Cryogenic options and concepts for the Muon Collider

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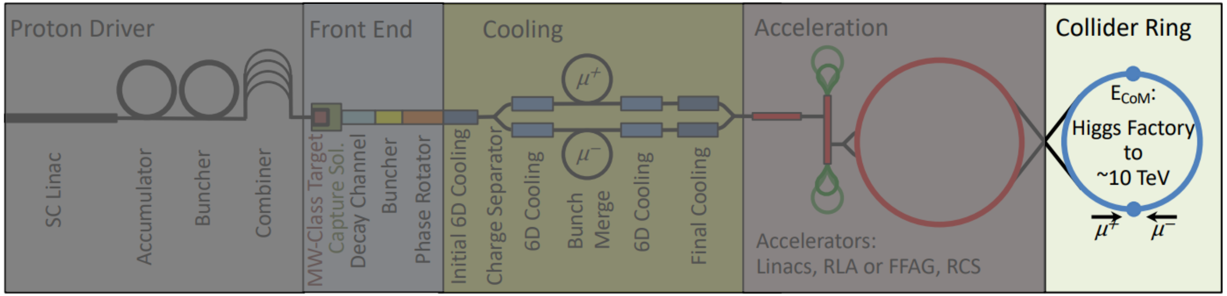
Foreword

- The study presented here is an **overview of cooling options** for collider-type magnets using a combined approach to the overall optimization of cryogenic infrastructures considering:
    - Sustainable magnet design;
    - Optimization of cryogenic infrastructures accounting for all temperature levels (*i.e.* not only coil)

- Here we focus on discussing the cooling options for the **collider ring**.

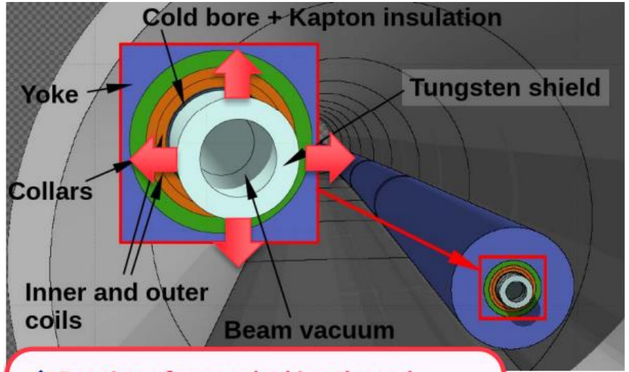


Source: MAP collaboration

Introduction

- The dipole (and quadrupole) **arc magnets** are starting to take shape, there is a **preliminary radial build** and **aperture**, the **beam-induced loads to the magnets are known**
- The rest of the **static heat loads need to be calculated** to have an idea of total heat load budget to the cold mass and the warmer “absorber” that intercepts incoming radiation
- The **operating temperature needs to be defined** → this depends not only on **conductor choice** and **magnet design**, but also on the **overall cost of cooling**
- This talk aims to define the range of **expected heat loads on the collider magnets** (cold mass and absorber), and to provide an **estimate of the resulting cooling effort** for each option

Input: radial build and beam-induced heat loads



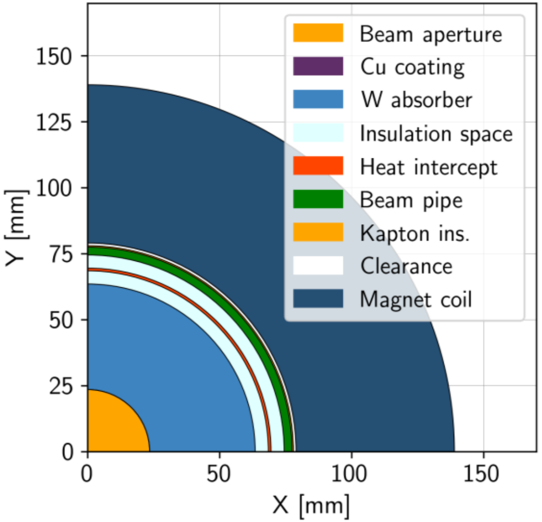
- ❖ **Fraction of power leaking through shielding similar for 3 TeV & 10 TeV**
- ❖ This power is mostly deposited in cold mass (including cold bore)

	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

Dimensions from **12/06/23** radial build:

• 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



Even for 2 cm shielding, power density on coil is <10 mW/cm^3

Calculations based on the 10 TeV machine!

Only beam-induced heat loads included; other contributions?

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

(steady-state) Heat loads in the collider magnets

Static heat inleaks:

- Thermal radiation from thermal shield
- Thermal radiation from absorber
- Conduction via support posts
- Conduction via absorber supports

Beam-induced losses:

- Muon decay
- Image currents
- Synchrotron radiation
- E-cloud

Resistive heating:

- Magnet splices
- Current leads intercepts
- Additional heaters/instrumentation?

Deposited in:

- External (cryostat) thermal shield
- Coil pack/cold mass
- Absorber

(steady-state) Heat loads in the collider magnets

- Calculations based on the 10 TeV machine

		Absorber	**Cold mass**	**Thermal shield**
Static heat in-leaks	Conduction via support posts	–	from absorber: $f(T_{absorber}, thick_{absorber})$ from thermal shield: $f(T_{shield})$	from RT: $f(T_{shield})$
	Thermal radiation	–	from absorber: $f(T_{absorber})$ from thermal shield: $f(T_{shield})$	from RT: $f(T_{shield})$
Beam-induced	Muon decay	500 W/m	$f(thick_{absorber})$: between 4 – 8 W/m	–
	Beam-gas scattering	negligible	negligible	–
	Synchrotron radiation	negligible	negligible	–
	Others	negligible	negligible	–
Resistive	Resistive splices	–	tbd	tbd

Heat loads at absorber level are independent of absorber, cold mass, and thermal shield *T*, and of absorber thickness

Considerations for heat load estimation

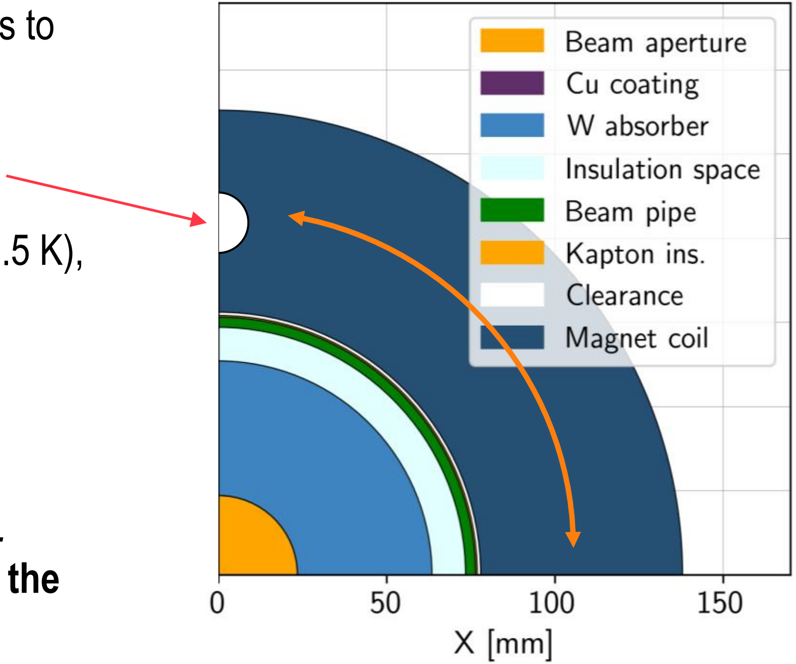
- **Cold mass temperature:** 2 K, 4.5 K, 10 K, 20 K (certain Δ*T* implied, see next slide)
- **Heat loads to cold mass *T*-dependent and absorber thickness-dependent:**
  - Beam-induced radiation penetrating the absorber, function of its thickness
  - Thermal radiation from external shield (w/ 30 layers MLI on shield, 10 layers on cold mass)
  - Conduction via external supports (cold mass “feet”) (taken from LHC supports, 7.1 W/foot at 75 K, 0.42 W/foot at 5 K)
  - Thermal radiation from absorber ($\varepsilon_{absorber}$ = 0.09, $\varepsilon_{beampipe}$ = 0.1)
  - Conduction via absorber supports (function of absorber weight, used PUMA rolls as guideline, EDMS 2443998)
  - Resistive heating (splices etc) – not considered

- **Absorber temperature:** 80 K, 100 K, 230 K, 250 K, 300 K
- **Heat load to absorber independent of temperature or thickness:** 500 W/m

- **External thermal shield (around cold mass) temperature:** 80 K

A comment on “coil/cold mass temperature”

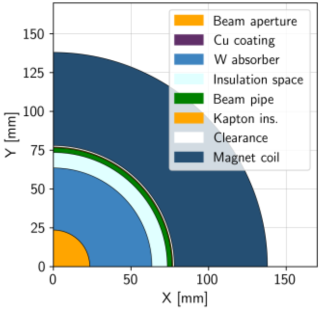
- “Coil” or “cold mass” temperature, in this exercise, refers to the **temperature at the cooling interface** (*i.e.* the temperature of the fluid **inside a cooling pipe**)
- When a range is given (*i.e.* He SC between 4.5 K and 5.5 K), it refers to the **temperature gradient accepted over a certain longitudinal distance,** *e.g.* an arc cell
- Regardless of the method of cooling, there will be an **additional temperature gradient in the coil pack**, *e.g.* radial or azimuthal **gradient as one moves away from the cooling source (orange arrow)**
  For the moment, we limit this gradient to ≈ 0.5 K



Heat load deposited at cold mass level

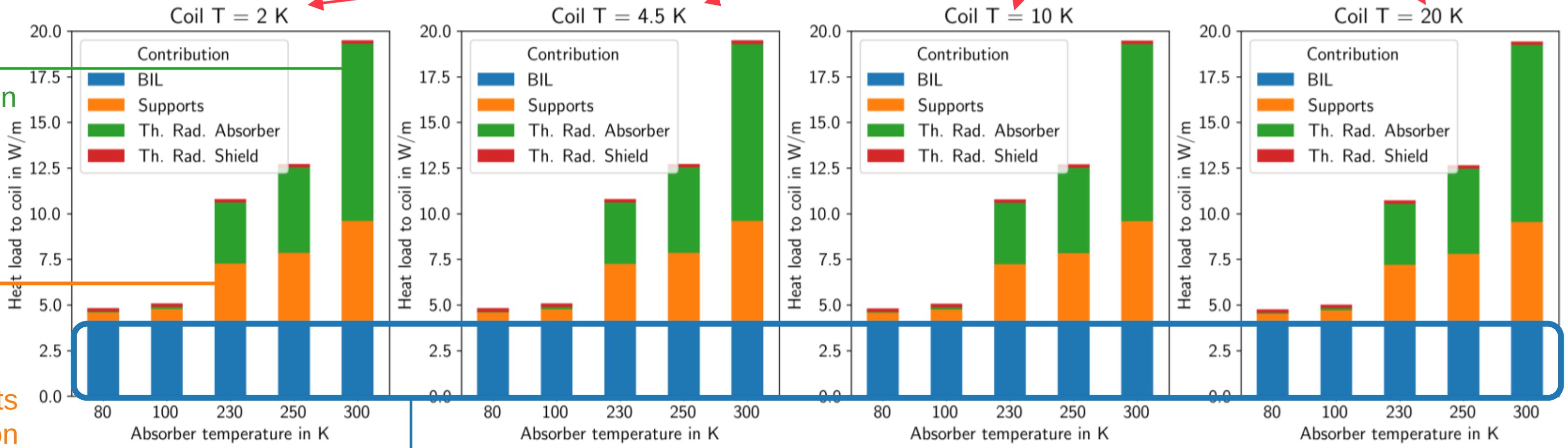
Baseline

- Heat load at cold mass level $f(T_{absorber}, T_{coil}, T_{thermal\ shield})$ shown for absorber thickness of 4 cm, and considering outer thermal shield at 80 K
- **No thermal shield or heat intercept between absorber and coil**



Heat load to the coils ~ independent of coil *T*, effort to extract the heat will depend heavily on it

No heat intercept between absorber and coil
Excessive contribution w.r.t. BIL



Heat load via supports
Excessive contribution w.r.t. BIL

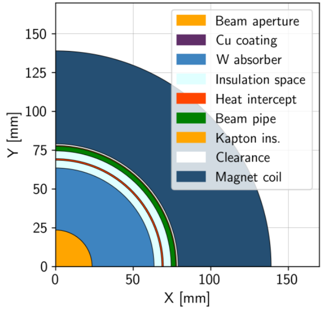
constant 4 W/m
for 4 cm-thick absorber

Optimization can have a significant impact on design (aperture)

Heat load deposited at cold mass level

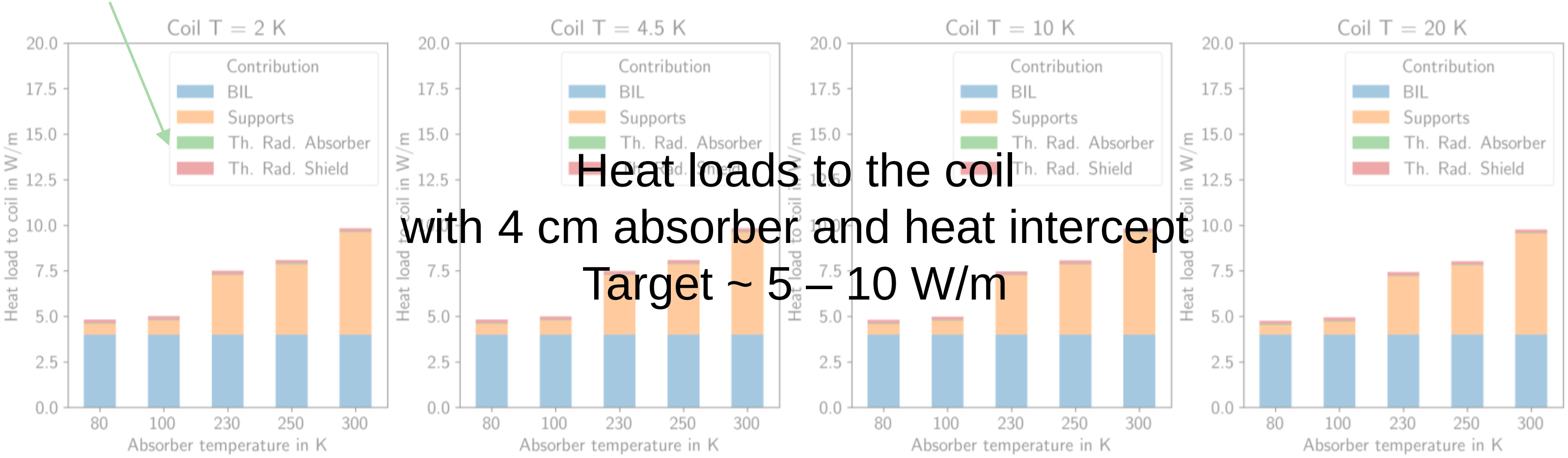
w/ heat intercept

- Heat load at cold mass level $f(T_{absorber}, T_{coil}, T_{thermal\ shield})$ shown for absorber thickness of 4 cm, and considering outer thermal shield at 80 K
- **With added heat intercept (shield) between the coil and the absorber**



Heat intercept at 80 K between coil and absorber reduces heat load to coil by ~ half for absorber $T > 230$ K

Heat intercept between coil and absorber!

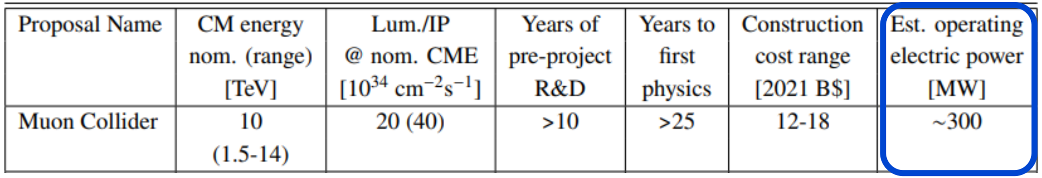


Heat loads to the coil
with 4 cm absorber and heat intercept
Target ~ 5 – 10 W/m

Supports not thermalized to this heat intercept, would possibly add too much complexity / integration issues, leading to a larger aperture

Power consumption budget for Cryogenics

- **Tentative objective:** take the operating electrical power estimated in the Snowmass report[1] for the Muon Collider:



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300

- Assume **10%** of that electrical power is used for cryogenic infrastructure → **30 MW**
- Of those 30 MW allocate **25 MW for the collider ring**

25 MW for the 10 TeV machine ➡ **2.5 MW/km** ➡ **2.5 kW/m**

We aim to stay at around **2.5 kW/m** of collider (lower is better! ☺)

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[1] Report of the Snowmass 2021 Collider Implementation Task Force, https://arxiv.org/abs/2208.06030

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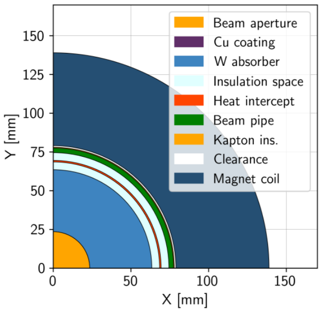
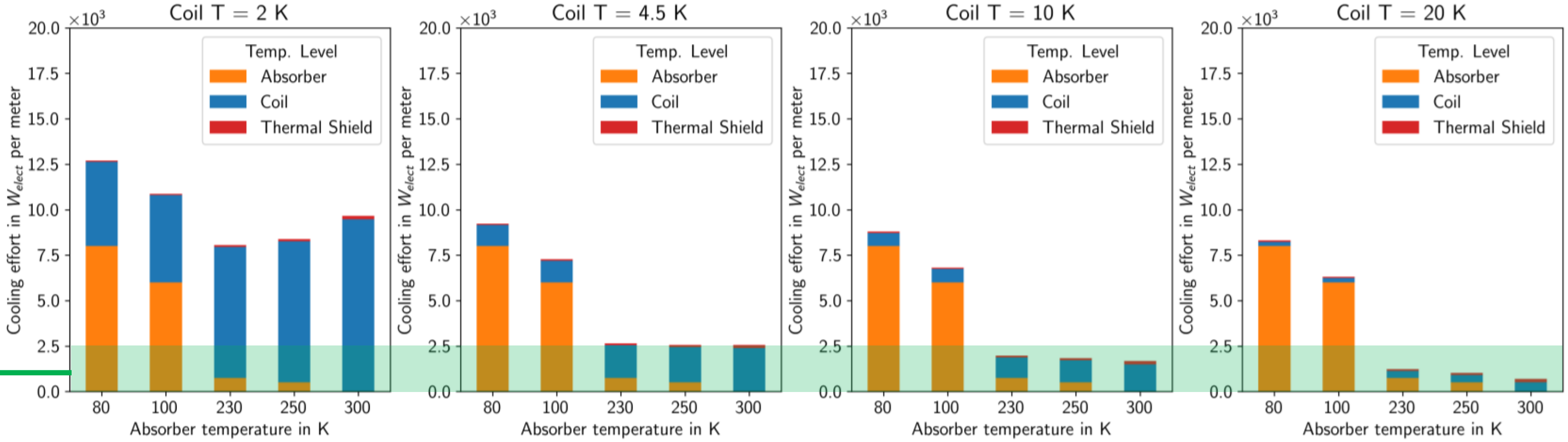
Power consumption at refrigerator I/F

4 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 (target ≤ 10 W/m)

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…)

Cooling modes (I)

- **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

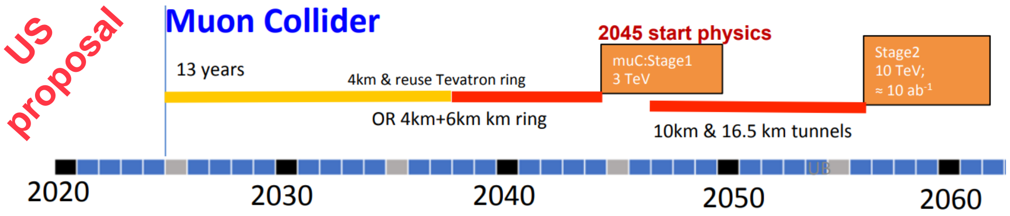
- Construction in ~15 years
- Magnetic fields within Nb_3Sn capabilities
- Nb_3Sn matured, usable
- Cooling at 4.5 K – 5.5 K using SC He
- Cooling at 4.5 K using He two-phase flow

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

Hybrid solutions do not seem advantageous considering limited field-free region space – esp. if considering separate temperature levels

- 2PF H_2 can provide stable T along magnet string with low mass flow rates, small pipes
- Safety assessment → will be considered only if critically necessary
- “Hindenburg syndrome” to overcome

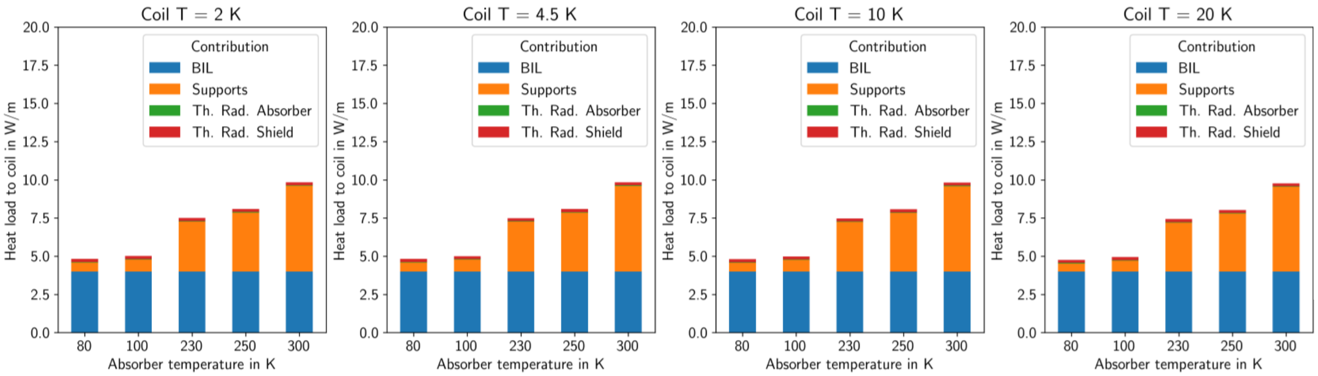


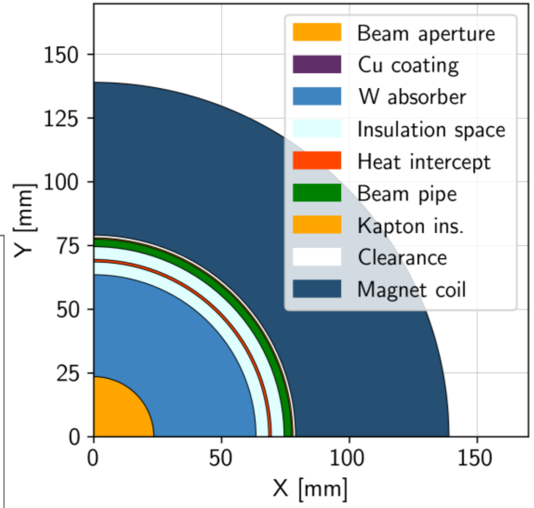
Source: D. Schulte, Muon Collider (link)

Cooling modes (II)

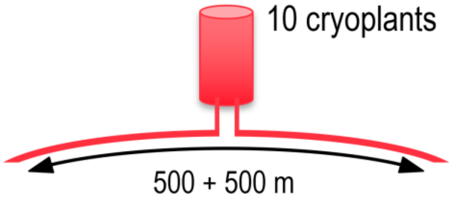
- **Cooling mode** (and **temperature**) will depend on the **choice of conductor**, which depends on the **maturity level** of the technology and on the **timescale of construction**
- **Limitations** will be the **arc cell** and **sector length**, driven by deliverable **mass flow rate** and **pressure drop** on the magnets and distribution line

We consider **4 cm absorber, with heat intercept** at 80 K between absorber and coil, and outer thermal shield at 80 K **as the new baseline**





Overall cooling scheme definition (cell and sector length) is an iterative process



Cost and availability

- Availability decreases with # of cryoplants
- Inversely, fewer cryoplants → longer sector length
- Max. 10 cryoplants in a 10 km ring

Limited $\dot{m}$ / cryoplant

- Higher heat load → $\dot{m}_{sector}$ increases → shorter sector length

Local heat extraction

- Coil design complexity increases with heat load; difficult above 10 W/m
- $\dot{m}$ is directly proportional to heat load

Max. Δp / arc cell

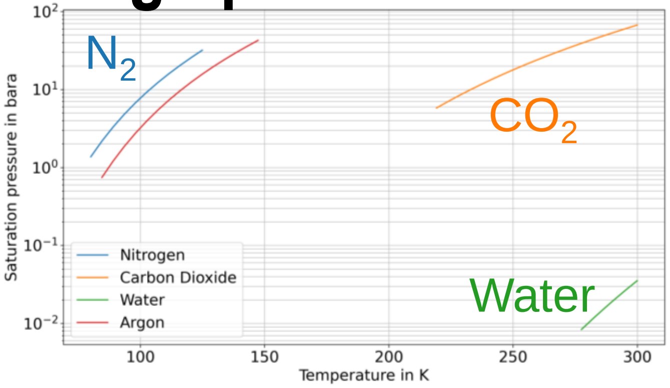
- Δp ∝ $\dot{m}^2$ and L^3 → cell length dictated by max. Δp in coil
- 2PF: cannot go into sub-atm pressure (~50 mbar available)

These **constraints** (max. Δp, max. $\dot{m}$) that limit the cell and sector length are also **valid for the absorber cooling circuit !**

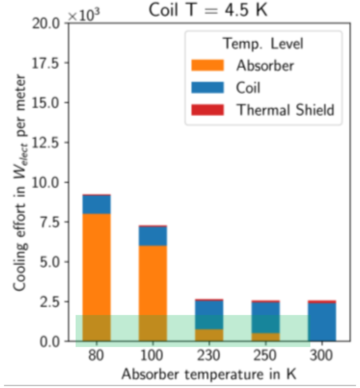
Considerations for absorber cooling options

- From initial assumptions:

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

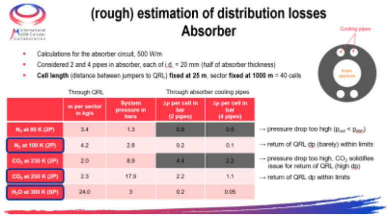


Cooling effort too high



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

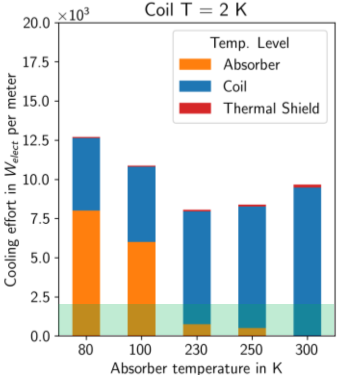
Considerations for coil cooling options

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

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

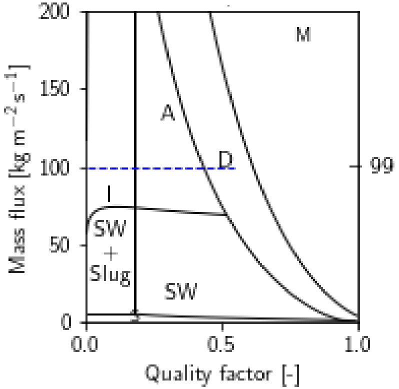
Message: $T_{coil} \geq 4.5$ K, supercritical cooling looks promising

Cooling effort too high



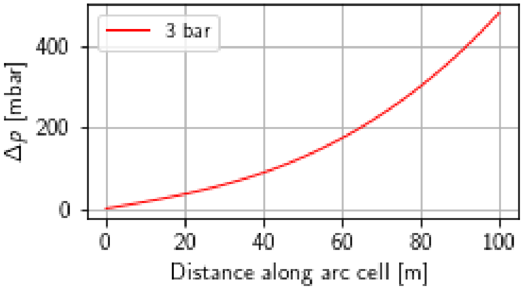
10 W/m, arc cell L=10 m,
8 mm, 2 parallel pipes
$\dot{m}_{sector}$=1000 g/s, dp=20 mbar

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



Considerations for coil cooling options

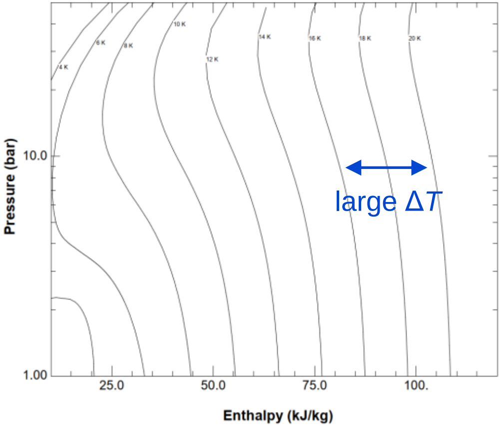
Options at $T \geq 10$ K (HTS, 10 TeV machine)

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

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

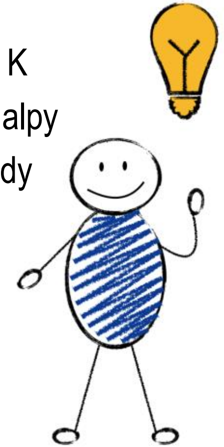
He gas cooling:

- 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



Summary

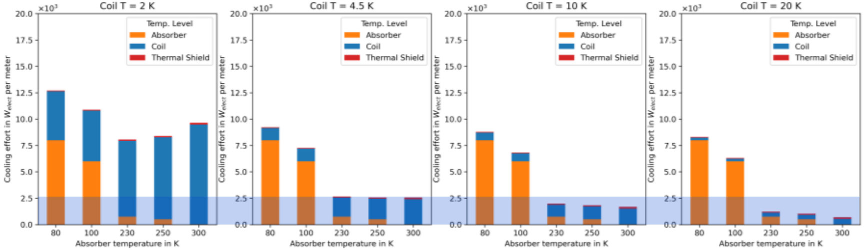
Energy consumption → ≤ 2.5 kW/m → $T_{absorber}$ ≥ 230 K

Absorber circuit → Operating T + distribution losses → $T_{absorber}$: 100 K or 250 K

Coil circuit → Total heat load + Required $\dot{m}$ → T_{coil}: 4.5 K to 20 K

Coil design → $\dot{Q}$ to coil ≤ 10 W/m → Heat intercept between coil and absorber needed

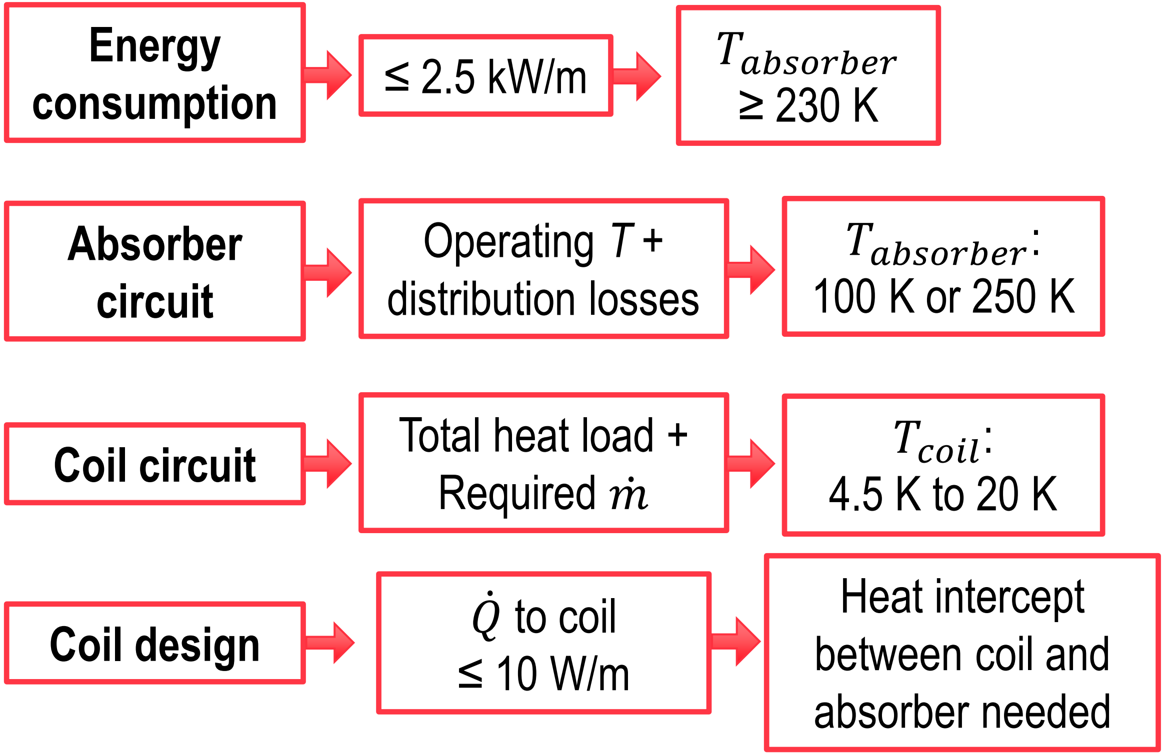
W/ heat intercept between coil and absorber!



	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

	$\dot{m}$ per sector in g/s (for various absorber T, i.e. ≠ heat loads)				
	80 K	100 K	230 K	250 K	300 K
H_2 at 20 K (2P)	14	15	22	24	29
He at 7.5-12.5 K (SC)	159	165	247	266	324
He at 4.5-5.5 K (SC)	258	268	401	433	526
He at 4.5 K (2P)	344	357	534	577	702
He II at 2 K (2P)	275	285	427	461	561

Summary



Energy consumption → $\leq$ 2.5 kW/m → $T_{absorber}$ $\geq$ 230 K

Absorber circuit → Operating T + distribution losses → $T_{absorber}$: 100 K or 250 K

Coil circuit → Total heat load + Required $\dot{m}$ → T_{coil}: 4.5 K to 20 K

Coil design → $\dot{Q}$ to coil $\leq$ 10 W/m → Heat intercept between coil and absorber needed

Combining requirements from both energy consumption and what is feasible at absorber and coil levels:

$T_{absorber}$ $\geq$ 250 K

T_{coil} $\geq$ 4.5 K

W_{elect} $\leq$ 2.5 kW/m

+ heat intercept

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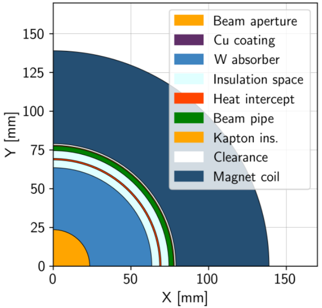
Thank you for your attention

Spare slides

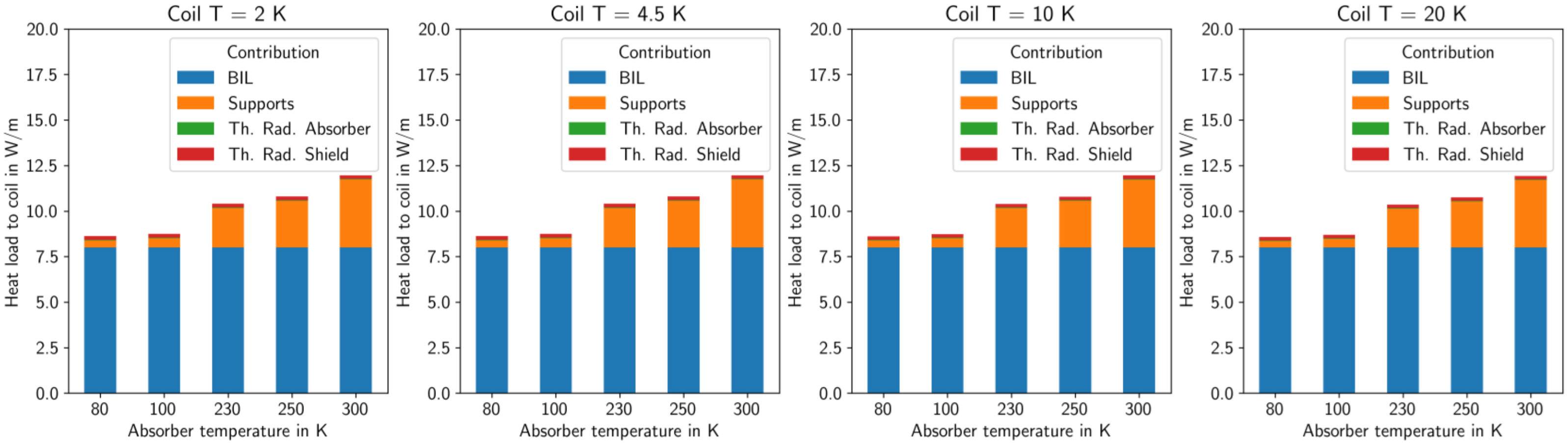
Heat load deposited at cold mass level

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**



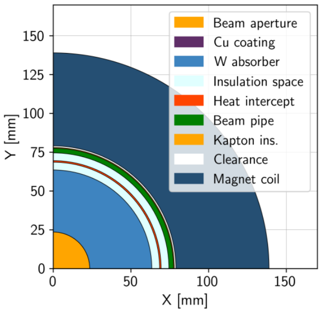
Heat intercept between coil and absorber!



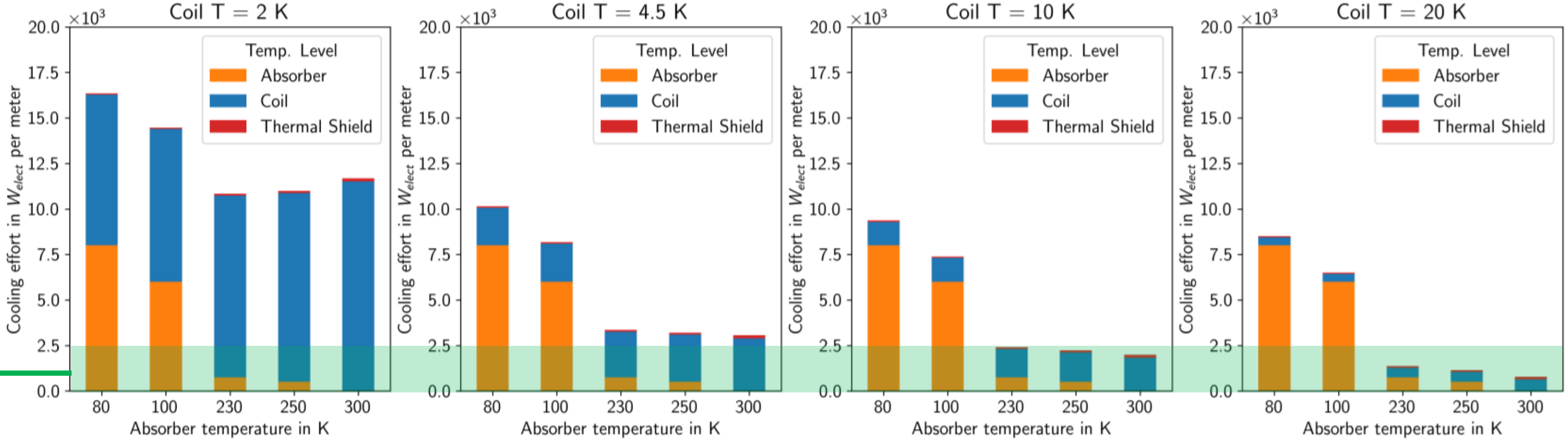
- Reducing the absorber thickness from 4 cm to 3 cm **doubles** the beam-induced load that penetrates shielding (**blue part**) while only reducing the heat load via the supports (**orange part**, which is weight-dependent) by 30%

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

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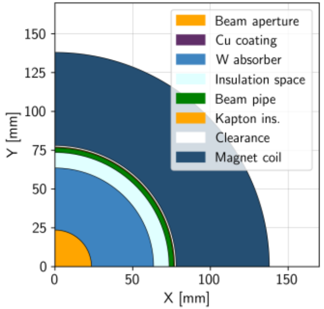
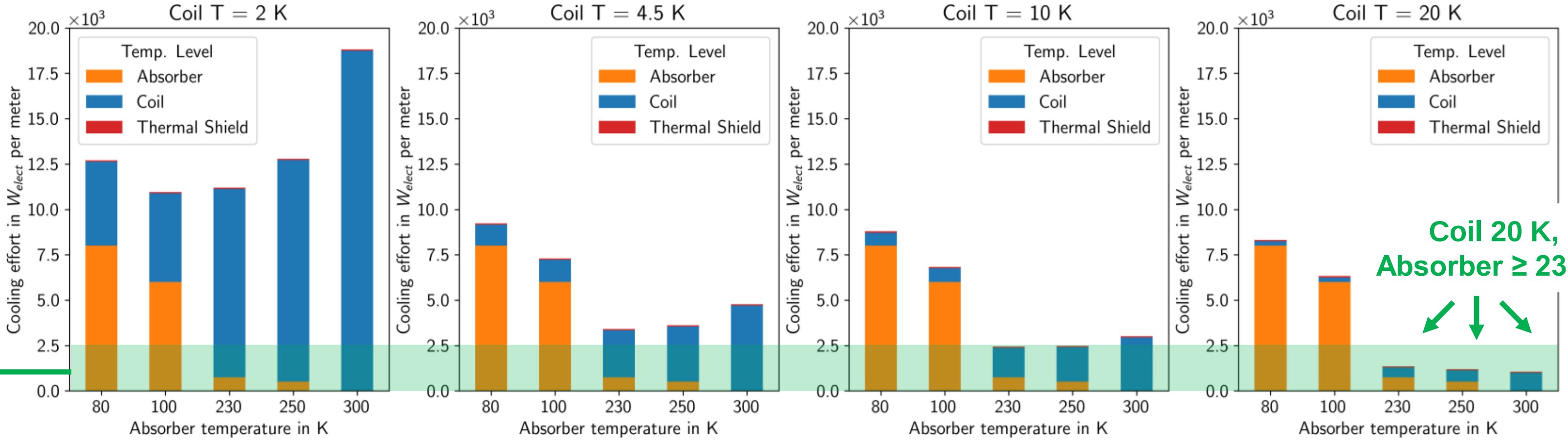
N.B. II: although COP^{-1} based on cryoplants using certain fluids, so far, we're talking only about temp. level, *i.e.*, no fluid-dependent costs considered (as distribution, special handling, etc…)

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



Target: 25 MW for Cryo in collider

Coil 20 K, Absorber ≥ 230 K

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…)

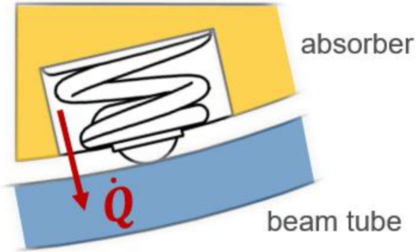
(Possible) solution for absorber supports from existing implementations

PUMA rolls

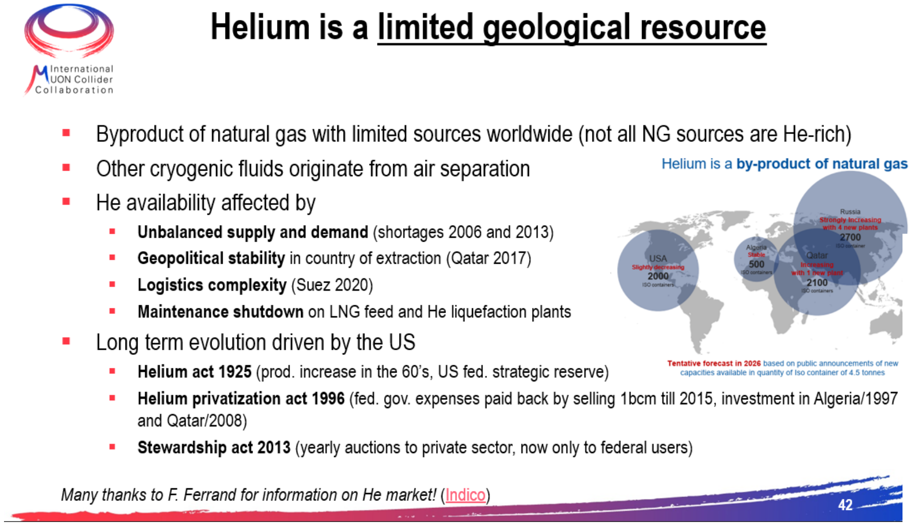
- Heat transfer measurements by J. Liberadzka-Porret at the Cryolab, EMDS # 2443998 (link)
  ≈ 1 W/roll under 500 N from RT to LN_2
  ≈ 0.1 W/roll under 500 N from LN_2 to LHe

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



Reminder from last annual meeting (link)



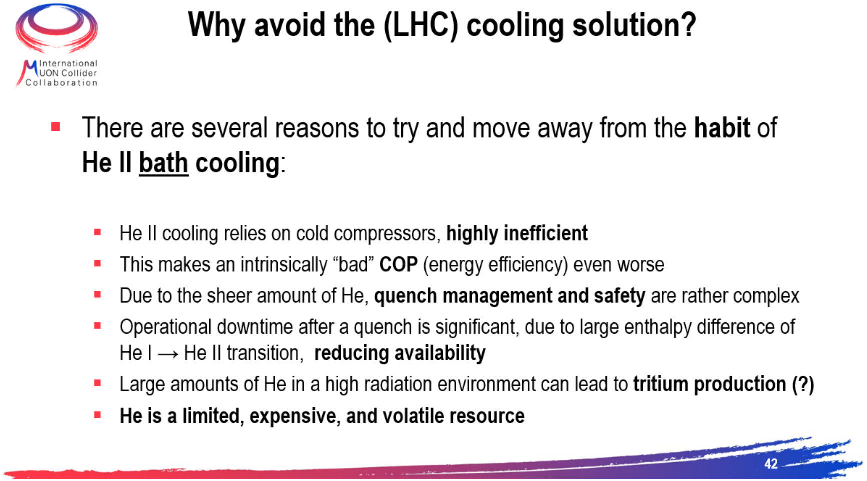
Helium is a limited geological resource

- Byproduct of natural gas with limited sources worldwide (not all NG sources are He-rich)
- Other cryogenic fluids originate from air separation
- He availability affected by
  - **Unbalanced supply and demand** (shortages 2006 and 2013)
  - **Geopolitical stability** in country of extraction (Qatar 2017)
  - **Logistics complexity** (Suez 2020)
  - **Maintenance shutdown** on LNG feed and He liquefaction plants
- Long term evolution driven by the US
  - **Helium act 1925** (prod. increase in the 60's, US fed. strategic reserve)
  - **Helium privatization act 1996** (fed. gov. expenses paid back by selling 1bcm till 2015, investment in Algeria/1997 and Qatar/2008)
  - **Stewardship act 2013** (yearly auctions to private sector, now only to federal users)

Helium is a **by-product of natural gas**

Tentative forecast in 2026 based on public announcements of new capacities available in quantity of Iso container of 4.5 tonnes

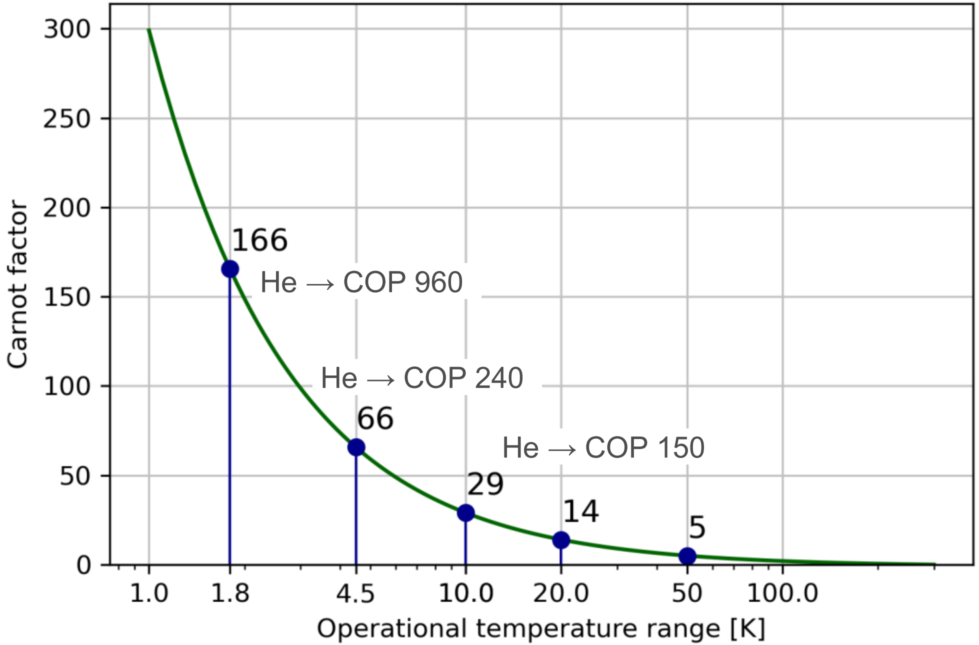
Many thanks to F. Ferrand for information on He market! (Indico)



Why avoid the (LHC) cooling solution?

- There are several reasons to try and move away from the **habit** of **He II bath cooling**:
  - He II cooling relies on cold compressors, **highly inefficient**
  - This makes an intrinsically "bad" **COP** (energy efficiency) even worse
  - Due to the sheer amount of He, **quench management and safety** are rather complex
  - Operational downtime after a quench is significant, due to large enthalpy difference of He I ⟶ He II transition, **reducing availability**
  - Large amounts of He in a high radiation environment can lead to **tritium production (?)**
  - **He is a limited, expensive, and volatile resource**

Thermodynamics of cryogenic refrigeration
Ideal Carnot ≠ Reality



- Carnot efficiency gives a **potential** reduction in operational costs
  - e.g. from 4.5 K to 10 K there is a **potential** factor 2.3 improvement in efficiency
- But **reality** (process inefficiencies) needs to be considered
  - Actual COP at refrigerator interface for 10 K is 150 *vs.* 240 at 4.5 K → factor 1.6 improvement in efficiency (W/W)
- Losses on distribution and heat extraction systems **still need to be added (up to 30%-50%!)**

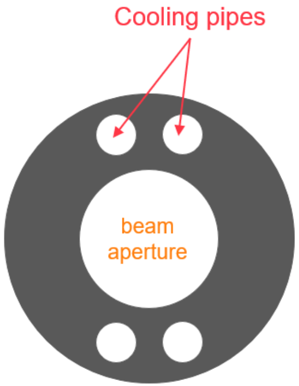
Power consumption at refrigerator I/F

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

Specific power requirement of refrigerators

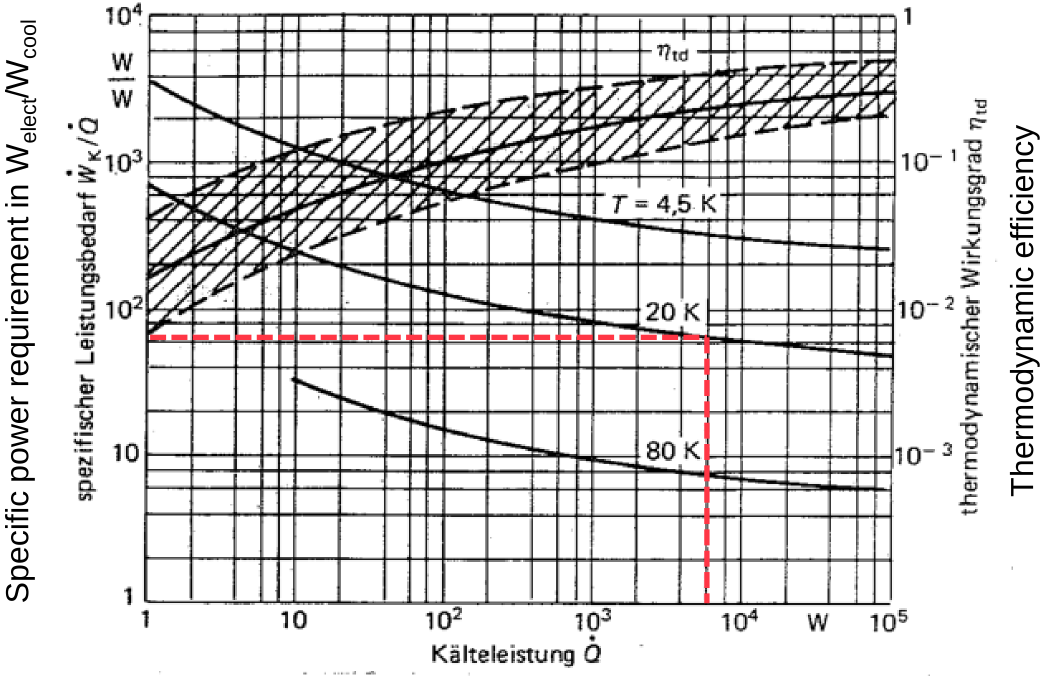
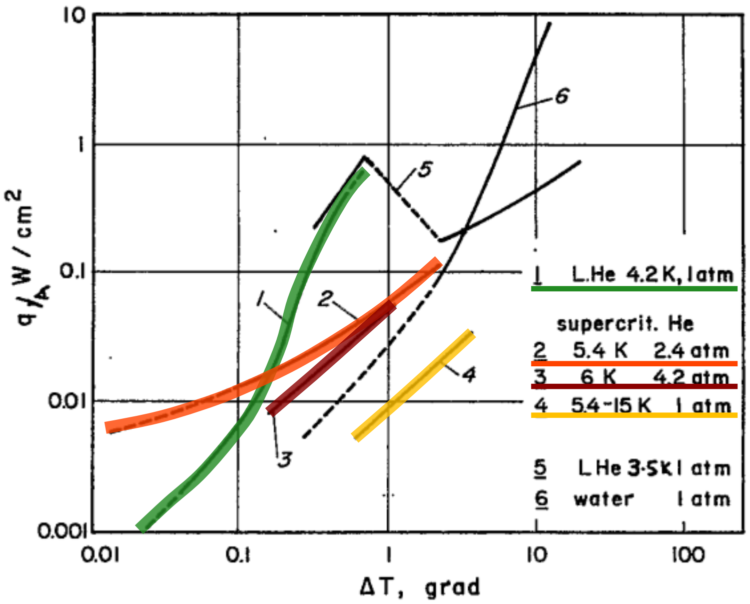


Figure 7-35. Specific power requirement of refrigerators and thermodynamic efficiency it of the cold power at different operating temperatures.

Source: Tieftemperatur–Technologie, von H. Frey und R. A. Haefer. Herausgegeben von F. X. Eder. VIII-Verlag, Düsseldorf 1981

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)*

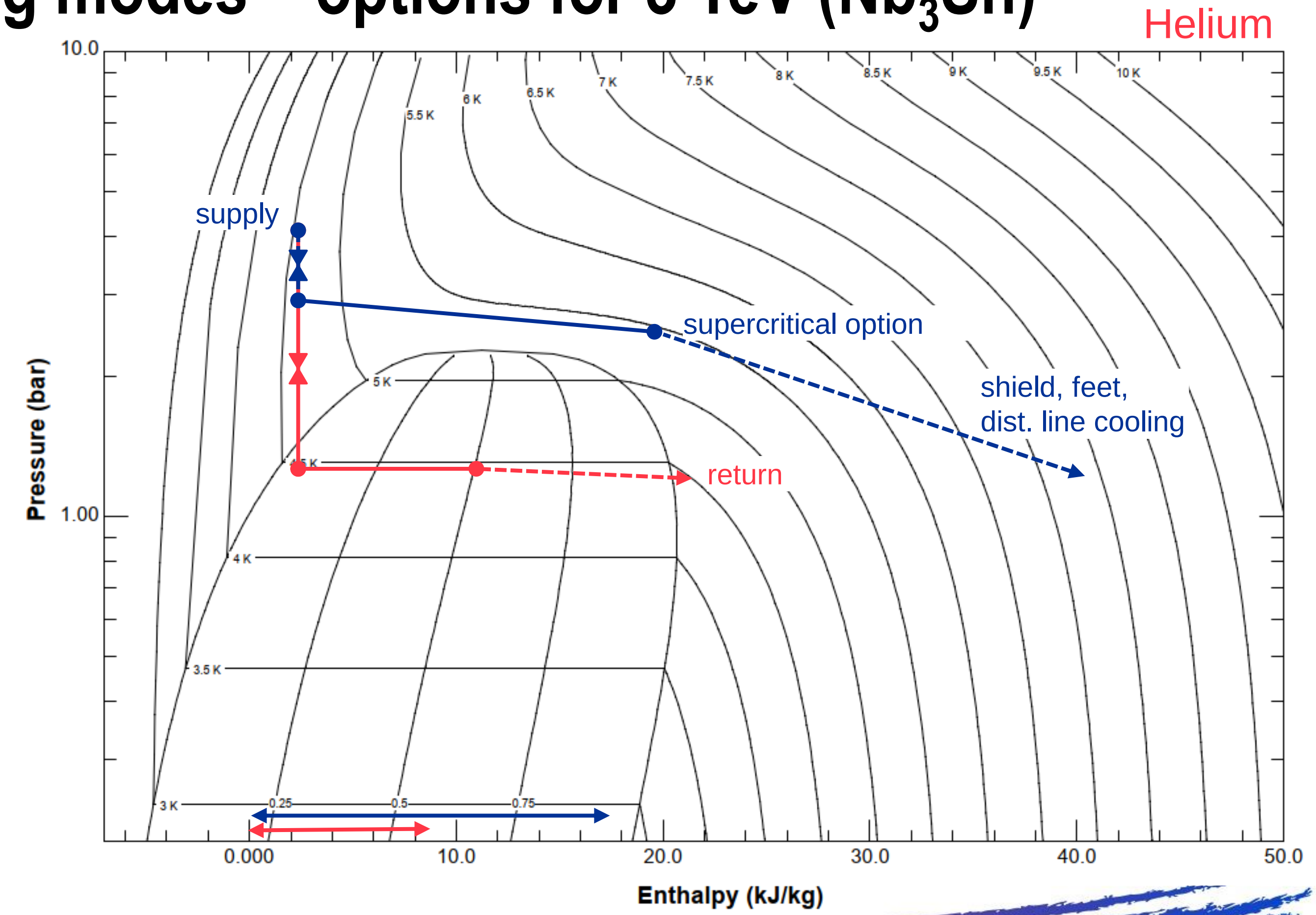
Cooling modes – options for 3 TeV (Nb_3Sn)

- **Two-phase option:**
  Expand from 3 to 1.3 bara into the two-phase region, two-phase cooling at 4.5 K

  Pros: high α, negligible Δ*T* along arc cell
  Cons: limited Δh due to onset of dry-out (see flow pattern map), complex control loop esp. if 2 parallel pipes

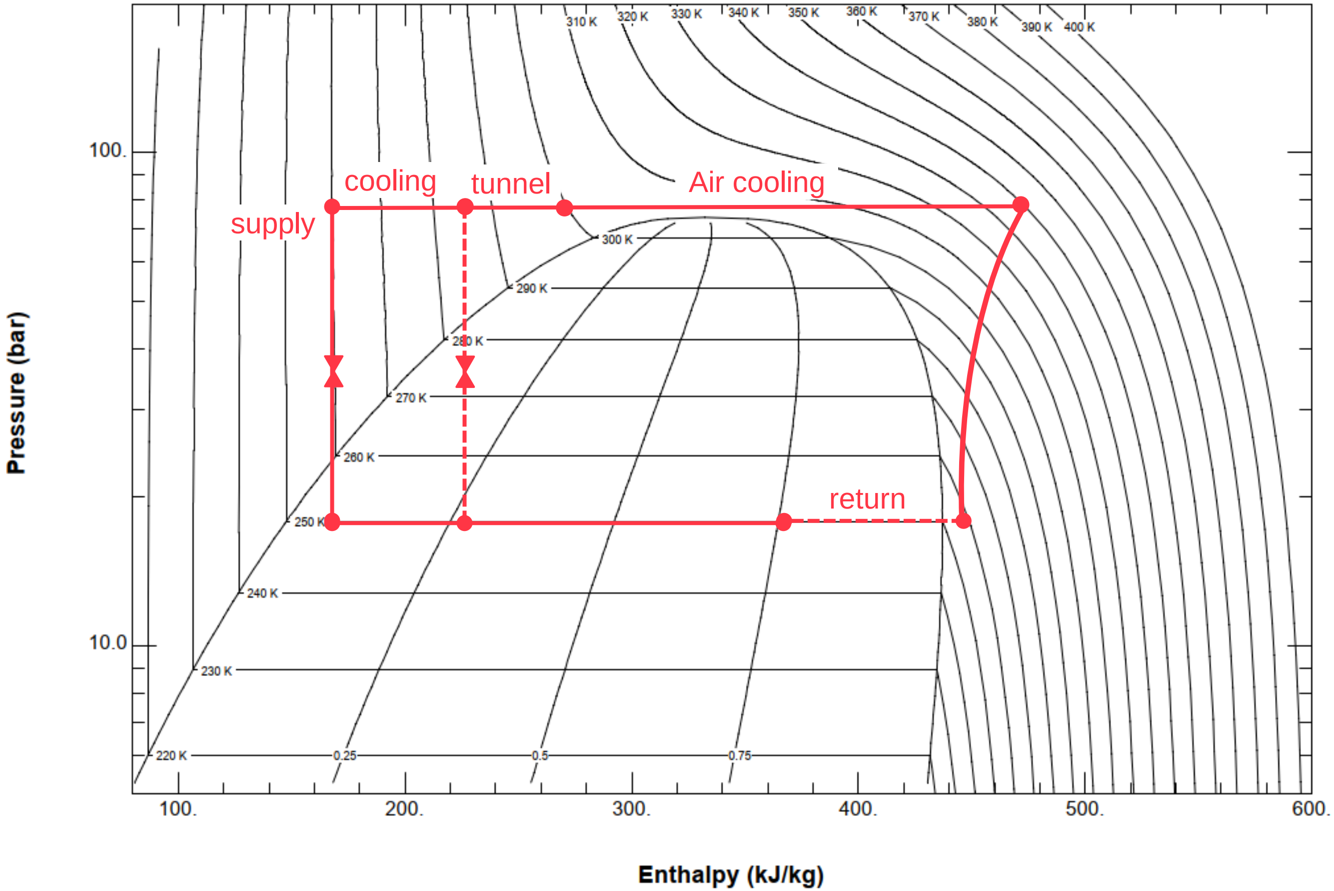
- **Supercritical option:**
  Use sc region from 3 to 2.5 bara allowing a certain Δ*T* (shown 4.5 K to 5.5 K)

  Pros: large Δh available, can use return for cooling with > 1 bar Δp available
  Cons: Δp needs to be ensured, α lower, some Δ*T* along cell to be accepted



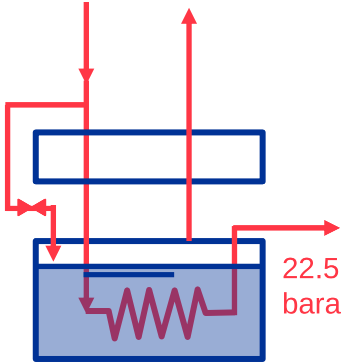
Carbon Dioxide

- 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



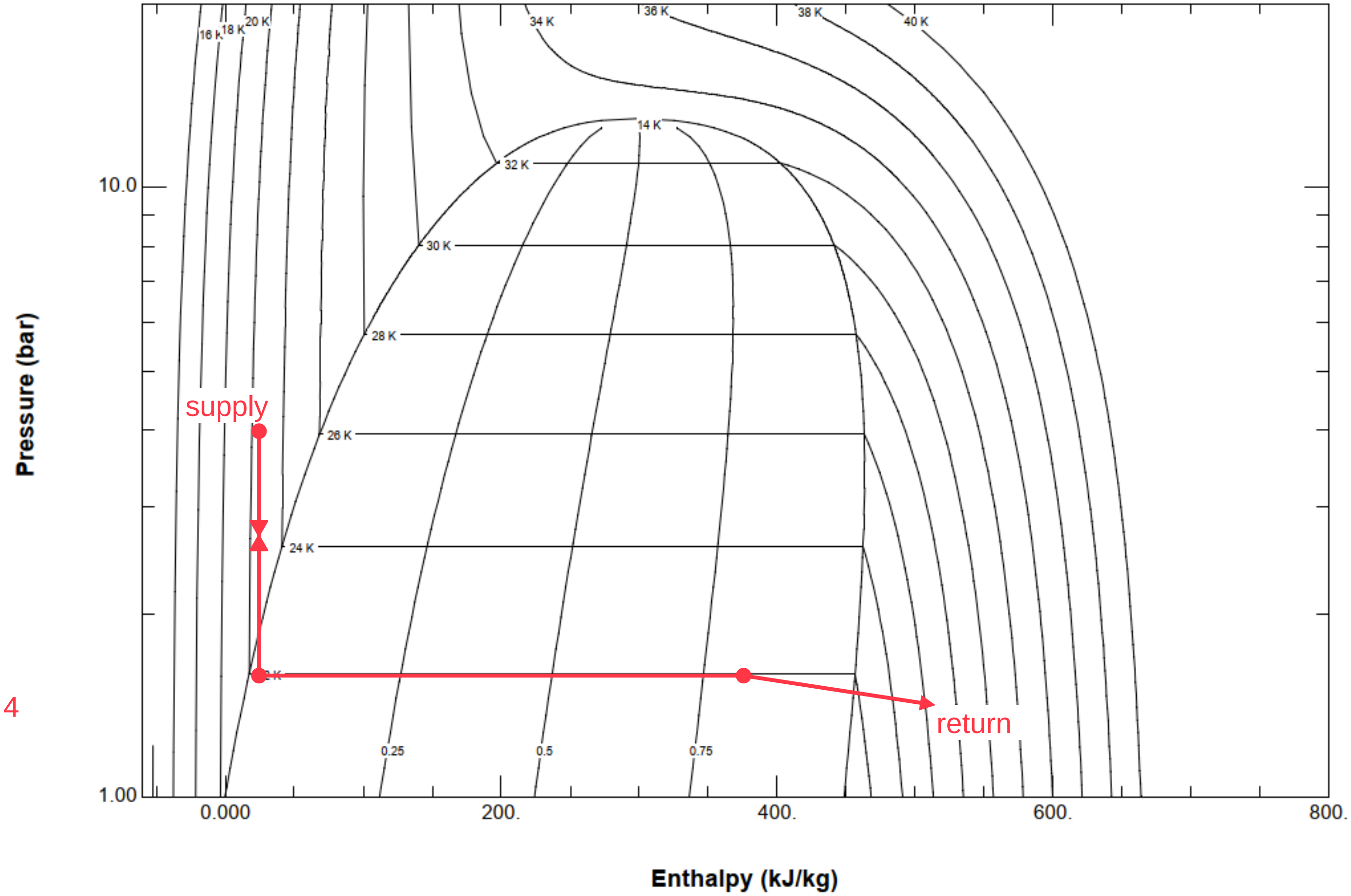
Hydrogen

- 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)