Cryogenic considerations for cooling SC links and application to the High-Luminosity LHC

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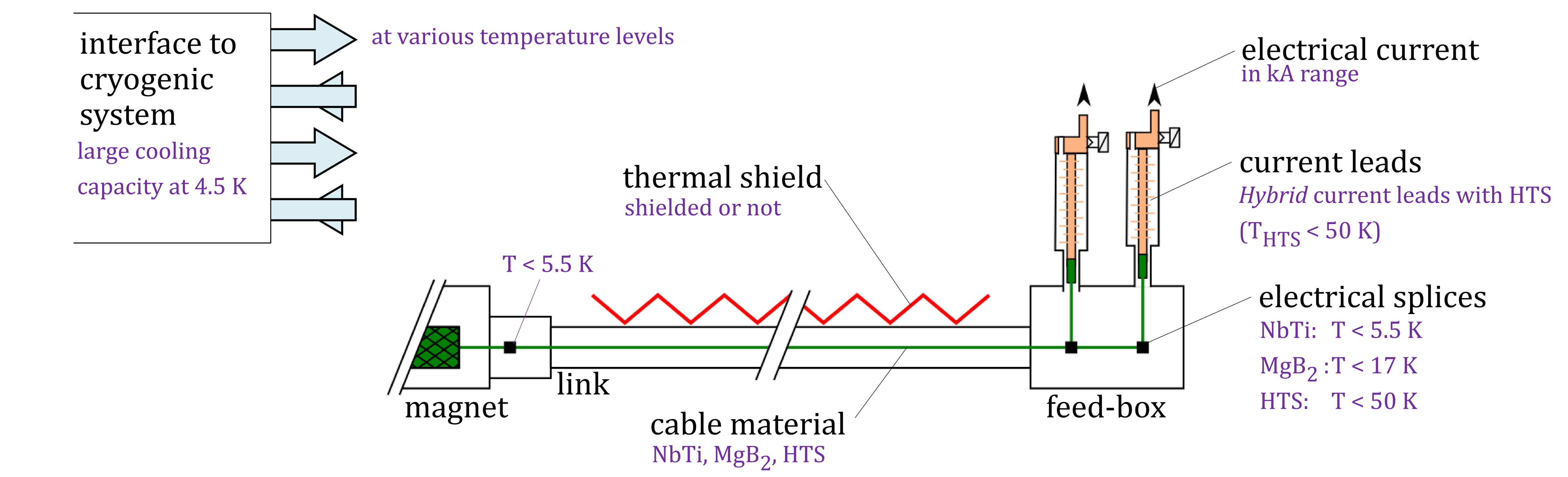
Introduction

- Superconducting (SC) magnets in particle accelerators can be powered remotely through SC links.
  - Overcomes limitations in space and radiation;
  - Allows installation in more favourable areas.
- The LHC has 5 SC links (4x 76 m and 1x 517 m), and new 100 m links are planned for the HL-LHC.
- When defining the cooling of a SC link, it is essential to integrate the link in the cryogenic infrastructure of the facility:
  - First, identifying the main driving parameters defining the cooling of the SC link.
  - Then, assessing their impact on the cryogenic infrastructure in terms of cooling power and economic significance.
- This poster presents:
  - An overview of some main cryogenic considerations.
  - Introduction to the cooling regimes of a SC link.
  - A parametric study, with focus on cooling schemes applicable for the HL-LHC.

Frame of this study:

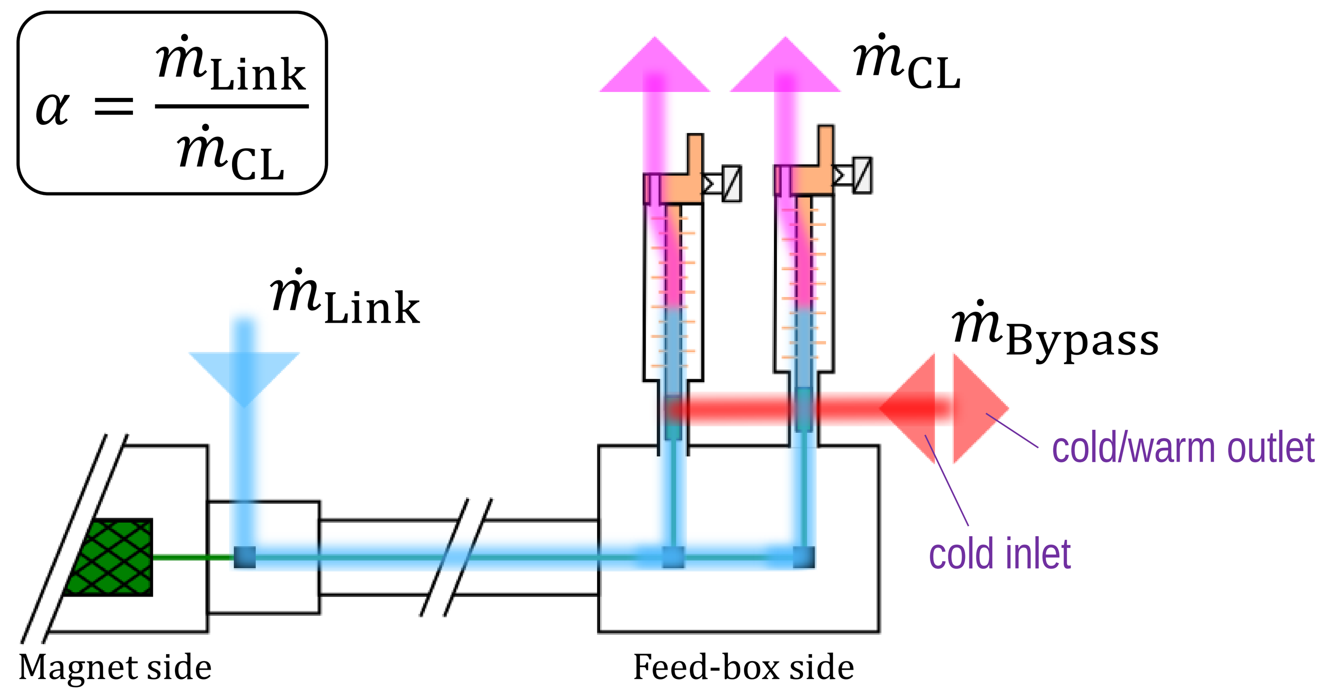
- For accelerator magnets (currents in kA; LTS <5K).
- Presence of a large cryogenic system.
- Magnet-to-Link splices with T<5.5 K.
- Considers only *hybrid* current Leads (with HTS).
- Not treated: fabrication technologies; physical or mechanical properties of SC cables.

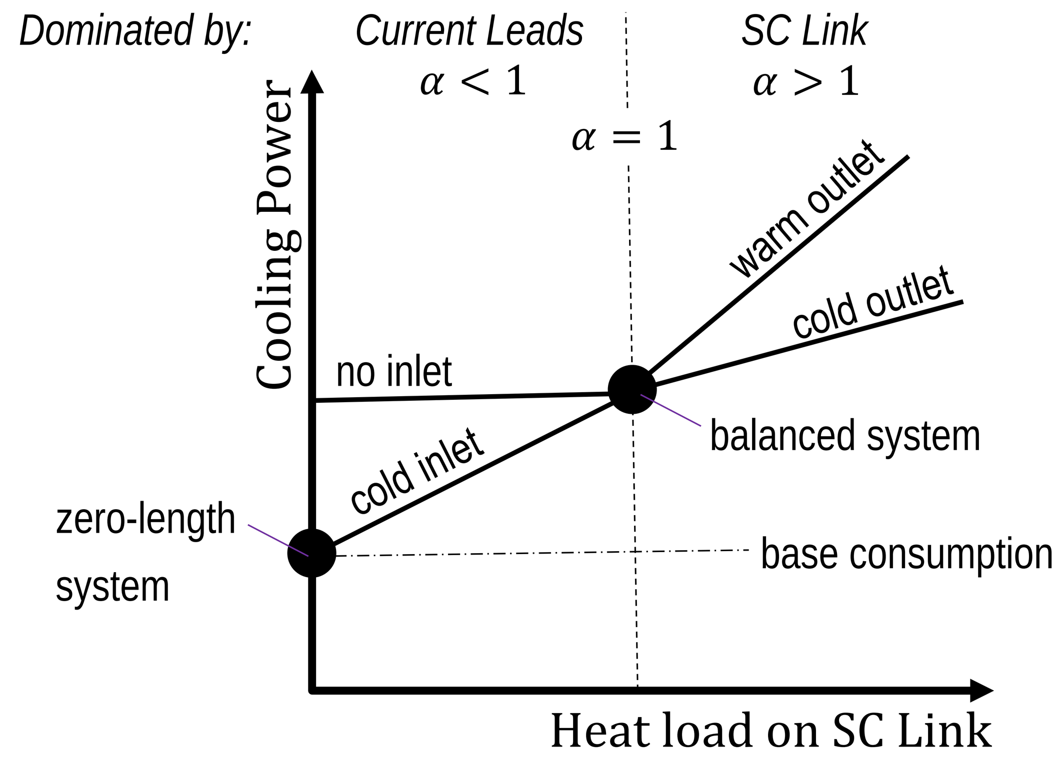
Main Considerations and Choices



Cooling Regimes

$$\alpha = \frac{\dot{m}_{\mathrm{Link}}}{\dot{m}_{\mathrm{CL}}}$$





Cooling Interfaces

Consumption of cooling circuits in terms of *equivalent cooling power at 4.5 K* for 1 g/s:

Inlet header: C	D	E_H	F_H	Outlet header
-	-	-	-	C
59	-	-	-	D
-	-	-	-	E_H
-	-	9	-	F_H
103	44	57	49	WRL

Suitable for NbTi, MgB_2

Suitable for HTS, Thermal Shield

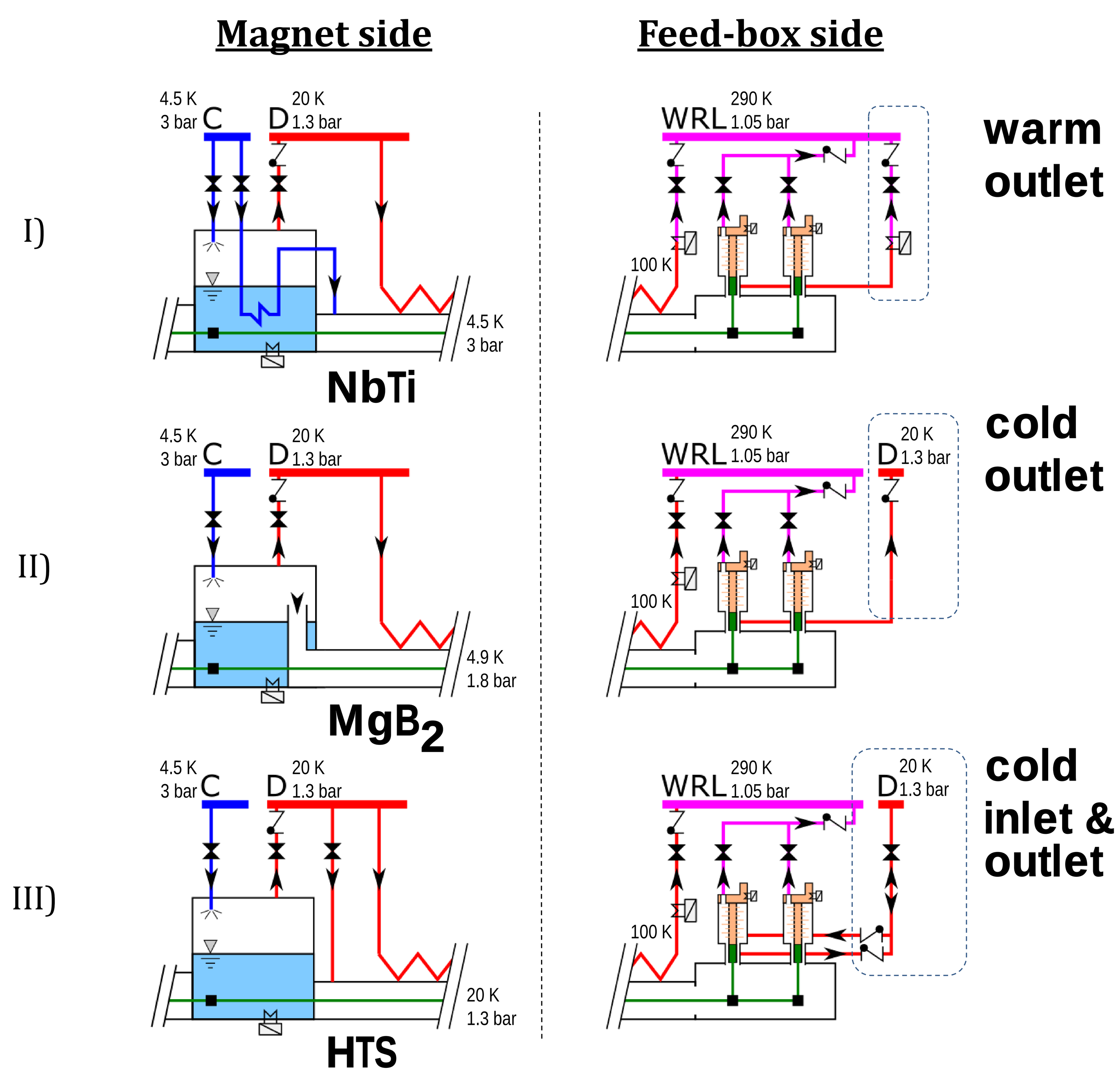
HELIUM PROPERTIES

Header	T [K]	p [bar]
C	4.5	3.0
D	20	1.3
~~E_H~~	~~40~~	~~24~~
~~F_H~~	~~60~~	~~23~~
WRL	290	1.05

Discarded due to $p_{max} < 5$ bar.

SC Material and Flow Scheme Configuration (Parametric Study)

Flow scheme matrix



Investigated parameter space

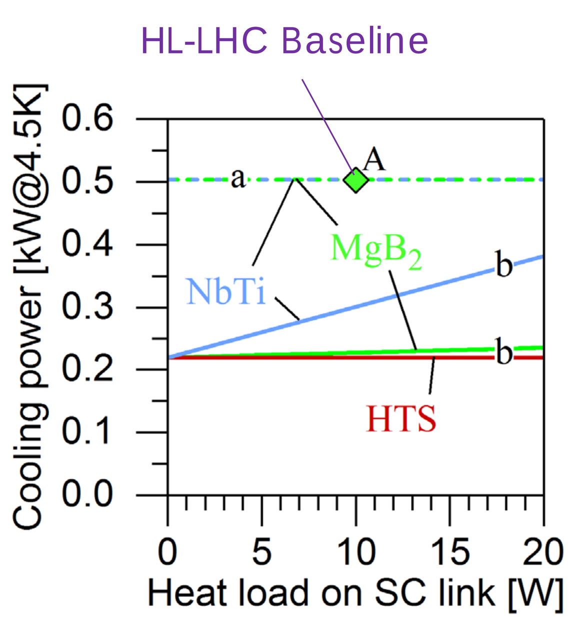
- Cable material (Magnet-side configuration): **NbTi, MgB2, HTS;**
- Current-lead flow: **2.5, 5.0, 7.5 g/s;**
- Heat load on SC link (incl. splices): **0 - 1000 W;**
- Bypass line (Feed-box side configuration): **warm outlet, cold outlet, cold inlet / outlet;**
- SC link with **thermal shield** or without thermal shield.

Chosen helium properties at the Inlet/Outlet of the superconducting link.

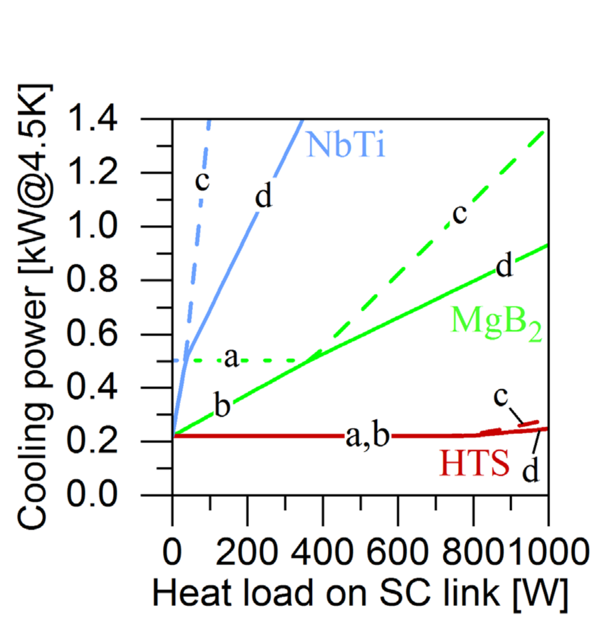
	Cable material	NbTi	MgB2	HTS
Inlet	Temperature [K]	4.5	4.9	20.0
	Pressure [bar]	3.0	1.8	1.3
Outlet	Temperature [K]	4.9	17.0	50.0
	Pressure [bar]	1.8	~1.8	~1.3

Required Cooling Power

Low-Load Link:



High-Load Link:



For unshielded link with $\dot{m}_{\mathrm{CL}} = 5$ g/s. Shield consumption is 0.11 W@4.5K per Watt on the shield.
A: HL-LHC project baseline; a: no inlet; b: cold inlet; c: warm outlet; d: cold outlet.

HL-LHC

- Project baseline: MgB_2 cable; 100 m long; $\dot{m}_{\mathrm{CL}} = 5$ g/s and warm outlet only.
- Recent changes resulted in the re-allocation of the electrical feed-boxes to areas with cryogenic interfaces → inlet/outlet solution is now possible.

Economical Implications

HL-LHC

- Adding a cold inlet gas supply saves 330 kCHF per link with respect to the baseline configuration.

Evaluation for link variants for the HL-LHC with cold input/output bypass and $\dot{m}_{\mathrm{CL}} = 5$ g/s.

	Cable material	NbTi	MgB_2	HTS
Cooling power [$W_{@4.5K}$]	Shielded	355	283*	275
	Unshielded	1838	594	220
Cryogenic Cost [kCHF]	Shielded	533	425*	413
	Unshielded	2757	891	330

* HL-LHC baseline (with warm bypass only): 503 W@4.5K and 755 kCHF.

Cryogenic Cost = Operational + Capital = 1.5 kCHF/W@4.5K

Operational cost ~ 1.0 MCHF for 10 years:

- Refers to electrical consumption.
- Electricity = 60 CHF/MWh; COP = 250 W/W; time = 65 000 h.

Capital cost ~ 0.5 MCHF:

- Price <u>adjustment</u> for a new plant of 18 kW@4.5K.

Conclusion

- The cooling is driven by the current-leads flow **or** by the links flow.
  - This impacts the cooling scheme efficiency.
- For **low-load links** with $\alpha < 1$:
  - Cold inlet bypass has more impact than the choice of SC material.
- For **high-load links**:
  - Significant gain by using a cold inlet/outlet bypass line.
- For **NbTi, MgB_2, HTS**:
  - NbTi requires a low-load link.
  - MgB2 & HTS, open the possibility of links with higher heat loads (unshielded!).
- A SC link is an integral part of a larger infrastructure.
  - Its design has economic implications at the refrigerator level.
  - Technological choices shall be assessed against their impact on the entire system.