Analysis of the Mu2e Calorimeter cooling system

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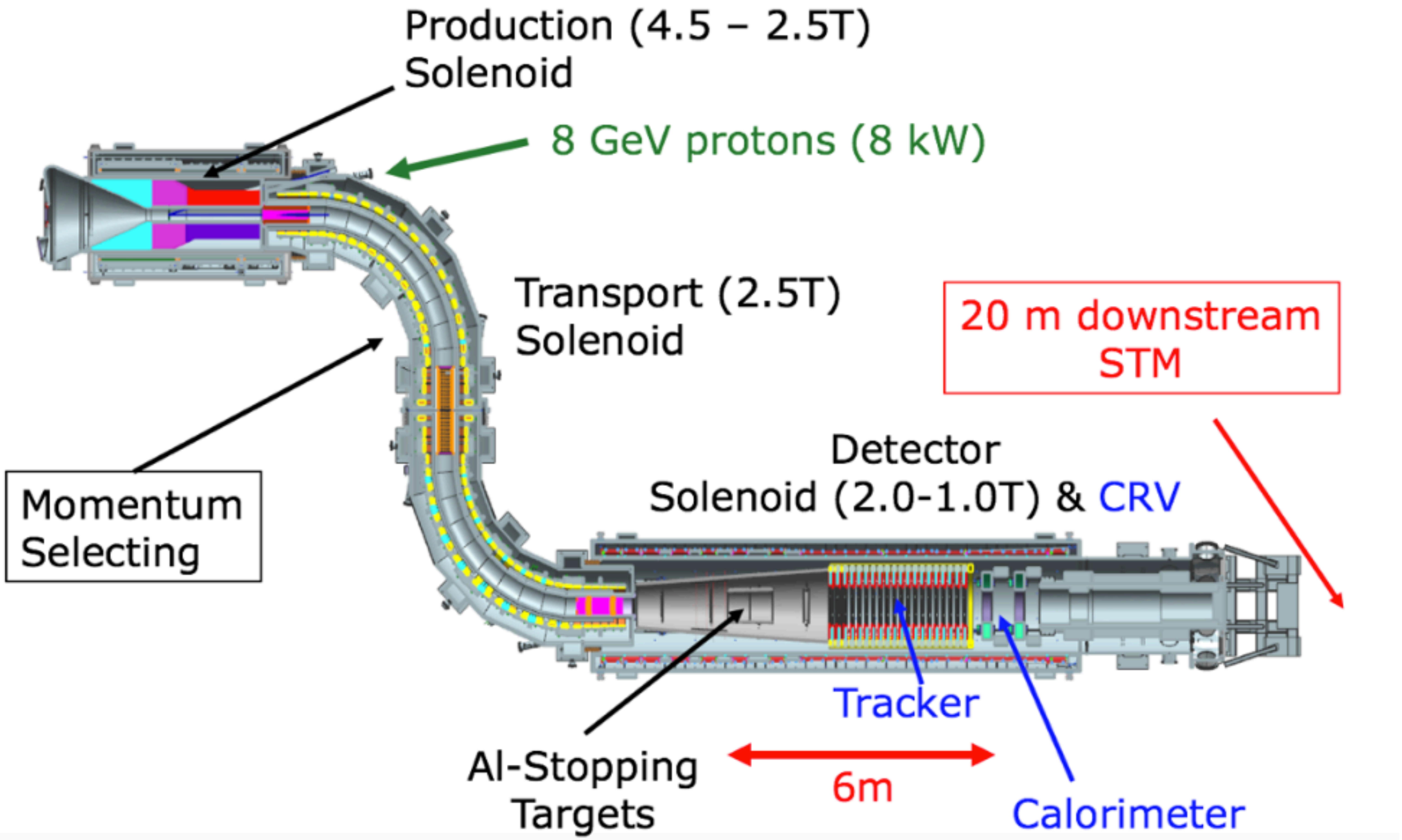
09/24/2019

The Mu2e experiment

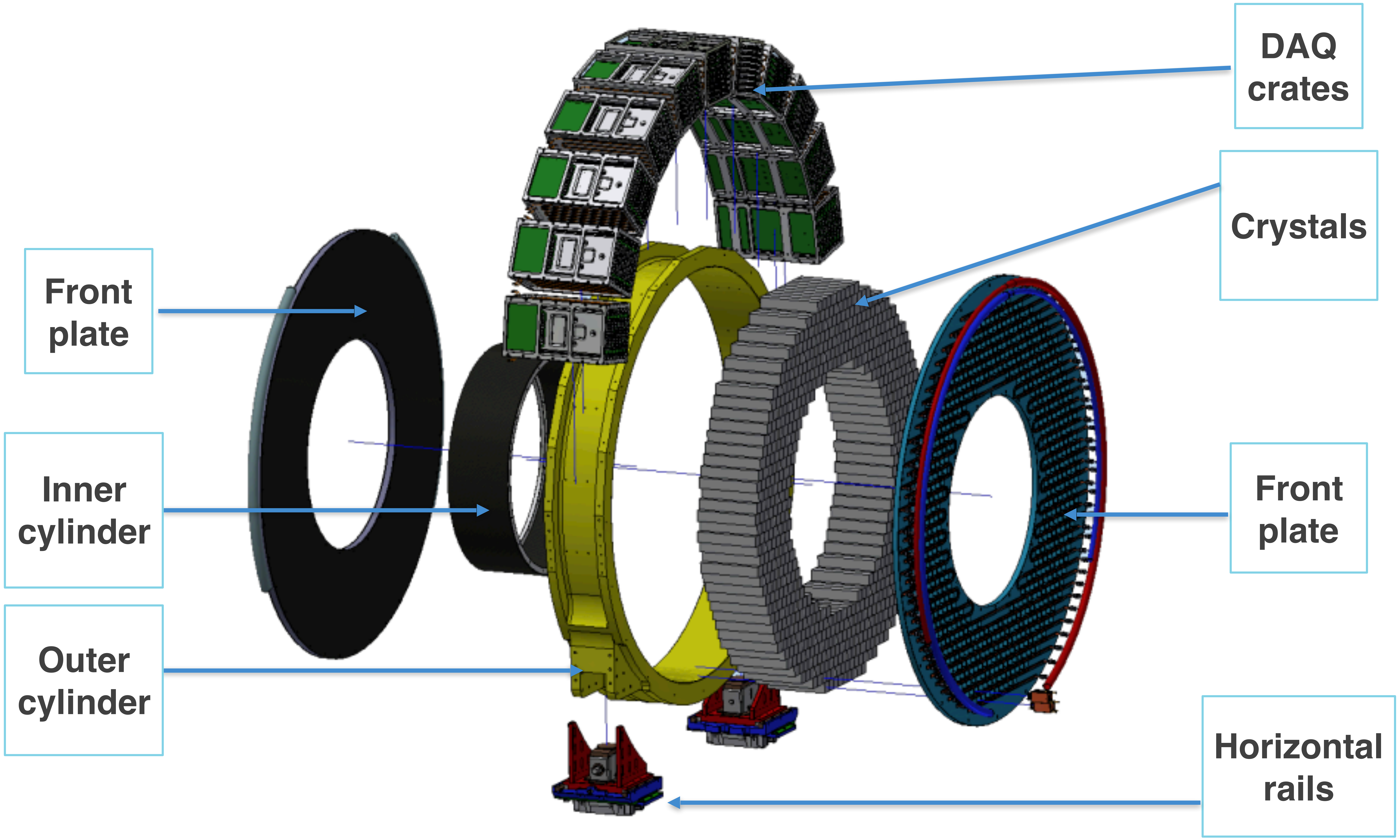
Purpose:

Research for coherent neutrinoless muon to electron conversion in the field of an aluminum nucleus.



The Calorimeter

- The calorimeter lies in the cryostat of the detector solenoid.
- Fundamental to support the tracker data
- Horizontal rails allow for maintenance

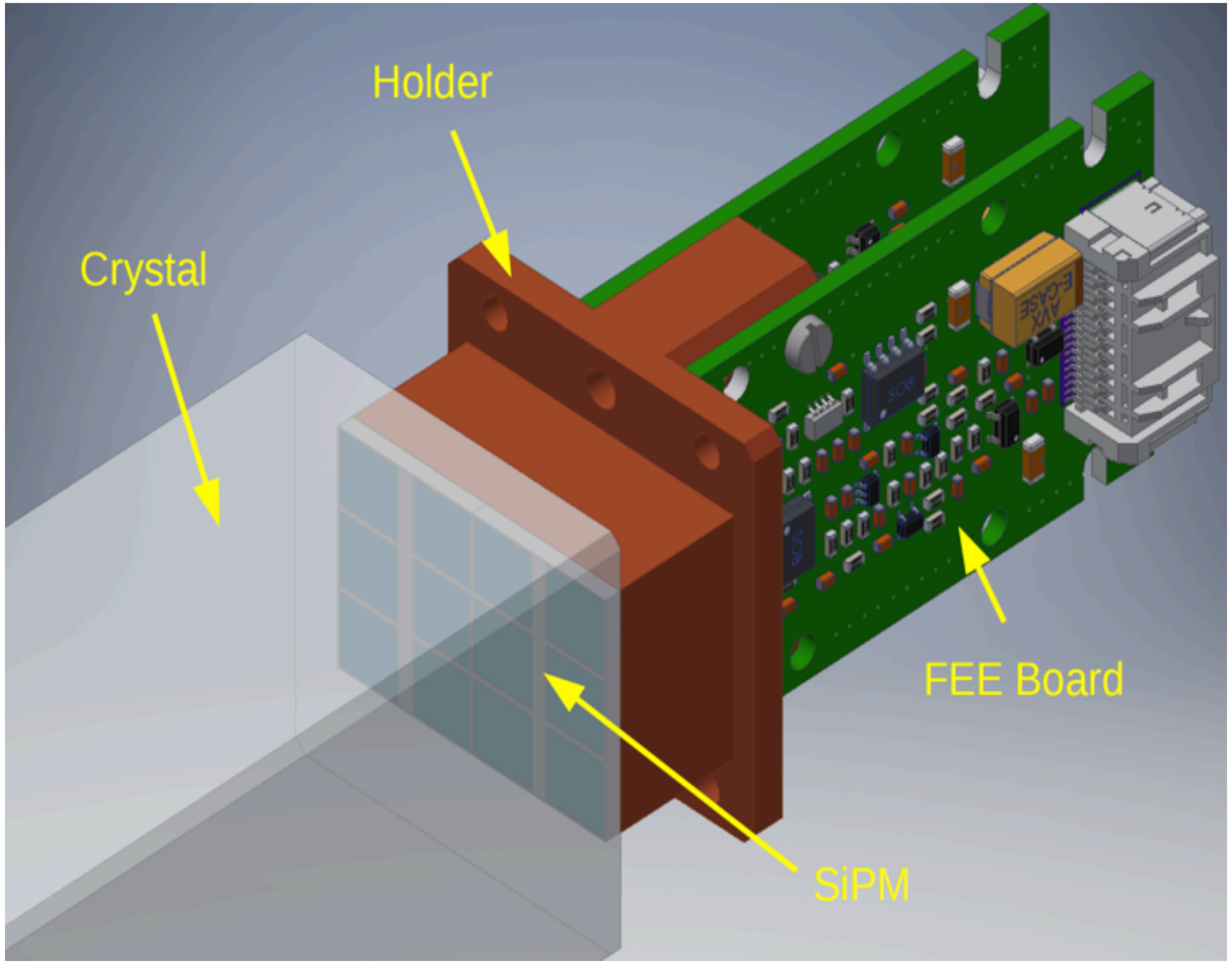


Calorimeter disk assembly

The Front End Electronics (FEE)

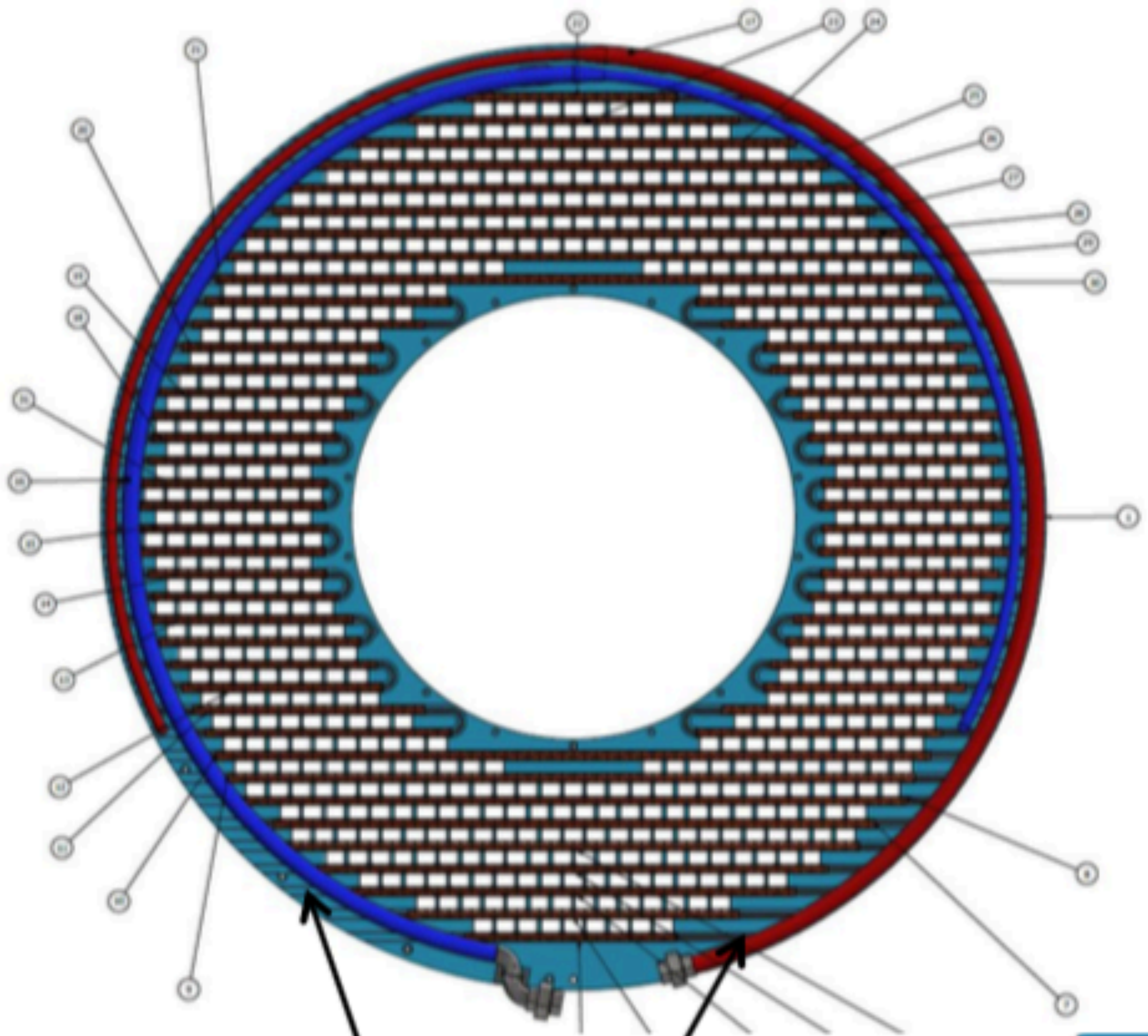
SiPM most critical components:
Temperature has to be below 0 °C
(below -10 °C after one/two years)

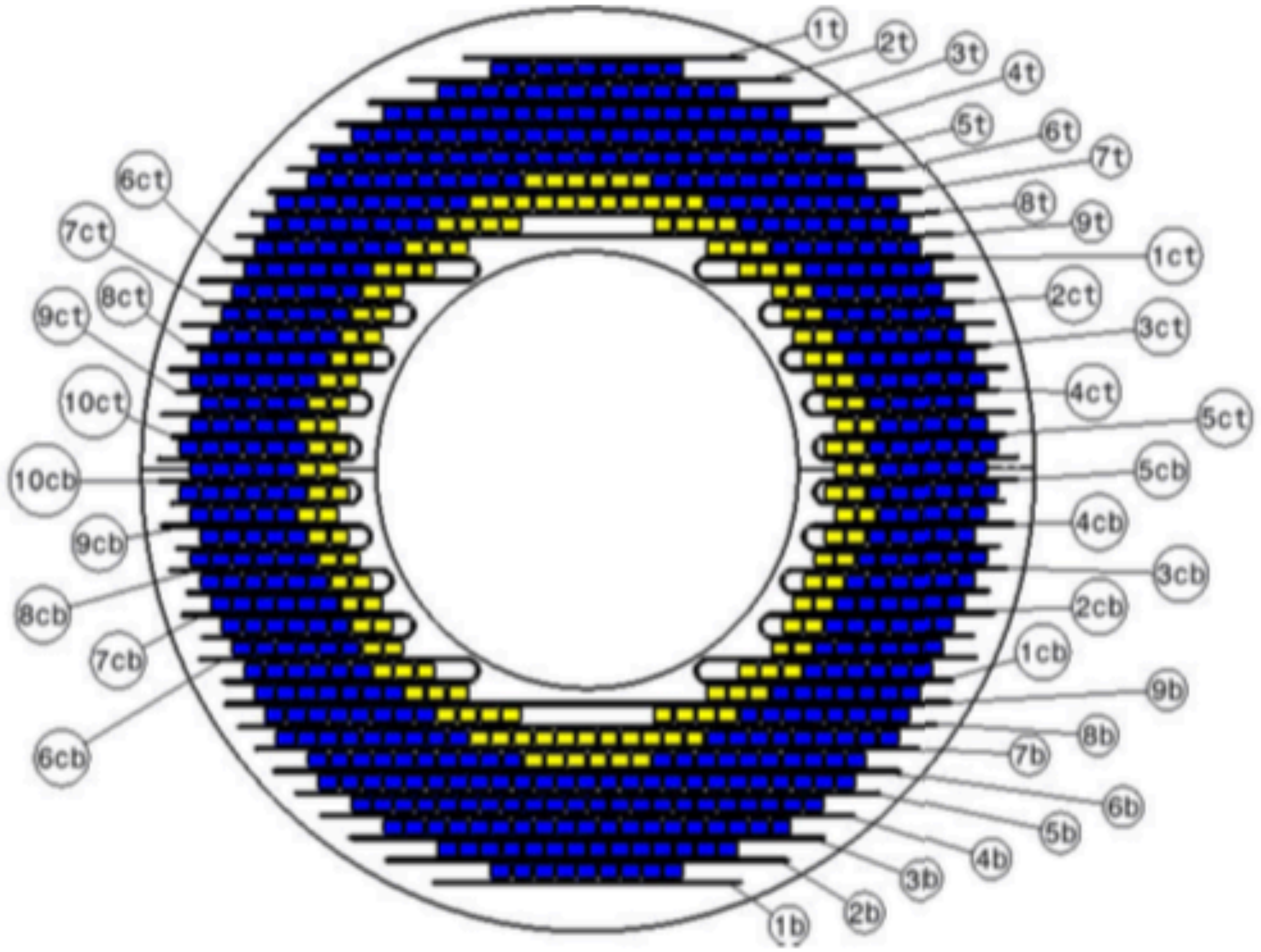
Need for a dedicated cooling system

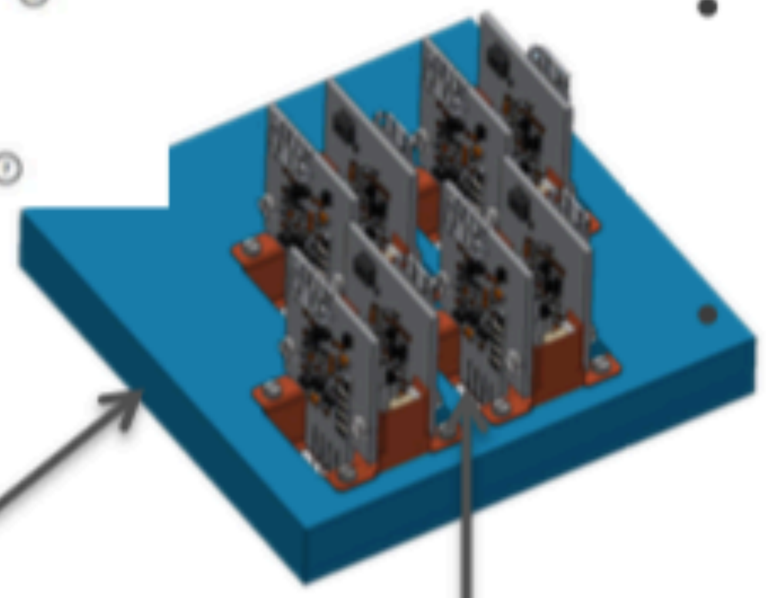


Cooling review (Raffaelli, Saputi et al.)

FEE cooling system design







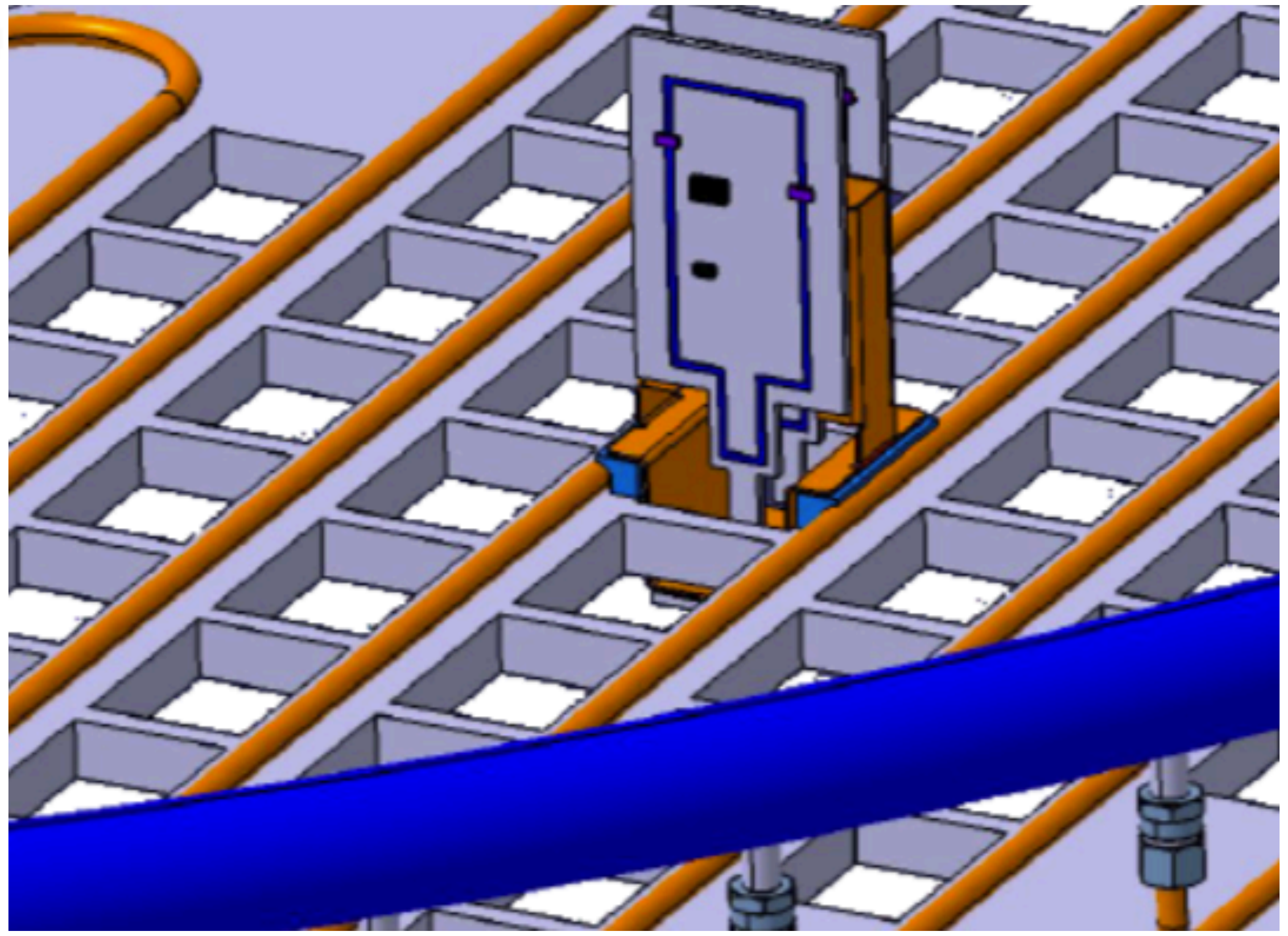
Inlet/Outlet Manifold

PEEK Cooling Plate

Thermal Contact with 2.5 mm screw

- The front end electronics cooling system is made by 18 straight tubes and 20 tube with 180° turn.

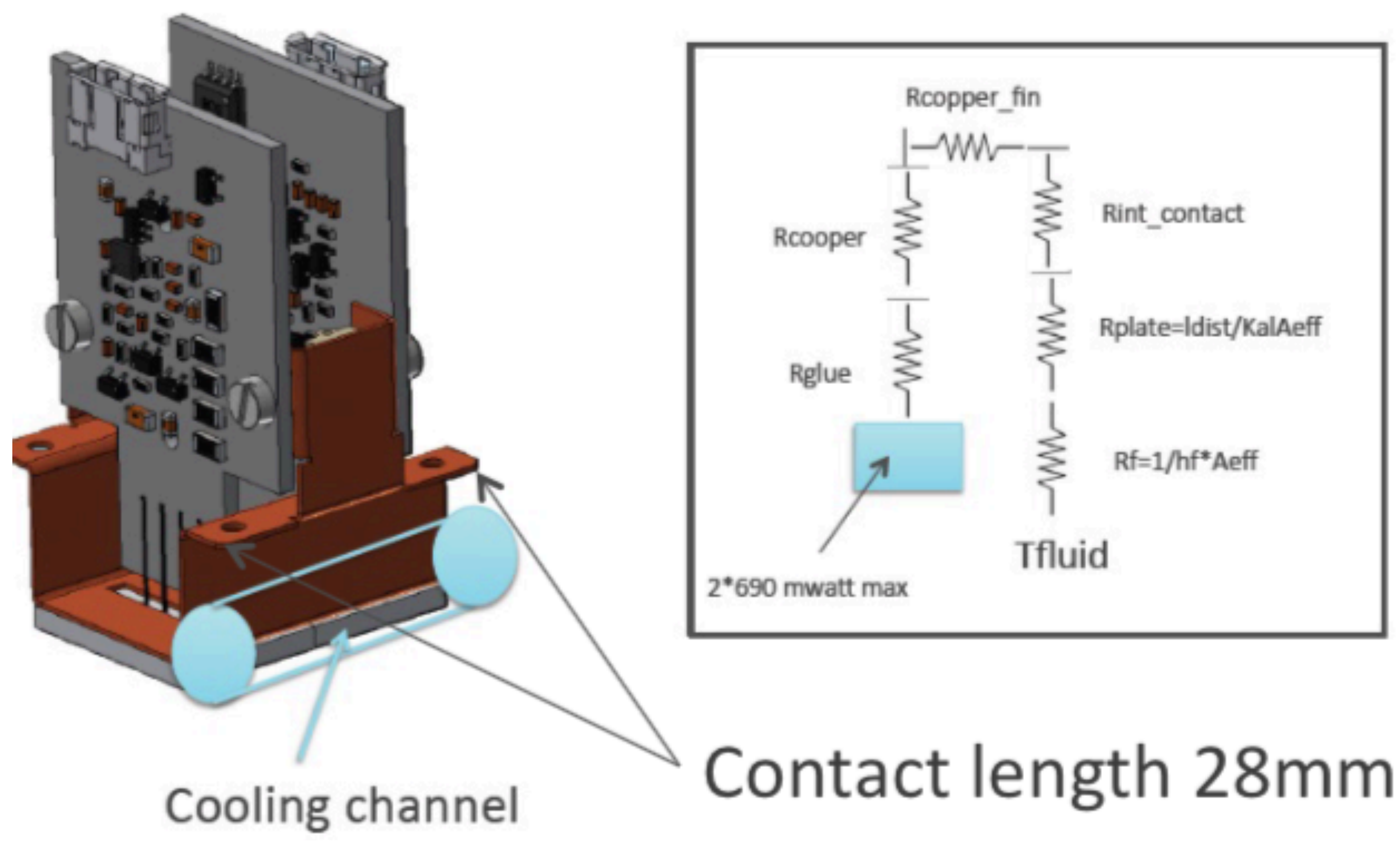
  The chosen configuration is easy to fabricate and has reasonable pressure losses (less than 2 bar).



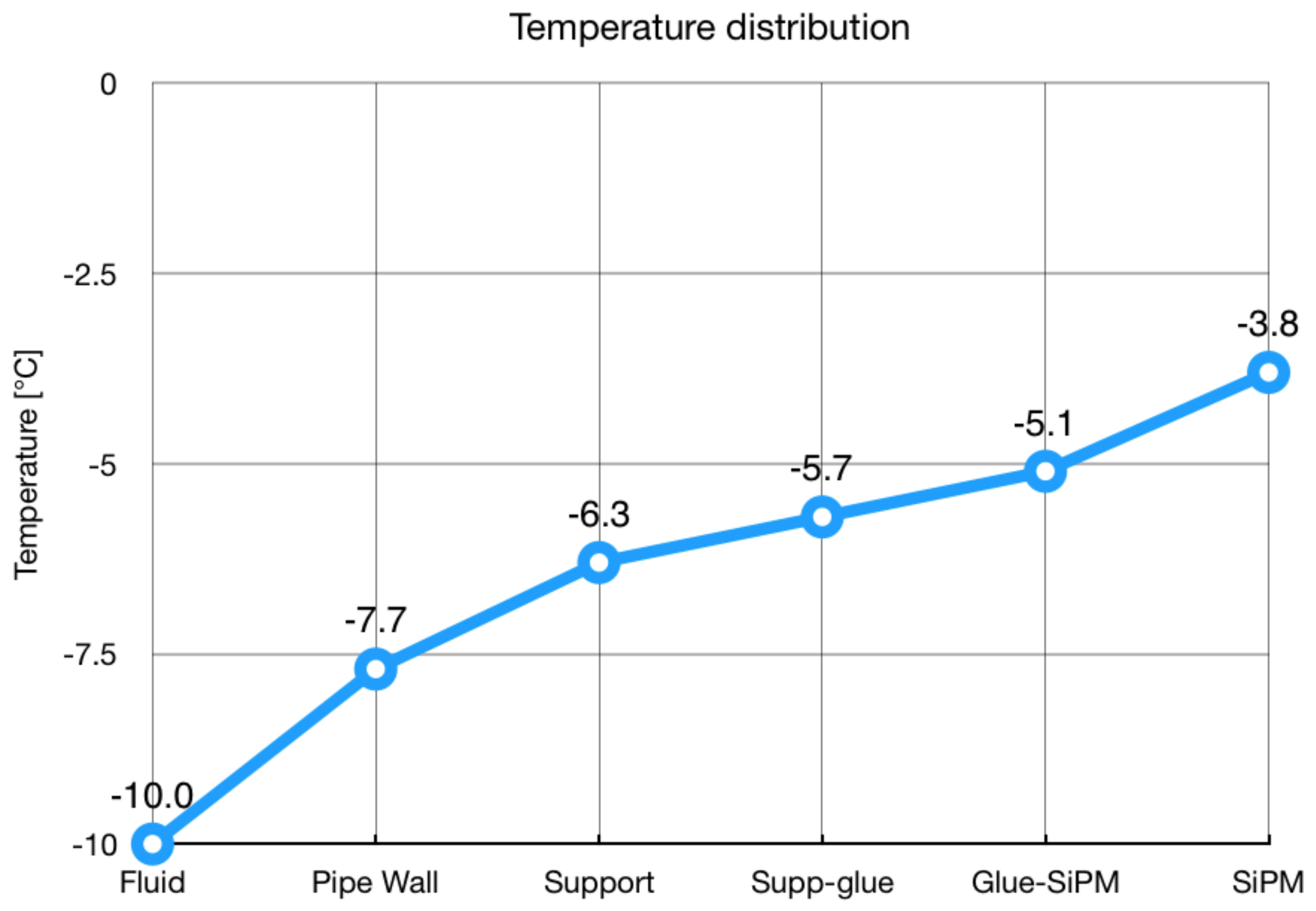
View of the cooling system

Cooling review (Raffaelli, Saputi et al.)

SiPM thermal model



(Leonardo Lucchesi, 2017)



(Leonardo Lucchesi, 2017)

$\Delta T = \dot{Q}R$ where $\dot{Q}$ and R are constant for a certain design

From simulations the temperature difference between fluid and SiPM is around **6.2 °C**

→ The fluid temperature must be at least 7°C colder than SiPM requirements

→ -20 °C TEMPERATURE SET POINT

Cooling fluid comparison: 35% Glycol & Perfluorohexane (freon)

	GLYCOL 35% (@-10°C)	PERFLUOROHEXANE (@-20°C)
$T_{freezing} \quad [C]$	-17	-90
$\rho \quad [kg/m^3]$	1040	1792
$c_p \quad [J/kgK]$	3759	983
$\mu \quad [mPa \cdot s]$	4.331	1370
$k \quad [W/Km]$	0.429	0.622
$P_{sat} \quad [Pa]$	253	3576
$Pr = \nu/\alpha$	38	21.7

Glycol can't be used at -20 °C

More compact system for freon

Higher DeltaT for freon

Lower losses for freon, but highly volatile

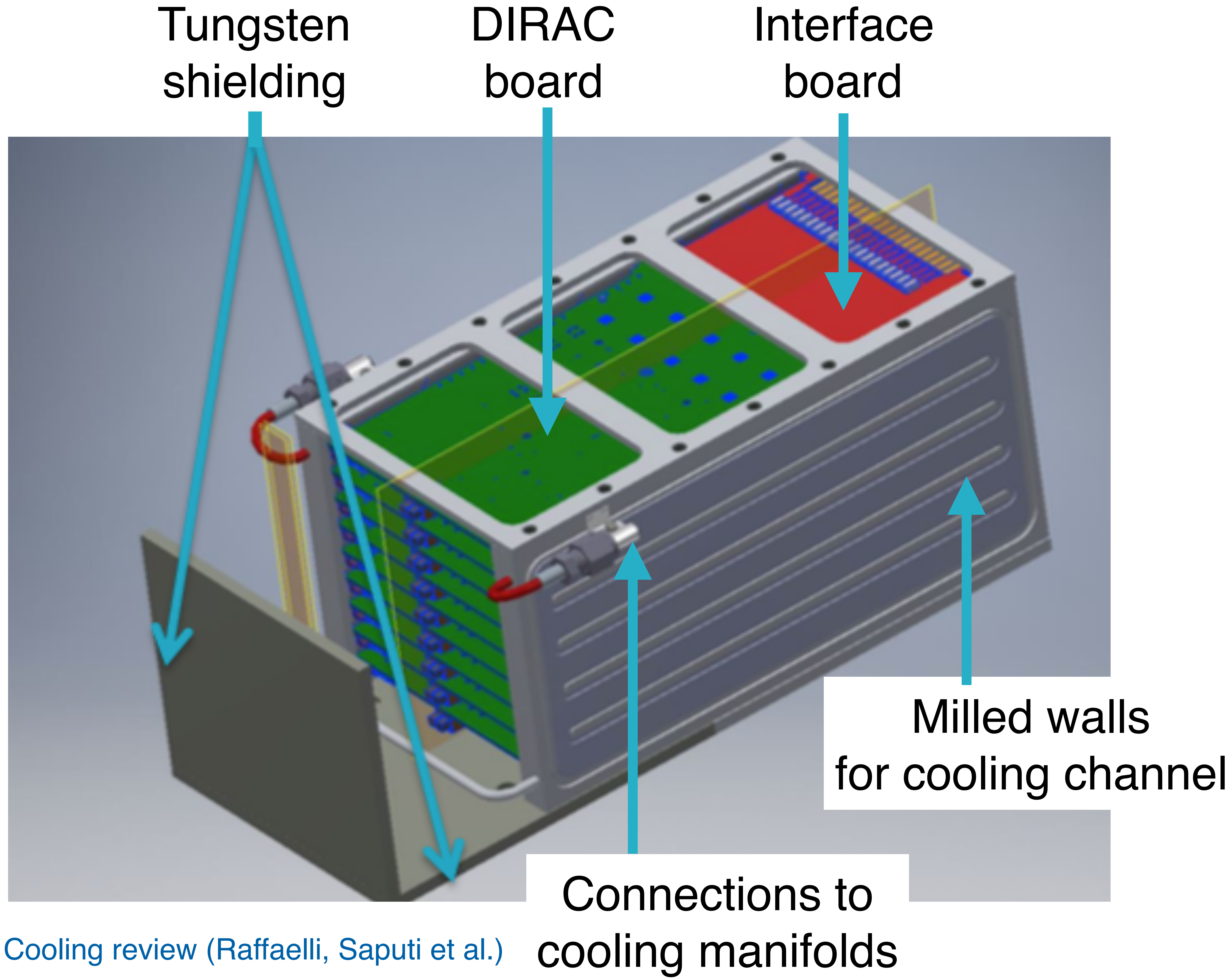
Better convection efficiency

Freon less suceptible to cavitation

Better convection/friction efficiency freon

FREON WARNING: Large values of global warming potential GWP. Need for safe handling and tight leakages equipment. Nonetheless is unavoidable to cool down SiPM to -10°C

Digitize and acquisition crates (DAQ) design

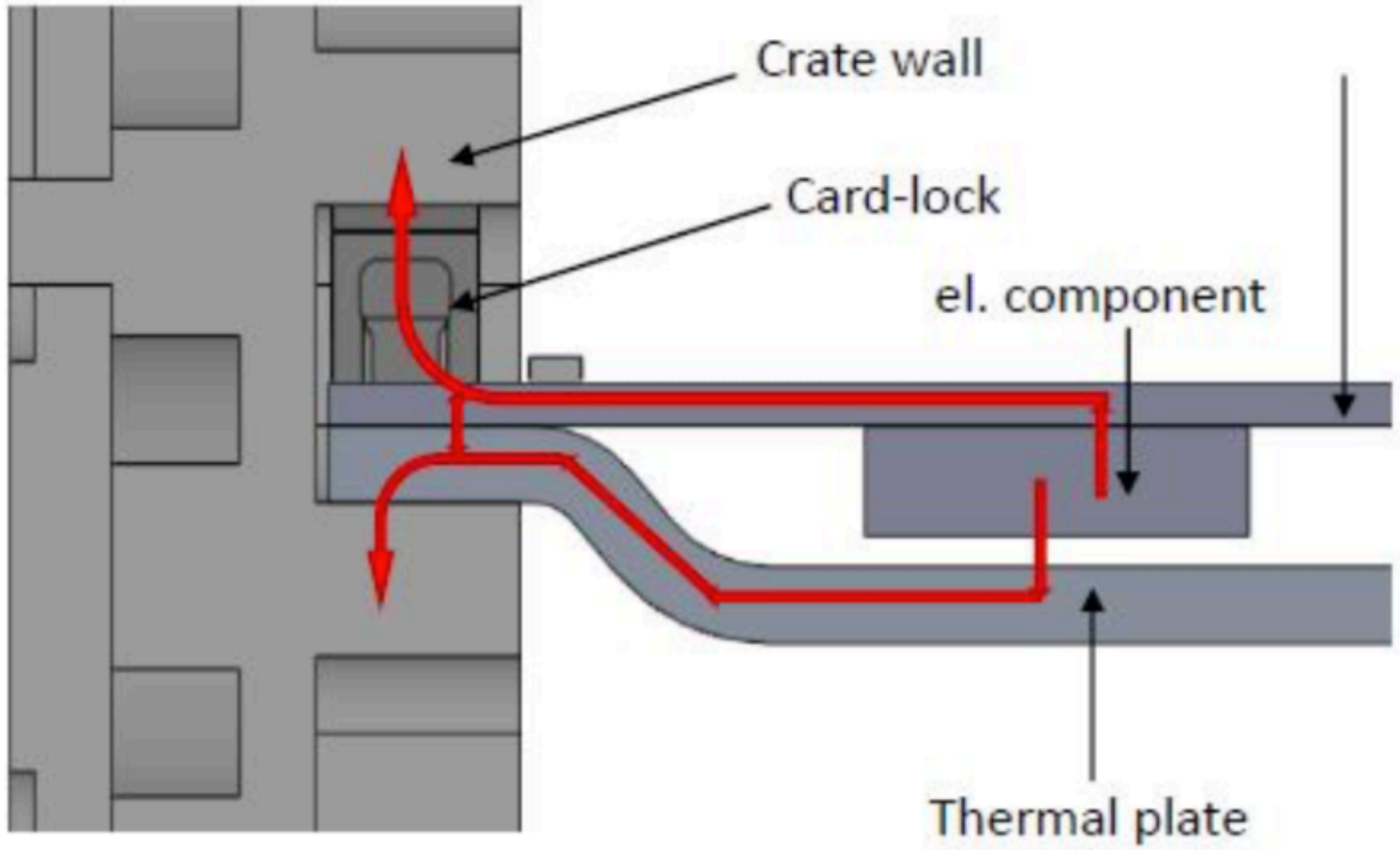


Cooling review (Raffaelli, Saputi et al.)

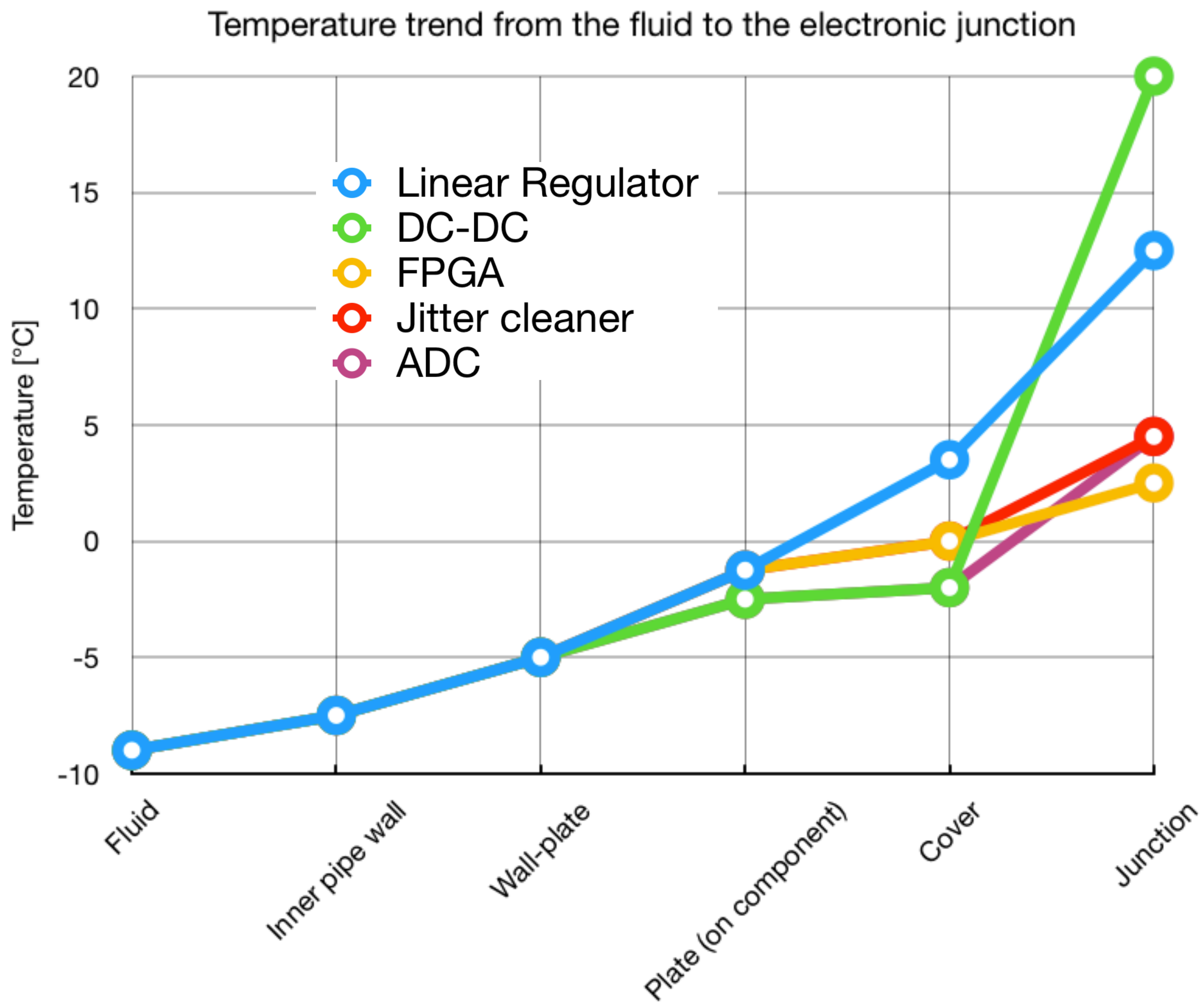
COMPONENTS:

- 10 Crates per disk
- 8 DAQ boards (DIRAC+interface) per crate
- 1 clock distribution board per crate

Crates thermal model



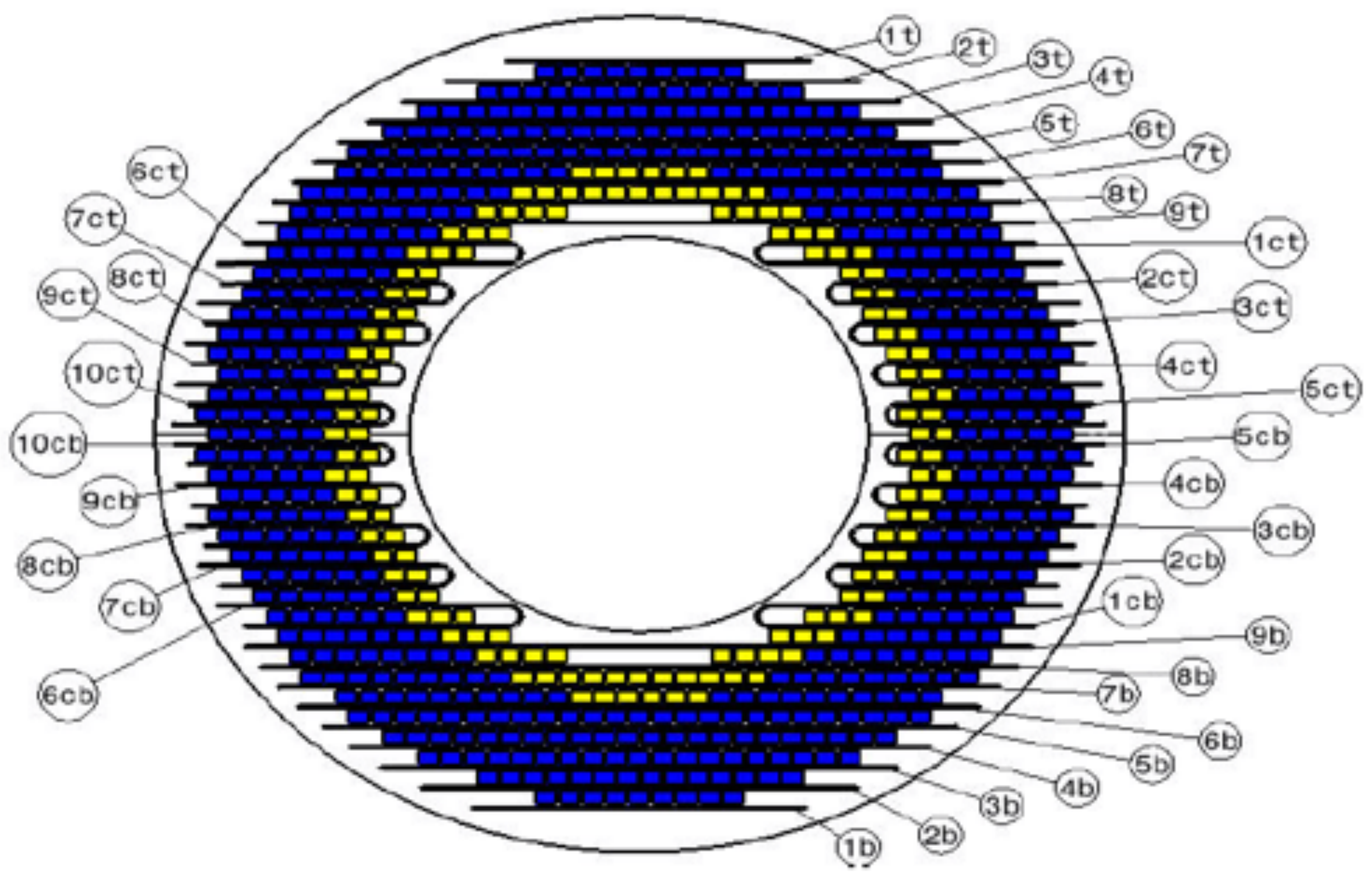
Francesco Ruiu 17/18



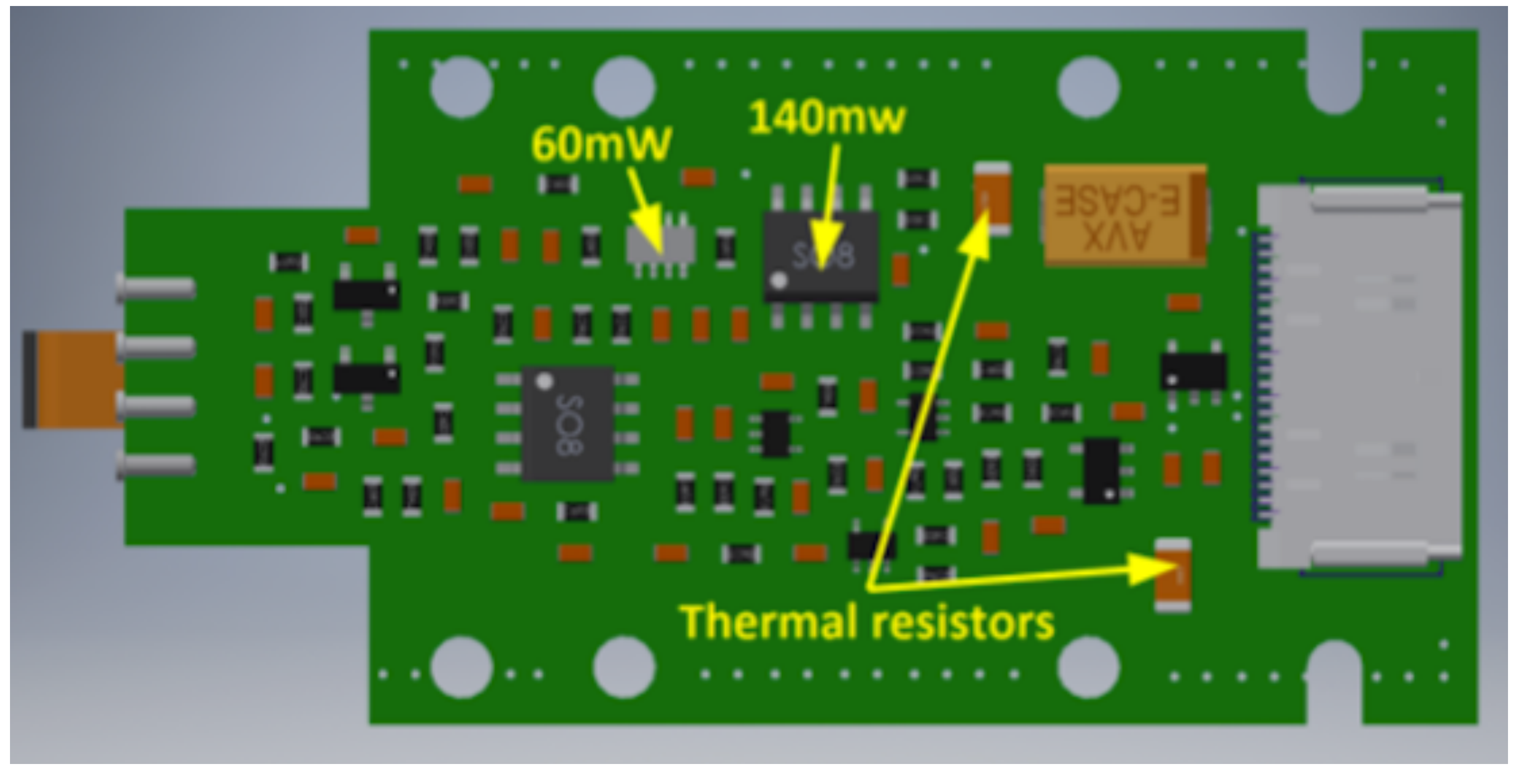
Francesco Ruiu 17/18

30 °C of max temperature difference between the most unlucky electronic component and the fluid temperature → DAQ line is not critical from temperature standpoint

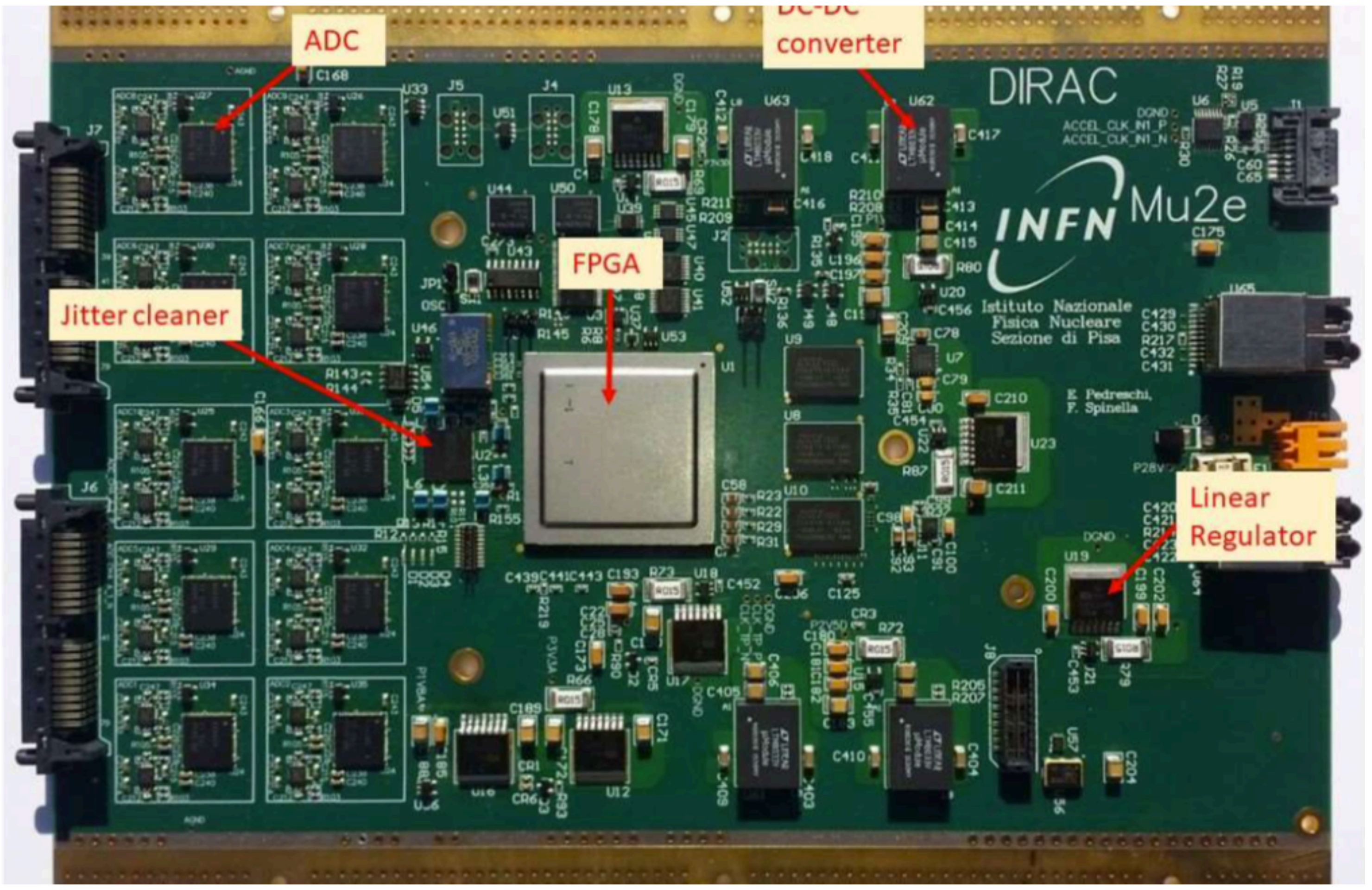
Thermal power summary



SiPM



FEE board



DIRAC board

COMPONENT	N°	UNIT POWER [W]	GROUP POWER [W]
Blue SiPM	2128	0.16	342
Yellow SiPM	568	0.48	274
FEE board	2696	0.36	957
DAQ crate	20	296	5920
Environment			308
Pump dissipation, margin of safety, etc..			3000
		TOTAL	**10.8 kW**

Design guidelines

1) Guidelines:

- Re > 3000 (convection efficiency)
- $T_{fl} < -10$ °C (SiPM constrain)
- $V_{fl} < 4.5$ m/s (head losses)

Assume

2) Assume:

- System layout
- Cooling fluid temperatures
- Piping diameters

3) Solve for:

- Components temperature
- Head losses

Check results

If satisfied select components

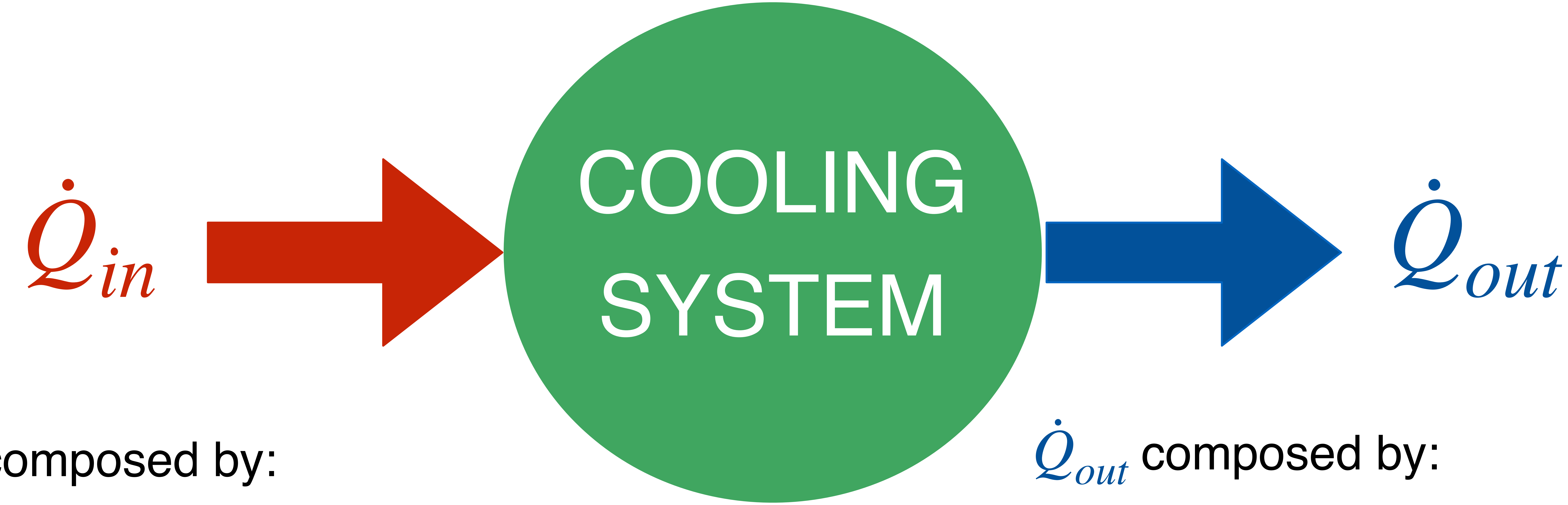
Mainly from:

$$\dot{m} = \dot{Q}/c_p \Delta T \qquad \& \qquad Re = \frac{4\dot{m}}{\mu \pi D}$$

$$\dot{m}_{FEE} = 2.5 \quad kg/s \ (\Delta T_{FEE.fl} = 1 \text{ °C})$$

$$\dot{m}_{DAQ} = 2 \quad kg/s \ (\Delta T_{DAQ.fl} = 3 \text{ °C})$$

System at thermal equilibrium



$\dot{Q}_{in}$ composed by:

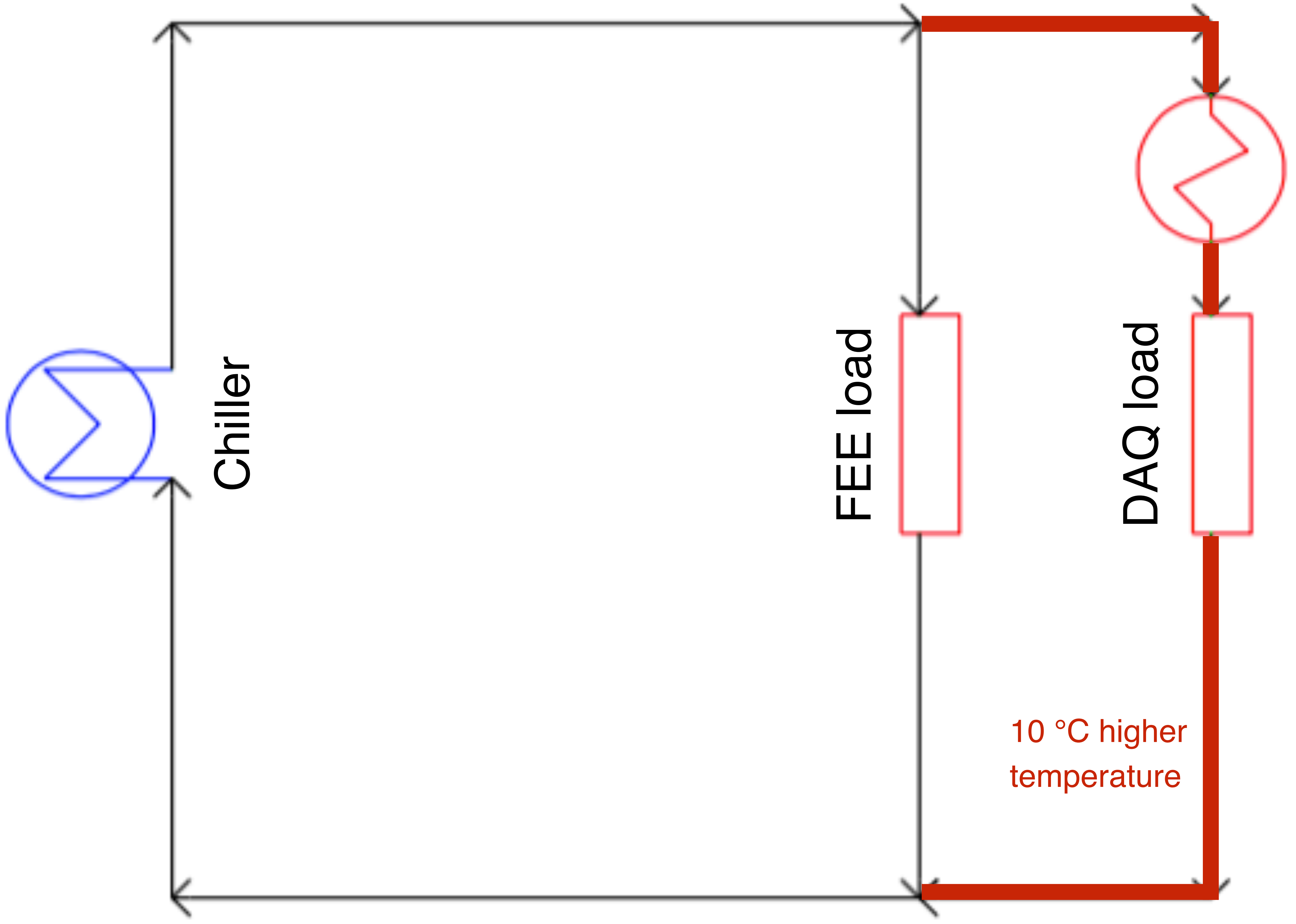
- SiPM
- FEE boards
- Crates boards
- Environment heat (depends on temperature set point)

$\dot{Q}_{out}$ composed by:

- Chiller cooling capacity (can be variable)

Problem of DAQ line heating

If the DAQ line temperature should ever be 10°C warmer than the FEE line because of Tracker problems, 2 kg/s of fluid should be warmed up and cooled down every cycle.



The "waste" of electric power becomes:

$$P = \dot{m}_{DAQ} c_p \Delta T \cdot 2 = 39.3 \text{ kW}$$

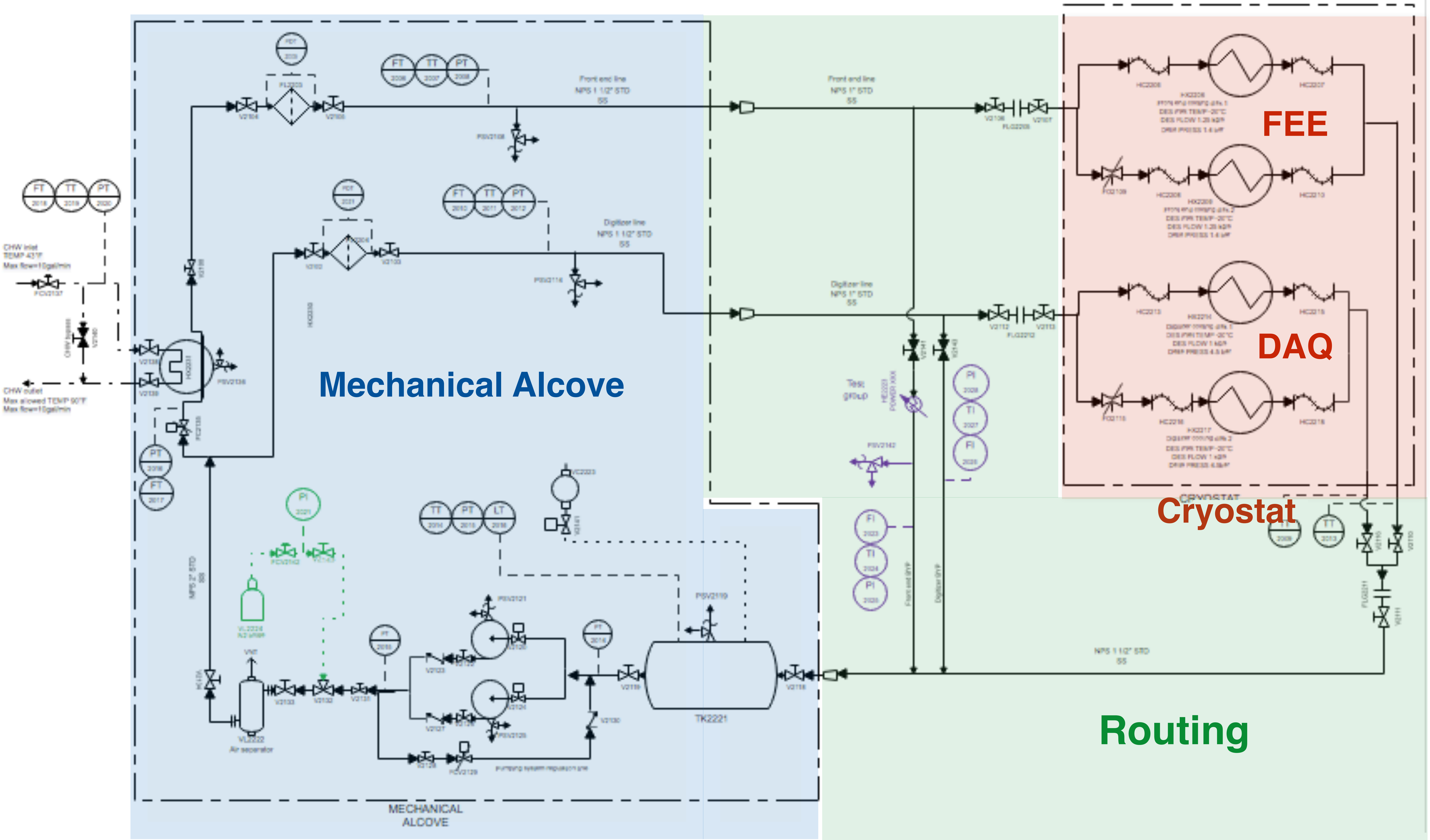
Impossible within electric power budget (25 kW).
Need for two independent cooling systems in this case

Single or double system?

- The FEE line must be able to work at -20 °C after an initial period at -10 °C
- If the -20 °C didn't upset the tracker the DAQ line could work at -20 °C in order to have a single circuit
- If the -20 °C couldn't be sustained is suggested to design 2 independent circuits. (At least 39.3 kW of electric energy waste running for 3 years, around 138 k$)

FEE Temp / DAQ Temp	-20 °C (almost surely)	-10 °C
-20 °C	SINGLE SYSTEM	DOUBLE SYSTEM
-10 °C	DOUBLE SYSTEM	SINGLE SYSTEM

Single system P&ID

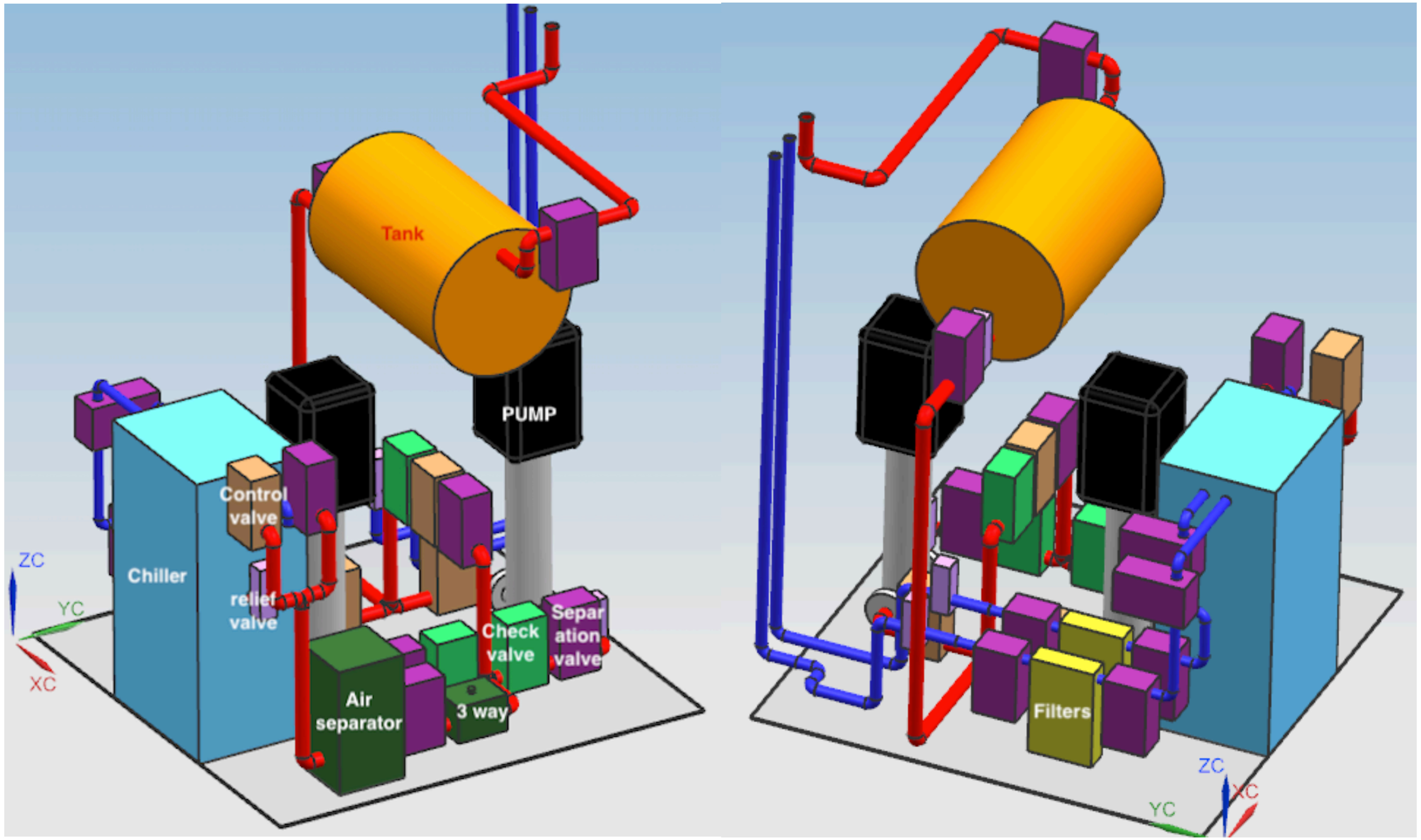


Mechanical Alcove: configuration

Placed in a mechanical room, outside the cryostat

COMPONENTS:

- 1 reservoir
- 1 chiller
- 2 pumps
- 2 filters
- 1 air separator
- 2 heaters
- 1 purging system
- 1 vacuum drainage system
- Valves & equipment

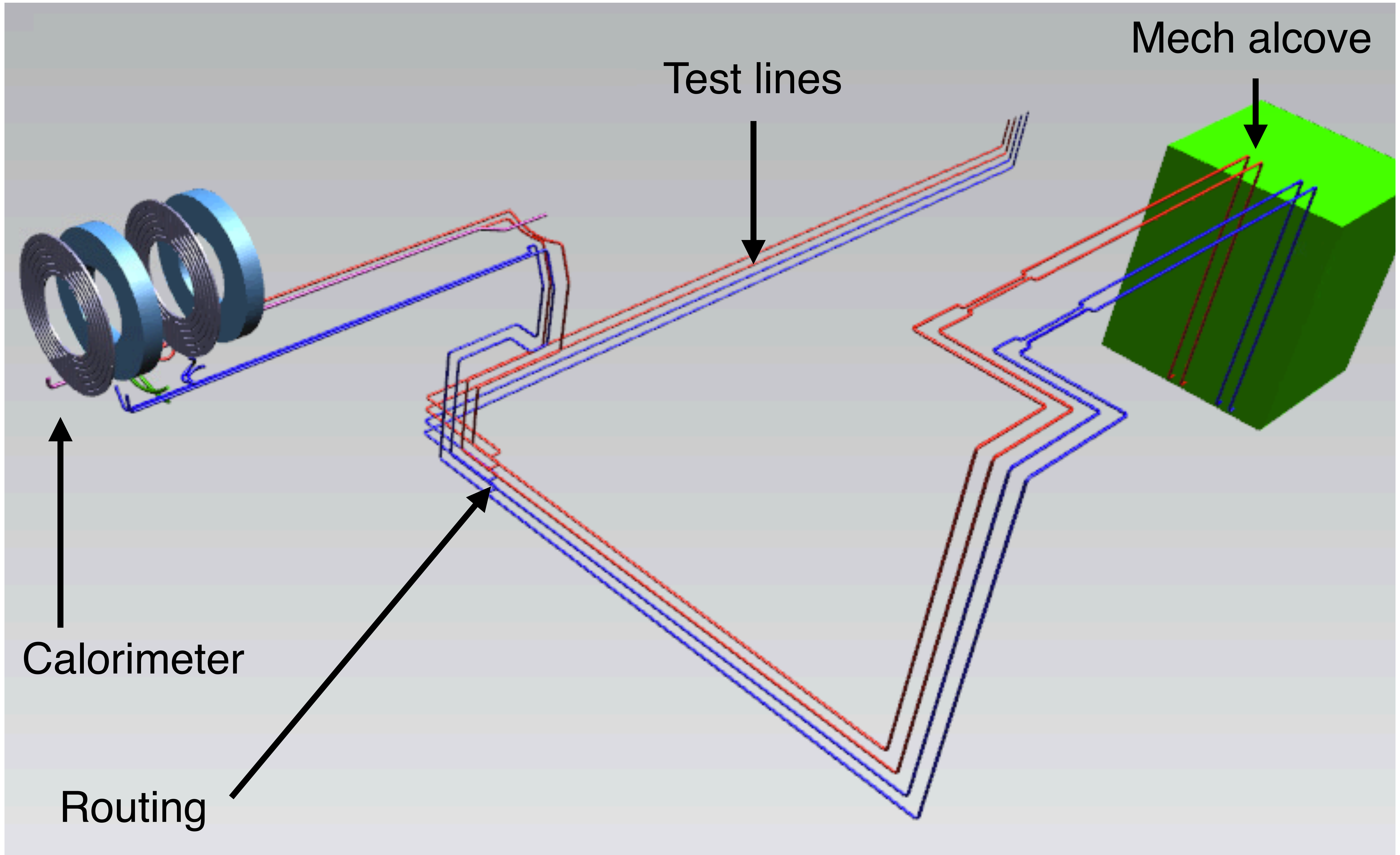


Routing system: configuration

Link between mechanical alcove and calorimeter.

COMPONENTS:

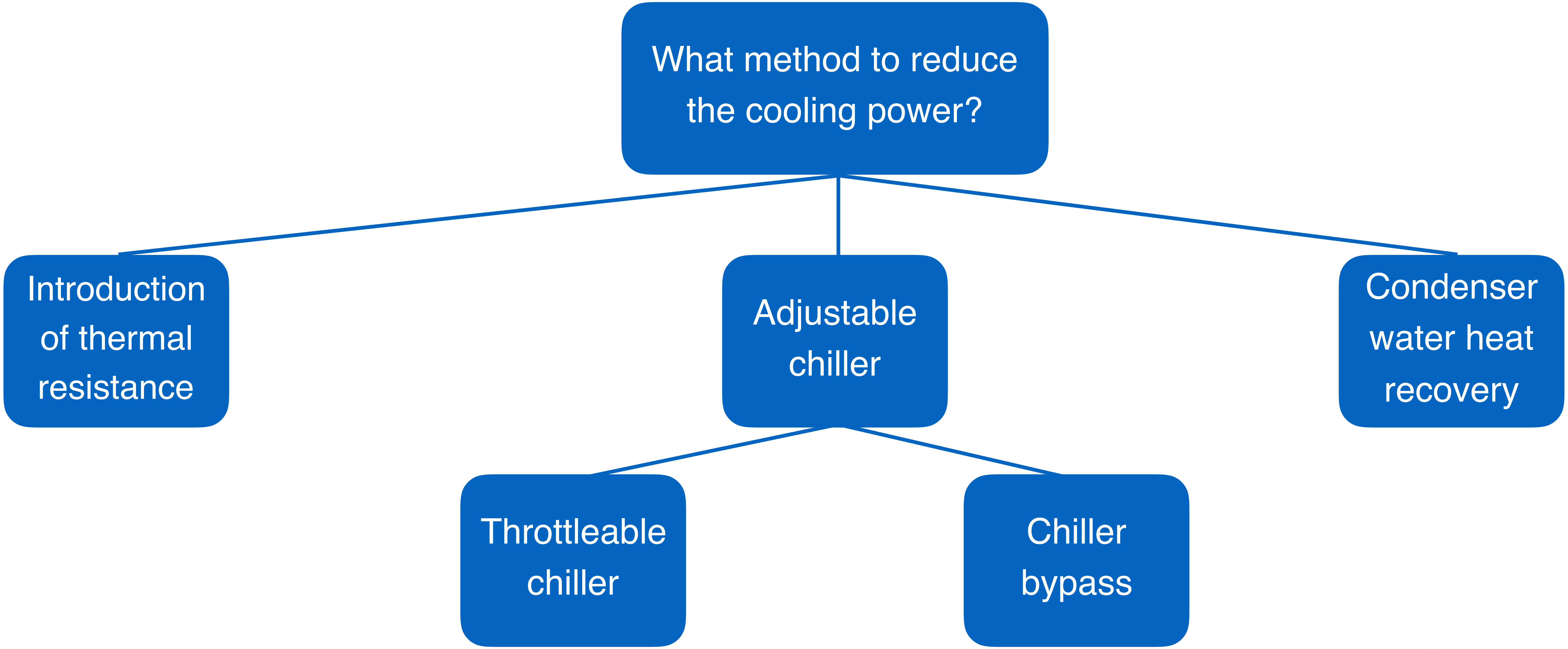
- 2 inlet lines (blue)
- 2 outlet lines (red)
- 4 test lines (endless lines)
- Valves & equipment



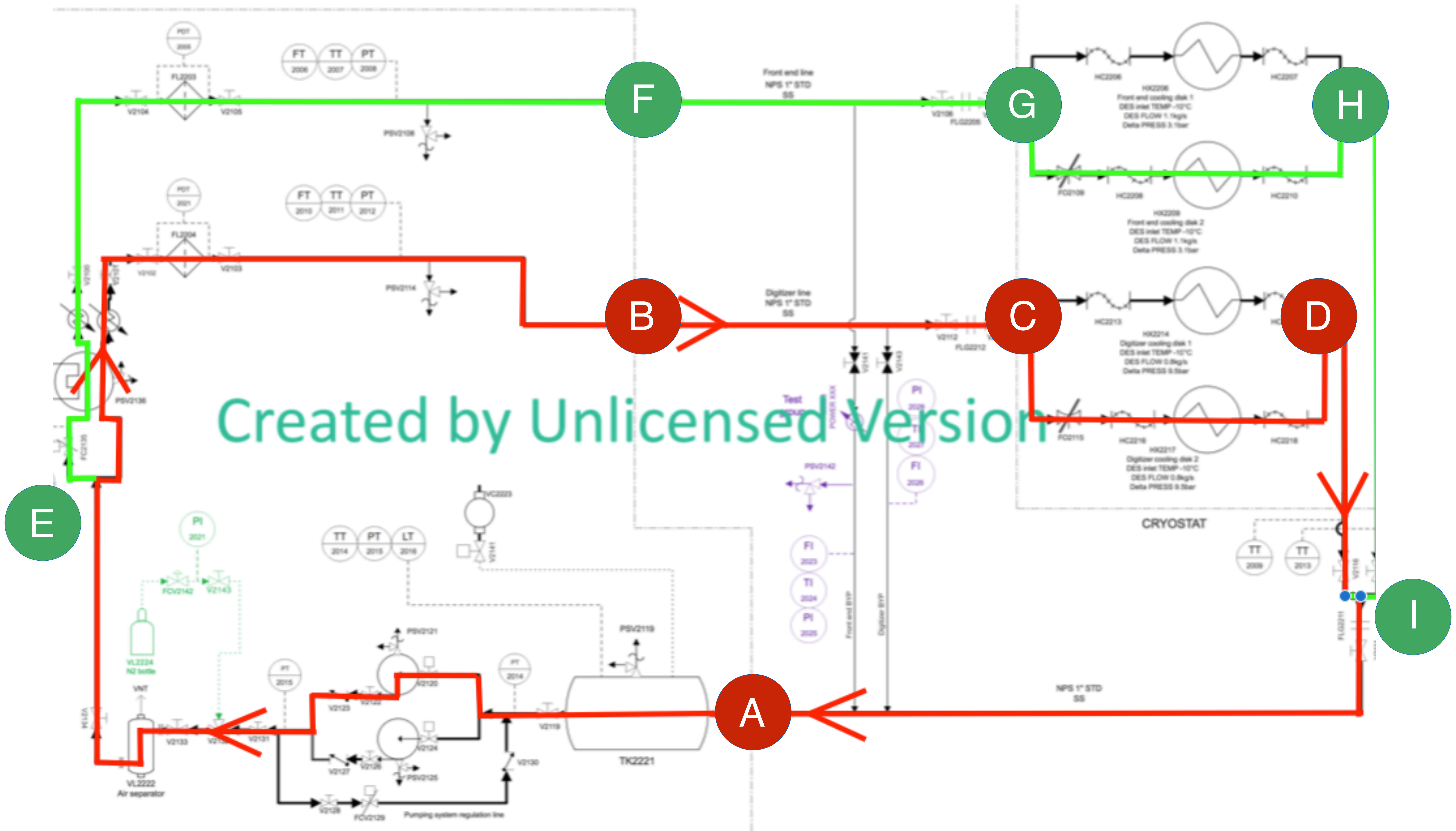
Old configuration's sketch. Needs to be updated (Teamcenter F10002515)

Temperature regulation of the system

- SiPM condition below -10 °C (system at -20°C) → Design set point
- SiPM condition below 0 °C (system at -10°C) → Need to lower the cooling capacity



Head loss: single system (-20 & -10 °C)



$$\dot{m}_{FEE} = 2.5 \quad kg/s$$

FEE PATH	HEAD LOSS [bar]
Mechanical alcove **A-E-F**	0.23
Routing FEE line **F-G**	1.56
FEE cooling line **G-H**	1.43
Common outlet line **H-A**	0.34
Valves & equipment	1.04
Margin of safety	10%
TOTAL	**5.1 bar**

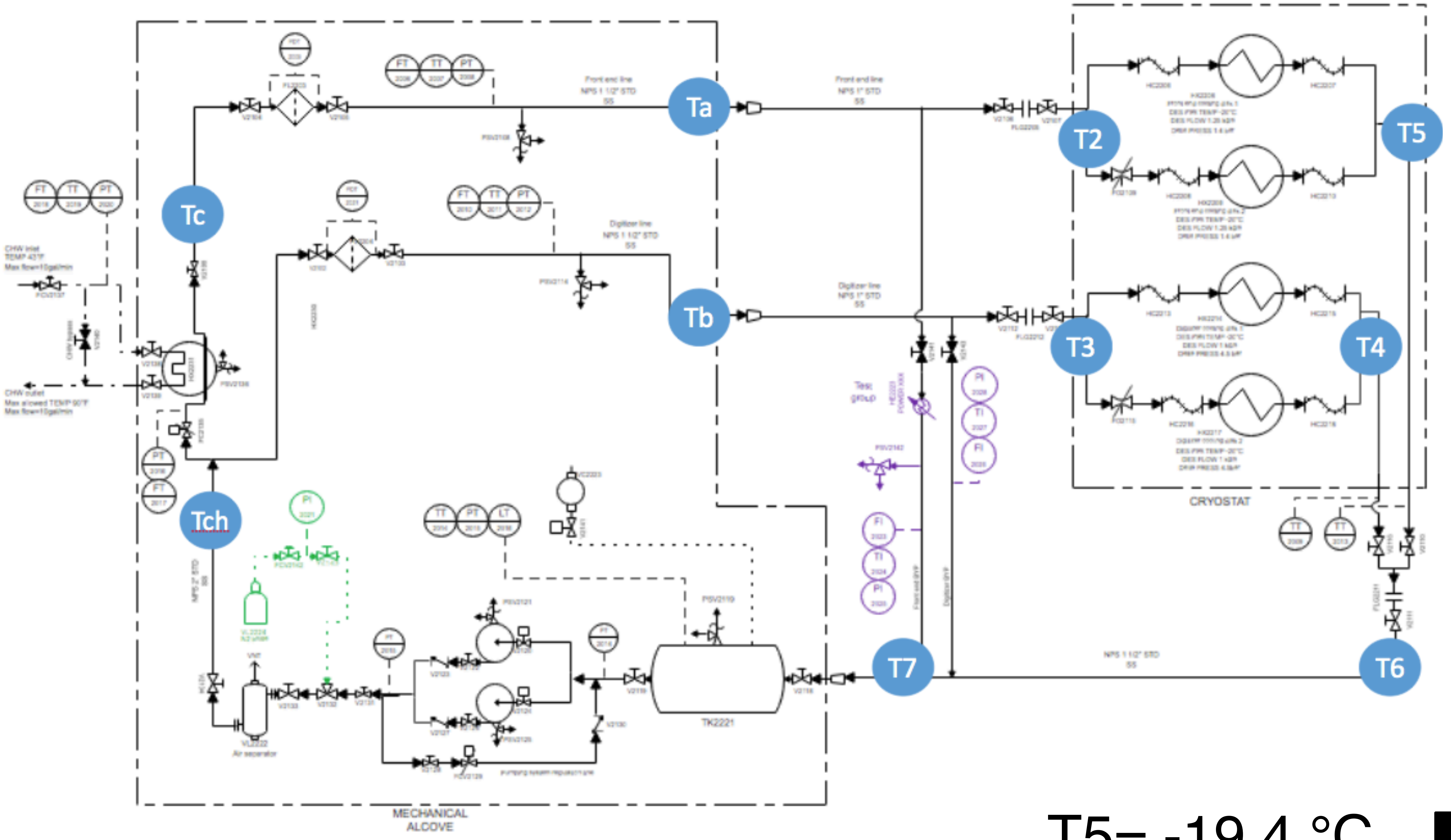
$$\dot{m}_{DAQ} = 2 \quad kg/s$$

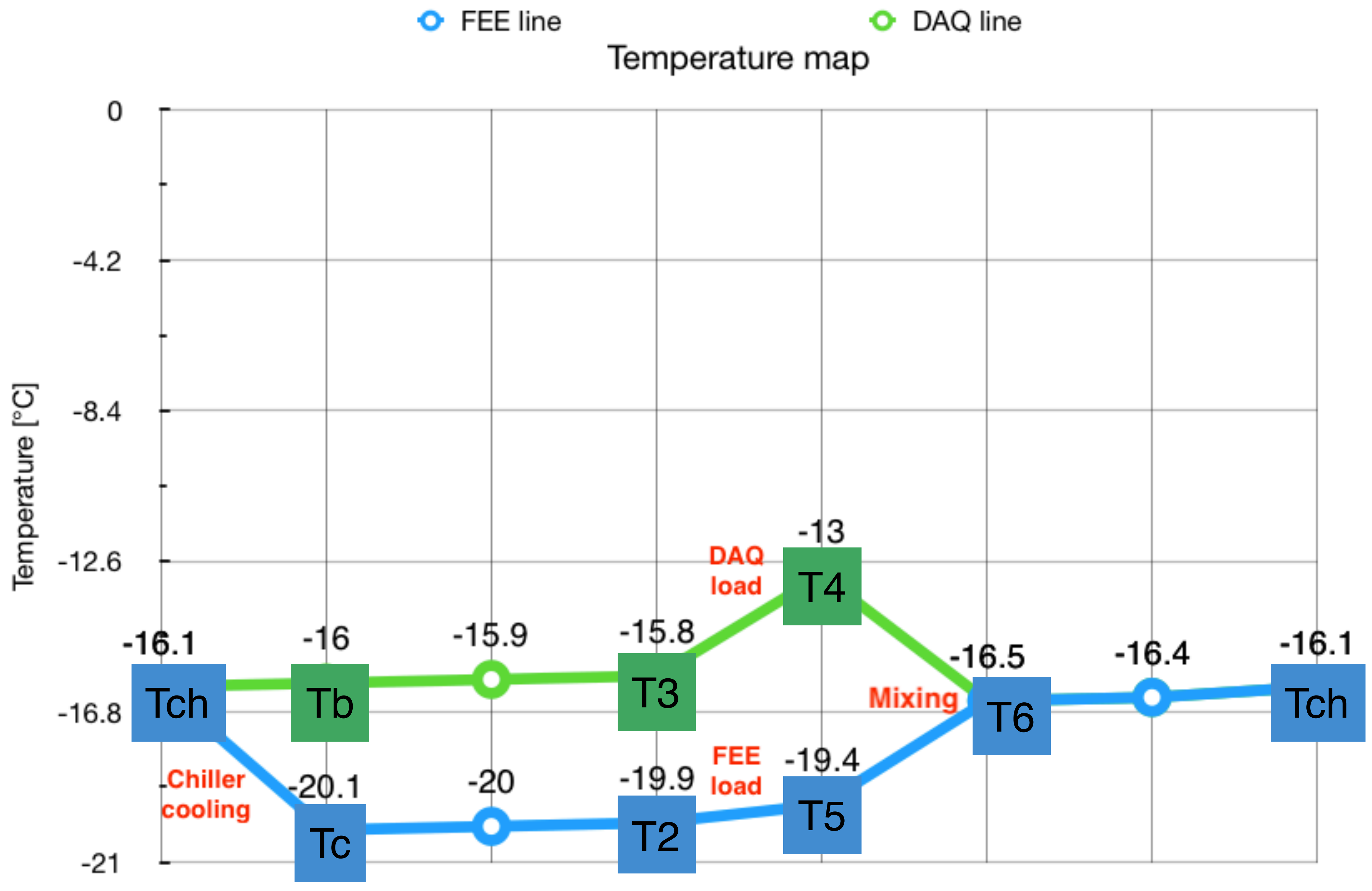
DAQ PATH	HEAD LOSS
Mechanical alcove **A-B**	0.23
Routing DAQ line **B-C**	0.99
Crates cooling line **C-D**	4.45 (9.1*)
Common outlet line **D-A**	0.34
Valves & equipment	1.04
Margin of safety	10%
TOTAL	**7.5 bar (13.6*)**

Pump head requirement

Balancing (dissipative) pressure between FEE and DAQ branch: 3 bar

Temperature map: single system at -20°C





T5= -19.4 °C ➡ $T_{SiPM} \simeq$ -13 °C

T4= -13 °C ➡ $T_{max.el} \simeq$ +17 °C

Thermal inertia of the system

From the enthalpy integral equation we get (ideally assuming constant c_p and $\dot{Q}_{in}$):

$$m_{tot} c_p \frac{dT}{dt} = \dot{Q}_{in} \quad \longrightarrow \quad \frac{\Delta T}{\Delta t \dot{Q}_{in}} = \frac{1}{m_{tot} c_p}$$

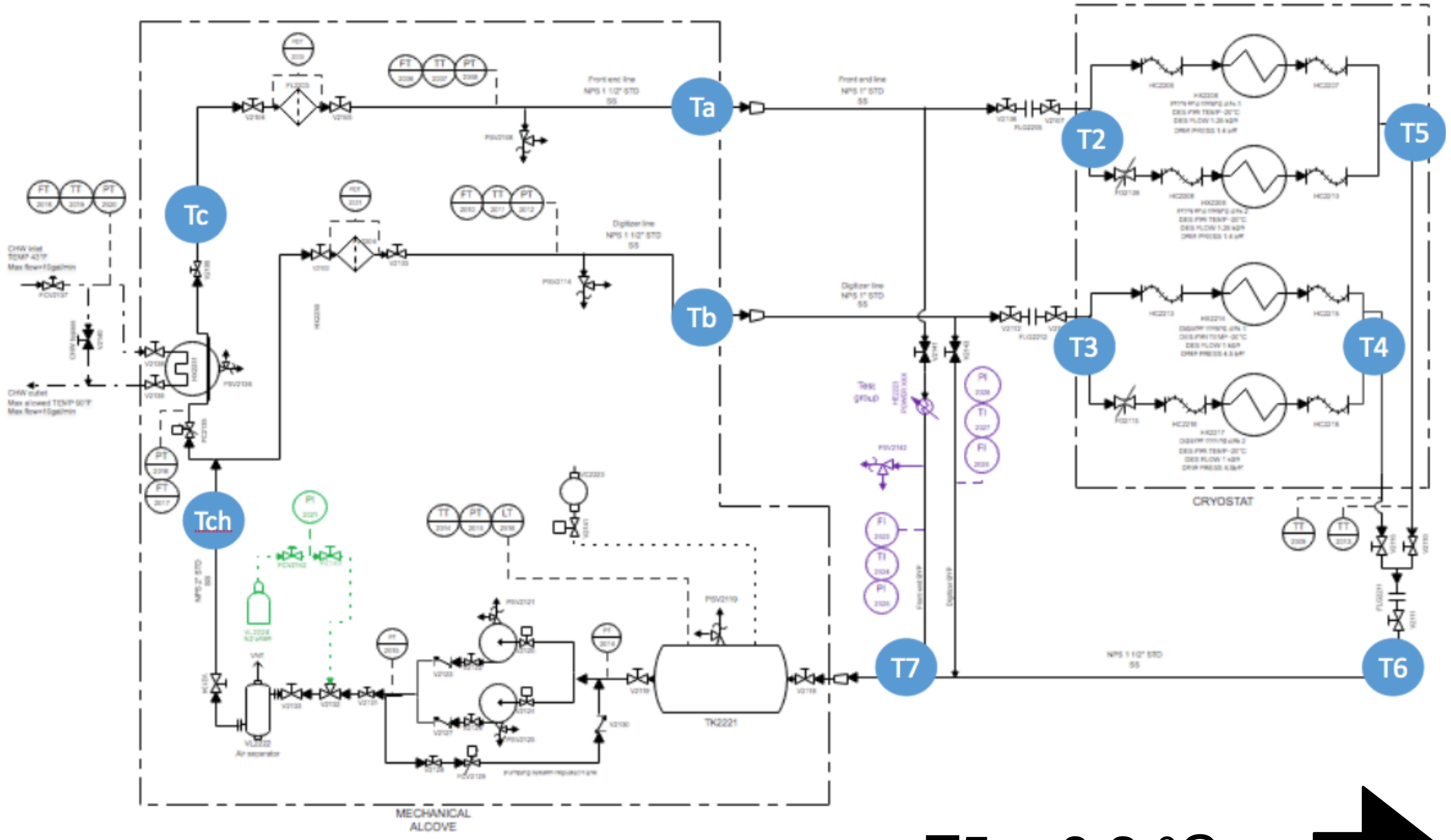
$$m_{tot} = 740 \text{ kg}$$
$$c_p = 980 \text{ J/kgK}$$

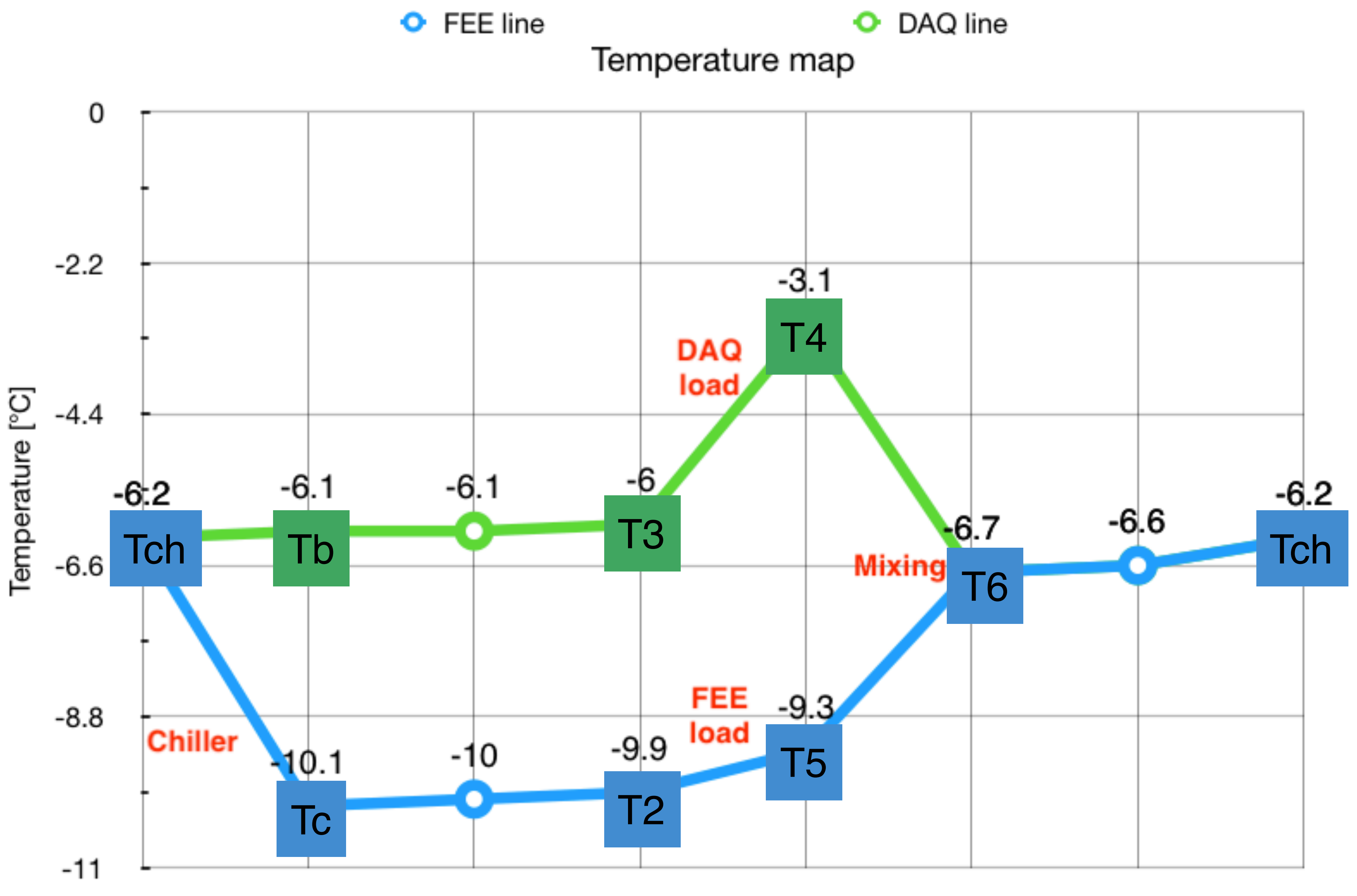
$$\longrightarrow \quad \frac{\Delta T}{\Delta t \dot{Q}_{in}} = 1.38 \cdot 10^{-3} \quad \frac{K}{s \cdot kW}$$

For instance:

- An incoming net power of 1 kW (different sources available) produces 10 °C of temperature raise in 2 hours
- Another solution is the utilisation of a VFD regulated chiller (higher initial cost but lower electric consumption in the long period operation)

Temperature map: single system at -10°C



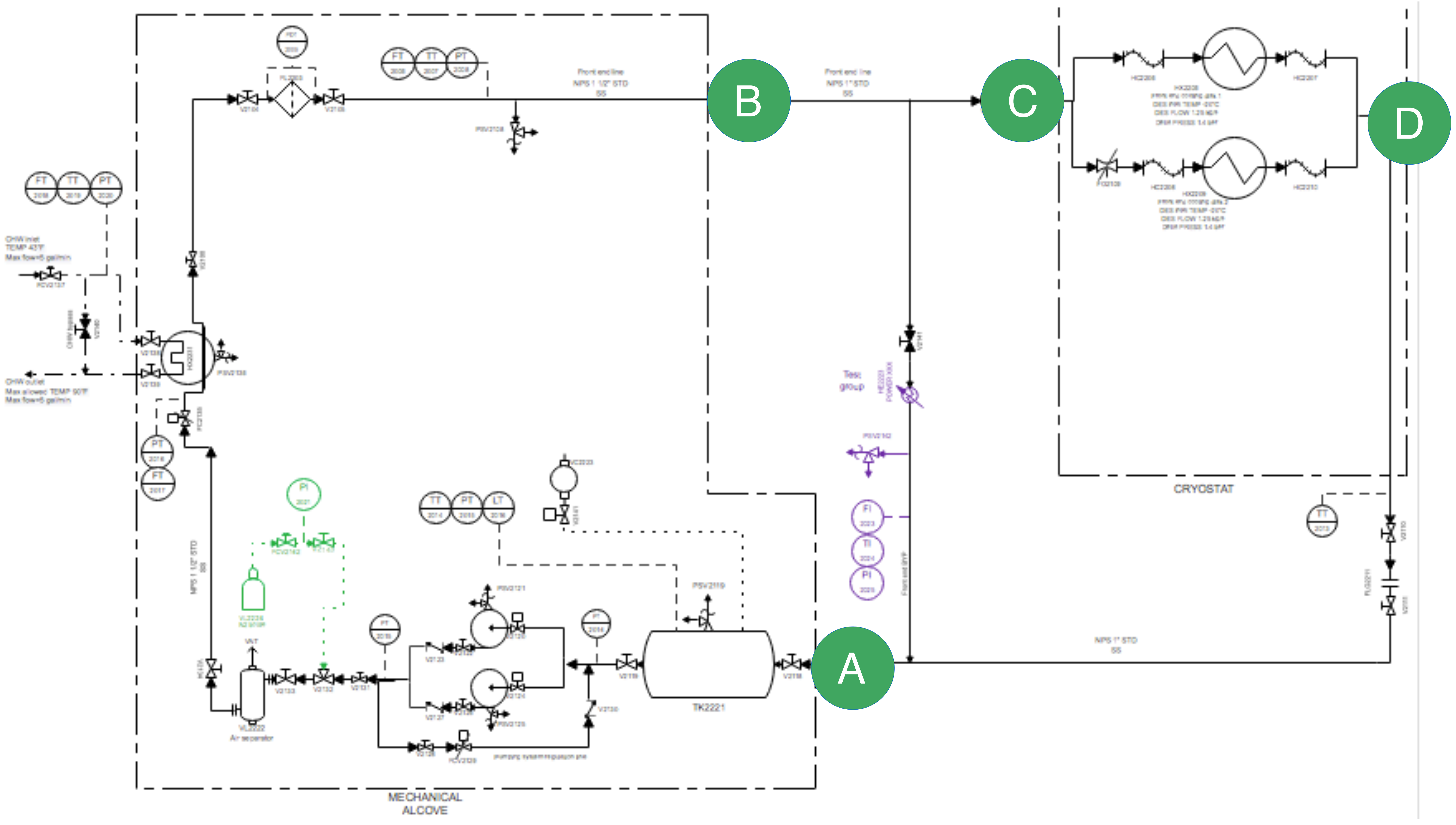


T5= -9.3 °C ➡ $T_{SiPM} \simeq$ -3 °C

T4= -3.1 °C ➡ $T_{max.el} \simeq$ +27 °C

Fermilab

Head loss double system: FEE line at -20°C



$$\dot{m}_{FEE} = 2.5 \quad kg/s$$

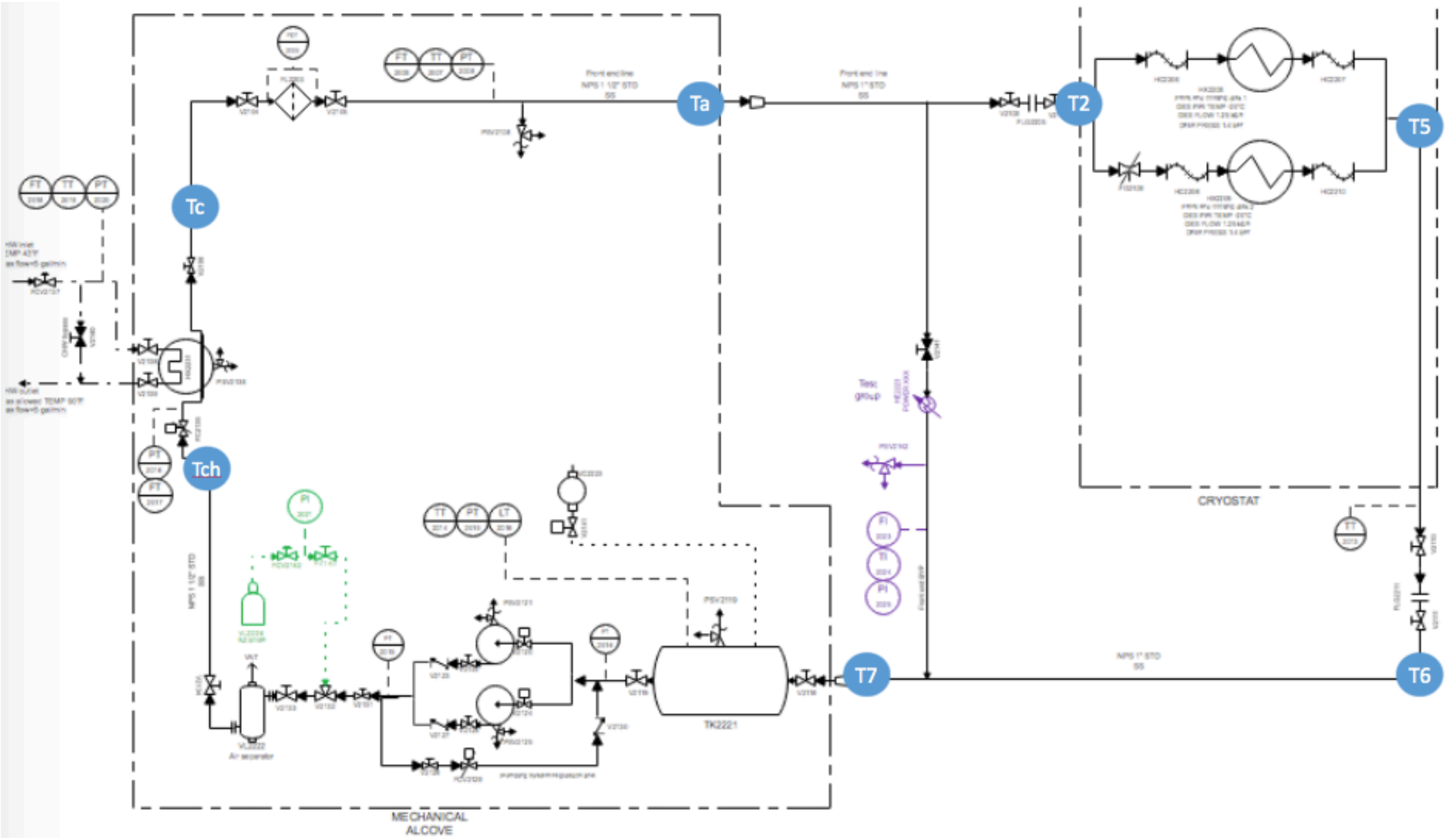
PATH	HEAD LOSS
Mechanical alcove **A-B**	0.26 bar
Routing FEE **B-C**	1.56 bar
FEE cooling line **C-D**	1.43 bar
Routing outlet line **D-A**	0.35 bar
Valves & equipment	1 bar
Margin of safety	10%
TOTAL	**5.1 bar**

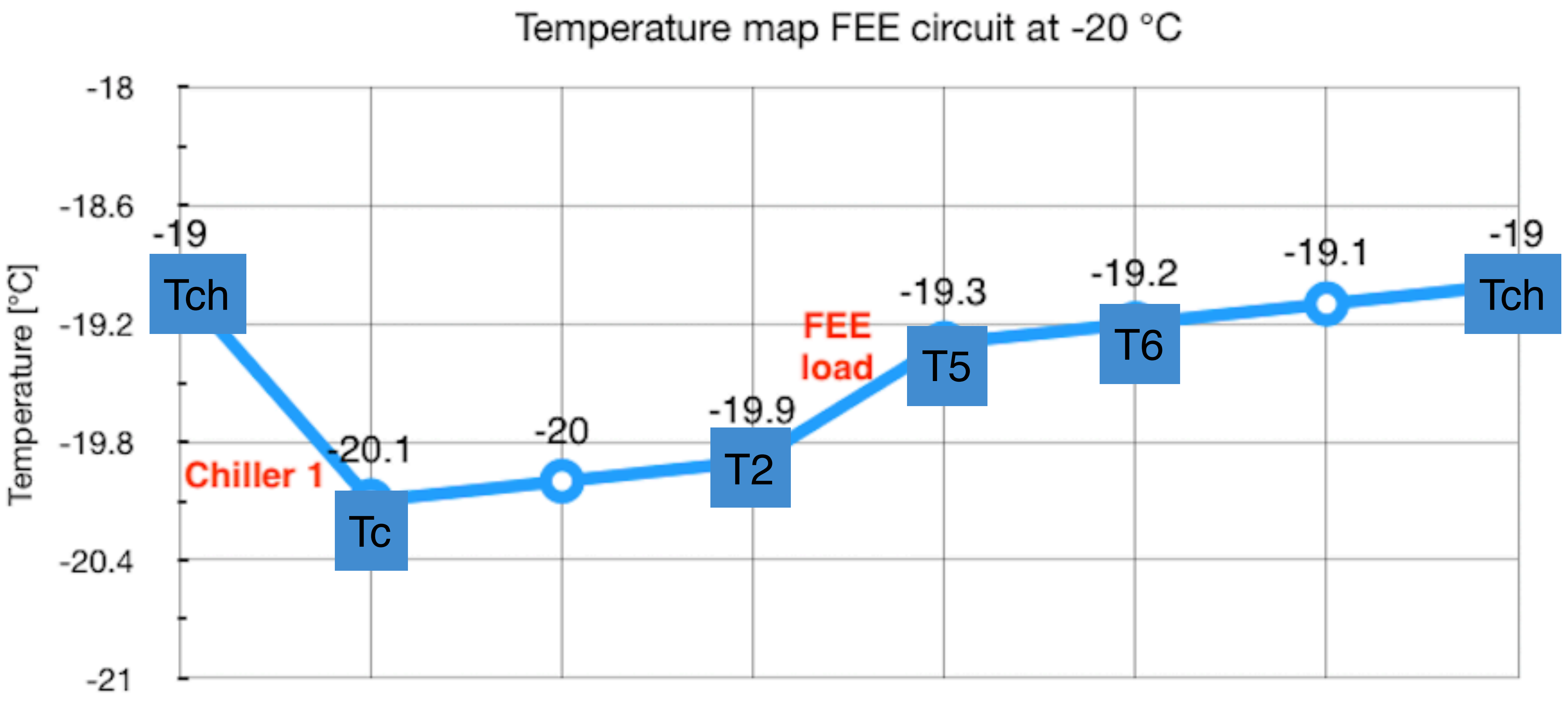
5.1 bar pump head requirement

(2.4 bar less than single system)

Fermilab

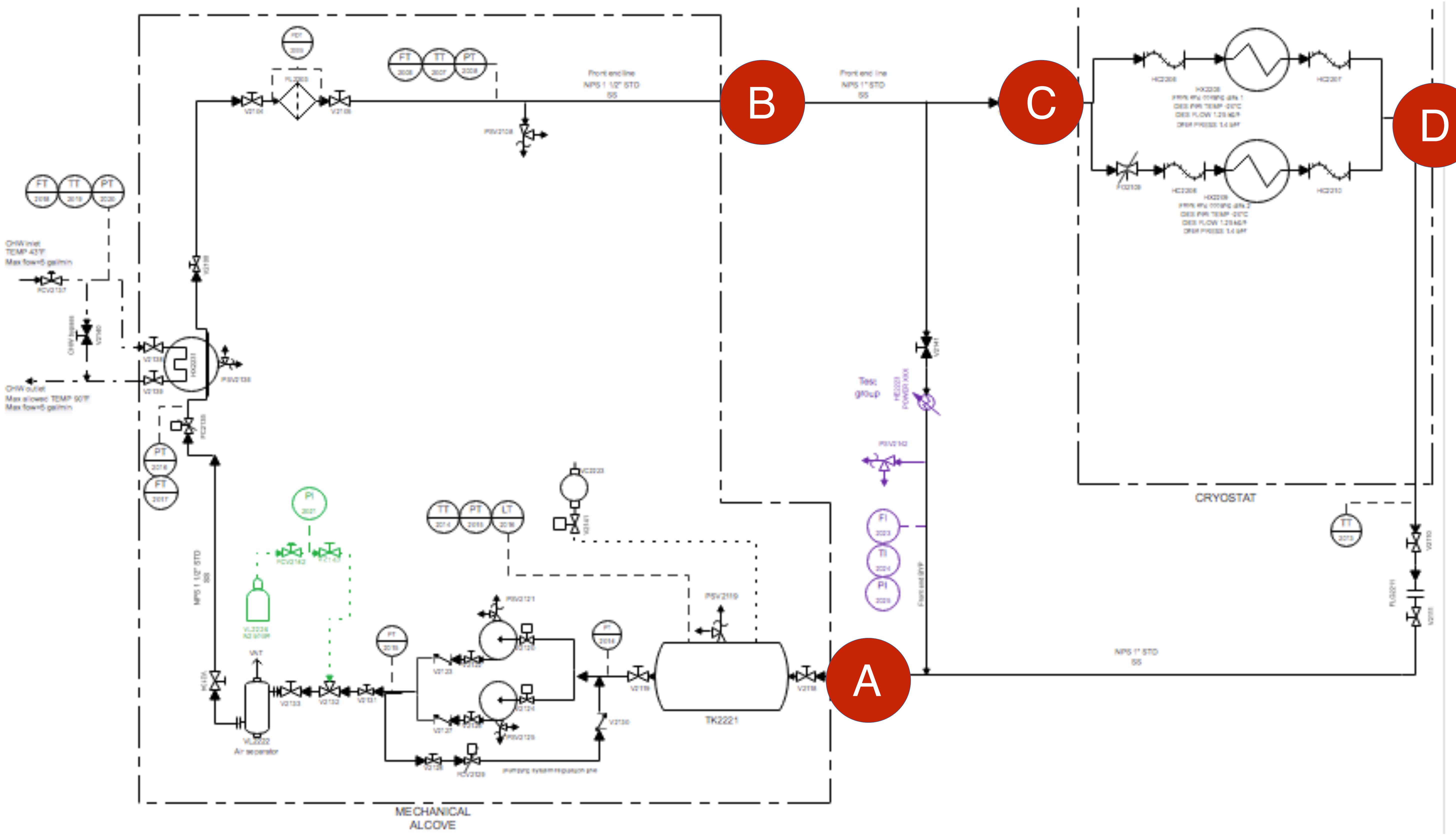
Temperature map double system: FEE at -20°C





T5= -19.3 °C ➡ $T_{SiPM} \simeq$ -13 °C OK!

Head loss double system: DAQ at -10°C

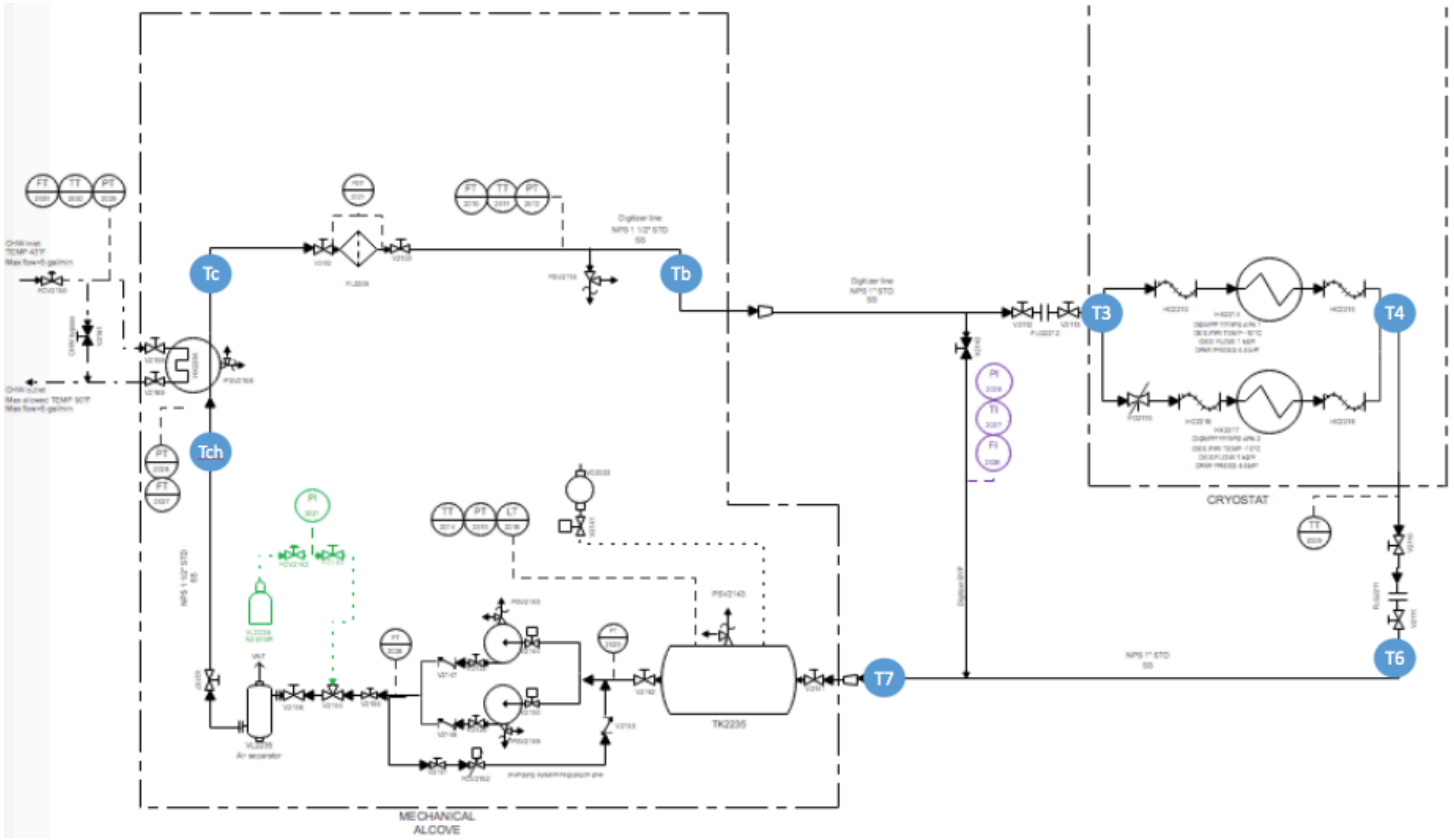


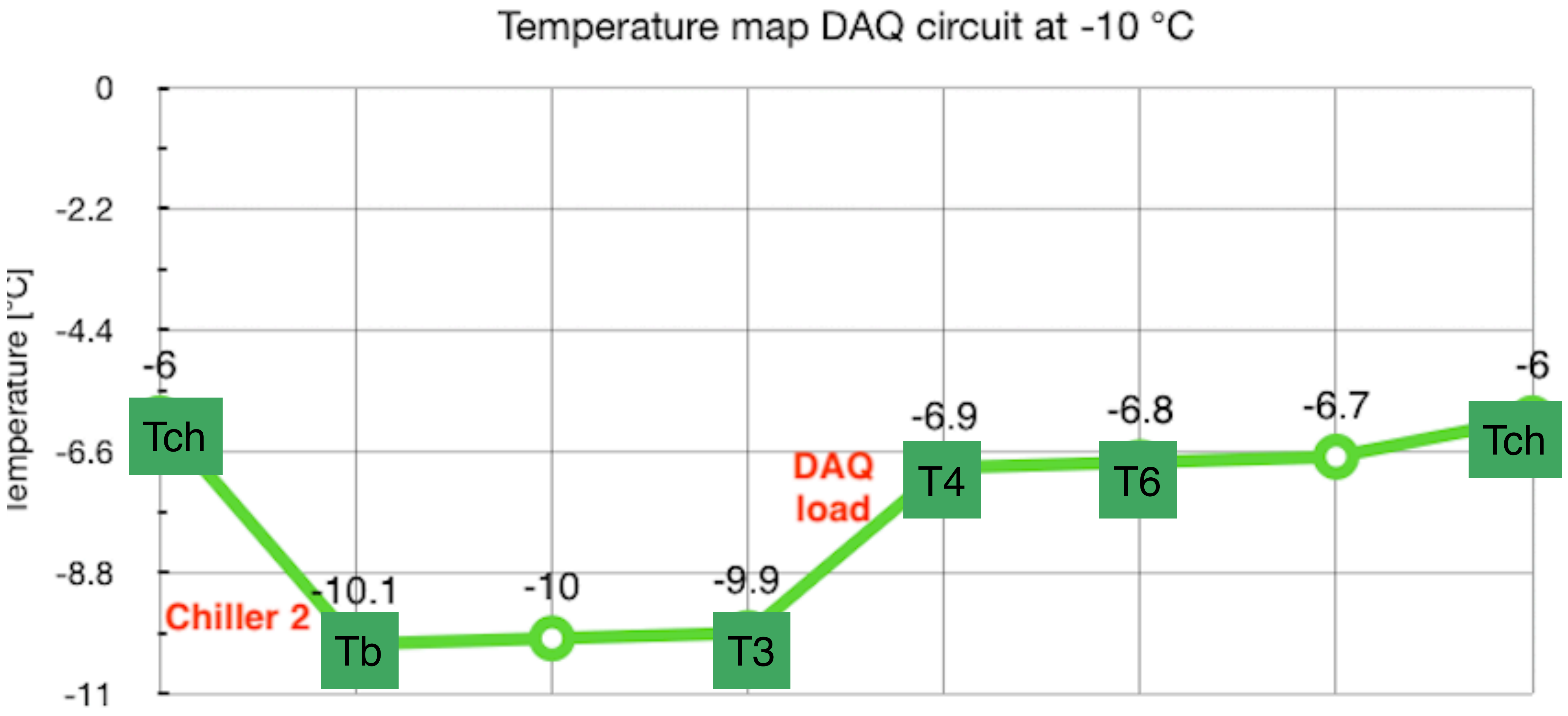
$$\dot{m}_{DAQ} = 2 \quad kg/s$$

PATH	HEAD LOSS
Mechanical alcove **A-B**	0.22 bar
Routing DAQ **B-C**	0.96 bar
DAQ cooling line **C-D**	4.3 bar
Routing outlet line **D-A**	0.34 bar
Valves & equipment	1.03 bar
Margin of safety	10%
TOTAL	**7.5 bar**

7.5 bar pump head requirement (similar to single system)

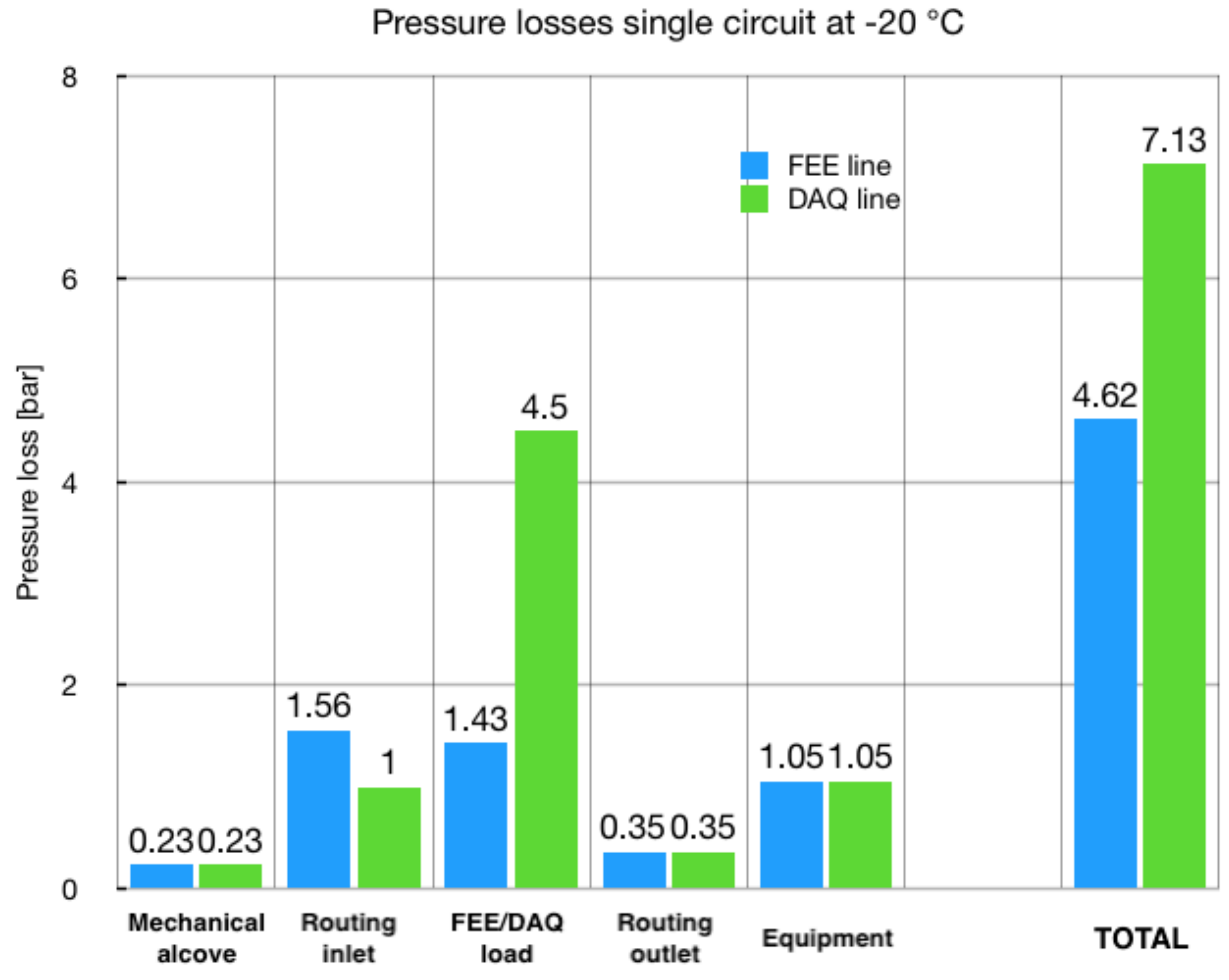
Fluid temperatures double system: DAQ at -10°C

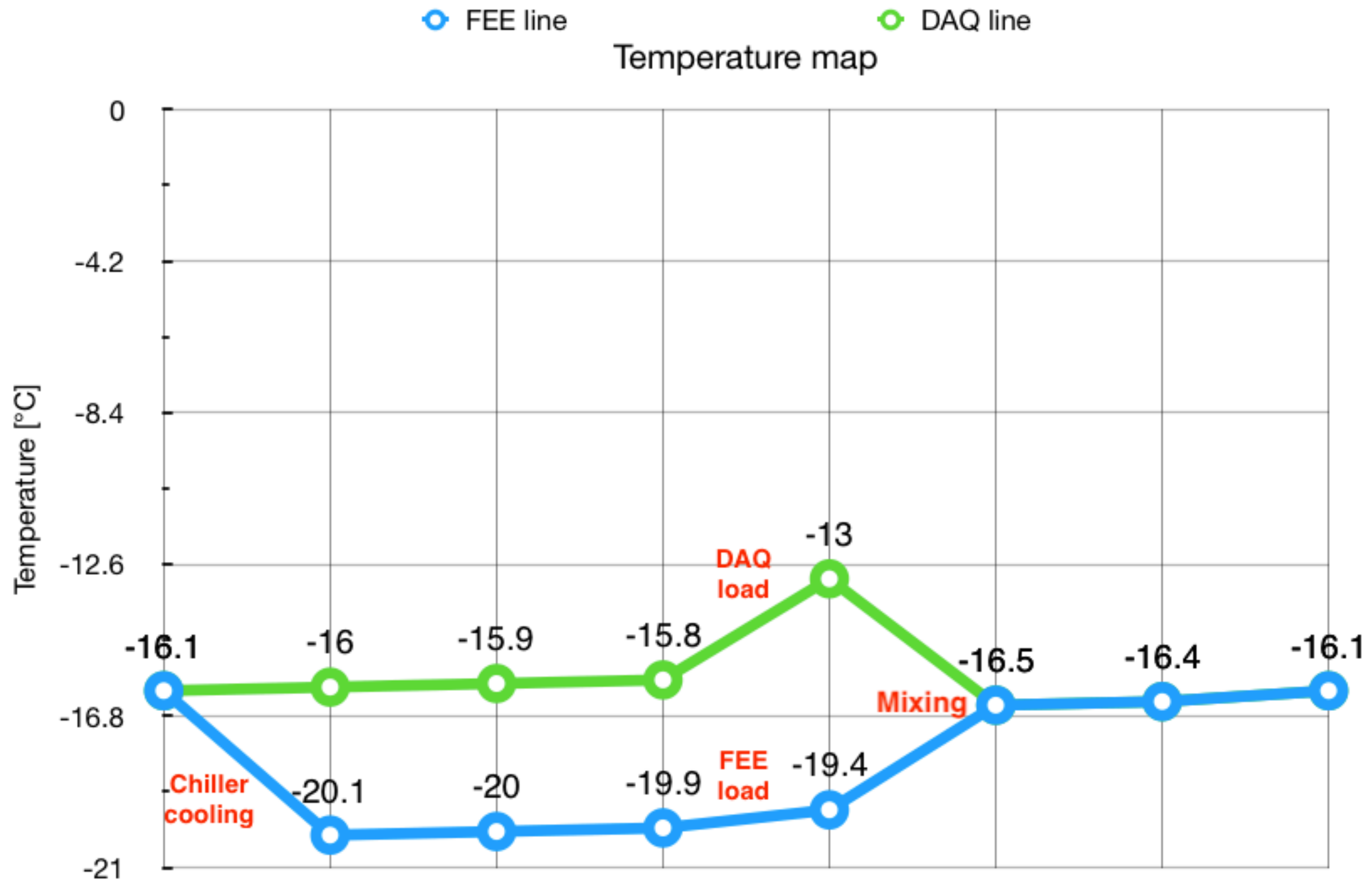




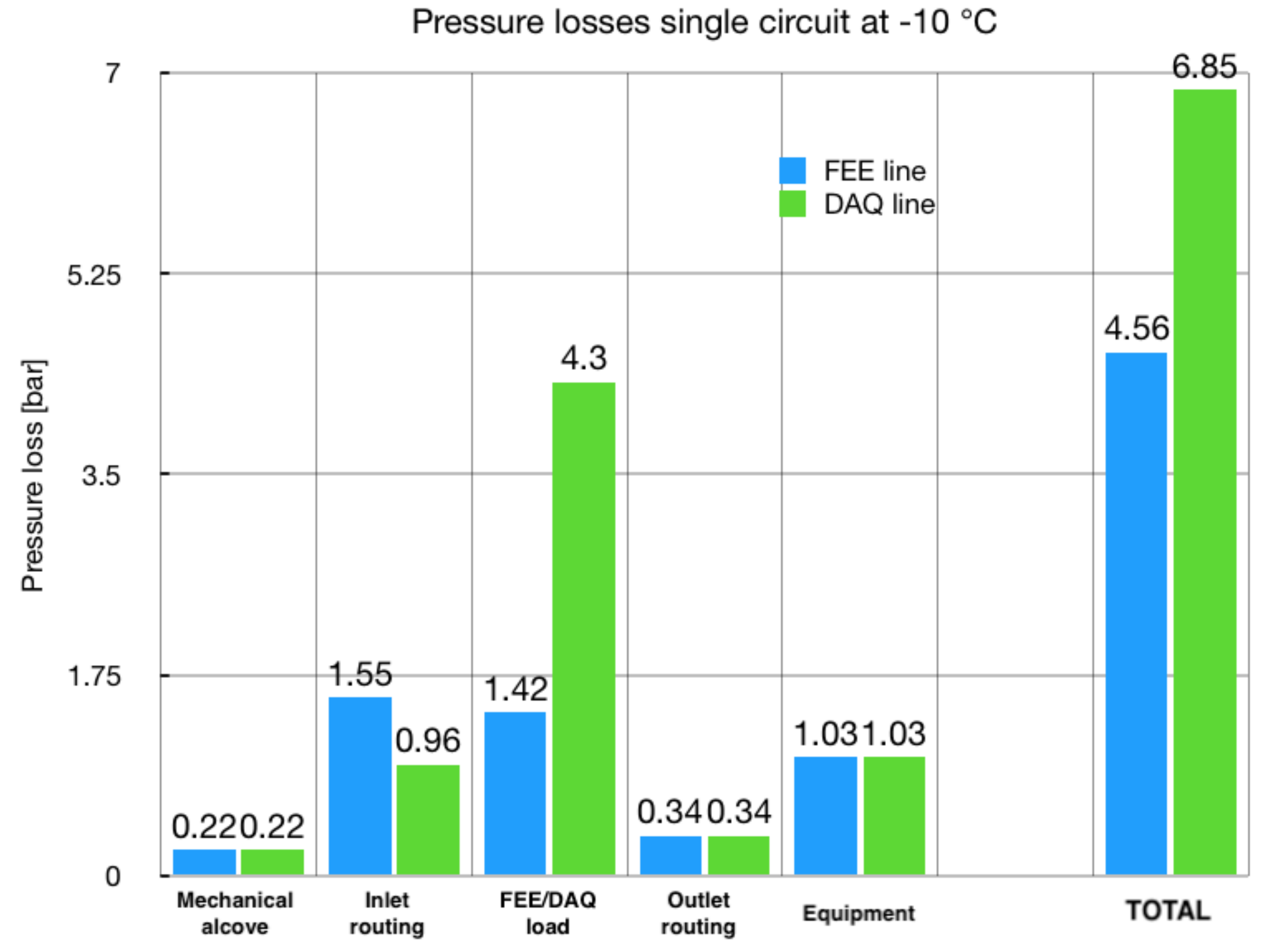
T4=-6.9 °C ➡ $T_{max.el} \simeq$ +23 °C OK!

Summary single system

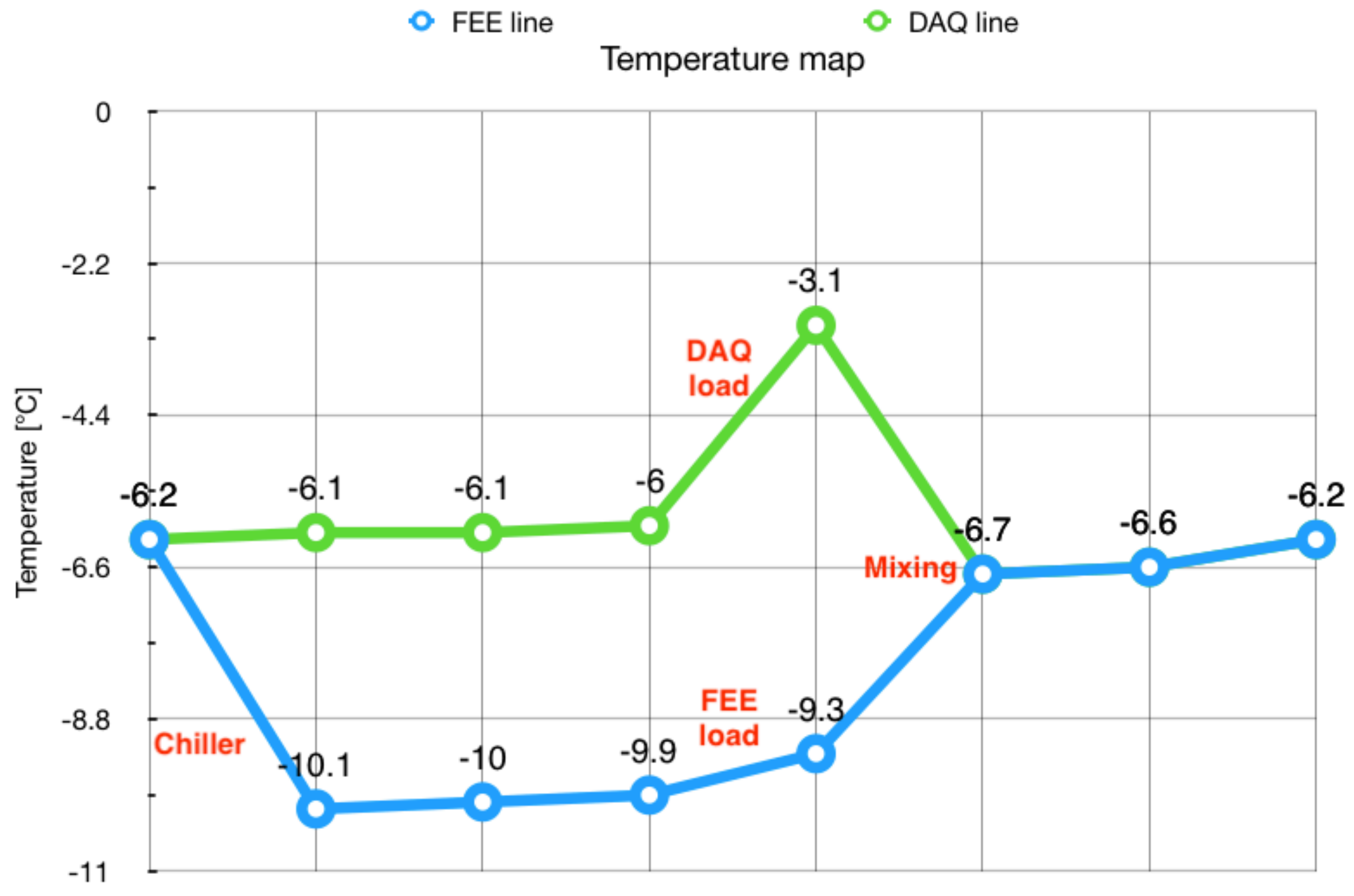




Switch from -20°C to -10°C

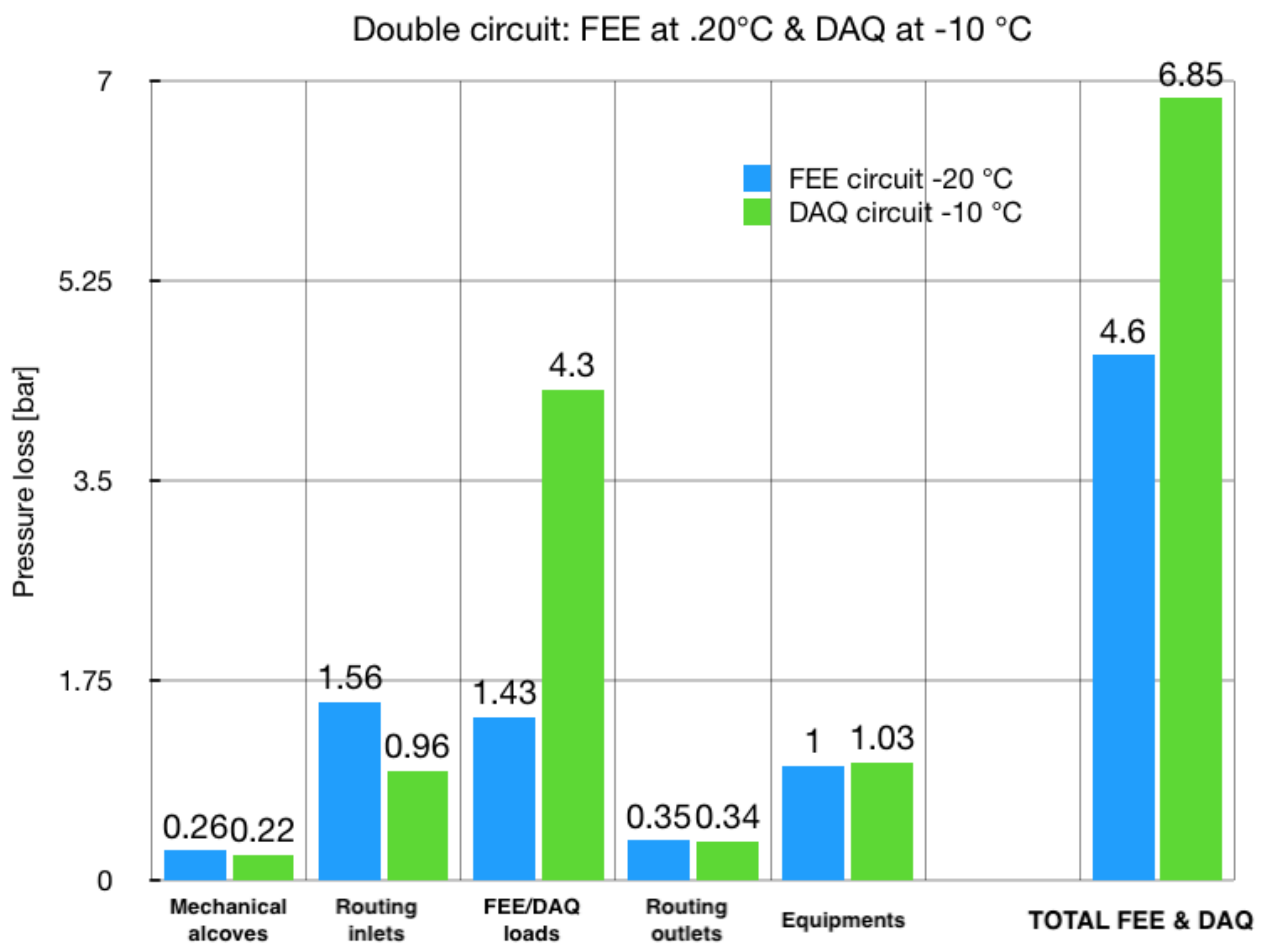


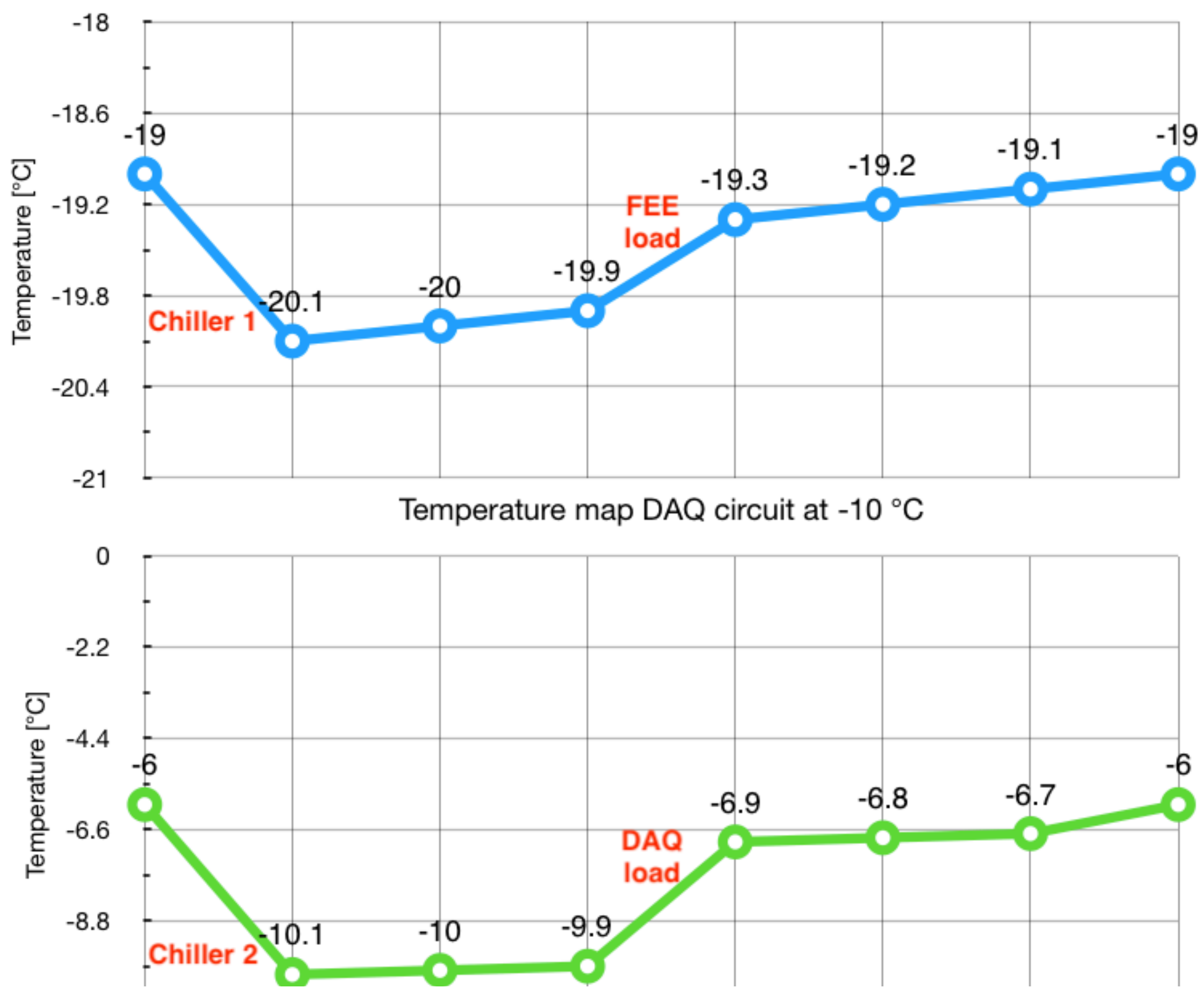
Only difference in temperatures. The pump works almost constantly (4.5 kg/s at 7.2 bar)



Fermilab

Summary double system

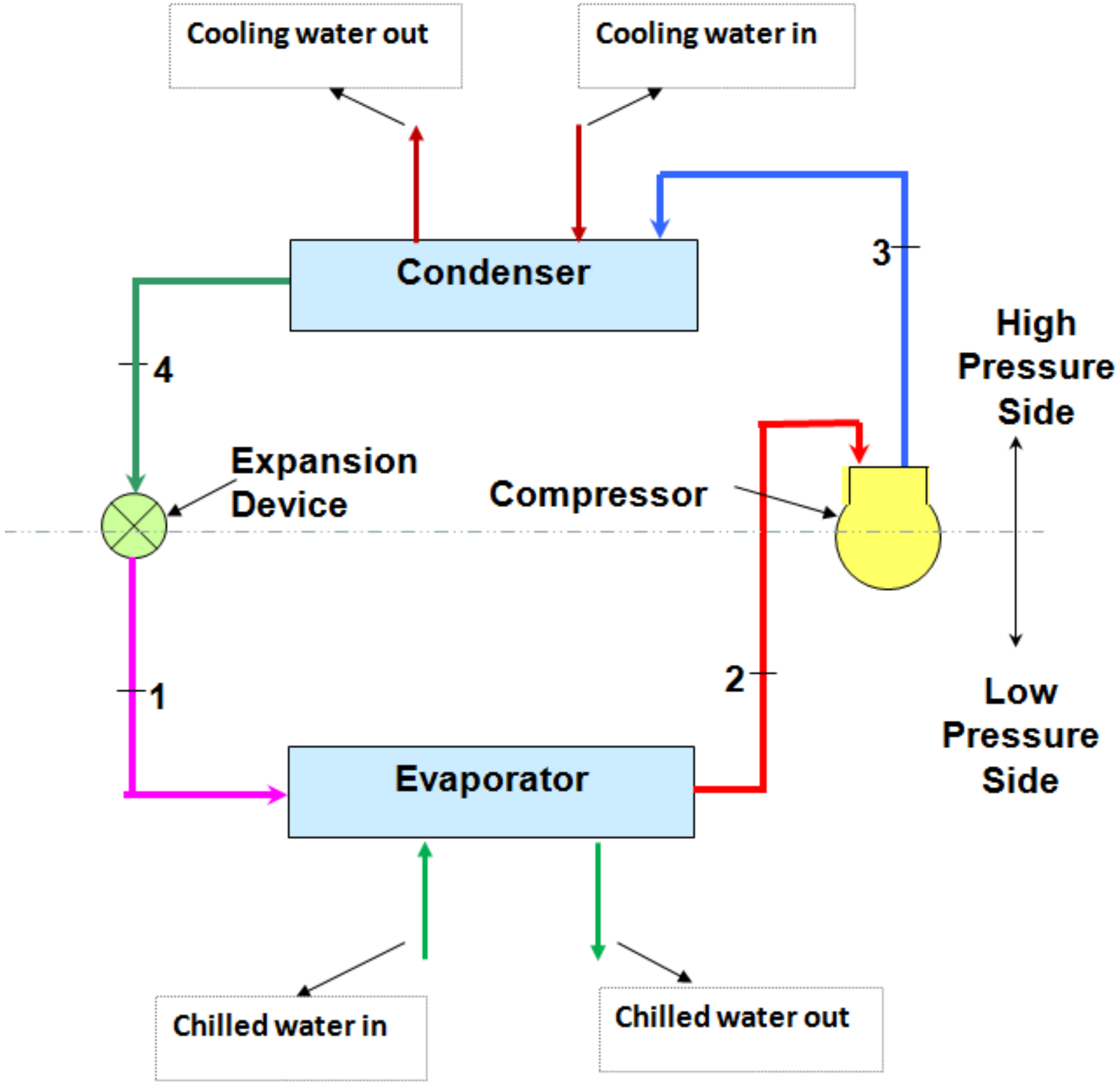




2 Different pumping requirements: 2 kg/s at 7.5 bar for DAQ, and 2.5 kg/s at 5.1 bar for FEE (including safety margins)

Chiller requirements (single system)

- Chemically compatible with the fluid
- One cooling line of 2.5 kg/s
- Inlet fluid temperature -16 °C
- Outlet fluid temperature -20 °C
- Peak cooling capacity 11 kW
- Cooling capacity range at least 5-11 kW
- Able to work at 10 °C warmer fluid set point
- Water cooled condenser
- Evaporator lines rated at 15 bar internal pressure



Chiller proposal

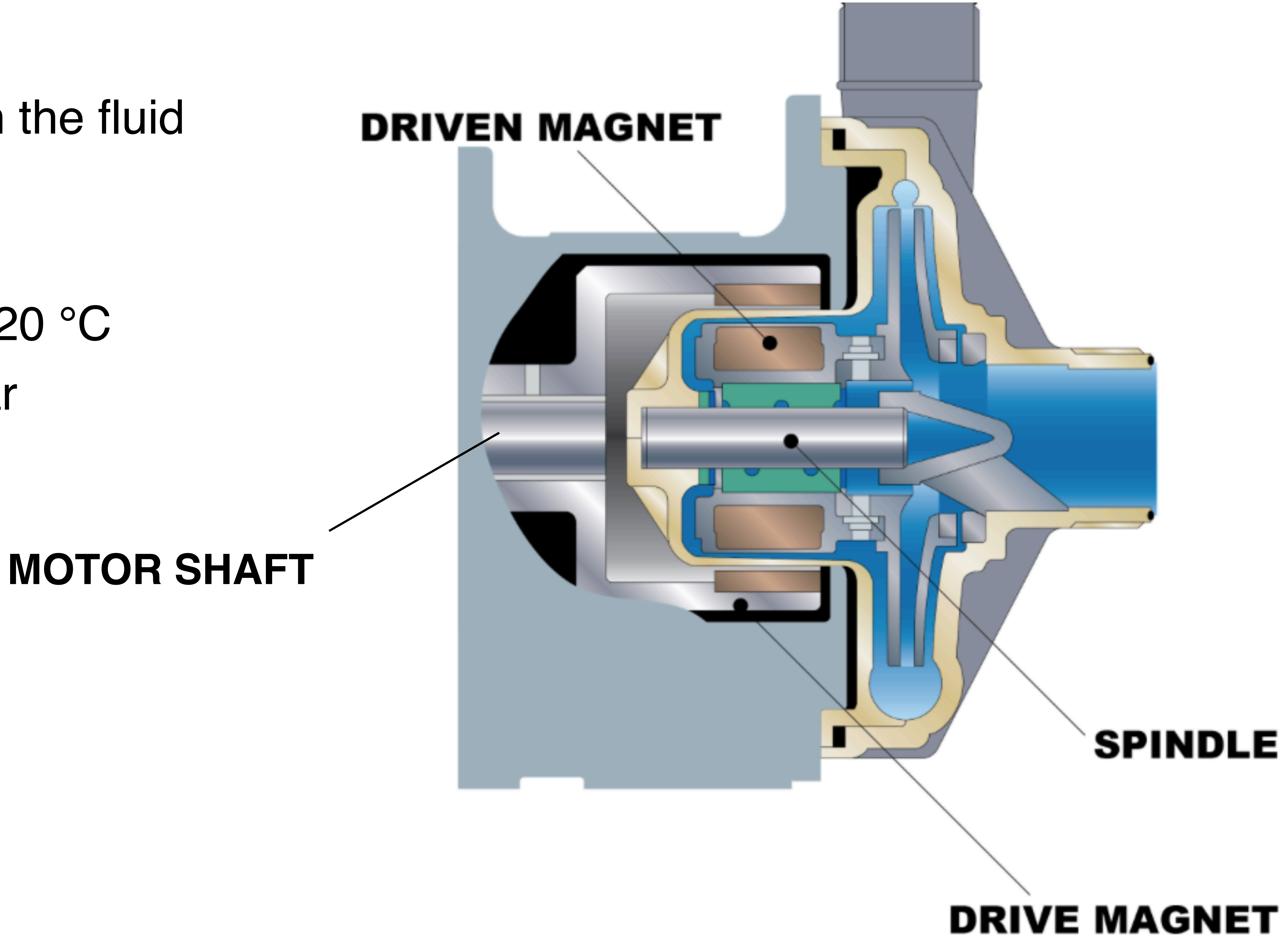
Chiller model PCW-03LLTX (Cooling technology INC)

- Refrigerant: R-404A
- Condenser: water cooled
- Leaving fluid T: -20 °C (up to -10°C)
- Entering fluid temperature T: -16 °C (up to -6°C)
- Cooling capacity: 11.55 kW
- Compressor power input: 4.38 kW
- Chiller capacity controller: hot gas bypass
- Total chiller power: 4 kW
- Dimensions: L1220 x W915 x H1524 mm
- Weight: 810 kg
- Price: 28,869.00 $

Pump requirements (single system)

- Chemically compatible with the fluid
- Flow rate: 4.5 kg/s
- Pumping head: 15 bar
- Design fluid temperature: -20 °C
- NPSH requested < 1.15 bar
- No leakages permitted

Centrifugal pump
(magnetic drive)

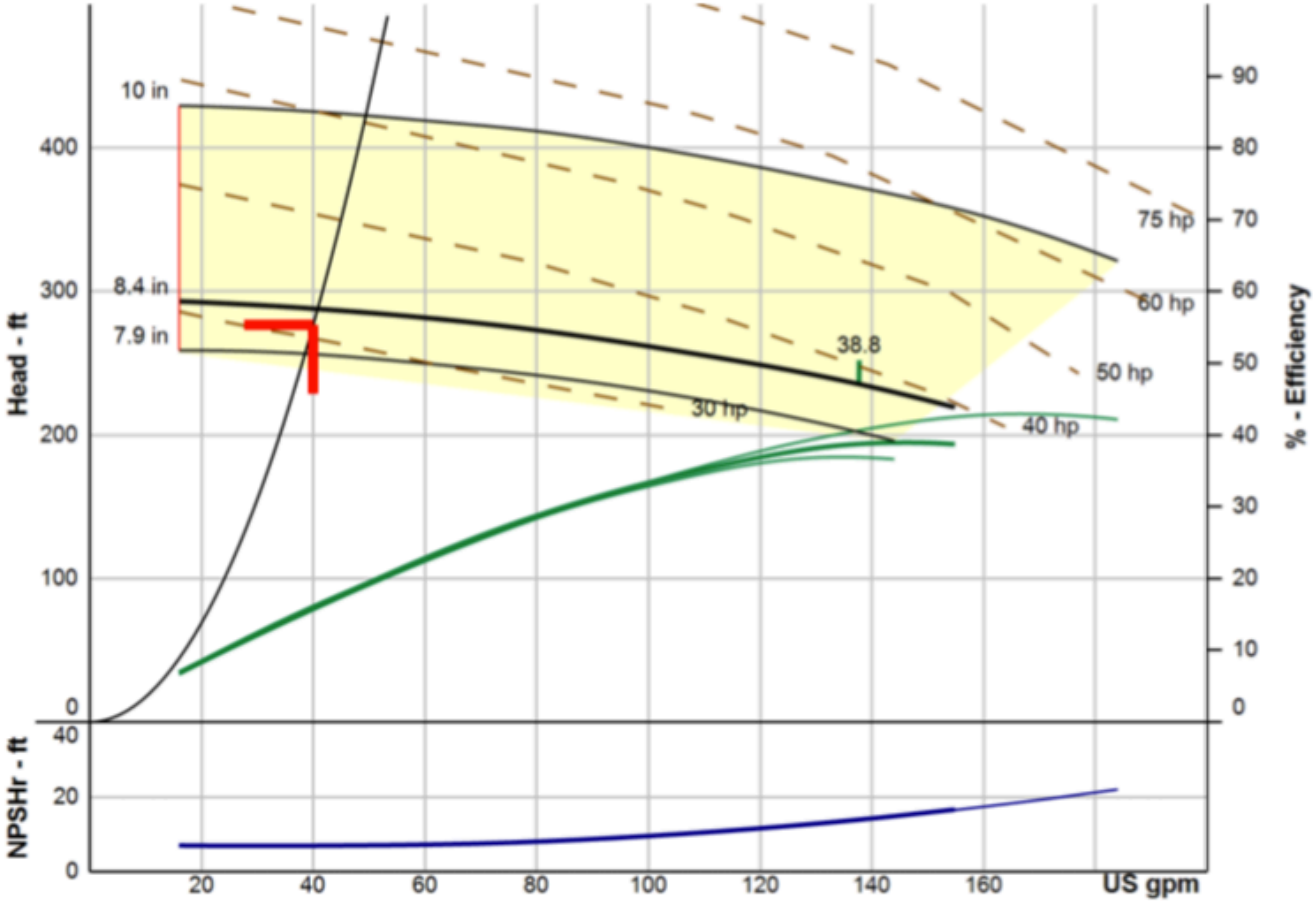


Pump proposal

Pump performance (Magnatex M-29039):

- Chemically compatible with the fluid
- Flow rate: 4.5 kg/s (40 GPM)
- Pumping head: 15.7 bar (293 ft freon)
- NPSH requested: 0.43 bar
- Hydraulic power: 3.92 kW
- Efficiency: 16%
- **Power: 24.5 kW**

Excessive electric power needed
(electric budget for the overall alcove is 25 kW)



Courtesy of Magnatek Pumps Inc.

To do

- Figure out a technical solution for the electric power constraint (series of “better” pumps, etc…)
- Foresee possible different working conditions, depending on later developments of SiPM & boards (change in temperature requirements etc..)
- Find machines suitable to work with the double system as well
- Experimental verification of the crates head loss
- Selection of all other equipment (valves, pipes etc..)