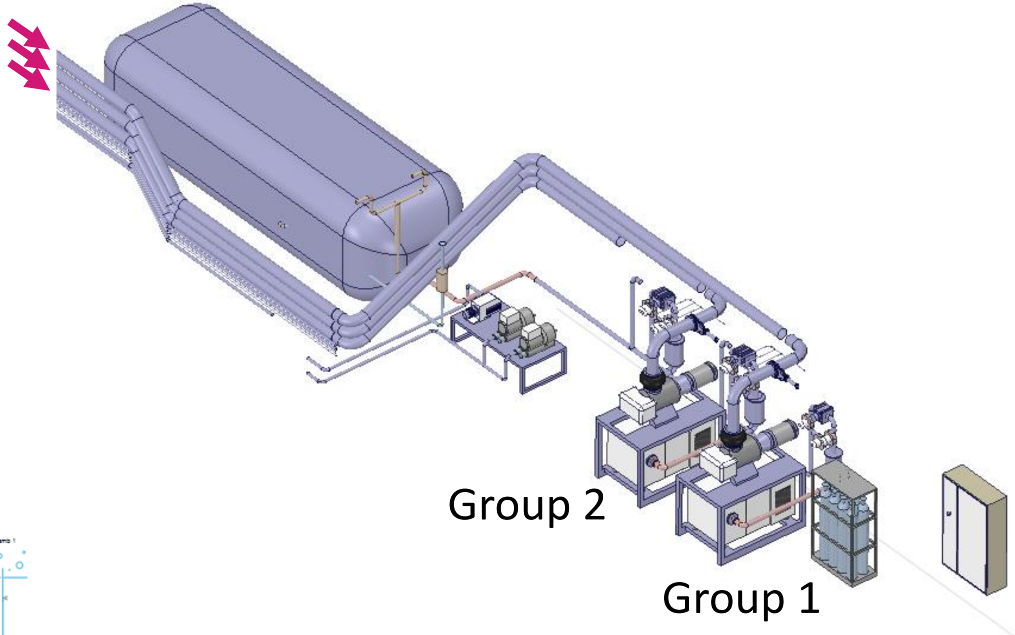


Illustration on the IJClab infrastructure



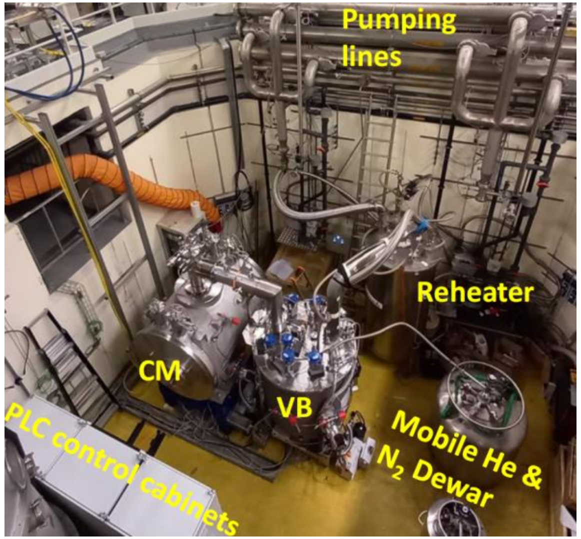


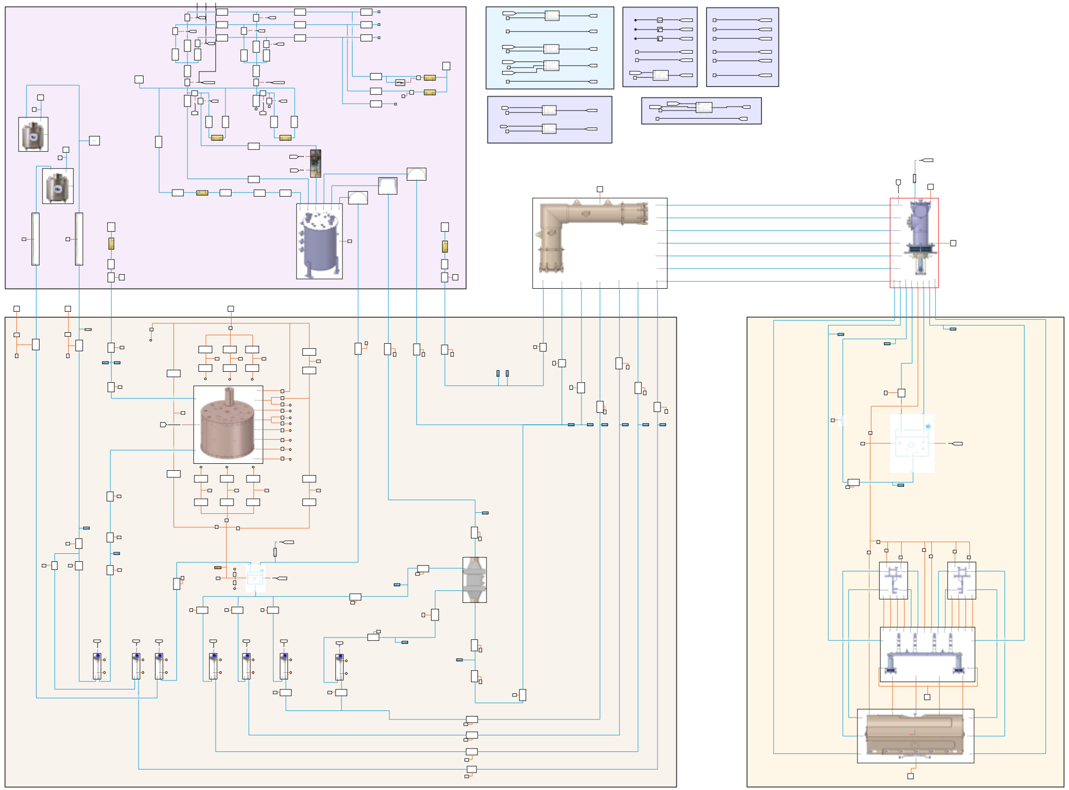
Summary of Simscape cryomodule model development

- For the time being, only the **cryogenic process**
  - Detailed component level model
  - Including supply and recovery infrastructures

- **Sequences and feedback loops implemented in Simscape**

- **Real-time capable** (about 30x faster than RT)

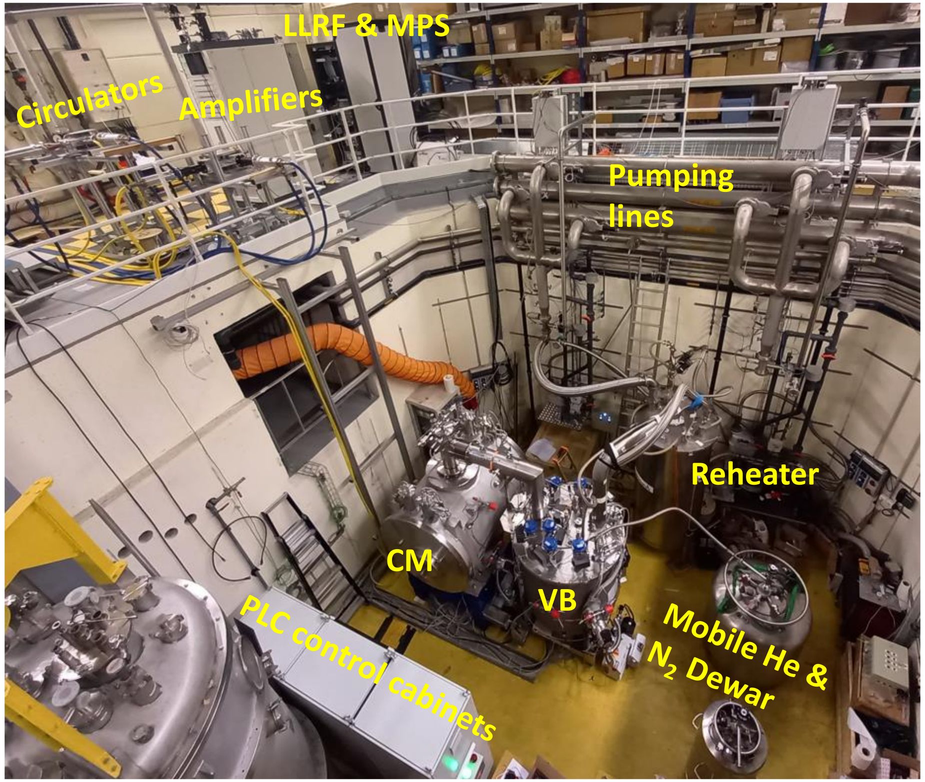




Validation of the model

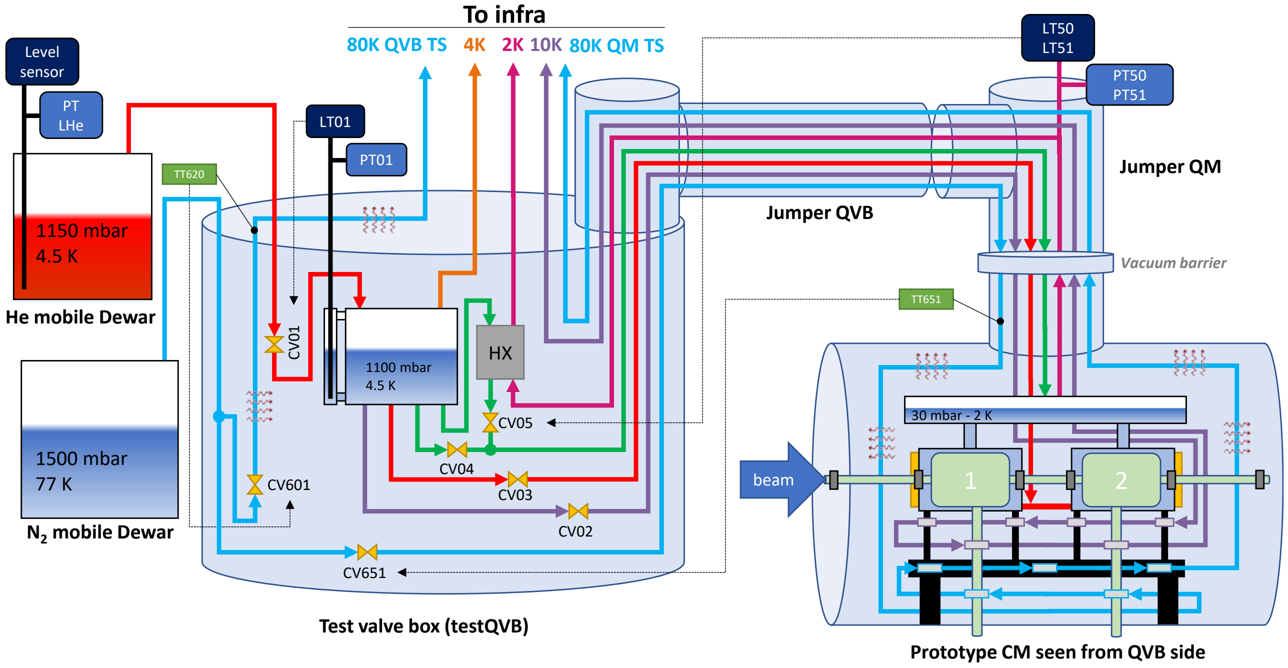
MINERVA prototype test overview

- « Cryogenic Debugging » tests (CD) = tests without cavity & FPC
  - October – December 2021
  - Goals
    - Commission the new test VB and test site
    - Measure the VB & CM heat loads
    - Train on cryogenic procedures for NC tests
    - Validate the superfluid He supply
- « RF debugging » stage cancelled
- « Nominal conditions » tests (NC)
  - Coming in Summer 2022



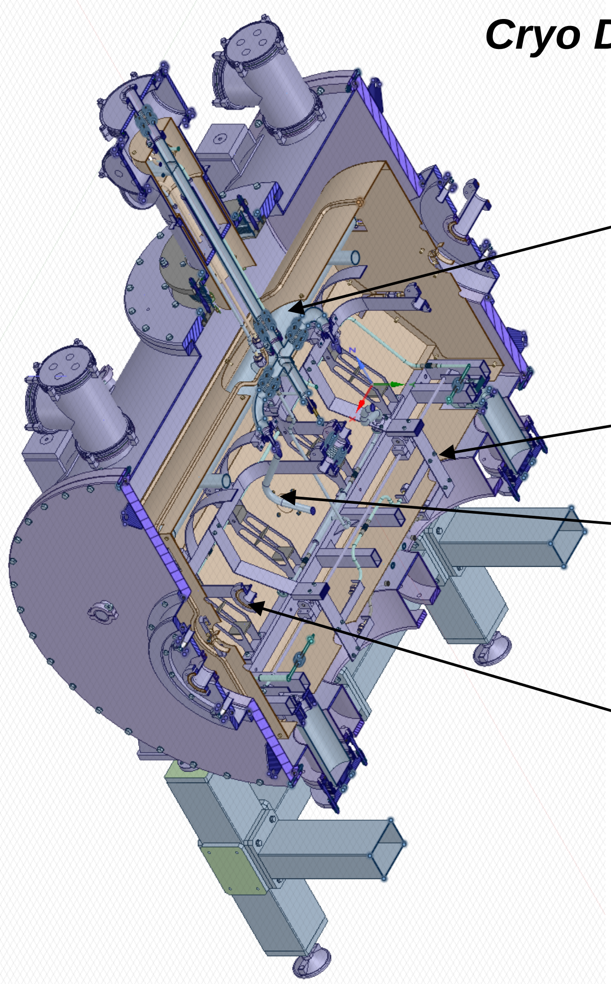
MINERVA cryogenic design highlights

- **CM design highlight**
  - **Superfluid production** in the valve box, transported through the jumper
  - **"10K" intermediate intercept:**
    - Cavity supports arms
    - Coupler tube LT ≠ «trace HX» like ESS
    - Exiting the CM through the jumper
- **Test VB ≠ serial VB**
- **Cryofluid supplied by mobile Dewar**
- **Test conditions ≠ LINAC**
  - Saturated LN_2 at 1.5 bar, instead of supercritical He at 50K, 15 bar
  - Saturated LHe instead of supercritical He at 4.5K, 3 bar



The prototype CM in « Cryogenic Debugging » config°

Cryo Debugging « CD » *versus* ***Nominal Conditions « NC »***



In both cases, an 11 L guard tank

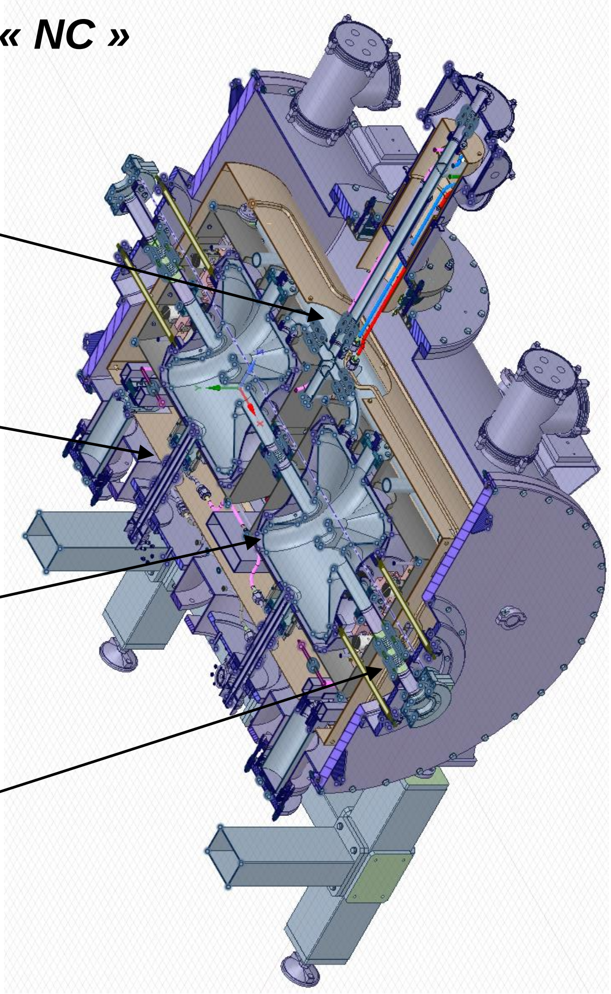
Bracket and SS tube instead of couplers

Cavity mock-up tanks = Ø25 SS tube 0.5L vs

Real cavity tanks ≈ 10L

No 300K → 2K transition

Transition 300K → 80K → 2K



Approach

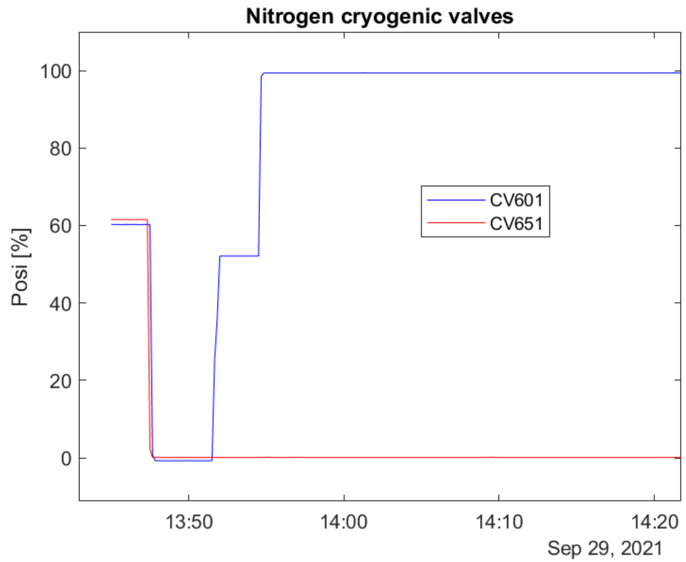
- Simulation inputs
  - Same **boundary conditions** as the tests
  - Same **valve position** as the tests

- Looking at:
  - The N_2 and He mass flow rates
  - The temperatures and pressures

- All that
  - In transient → influence of thermal masses, thermal length, fluid volumes …
  - In steady-state → checking the static heat loads …

- Remarks
  - The model can show **significant deviations**, due to **unknows on the hardware** (tightening torque, presence of thermal grease, complex geometry …)
  - Preparing **additional instrumentation** for the tests in NC

→ **connection to prototype supporting task !**



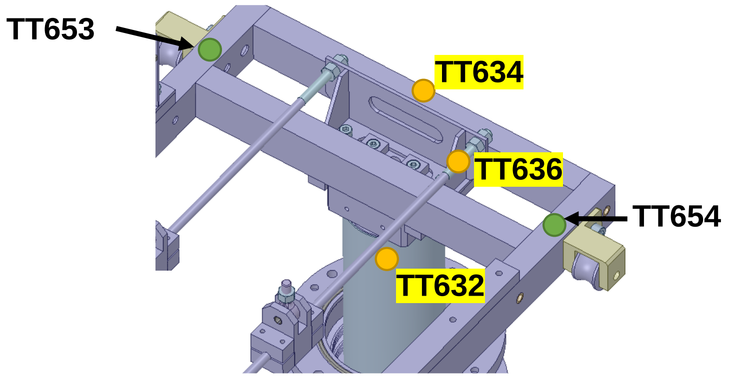
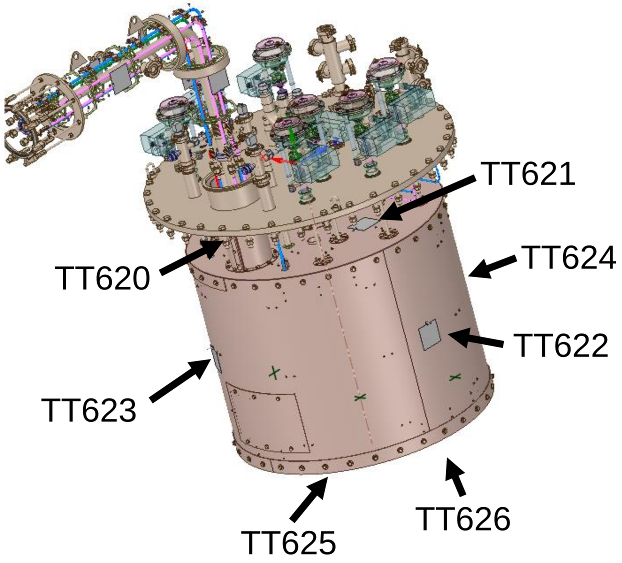
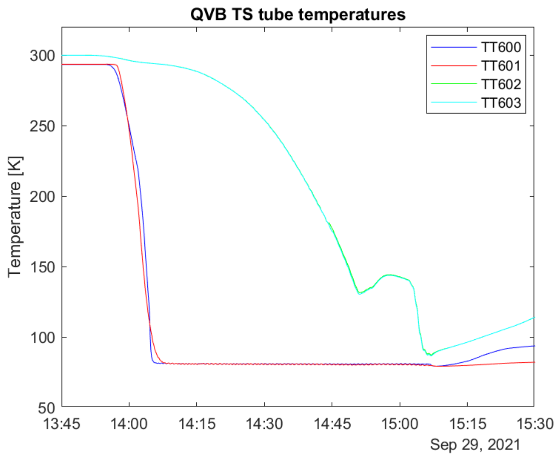


Illustration on the VB thermal shield cool-down

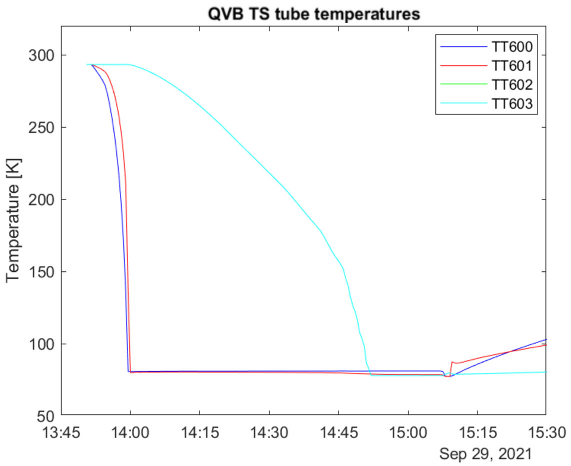
- Notes on TS envelope temperature
  - Empirical contact resistance needed between the TS cylinder and top
  - Around 15:00, a change in the boiling regime in vertical cooling pipes → we do not model at the moment

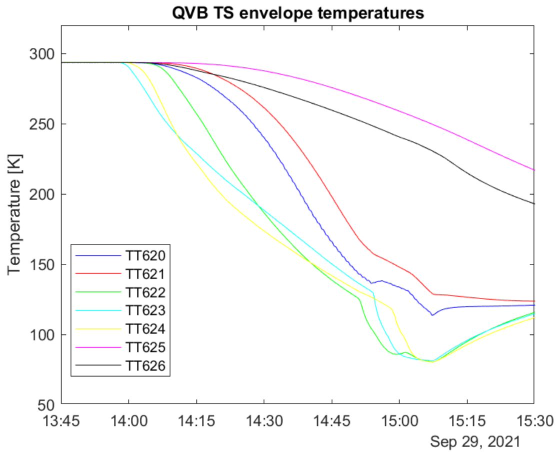


Test



Sim





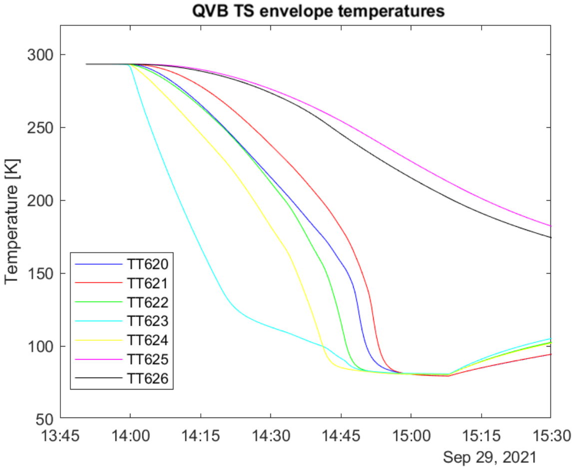
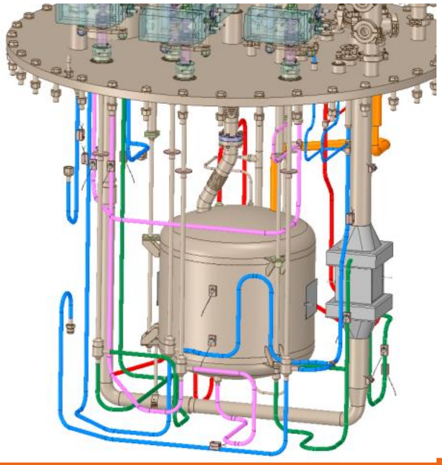


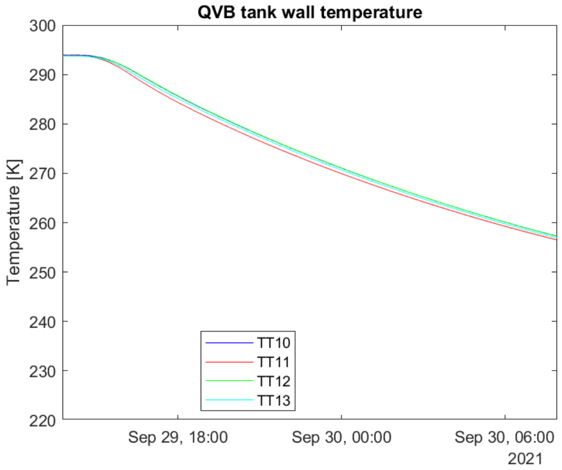
Illustration on the VB thermal shield cool-down

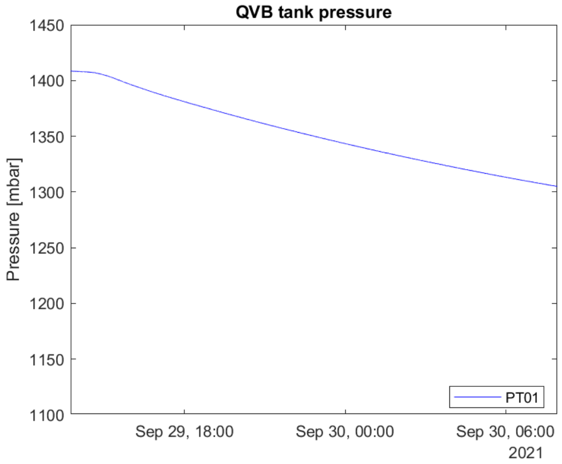
- Notes on VB tank temperature and pressure
  - The tank inlet outlet were closed, the tank had been pressurised at 1410 mbar

  - Overprediction of the radiative heat transfer between the TS and the cold mass



Test





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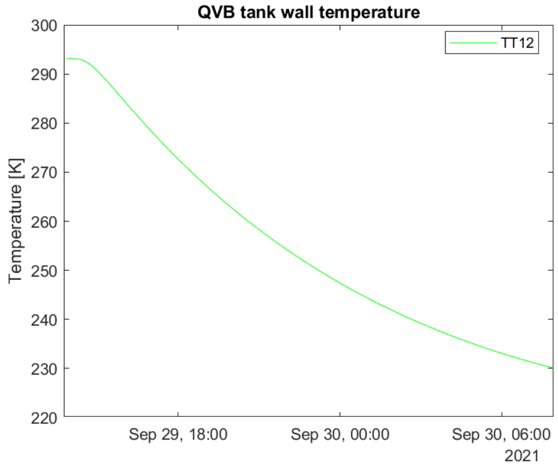
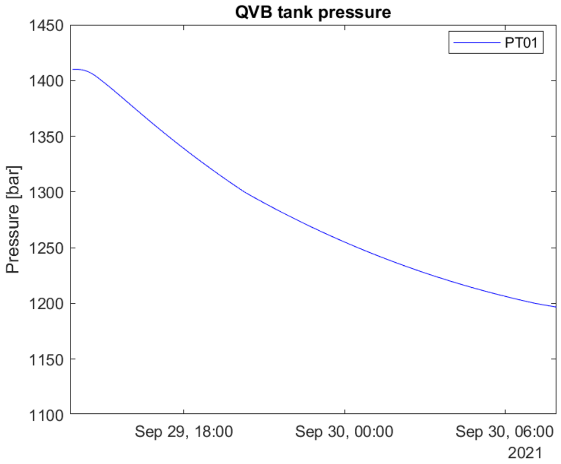
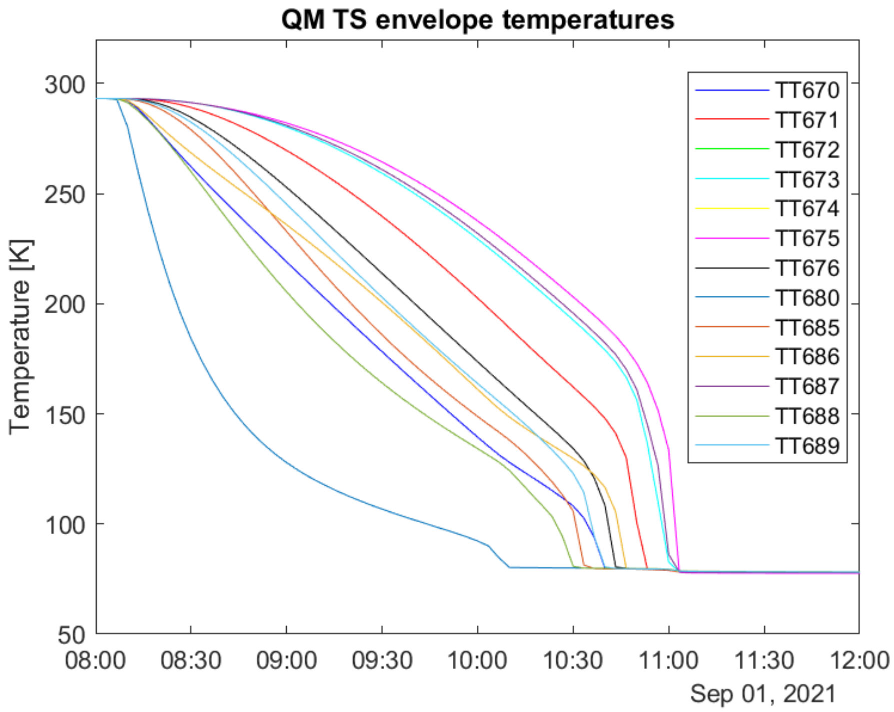




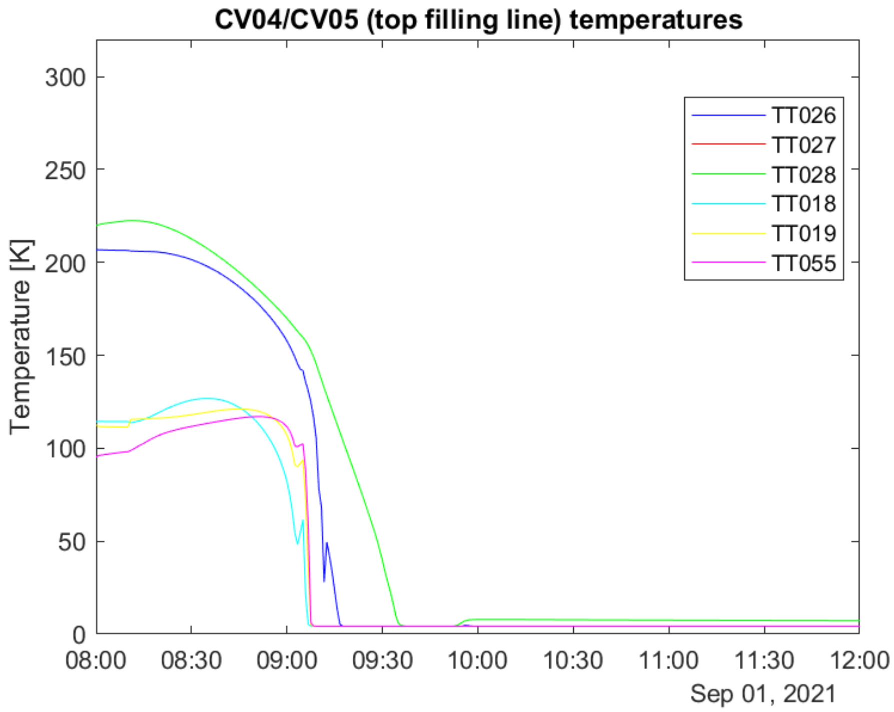
CM thermal shield cool-down & CM 4K cool-down

- On-going ..

Sim



Sim



Conclusion

Summary and perspectives

- Progress on component modelling
  - Model version in CD (Cryo Debugging) done 100%
  - Rush for NC (Nominal Conditions):
    - Update cold mass from CD to NC: cavity, CTS
    - Superfluid operation details
    - Cavity and tuning system RF models
- Progress on validation
  - TS cool-down → 100%
  - 4K cool-down → 70%
  - 2K cool-down → 50%
  - 80K, 4K, 2K steady → 100%
- As said, because of some unknowns, we get only a partial validation
  - Waiting for more sensors installed in NC phase
- Using the model anyway in // for different applications


Thank you!

Annexe

Test pit helium and nitrogen flowmeters & recovery

- **Two nitrogen flow measurement stations**
  - Each equipped with both a mass and a volumetric flowmeter
- **2K and 4K tank exhaust flowrate measurements**
  - 4K tank = Site 4
  - 2K tank (4K mode) = Site 3 through pumping line 3
  - 2K tank (2K mode) = Pumping Room through pumping line 1
- **Dedicated 10K loop flowmeter**
- **2 pumping groups**
  - Each having its own flowmeter

→ Possible to measure all cryofluid flowrate in all modes (4K and 2K)