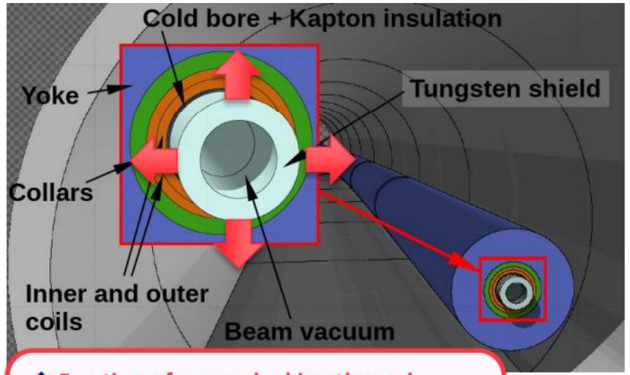
Cryogenic options for future accelerators: case study for the Muon Collider ring

P. Borges de Sousa,
B. Naydenov, L. Delprat, T. Koettig and R. van Weelderen

ICEC29/ICMC 2024
22nd – 26th July 2024, Geneva, Switzerland

Introduction

- Collider magnets will see **unprecedented beam-induced losses** → radiation, power deposition
- A **radiation absorber** ("enhanced" beam screen, similar to HL-LHC) **is required**, intercepts **≈ 500 W/m** from muon decay
- Heat load needs to be extracted at highest possible *T* → **"warm" object inside magnet cold bore**
- **We need to:**
  - **Estimate heat loads** to cold mass and other parts of the system
  - **Define *T* levels of cold mass, absorber**, shields
  - **Estimate required cooling effort** for the collider



- 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 must include substantial contributions, *e.g.*, conduction, thermal radiation, supports…

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

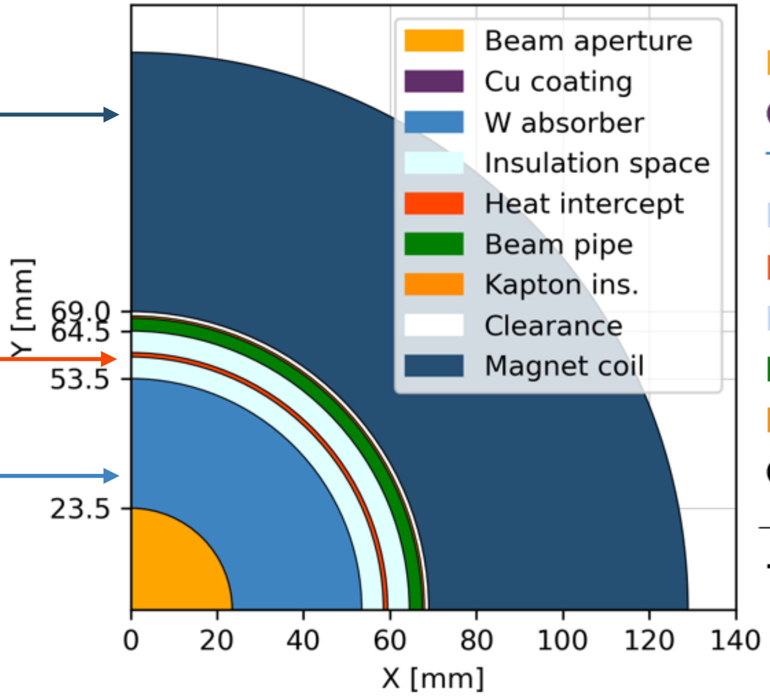
Radial build for collider arc magnets

- **First step is to sketch the radial build** of a “typical” collider magnet:
  - What components must be there?
  - Input from magnet design, beam optics, vacuum, and cryogenics
  - How large is the resulting aperture?

T depends on conductor; between 2 K and 20 K

Inner shield

High heat load; must be at “high” *T* (*e.g.* RT)



	Δr
Beam aperture (5σ)	23.49 mm
Cu layer beam screen	0.01 mm
Tungsten absorber	20-40 mm
Insulation space	5 mm
Heat intercept	1 mm
Insulation space	5 mm
Beam pipe	3 mm
Kapton insulation	0.5 mm
Clearance to coils	1 mm
Total magnet aperture	**118-158 mm (diameter)**

Estimation of steady-state heat loads

Sources of heat load

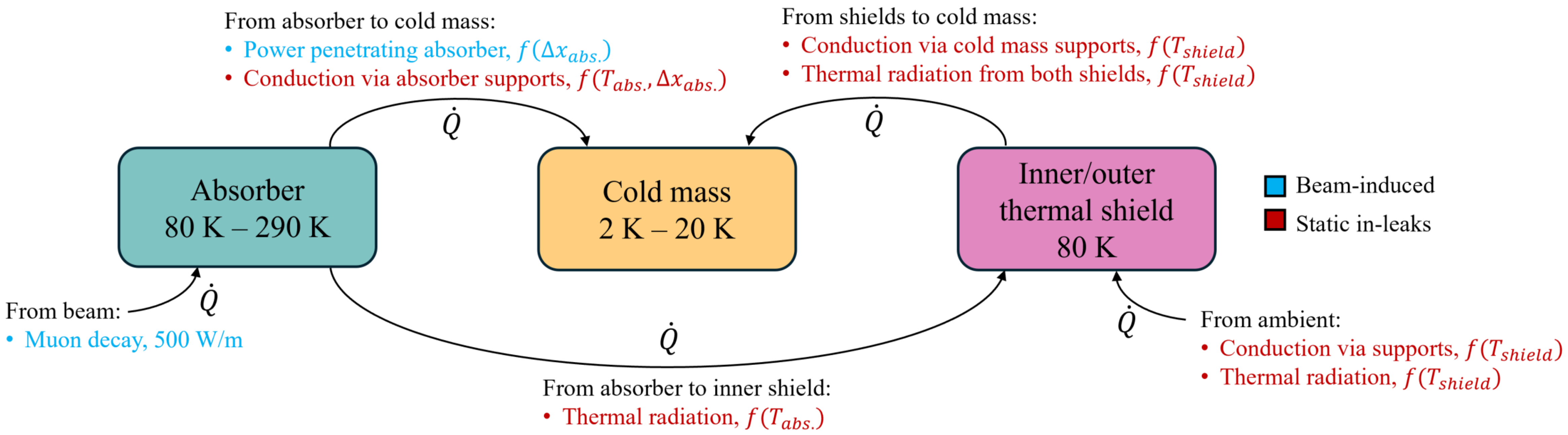
- Static heat in-leaks
- Resistive
- Beam-induced

… get deposited on…

- Cold Mass
- Inner and outer shields
- Absorber

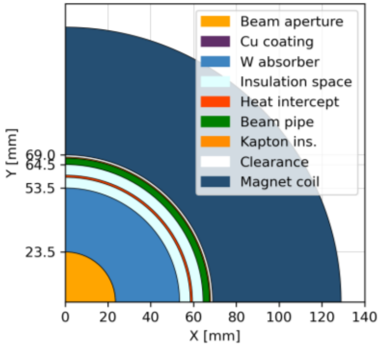
Temp. levels

Estimation of steady-state heat loads



Note: The "temperature" refers to the **nominal operating temperature at the cooling interface** (i.e. inlet fluid *T* inside a cooling pipe) → in reality it will be a **range both radially and longitudinally** (*i.e.* over a magnet and/or over a cell)

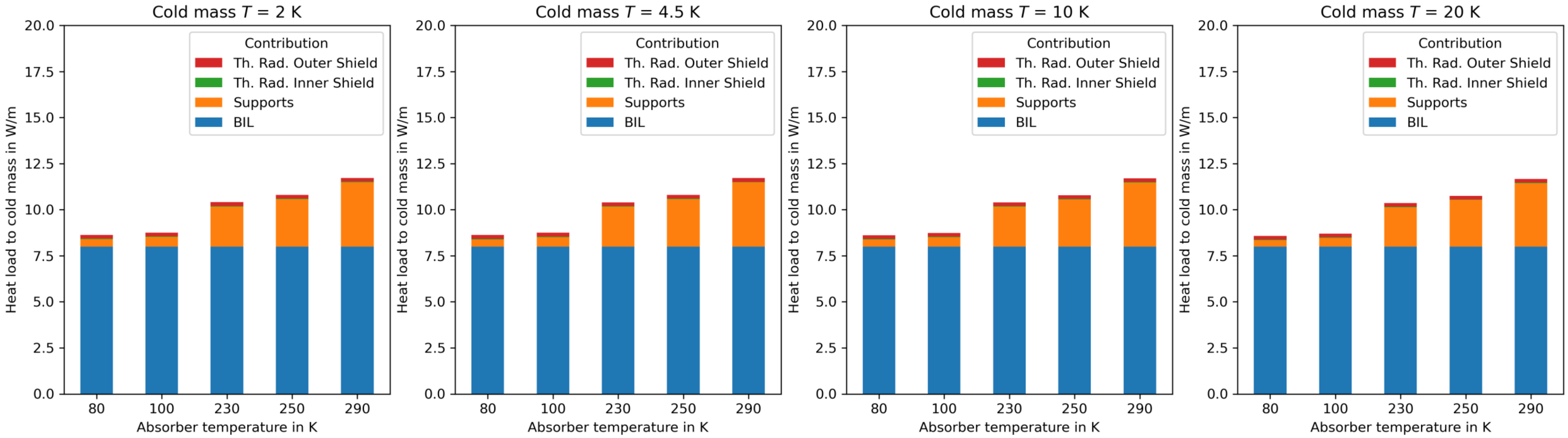
Heat load deposited on the cold mass



- Calculated for $\Delta x_{abs} = 30$ mm, $T_{abs} = [80{,}290]$ K, $T_{shields} = 80$ K
- Heat load on absorber = 500 W/m
- Heat load to shields at 80 K between 4 and 11 W/m

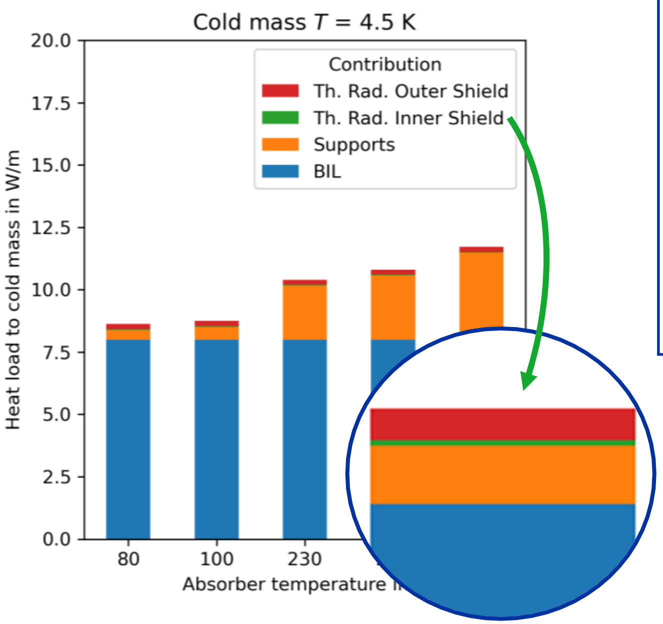
Heat load to the cold mass:
- ≈ 10 – 12 W/m
- ~ independent of T_{CM}

but effort to extract the heat will depend heavily on it!



Heat load on CM: effect of inner shield

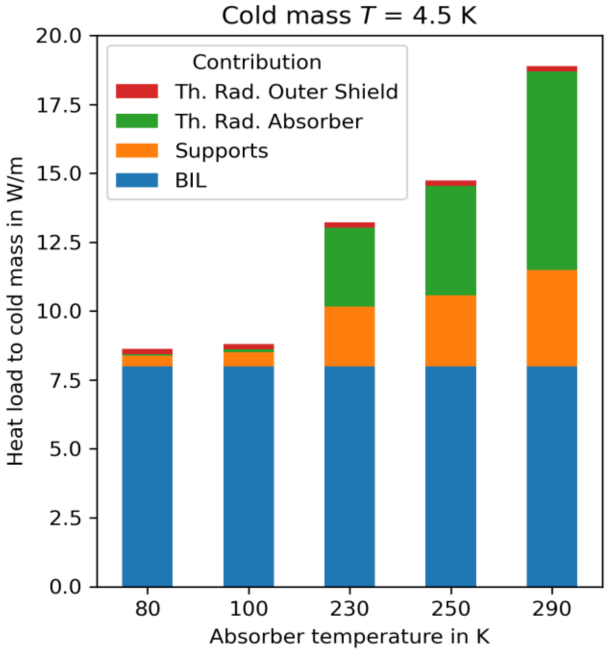
- One of the challenges of magnet design for the collider is **size of aperture**
- Why not suppress the inner thermal shield?

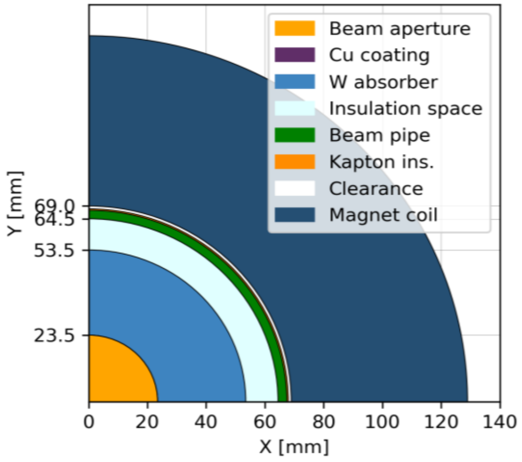


If no inner shield:

- $\dot{Q}$ from absorber to cold mass becomes comparable to BIL.
- Inner thermal shield between absorber and cold mass is compulsory.

For comparison: heat load to cold mass in the absence of an inner thermal shield (example T_{CM} = 4.5 K)





Power consumption budget for cryogenic infrastructure

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

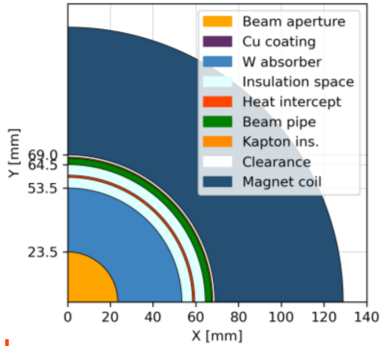
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300

- 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_{el} for the 10 TeV, 10 km machine ➡ 2.5 MW_{el}/km ➡ **2.5 kW_{el}/m**

We aim to stay at around 2.5 kW_{el}/m of collider (lower is better! ☺)

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

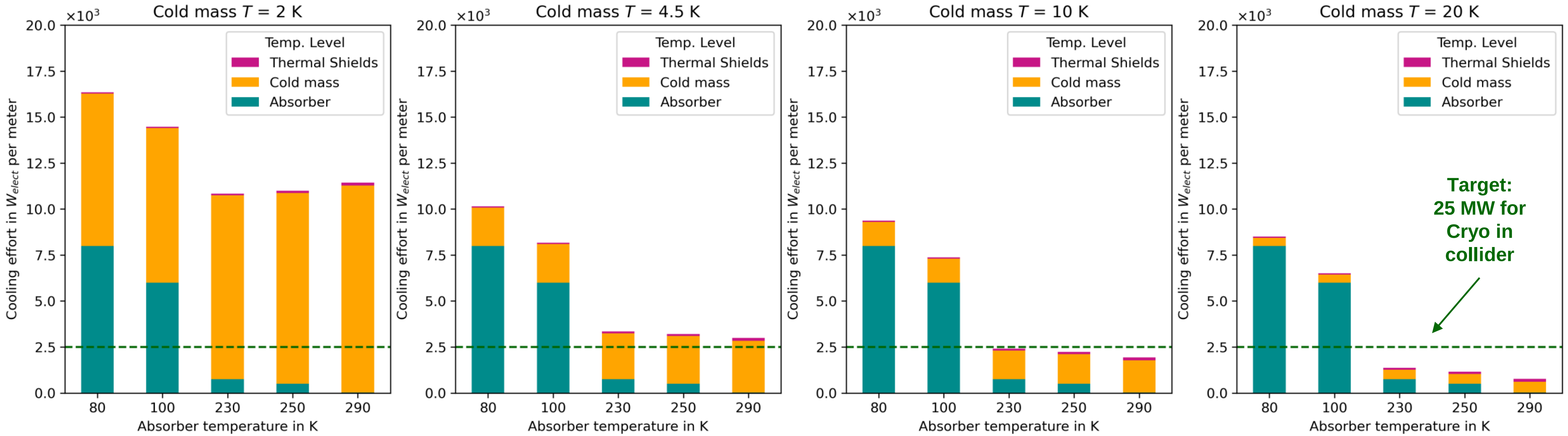
Power consumption at refrigerator I/F



- Calculated for $\Delta x_{abs} = 30$ mm, $T_{abs} = [80,290]$ K, $T_{shields} = 80$ K

To stay within "budget": $T_{CM} \geq 4.5$ K and $T_{abs} \geq 230$ K

< 100 K → LN_2
230 < T < 280 K: CO_2
> 280 K: H_2O



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.…)

Considerations for cooling options

Energy consumption
- Target for collider ring 25 MW electrical consumption
- Target ≥ 4.5 K coil T

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 $\dot{m}$ and Δp per cryoplant

Reduced complexity
- Minimise # jumpers (*i.e.* long arc cells), short interconnects
- Reduce # of temperature levels provided
- Function of the nature and T range of the fluid
- Reduced fluid content in cryostats

What fluid options to consider?

- **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

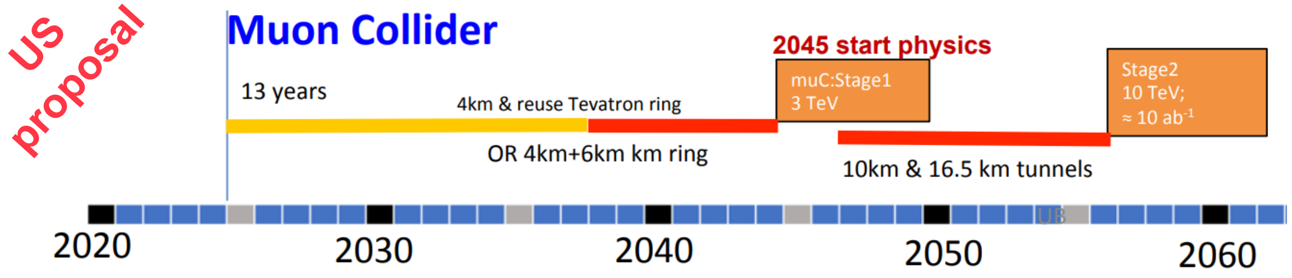
- Construction in ~15 years
- Magnetic fields within Nb_3Sn capabilities
- Nb_3Sn matured, usable
- Cooling at 4.5 K – 5.5 K using SC He
- Cooling at 4.5 K using He two-phase flow

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)

Conclusions and outlook

From this study, the following guidelines can be established for the collider magnets:

- Nominal temperature of absorber ≥ 250 K
- Heat load to cold mass ≤ 10-12 W/m, requires absorber ≥ 30 mm and thermal shield between CM and absorber
- Nominal temperature of cold mass ≥ 4.5 K
- Overall electrical power consumption of the cryogenic system for the collider ≤ 2.5 kW/m
- Cryogenic design based on forced flow along cooling channels (as opposed to immersion cooling) to reduce the overall amount of coolant

Next steps for the collider ring studies:

- Ramping losses need to be quantified → might become the driving factor for sizing the cryogenic system
- R&D to explore limits of two-phase flow and supercritical cooling using He and H_2 in confined geometries

Thank you for your attention!