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FCC WEEK 2025

Semi-Dry Cavity Cooling of SRF Cavities at Temperatures above 4.5 K

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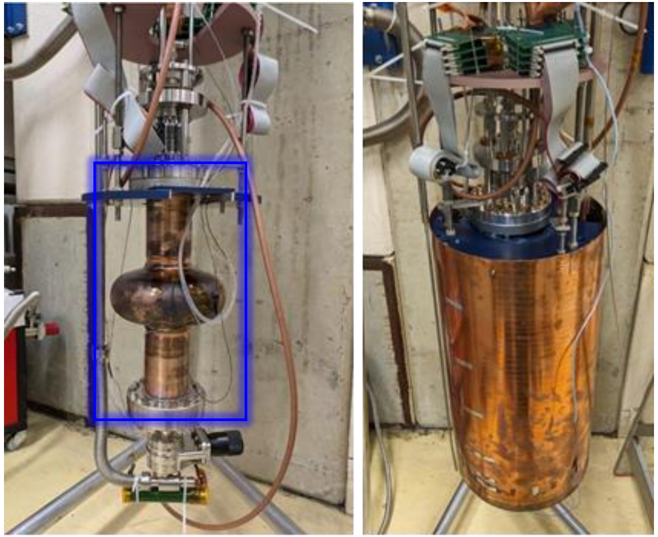
Content

- **Concept of “semi-dry” cooling SRF cavities**
- **Experimental setup**
- **Results from the “cryocooler standalone and boosted operation” 1.3 GHz cavity**
- **Integrated cooling features in the cavity surface – cavity wall mock-up**
- **Grooved cavity production**
- **Summary**

Standard cryomodule vs. dry cavity cooling

LHe bath cooling

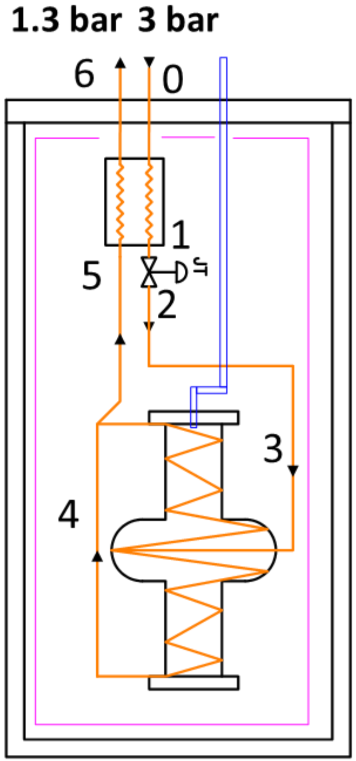


Use of a thermal shield in He gas for slow Tc cooldown from 20 K

Pros vs. Cons.

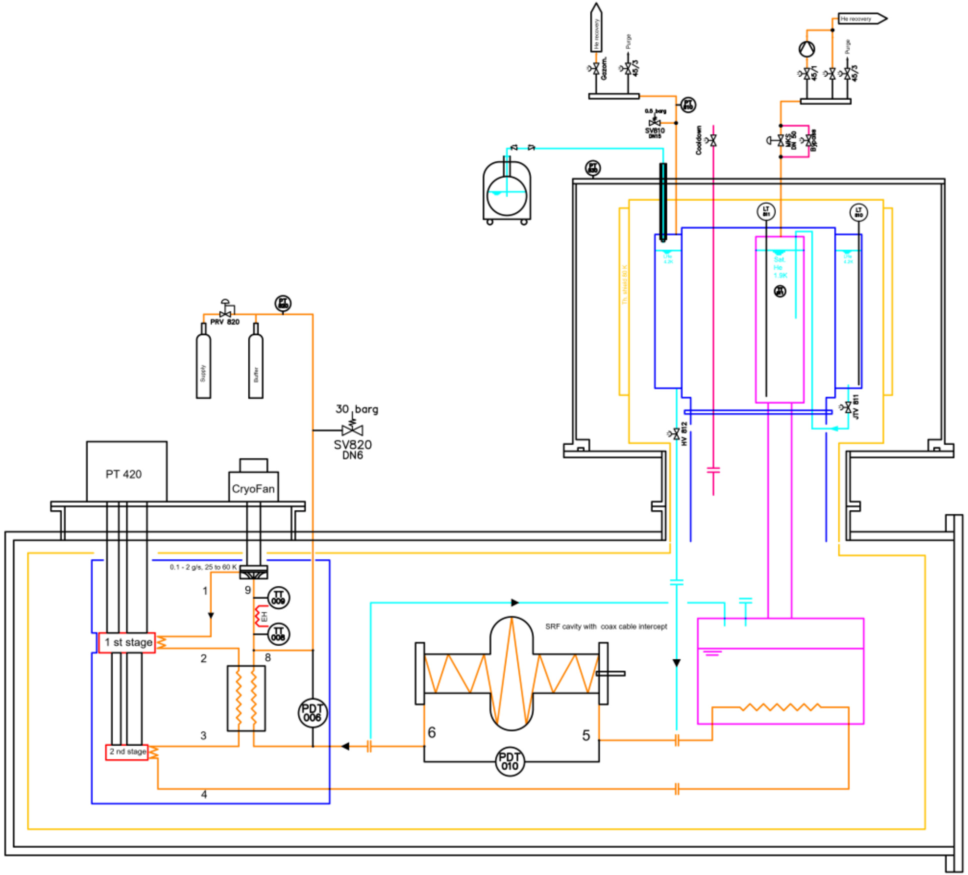
- LHe content (reduced safety hazards)
- Pressure safety of the vessel
- Material transitions
- T_c transition front => trapped flux*
- Temperature profile
- Cooling performance

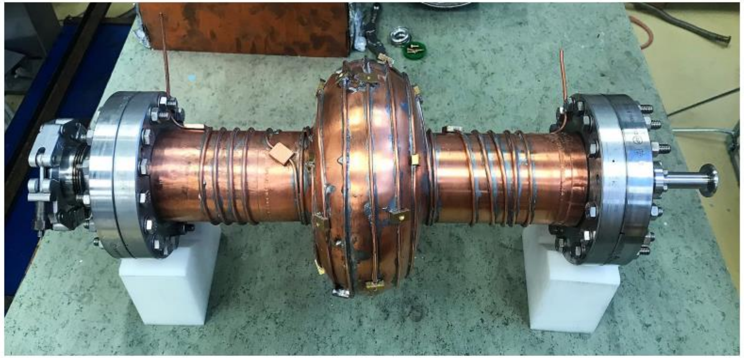
  => free conv. vs. forced flow
- Add. cooling features vs. no He vessel
- Mechanical tuners at cold
- Option for cavity cooling for FCC?



*coated cavities want small thermal gradients during transition: Seebeck vs. Meissner bulk Nb looking for fast cooldown through T_c expel magnetic flux

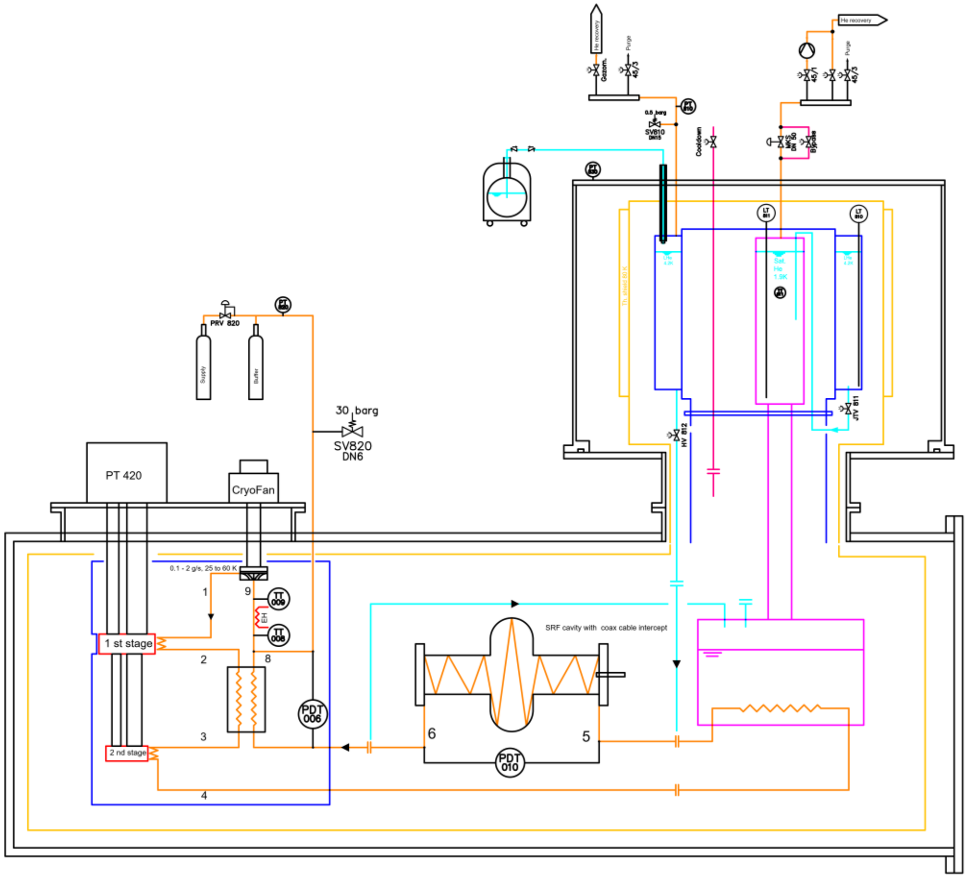
P&ID with LHe booster HEX and 1.3 GHz test cavity





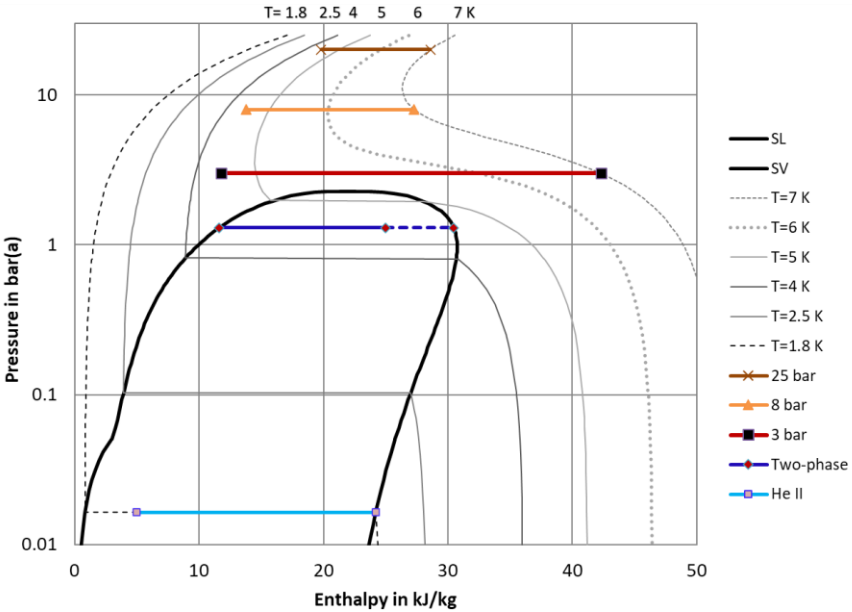
Radiofrequency cavity (1.3 GHz), bulk Cu with soldered capillary Ø3 x 0.5 mm with 8 m length

P&ID with LHe booster HEX



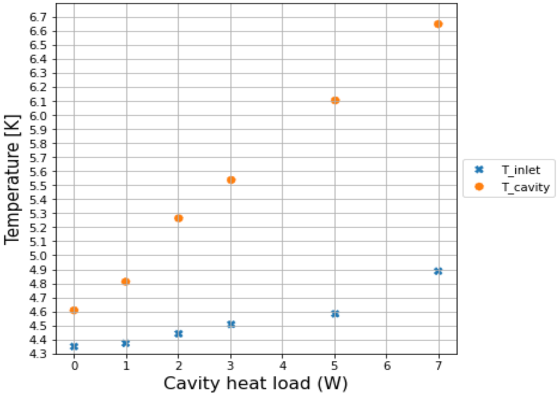
Possible fluid conditions

- LHe two-phase flow
- Supercritical He @ 3 bara, 4.5 K
- GHe @ 8 bara, 4.5 K
- GHe @ 25 bara, 4.5 K

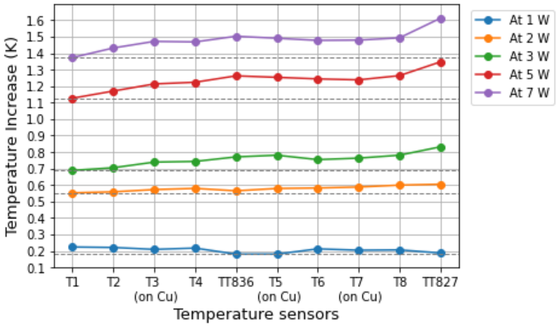


Inlet & Cavity temperature distribution supercritical He flow condition

Cavity & inlet temperature at each heat load level for the optimal system performance at 3-4 bar He flow



Local temperature increase across the entire length of the cavity 3-4 bar He flow



- *Temperature gradient < 20 mK up to 2 W*
- *As the heat load increases, the temperature rise becomes slightly more pronounced, reaching around 220 mK at 7 W*

✓ *Copper effectively maintains an almost uniform temperature rise over the length of the cavity with added heat load.*

For no introduced heat load – 0 W

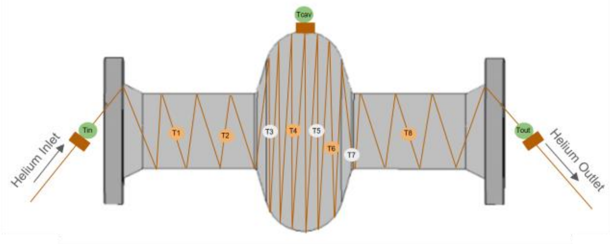
Inlet Temperature: 4.35 K ± 20 mK
Cavity Temp range: 4.60 K ± 20 mK

At 7 W introduced heat load

Inlet Temperature: 4.90 K ± 20 mK
Cavity Temp range: 6.65 K ± 20 mK

Residual heat load of approximately 1 W

$$\alpha_{He2tube}/\lambda_{tube} = 1/9 \qquad \lambda_{tube}/\lambda_{Cav} = 1/4$$



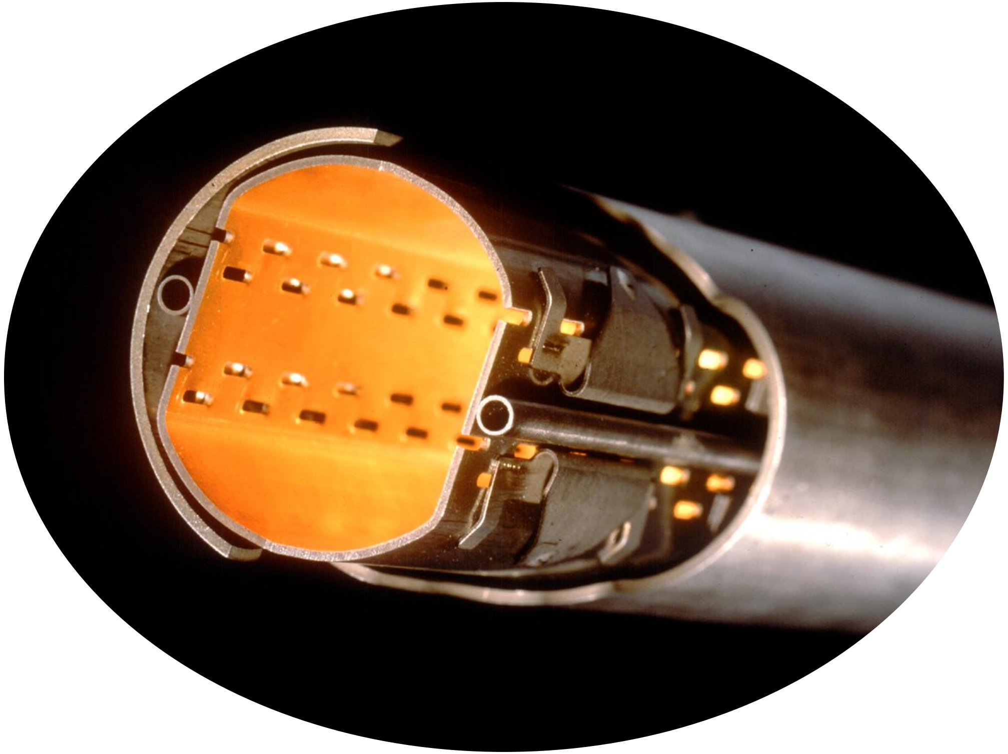
● (TVO) **Tin** located on the capillary (inlet)
● (TVO) **Tcav** located on the cavity equator, measuring the average centured temperature
● (TVO) **Tout** located on the capillary (outlet)

● (Allen Bradley) **T1,T2,T4,T6,T8** located on the capillary
● (Allen Bradley) **T3,T5,T7** located on the Cu cavity surface

Example from the LEP water cooled cavities

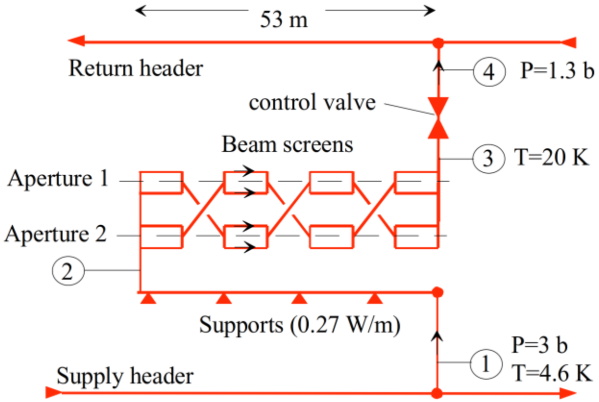
Cu cavity with water cooling circuits

Example from the LHC operation - Beam Screen cooling



LHC beam screen cooling with two-parallel capillaries of d_i=3.7 mm

Supercritical He flow at 3 bar a, 4.5 K

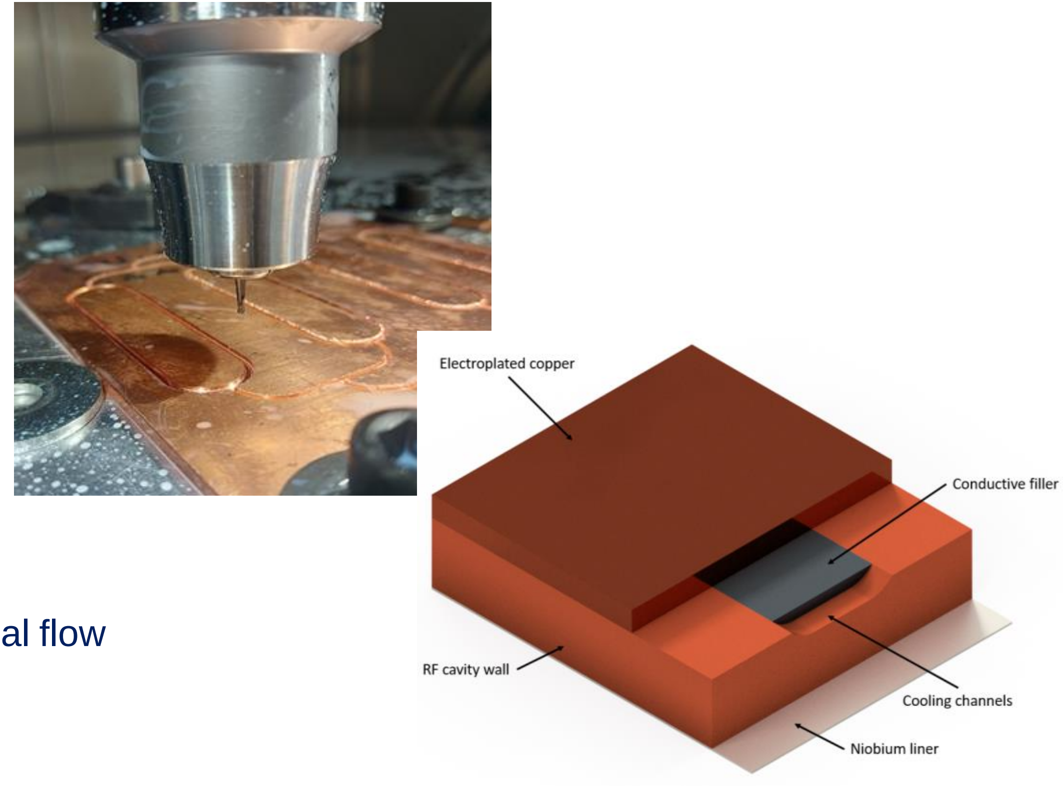


Integration of cooling channels in the Cu cavity wall => grooves

Procedure:

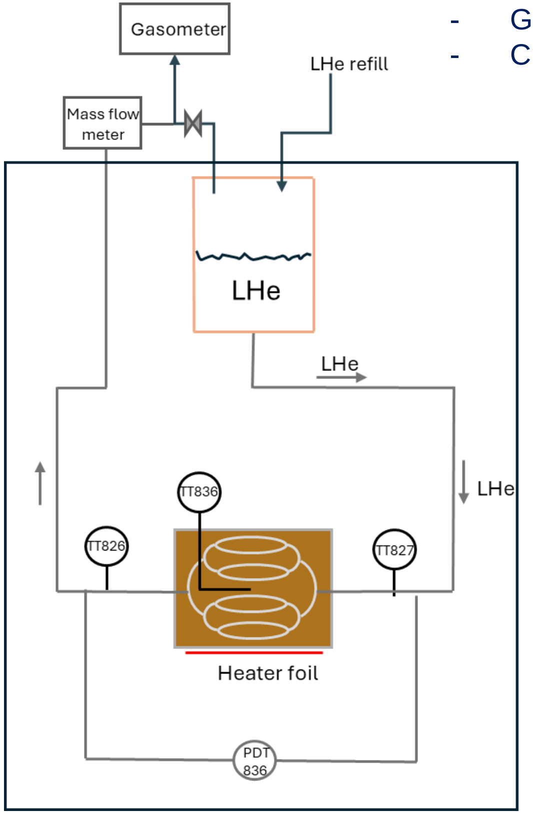
- Grove machining
  - Filling with conductive wax
  - 20-50% graphite charged
- Hard wax (jewellers wax)
- Removal of excess material
- Cleaning
- Electroplating with copper
- Machining
- Connections

- Testing with LHe two-phase and supercritical flow

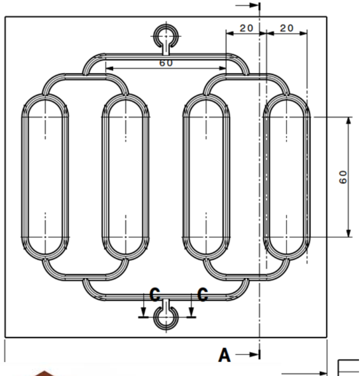


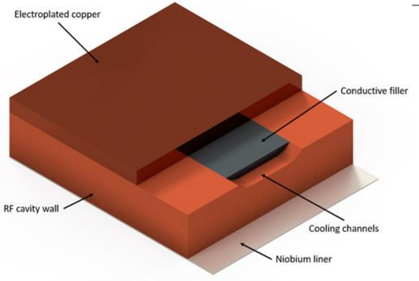
Courtesy: CERN EN-MME

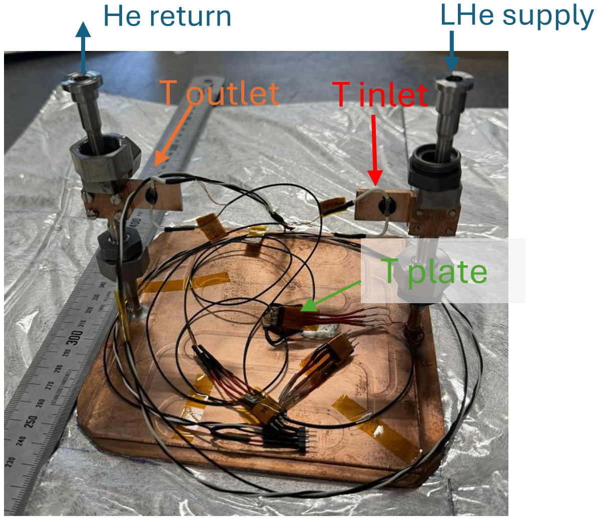
Dry Cavity Cooling: Mock-up plate results in two-phase flow



- Grooves are machined into the Cu substate (cavity wall) and electroplated
- Cryo performance with low pressure LHe two-phase flow @ 4.3 K in the Cryolab



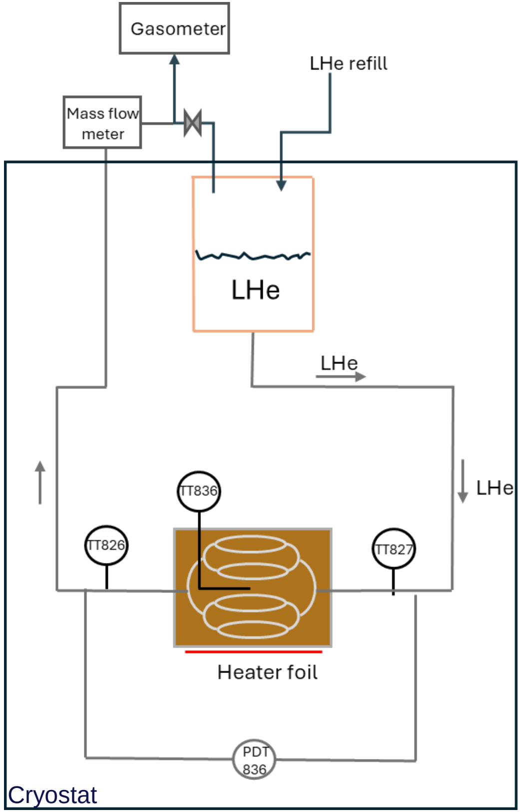




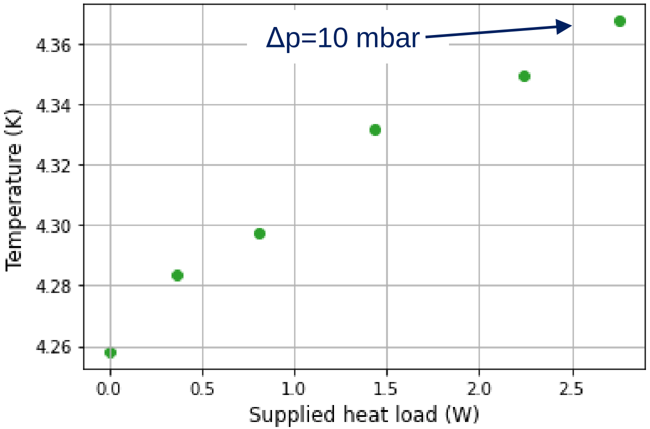
Two ways for controlling the mass flow rate:

1. Supplying liquid helium from reservoir, flow driven by hydrostatic pressure differences: → Helium supply: p=1 bar / 4.2 K
2. Pressurising the supply reaching a higher mass flow rate → Helium supply: p=1.1 bar / 4.3 K

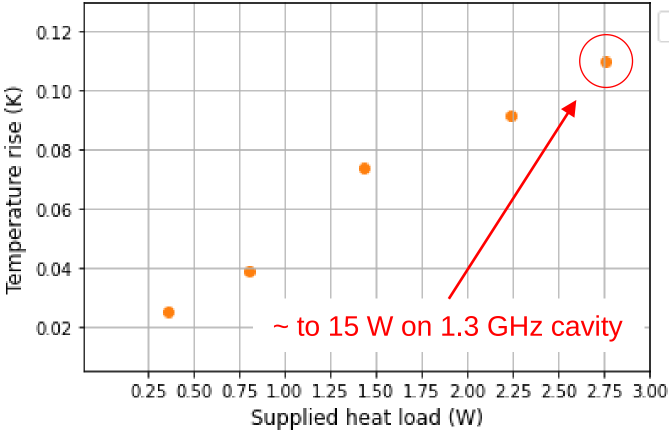
- Grooves are machined into the Cu substate (cavity wall) and electroplated
- Cryo performance is measured with:
    - **Low pressure LHe two-phase flow @ 4.25 K in the CERN Cryolab**
    - High pressure supercritical He flow @ 3-4 bar and 8-9 bar



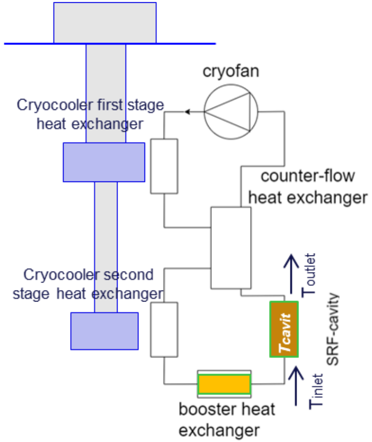
Temperatures at each heat load level



Temperature rise at each heat load level

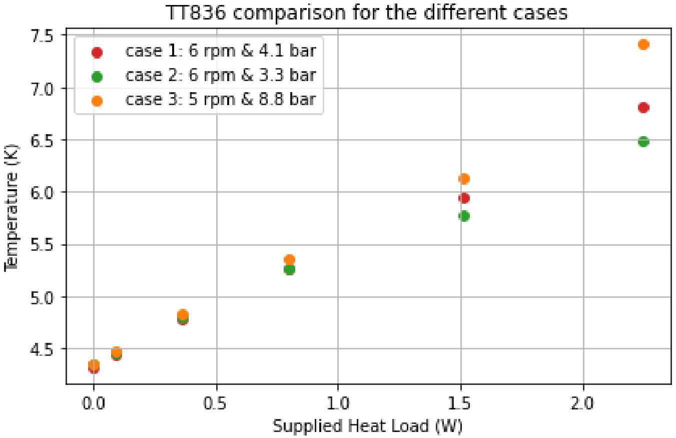


Accuracy estimation: Pressure drop: ± 0.35 mbar, Temperature: ± 0.045 K, Temperature rise: ± 0.01 K

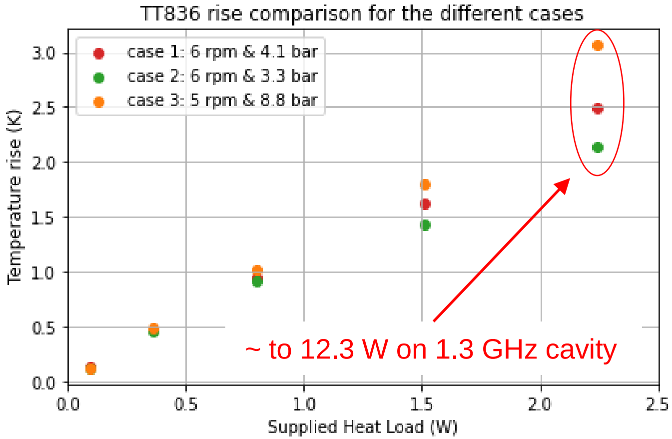


- Grooves are machined into the Cu substate (cavity wall) and electroplated
- Cryo performance is measured with:
  - Low pressure LHe two-phase flow @ 4.25 K in the CERN Cryolab
  - **High pressure supercritical He flow @ 3-4 bar and 9 bar**

TT836 / Plate Temperature
comparison for the different cases



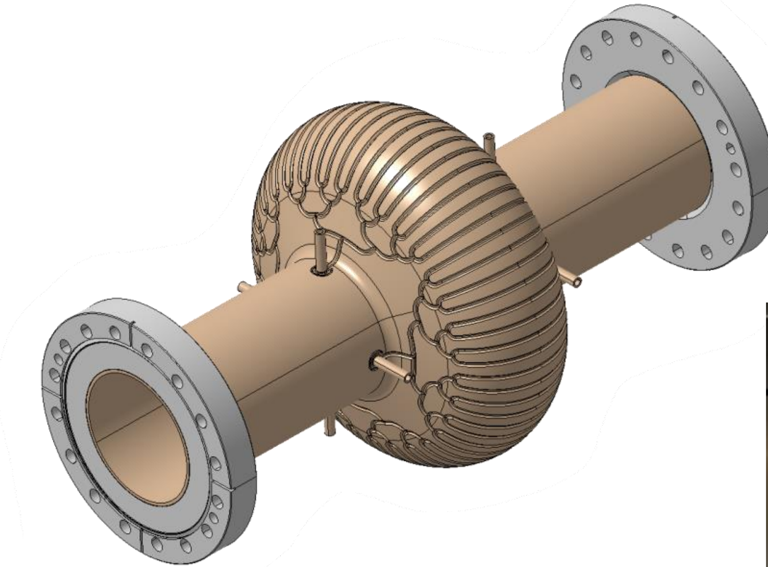
TT836 / Plate Temperature rise from 0 to 2.25 W
comparison for the different cases



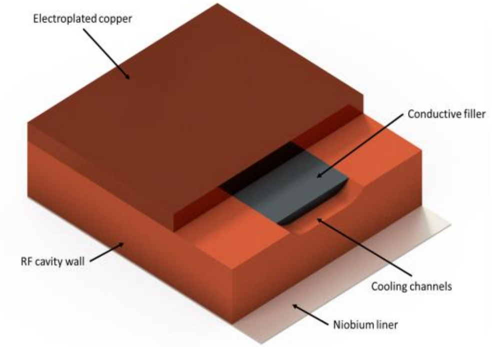
~ to 12.3 W on 1.3 GHz cavity

Accuracy estimation: Pressure drop: ± 0.35 mbar, Temperature: ± 0.045 K, Temperature rise: ± 0.01 K

Application to an R&D 1.3 GHz cavity



Design of integrated cooling channels in a 1.3 GHz cavity wall.



Design and fabricated Cu mock-up plate, wax filled grooves.

First manufacturing steps in the CERN main workshop.

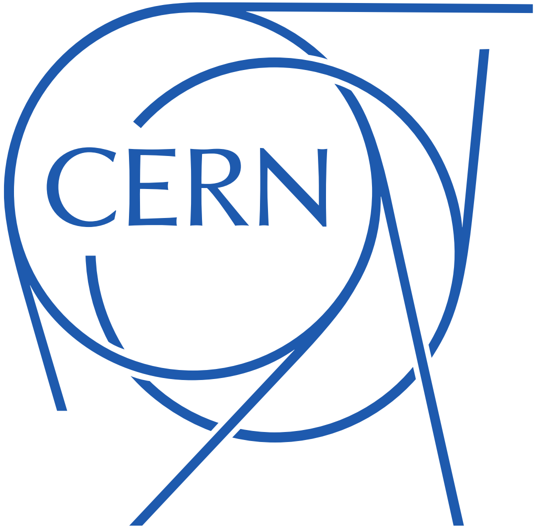
Conclusion and Status May 2025

- Combination of three very promising technologies:
  - Semi-dry cavity cooling
  - A15 coatings like Nb_3Sn on Cu
  - Electroforming or integrated channel manufacturing

- Huge impact on possible CM designs, drastically reduced He content (30-50x)
- Cavity cooling => feasibility of remote cooling systems, reaching cooling requirements with supercritical flow.
  - ✓ **6.5 K** cavity temperature @ **1 W** + residuals / Cryocooler standalone operation
  - ✓ **6.6 K** cavity temperature @ **7 W** + residuals / Booster heat exchanger integrated operation
- Groove mock-up:
  - ✓ tested in two-phase flow, leak tight at cold with 1.3 bar, small temperature rise, pressure drop OK
  - ✓ tested in supercritical flow, leak tight at cold with up to 10 bar, smallest ΔT=2.1 K for 3.3 bar (QRL like)

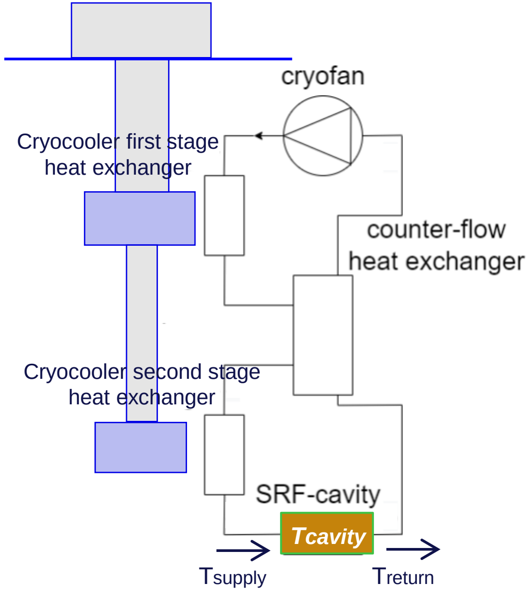
Next steps:

- Proceed with a 1st full-scale 1.3 GHz machined cavity for thermal test
- Produce a coated 1.3 GHz cavity for full RF and thermal tests

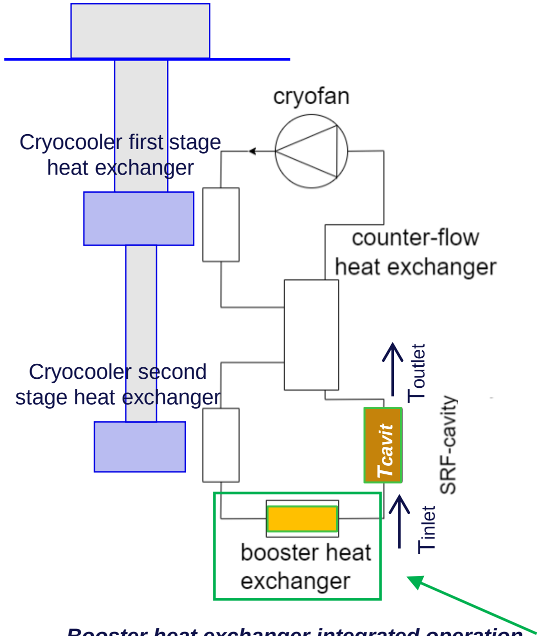

CERN

Dry cavity cooling concept – cryocooler based for testing

Cooling power is supplied by a ***cryocooler*** *in combination with a* ***closed fluid circulation loop***



Cryocooler standalone operation



Booster heat exchanger integrated operation

Inside a 4.2 K liquid helium bath

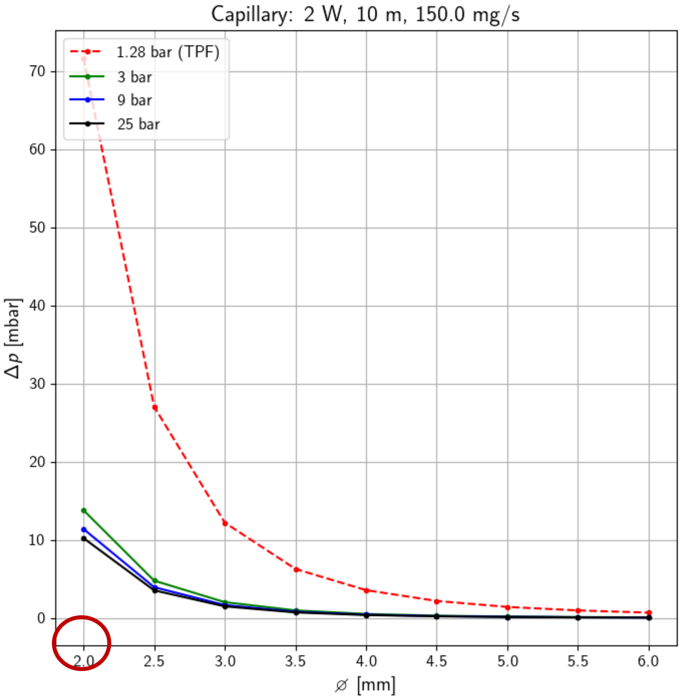
Radiofrequency (1.3 GHz) Cu cavity with soldered capillary

Booster Heat Exchanger:

Will provide the necessary cooling to achieve *a lower and constant inlet temperature* to the cavity *and to also achieve a lower cavity temperature with higher possible heat loads.*

Helium simulation code for capillary flow

Pressure drop He flow in the capillary



Temperature difference He flow to capillary wall