Cryogenic options for the Muon Collider

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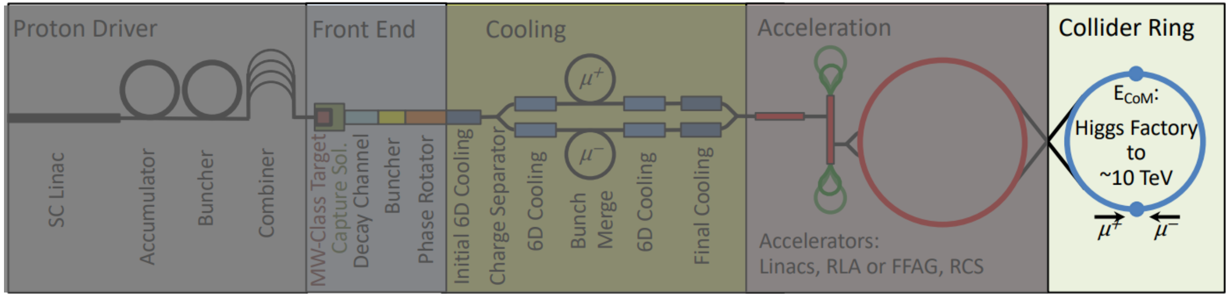
11-14 October 2022, CERN

Disclaimer !

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

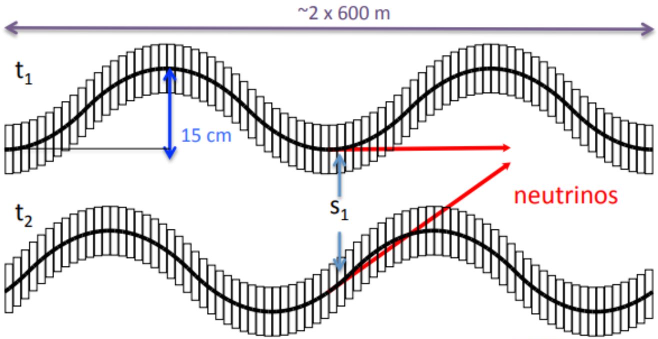
Source: MAP collaboration



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

A few key numbers for the collider ring

- **High field,** high gradient magnets with **large apertures**, **shielding** drives aperture
- **Beam losses O(500 W/m)** (1/3 beam energy)
- **Heat loads on magnet O(5-10 W/m), 1% total load (see talk A. Lechner)**
- **Short** dipole field-free gaps between magnets **O(0.2 m)**
- **Magnets mounted on movers** for beam deflection



Source: D. Schulte, Muon Collider Panel Seminar (Indico)

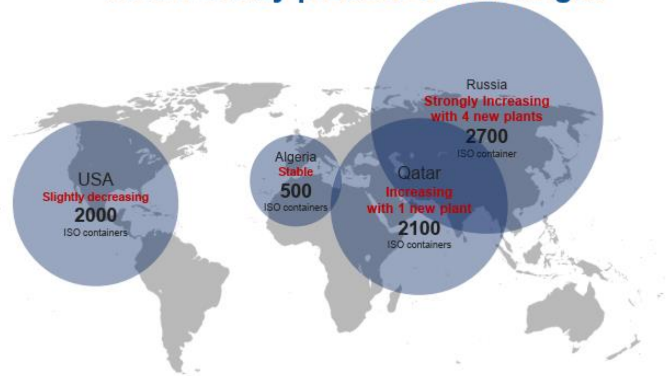
Why avoid the (LHC) cooling solution?

- 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**

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)

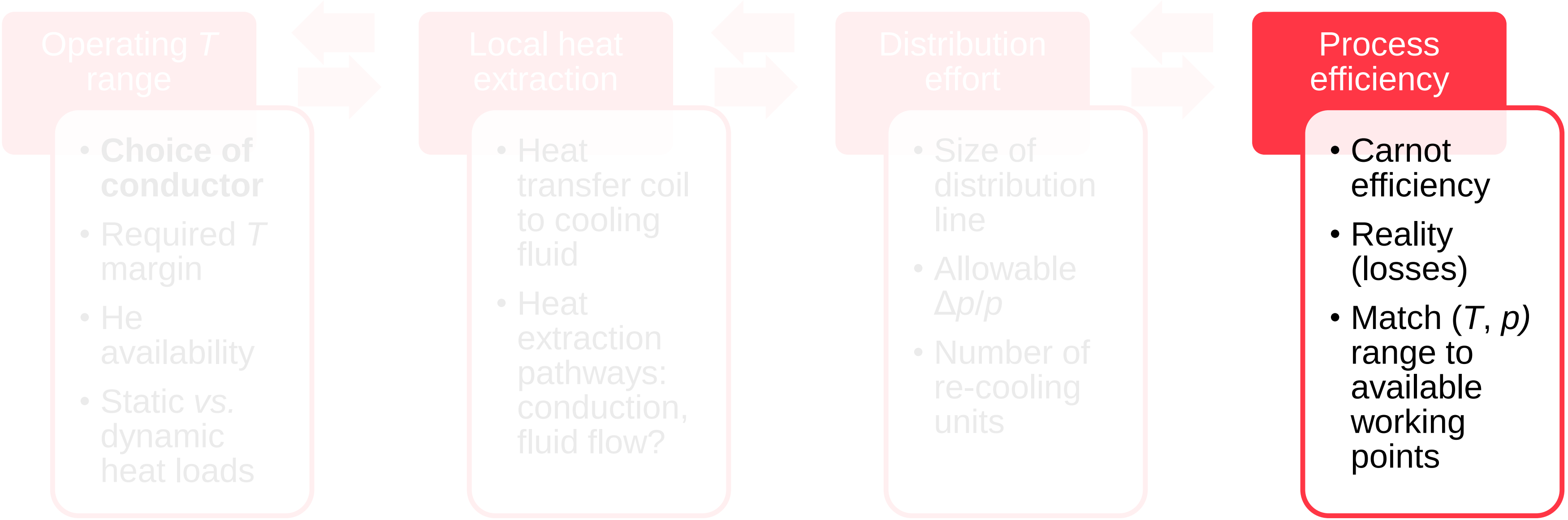
Helium is a **by-product of natural gas**



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)

Choice of cooling strategy



Operating *T* range

- **Choice of conductor**
- Required *T* margin
- He availability
- Static *vs.* dynamic heat loads

Local heat extraction

- Heat transfer coil to cooling fluid
- Heat extraction pathways: conduction, fluid flow?

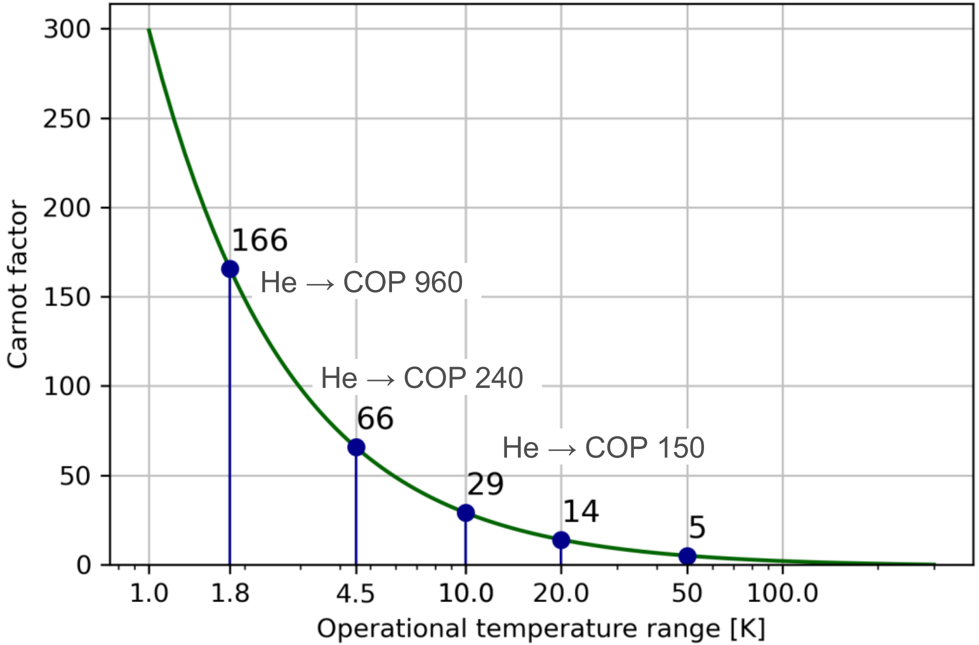
Distribution effort

- Size of distribution line
- Allowable $\Delta p/p$
- Number of re-cooling units

Process efficiency

- Carnot efficiency
- Reality (losses)
- Match (T, p) range to available working points

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%!)**

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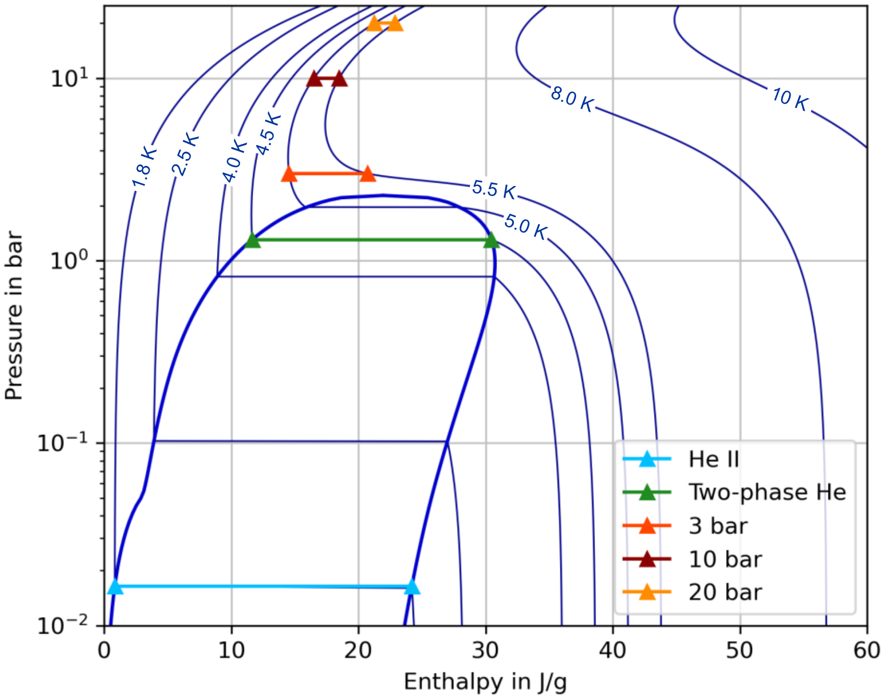
Cooling options below 10 K – LTS range



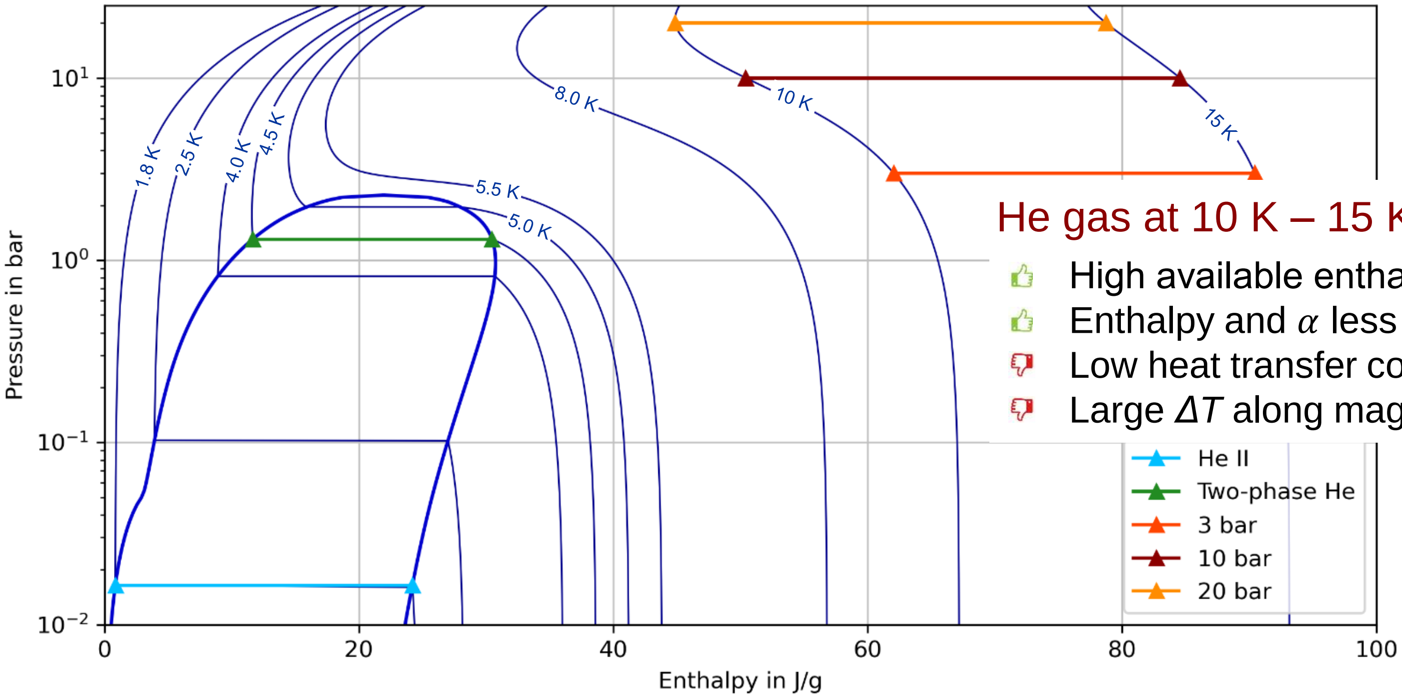
Two-phase He

- 👍 Temperature stability
- 👍 Highest heat transfer coefficient α
- 👍 Small ΔT if forced flow
- 👍 High available enthalpy diff. → low $\dot{m}$
- 👎 High relative pressure drop $\Delta p/p$
- 👎 High He content if bath cooling
- 👎 Forced flow → complex flow patterns

Supercritical He at 5 K – 5.5 K

- 👍 Single phase-flow advantages
- 👍 Lower $\Delta p/p$
- 👍 Some ΔT along magnet length
- 👍 Lower α than two-phase, pressure-dependent
- 👍 Lower available Δh, pressure-dependent

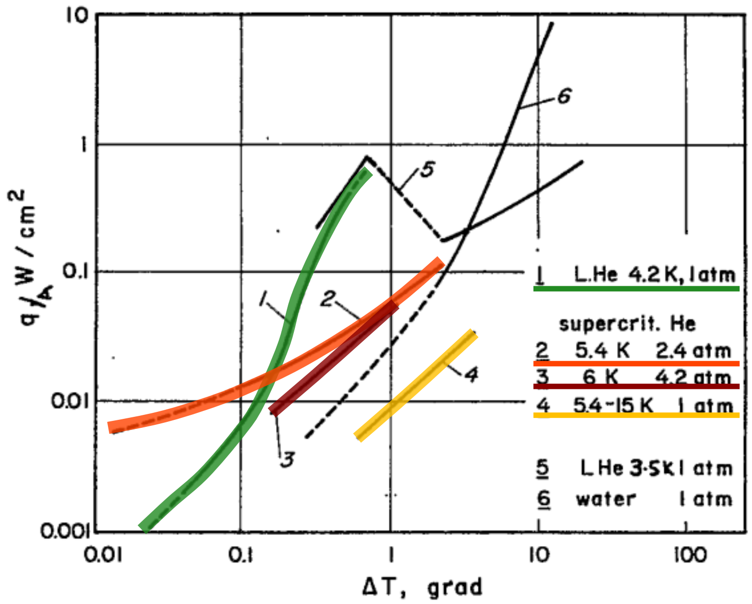
Cooling options above 10 K – (low) HTS range



He gas at 10 K – 15 K

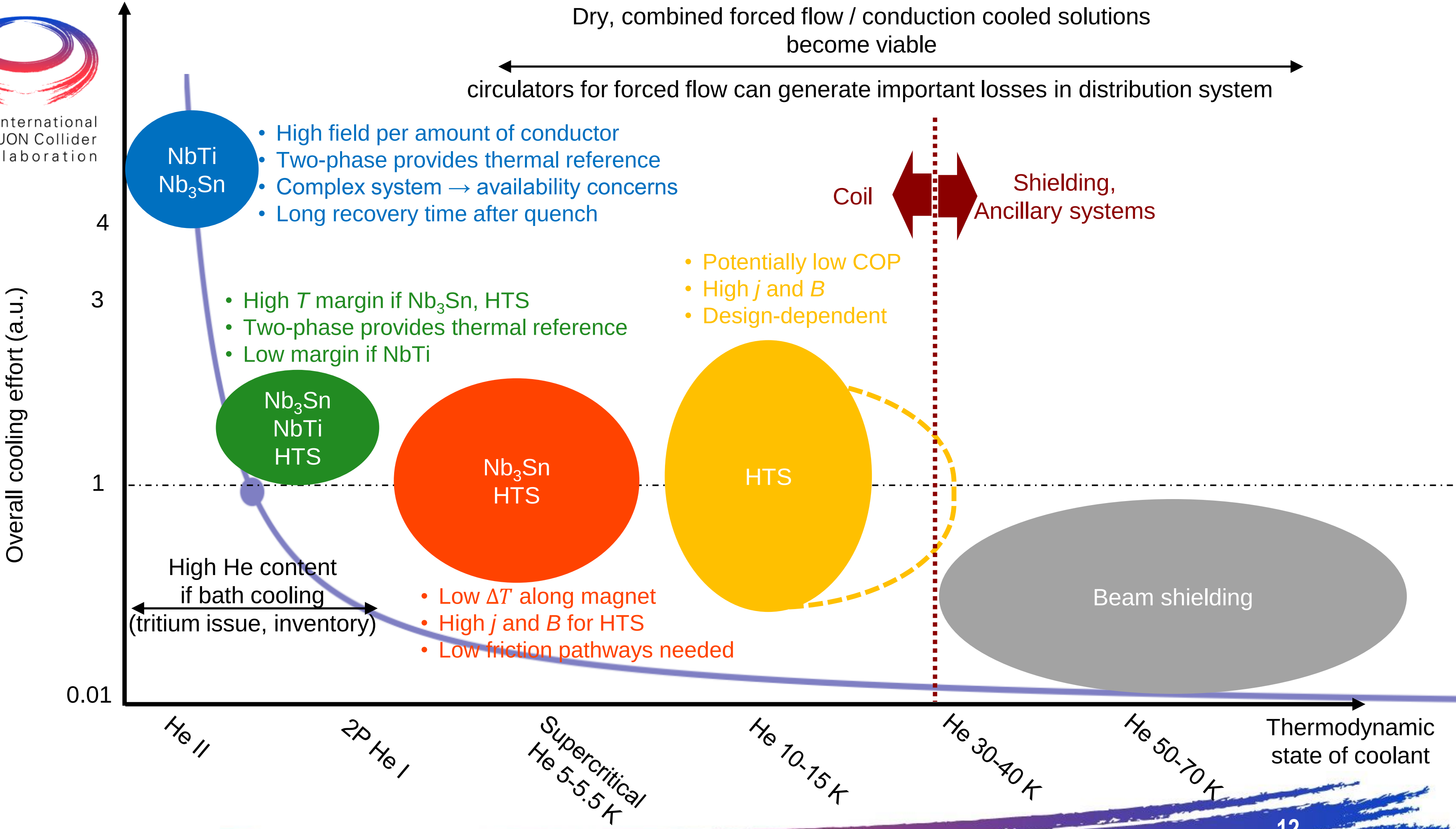
- 👍 High available enthalpy diff. → low $\dot{m}$
- 👍 Enthalpy and α less pressure-dependent
- 👎 Low heat transfer coefficient α
- 👎 Large ΔT along magnet length

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)



Dry, combined forced flow / conduction cooled solutions become viable

circulators for forced flow can generate important losses in distribution system

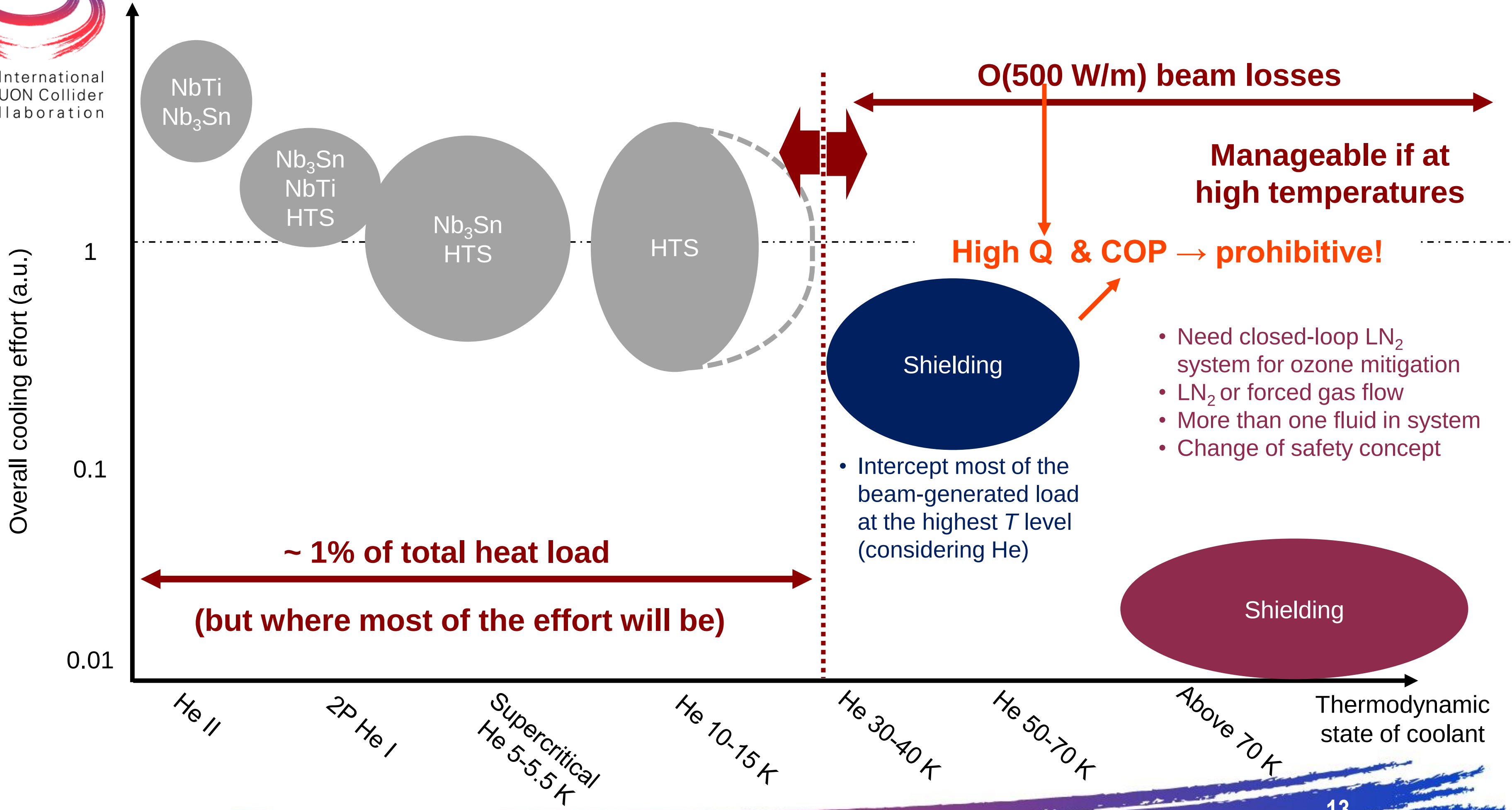
- High field per amount of conductor
- Two-phase provides thermal reference
- Complex system → availability concerns
- Long recovery time after quench

- High *T* margin if Nb$_3$Sn, HTS
- Two-phase provides thermal reference
- Low margin if NbTi

- Potentially low COP
- High *j* and *B*
- Design-dependent

High He content
if bath cooling
(tritium issue, inventory)

- Low Δ*T* along magnet
- High *j* and *B* for HTS
- Low friction pathways needed



O(500 W/m) beam losses

Manageable if at high temperatures

High Q & COP → prohibitive!

- Need closed-loop LN_2 system for ozone mitigation
- LN_2 or forced gas flow
- More than one fluid in system
- Change of safety concept

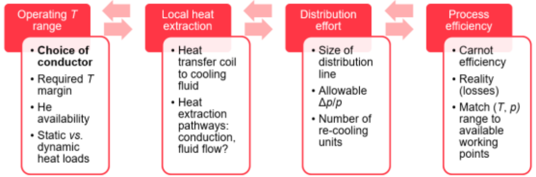
- Intercept most of the beam-generated load at the highest *T* level (considering He)

~ 1% of total heat load

(but where most of the effort will be)

Key takeaways (I)

- There is **no easy, straightforward answer** to the question “what is the most efficient cooling option for the muon collider magnets?”
- Solution will depend on choice of conductor, operating temperature, local heat extraction, distribution strategy and associated losses
- Carnot factor and COP should be taken as a potential improvement, but **a correct assessment can only be made after considering the whole process, distribution and local heat extraction chain at a certain temperature range**
- When opting for cooling solutions, esp. those that rely on forced flow, **magnet design with the cooling circuit in mind is crucial**



Operating T range
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Key takeaways (II)

- **For Nb_3Sn technology**, two-phase He circulating in channels close to the magnet or single-phase supercritical flow can be a solution minimising He content while keeping a reasonably small temperature gradient (**potential COP = 240 W/W**)
- **For HTS**, the same options can be considered, but temperature range can be extended to forced flow of He gas at temperatures up to 30 K; larger temperature gradients need to be accepted for the same heat extraction **(potential COP = 80 – 150 W/W**)
- **For components with extremely high heat loads such as beam shielding**, sustainability for high power and COP drives options starting at temperatures close to that of LN_2 (**potential COP < 10 W/W**)

Thank you
for your attention!

Source: Comics Kingdom (link)

Spare slides

Important questions that went unaddressed (I)

- “Nelium” as a possible refrigerant – might be a good idea to extract heat loads at higher temperatures
- Helium activation – reduce He content close to the cold mass as much as possible
- Very small interconnection regions, moving magnets ⟶ showstopper?
- He bubble ‘sinking’ due to high magnetic field gradients
- Beam screen heat loads 1/3 beam energy i.e. 500 W/m
- Absorbers and LH2 evaporation due to the beam are also a possible issue
- High losses from RF and ramping losses also to be addressed
- Target solenoid: can we work at 20 K instead of 4 K? Where is the optimum with temperature/heat load/bore?

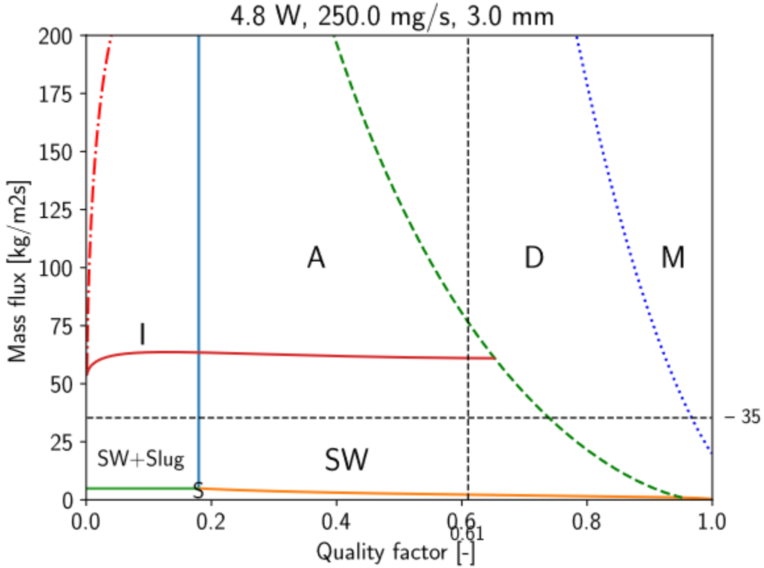
Important questions that went unaddressed (II)

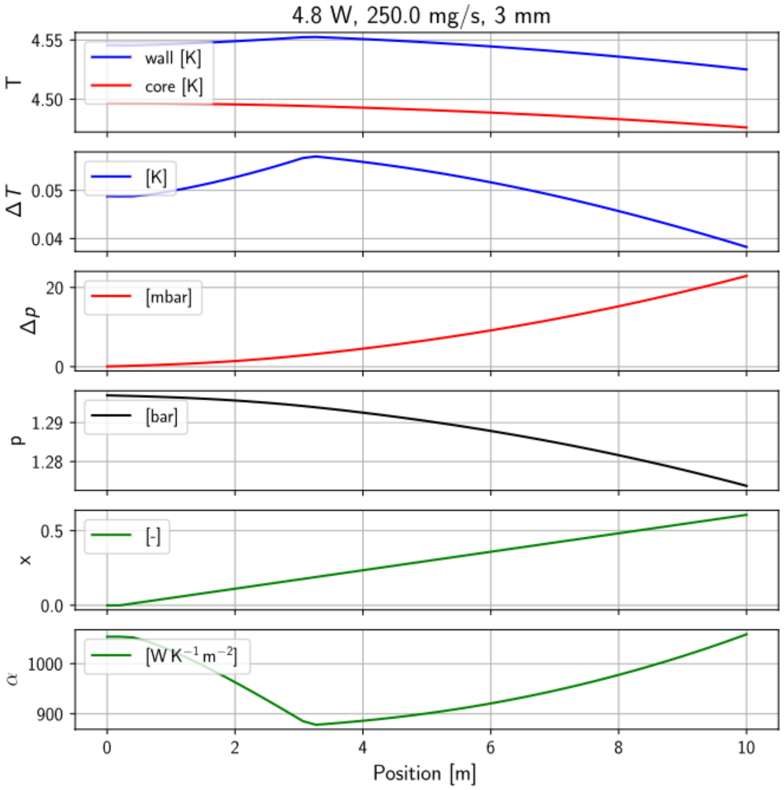
- Accelerator: accelerator ring is going to be SC magnets interleaved with NC magnets. This makes for warm-to-cold interconnections every 10 m or so, with an interconnect space of 50 cm or less. How to achieve this?
- Can we have the yoke outside/warm?
- Can we have completely warm beam screen/absorber?
- How does ortho-to-para hydrogen conversion behave in the presence of (high) magnetic fields?

Example two-phase He flow in channel

courtesy B. Naydenov, see (link)

Flow pattern map and key quantities of interest in simulated two-phase He flow in a channel. The temperature along the channel decreases, while pressure drop and vapour quality increase. Note the variation of the heat transfer coefficient α along the channel.

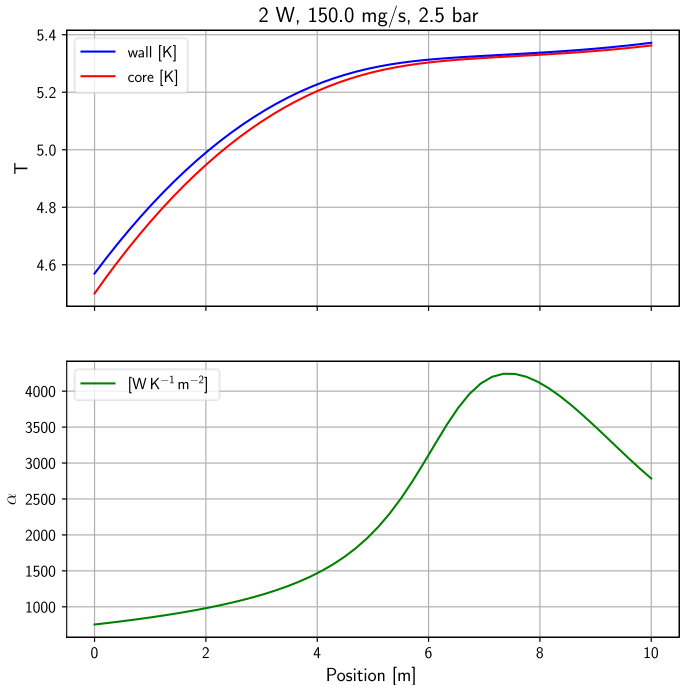


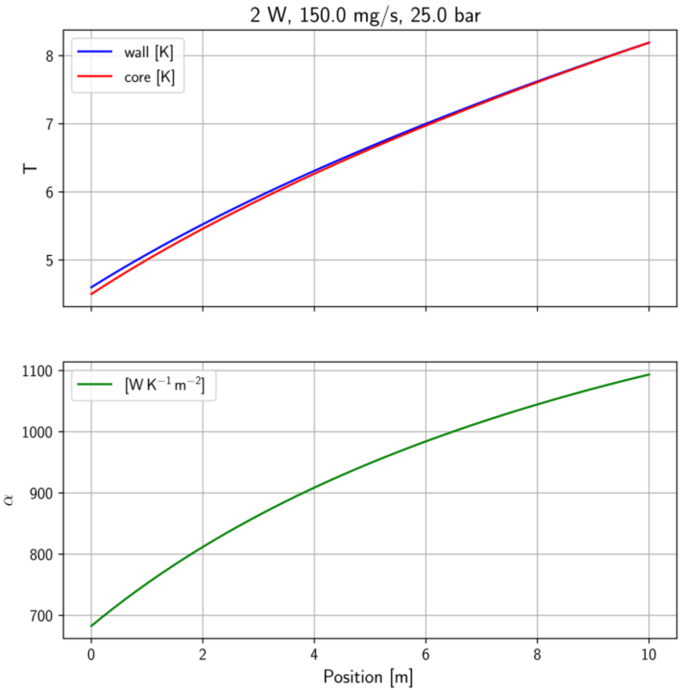


Example supercritical vs. gas flow in channel

courtesy B. Naydenov, see (link)

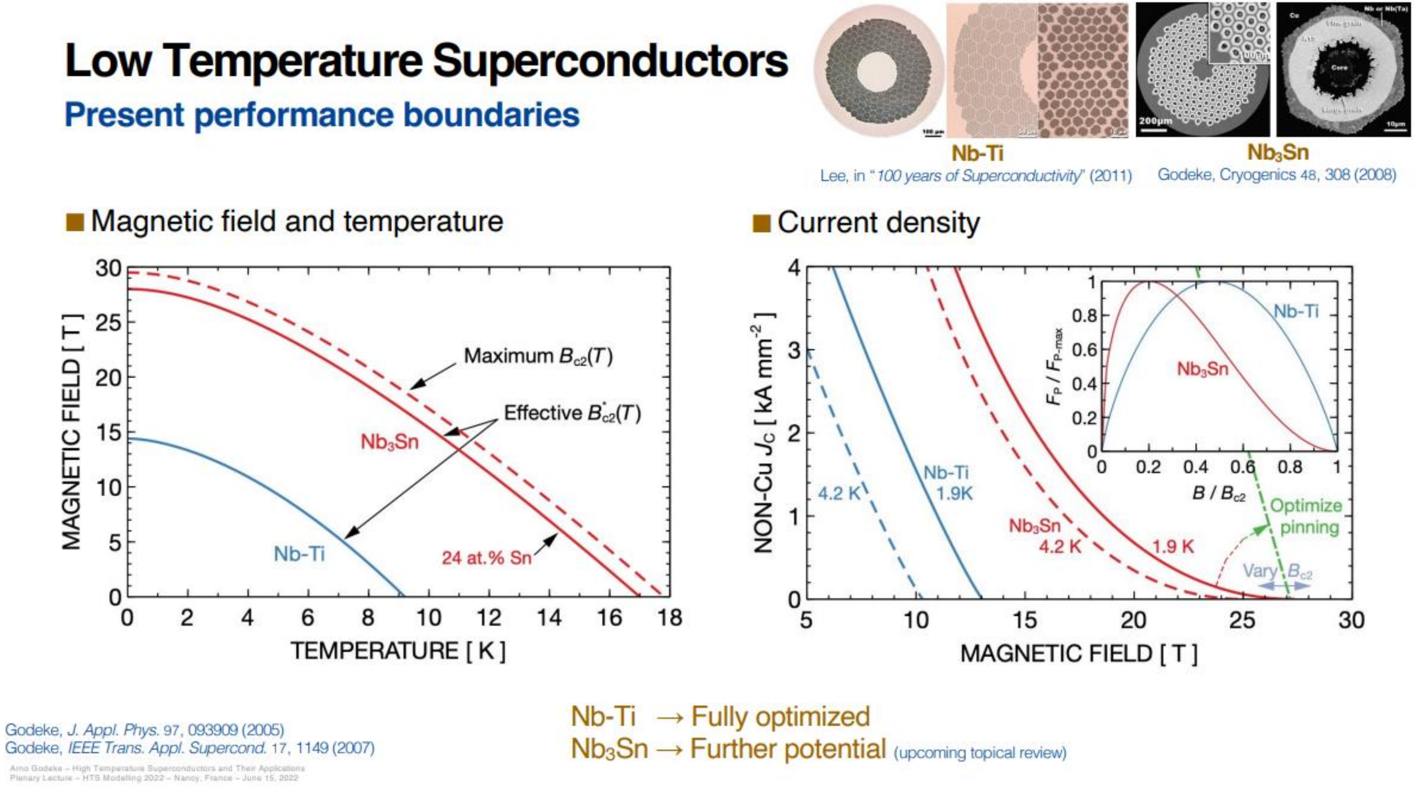
Temperature evolution and heat transfer coefficient α along a channel for simulated 2.5 bar and 25 bar forced He flow. Note the lower ΔT and higher α in the 2.5 bar (supercritical) case for same heat load and mass flow rate conditions.





LTS performance boundaries

from A. Godeke’s plenary lecture at HTS Modelling 2022 (link)



Low Temperature Superconductors

Present performance boundaries

Nb-Ti

Lee, in “*100 years of Superconductivity*” (2011)

Nb_3Sn

Godeke, Cryogenics 48, 308 (2008)

- Magnetic field and temperature
- Current density

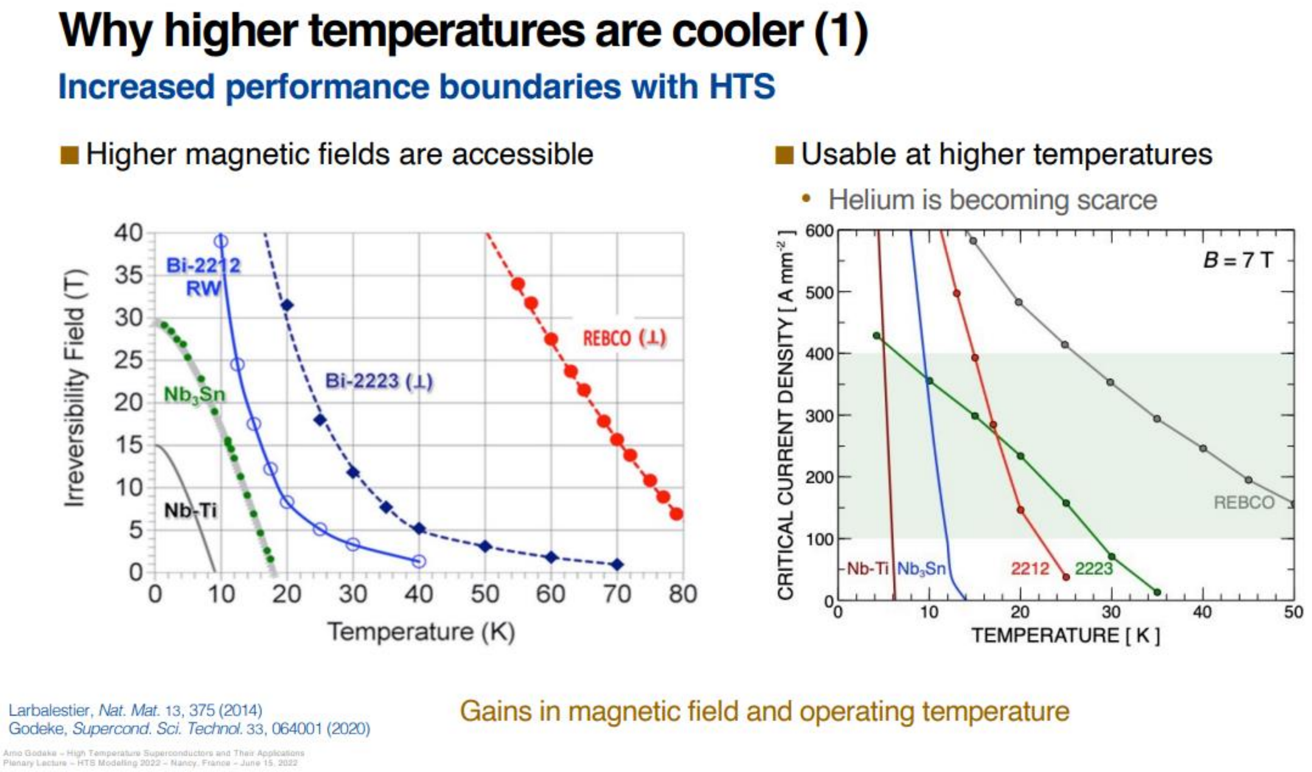
Godeke, *J. Appl. Phys.* 97, 093909 (2005)
Godeke, *IEEE Trans. Appl. Supercond.* 17, 1149 (2007)

Arno Godeke – High Temperature Superconductors and Their Applications
Plenary Lecture – HTS Modelling 2022 – Nancy, France – June 15, 2022

Nb-Ti → Fully optimized
Nb_3Sn → Further potential (upcoming topical review)

HTS performance boundaries

from A. Godeke's plenary lecture at HTS Modelling 2022 (link)



Why higher temperatures are cooler (1)

Increased performance boundaries with HTS

- Higher magnetic fields are accessible
- Usable at higher temperatures
  - Helium is becoming scarce

Larbalestier, *Nat. Mat.* 13, 375 (2014)
Godeke, *Supercond. Sci. Technol.* 33, 064001 (2020)

Gains in magnetic field and operating temperature

Arno Godeke – High Temperature Superconductors and Their Applications
Plenary Lecture – HTS Modelling 2022 – Nancy, France – June 15, 2022