Muon Collider
Magnet Technology Options
Internal Review

Cooling

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Cooling options – main drivers

Energy consumption

Target for collider ring 25 MW electrical consumption

Cryo availability

Availability increases with lower # of cryoplants

Local heat extraction

Coil design complexity increases with heat load

Target ≤ 10 W/m

Choice of conductor

Determines temperature level and allowed ΔT

Distribution losses

Allowable Δp and ultimately $\dot{m}$ will determine arc cell length

Sector length will depend on deliverable $\dot{m}$ per cryoplant

Reduced complexity

Minimise # jumpers (*i.e.* as long arc cells), short interconnects

Reduce # of temperature levels provided

Function of the nature and T range of the fluid

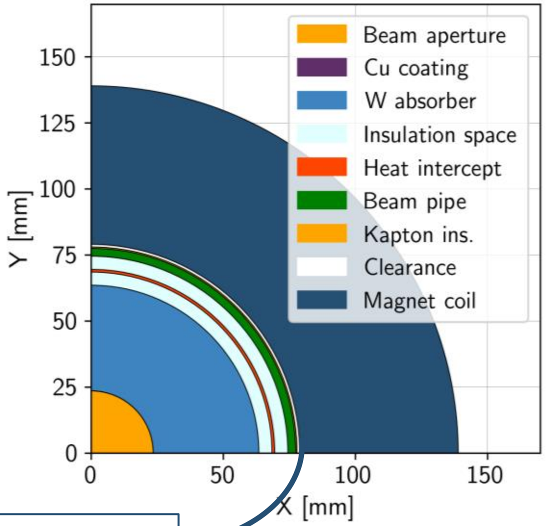
Reduced He content in cryostats

Updated radial build for collider arc magnets

- Radial build has evolved to include a **heat intercept** between the absorber and the coil

Beam aperture (5σ)	23.5 mm radius
Cu layer beam screen	0.01 mm thick
Tungsten absorber	40 mm thick
Insulation space	5 mm thick
Heat intercept	1 mm thick
Insulation space	5 mm thick
Beam pipe	3 mm thick
Kapton insulation	0.5 mm thick
Clearance	1 mm thick
Coil pack*	(60 mm thick)

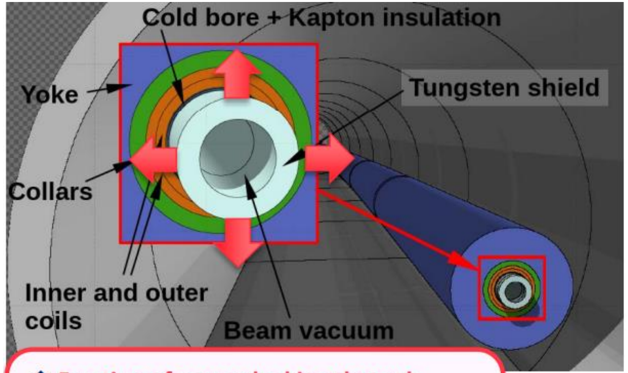
*thickness TBD, placeholder



Coil aperture 158 mm

Updated radial build for collider arc magnets

- Radial build has evolved to include a **heat intercept** between the absorber and the coil
- Baseline for heat load estimation/power consumption is **10 TeV machine**



- **Fraction of power leaking through shielding similar for 3 TeV & 10 TeV**
- This power is mostly deposited in cold mass (including cold bore)

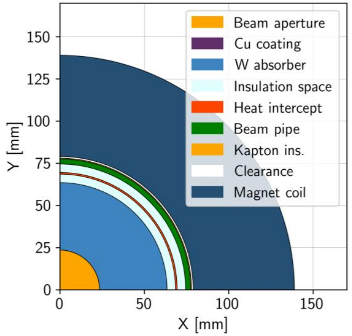
	To absorber	To cold mass		
	Power carried by decay e$^-$/e$^+$:	Power penetrating shielding		
		2 cm	3 cm	4 cm
3 TeV	410 W/m	14 W/m	6 W/m	3 W/m
10 TeV	500 W/m	18 W/m	8 W/m	4 W/m

From muon decay; total heat load will include substantial contributions, *e.g.* conduction, thermal radiation…

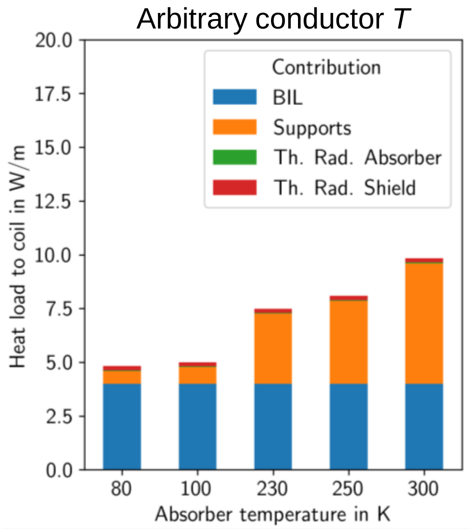
Source: Informal meeting on muon collider absorber, vacuum and cryogenics integration (18 January 2023) · Indico (cern.ch)

Heat load deposited at cold mass level

w/ heat intercept



- Heat load estimated considering a heat intercept (between coil and absorber) and a thermal shield external to the cold mass at 80 K, and as a function of:
  - Coil temperature;
  - Absorber temperature;
  - Absorber thickness.
- **Note:** absorber is not considered to be part of the cold mass
- Heat load ~ independent of coil *T* (cooling effort heavily does, see next slide)
- Heat intercept cuts heat load by (thermal) radiation from the absorber to negligible values (total heat load doubles without it)
- Contribution from absorber supports considered disproportionate w.r.t. unavoidable beam-induced loads for $T_{abs} \geq 100$ K

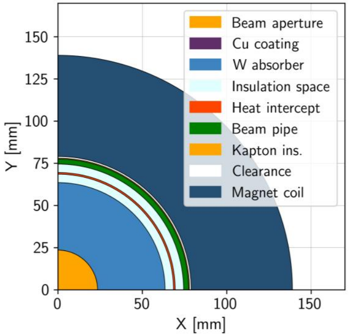


Shown: Heat load to coil in W/m, for heat intercept and thermal shield at 80 K, absorber thickness 4 cm, coil at 4.5 K

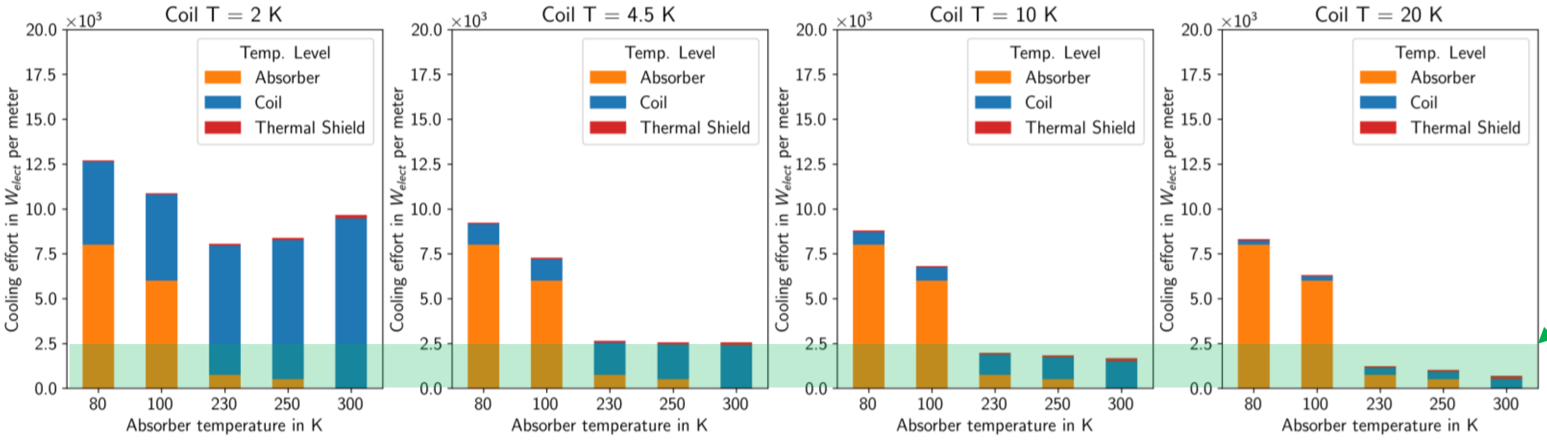
Target: Heat load to coil ≤ 10 W/m

Power consumption at refrigerator I/F

w/ heat intercept



- Power consumption estimated for shown heat loads at various **coil** and **absorber temperatures**
- Different colours in the plots mean cooling effort at a different *T* level
- Not included: distribution losses, based purely on COP^{-1} (see spares)



Shown: Cooling effort at refrigerator I/F, absorber thickness 4 cm, shield and heat intercept 80 K

Target:
25 MW for Cryo in collider
(2.5 kW$_{el}$/m)

Message: 25 MW total for 10 km collider ring →

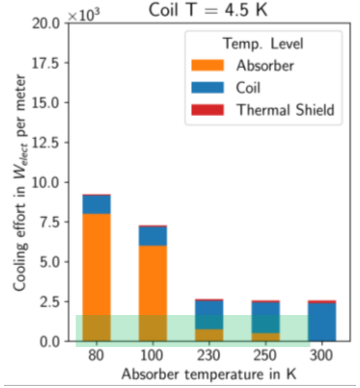
- $T_{coil} \geq 4.5$ K
- $T_{abs} \geq 200$ K

Considerations for absorber cooling options

- From initial assumptions:

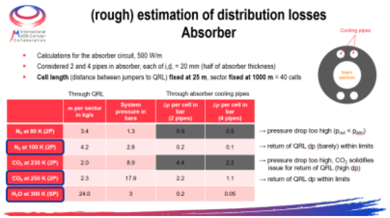
Absorber temperature: ~~80 K, 100 K~~, ~~230 K~~, 250 K, 300 K

Cooling effort too high



Δp too high even for short cells, CO_2 solidifies

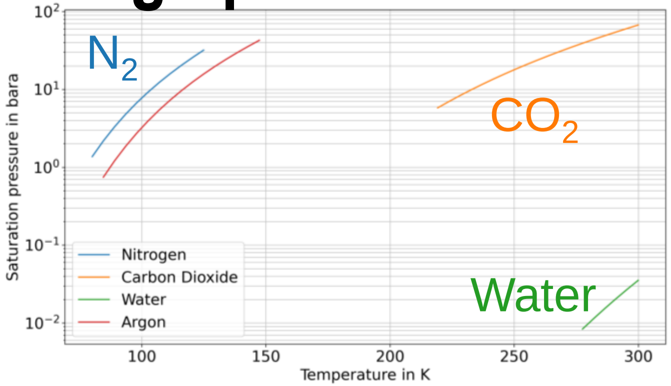
(see spare slides)



(rough) estimation of distribution losses
Absorber

- Calculations for the absorber circuit, 500 W/m
- Considered 2 and 4 pipes in absorber, each of i.d. = 20 mm (half of absorber thickness)
- **Cell length** (distance between jumpers to QRL) **fixed at 25 m**, sector **fixed at 1000 m** = 40 cells

	Through QRL		Through absorber cooling pipes		
	ṁ per sector in kg/s	System pressure in bara	Δp per cell in bar (2 pipes)	Δp per cell in bar (4 pipes)	
N_2 at 80 K (2P)	3.4	1.3	0.9	0.5	→ pressure drop too high ($p_{out} < p_{atm}$)
N_2 at 100 K (2P)	4.2	2.8	0.2	0.1	→ return of QRL dp (barely) within limits
CO_2 at 230 K (2P)	2.0	8.9	4.4	2.2	→ pressure drop too high, CO_2 solidifies issue for return of QRL (high dp)
CO_2 at 250 K (2P)	2.3	17.9	2.2	1.1	→ return of QRL dp within limits
H_2O at 300 K (SP)	24.0	3	0.2	0.05	



T level	250 K	300 K
Fluid	CO_2	Water
Mass flow rate	+	+/- (10x higher)
Operating pressure	+/- (60+ bara)	+ (3-10 bara)
Δp	+/-	+ (smaller pipes)
Heat transferred to coil	+	− (20% higher)
COP^{-1}	+/-	+ (only distrib.)
Rad. hardness	+	− (mitigation needed)
Risks to machine	+	− (freezing; expansion)

Message: $T_{abs} \geq 250$ K

Considerations for coil cooling options

- **Cooling mode** (and **temperature**) will depend on the **choice of conductor**, which depends on the **maturity level** of the technology and on the **timescale of construction**

3 TeV machine

- Construction in ~15 years
- Magnetic fields within Nb_3Sn capabilities
- Nb_3Sn matured, usable
- Cooling at 4.5 K – 5.5 K using SC He
- Cooling at 4.5 K using He two-phase flow

10 TeV machine

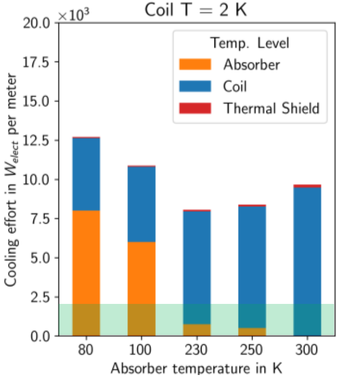
- Construction in ~25-30 years
- HTS preferred for sustainable collider
- Needs development
- Cooling at 10 K – 15 K or above
- He or H_2 possible; in-depth study needed

Considerations for coil cooling options

Options at $T \leq 5.5$ K (Nb_3Sn, 3 TeV machine)

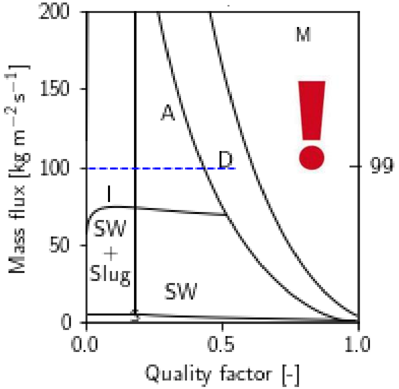
Coil *T*: ~~2 K~~, 4.5 K 2PF, 4.5 K sc

Cooling effort too high



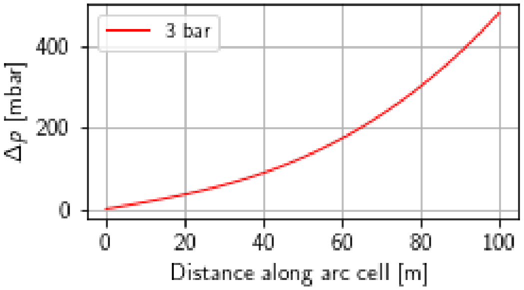
10 W/m, arc cell L=10 m,
8 mm, 2 parallel pipes
$\dot{m}_{sector}$=1000 g/s, dp=20 mbar

Flow stability and control



10 W/m, arc cell L=100 m,
13 mm, 2 parallel pipes
$\dot{m}_{sector}$=500 g/s, dp=500 mbar

Promising; no major showstopper identified so far



Message: $T_{coil} \geq 4.5$ K, supercritical cooling looks promising

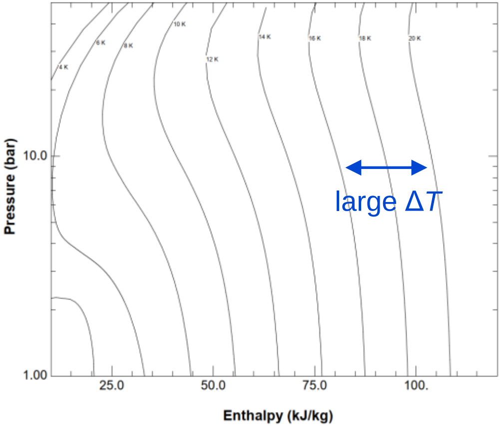
Considerations for coil cooling options

Options at $T \geq 10$ K (HTS, 10 TeV machine)

Coil T: ΔT around 10 K, ΔT around 20 K, 20 K 2PF

He gas cooling:

- Large ΔT, 5 K -10 K
- Heat transfer starts to break down



H_2 two-phase flow:

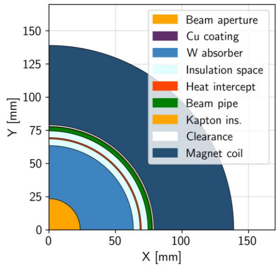
- Possible for $T > 21$ K
- High available enthalpy
- Needs in-depth study

Message: above 4.5 K any He-based cooling involves a sizeable ΔT

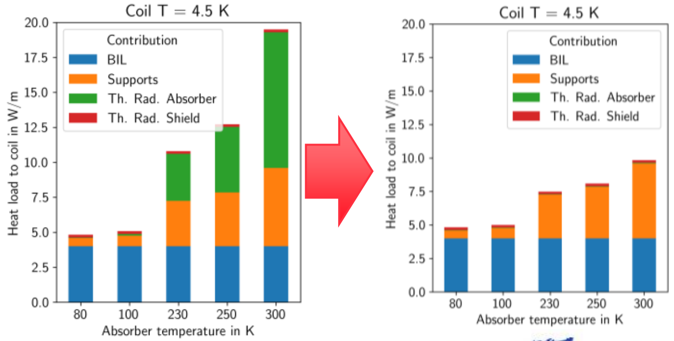
Evaluation of technology options for magnet cooling Collider Ring

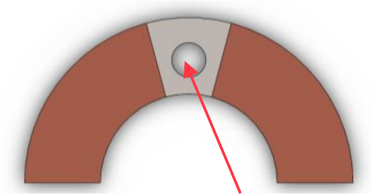
Done:

- Critical contributors to total heat load deposited on the coil identified
- Absorber must operate at or above 250 K (overall cooling effort, distr. losses)
- Heat intercept between coil and absorber is a necessity
- Electrical power consumption of collider ring cryogenics estimated
- Coil must operate at or above 4.5 K
- Preliminary evaluation of possible cooling schemes, limitations



Heat intercept added





Cooling pipe

!

Evaluation of technology options for magnet cooling Collider Ring

Needs attention:

- Contribution from absorber **supports** considered disproportionate → effort should be put into the design of an optimized support for the MC absorber conditions
- Preliminary **cross-section of the coil** (and absorber) should be outlined to estimate max. cooling tube size, number, position → allows for some boundaries to cooling scheme layouts
- **Cooling options for LTS** (around 5 K) examined, **promising** → need R&D to explore the limits of two-phase flow and supercritical cooling in confined geometries
- **Cooling options for HTS** (if 10K+) **need in-depth study** → He gas cooling does not provide efficient heat transfer; H_2 cooling needs demonstration and change of mindset, safety assessment
- **Cooling of absorber** with CO_2/water needs in-depth review of the base assumptions, esp. risk-related
- **Current leads:** neither heat loads nor cooling options have been addressed

Thank you for your attention

Spare slides

Evaluation of technology options for magnet cooling
Rest of the MC complex

Accelerator ring:

- Need to converge on a basic design for 3 TeV and/or 10 TeV to identify bottlenecks
- Special attention must be given to multiple cold-to-warm transitions, (very) short interconnect space
- Considerations on technology options investigated for collider ring, can be applicable to accelerator

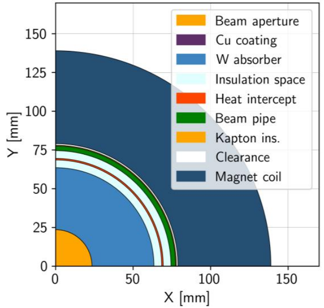
6D cooling cell, target magnets:

- Specific magnets (interaction region magnets, target solenoid, cooling cell) need tailored, possibly less energy-optimized solutions – study to be carried out once preliminary specifications are fixed

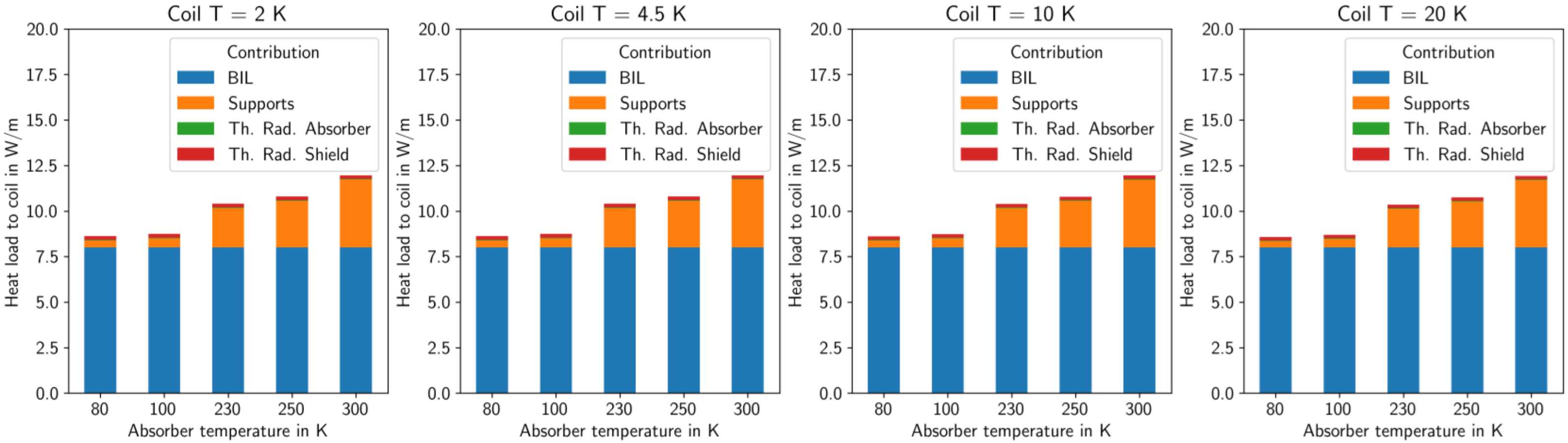
Heat load deposited at cold mass level

w/ heat intercept

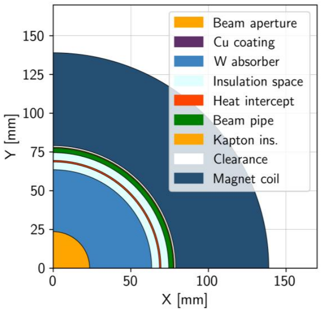
- Heat load at cold mass level $f(T_{absorber}, T_{coil}, T_{thermal\ shield})$ shown for absorber thickness of **3 cm**, and considering outer thermal shield at 80 K
- **With added heat intercept (shield) between the coil and the absorber**



Heat intercept between coil and absorber!



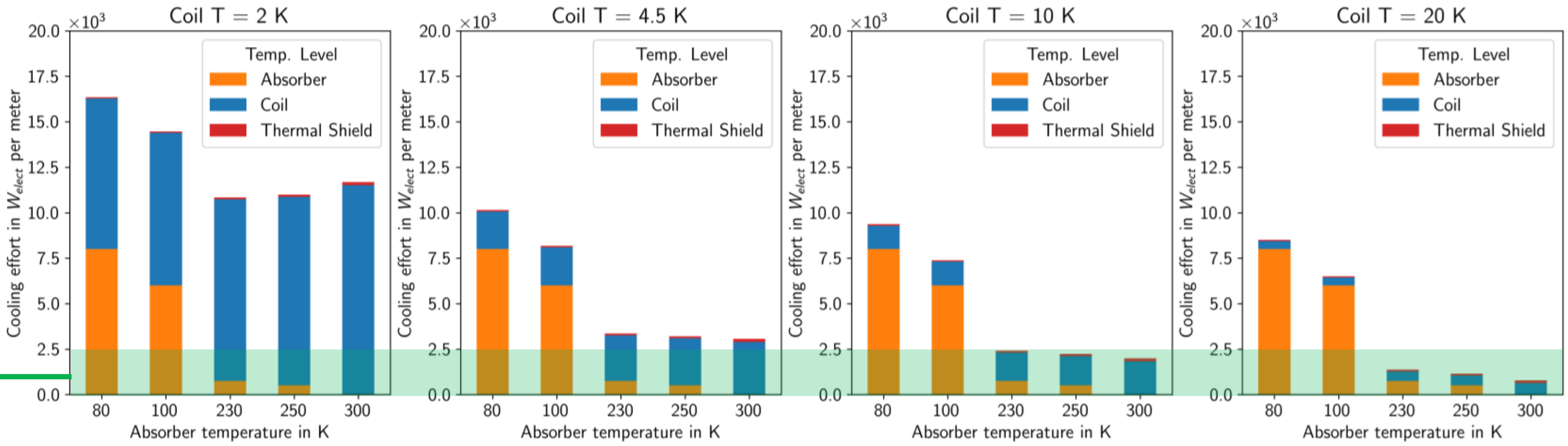
- Reducing the absorber thickness from 4 cm to 3 cm **doubles** the beam-induced load that penetrates shielding (**blue part**) while only reducing the heat load via the supports (**orange part**, which is weight-dependent) by 30%



Power consumption at refrigerator I/F

3 cm absorber, w/ heat intercept

Blue: electrical power required to provide cooling power at cold mass temp. level
Orange: electrical power required to provide cooling power at absorber temp. level
Red: electrical power required to provide cooling power at thermal shield temp. level



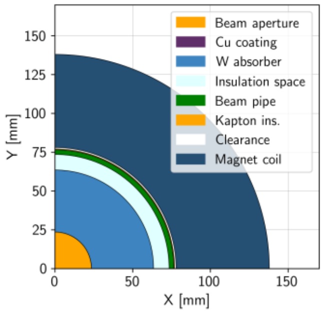
Target: 25 MW for Cryo in collider

The larger the **blue** component → the more difficult the coil design

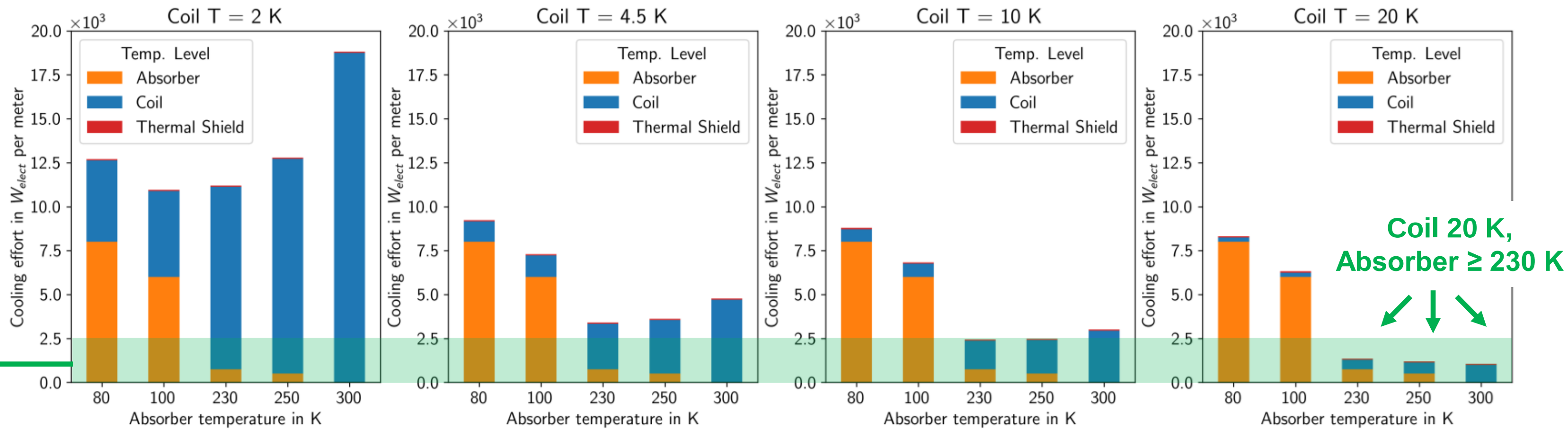
N.B. I: the cost to extract heat at 300 K is nearly zero, reflecting the fact that the distribution effort (circulation) is **not yet included**
N.B. II: although COP^{-1} based on cryoplants using certain fluids, so far, we're talking only about temp. level, *i.e.*, no fluid-dependent costs considered (as distribution, special handling, etc…)

Power consumption at refrigerator I/F

4 cm absorber, baseline



Blue: electrical power required to provide cooling power at cold mass temp. level
Orange: electrical power required to provide cooling power at absorber temp. level
Red: electrical power required to provide cooling power at thermal shield temp. level



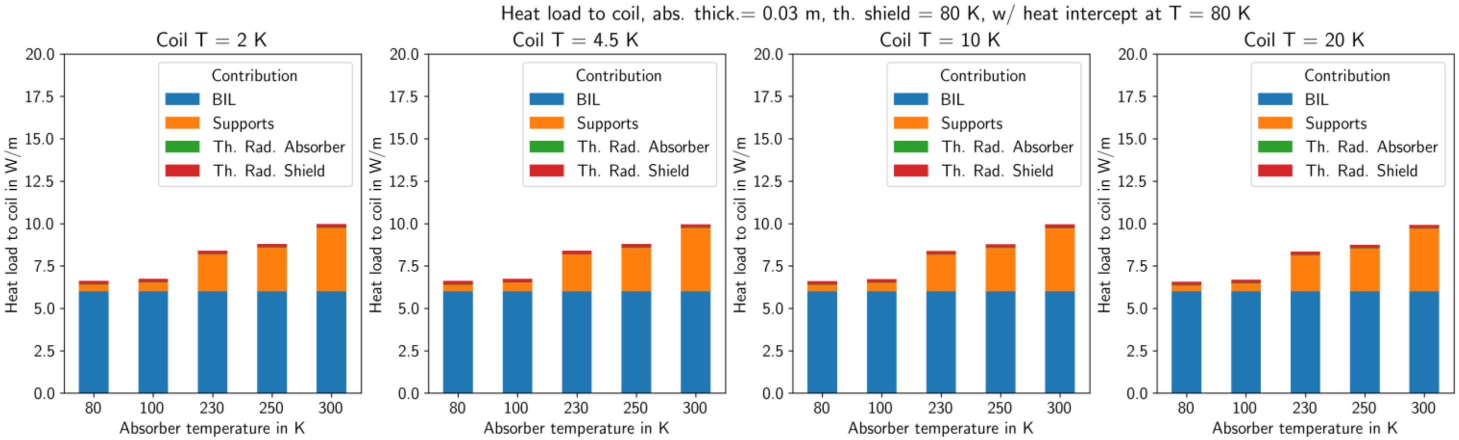
Coil 20 K, Absorber ≥ 230 K

Target: 25 MW for Cryo in collider

The larger the **blue** component → the more difficult the coil design

N.B. I: For assumptions on calculation of cooling effort from heat loads, see spare slides
N.B. II: the cost to extract heat at 300 K is nearly zero, reflecting the fact that the distribution effort (circulation) is **not yet included**
N.B. III: although COP^{-1} based on cryoplants using certain fluids, so far, we're talking only about temp. level, *i.e.*, no fluid-dependent costs considered (as distribution, special handling, etc…)

Calculations for a 3 TeV machine, abs. 3 cm



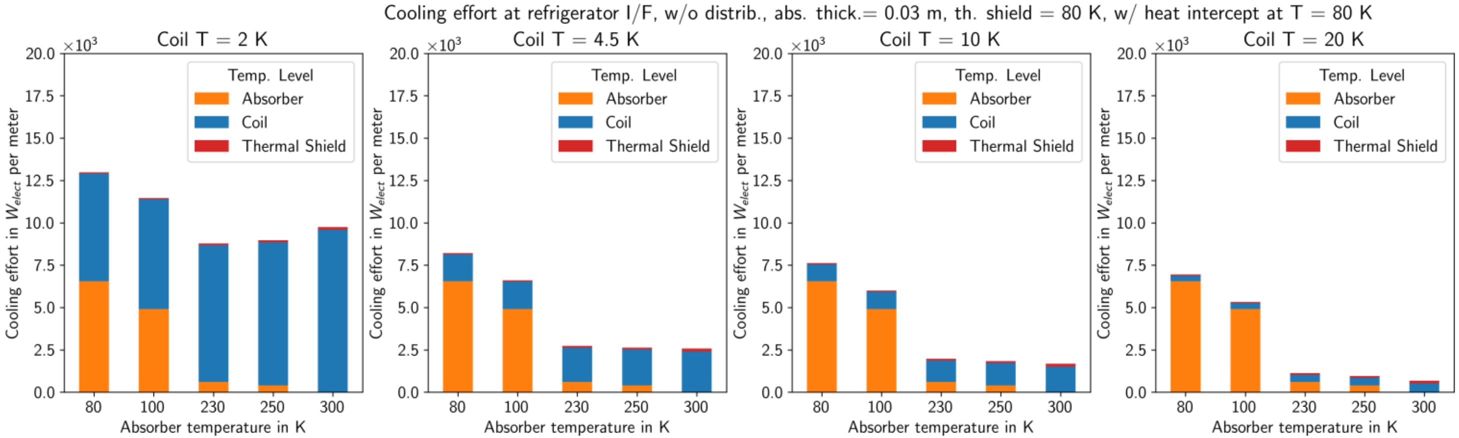
Heat load to coil, abs. thick.= 0.03 m, th. shield = 80 K, w/ heat intercept at T = 80 K

Coil T = 2 K

Coil T = 4.5 K

Coil T = 10 K

Coil T = 20 K



Cooling effort at refrigerator I/F, w/o distrib., abs. thick.= 0.03 m, th. shield = 80 K, w/ heat intercept at T = 80 K

Coil T = 2 K

Coil T = 4.5 K

Coil T = 10 K

Coil T = 20 K

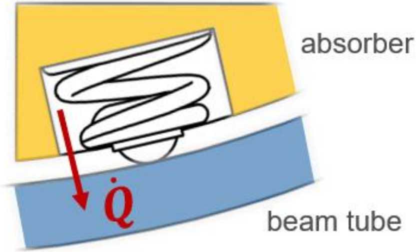
(Possible) solution for absorber supports from existing implementations

PUMA rolls

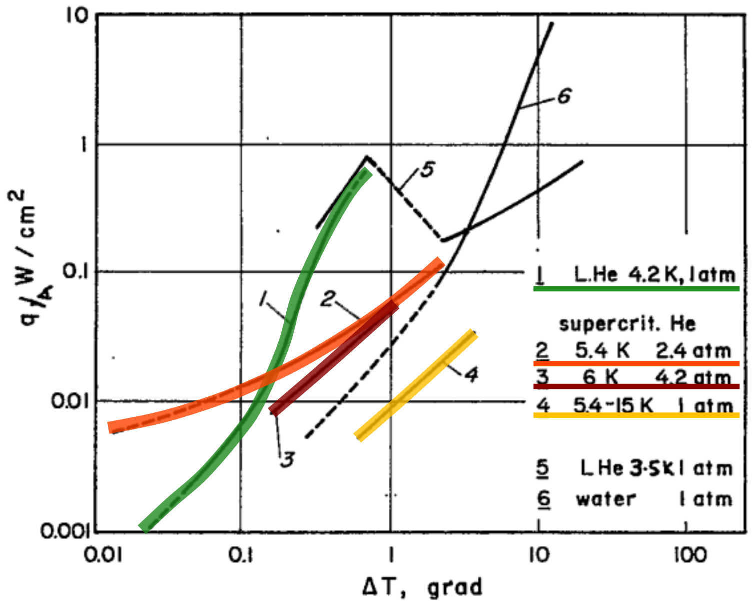
- Heat transfer measurements by J. Liberadzka-Porret at the Cryolab, EMDS # 2443998 (link)
  ≈ 1 W/roll under 500 N from RT to LN_2
  ≈ 0.1 W/roll under 500 N from LN_2 to LHe

HL-LHC beam screen springs

- Heat transfer measurements at the Cryolab, EMDS # 2042522 (link)
  ≈ 0.05 W/roll under 15 N from RT to LHe



Two- *vs.* single-phase flow local heat extraction
Implications for magnet design



- Heat transfer coefficient α in **liquid He** is O(1) – O(2) higher than options using high-speed, high-pressure gas/**supercritical fluid**
- If **heat exchange area is limited**, choice of **cooling strategy needs to be adapted** to provide the best possible heat transfer coefficient
- **Magnet design** should strive to incorporate**, from the start**, **heat extraction pathways** as close as possible to the coil and **maximise heat transfer exchange area**

Smith, *Review of heat transfer to helium I* (link)

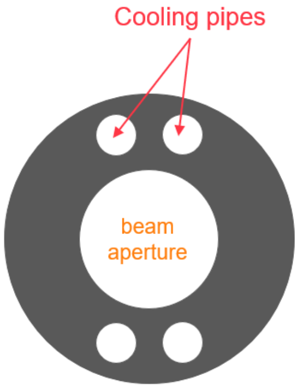
Power consumption at refrigerator I/F

From heat loads to power consumption

- For each temperature level of absorber, cold mass, and external thermal shield, the inverse coefficient of performance (COP^{-1}) at refrigerator interface was estimated to give a semi-realistic power consumption per meter of collider magnet.
- The heat load from each temp. level (slides 9/10) is multiplied by the COP^{-1} to give a total electrical cost
- Distribution (*e.g.* pumps to circulate fluids) is not yet included in the "bill"
- Considerations:

Temperature level	COP^{-1} in W_{elect}/W_{cool}	Source
250 K	1	CO_2 plant ATLAS ITk
100 K	12	LN_2 plant ATLAS
80 K	16	LN_2 plant ATLAS
20 K	50	20 K/50 kW plot Frey (see spares)
10 K	150	LHC cryoplant data
4.5 K	240	LHC cryoplant data
2.0 K	960	LHC cryoplant data

(rough) estimation of distribution losses
Absorber



- Calculations for the absorber circuit, 500 W/m
- Considered 2 and 4 pipes in absorber, each of i.d. = 20 mm (half of absorber thickness)
- **Cell length** (distance between jumpers to QRL) **fixed at 25 m**, sector **fixed at 1000 m** = 40 cells

	Through QRL		Through absorber cooling pipes	
	$\dot{m}$ per sector in kg/s	System pressure in bara	Δp per cell in bar (2 pipes)	Δp per cell in bar (4 pipes)
N_2 at 80 K (2P)	3.4	1.3	0.9	0.5
N_2 at 100 K (2P)	4.2	2.8	0.2	0.1
CO_2 at 230 K (2P)	2.0	8.9	4.4	2.2
CO_2 at 250 K (2P)	2.3	17.9	2.2	1.1
H_2O at 300 K (SP)	24.0	3	0.2	0.05

→ pressure drop too high ($p_{out} < p_{atm}$)

→ return of QRL dp (barely) within limits

→ pressure drop too high, CO_2 solidifies
issue for return of QRL (high dp)

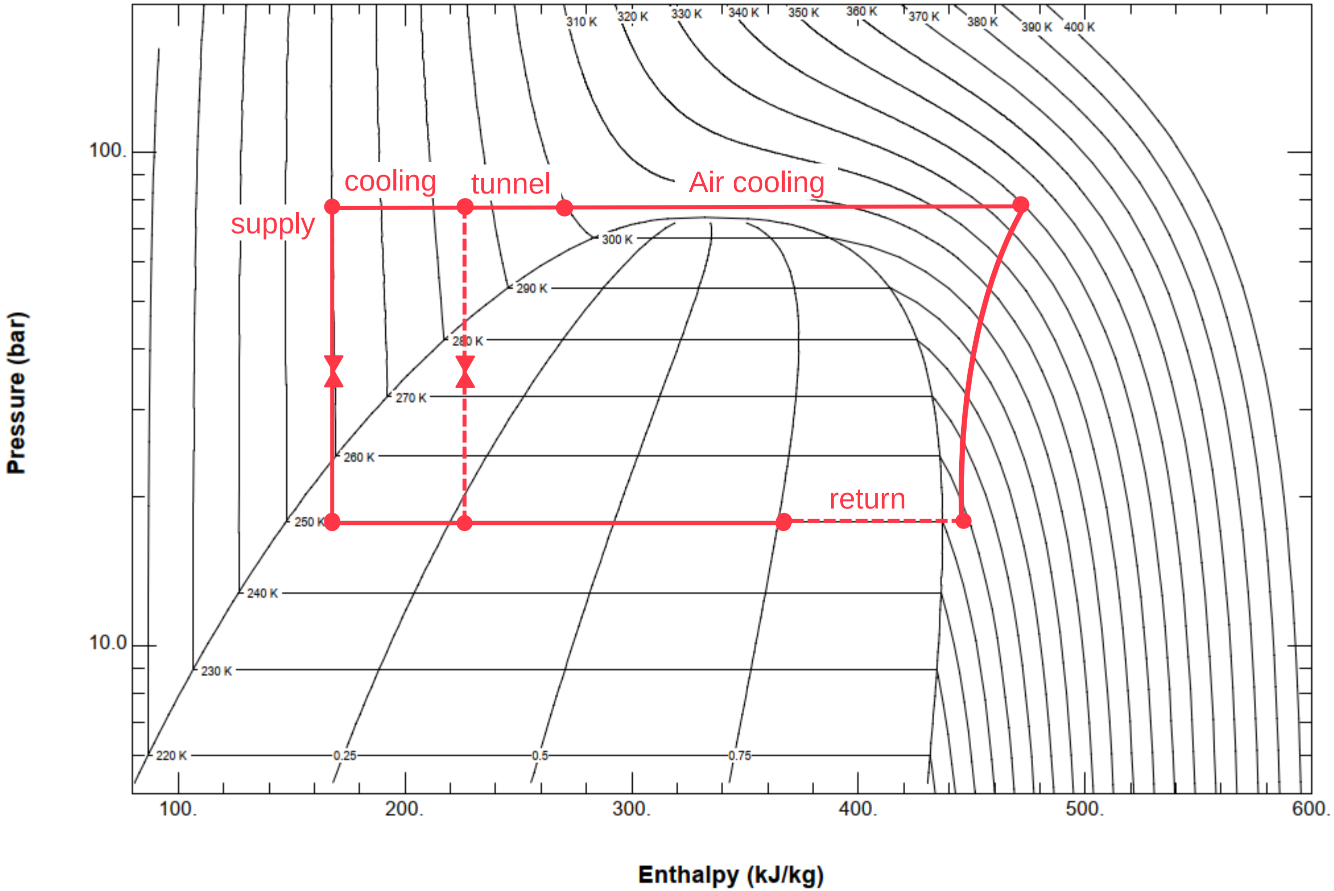
→ return of QRL dp within limits

Proposed work program

- Currently **no work program specifically defined for cryo developments**
- However, a few items have been identified as being of interest:
  - Use of extrapolated flow pattern maps (from CO_2) needs to be validated for two-phase flow in He and H_2
  - Explore the limits of heat transfer and pressure drop for sc He cooling
  - Investigation into cryoplant capabilities, deliverable $\dot{m}$ and $\dot{Q}_{cooling}$
  - Assessment if H_2 cooling is feasible, implications on safety
  - Design of optimized supports and heat intercept for absorber

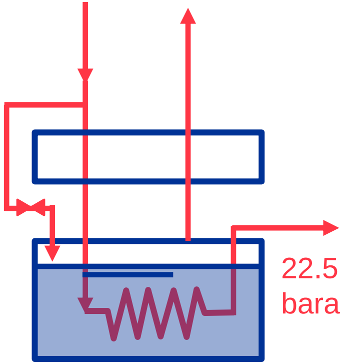
Carbon Dioxide

- Two-phase flow
  at 250 K, 20 bara,
  expanded from 70 bara, 260 K
- Depending how we enter the two-phase region, cooling at “tunnel” or room temperature would be sufficient
- Other cooling schemes possible, to be investigated



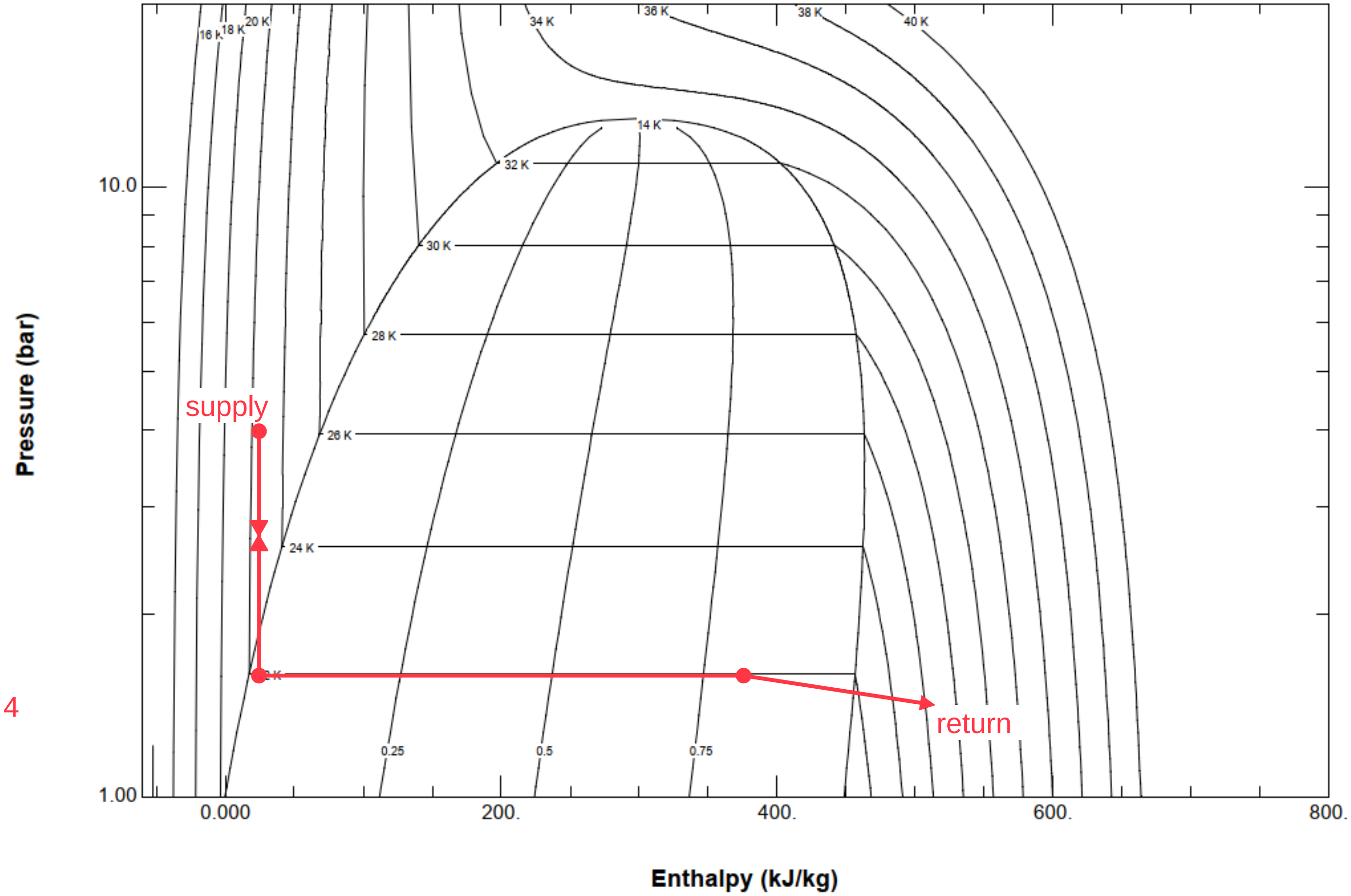
Hydrogen

- Supply subcooled liquid at 4 bara, 22.5 K, expand to 1.3 bara into the two-phase region, two-phase cooling at 21.2 K



22.5 K, 4 bara

21.2 K, 1.3 bara



Helium

- Expand from 3 to 1.3 bara into the two-phase region, two-phase cooling at 4.5 K (red)
- Use supercritical region allowing a certain temperature gradient (shown 4.5 K to 5.5 K) (blue)