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MUON Collider
Collaboration

Cryogenic options for future accelerators:
Muon Collider

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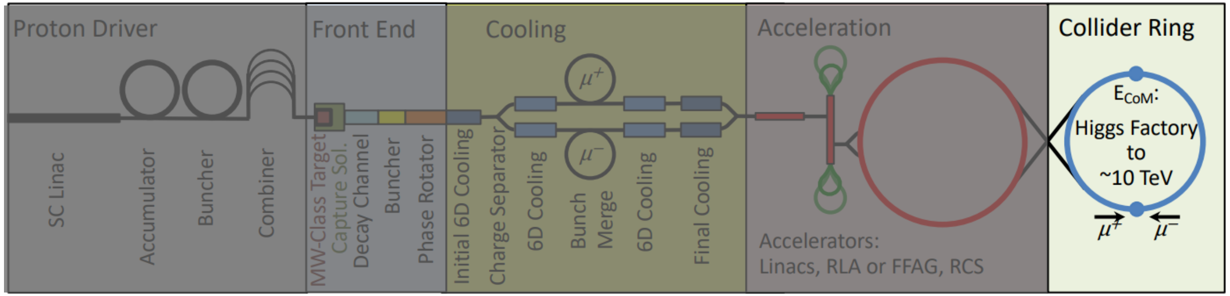
Introduction

- 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

Disclaimer !

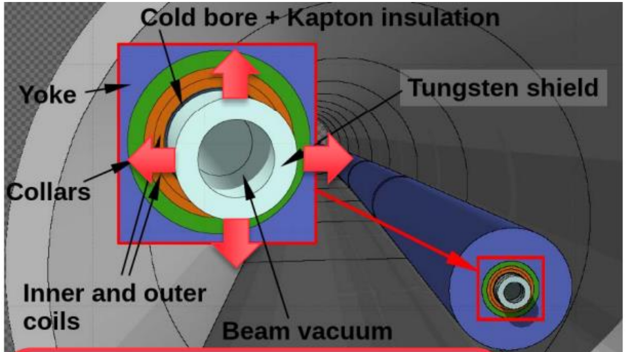
Here we focus on cryogenic options for the **collider**.

Source: MAP collaboration



One-of-a-kind magnets (and more) on the rest of the accelerator chain can potentially be allowed to have tailored, less optimised solutions, which are outside of the scope of this talk

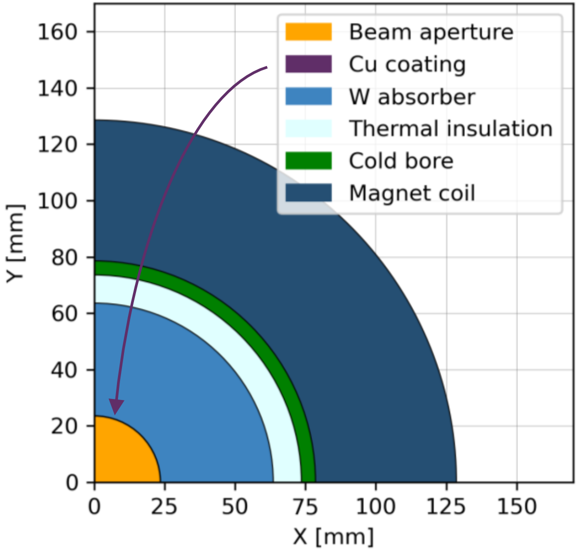
Input: radial build and beam-induced heat loads



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

Dimensions from option II radial build:

Beam aperture (5σ)	23.5 mm radius
Cu layer beam screen	0.1 mm thick
Tungsten absorber	40 mm thick
Thermal insulation	10 mm thick
Cold bore	5 mm thick
Coil pack	50 mm thick



	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

Calculations based on the 10 TeV machine!

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

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

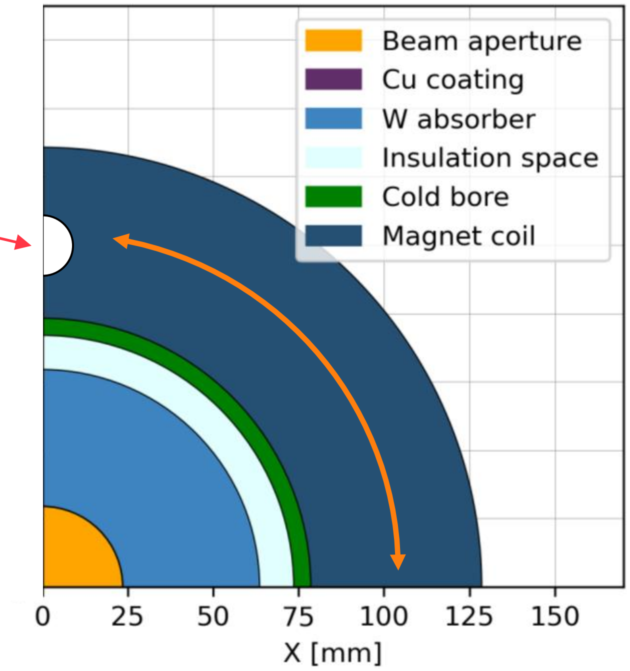
- **Cold mass temperature:** 2 K, 4.5 K, 10 K, 20 K
- **Heat loads to cold mass *T*-dependent and absorber thickness-dependent:**
    - Beam-induced radiation penetrating the absorber, function of its thickness
    - Thermal radiation from external shield (w/ 30 layers MLI on shield, 10 layers on cold 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

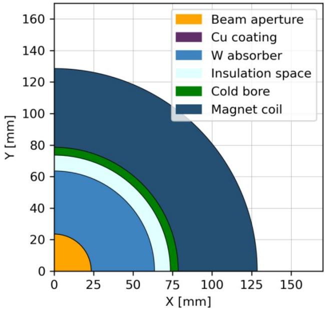
A comment on “coil/cold mass temperature”

- “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

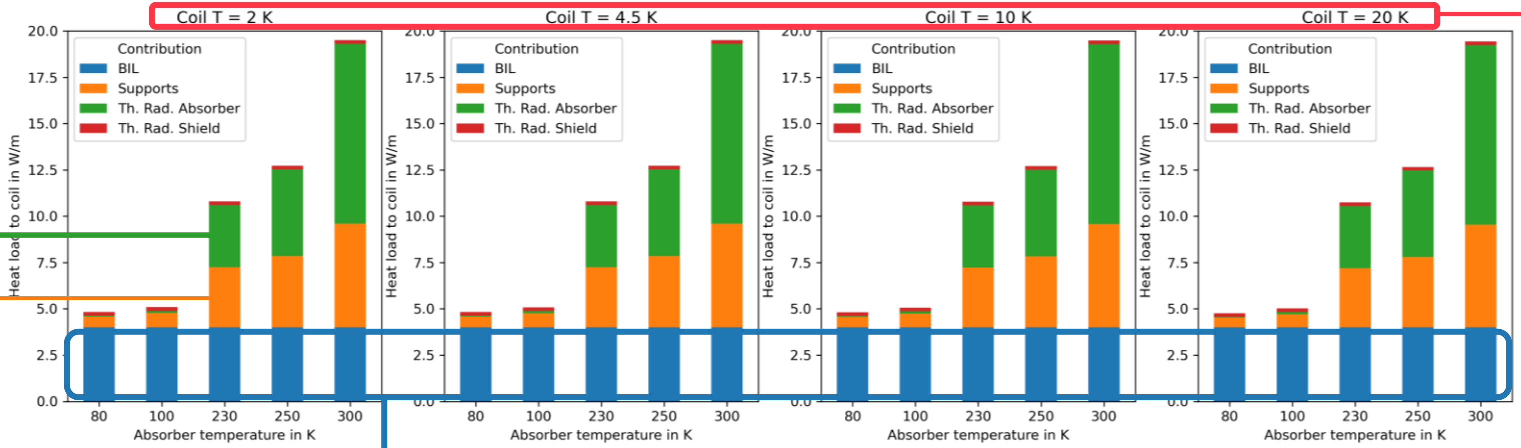


Heat load deposited at cold mass level

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 heat intercept between absorber and coil present
Excessive contribution

Heat load via supports
Excessive contribution

Optimization can have a significant impact on design (aperture)

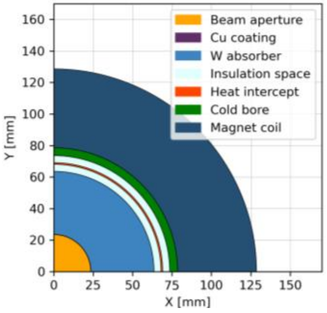
constant 4 W/m
for 4 cm-thick absorber

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

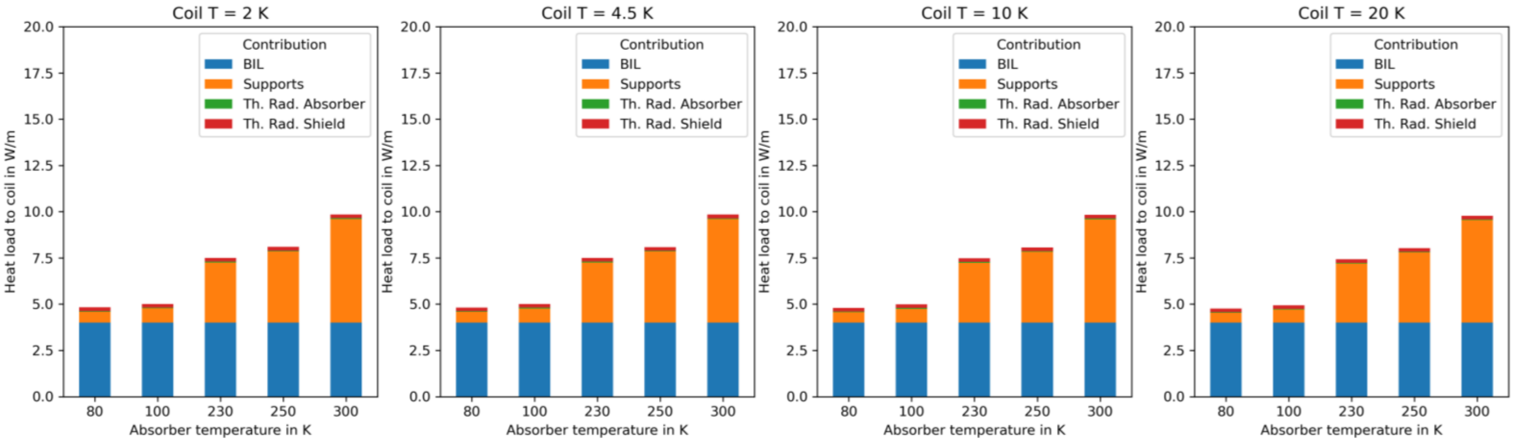
Heat load deposited at cold mass level

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 thermal radiation intercept between the coil and the absorber**



W/ heat intercept between coil and absorber!

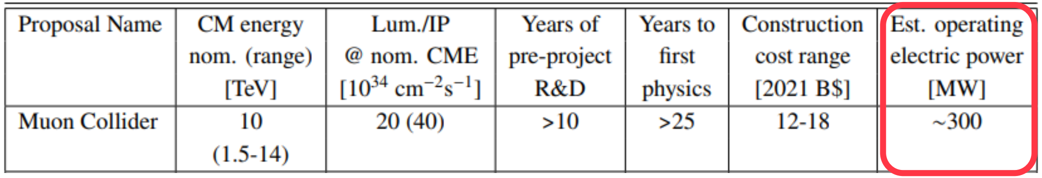


→ Addition of a **heat intercept at 80 K between coil and absorber** reduces **heat load to coil from absorber** by ~ half for absorber temperatures above 230 K

→ **Supports not thermalized** to this heat intercept, would possibly add to 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	$\sim$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

Power consumption at refrigerator I/F

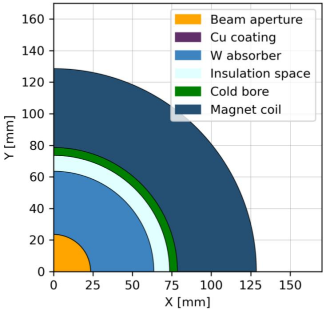
From heat loads to power consumption

- 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:

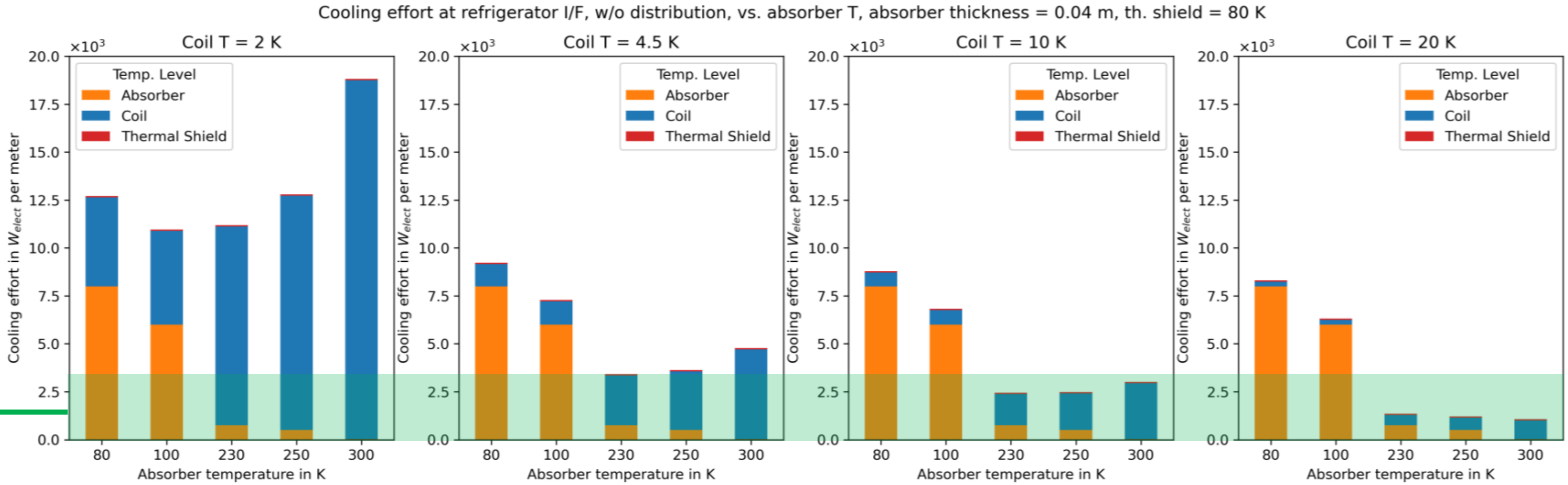
Temperature level	COP^{-1} in W_{elect}/W_{cool}	Source
250 K	1	CO_2 plant ATLAS ITk
100 K	12	LN_2 plant ATLAS
80 K	16	LN_2 plant ATLAS
20 K	50	20 K/50 kW plot Frey (see spares)
10 K	150	LHC cryoplant data
4.5 K	240	LHC cryoplant data
2.0 K	960	LHC cryoplant data

Power consumption at refrigerator I/F

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



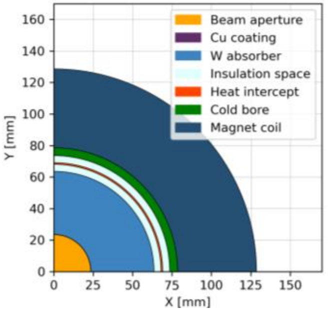
Target for 25 MW for Cryo in collider

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

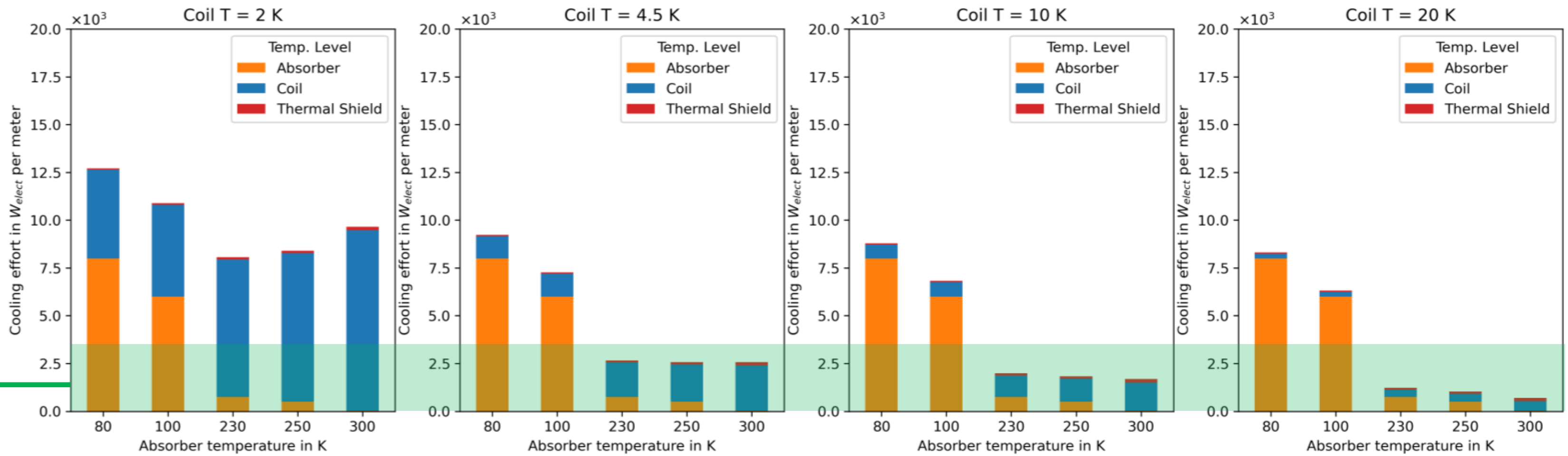
w/ heat intercept



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

W/ heat intercept between coil and absorber!

Target for 25 MW for Cryo in collider


Cooling effort at refrigerator I/F, w/o distribution, vs. absorber T, absorber thickness = 0.04 m, th. shield = 80 K, w/ thermal intercept between absorber and coil at T = 80 K

Coil T = 2 K

Coil T = 4.5 K

Coil T = 10 K

Coil T = 20 K

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

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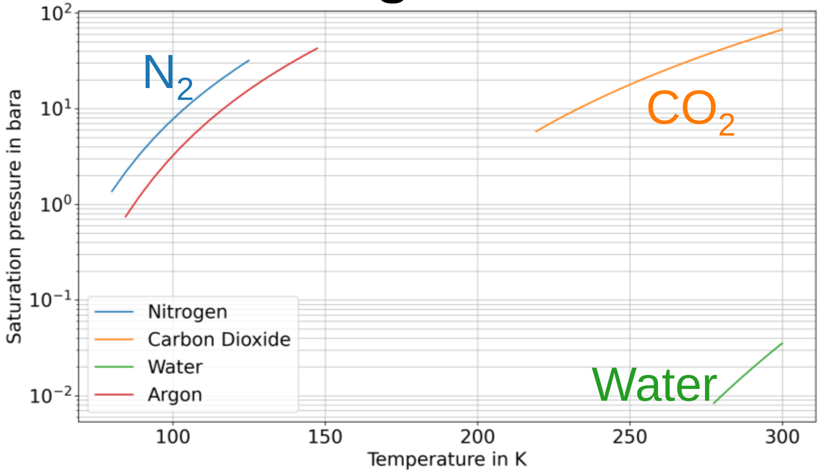
N.B. II: although COP^{-1} based on cryoplants using certain fluids, so far, we're talking only about temp. level, *i.e.*, no fluid-dependent costs considered (as distribution, special handling, etc…)

Fluid options for absorber cooling

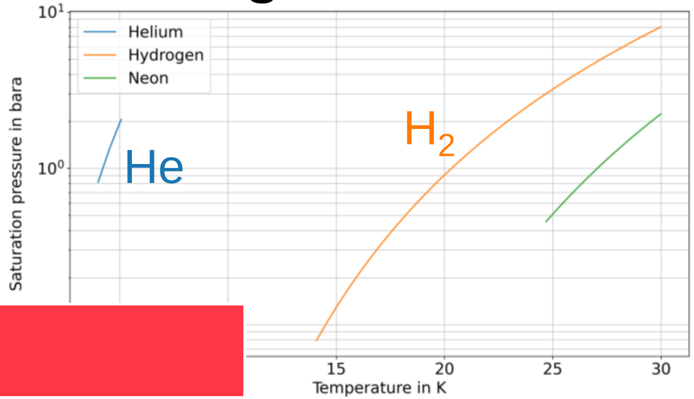
- Currently, baseline is no thermal shield between cold mass and absorber present to intercept heat load, prompting a lower temperature for the absorber
- Potential to integrate external thermal shield cooling at the return of absorber cooling circuit



Temperature level	Cooling fluid	Remarks
300 K – 305 K	single-phase water	• Freezing issue if no BI heat load, needs EH compensation? • Not compatible with radiation? Free radicals, corrosion?
250 K	two-phase CO_2	• Higher end of the temperature range, intrinsically low COP^{-1} • Radiation hard, high latent heat → low mass flow rates needed • Requires 60+ bara
100 K	two-phase N_2	• Lower end of the temperature range, COP^{-1} will be higher • Can provide two-phase option or gas flow • Cooling scheme could be tailored so that return of absorber circuit provides shield cooling circuit
80 K	two-phase N_2	

Fluid options for cold mass cooling

- Hydrogen can be an viable choice for HTS only as T > 20 K
- Needs to be studied w.r.t. safety and impact on material integrity
- He is an established technology as opposed to magnet cooling with LH_2



Temperature level	Cooling fluid	Remarks
20 K	two-phase H_2	• Very high latent heat → low mass flow rates possible • Constant temperature provided • Viable option for cooling of HTS magnets • Ortho-para conversion needs to be addressed at refrigerator level • Material choices more stringent due to H_2 embrittlement
10 K	supercritical He	• Large temperature gradient along sector, 5 K – 10 K, 5 K – 15 K • Viable option for cooling of HTS magnets
4.5 – 5.5 K	supercritical He	• Temperature gradient along sector (4.5 K – 6 K) • Viable option for cooling of HTS magnets, maybe even Nb_3Sn
4.5 K	two-phase He	• Constant temperature provided
2 K	He II	• Technology well known, too energetically costly even if using confined two-phase flow in pipes • Frictional losses important

Distribution losses

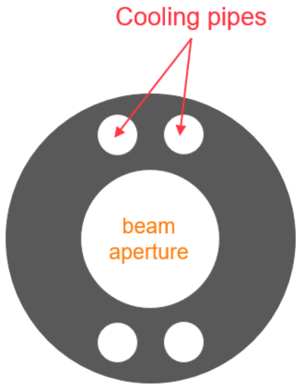
“What does an arc cell / sector look like?”

- Previous slides detailed heat loads to both cold mass and absorber, and estimated a cooling effort at refrigerator interface for each combination of temperature level, but no cooling fluid was assigned

- By choosing a fluid and a cooling scheme, *i.e.* “cooling at 4.5 K using two-phase He confined in cooling pipes”, we can estimate the distribution losses and the feasibility of the various schemes

- At the moment, the distribution effort is estimated in terms of maximum allowable pressure drop in the magnet circuit (which determines the “arc cell” size, *i.e.* the distance between re-cooling stations) and in the distribution line (which determines the sector size)

(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 ($p_{out} < p_{atm}$)

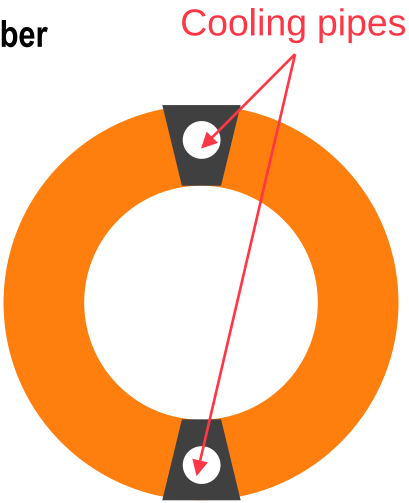
→ return of QRL dp (barely) within limits

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

→ return of QRL dp within limits

(rough) estimation of distribution losses
Cold Mass

- Calculations for the coil/cold mass circuit **considering heat intercept between coil and absorber**
- Considered 2 pipes in coil/cold mass, each of i.d. = 20 mm (fits in a pole wedge)
- Cell length (distance between jumpers to QRL) fixed at 25 m, sector fixed at 1000 m = 40 cells



	$\dot{m}$ 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

For comparison: LHC cryoplant can provide 250 g/s per sector at 4.5 K

Summary

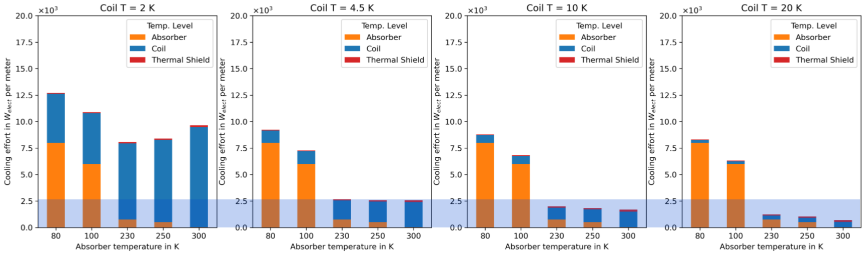
Energy consumption → ≤ 2.5 kW/m → $T_{absorber}$ ≥ 230 K

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!



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

$T_{absorber}$ ≥ 250 K

T_{coil} ≥ 4.5 K

W_{elect} ≤ 2.5 kW/m

+ heat intercept

Open points – food for thought

- Absorber mechanical supporting structure needs attention
  - Currently no known design for supports
  - Heat load needs to be closely monitored as it is one of the major contributions to the total heat load at coil level
  - Alternatively, could absorber be (mostly) supported at ends?

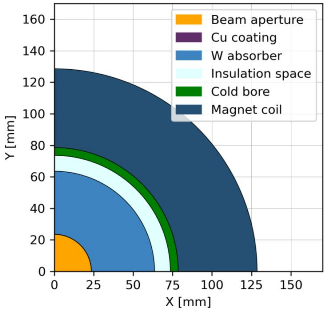
- Temperature stability of magnet + cooling circuit not yet studied
  - Need to include heat loads due to transient mechanisms such as ramping
  - Thermal analysis in case of quench will be required

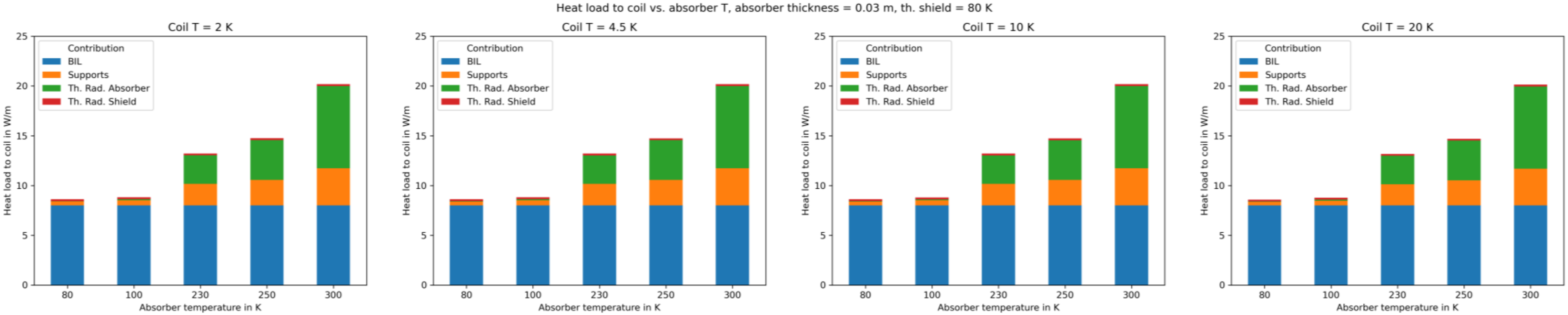
- Radial build of collider magnets
  - Magnet aperture considered in this study is 158 mm (4 cm absorber), already with very little margin for adding a heat intercept/thermal shield to thermally decouple absorber and magnet coil

Thank you for your attention

Spare slides

Heat load at cold mass – 3 cm absorber

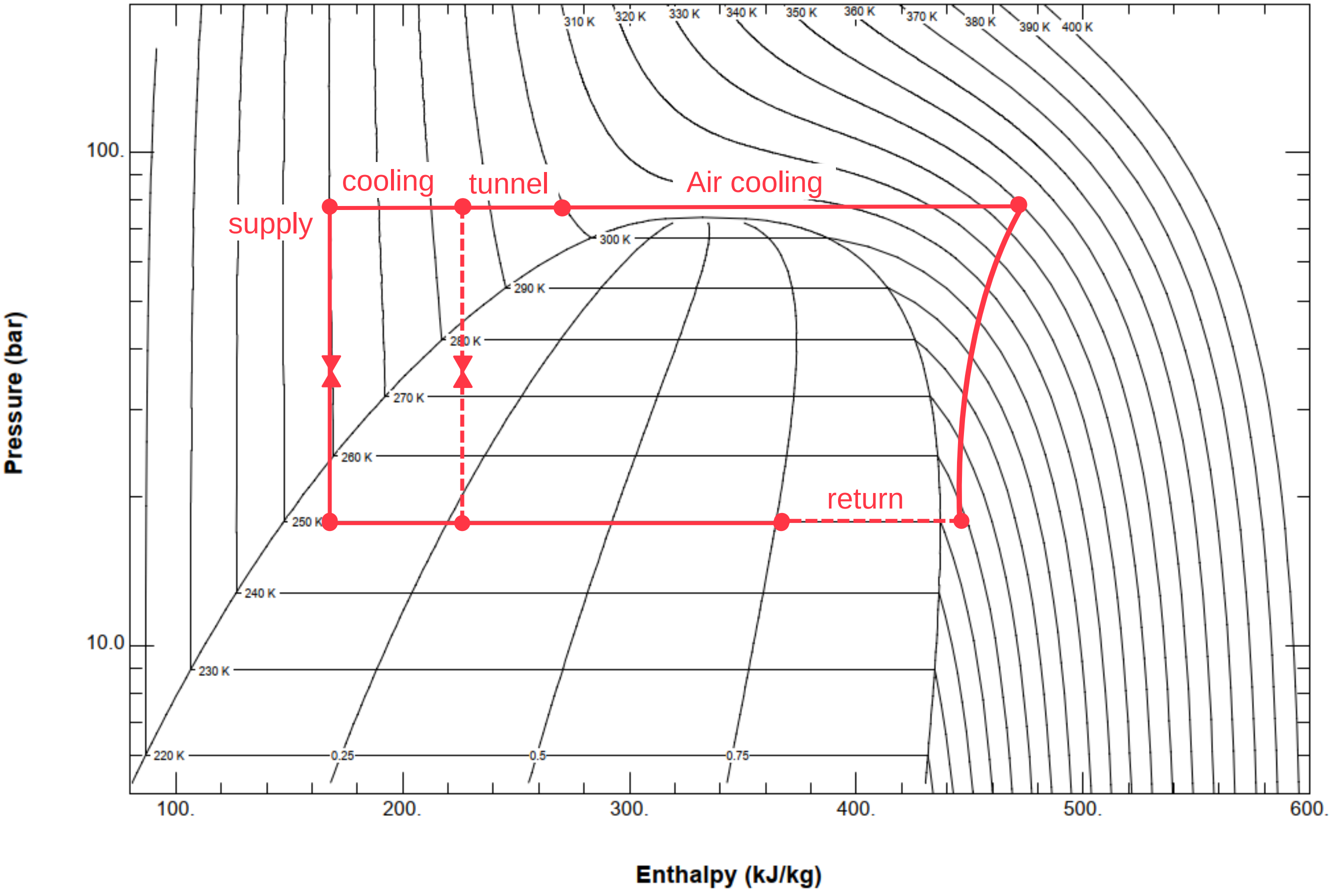




- Reducing the absorber thickness from 4 cm to 3 cm **doubles** the beam-induced load that penetrates shielding (**blue part**) while only reducing the heat load via the supports (**orange part**, which is weight-dependent) by 30%

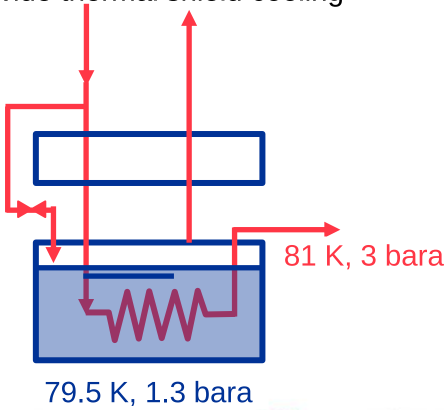
Carbon Dioxide

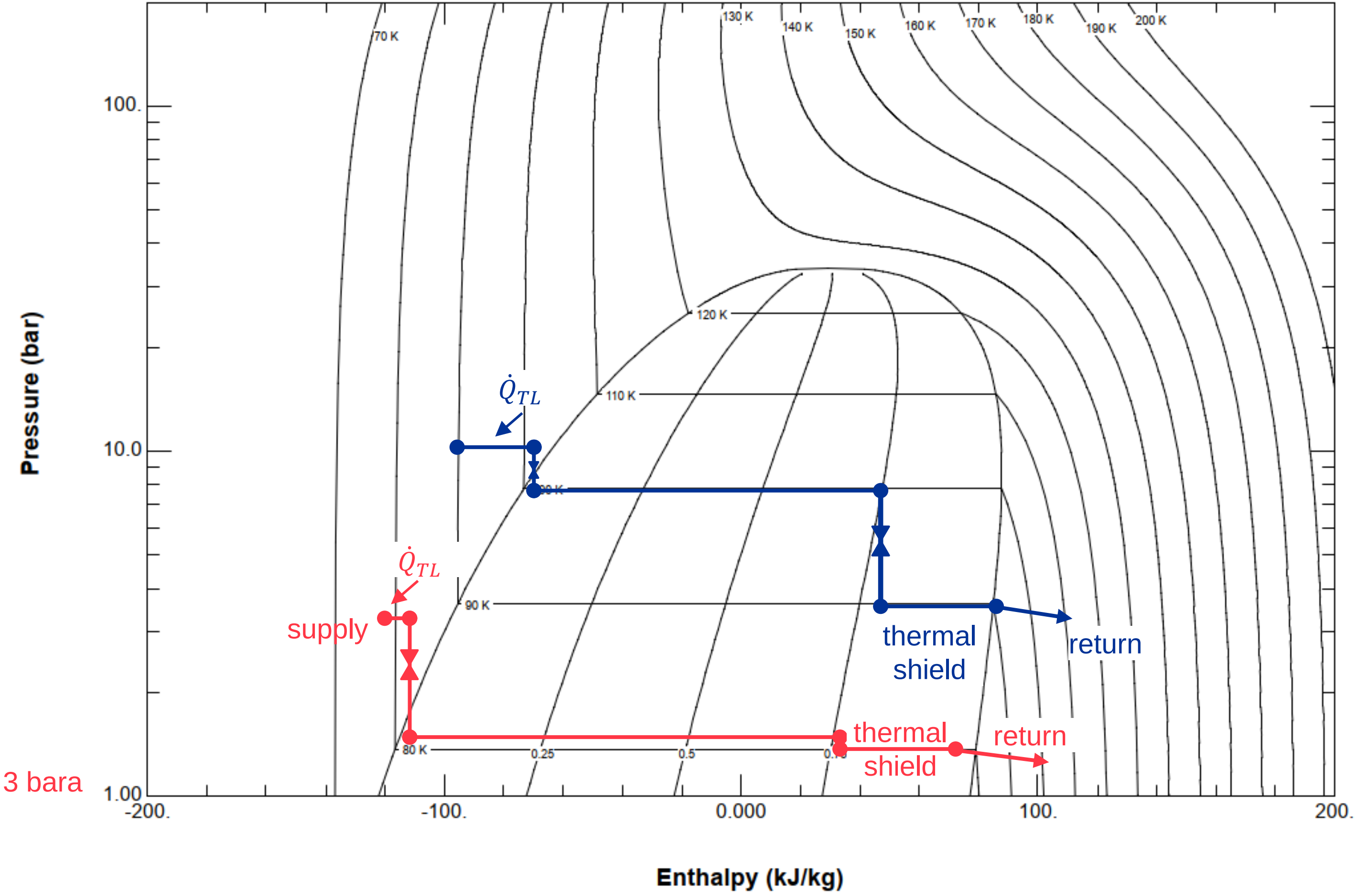
- Two-phase flow
  at 250 K, 20 bara,
  expanded from 70 bara, 260 K
- Depending how we enter the two-phase region, cooling at “tunnel” or room temperature would be sufficient
- Other cooling schemes possible, to be investigated



Nitrogen

- Supply subcooled liquid at 10 ba
90 K, heat to 103 K, expand to 8
bara into the two-phase region,
two-phase cooling at 100 K (blue
- Supply subcooled liquid at 3 bar
81 K, expand to 1.5 bara into the
two-phase region, two-phase
cooling at 81 K (red)
- Could use return of absorber circ
to provide thermal shield cooling





Hydrogen

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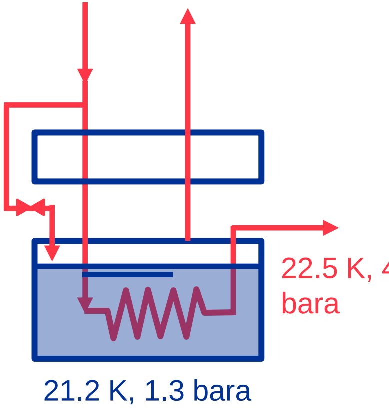
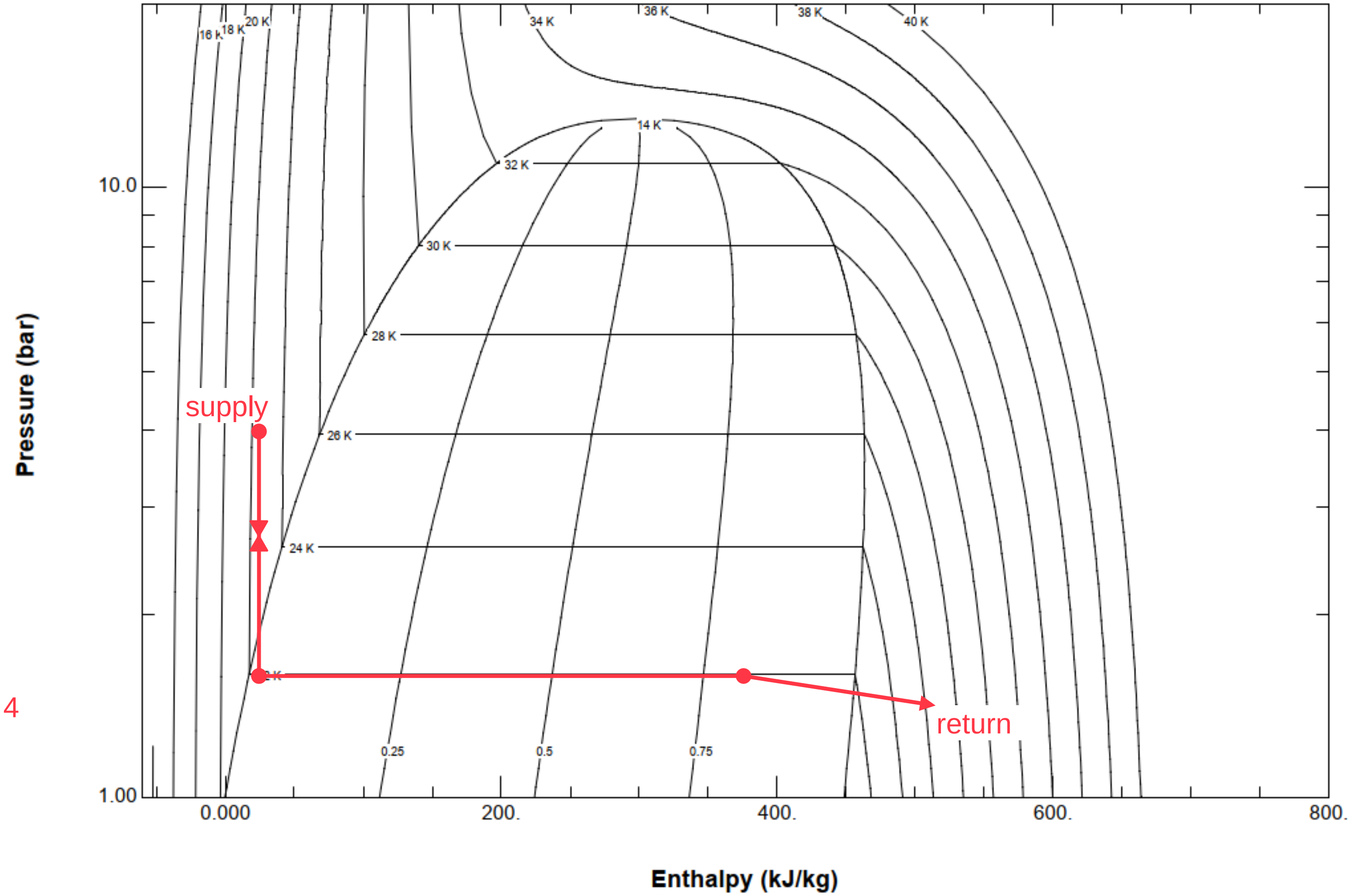
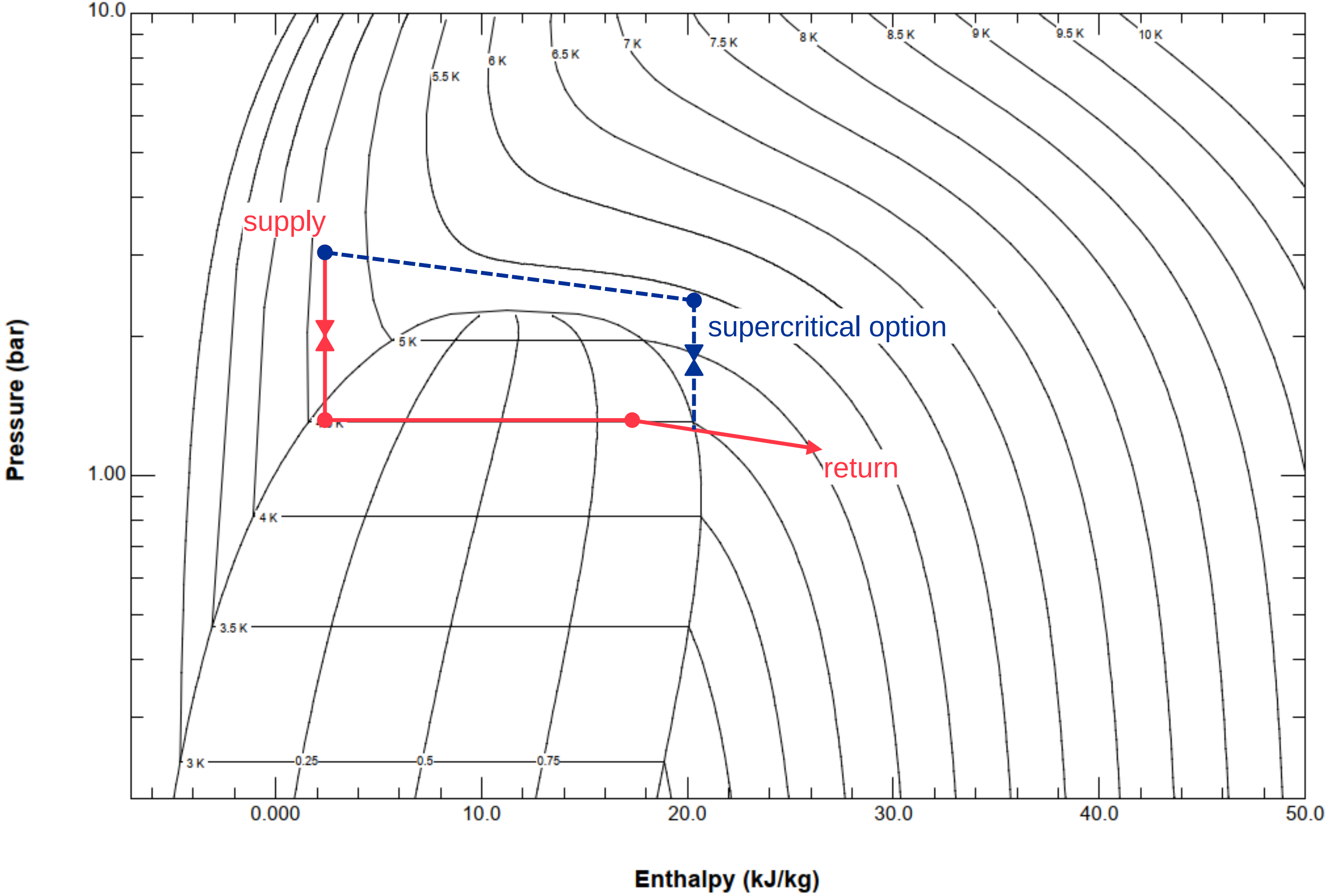
- Supply subcooled liquid at 4 bara, 22.5 K, expand to 1.3 bara into the two-phase region, two-phase cooling at 21.2 K



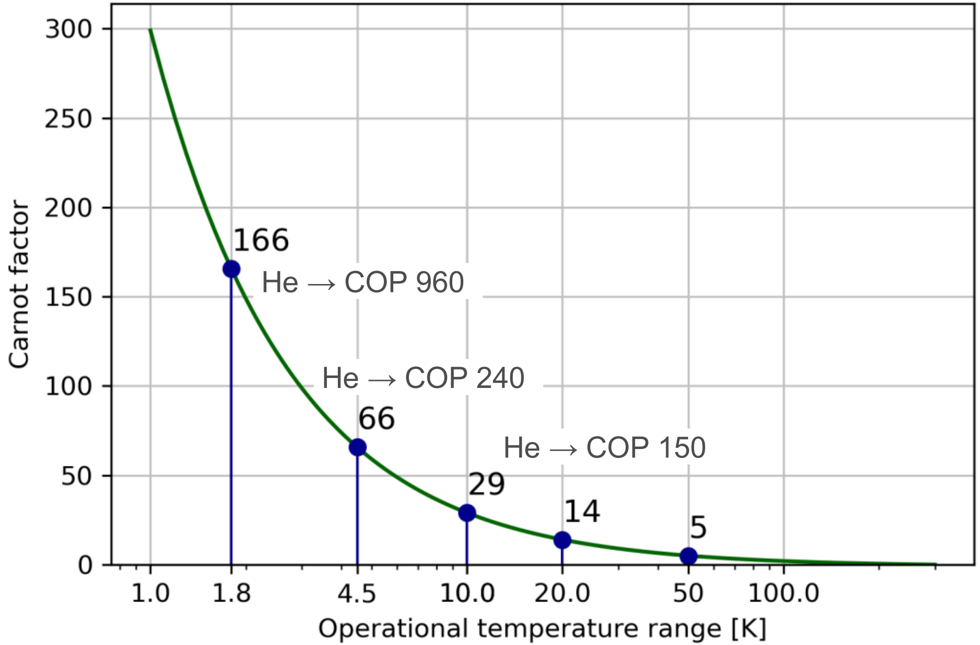


Helium

- 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)



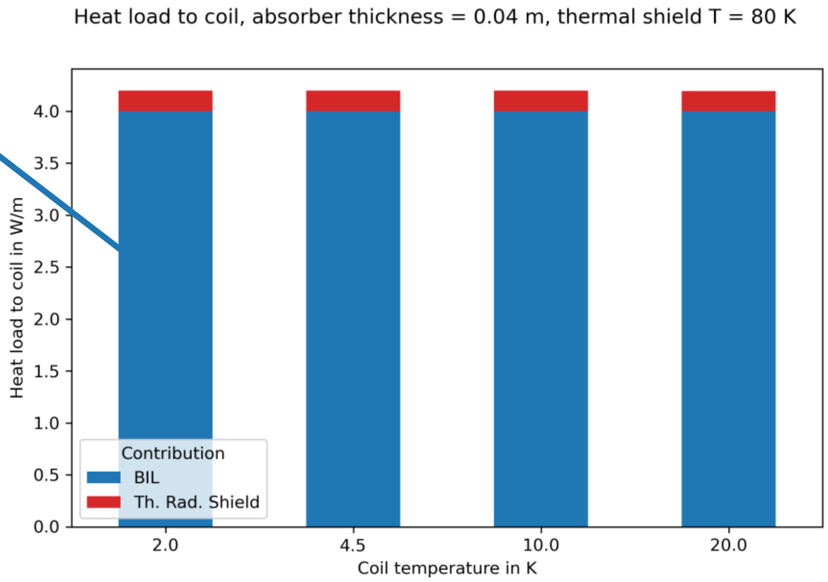
Thermodynamics of cryogenic refrigeration
Ideal Carnot ≠ Reality



- 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%!)**

Heat load deposited at cold mass level

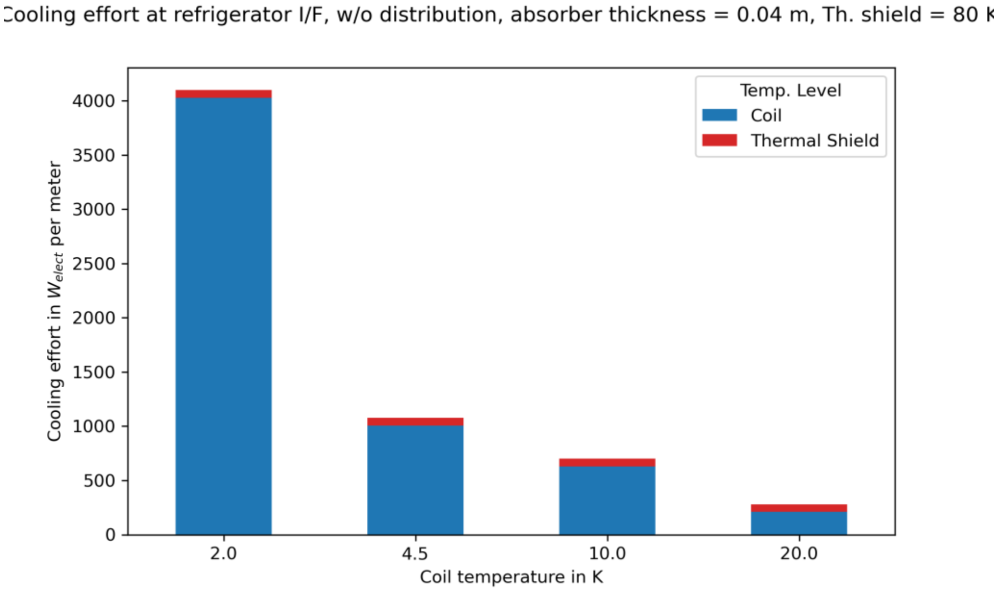
- Heat load at cold mass level $f(T_{coil}, T_{thermal\ shield})$
- **Assuming no** radiation + conduction from supports coming from the absorber



constant 4 W/m for 4 cm-thick absorber

Thermodynamic effort at refrigerator interface

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



Assuming there is no radiation + conduction from supports coming from the absorber, also excluded the effort to remove the 500 W/m from absorber level

Specific power requirement of refrigerators

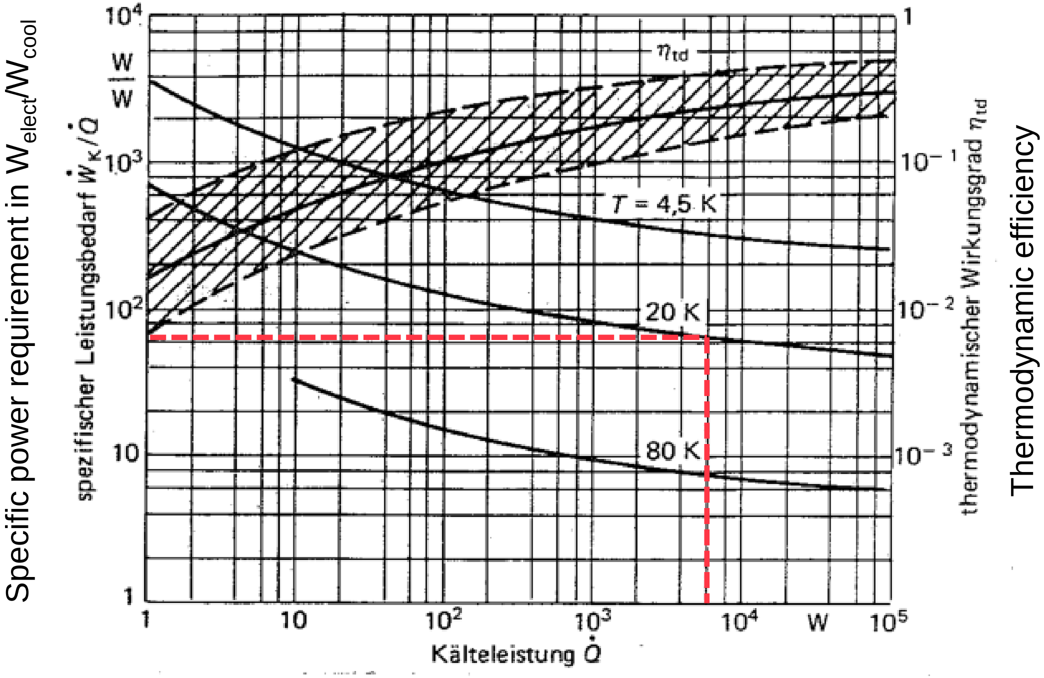


Figure 7-35. Specific power requirement of refrigerators and thermodynamic efficiency it of the cold power at different operating temperatures.

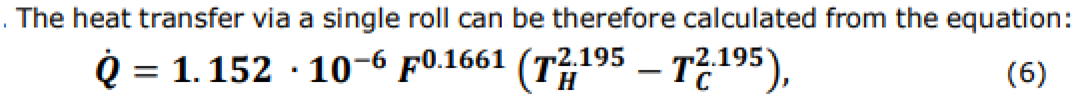
Source: Tieftemperatur–Technologie, von H. Frey und R. A. Haefer. Herausgegeben von F. X. Eder. VIII-Verlag, Düsseldorf 1981

Example of absorber support – PUMA rolls

J. Liberadzka-Porret, 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

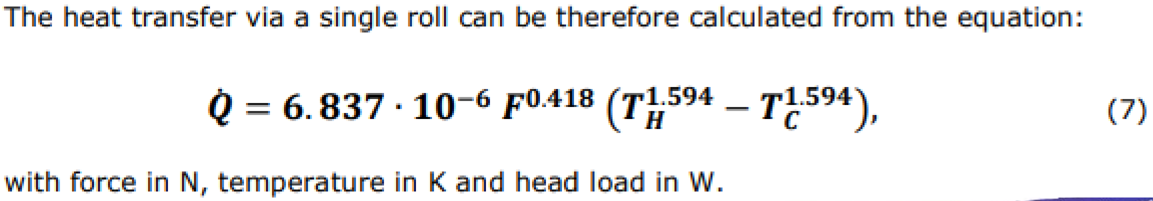
RT to LN_2



. The heat transfer via a single roll can be therefore calculated from the equation:

$$\dot{Q} = 1.152 \cdot 10^{-6} F^{0.1661} \left(T_H^{2.195} - T_C^{2.195}\right), \qquad (6)$$

LN_2 to LHe



The heat transfer via a single roll can be therefore calculated from the equation:

$$\dot{Q} = 6.837 \cdot 10^{-6} F^{0.418} \left(T_H^{1.594} - T_C^{1.594}\right), \qquad (7)$$

with force in N, temperature in K and head load in W.