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Design of the cryogenic loop for the superconducting toroidal field magnets of the Divertor Tokamak Test

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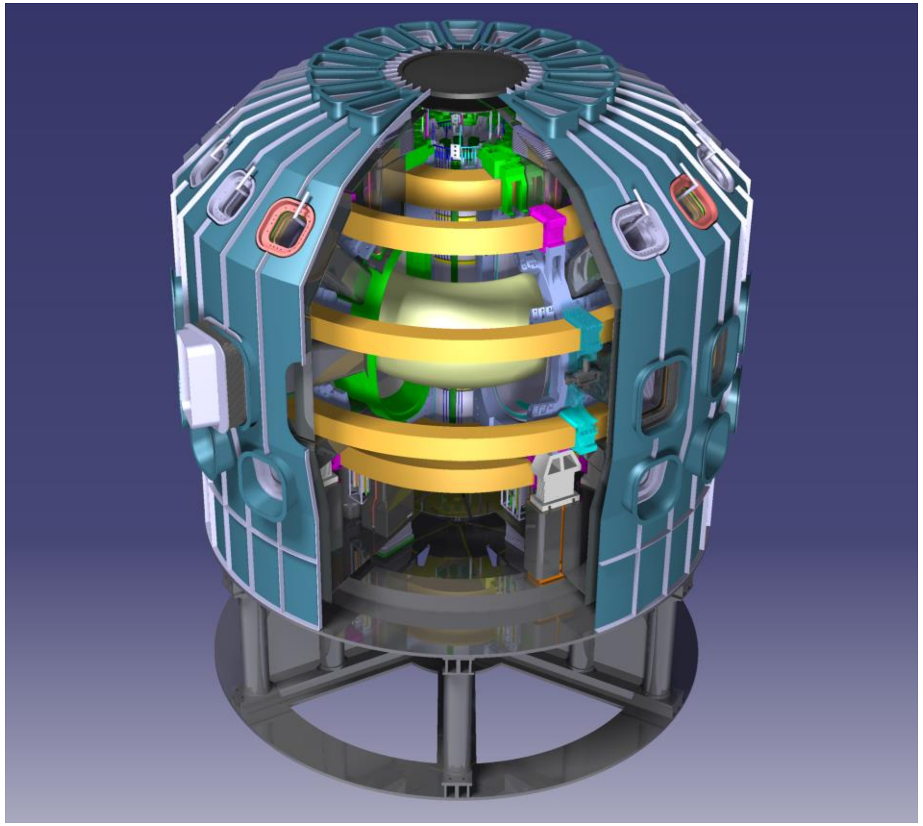
Outline

- The DTT facility and cryogenic loops
- Aim of the work
- Cryoline dimensioning
- 4C system-level model for the reference TF cooling loop
  - Results
- Alternative TF cooling strategies
  - Results
- Conclusions and perspectives

Divertor Tokamak Test (DTT) facility

- DTT → Tokamak under construction at ENEA Frascati research center
- High field **superconducting (SC) tokamak** (6T) carrying 5.5 MA plasma current (~ 100 s plasma pulses)
- AIM OF THE PROJECT: investigate alternative power exhaust solutions in EU DEMO relevant conditions
- **LTS magnets** (actively cooled at ~4.5 K)



[DTT Project website, accessed on April 2023]

- Major radius R_0 = 2.19 m
- Minor radius a = 0.7 m

DTT SC magnets system

- SC magnets cooled to their operative temperature by **SHe at 4.5 K and ~5 bar**
- Cable-in-conduit conductor (CICC) configuration adopted
- SHe distribution to magnets (& other cryogenic users) by suitable **cryogenic loops**

6 Central Solenoid (CS) module coils
Nb_3Sn CICCs

18 Toroidal Field (TF) coils
Nb_3Sn CICCs

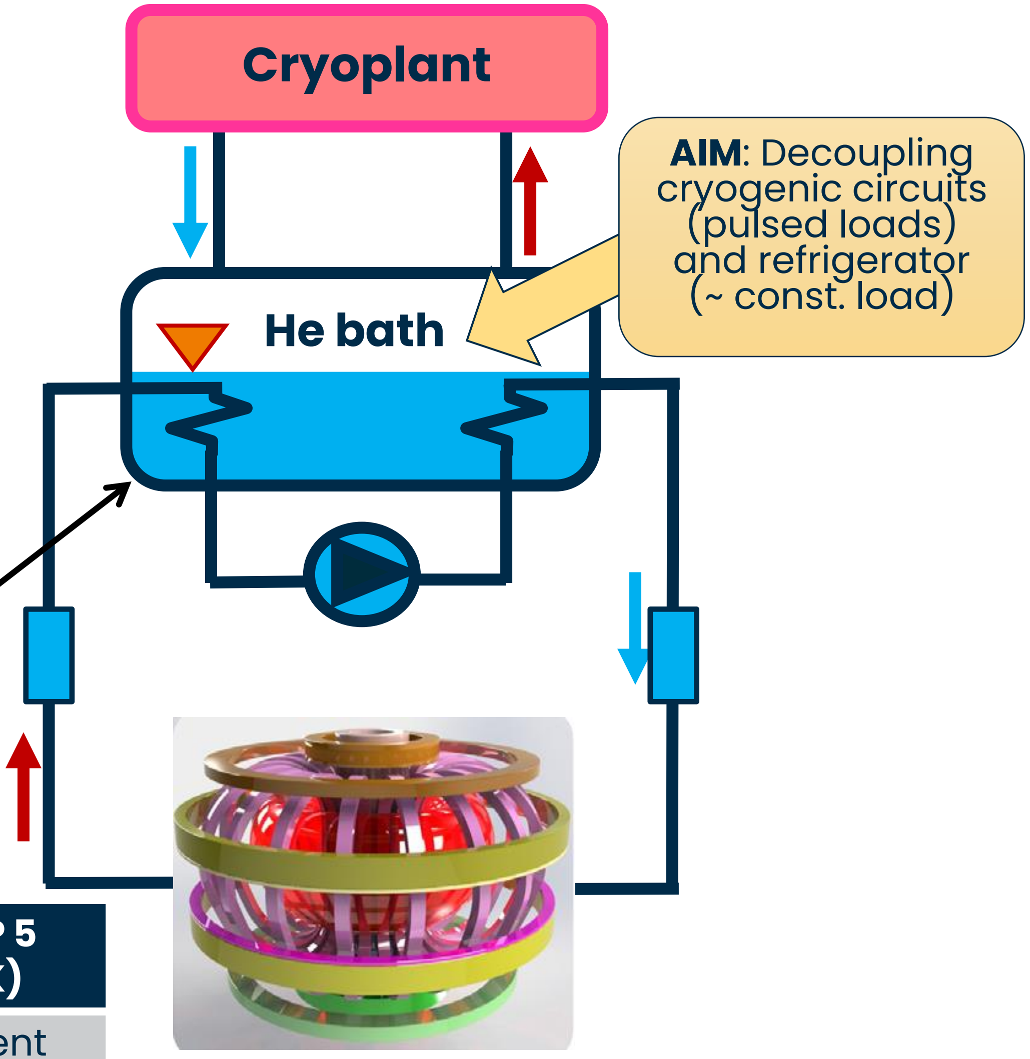
6 Poloidal Field (PF) coils
- 4 NbTi
- 2 Nb_3Sn

CICCs

[A. Di Zenobio, et al., FED 2017]

DTT cooling loops

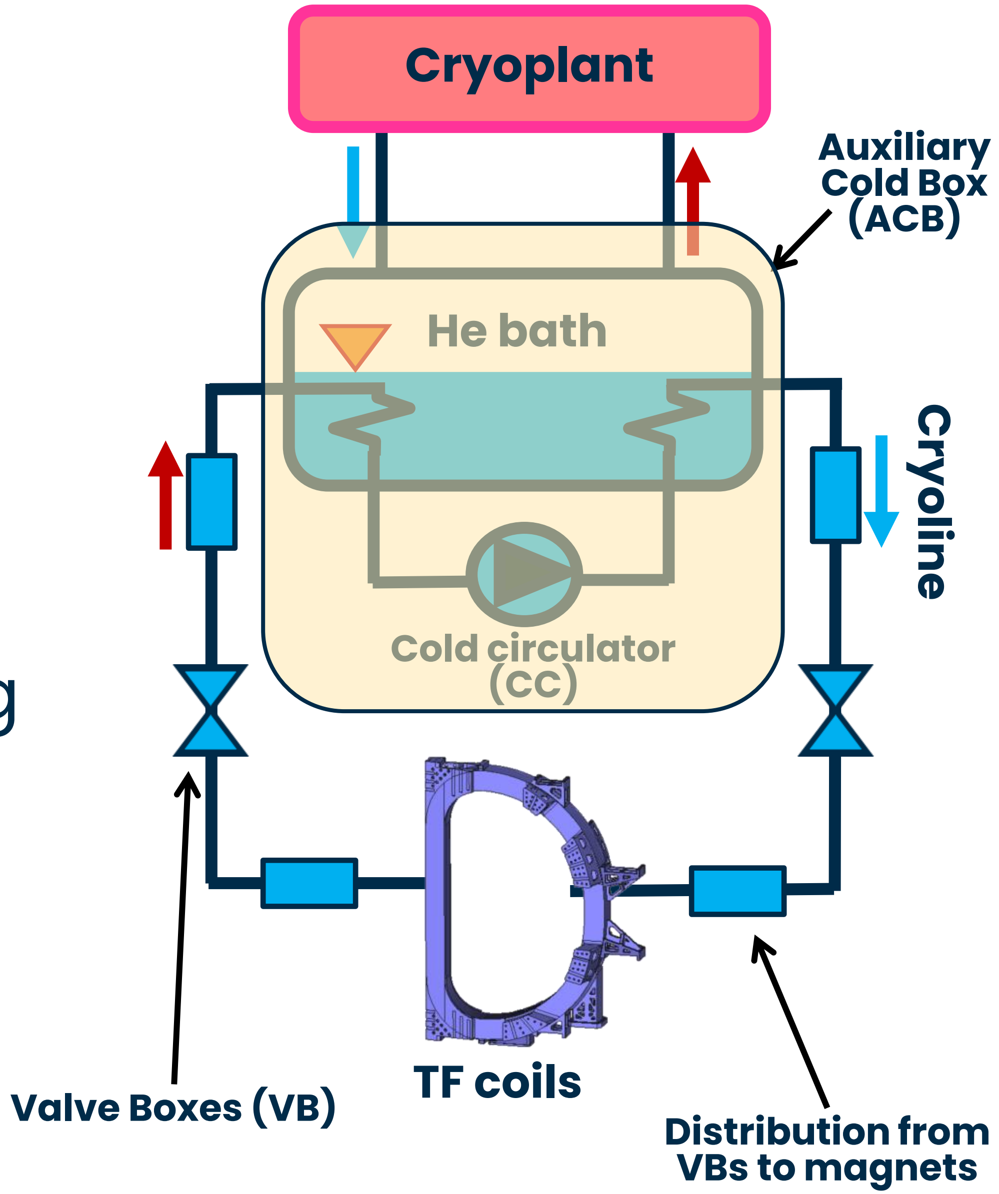
- **5 cooling circuits** for the different cryogenic users at different working temperatures (i.e. 4.5 K, 50 K & 80 K)
- Magnets cooling loops should be able to handle both **static heat load** from the cryostat, and **pulsed heat load** deposited in coils during the plasma operation
- Heat transferred to a thermal buffer (→ saturated liquid **He bath**)



LOOP 1 (4,5 K)	LOOP 2 (4.5 K)	LOOP 3 (4.5 K)	LOOP 4 (80 K)	LOOP 5 (50 K)
TF WP & casings + gravity support thermal anchor	PF, CS coils	Cryopanels of the cryopumps	Thermal shield, GS, cryopump chevron baffles, VB&CTB th. shield	Current leads

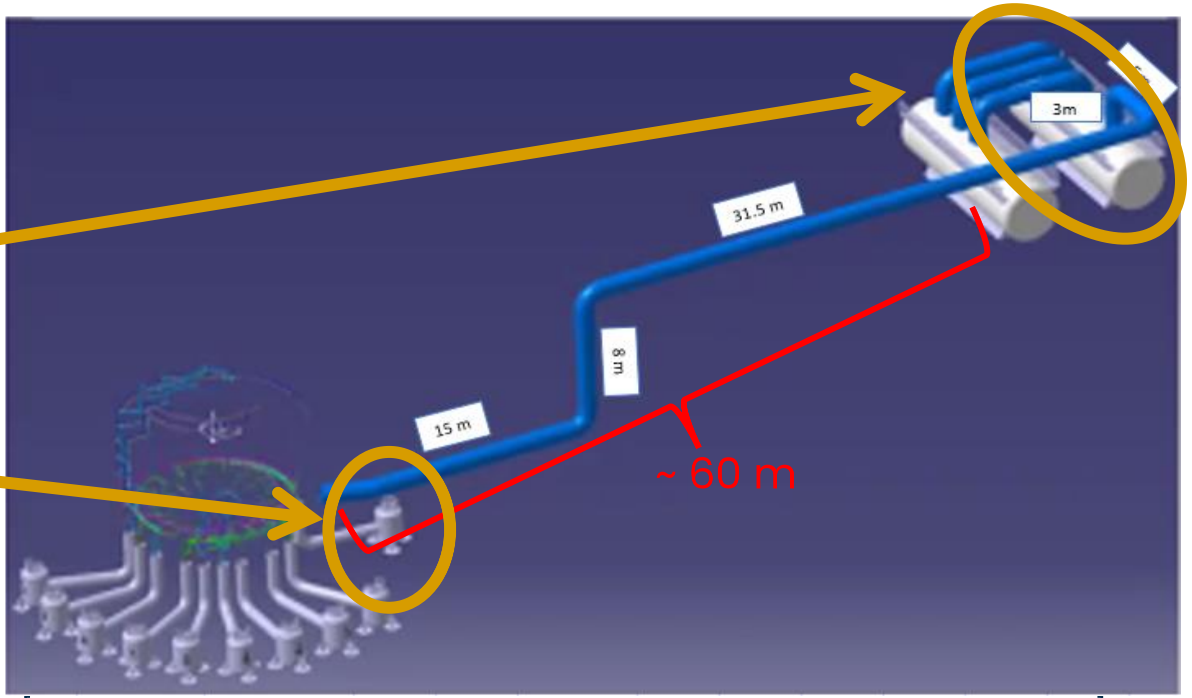
Aim of the work

- Develop system-level dynamic models of the DTT TF cooling loop **using the state-of-the-art 4C code**
- Preliminary dimensioning of main distribution lines for **TF cooling loops**
- Simulate different layouts and cooling strategies during pulsed plasma operation to **support the design optimization** of the DTT TF cryogenic circuit



Cryodistribution – DTT cryoline

- DTT cryoline → L=60 m
- SHe supply from the Auxiliary Cold Box (ACB) in the refrigerator building to the Valve Boxes (VBs)
- Contains all the distribution lines for the different cryogenic users (including supply/return lines for TF cooling loop)



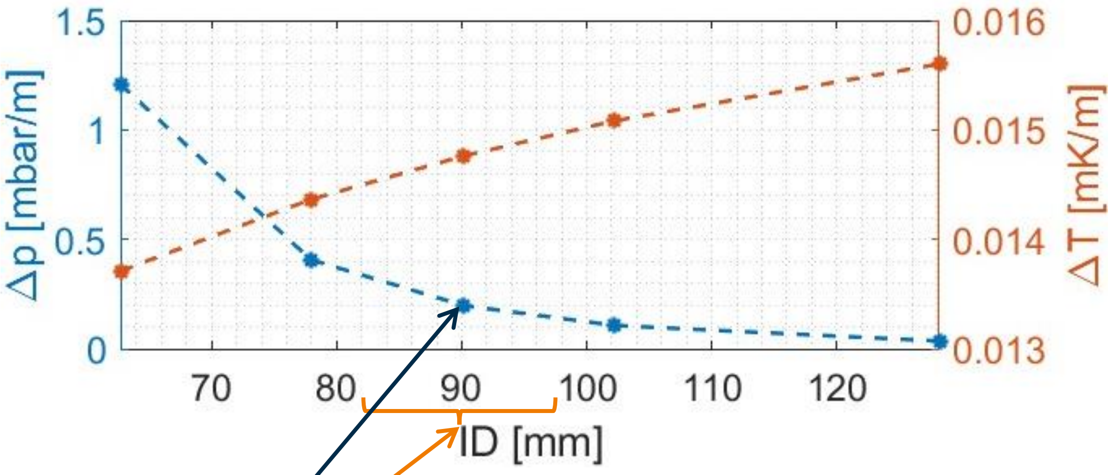
[CAD from: DTT-R14_0R219_20211221_DTT2021-step_DTT2019_00355]

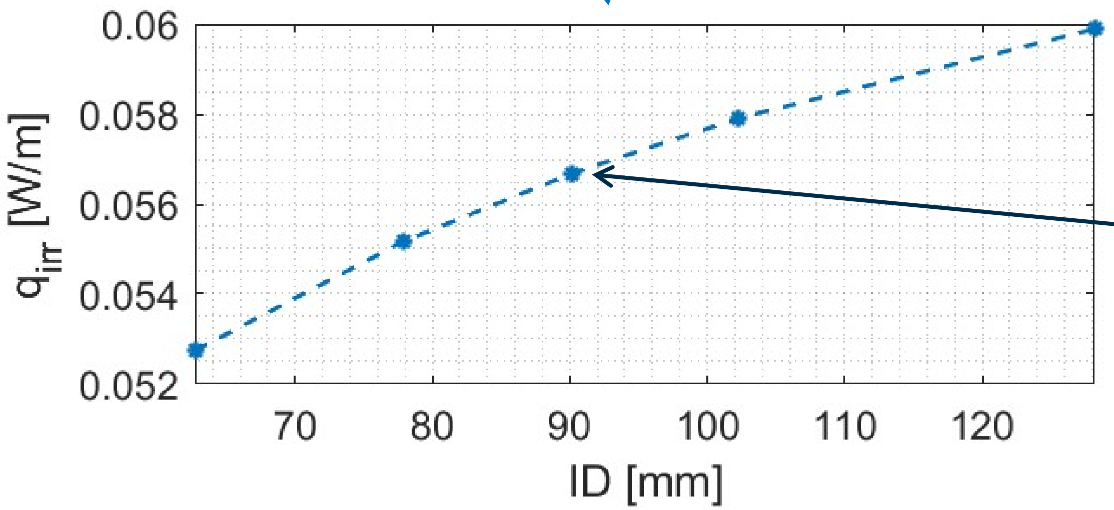
INPUTS for calculation:

- Interface (cryoline external pipe) at **80 K**
- MLI **radiation shield** (emissivity ε = 0.02)
- Pipe relative **roughness** = 0.0003

TF cooling loop cryoline dimensioning

- Choice of the pipe diameter → trade-off between:
  - ➢ **Pressure drop** along the pipe (decreasing as diameter increases)
  - ➢ Radiative **heat losses** (increasing as the diameter increases)





Reasonably low pressure drops and low radiative heat losses at the same time

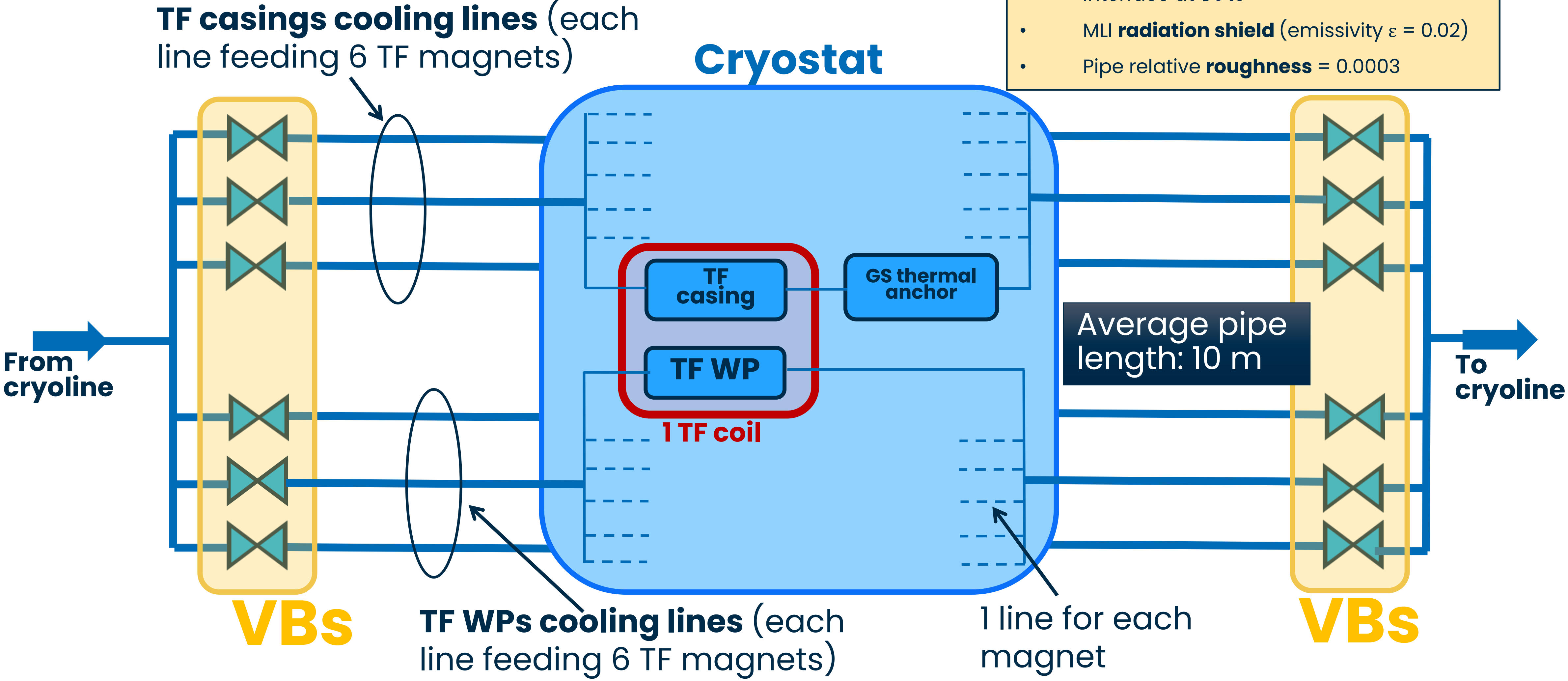
DN90 pipe dimension chosen for the TF (WP + casings) cryoline:

- Pressure drop (~ **0.2 mbar/m**)
- Irradiated flux ~ 0.056 W/m → low ΔT (**0.015 mK/m**)

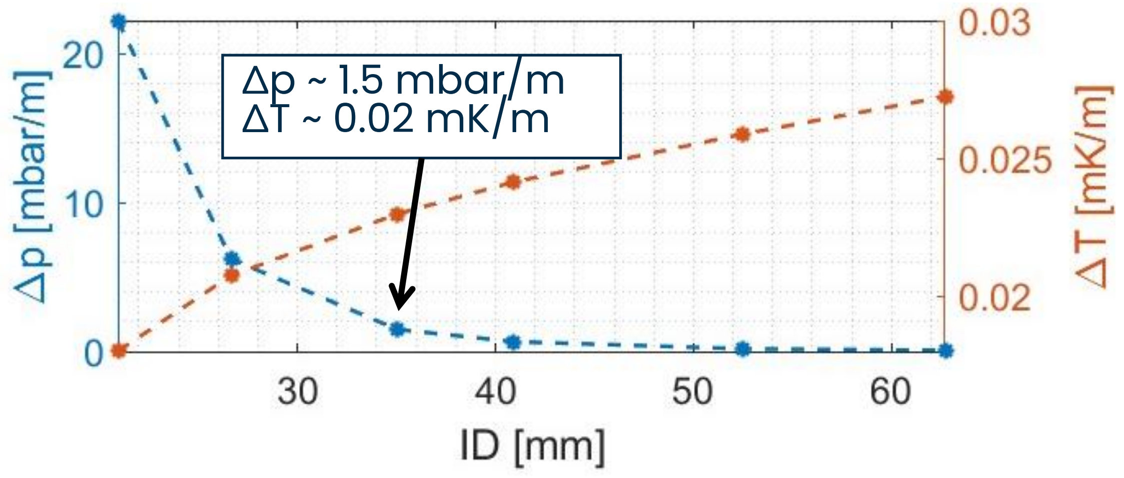
TF distribution from VBs to cryostat

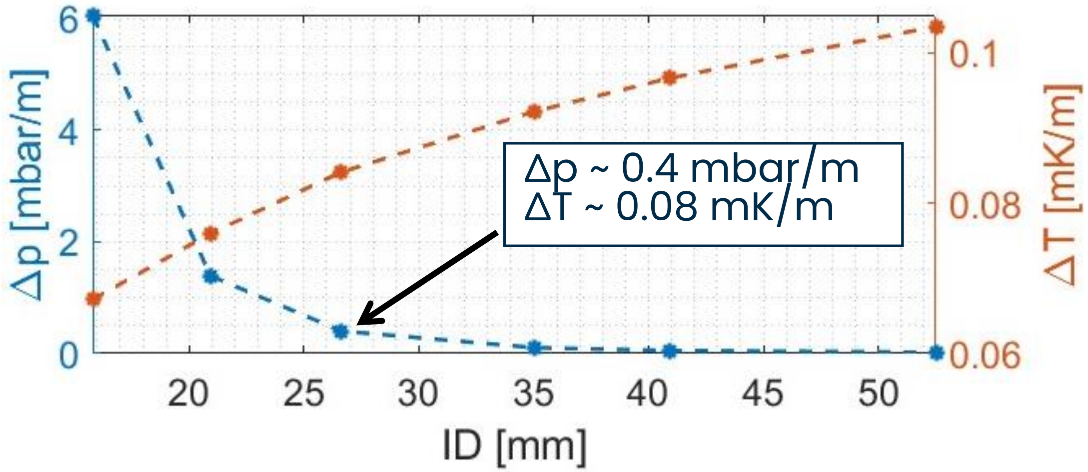
INPUTS for calculations:

- Interface at **80 K**
- MLI **radiation shield** (emissivity ε = 0.02)
- Pipe relative **roughness** = 0.0003



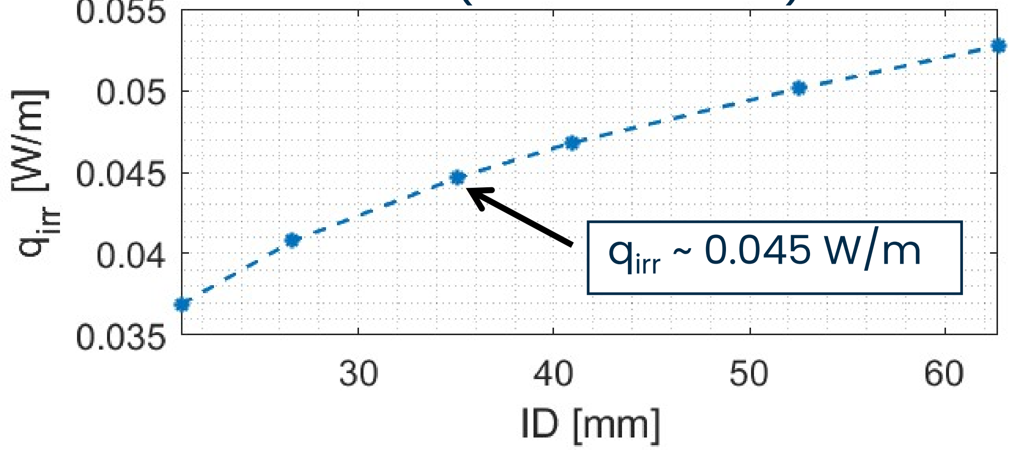
Dimensioning of the distribution lines from VBs to cryostat

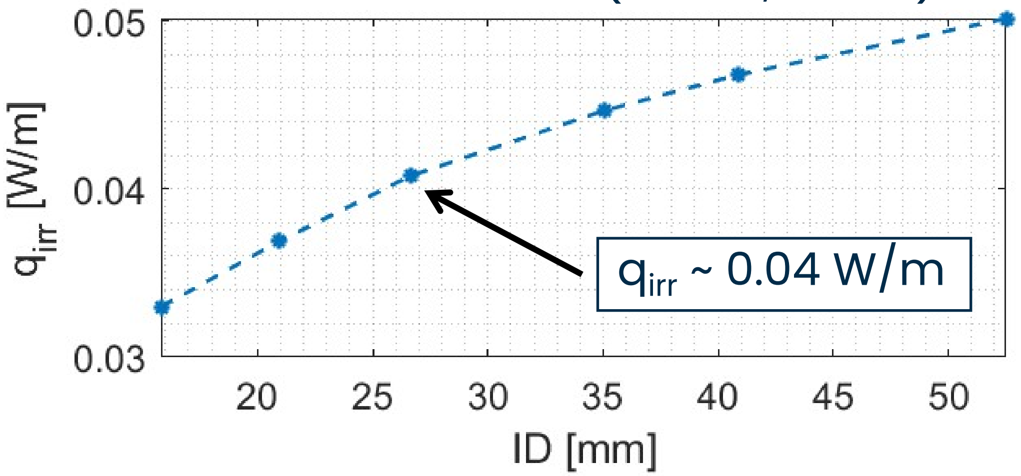




TF WPs → **DN32 pipe** (OD 42.16 mm)

TF casings → **DN25 pipe** (OD 33,4 mm)

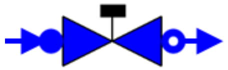
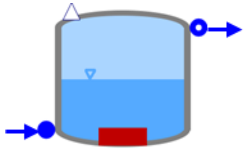
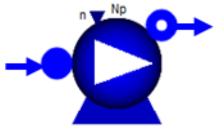
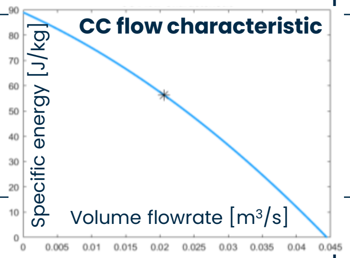




Main components of the model

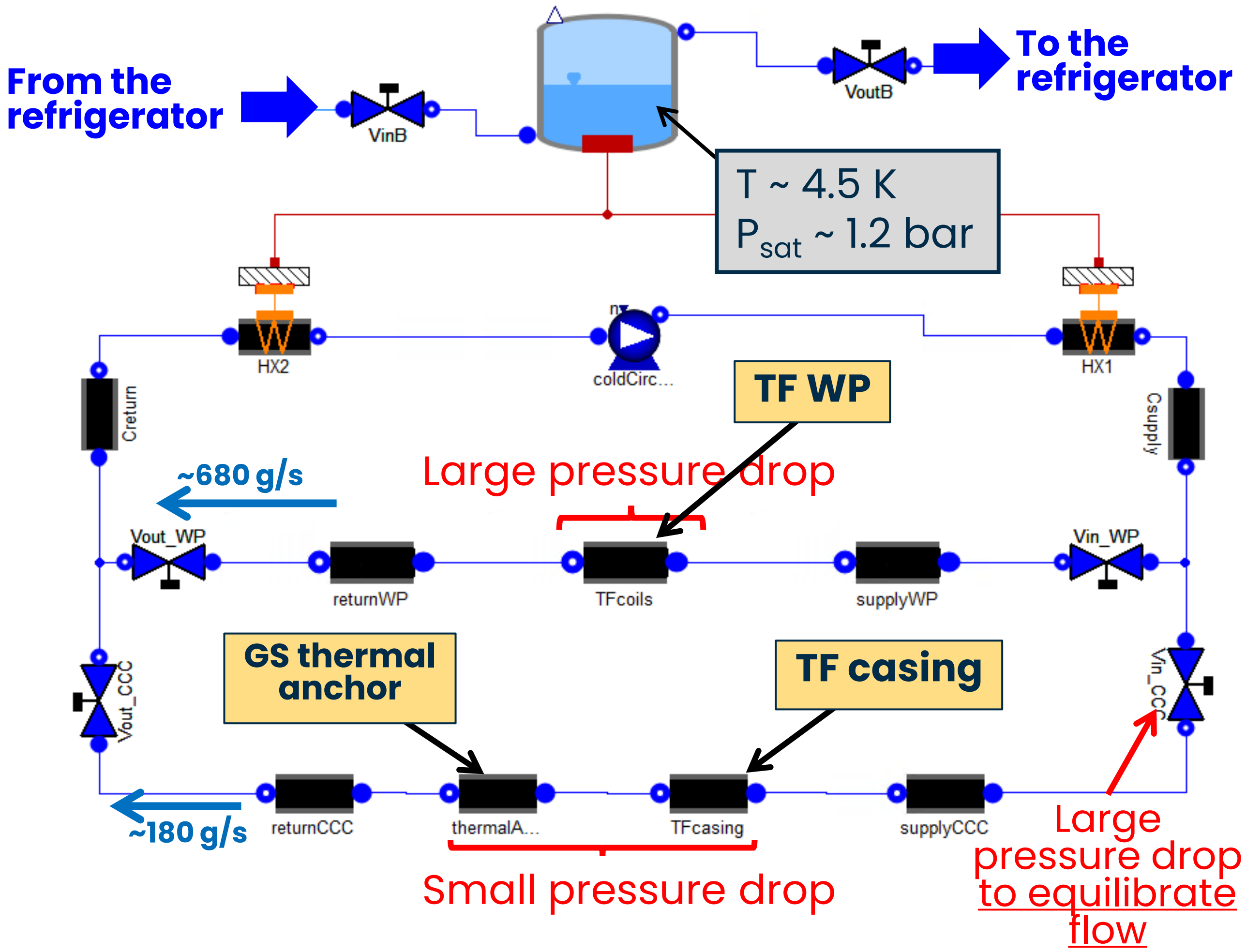
He properties (function of T and p) from ExternalMedia library → interface between external codes for He properties computing and Modelica-compatible models

Dynamic balance equations are solved

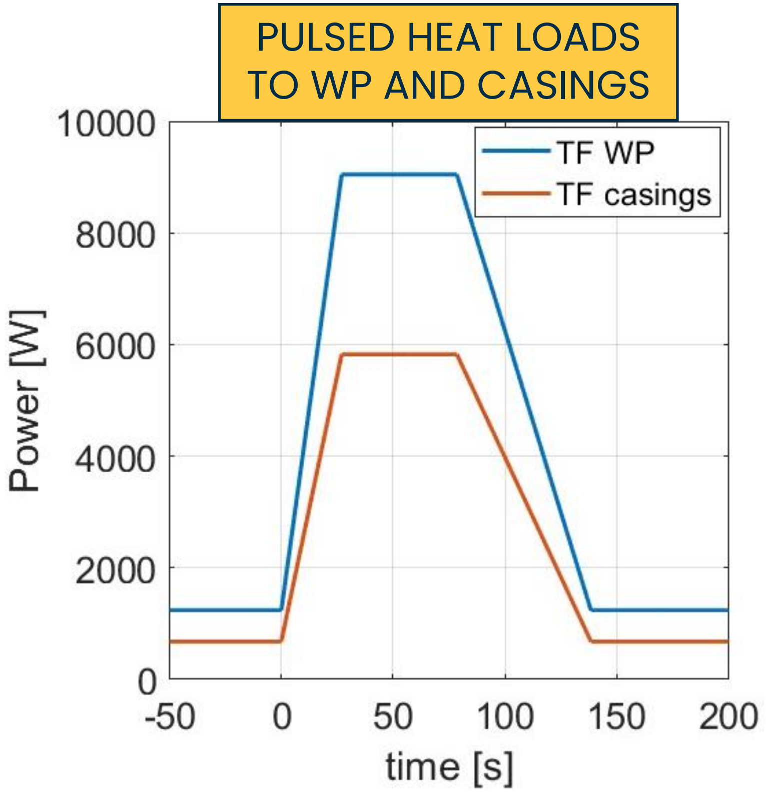
Component	Symbol	Assumptions	Input	Main equations
Pipe / HX(1D)		1D	Geometry, Friction, HTC	Cons. mass/ momentum / energy
Valve		Volume is neglected	C_v, opening, characteristic type, rangeability	Cons. mass / energy, characteristic
LHe bath		0D, only vapor is extracted	Volume	Cons. mass / energy for both phases
Pump		0D, η_{iso} constant Volume is neglected	$\Delta p(dm/dt)$ **characteristic** 	Cons. mass / energy, characteristic

Cooling loop model for TF winding packs and casing: reference layout

- TF conductors and TF casings fed by the same cold circulator (CC) and cooled in parallel
- GS thermal anchor at 4.5 K cooled in series with the TF casings
- Supply/return lines (from ACB to VBs) in common for the two parallel branches



Simulation setup

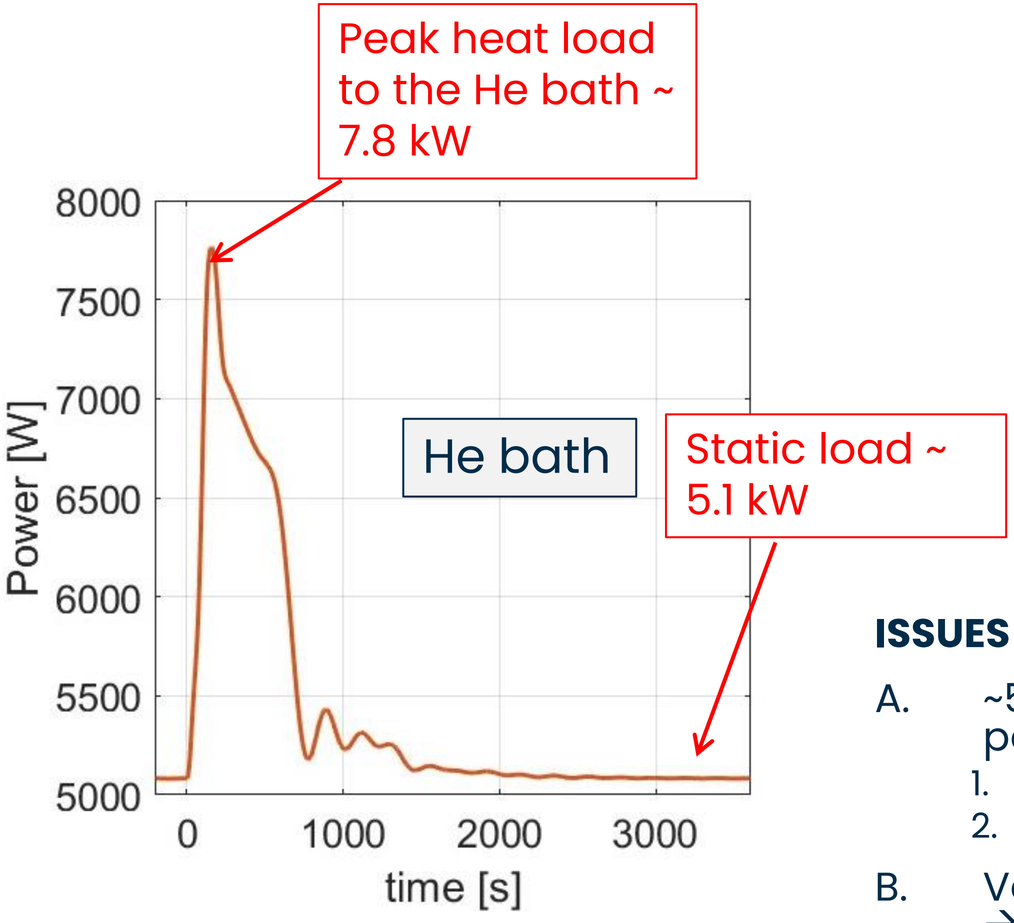


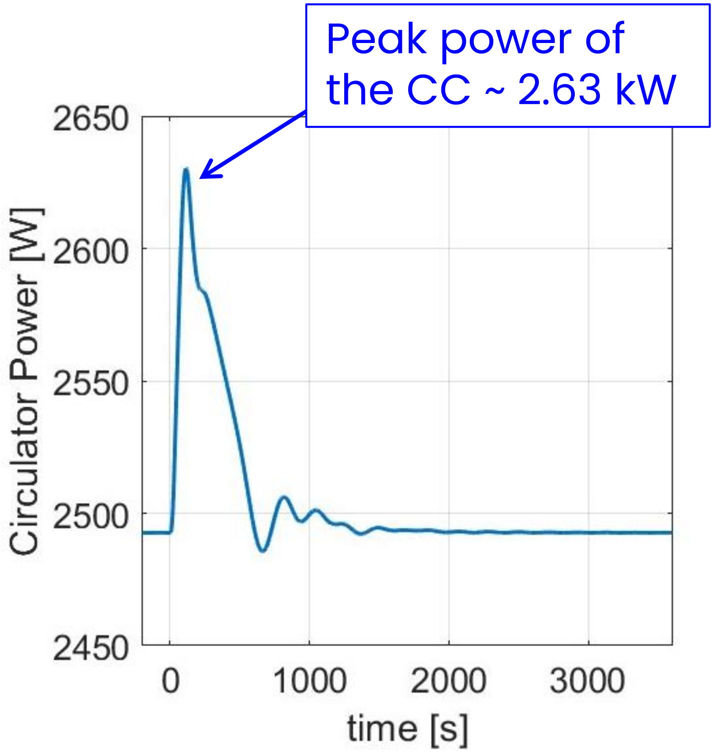
If static heat loads only:

- He bath Temperature **4.5 K** (p_{sat} ~ 1.2 bar) → WPs inlet T ~ 4.58 K
- Δp along WPs ~ **2 bar**
- Total **dm/dt ~ 860 g/s** (WPs: 680 g/s, casing: 180 g/s)

Pulsed heat loads to TF conductors and structures due to **nuclear load** coming from the plasma pulsed operation (period: 3600 s) → Nuclear heat load computed by detailed analyses on the coils [Villari et al., FED, 2020]

Results





ISSUES asking for optimization:

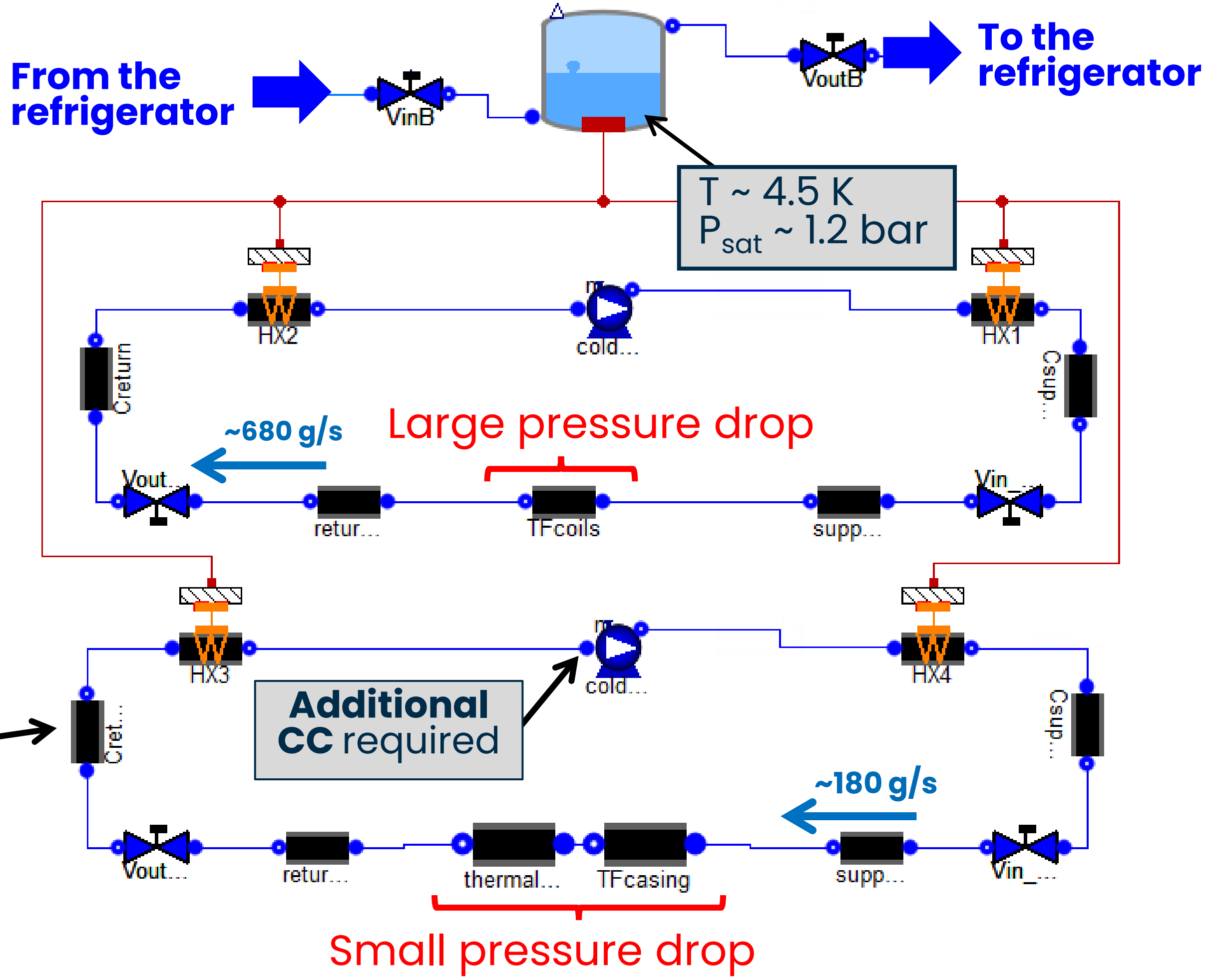
A. ~50% of the static heat load to thermal buffer due to the CC work → possible reduction by
   1. Alternative configurations
   2. Reduction of the CC pressure head (and dm/dt)

B. Very high peak heat load, affecting the refrigerator power and its cost → investigate options to reduce it

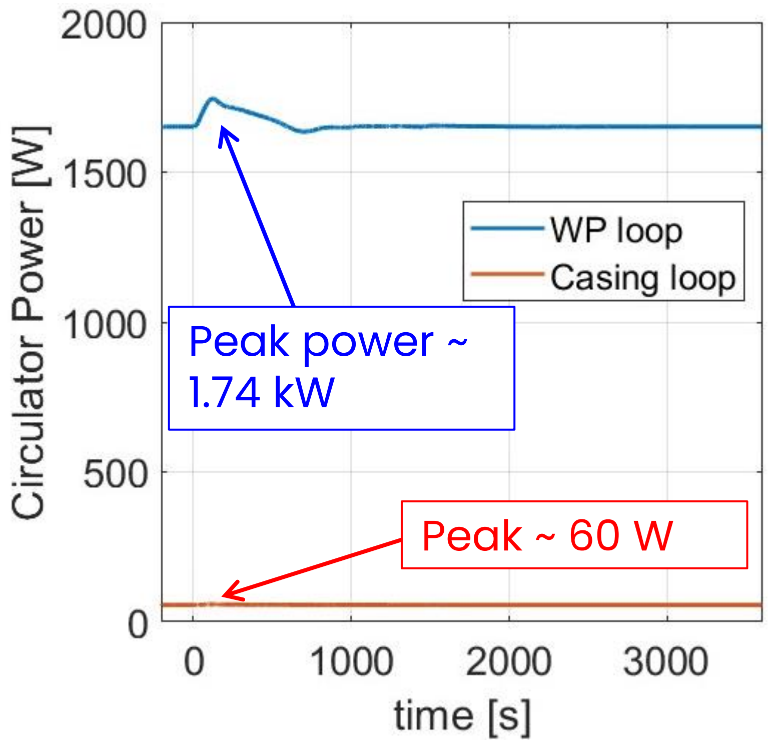
A.1 - Alternative configuration: separate circuits for TF winding pack and casing

- TF conductors and TF casings cooled by **two independent loop** (additional CC for casing loop)
- Both circuits still coupled with the same helium bath
- **Lower power to the He bath expected** due to lower CC pressure head in the TF casing circuit

Pipe diameter dimensioning for the **additional supply/return cryolines** of the casing cooling loop (low dm/dt):
- **DN32** (instead of DN100)



A.1 – Results



Total CC Peak power (WPs + casings) ~ **1.8 kW**

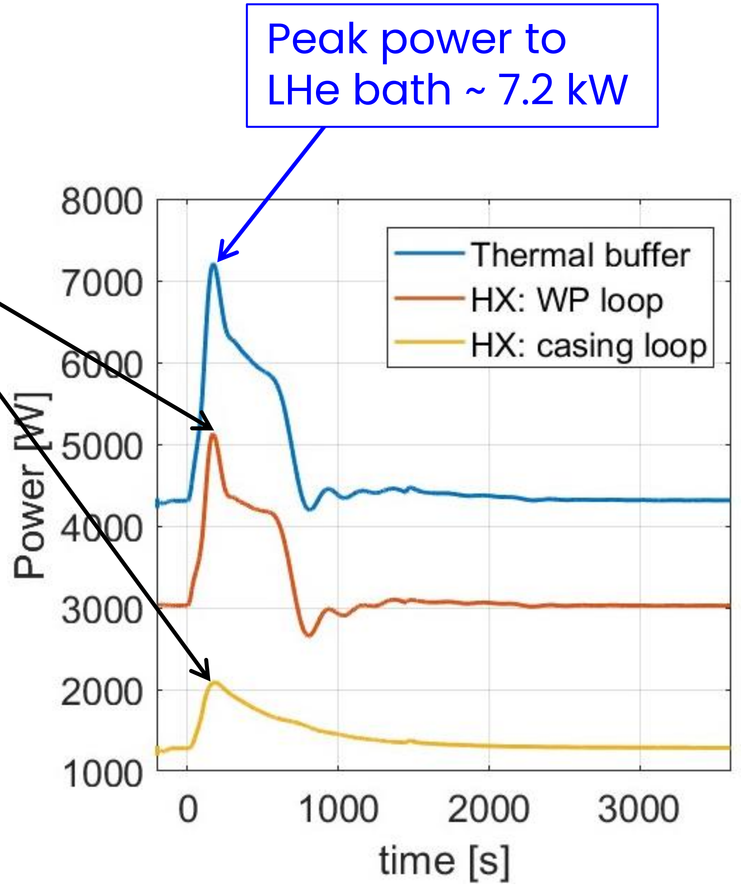
~ 0.8 kW at 4.5 K saved wrt the reference configuration

Peak loads from the two circuits to the thermal buffer ~ simultaneous

OPTIMIZATION B to reduce the peak heat load: delay the peak load of the casing circuit to the He bath

Two possible options:

1. **Increase cryoline pipe dimensions**
2. **Reduce CC rotational speed** during heat pulse

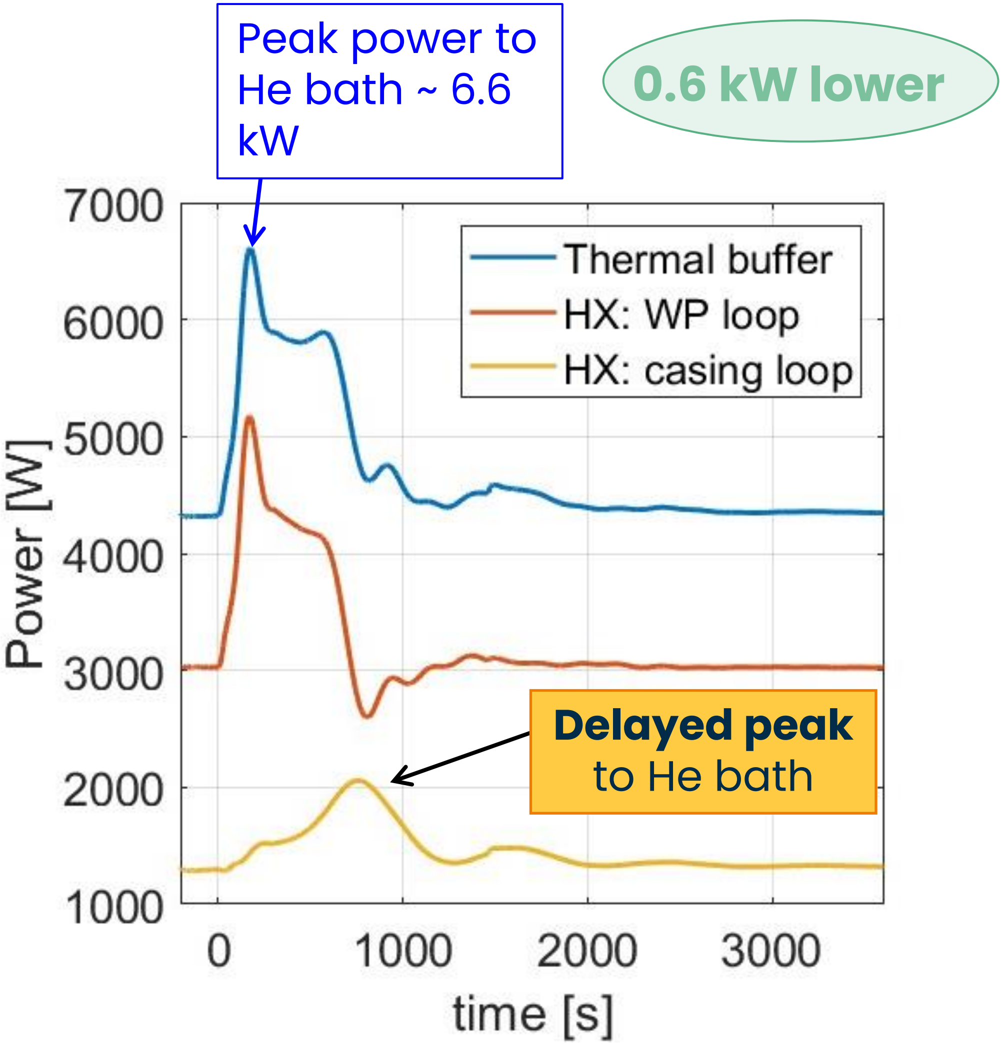


B.1 - Separate circuits optimization

- Peak power to thermal buffer delayed by **increasing diameter and length** of the return pipe of the casing cooling circuit cryoline
- Best results in terms of reduction of the total peak power to thermal buffer:
  - ➢ **DN100**
  - ➢ **Additional 90 m** pipe length

Drawbacks:

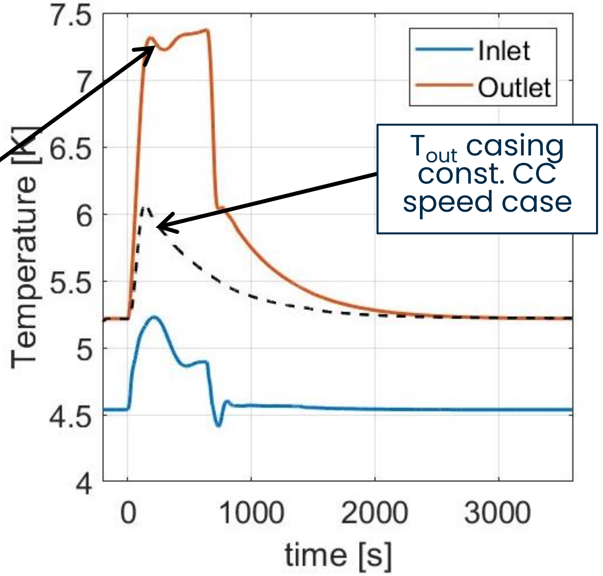
- – More complex distribution layout (increased pipe length)
- – Greater radiative losses on cryoline

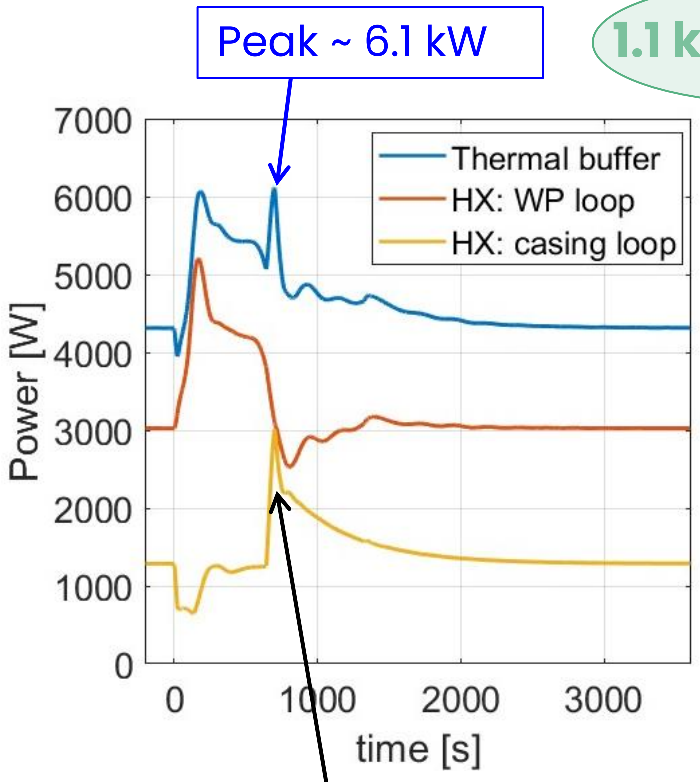


B.2 - Separate circuits optimization

- CC (casing loop) **rotational speed reduced at ~¼ of its nominal value** → reduced dm/dt → delayed heat load transfer to the thermal buffer
- Duration: **600 s** starting from the beginning of the plasma pulses (i.e. 0 s)
- High heat deposition in TF casings (used as thermal buffer)

He Temperature at Outlet casing ~ 1.3 K higher (wrt case with const. CC speed) during the peak





1.1 kW lower !!

Heat load to LHe bath from casing cooling circuit **shifted forward**

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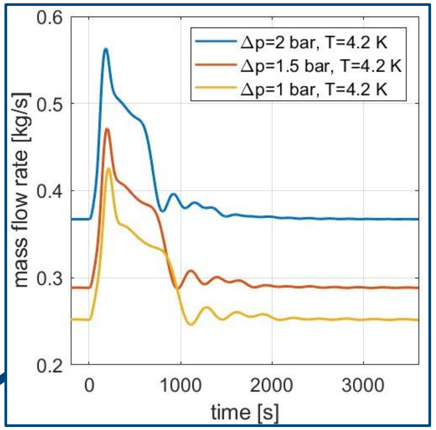
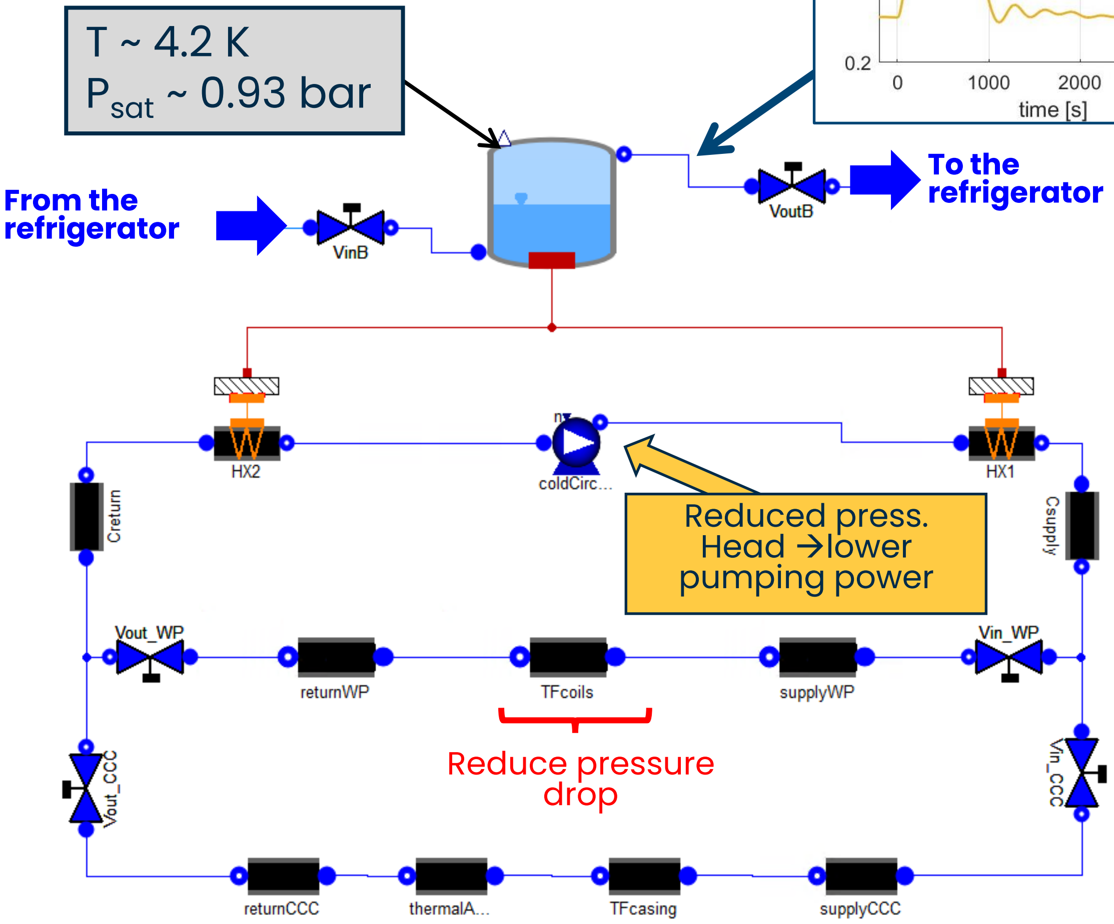
A.2 - CC pressure head reduction

- Alternative optimization strategy: **reduction of CC pressure head** (and dm/dt) → TF WP Δp below the 2 bar of the reference configuration
- Simulation performed by reducing the CC pressure head such to have pressure drop along the TF WP of 1.5 and 1 bar



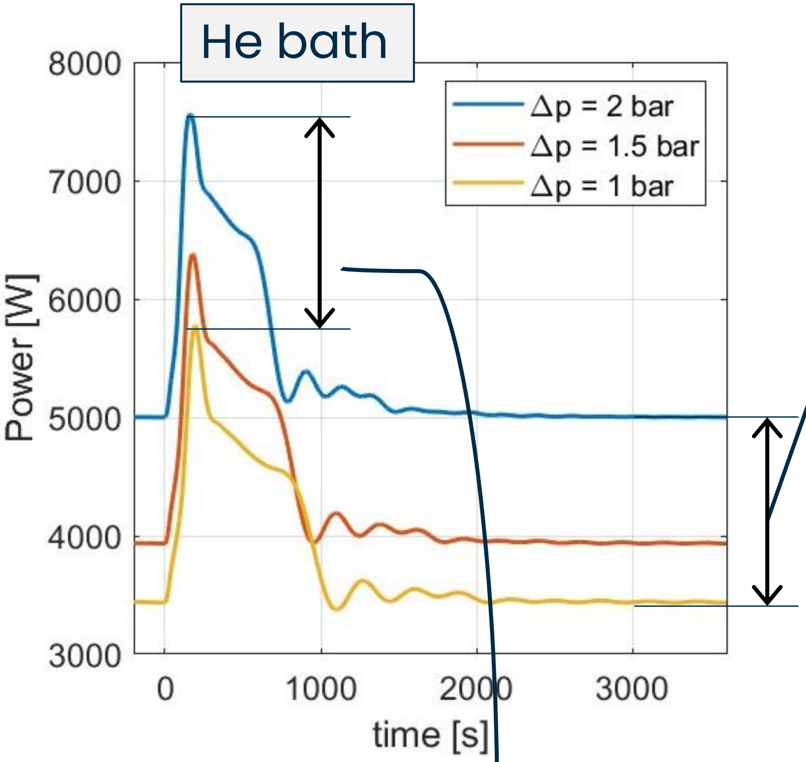


Drawback: lower T margin for the conductors

LHe bath operating temperature reduced to 4.2 K → Tin coil ~4.3 K

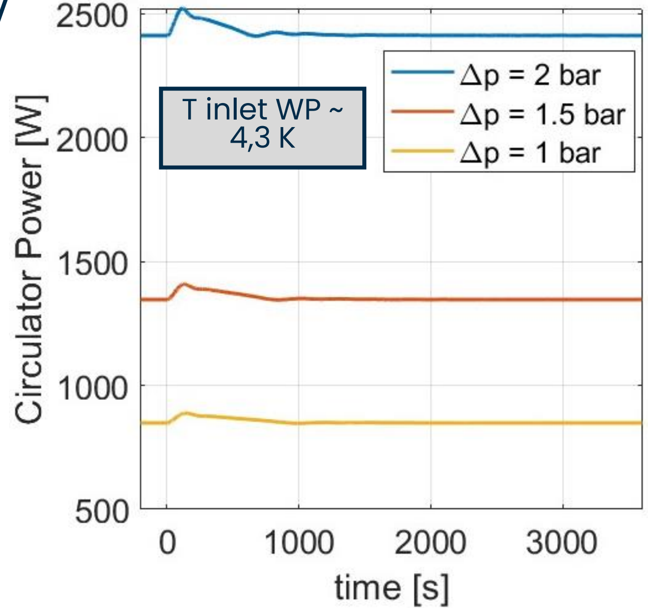
(Additional cold compressor required downstream the LHe bath: <u>mass flow rate to be processed computed by 4C</u>)

A.2 – Results

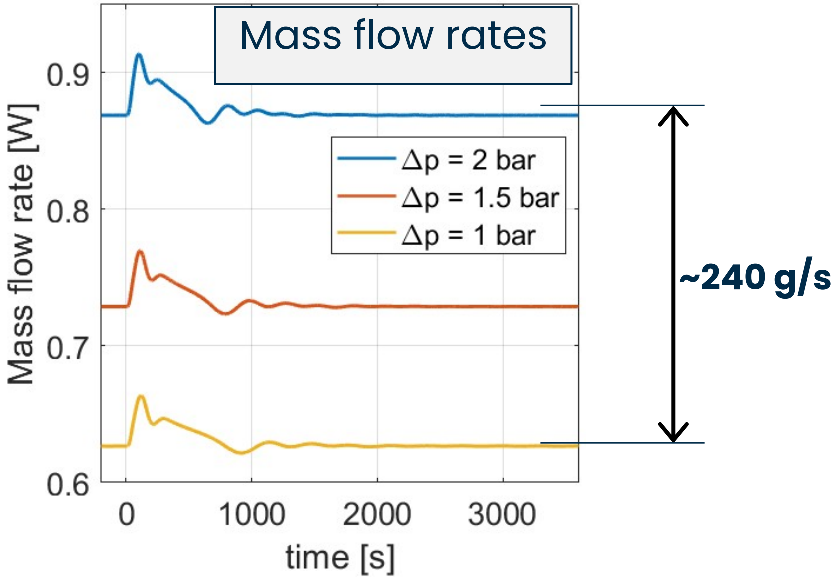


Peak load to the LHe bath 1.8 kW lower from Δp=2 bar to Δp=1 bar

Base load to the LHe bath 1.5 kW lower from Δp=2 bar to Δp=1 bar



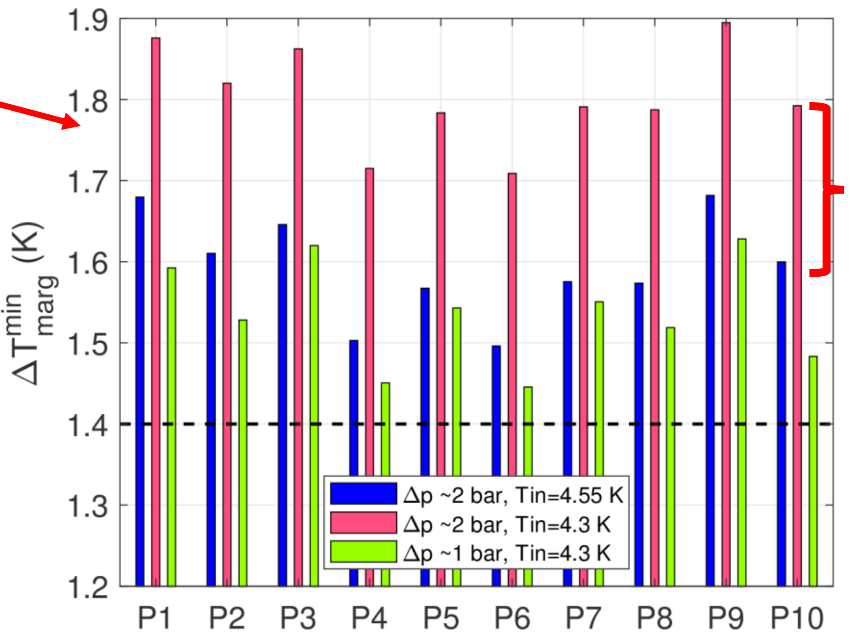
~ **65% pumping power reduction** for Δp=1 bar wrt reference design



Reduced dm/dt flowing in the pancakes cooling channels:
From ~ 3.8 g/s (Δp~2 bar) to ~ 2.1 g/s (Δp~1 bar)

A.2 - Effects of the reduced CC pressure head

- **Detailed analyses** on the effects of the pressure drop (and LHe bath operative T) reduction **for the 10 pancakes of a TF conductor**, performed with 4C code
- **Nuclear heat load from the 2020** version of the **DN scenario** [Villari, et al., FED, 2020] → no neutron shield and increased heat load at outboard to account for the removal of the Port Collars.
- This heat load will be updated to the more recent scenarios and heat loads, when available



Reduction of LHe bath T from 4.5 to 4.2 K: **T margin gain ~0.2 K**, allowing to reduce the TF CC pressure head by ~1 bar

Conclusions and perspective

Conclusions:

DTT TF cooling loop dynamic models have been implemented using the 4C code and used to compare alternative optimization proposals:

- **Separate cryogenic loops** for TF WP and casing **layout** → cooling power reduction of **~34%** and peak load to He bath ~1.7 kW lower (wrt reference design)
  - DRAWBACKS: additional cryolines and CC needed
- **Reduced CC pressure head & bath operative T** → cooling power reduction up to **~65%** wrt the reference design(case of 1 bar Δp in TF WPs)
  - DRAWBACKS: additional cold compressor downstream the He bath, reduced T margin if pressure head is overly reduced

The economical feasibility of the different solutions is being addressed by DTT

Perspectives:

- Dimensioning of the additional cold compressor downstream the LHe bath (case of operative T~4.2 K)
- Simulation of the other relevant normal operation transient, the **TF cooldown** in the cryoplant
- Development of cooling loop model for the **DTT PF & CS cooling circuits**

Thank you for your kind attention

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