Dry Cooling Strategies for Accelerator Components

(Cryocooler based cooling stations)

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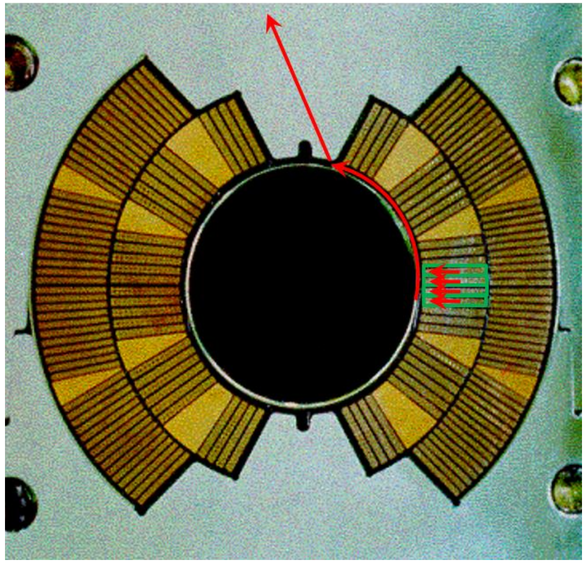
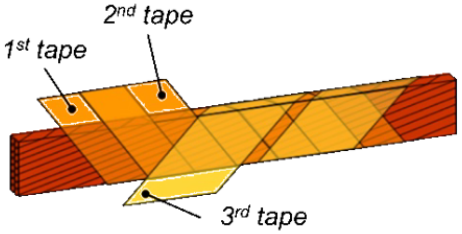
- Introduction, from liquid bath cooling towards conduction cooled devices
- Cryocooler based systems – additional cooling loops
- Counter-flow HEXs
- Application examples
- Summary

NbTi superconducting magnets in the LHC at CERN

- Bath cooled magnets, heat extraction by He II @ 1.9 K pressurised
- 130 ton minimum He inventory for the LHC incl. detectors, e.g. LHC dipole magnet V_{He}=28 l/m
- Safety in underground installations, complex inventory management, He cost and availability …

Cold-source





NbTi - cable is:

- non-impregnated

- Electrically insulated by partially overlapping layers of Kapton

--> porous to helium

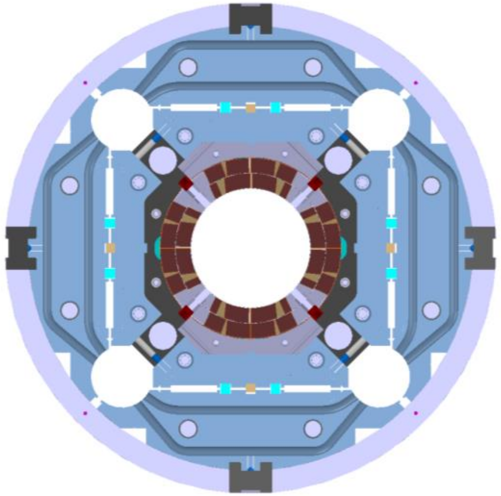
In *fully immersed* magnets the heat generated in the coil-pack must find its way out to the cold-source via helium path-ways kept clear in the cold-mass construct

In the example left, of the LHC main dipole, heat flows from the coil pack into the annular space between beam-pipe and coil-pack and out via space between the collar laminations

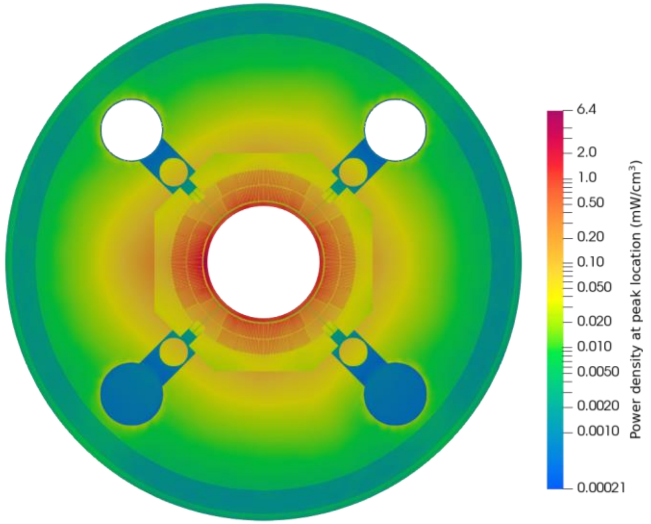
Nb_3Sn fully impregnated magnet coils for HL-LHC at CERN

- New electrical and thermal insulation scheme for fully epoxy impregnated coil packages
- He II cooling via the annular gap between beam tube and coil package, HL-LHC MQXF magnet V_{He}=30 l/m
- Numerical simulation of heat transfer, He II cooling performance, temperature distribution and Temp. margin

MQXF v7 + cold mass
(ST0703448)

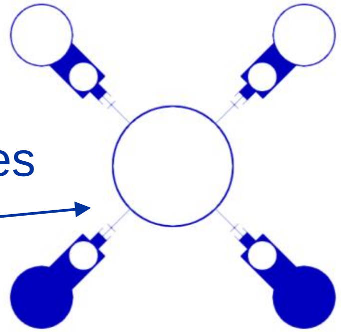


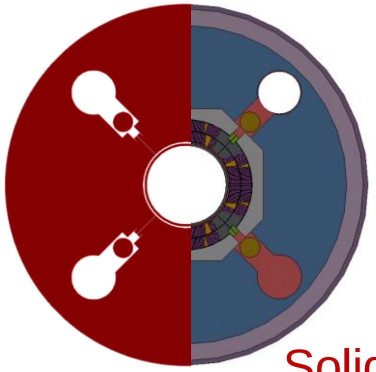
Q2B IR1-HC – power dep. @ peak loc.



Numerical assessment

He II region
(connected passages
via poles)

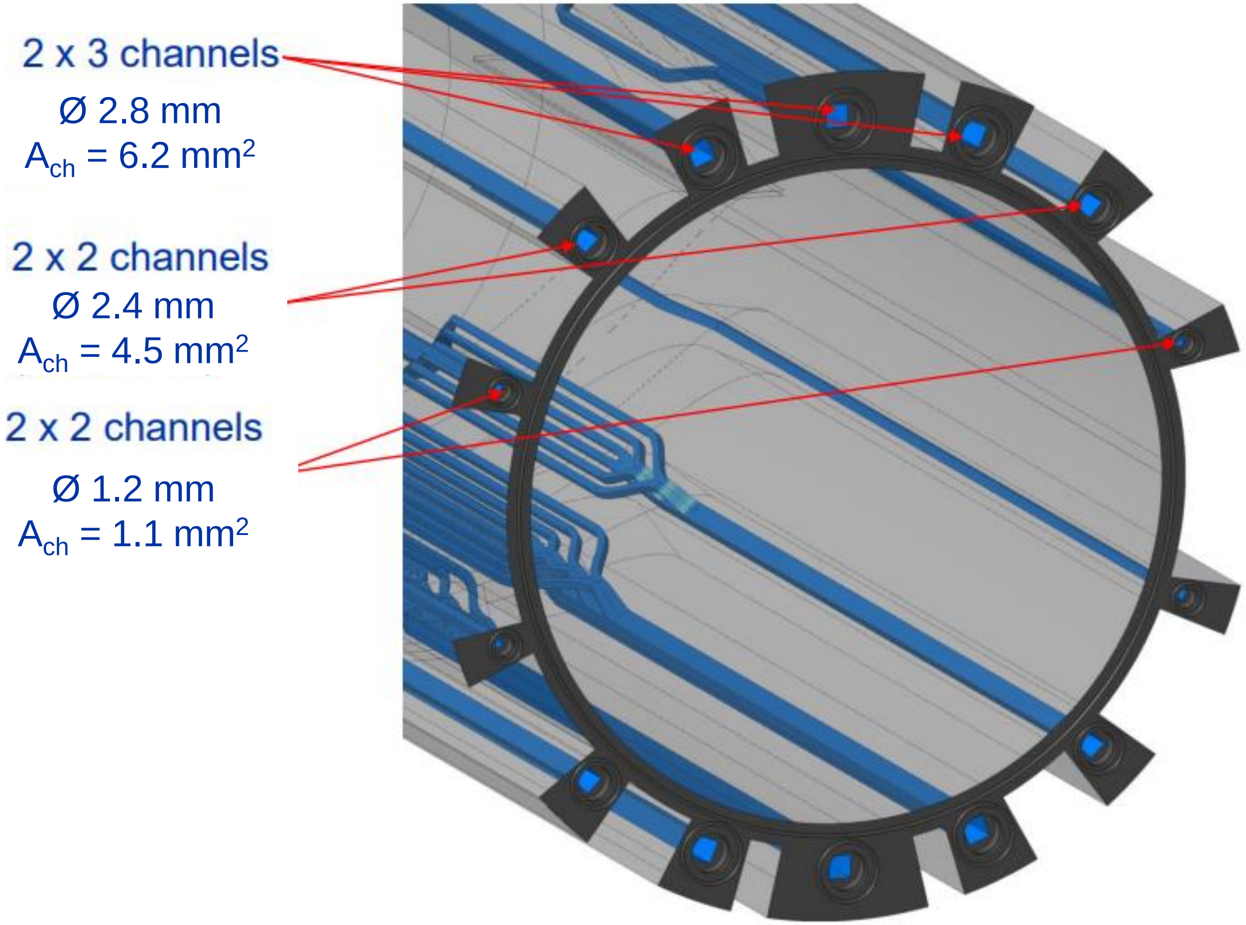




Solid region (17 parts)

Dry cooled prototype of a gantry magnet, design

Stainless steel former, 3D printed incl. cooling channels => Cooling channel size and distribution – inner layer,



2 x 3 channels
Ø 2.8 mm
A_{ch} = 6.2 mm^2

2 x 2 channels
Ø 2.4 mm
A_{ch} = 4.5 mm^2

2 x 2 channels
Ø 1.2 mm
A_{ch} = 1.1 mm^2

- 28 channels in parallel for two layers of coil (2x14)
- Heat load on inner layer ≈ 3 W
- Required $\dot{m}$ to extract 3 W between 4.5 K and 4.7 K using He at 3 bara ≈ 3.2 g/s

- How does this flow distribute over the 14 parallel branches? (assuming equal length)

Branch Ø [mm]	1.2	2.4	2.8
$\dot{m}$ [g/s]	0.036	0.235	0.353
% of total $\dot{m}$	1.1%	7.3%	11%

- What's the overall pressure drop?
  Δp = 1.5 mbar assuming 1.5 m length of circuit
  (same $\dot{m}$ at 300 K, 3 bara is ≈ 600 mbar)
- Heat transfer coefficients He flow to former

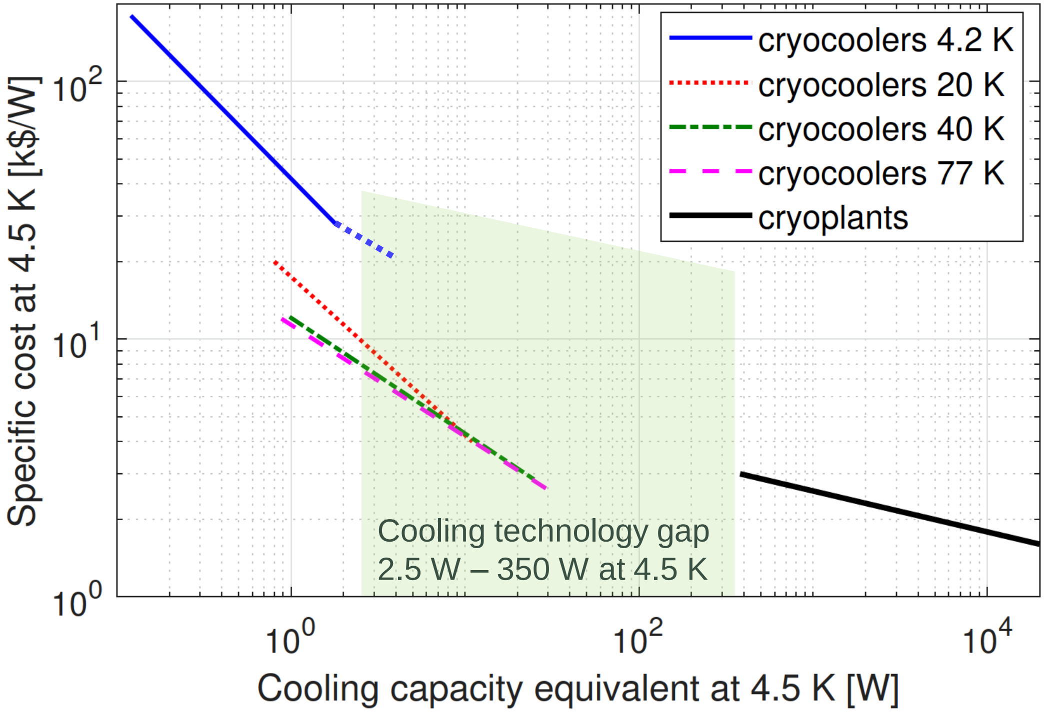
Adapted from G. Ceruti, Weekly Meeting 13 (26 January 2024) · Indico (cern.ch)

Cryocooler as cooling source

Keeping in mind large scale applications with their distribution system

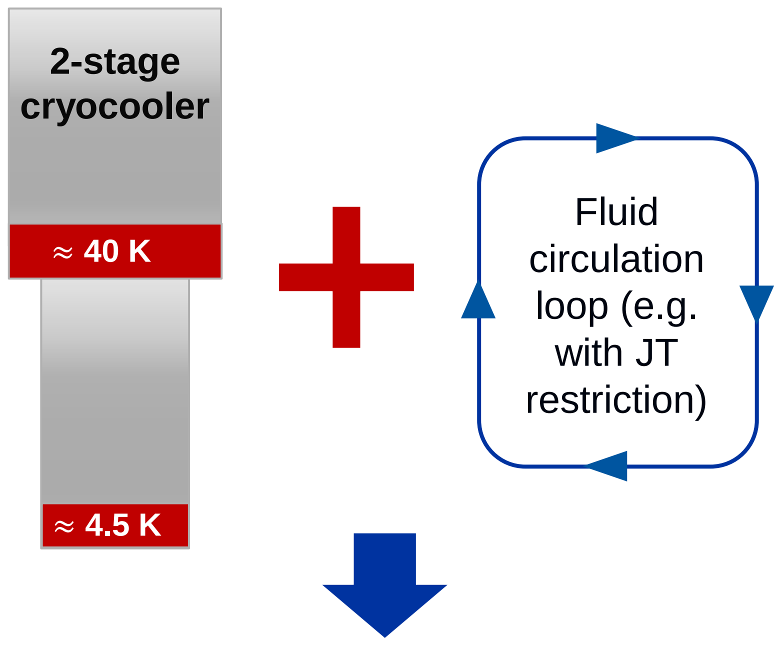
Background: remote cooling

- Several applications require a cooling capacity of several Watts at 4.5 K → cooling capacity between cryocoolers and cryoplants



Map adapted from: L. Decker, “*Overview on cryogenic refrigeration cycles for large scale HTS applications*”, 2016.

Remote cooling principle = Cooling source + convection loop



<u>Increased cooling capacity</u> + <u>dry</u>, <u>vibration-free</u>, <u>distributed</u>, <u>remote</u> cooling for a number of applications

High-tech applications for remote cooling circuits

- Cryogenic cooling of IR cameras / spectrometers in space (e.g. NICMOS on Hubble Space Telescope)
- Pre-cooling of dilution refrigerators for quantum sensing/computing

→ from 2 integrated PTR to remote PTR box to cryoplant connection

~250mm
(2010)

Image: Oxford Instruments

~500mm
(2015)

Image: BlueFors

~1000mm
(2021)

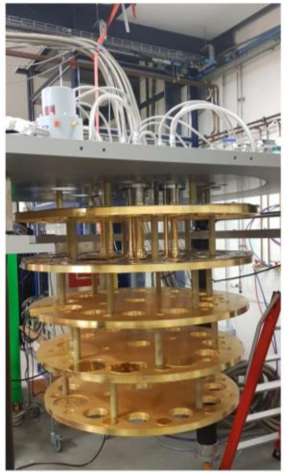


Image: Leiden Cryogenics

~2000mm
(2025)

Platform will use an existing helium cryoplant, specified at **600 W @ 4.5 K**

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- Next generation of gravitational wave detectors => mirror cooling @ 4 K – 20 K

Cryogenic mirrors of gravitational wave detectors (e.g. KAGRA)

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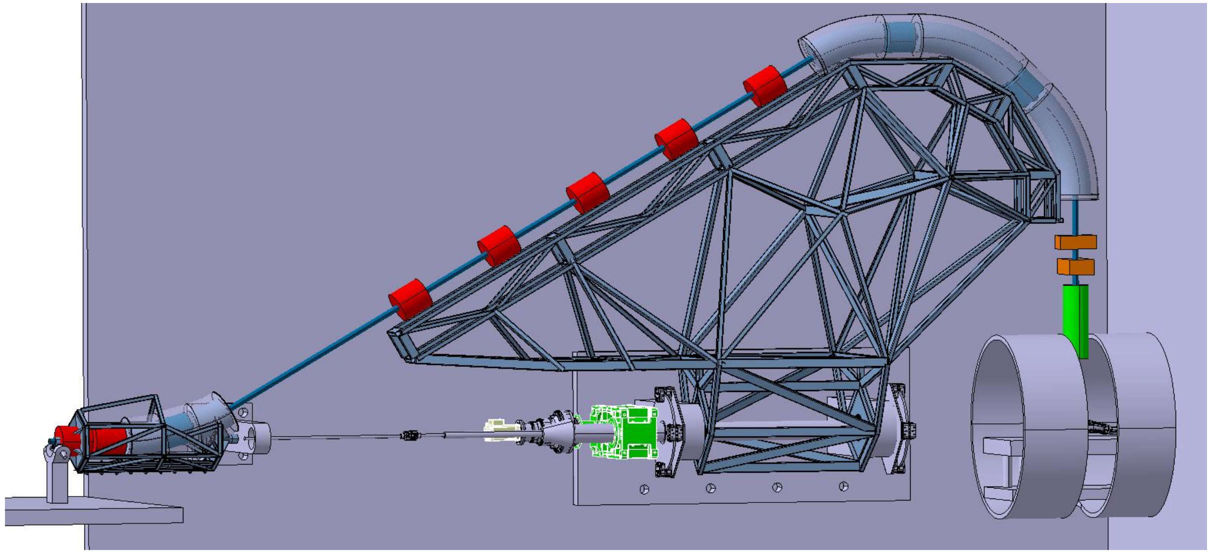
- SC gantries for proton/heavy-ion therapy

Courtesy: L. Gentini



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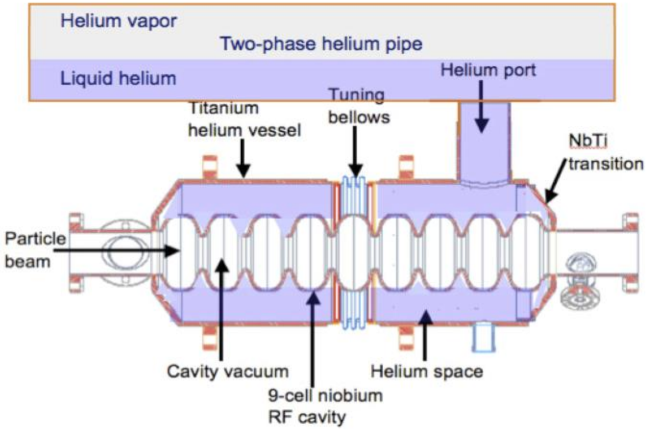
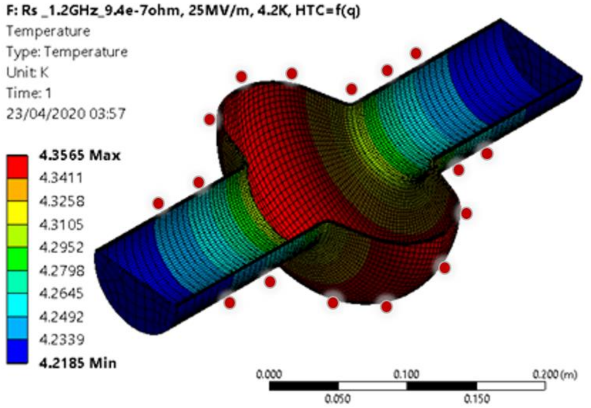
- SC RF cavities in particle accelerators





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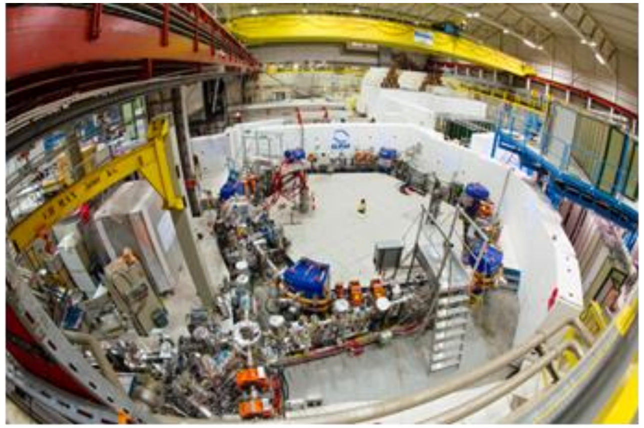
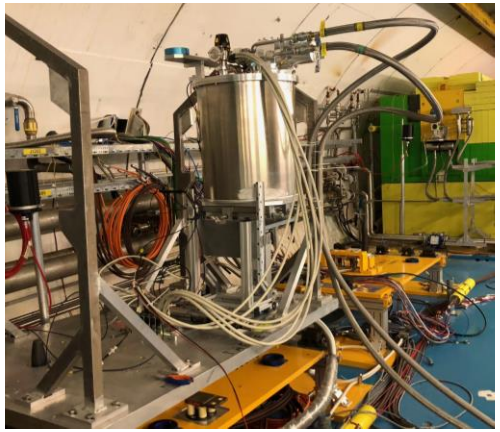
- SC gantries for proton/heavy-ion therapy
- SC RF cavities in particle accelerators
- Cryostats in confined/radioactive environments etc. that require separation of cooling source from CIF



SQUID sensors in anti-proton decelerator at CERN

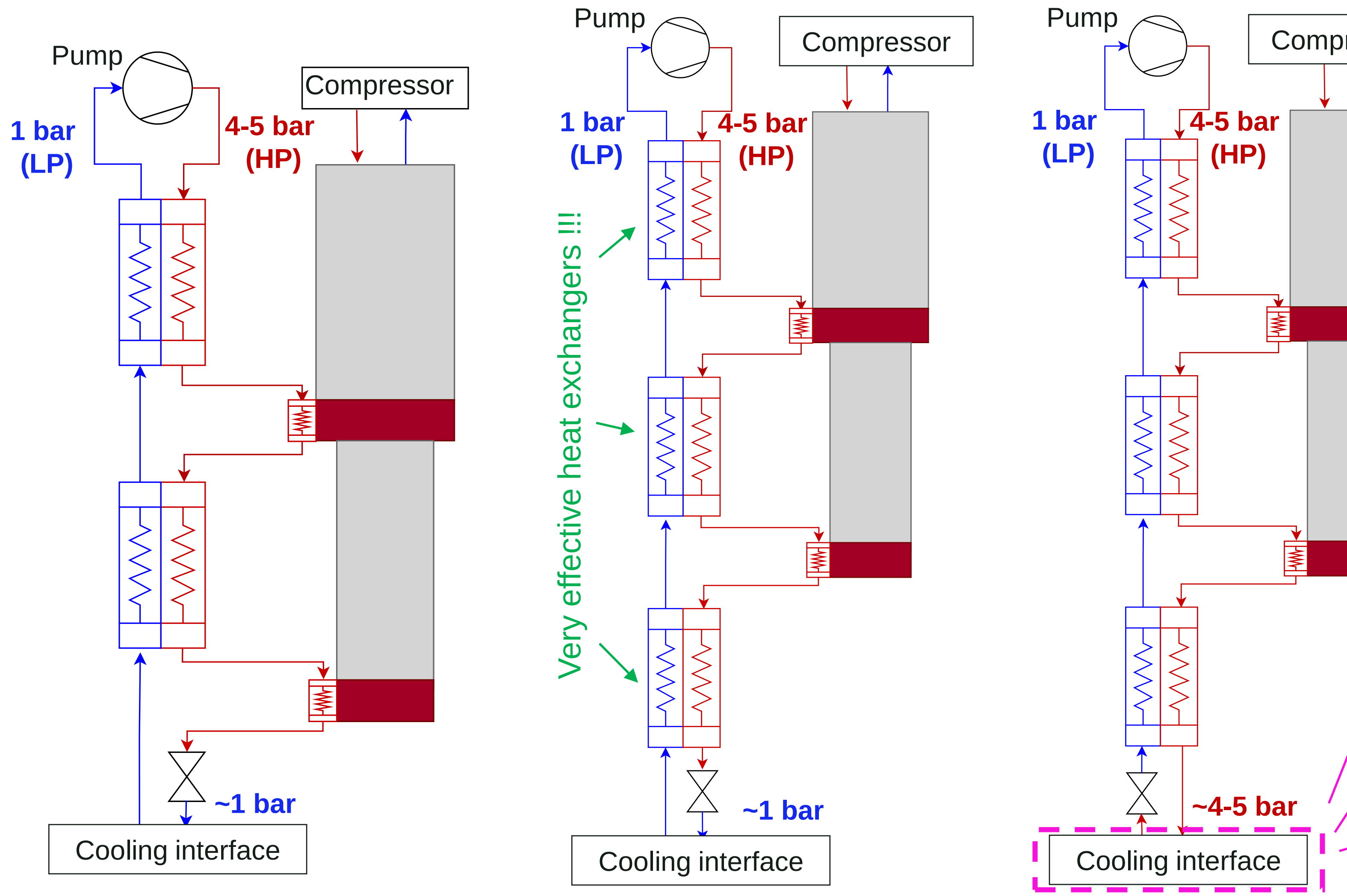


Equipment in high-radiation CHARM facility at CERN

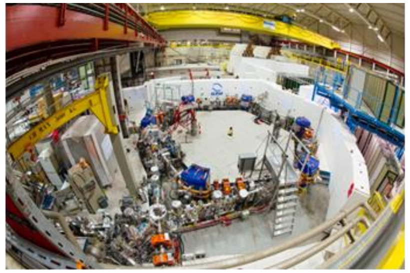
Remote cooling loops

High effectiveness counter-flow heat exchangers (CFHEX)

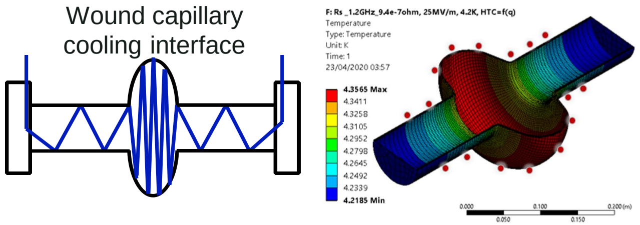
Remote cooling arrangements

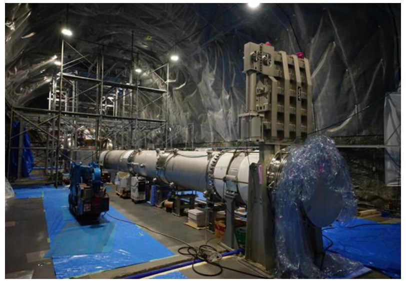


Option for SQUID sensor cooling in CERN Antiproton Decelerator



Alternative cooling of superconducting RF cavities for particle accelerators



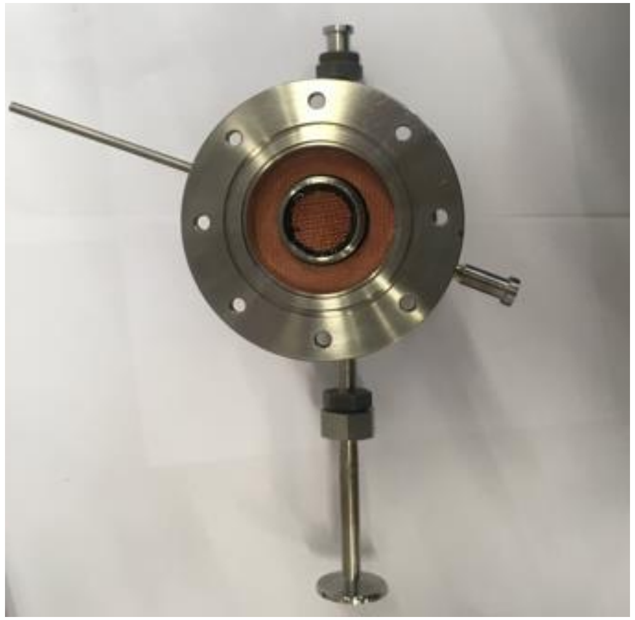


Cryogenic mirrors of gravitational wave detectors (e.g. KAGRA)

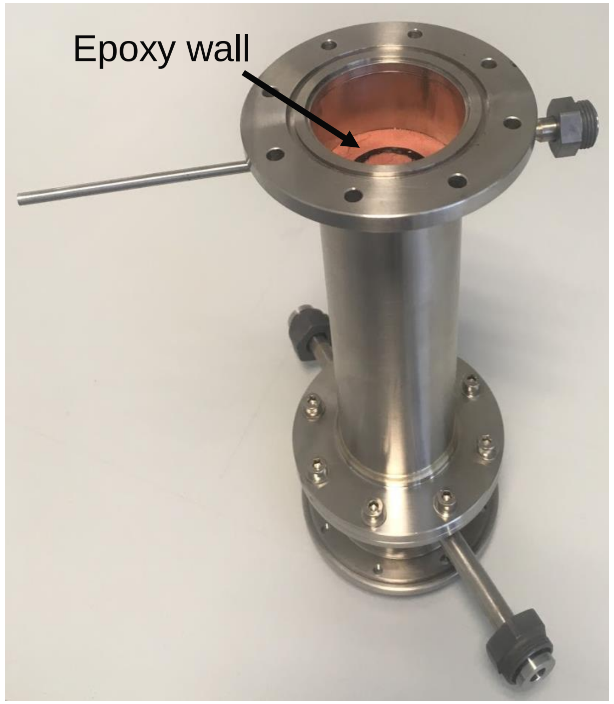
Transparent-wall concept

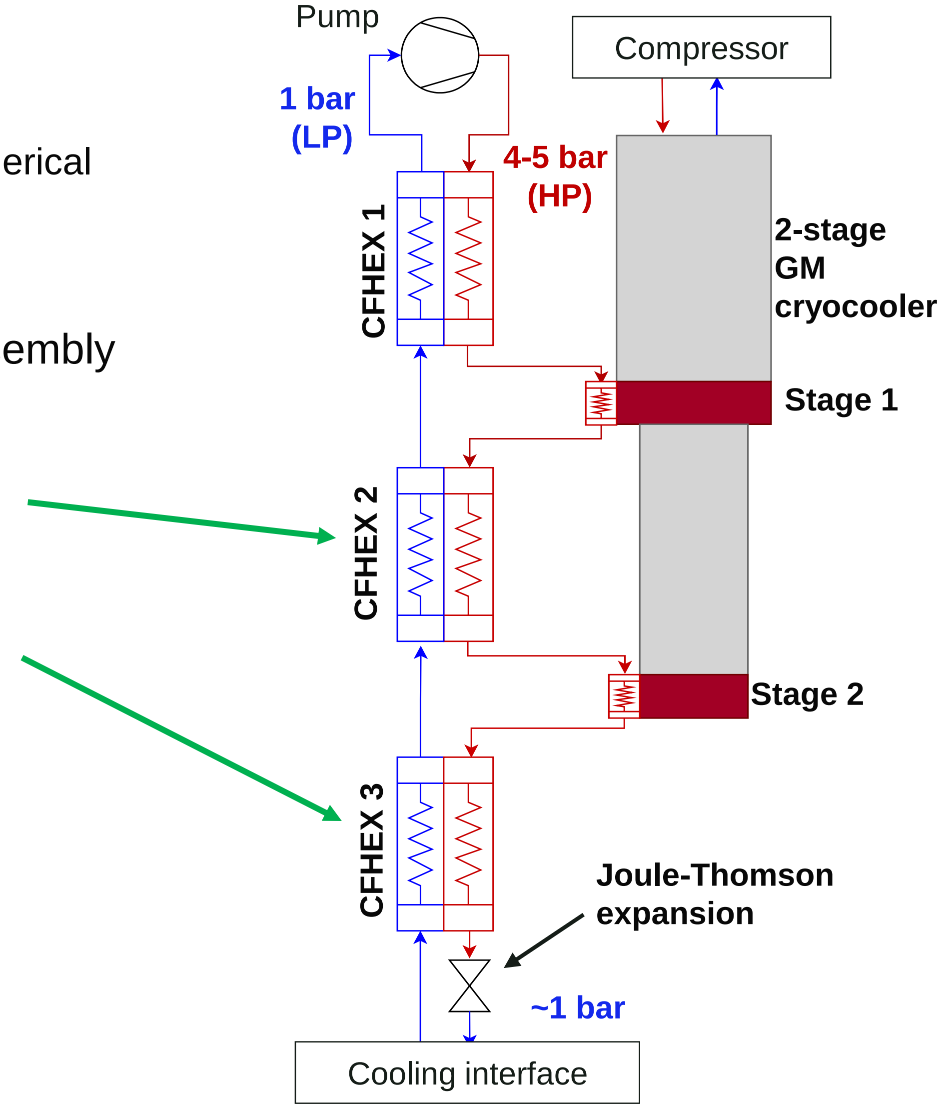
- Careful sizing for operation in the 10 K - 50 K and 4.5 K – 10 K ranges using the numerical model [1]

Top view



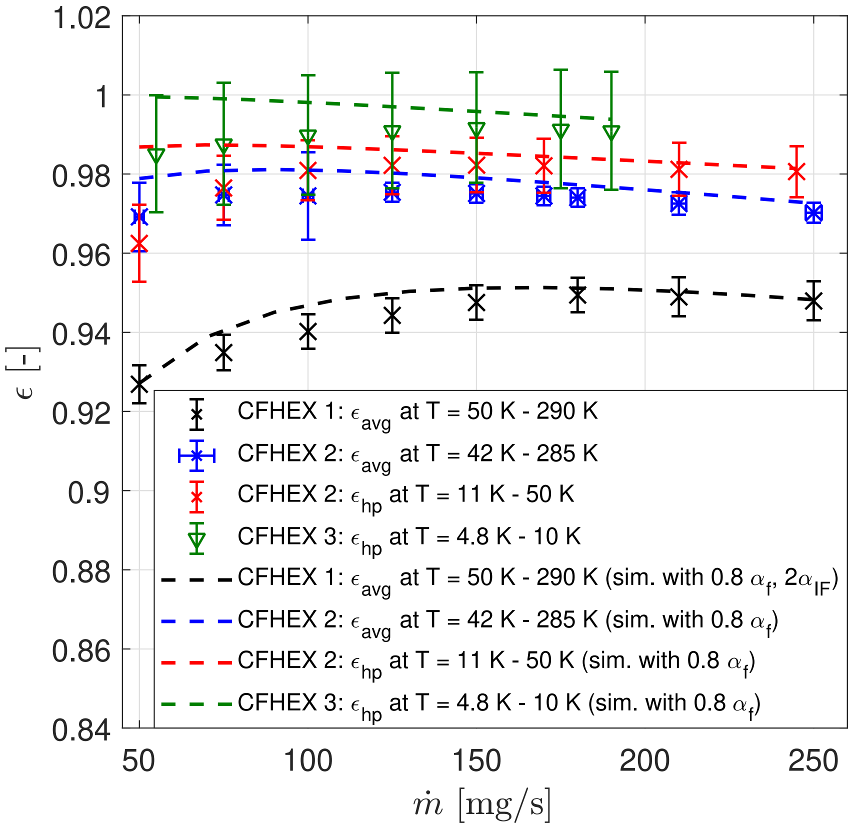
Transparent-wall CFHEX during assembly

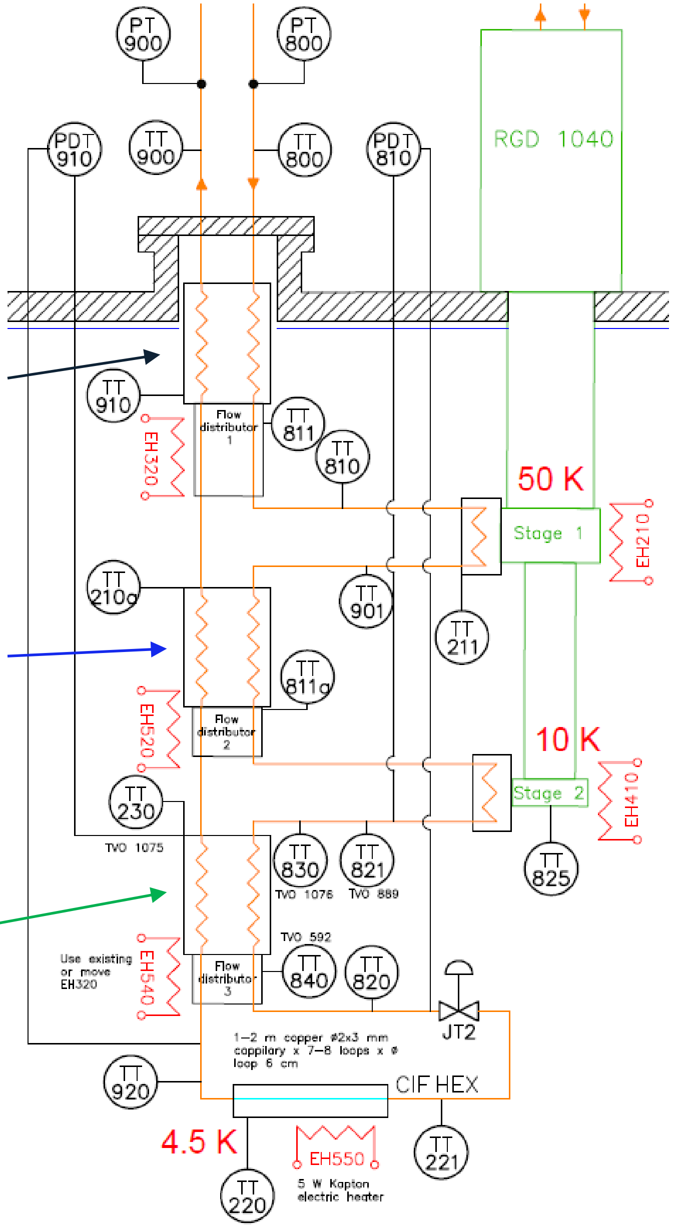




Performance: CFHEX effectiveness

- Transparent-wall designs were implemented for the two coldest CFHEXs
- Very high experimental performance achieved with the novel transparent-wall design





NTU=18.6

($\epsilon = 94.9$ %)

NTU = 55

($\epsilon = 98.2$ %)

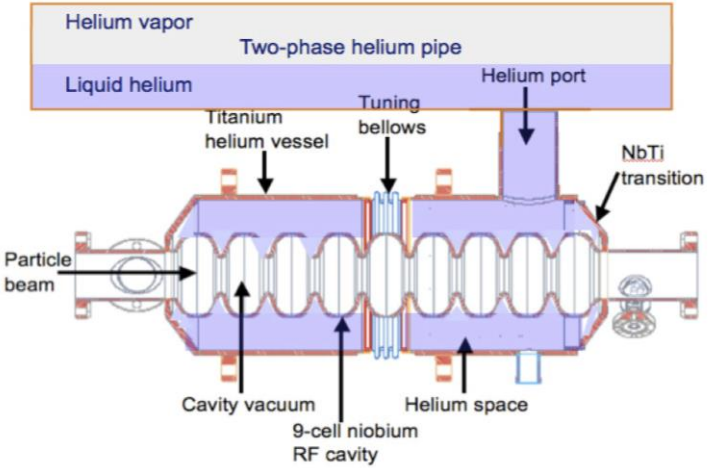
NTU >124

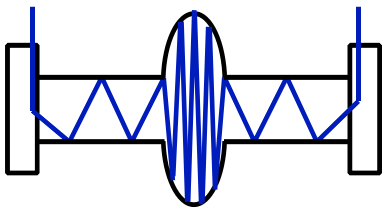
($\epsilon = 99.2$ %)

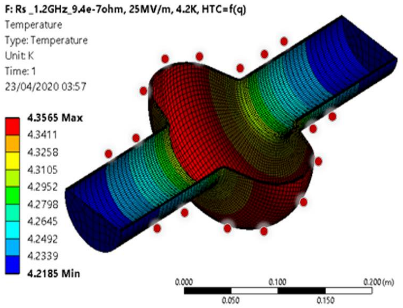
Application examples

Applications: dry SRF cavity cooling

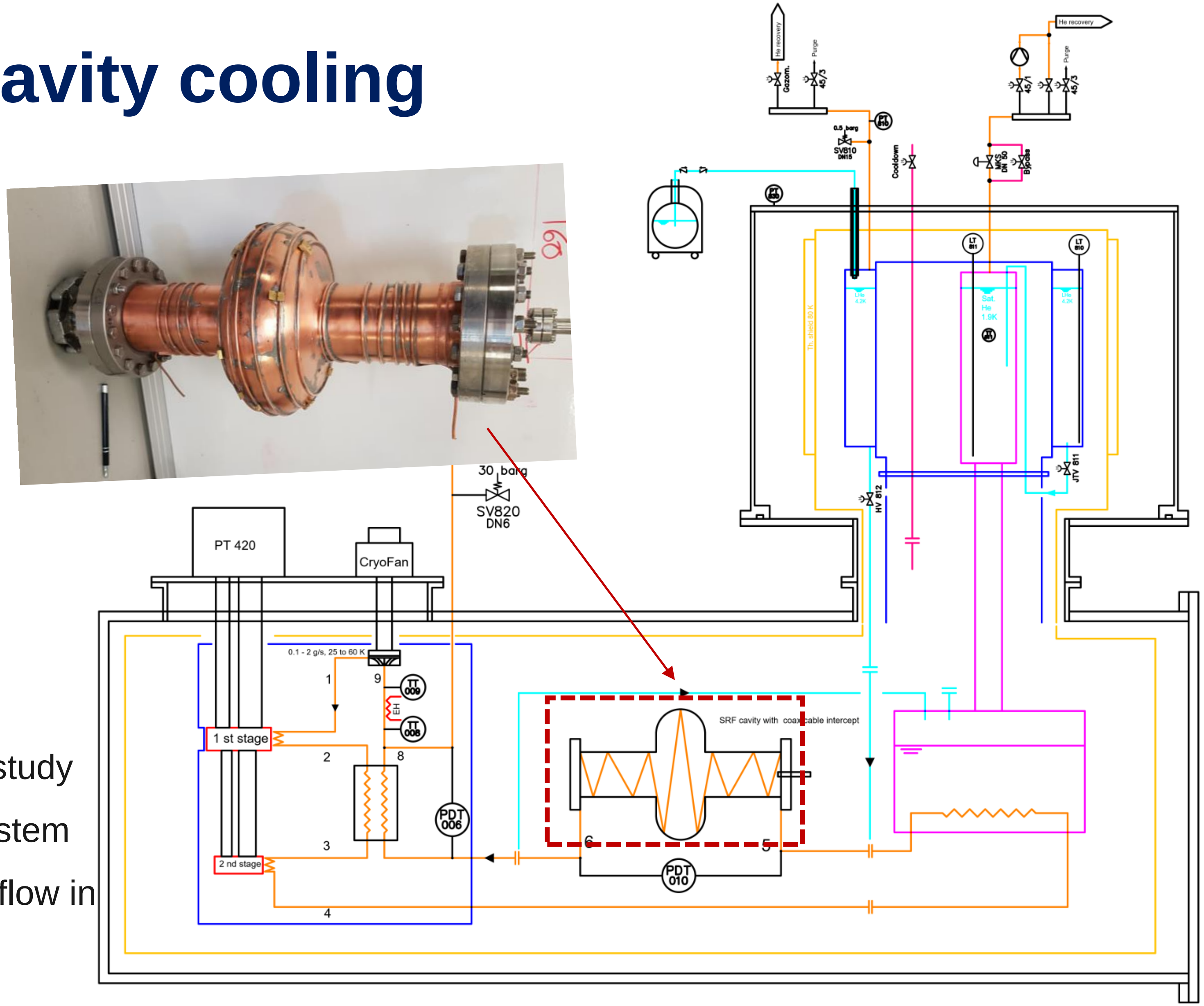
Dry cooling principle



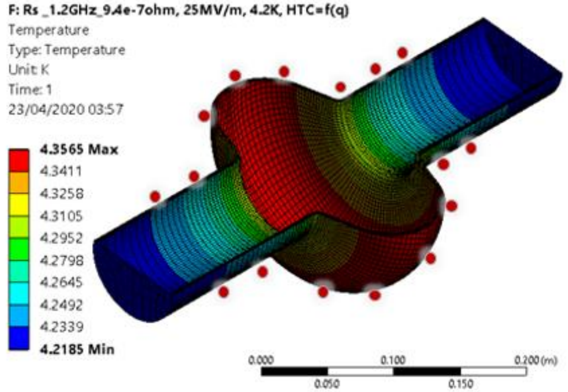




Test setup to study dry colling (system performance, flow in the capillary)



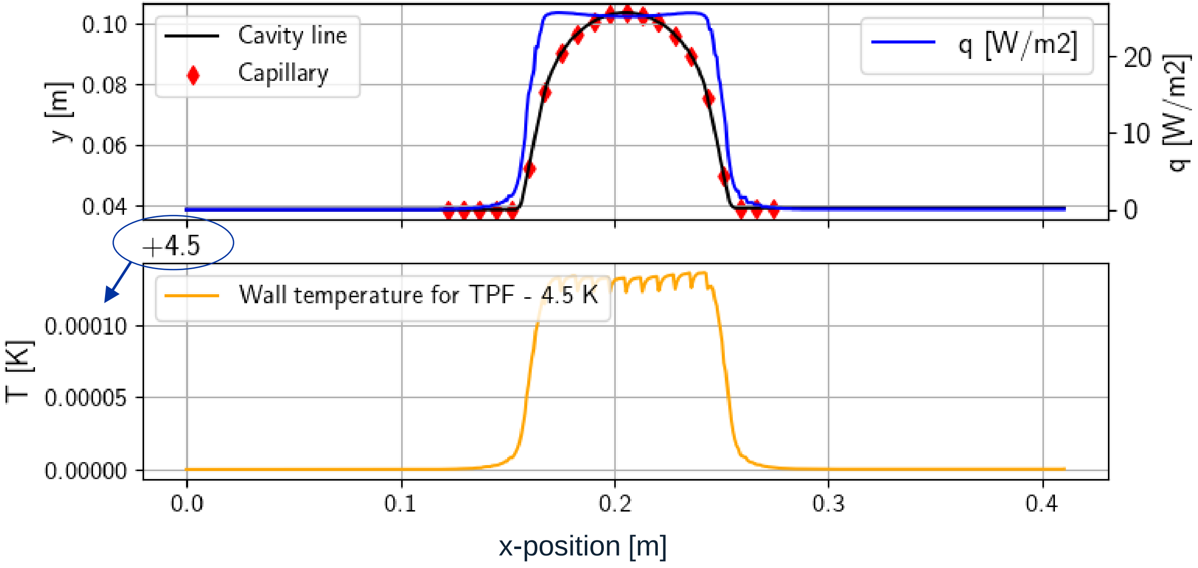
Cavity wall temperature distribution



Numerical simulation!
to be validated by the experiments

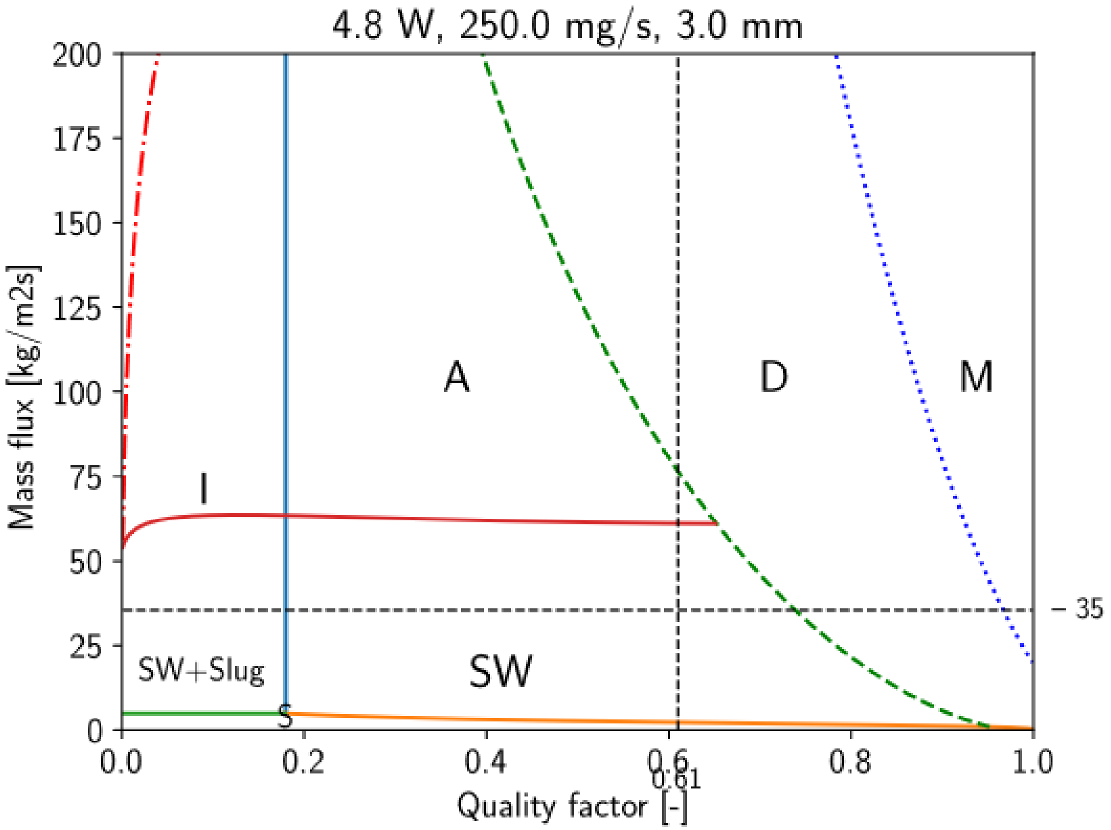
He two-phase flow (TPF)

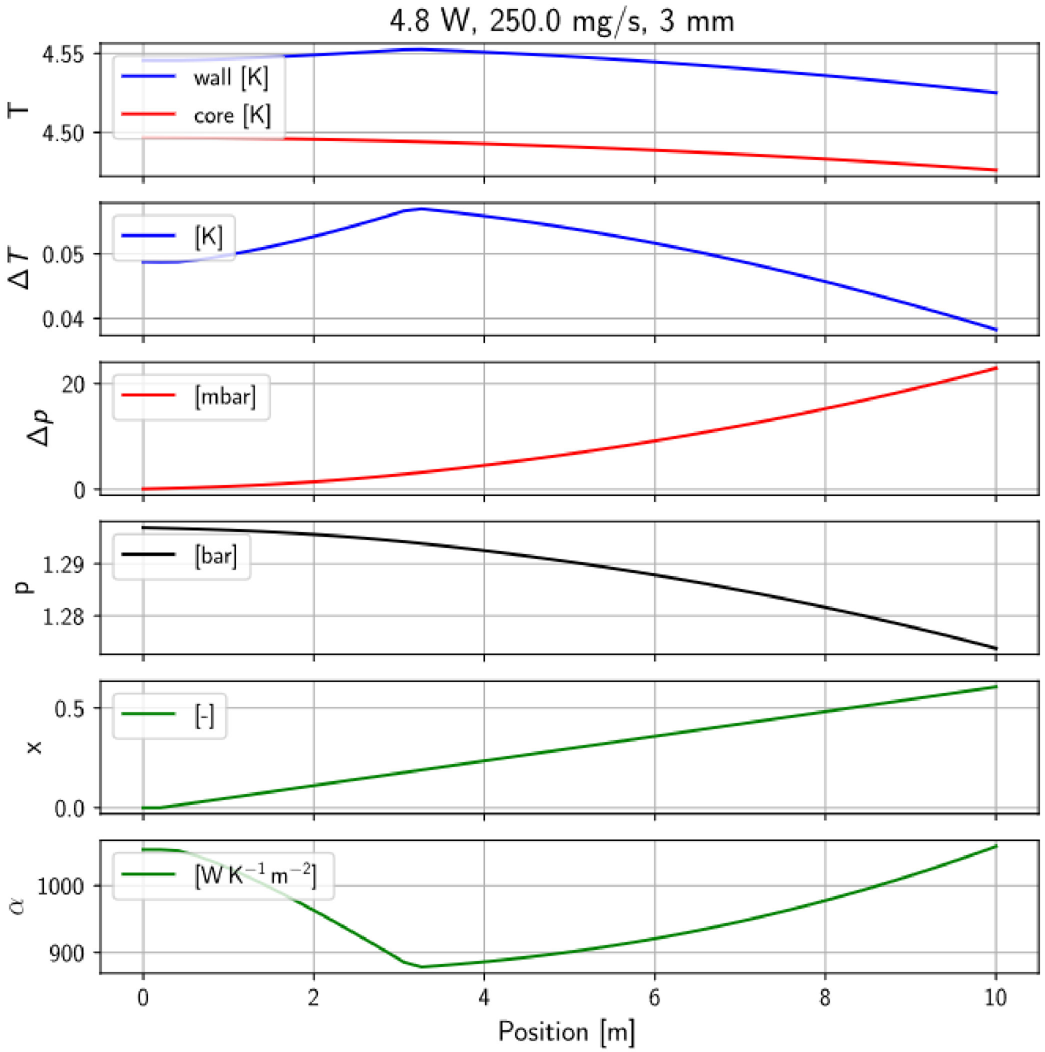
Capillary: 21 loops, spacing 0.75 cm, length 10.57 m, power 2 W



Two-phase flow – flow pattern map calculations

Heat loads and mass flow





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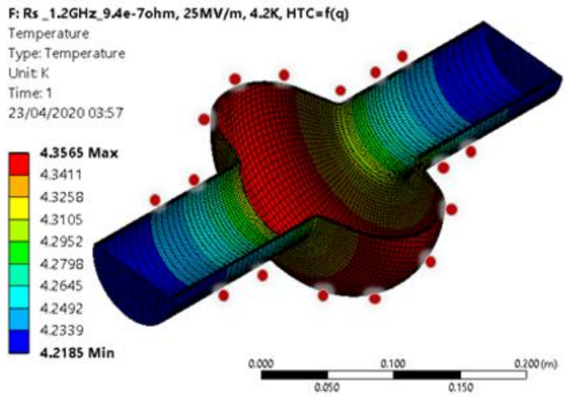

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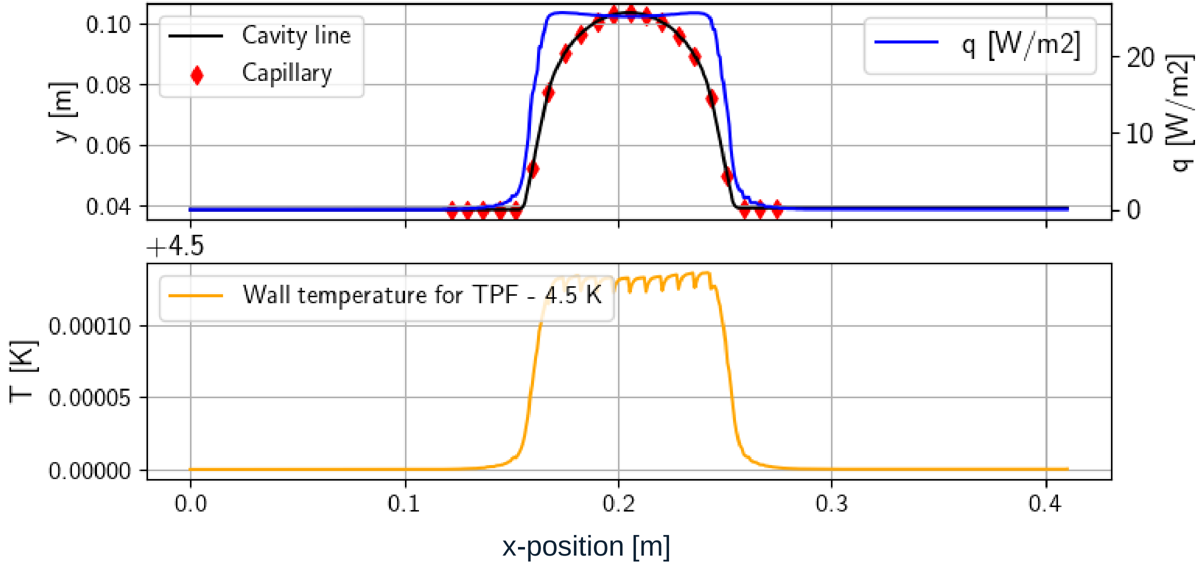
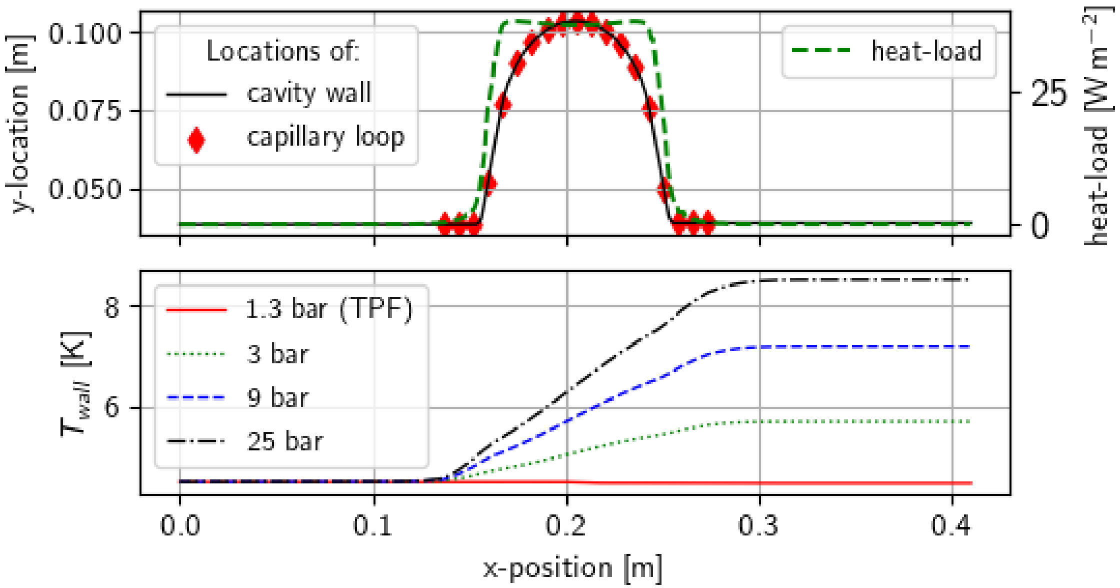


Flow options – a comparison

Capillary: 21 loops, spacing 0.75 cm, length 10.57 m, power 3 W

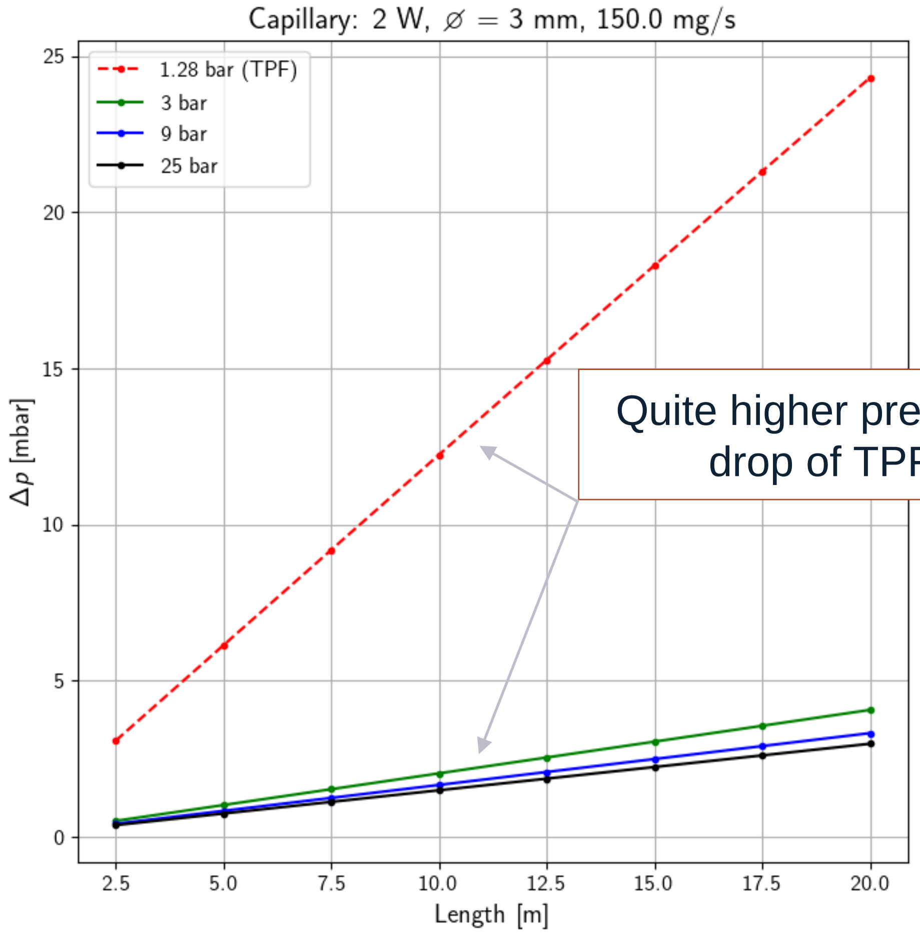


Courtesy: A. Onufrena et al. CEC 2021, IOP Conf. Series: Materials Science and Engineering

Optimum cooling tube diameter/length/fluid pressure

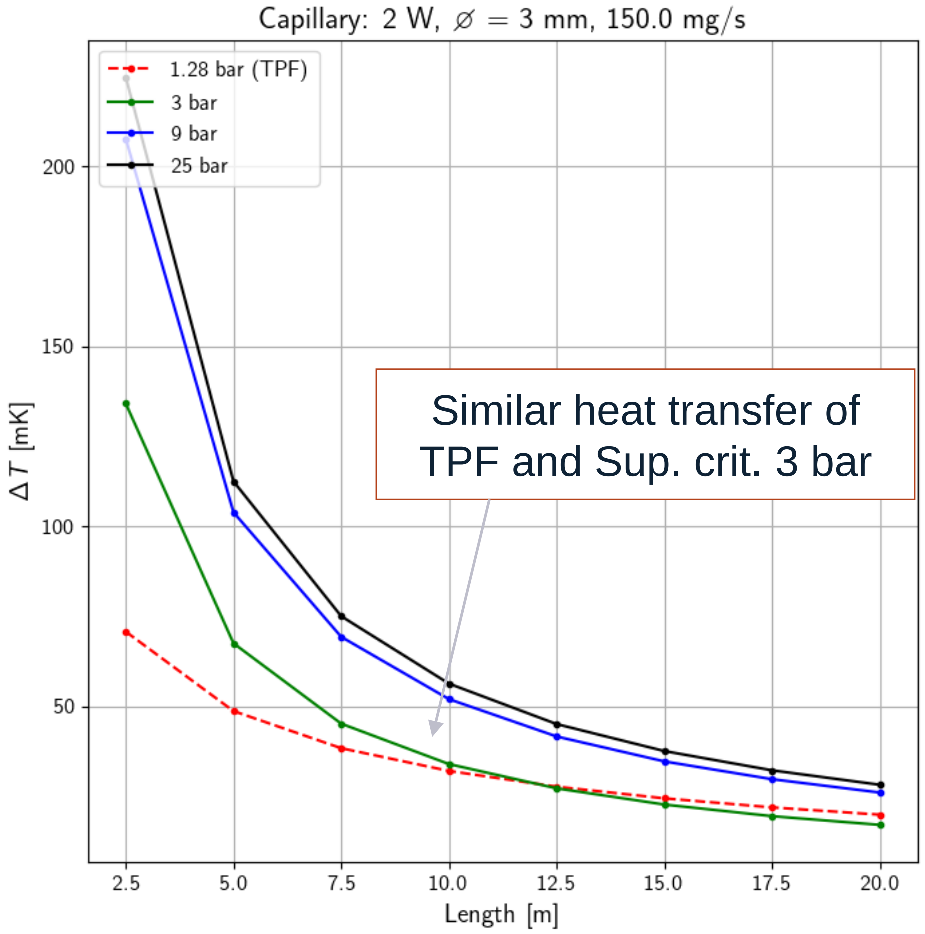
Numerical simulation of friction and heat transfer, a comparison of flow conditions

Pressure drop comparison



Quite higher pressure drop of TPF

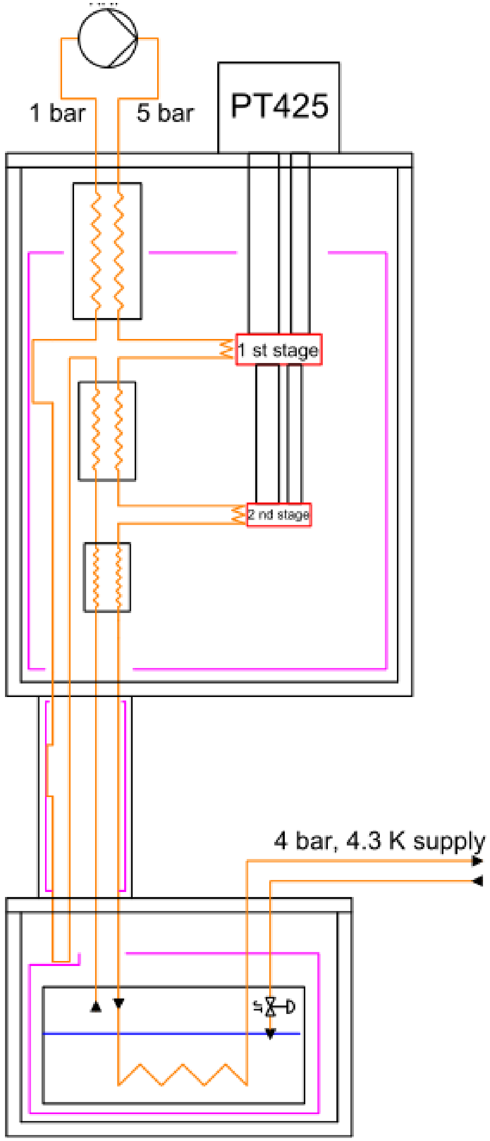
Temperature difference tube wall to fluid core



Similar heat transfer of TPF and Sup. crit. 3 bar

Remote cooling loops with boosted performance

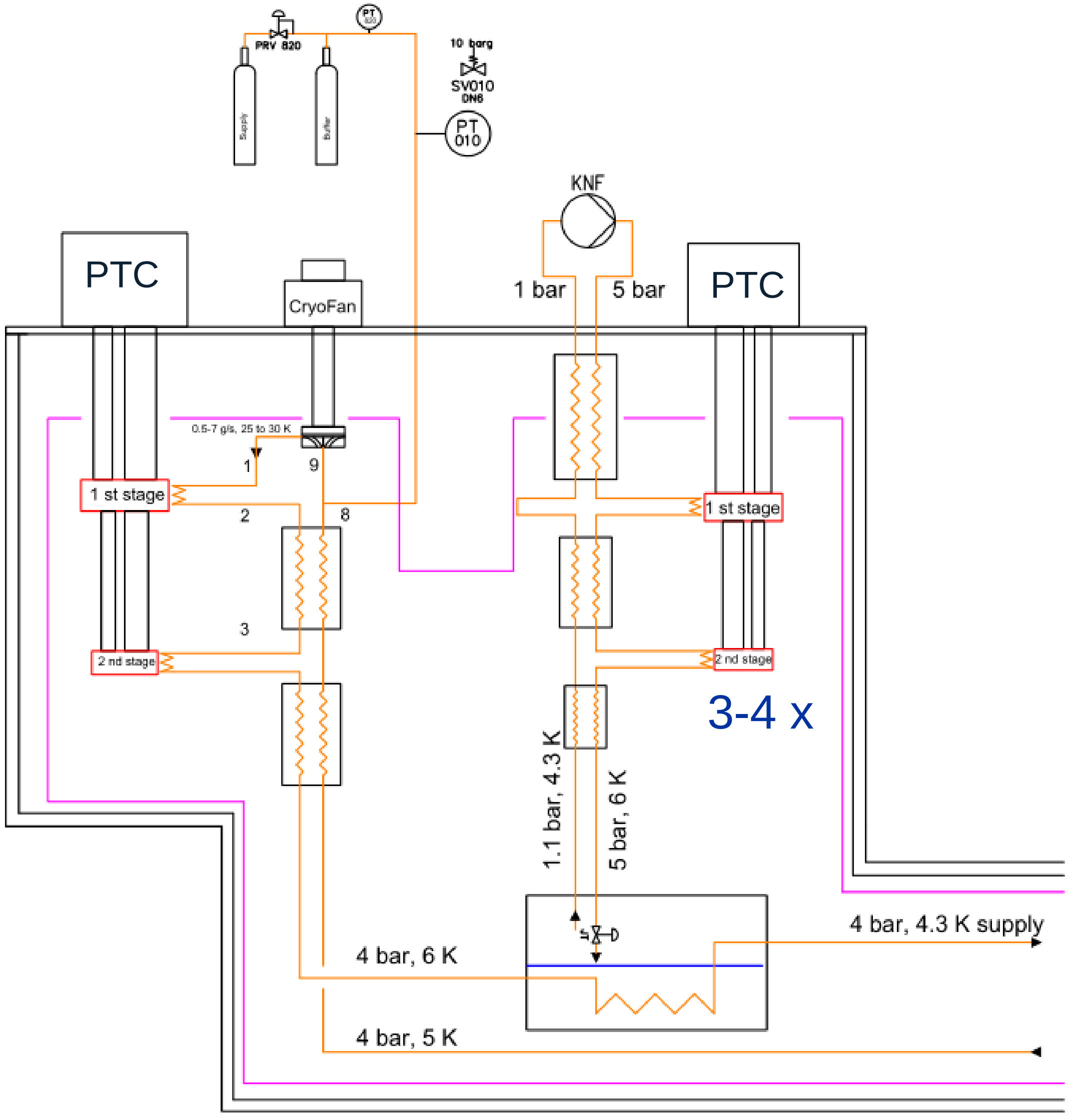
Subcooled 4 bar cooling loop



Remarks:

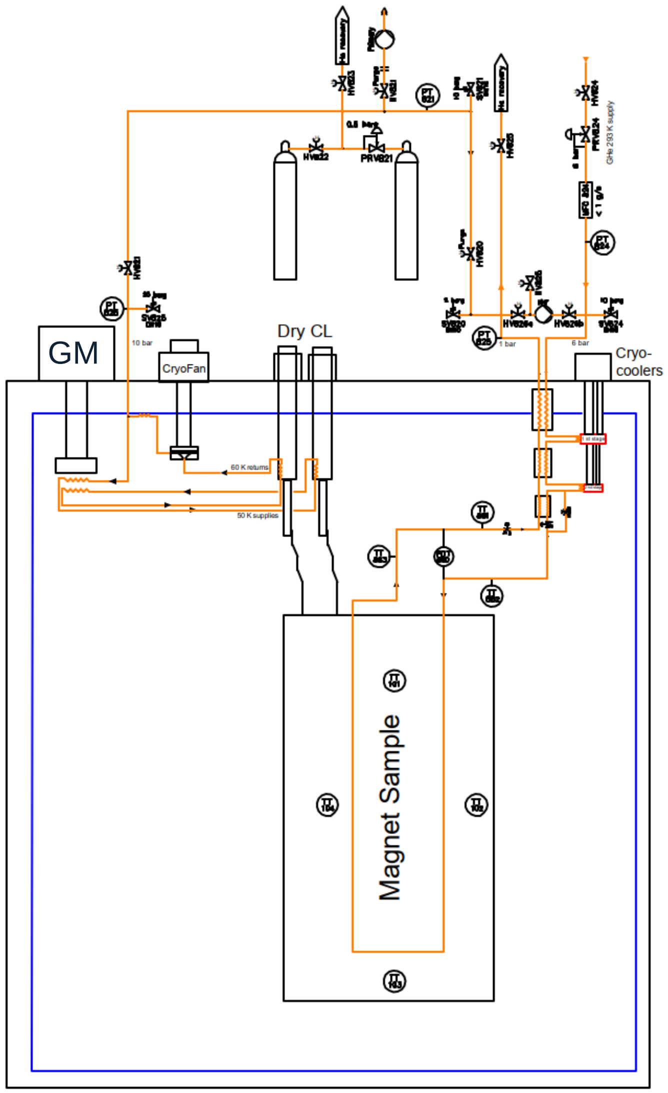
- Single phase flow above crit. pressure
- Good heat transfer
- CryoFan works better at higher pressure (density)
- JT cryocooler systems exit in industry e.g. 9 W @ 4.2 K

Subcooled 4 bar cooling loop – high Q

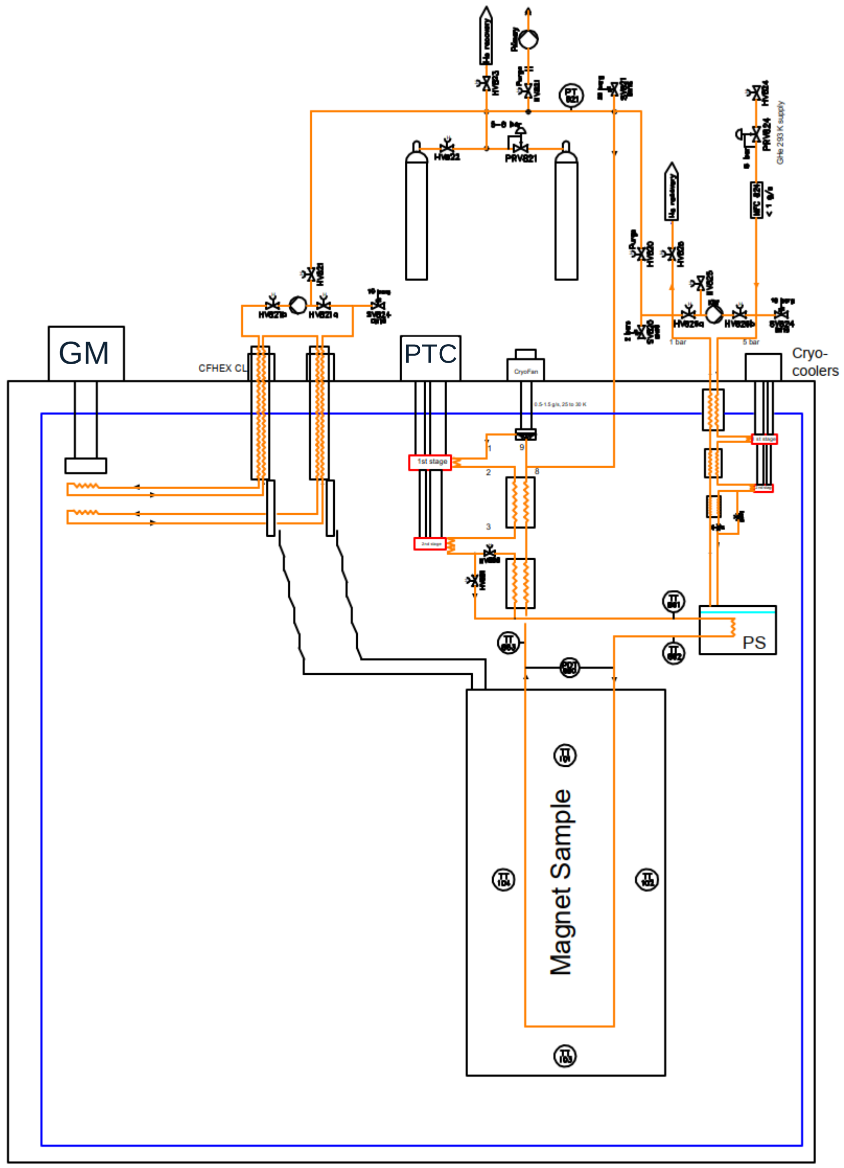


Envisaged dry cooling test stations at the Cryolab at CERN

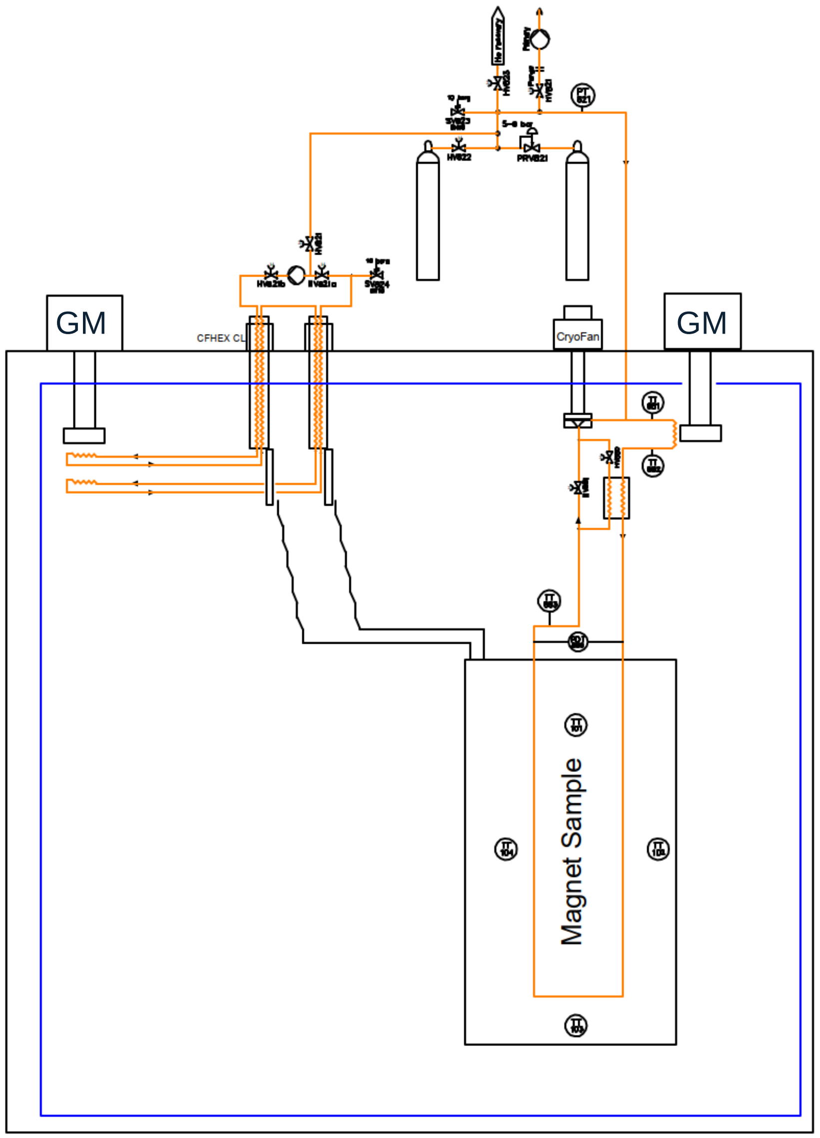
4.25 K two-phase flow
or SC m< 1 g/s



4.5 K<T<10 K, SC m< 1.5 g/s



18 K<T<25 K, SC m< 5 g/s



Summary

- **Dry cooling**
  - Enables effective cooling of novel magnet, cavity and detector concepts
  - Enables stand alone systems with a physical separation between the cooling source and the object
  - Small test stations with an emphasis on large scale conditions
  - Future developments towards higher Tc materials Nb_3Sn on Cu for cavities or HTS magnets => 20 K

- **Numerical** assessment of fluid flow heat transfer and conduction pathway is required:
  - Benefits from reliable, experimentally obtained material properties and interface data
  - Enables the parametric study of heat transfer mechanisms in large-scale complex structures
  - Can be used early on to aid in magnet design w.r.t. heat extraction and safe operating temperatures

Thank you for your attention!