Cooling for superconducting cables

Clean Hydrogen Technologies – Linde Technology
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Juni 2021

Making our world more productive

Gliederung

1. Motivation for superconducting cables
2. Overall Set-up
3. Cold distribution system
4. Refrigeration:
   - liquid nitrogen - based system (open cycle system)
   - refrigerator-based systems (closed cycle systems)
     - Stirling type
     - reversed Brayton type
5. Summary

Research
Focus: Physics, material science and phenomena

→

Development
Focus: Feasibility, demonstration

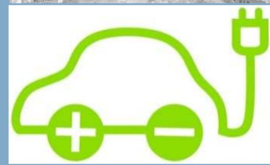
→

Commercialization
Focus: technoeconomics, operation model, reliability/availability

Weitere Urbanisierung verstärkt den Bedarf für innovative technische Lösungen in Stromübertragung und Verteilung

Haupttreiber:

- ➢ Verdichtung von Städten → steigende Stromversorgungsdichte
- ➢ Elektrifizierung
  - E-mobility
  - Transport (Bahn etc.)
  - Klimatisierung
  - Infrastruktur für digitale Dienste
- ➢ Wachsender individuelle Stromverbrauch
- ➢ Natürliche Alterung der bestehenden Strom-Infrastruktur



Räumliche Limitationen und Begrenzungen für städtische Infrastruktur

Wachsender Strombedarf, hohe Anforderungen an Qualität der Stromversorgung, sowie Umweltaspekte

Hoher Bedarf für innovative Stromübertragungs- und Verteilungskonzepte wie das HTSL Kabel

Lösung:

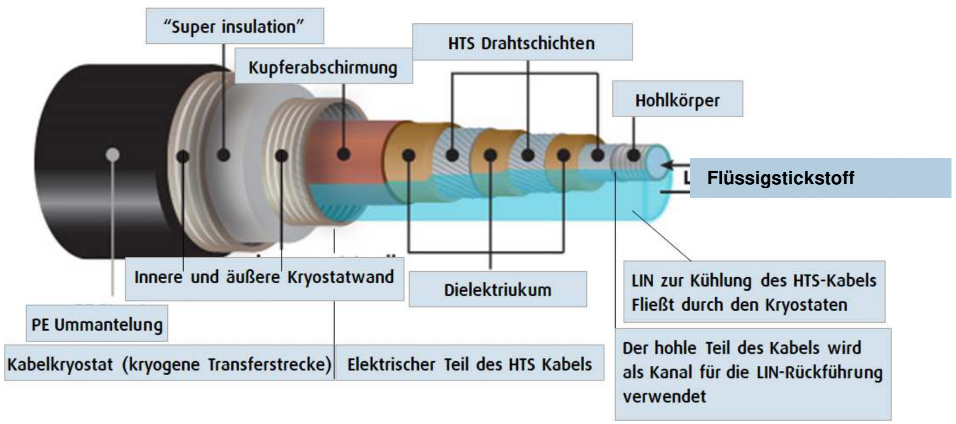
- Supraleitendes Kabel gekühlt @ 65-80 K

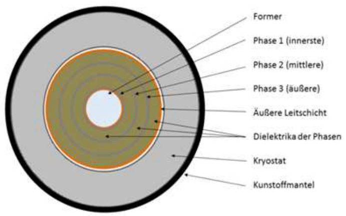
Vorteile:

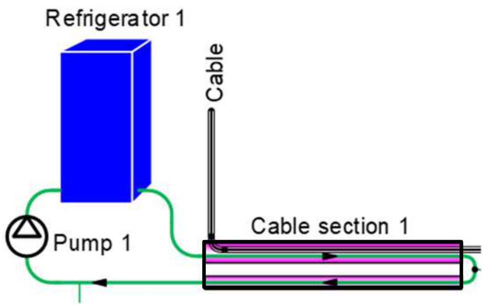
- Keine thermische Emissionen
- geringe elektro-magnetische Emissionen
- So gut wie unsichtbares Kabel
- Öffentliche Akzeptanz

Kabelsystem-Konstruktion
typische Optionen

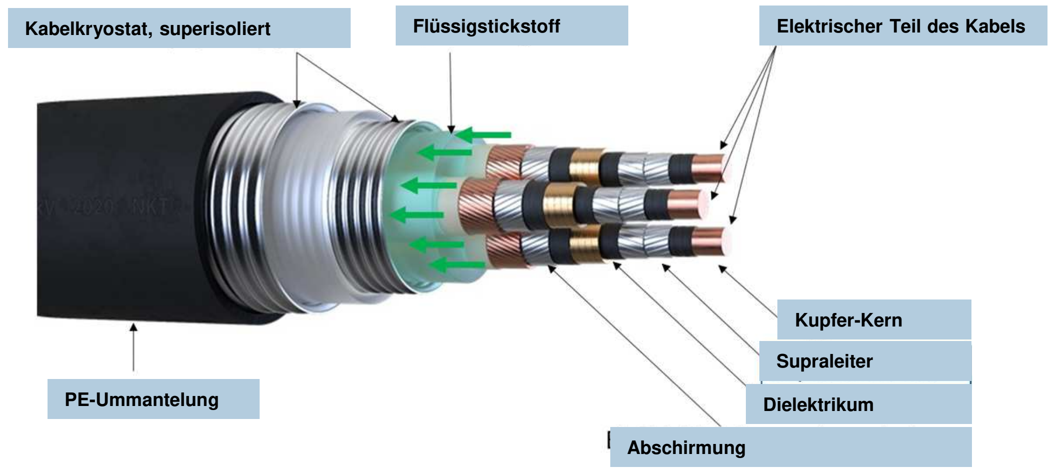
Triax-Design

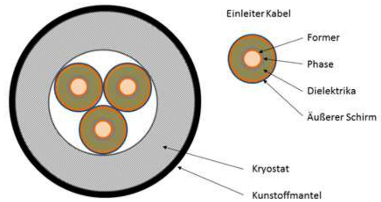


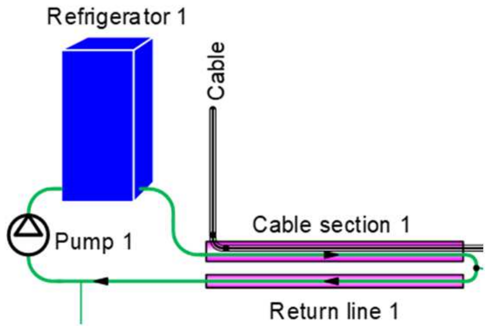




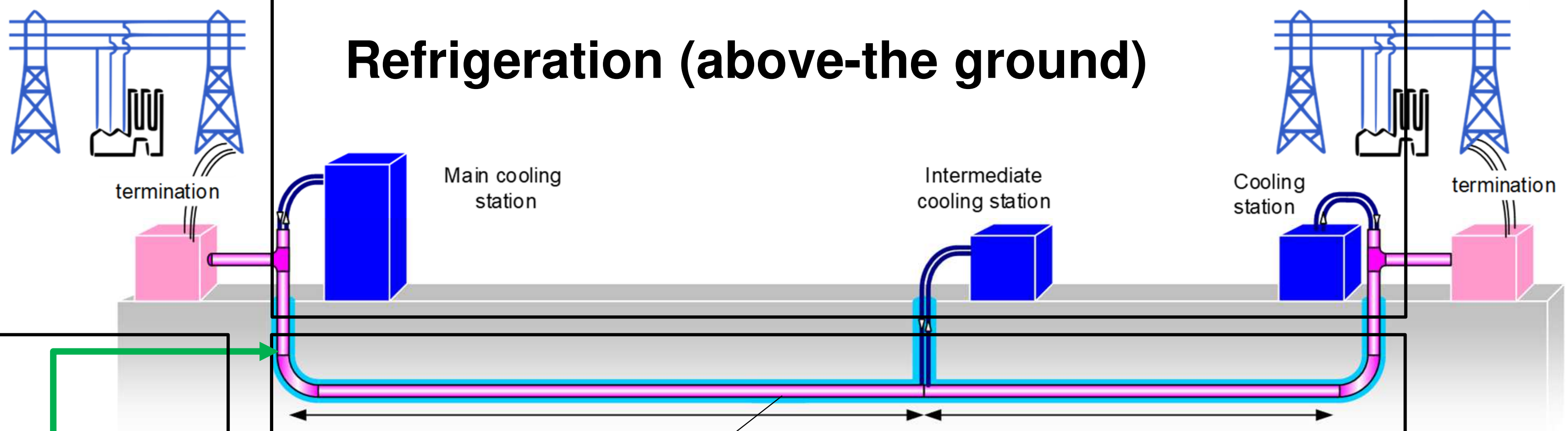
„3-in-1"-Design







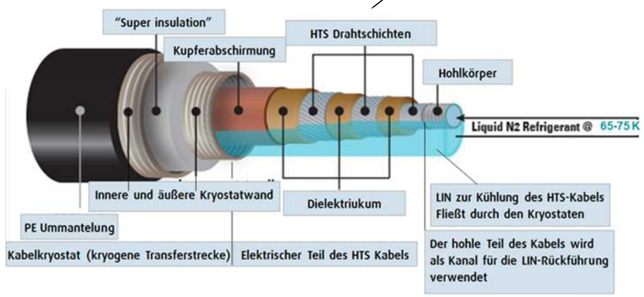
Distributed Cooling system
Principle



LIN-supply

Liquid nitrogen supply for make-up, cool-down and cooling purposes

Cold distribution system



Cable Assembly

Closed liquid nitrogen cycle:

- Liquid nitrogen (LIN) is pumped to high pressure (15 bar) and cooled to 65 K by means of a refrigerator
- LIN flows through the cable, adsorbs the heat from the cable and becomes warmer

Cold distribution system
potential options

Cold distribution system

- Concepts without return line
  - Closed loop-cable (Ringleitung)
  - batch operation (Pendelleitung)
  - Return without return line, for example per trucks
  - No return, LIN is utilized at the far end of the cable
- Concepts with return line
  - separate return line → CAPEX: higher; max feasible cable length: longer
  - Integrated return line (counter-current flow) → CAPEX: lower; max feasible cable length: shorter

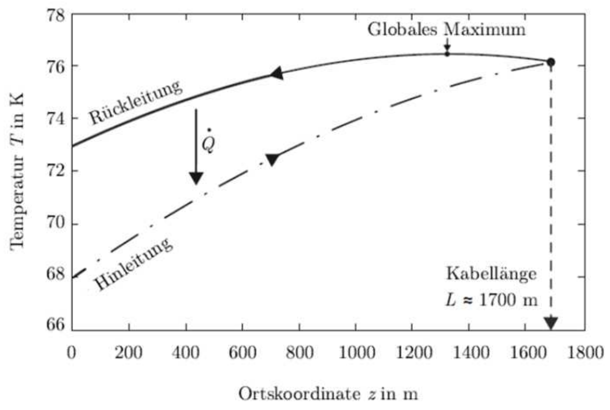
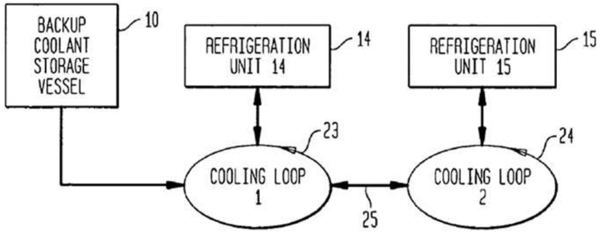


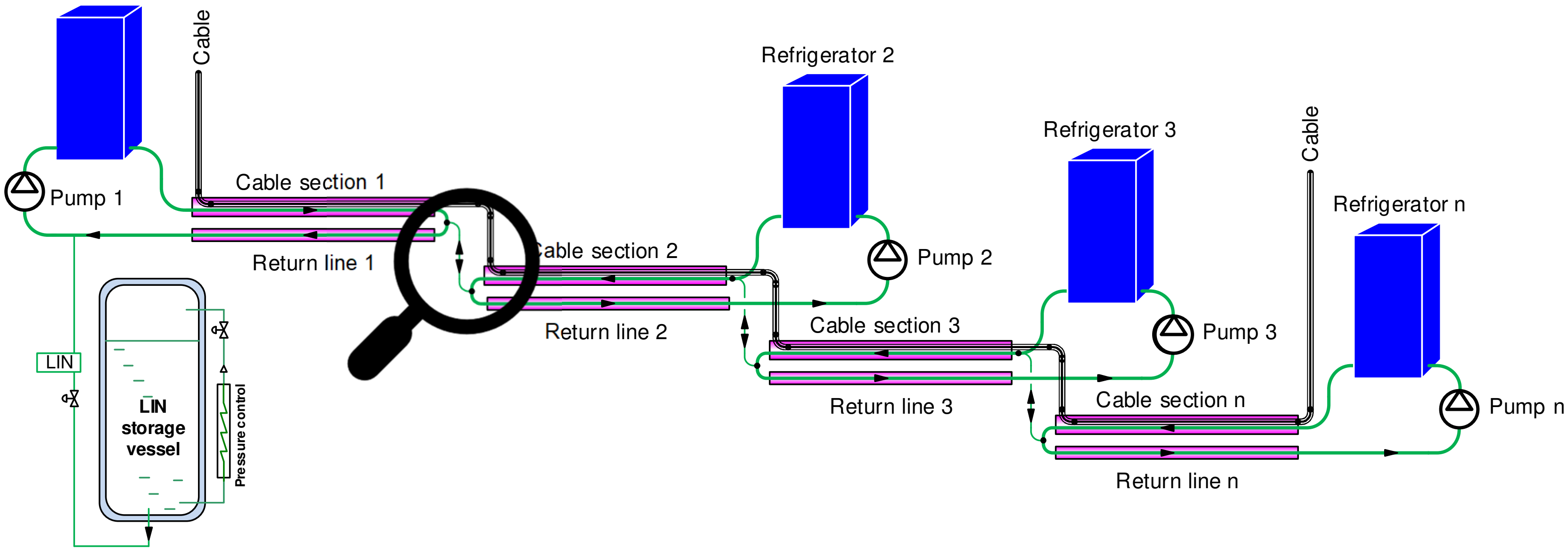
Abbildung 4.3: Axiales Temperaturprofil in Hin- und Rückleitung eines *koaxialen* HTS-Kabelsystems mit integrierter Rückleitung nach SHABAGIN ET AL. 2017.

An example of
cold distribution system



Two special features:

- **n** loops containing "cable section" and "return line" per loop
- all loops are connected by means of an interconnecting line



Ron Lee,
Backup Cryogenic
Refrigeration System
US 7,263,845 B2

mind. 10 erfolgreiche Demonstrationsprojekte weltweit
Technische Machbarkeit bestätigt, Schwachstelle: Kosten

4 Beispiele

Albany USA
Kryotechnik: BOC/Linde
Kabellänge: 350 m
Kapazität: 48 MVA AC (34.5 kV, 0.8kA), Betrieb : **2006 - 2009**

LIPA1&2 Long Island, NY
Kryotechnik : Air Liquide
Kabellänge : 600 m
Kapazität : 574MVA AC (138kV, 2.4kA), Betrieb: **seit 2008**

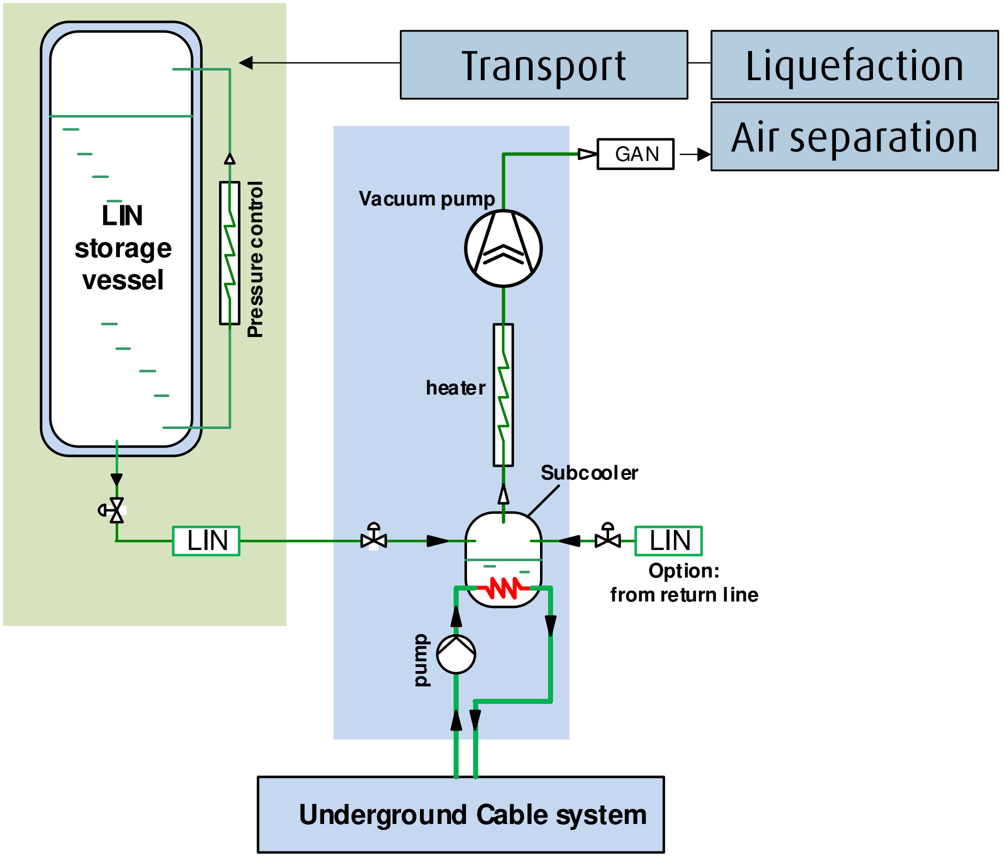
Ampacity Essen, Germany
Kryotechnik: Messer
Kabellänge : 1,000 m
Kapazität : 40MVA AC (10kV, 2.3kA)
Betrieb: seit **2014**

Bixby, Columbus, OH
Kryotechnik: Praxair, Kabel: NKT
Kabellänge : 200 m
Kapazität : 69MVA AC (13.2kV)
Betrieb: **2006 - 2012**

MACHBARKEIT BESTÄTIGT, KOSTEN NOCH NICHT WETTBEWERBSFÄHIG

Weitere Entwicklung und Systemoptimierung sind erforderlich

Benchmark
Open cycle system



Pro:

- Reliable
- moderate efficiency (comment below)
- Low initial capital investment, therefore preferred for projects with limited duration
- Clear business/operation model

Contra:

- Low potential for improvement

References:

- Albany, Ampacity etc.

Efficiency:

- best case (cooling water temperature 27°C, nitrogen liquefier efficiency 40%, pressure in LIN storage vessel 1 bar) : P/Q_0 = **13.3**
- Realistic case (cooling water temperature 27°C, nitrogen liquefier efficiency 38%, pressure in LIN storage vessel 5 bar) : P/Q_0 = **15.8**

(transport and corresponding power is not considered
air separation and corresponding power is not considered)

Benchmark
Stirling refrigerator

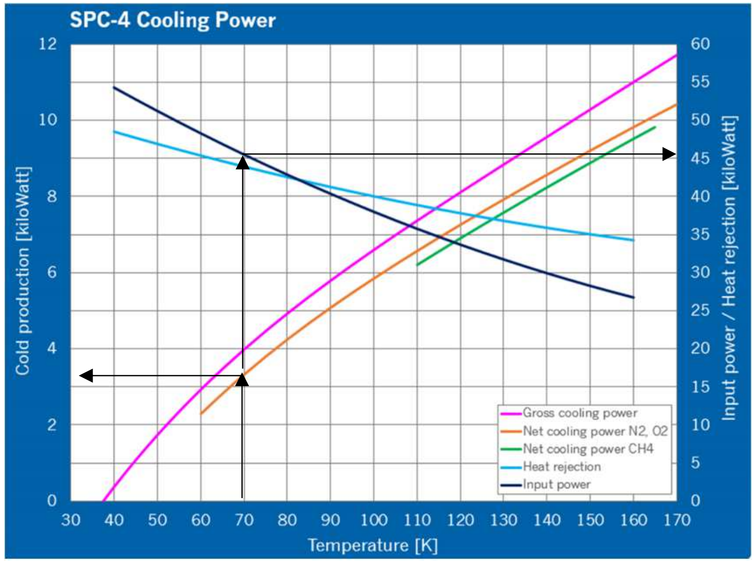
Benchmark: Stirling refrigerator (SPC-4)

Pro:

- high efficiency

Contra

- High maintenance efforts
- Low cooling capacity per unit → high number of units required
- Low potential for improvement
- Unclear model for operation



Efficiency:

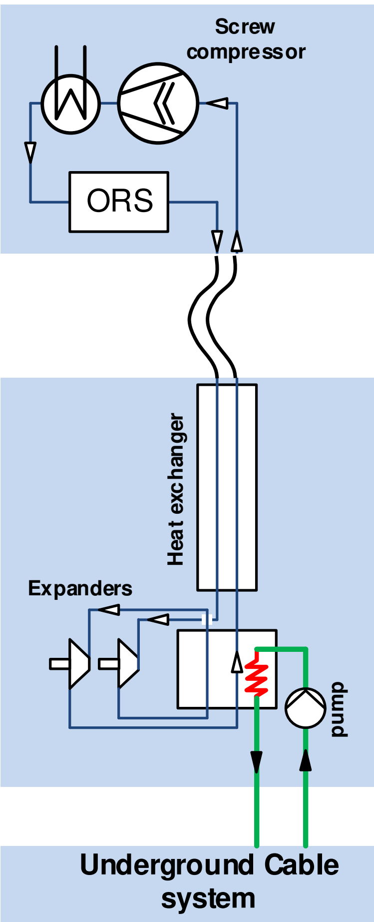
- best case (cooling water temperature 15°C) cooling capacity Q_0 = 3.3kW@70 K, Input Power P=46 kW → Carnot efficiency = 22.3%, **P/Q_0 = 13.9**
- Realistic case (cooling water temperature 30°C) cooling capacity Q_0 = 3.2 kW@70 K, Input Power P=48.3 kW : Carnot efficiency = 22.1%, **P/Q_0 = 15.1**

References:

- Albany etc

Reversed Brayton process refrigerators

Based on oil-flooded screw compressor



Pro

- Cost-efficient
- Reliable, referenced
- Options for improvement are available

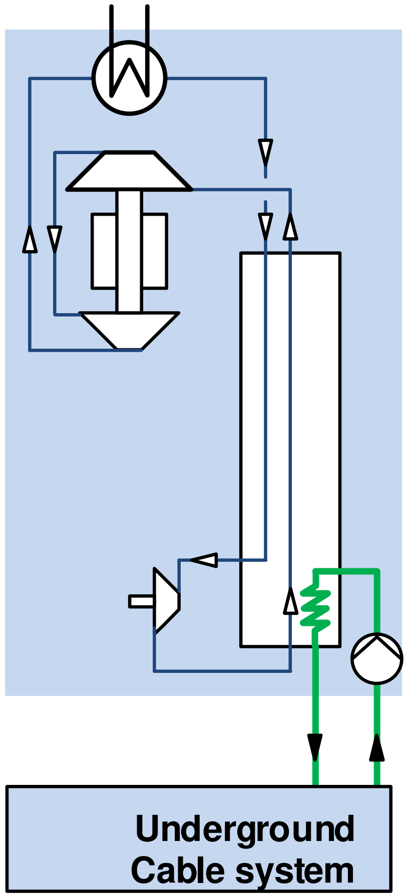
Contra

- moderate efficiency (high-efficiency expander, but low-efficiency compressor) @ cooling temperature T_0 = 70K, @ cooling water temperature 30°C P/Q_0 = 14.25, Carnot efficiency = 23.4%, for cost-optimized process design or even higher for energy-optimized process design
- Unclear model for operation

References:

- LIPA - I

Based on centrifugal compressor



Pro (Expectations)

- High efficiency
  However, the expectations on high efficiency are still not confirmed yet
  - NeoKelvin 2kW, TNSC: P/Qo > 27.5,
  - TBF175 Air Liquide): P/Qo > 23
- Low-maintenance
- Options for improvement are available

Contra

- Probably more expensive than Helium-based system due to sophisticated hardware components: turbo-compressor, magnetic bearings, neon as refrigerant
- Unclear model for operation

References:

- LIPA-II

Summary
(relates to cooling system)

1. Clear understanding for cooling technology for HTSC cable is available,
2. Clear understanding for overall setup/architecture is developed,
3. Refrigeration system:
   liquid nitrogen - based system (open cycle system) is suitable more for: short cables, focus on low CAPEX-project
4. Refrigeration system:
   - system based on reversed Brayton process is preferred solution,
   - recently, system based on screw compressor is better in terms of power and cost,
   - potentially, in near future, system based on centrifugal compressor may become competitive.
5. Discussion about business/operation model is required.