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HTS power applications and cooling system developments in Europe

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4th IWC-HTS, 23-25 October 2024, Matsue, Japan

Outline

- Overview on **HTS power applications** in Europe
  - HTS power transmission cables
  - HTS busbars
  - HTS fault current limiters

- Specific **cooling system developments**
  - State-of-the-art cooling systems
  - CMRC: An emerging cryogenic technology

HTS POWER TRANSMISSION CABLES

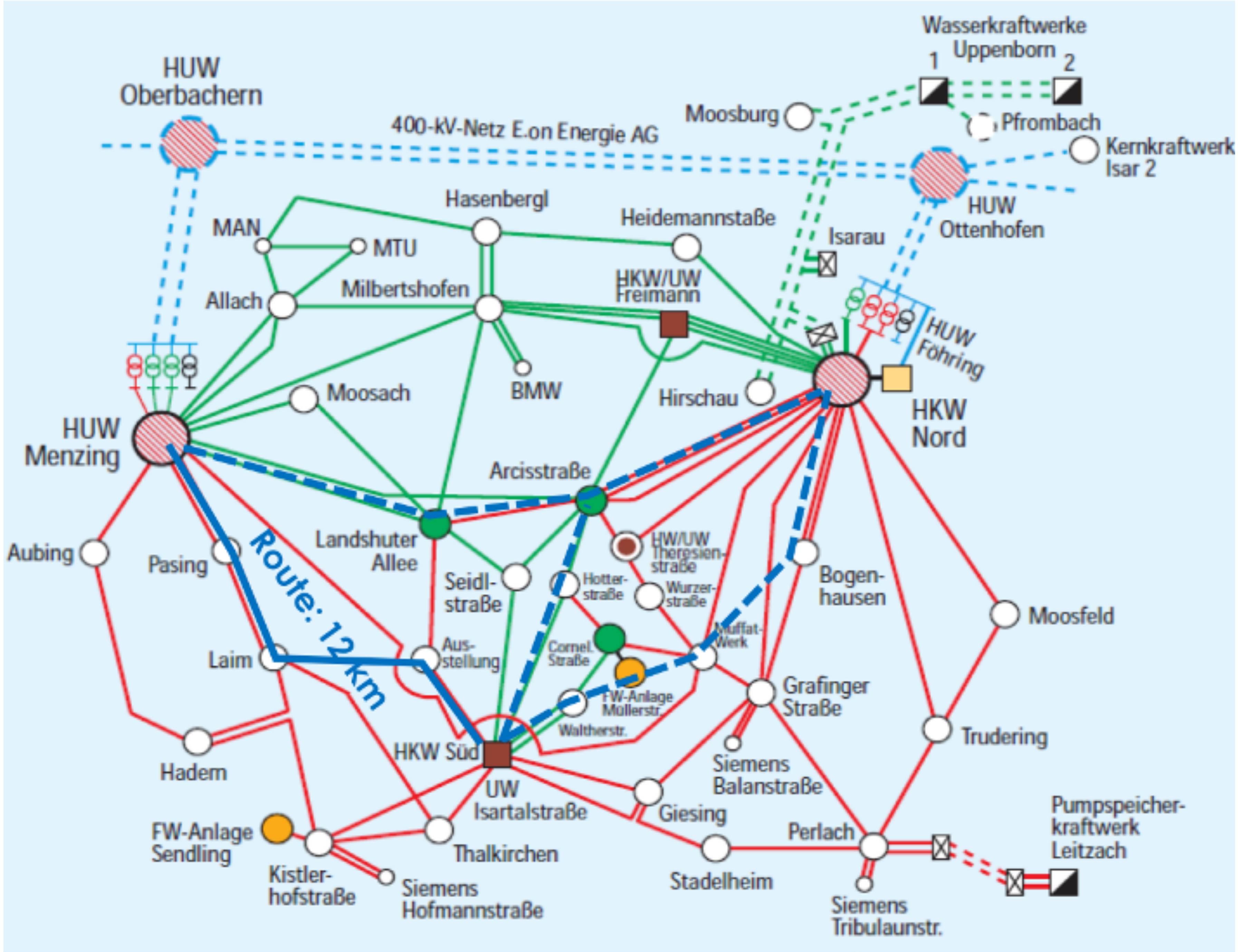
- 110 kV AC 500 MVA cable, **SWM SuperLink**, Munich
- 1.5 kV DC cable at Railway Station, **SuperRail**, Paris

SWM SuperLink Project, Munich

Urging problem of the city utility

Rebuilding the **distribution grid** and establishing a **500 MVA connection across the city**

- Necessary **change** in **cable technology**
  - Non-availability of gas-pressure cables
- **Strong renewal pressure**
  - 80+ % cables installed before 1980
  - Enormous volume >90 HV cable sections
- **Connection of gas power station** in the south to transmission grid (NW) **across the city**
- **Avoidance** of new 400/110 kV **main substation**
  - Space, cost



SuperLink – Project options

- **Alternative solutions for transport of 500 MVA over 12 km**

400 kV XLPE cable system

E.g. tunnel solution,
as in Berlin, London, etc.

400 kV overhead line

Not feasible in the city

Multiple 110 kV XLPE cable systems

Five systems and routes
Limited bending radii
Soil warming (spacing)

110 kV HTS cable

Novel technology

SuperLink – Project assessment

Alternative solutions – Assessment by the network operator

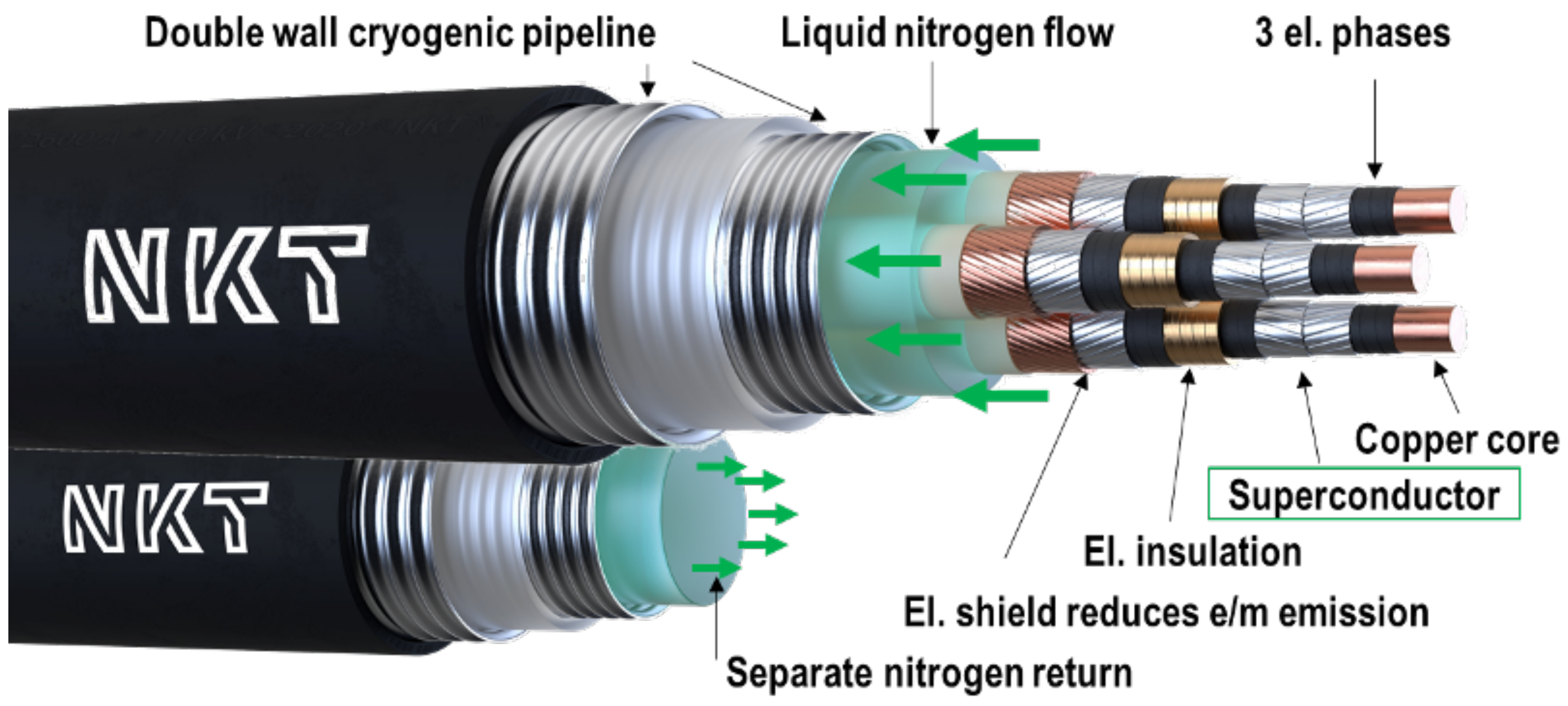
Criteria	400 kV XLPE	400 kV OHL	Multiple 110 kV	110 KV HTS
Minimum space	🙁	🙁	🙁	🙂
Public acceptance	🙁	🙁	😐	🙂
Economic feasibility	🙁	🙂	🙁	😐
Technical maturity	🙂	🙂	🙂	😐
City grid integration	🙁	🙁	🙂	🙂
Power density	🙂	🙂	🙁	🙂
Low loss	🙁	😐	🙁	🙂

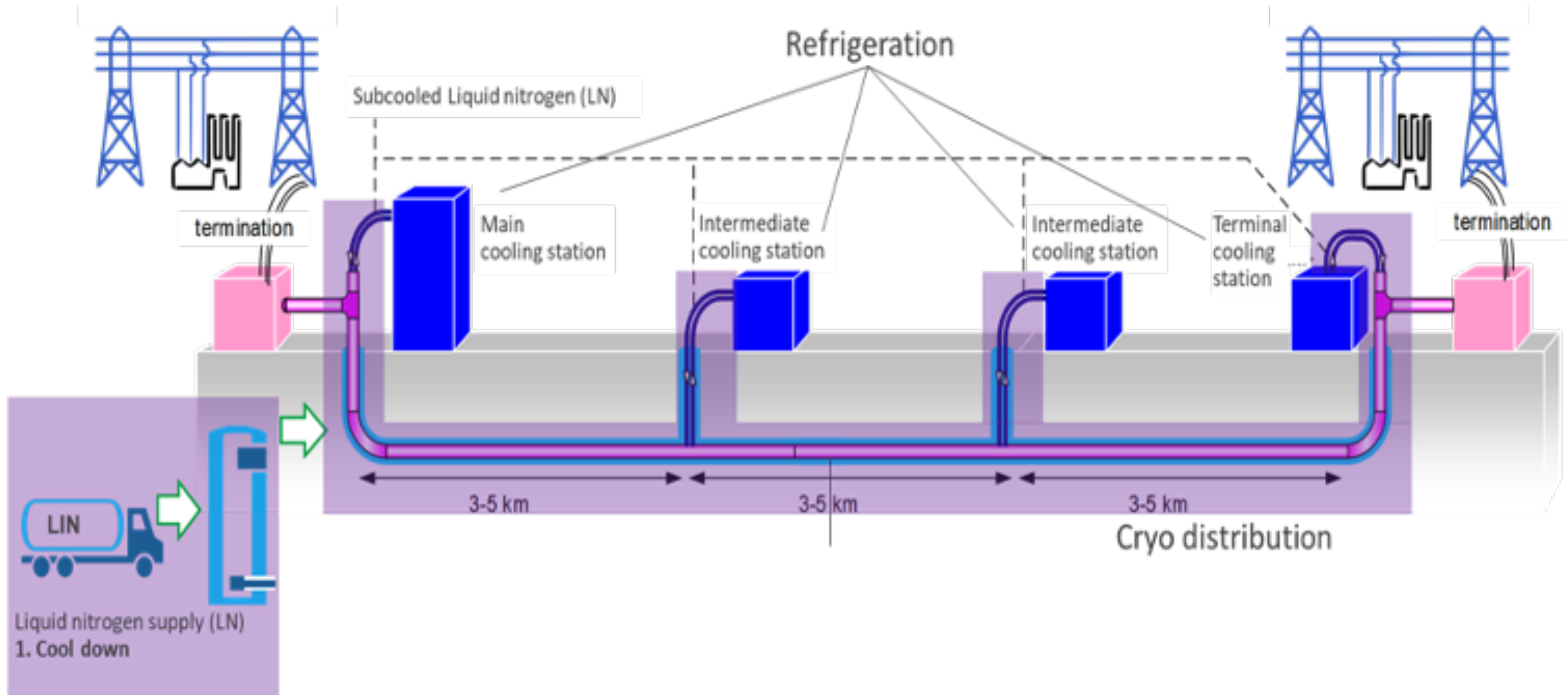
The **HTS option** is very attractive, but needs development

SuperLink – Consortium

SuperLink – Objectives

- **Cable design**
  - Three HTS phases in one cryostat
  - 110 kV, 500 MVA, 2.6 kA_{rms} (3.7 kA_{peak})
  - Low AC-losses < 0.5 W/m/phase
  - Separate LN_2 return pipe (single, one-way cable)
- **Distributed closed cooling system**
  - LN_2 sub-cooling with Turbo Brayton coolers
    - Efficiency target $\eta = 30\,\%\,\mathrm{Carnot}$
  - Specific cooling power: 6 kW/km
  - Intermediate cooling and pumping stations
    - $\dot{Q}_0 \approx 30\,\mathrm{kW}$ @ $(64 \ldots 74)\,\mathrm{K}$ per station
  - Long lifetime of components 20-50 years
  - Redundancy

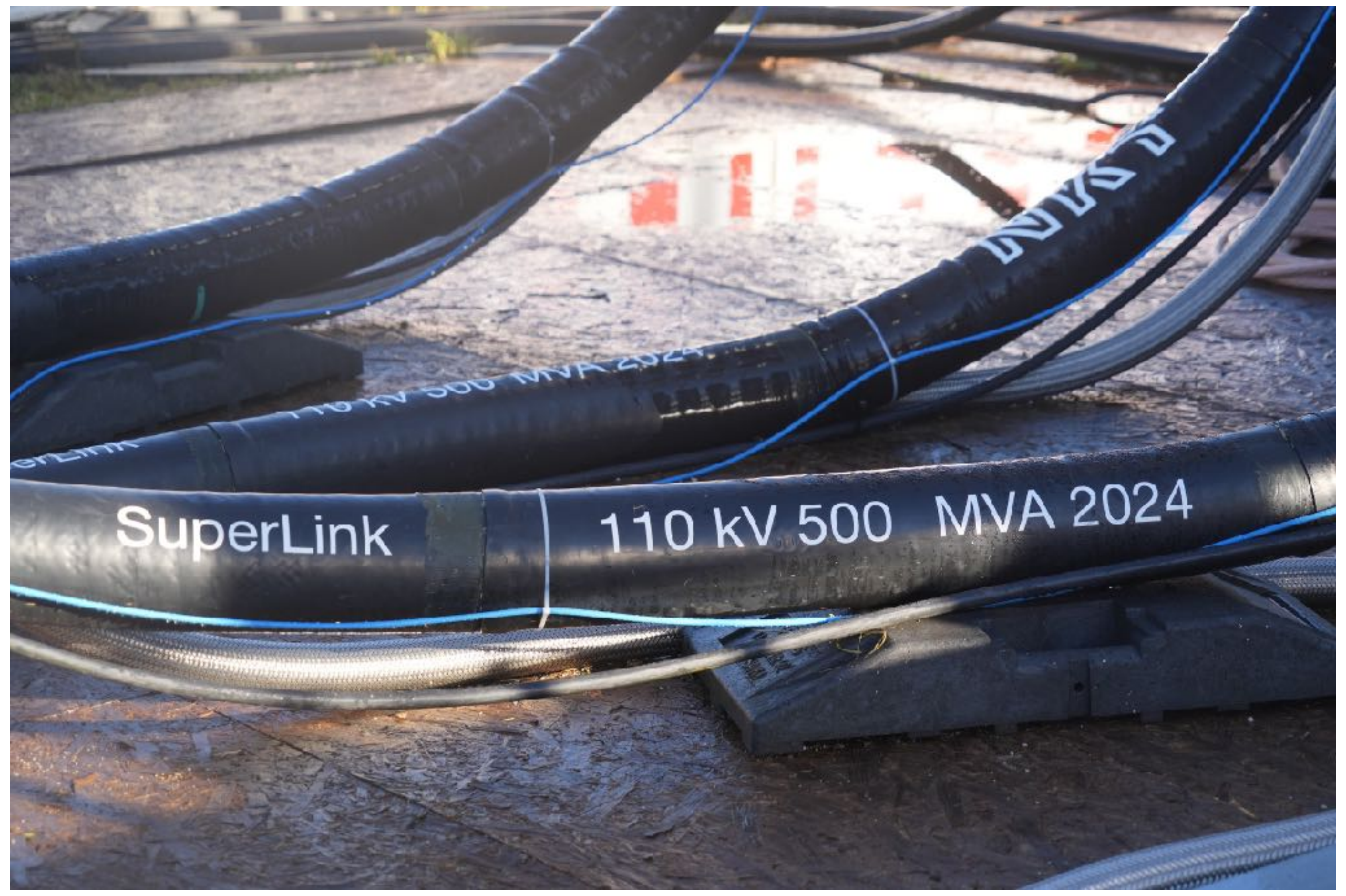


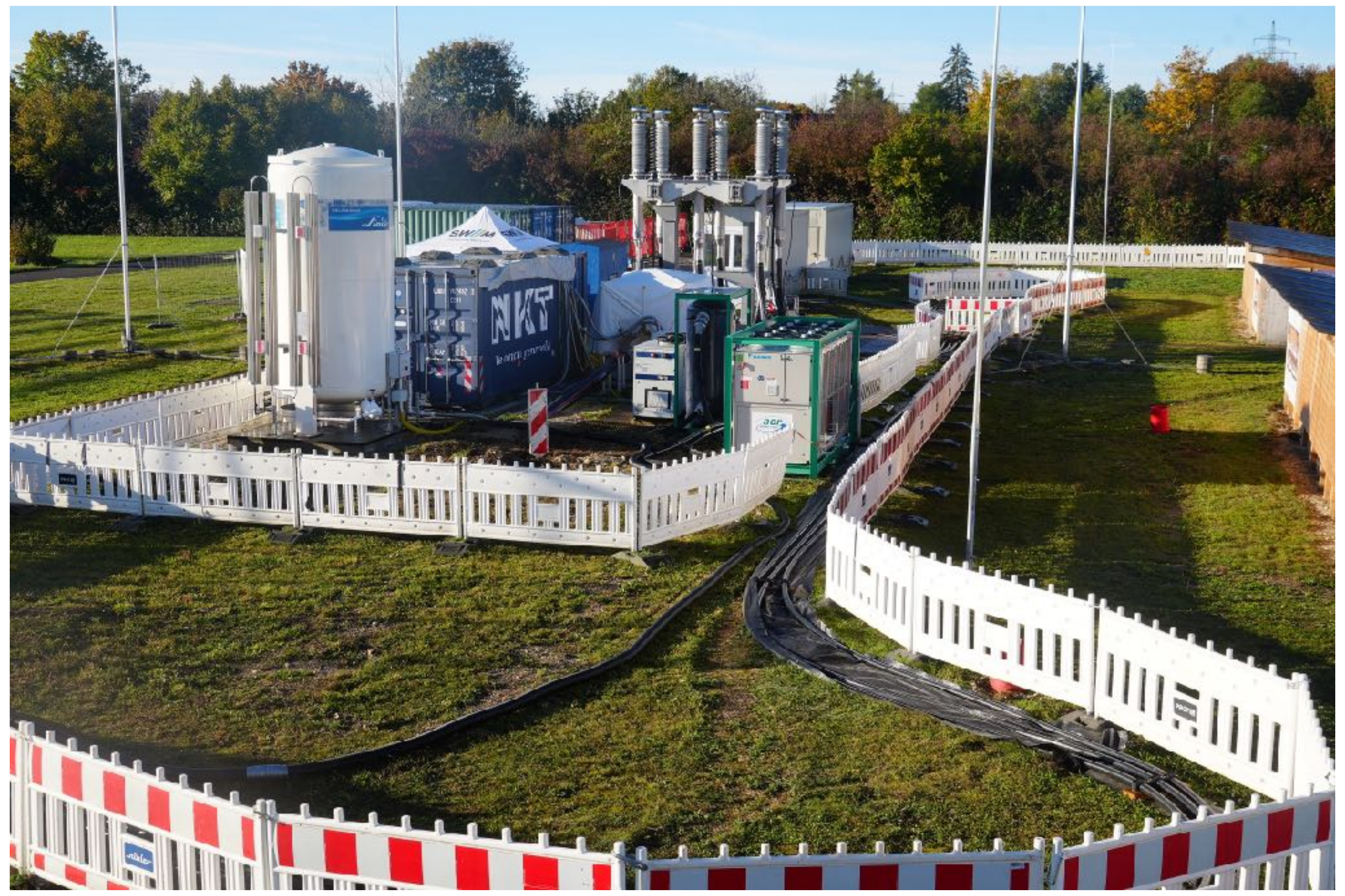


SuperLink – Status

- Commissioning of 150 m DEMO in **10/2024** ✅
  - Contains all major cable components
  - **No cooling station** prototype within the project
- Long-time testing until **04/2025**

Press release: https://www.swm.de/unternehmen/presse/pressemitteilungen/2024/10-2024/swm-supralink





SuperRail, Gare Montparnasse, Paris

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- Need to **increase the traffic on the railway network** in densely populated areas with high constraint to comply with 2030 carbon reduction objectives
  - **50 Mio.** passengers in 2020 → **90 Mio.** in 2030
- Conventional **Cu cables not possible** due to limitations in existing rights of ways
  - Many spacial constraints; Very high risks with century old constructions and presence of many other networks (water, gas, telecom)



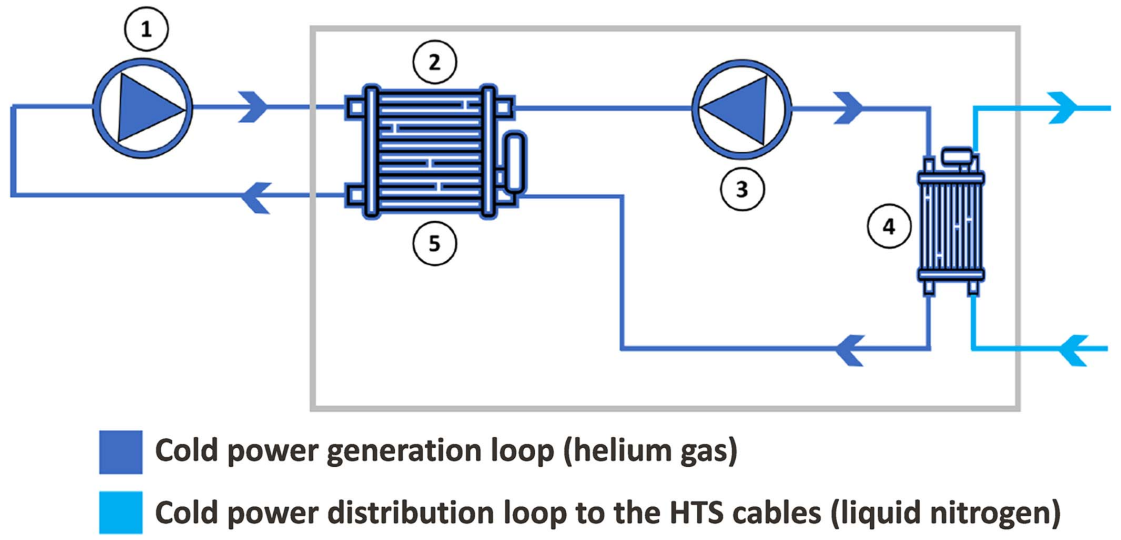

CentraleSupélec UNIVERSITÉ DE LORRAINE Nexans ABSOLUT SYSTEM SNCF RÉSEAU

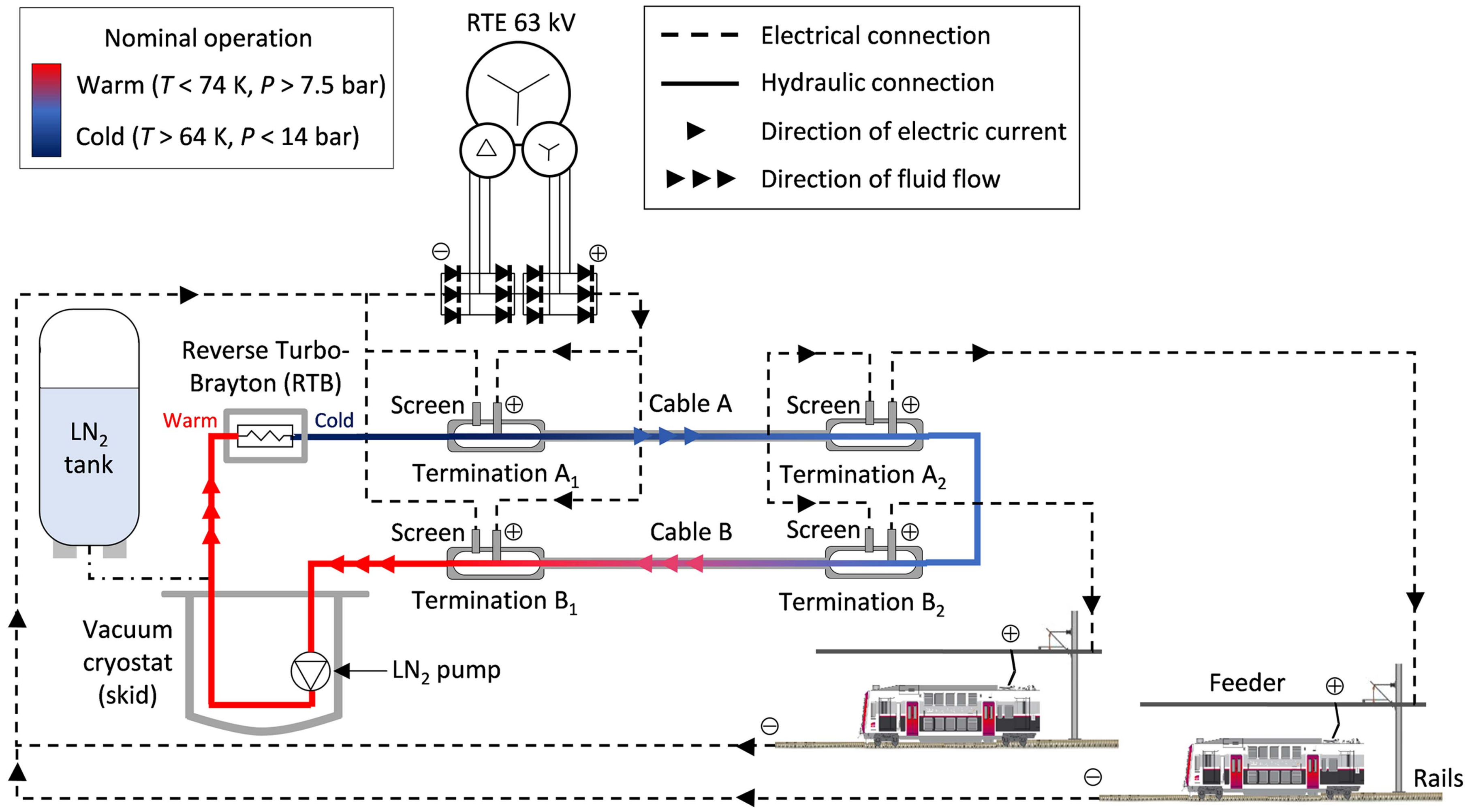
Source: A. Allais et al., SuperRail – HTS Installation am Gare Montparnasse, ZIEHL IX Workshop, Berlin, 11.04.2024

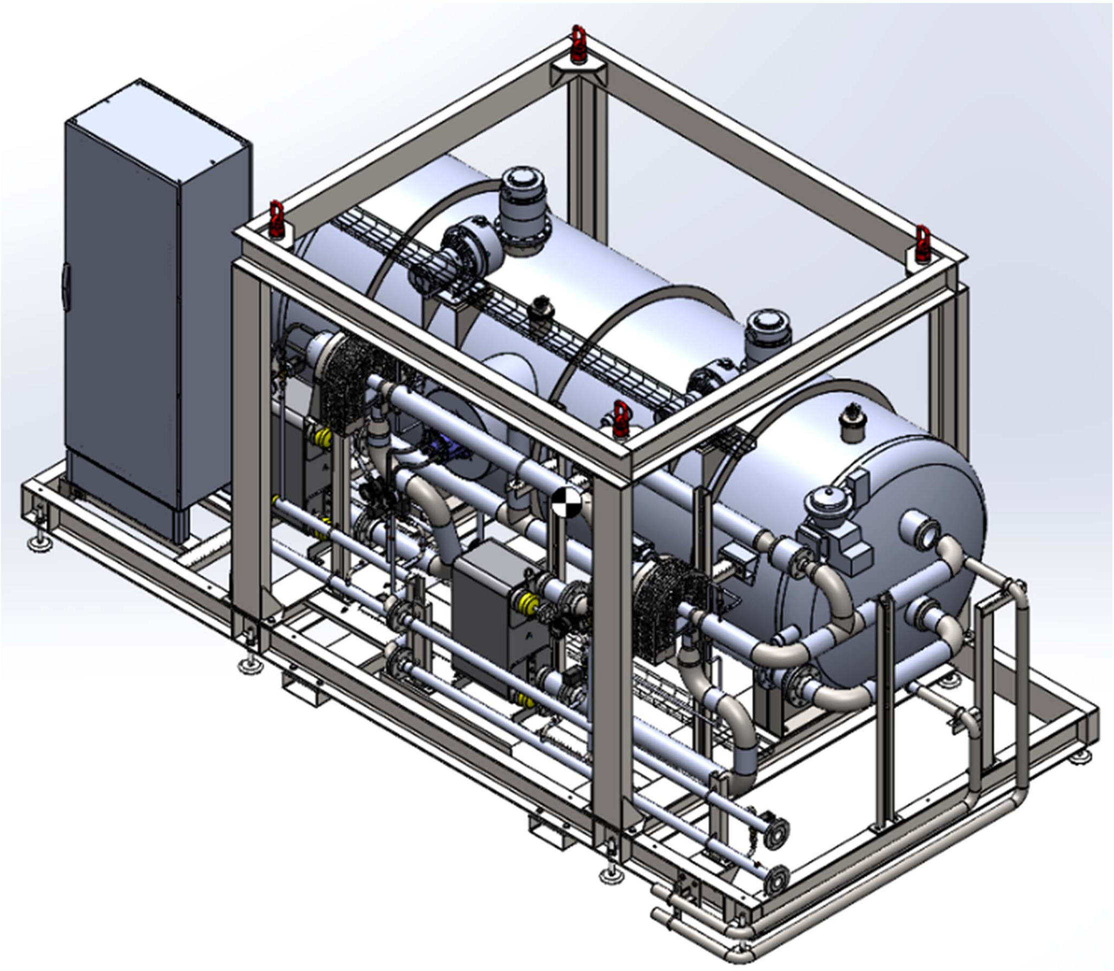
- **Innovative solution: Two HTS** 3500 A @ 1500 VDC cables

SuperRail – Cooling system

- LN$_2$ sub-cooling with Turbo-Brayton cooler
  - Cooling power of **1.7 kW @ 67 K** for the entire cable system
    - **70 %** required for the **terminations**





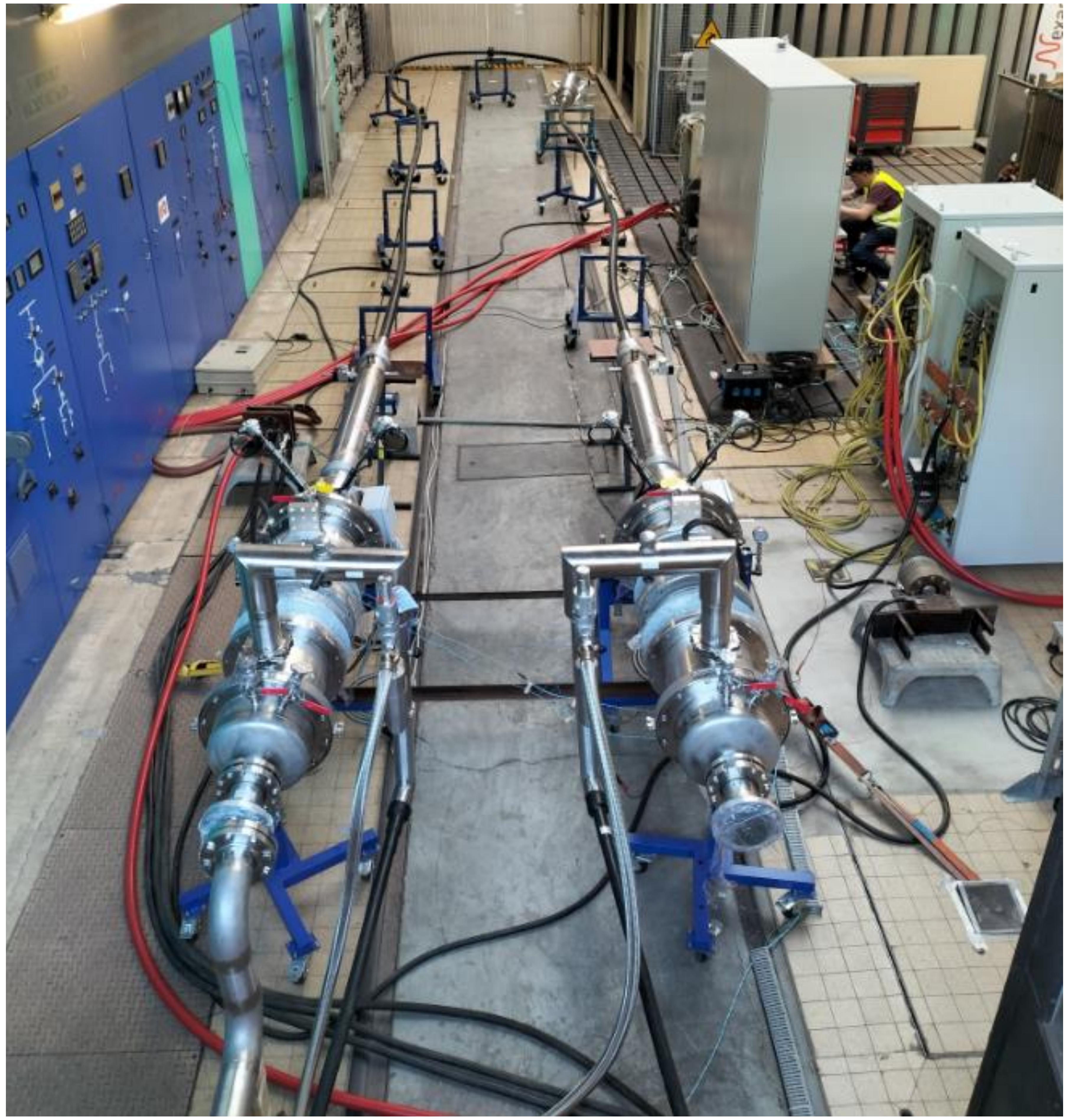


- Supply flow in first HTS cable; return flow in second cable
- Skid for LN$_2$ handling
- CAD model of helium Turbo-Brayton

Source: A. Allais et al., SuperRail – World-First HTS Cable to be Installed on a Railway Network in France, IEEE TASC (2024), DOI: 10.1109/TASC.2024.3356450

SuperRail – Status

- Type test in SNCF laboratory completed ✅ →
- Cable system installed in 2024 ✅
- Cooling system production ongoing
- Commissioning planned in 2025



CentraleSupélec · UNIVERSITÉ DE LORRAINE · Nexans · ABSOLUT SYSTEM INNOVATIVE CRYOGENIC SOLUTIONS · SNCF RÉSEAU

Source: A. Allais et al., SuperRail – HTS Installation am Gare Montparnasse, ZIEHL IX Workshop, Berlin, 11.04.2024

EU project SCARLET

Superconducting CAbles foR sustainabLe Energy Transition

Karlsruhe Institute of Technology

- **Goal:** develop and industrially manufacture MVDC superconducting cable systems at the gigawatt level, bringing them to the last qualification step before commercialization
- Expertise from 15 industry and research organizations in the fields of material sciences, cryogenics, energy systems and electrical engineering

  - Project website: https://scarlet-project.eu/

HTS BUSBARS

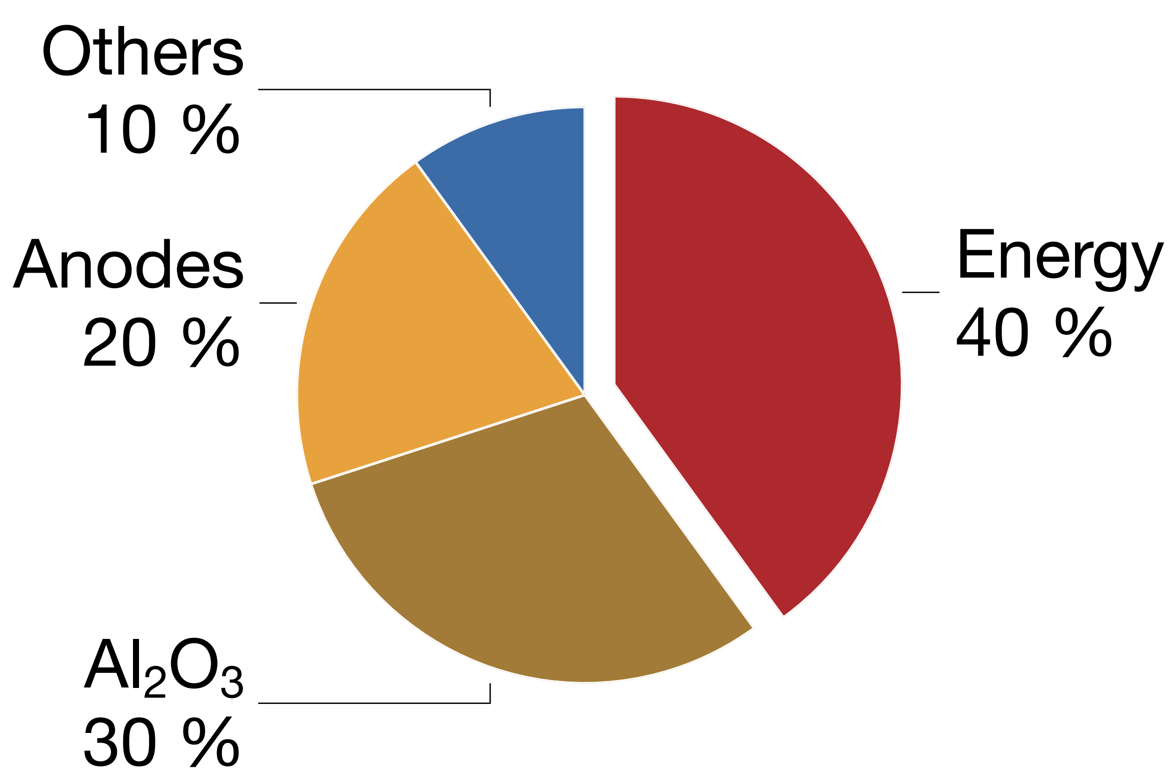
- 200 kA DC Current Return, TRIMET Aluminum Factory, Hamburg

Application

Source: W. Reiser, DEMO200 und Perspektiven, ZIEHL IX Workshop, Berlin, 11.04.2024

Operation
- 365 d/a
- 24 h/d
- 200 kA DC

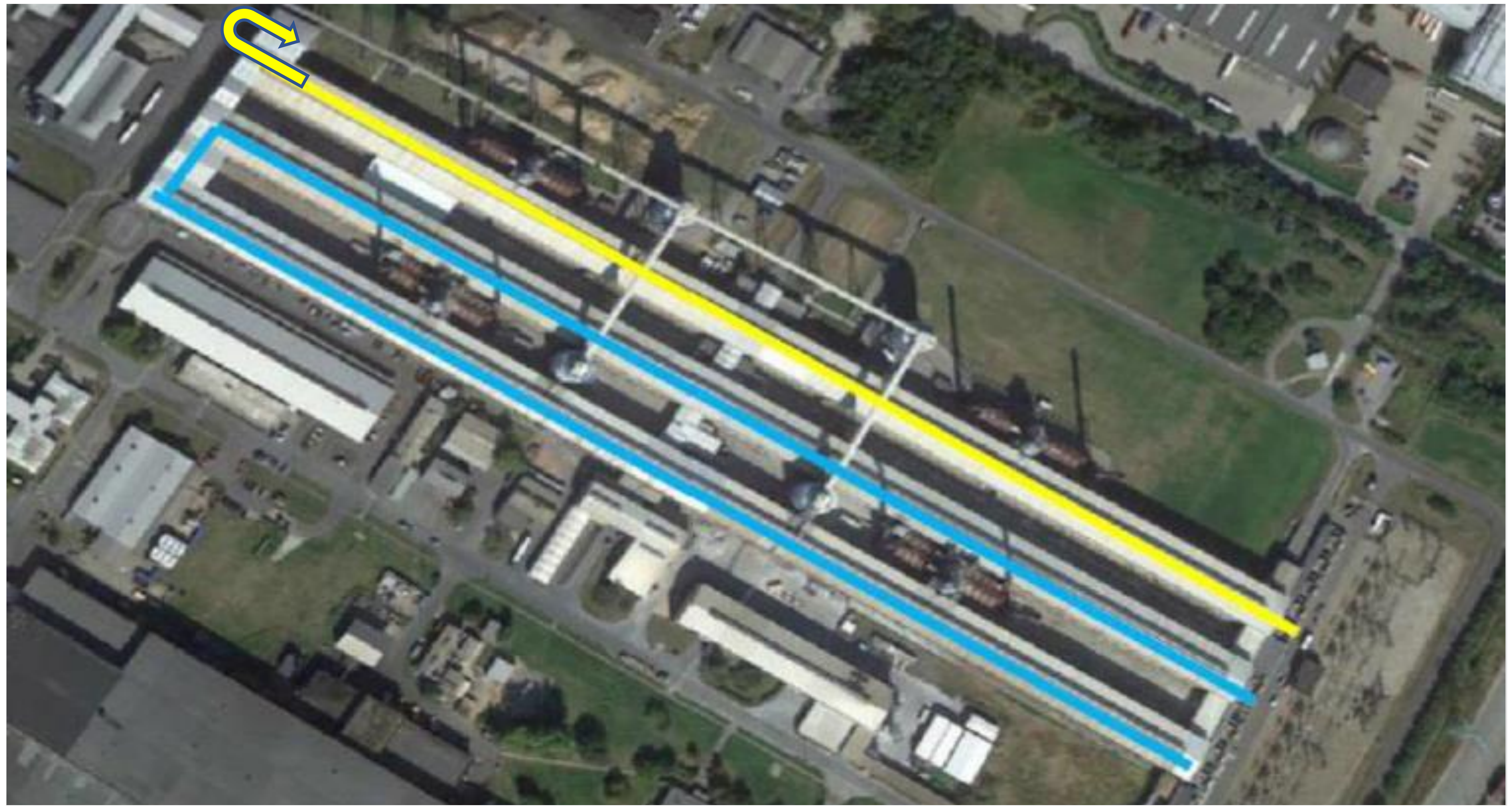
OpEx



Technical concept

Electrical layout

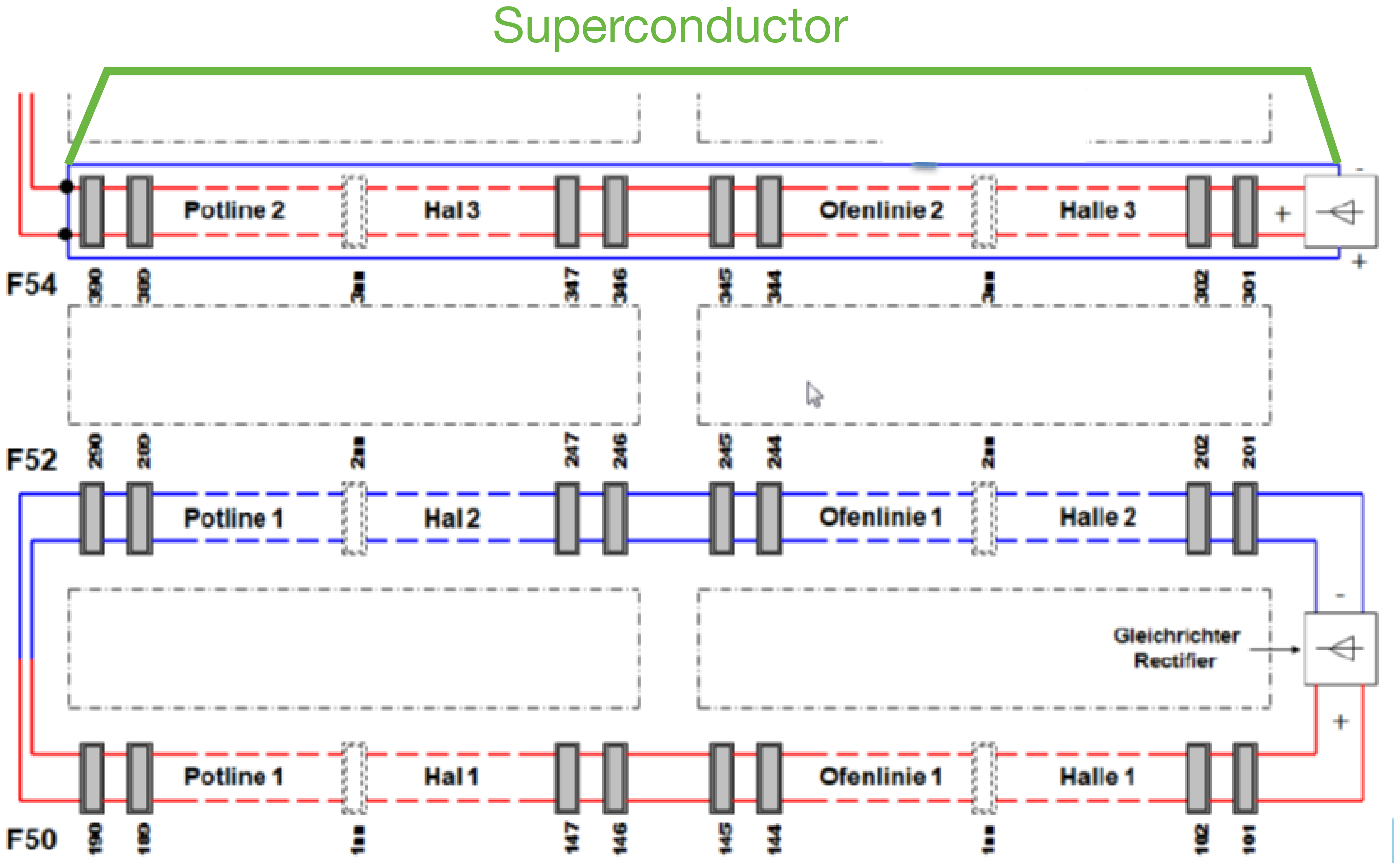
- Blue: Current return via 2. hall
- Yellow: Current retur via busbar



Source: W. Reiser, DEMO200 und Perspektiven, ZIEHL IX Workshop, Berlin, 11.04.2024

New concept

- Superconductor parallel to existing aluminum return busbar



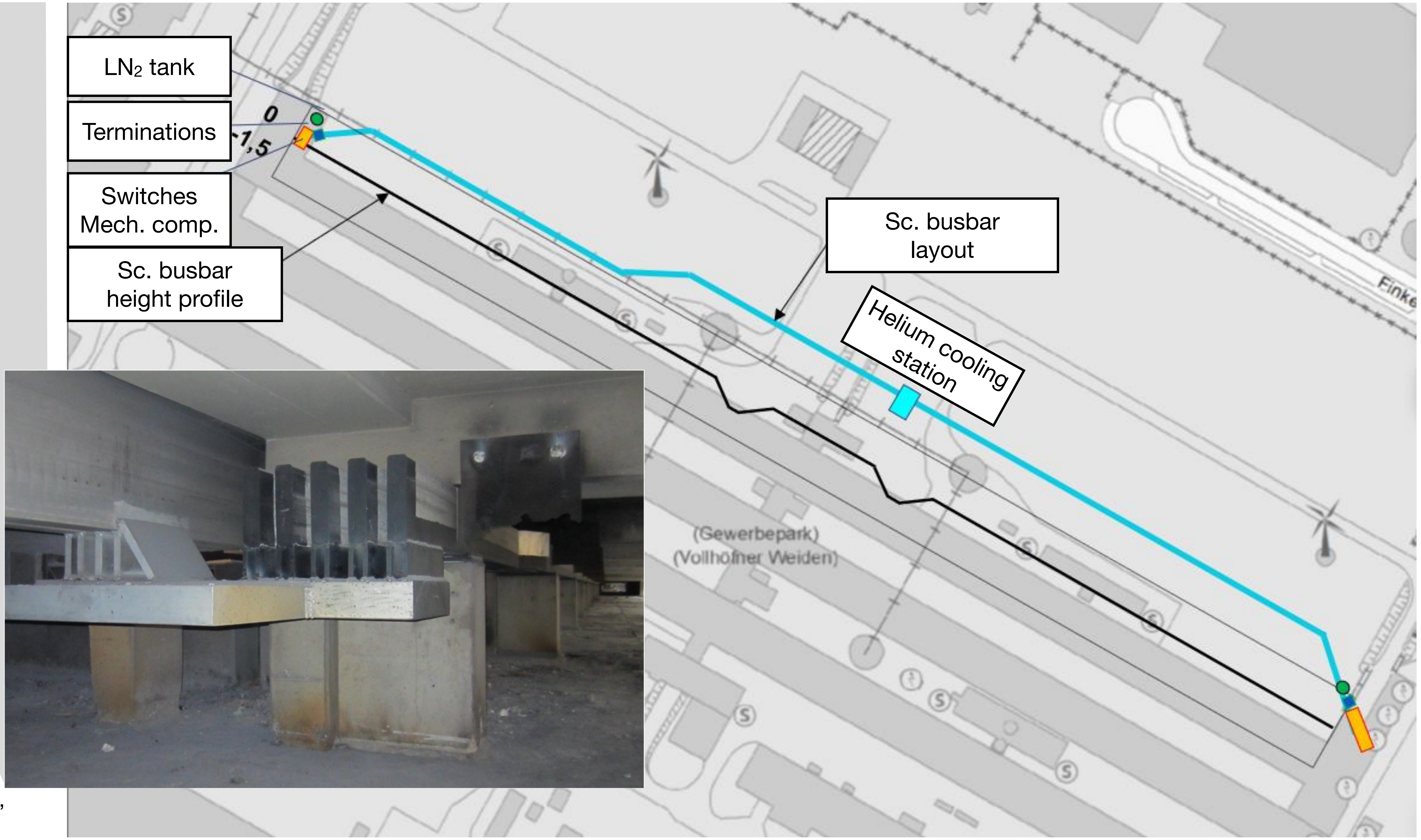
Impact of HTS

Al return busbar

- Length 600 m
- Nominal current 200 kA
- Voltage drop 12 V
- **Electric losses 20 GWh/a**
- **Equiv. cost 1 M€/a**

HTS busbar

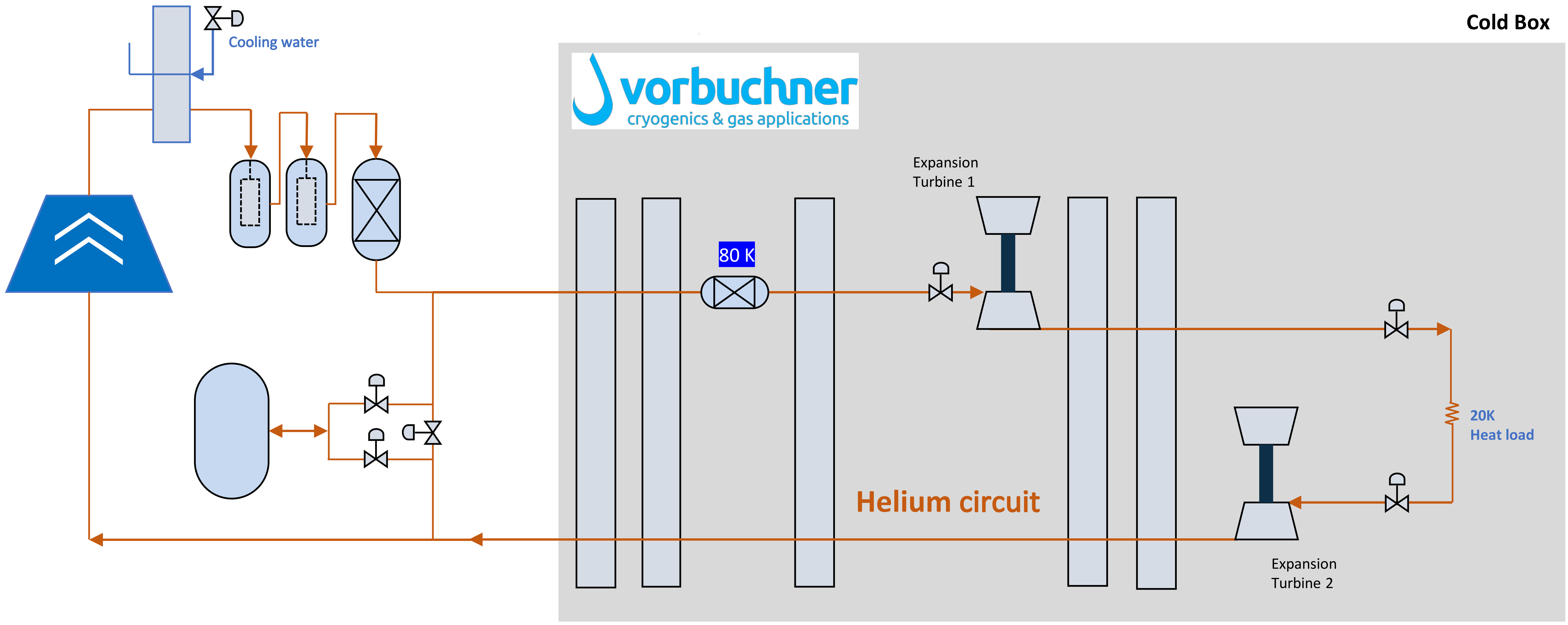
- **Losses < 10 %**
- Reduction by 8.000 t CO_2 equivalent/a



Source: W. Reiser, DEMO200 und Perspektiven, ZIEHL IX Workshop, Berlin, 11.04.2024

Cooling concept

- 200 kA **terminations** cooled by **evaporation of LN_2**
- 600 m **HTS busbar** cooled with **helium at 20 K**



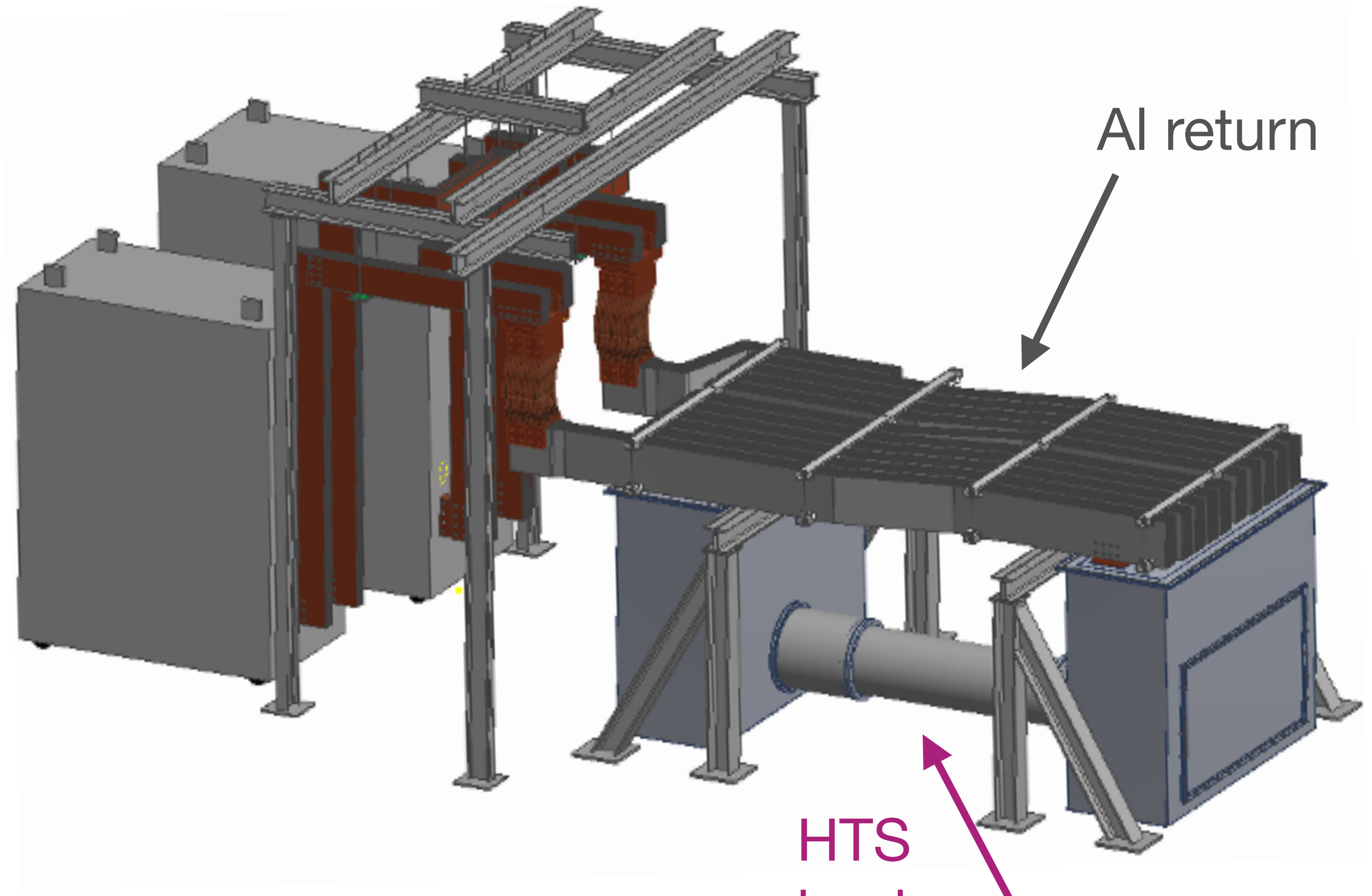
Refrigerant	Helium
LN_2 pre-cooling	No
Cooling capacity	**1.2 kW @ 20 K**
Power input	95 kW
Efficiency	**18 % Carnot**

Source: W. Vorbuchner, 20 K Kälteanlagen für Supraleiter, ZIEHL IX Workshop, Berlin, 11.04.2024

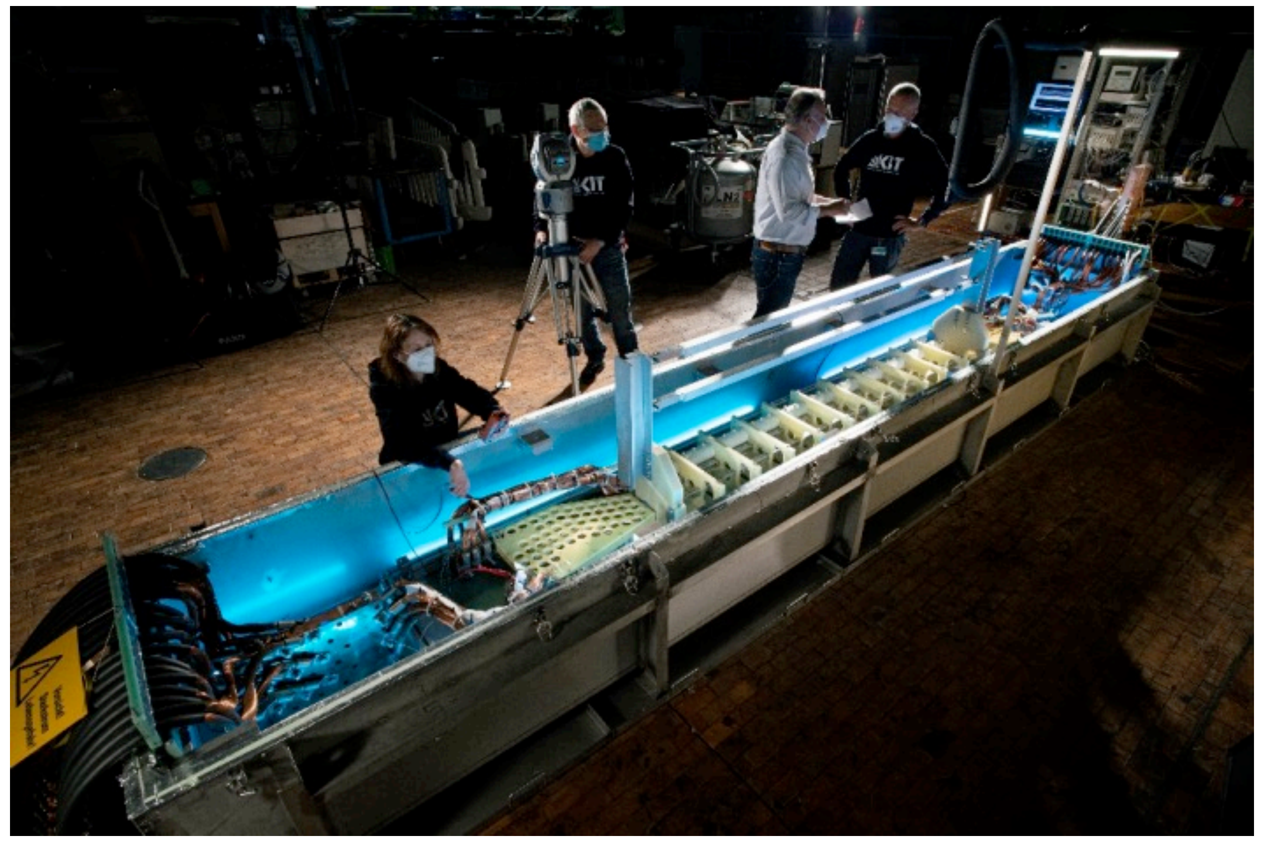
Test results & outlook

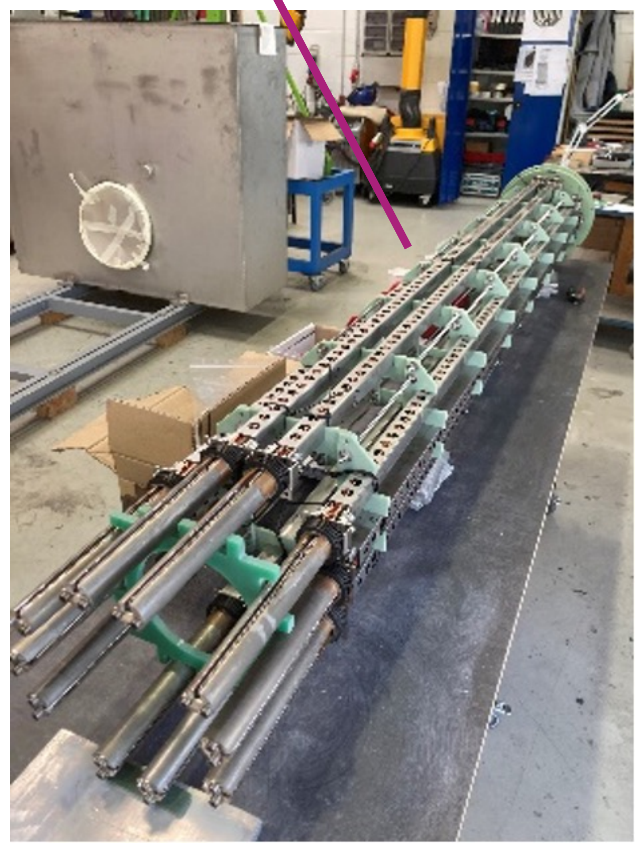
- **DEMO200** setup tested in **09/2024**
  - 170 kA current test at TRIMET passed ✅
  - HTS busbar carried 189 kA @ 77 K ✅
    (200 kA @ 70 K will be achieved in final system)

- A 600 m 200 kA **permanent installation** will be **realized by 2027** within the real-world lab **SuprAL**



TRIMET aluminum plant in Hamburg





Successful test of a 20 kA module at KIT

High-current industrial applications

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Chlorine electrolysis
20 kA, Germany

Industry	Current	Lenght
Chlorine electrolysis	20 kA	30-300 m
Datacenter	10-40 kA	40-500 m
Copper electrolysis	40-80 kA	200-400 m
Zinc electrolysis	(120-) 200 kA	100-300 m
Aluminum mills	200-350 (500) kA	100-1200 m
All electrolysis, e.g. Na, Mg, F / furnaces / graphitization		

Source: W. Reiser, DEMO200 und Perspektiven, ZIEHL IX Workshop, Berlin, 11.04.2024

Aluminum mill
200 kA, Dubai

Zinc electrolysis
200 kA, India

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HTS FAULT CURRENT LIMITERS

- 220 kV AC SFCL in Moscow
- 380 kV AC SFCL Feasibility Study

220 kV SFCL by SuperOx

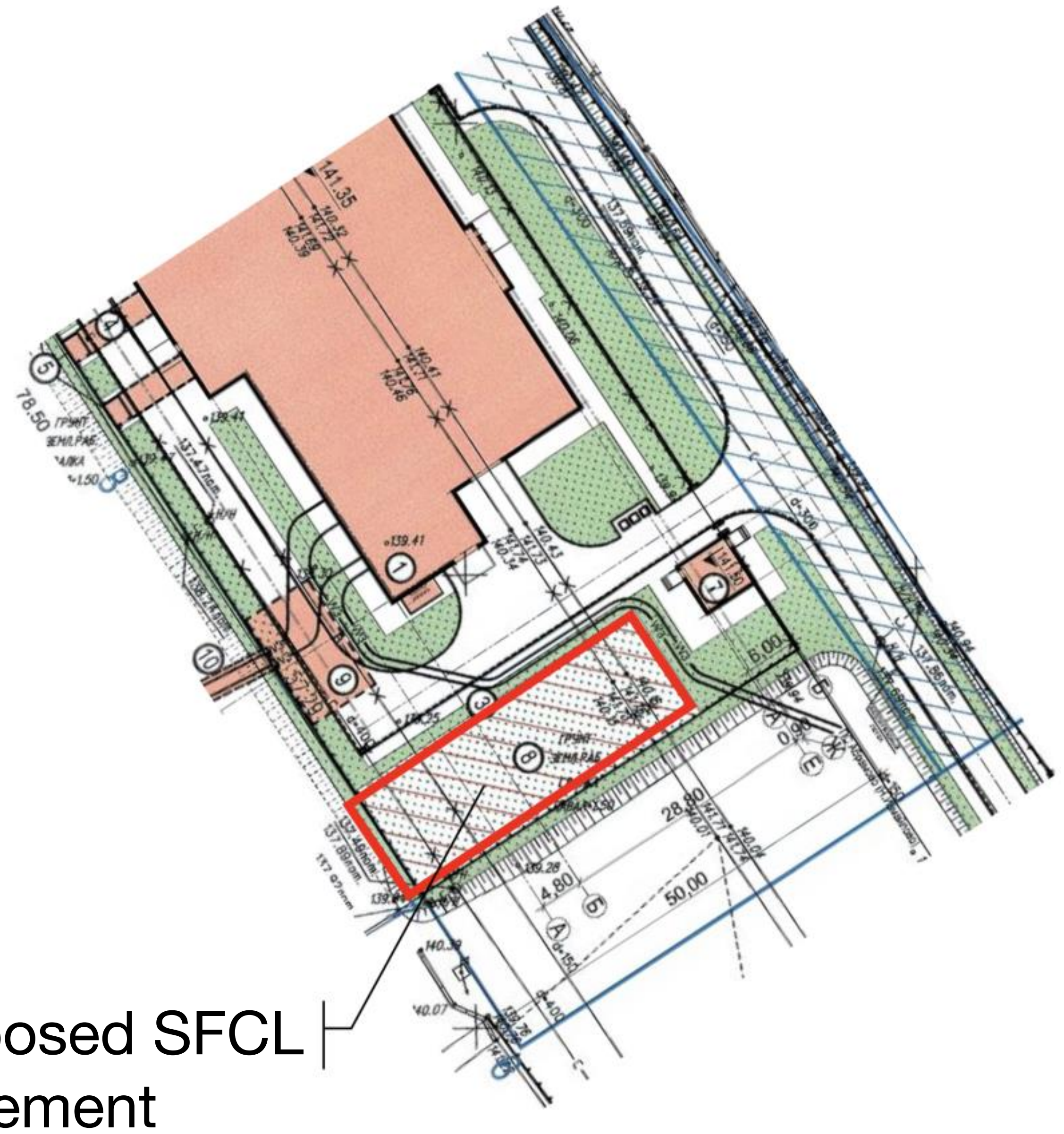
Pilot SFCL 220 kV (2019)

- Customer: JSC “UNECO” Federal Grid Company
- Position: 220/20 kV Substation, Moscow (West)
- Voltage class: 220 kV
- Quantity: 1 (3-phases)
- **Continuous operation** in electrical grid **since 2019**
- SuperOx provides full maintenance of HTS SFCL

HTS SFCL placement at Mnevniki substation

New Series-type 220 kV SFCLs

- Customer: JSC “UNECO” Federal Grid Company
- Position: 220/20 kV Substation, Moscow (East)
- Quantity: 2 (6-phases)
- Voltage class: 220 kV
- SuperOx provides consulting during engineering (ongoing)

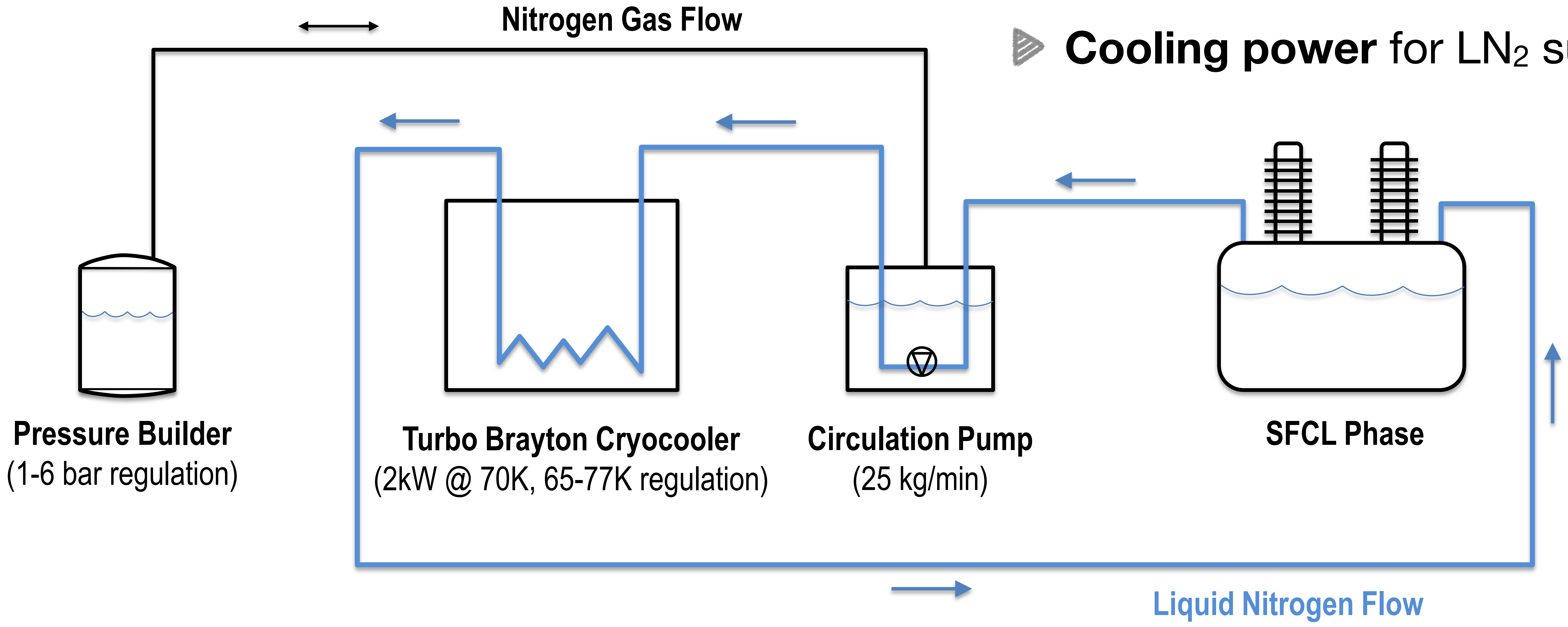


Proposed SFCL placement

Source: Mikhail Moyzykh, Development of applied superconducting technologies in SuperOx, EUCAS, Bologna, 2023

Cryogenic system design

- **Each SFCL phase** is equipped with its **own cooling sub-system**
- By-passes between phases provide redundancy



- **Cooling power** for LN_2 sub-cooling $3 \times 2\,\mathrm{kW}$ @ $70\,\mathrm{K}$

Source: Sergey Samoilenkov et al., First Russian 220 kV superconducting fault current limiter for application in city grid, ASC Virtual Conference, 2020

Pilot SFCL – Cooling system maintenance

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SFCL Layout

- 3 phases (HV HTS part)
- **Cryogenic system** (LV auxiliaries), including:
  - 3 Turbo Brayton coolers (one per phase)
  - 1 LN_2 distribution system
  - 1 water chiller

Statistics 2019-2023

- Phases (HV HTS part) operated correctly
- Cryogenic system (LV auxiliaries)
  - **Several malfunctions** occurred and successfully recovered

Source: Mikhail Moyzykh, Development of applied superconducting technologies in SuperOx, EUCAS, Bologna, 2023

List of cryogenic system malfunctions

№	Failure description	Solution
1	Shutdown of the cryogenic cooling system	Implementation of automatic restart
2	LN_2 leakage – control system error	Control system software update
3	Cryocooler failure – manufacturing defect	Compressor turbine replacement
4	Chiller failure – manufacturing defect	Condenser repair (leak fixing)
5	LN_2 level sensor failure	Gas fittings replacement
6	Chiller failure – manufacturing defect	Pump replacement
7	Wear of cryopump bearings	Bearings replacement

German Network Extension Plan NEP2037/2045 (2023)

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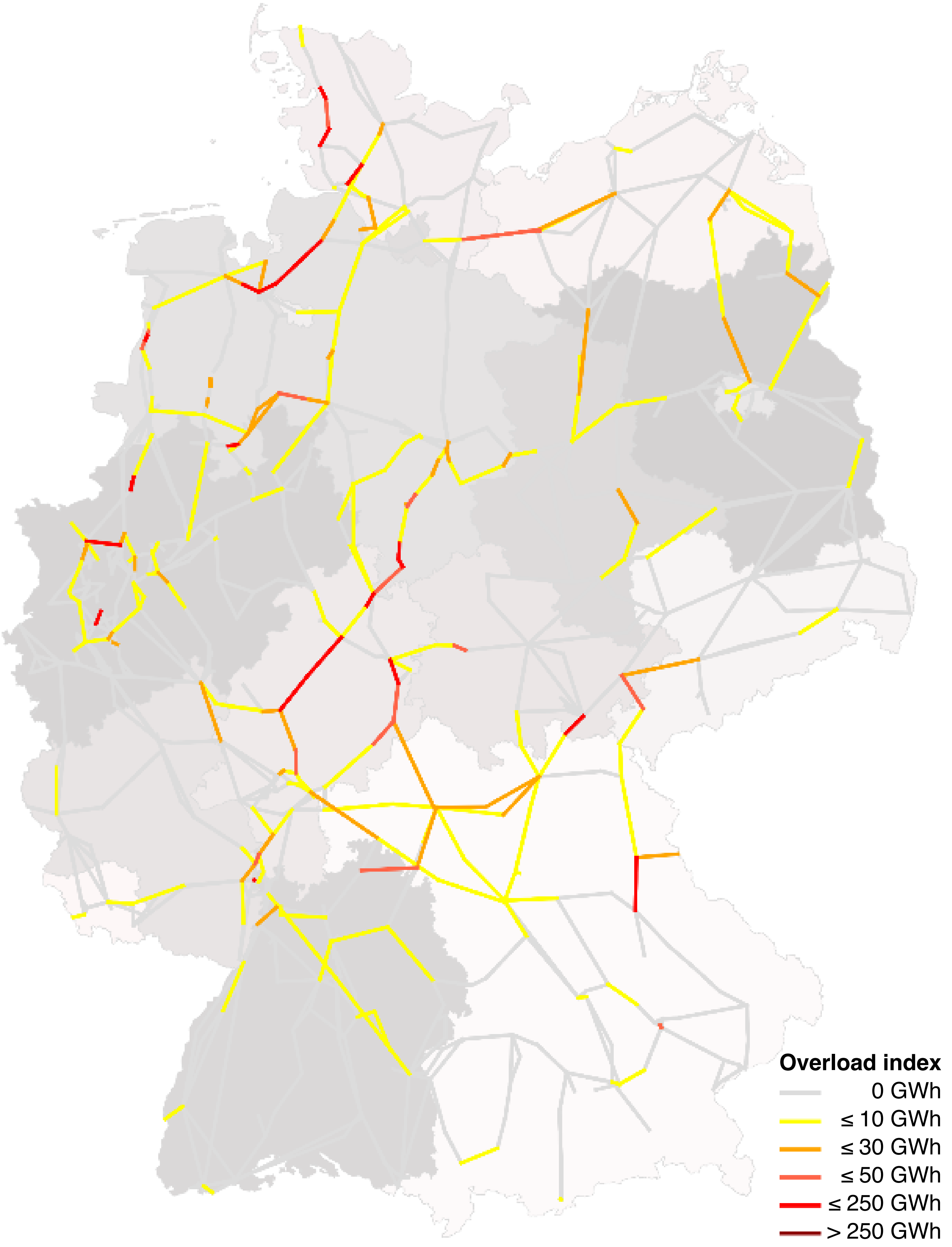
Installed power	Status (2020/2021)	2037 (NEP 2023)	2045 (NEP 2023)
PV	59 GW	345 GW	400-445 GW
Offshore Wind	8 GW	51-59 GW	70 GW
Onshore Wind	56 GW	158-162 GW	160-180 GW

Additional scenario B 2037	Line length	Investment
Offshore	9.300 km	103,5 Mrd. €
Onshore	12.430 km	94,5 Mrd. €
Summe	21.730 km	198,0 Mrd. €

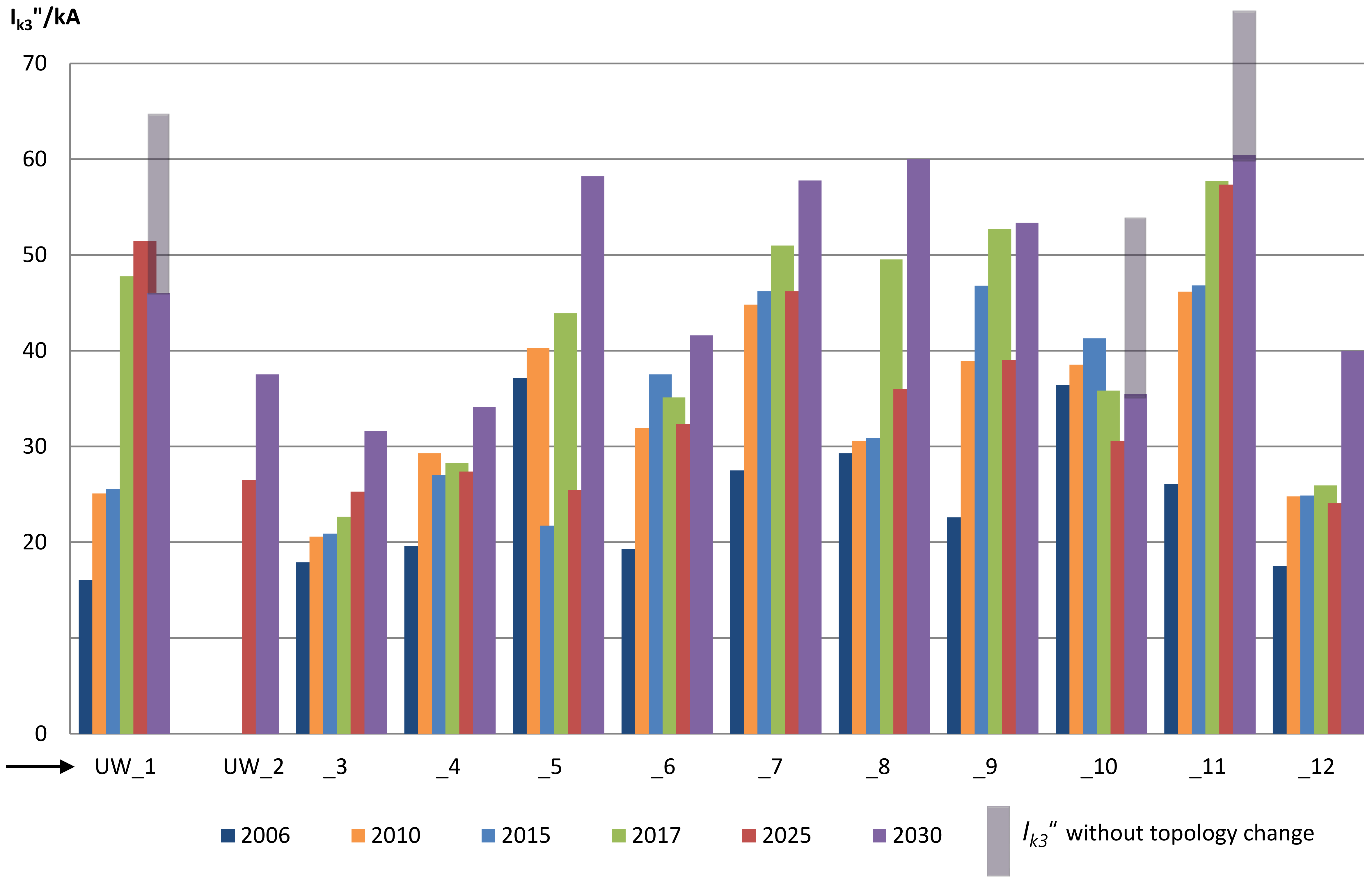
Source: Transmission System Operators

- There will be a **huge grid extension** due to the energy transition



Motivation for 380 kV SFCL

- Development of **short-circuit currents (SCC)** in parts of the **German 380 kV grid**



Exemplary substations →

- Additional HV grid extension

Scenario B 2037	Total line length	Invest.
Offshore	**9300 km**	103.5 Mrd. €
Onshore	**12430 km**	94.5 Mrd. €
Total	**21730 km**	198.0 Mrd. €

Source:
Network development plan NEP2037/2045 (2023) dated 24 March 24 2023

- Grid extension leads to **increase of SSC** at certain grid connection points

Requirements on 380 kV SFCL

- Electrical SFCL requirements

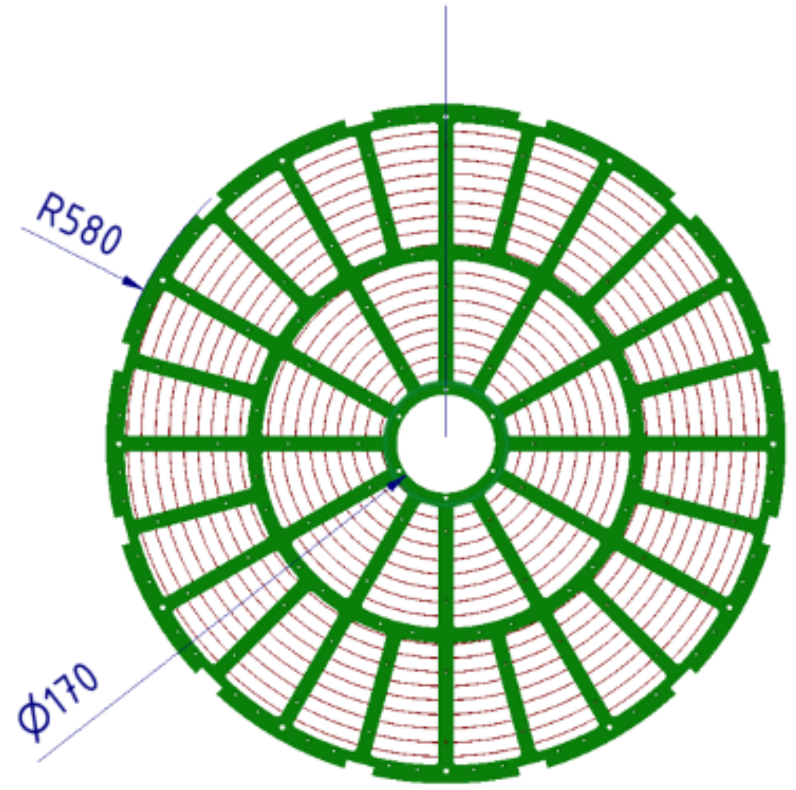
Parameter	AIS Bus Coupler
Nominal voltage U_n	380 kV
Temporary highest voltage for equipment U_{max}	440 kV
Nominal current I_n	5.0 kA
Max. short-circuit current without limiter I''_k	63 kA
Max. limited current with FCL $I''_{k,lim}$	19 kA
Fault duration t_d	0.25 s

Source: https://www.ksp.kit.edu/site/books/series/karlsruher-schriftenreihe-zur-supraleitung-3/

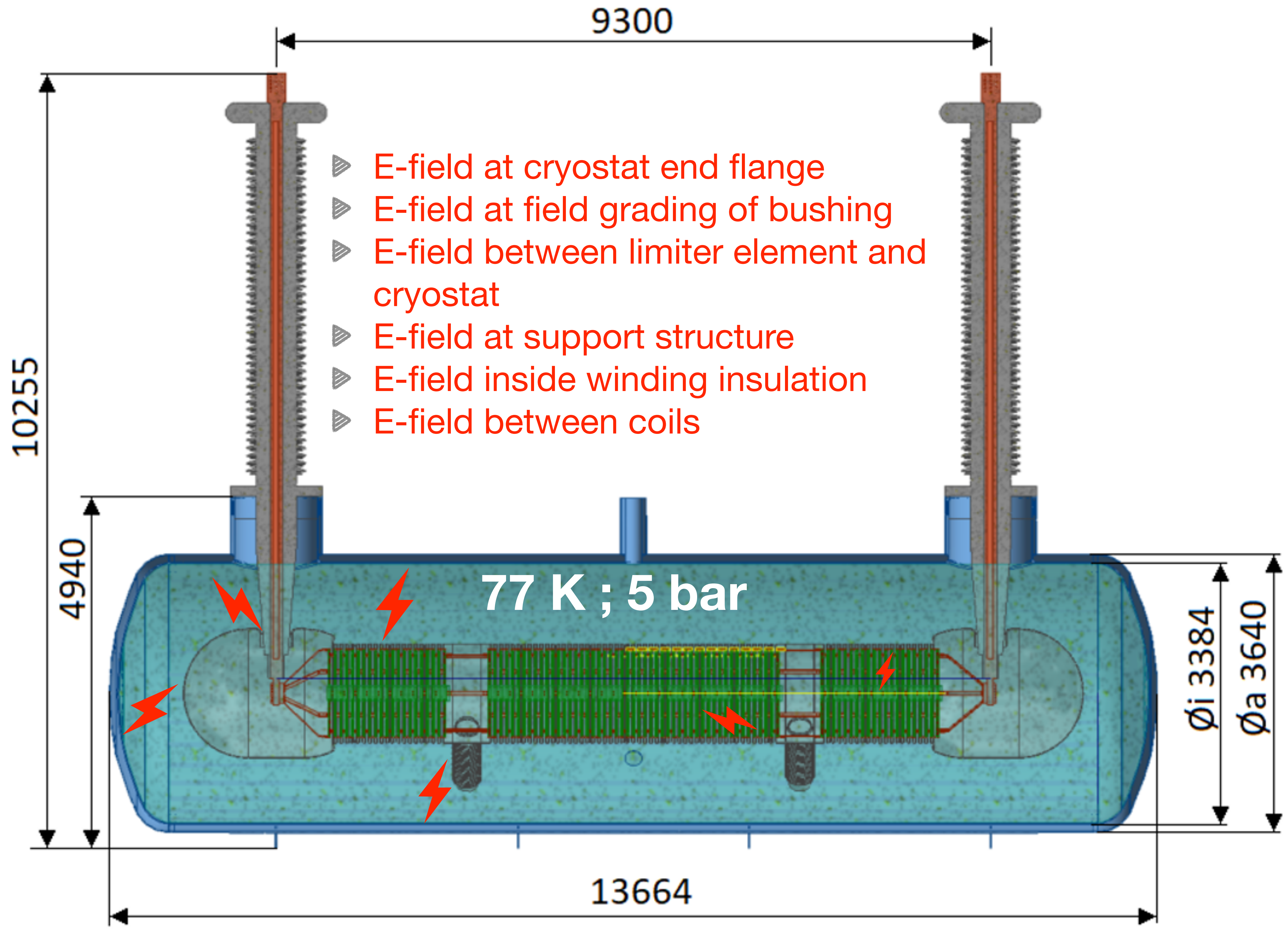
Complete study available

System layout for one phase

- **Sub-cooled LN_2** for electric insulation



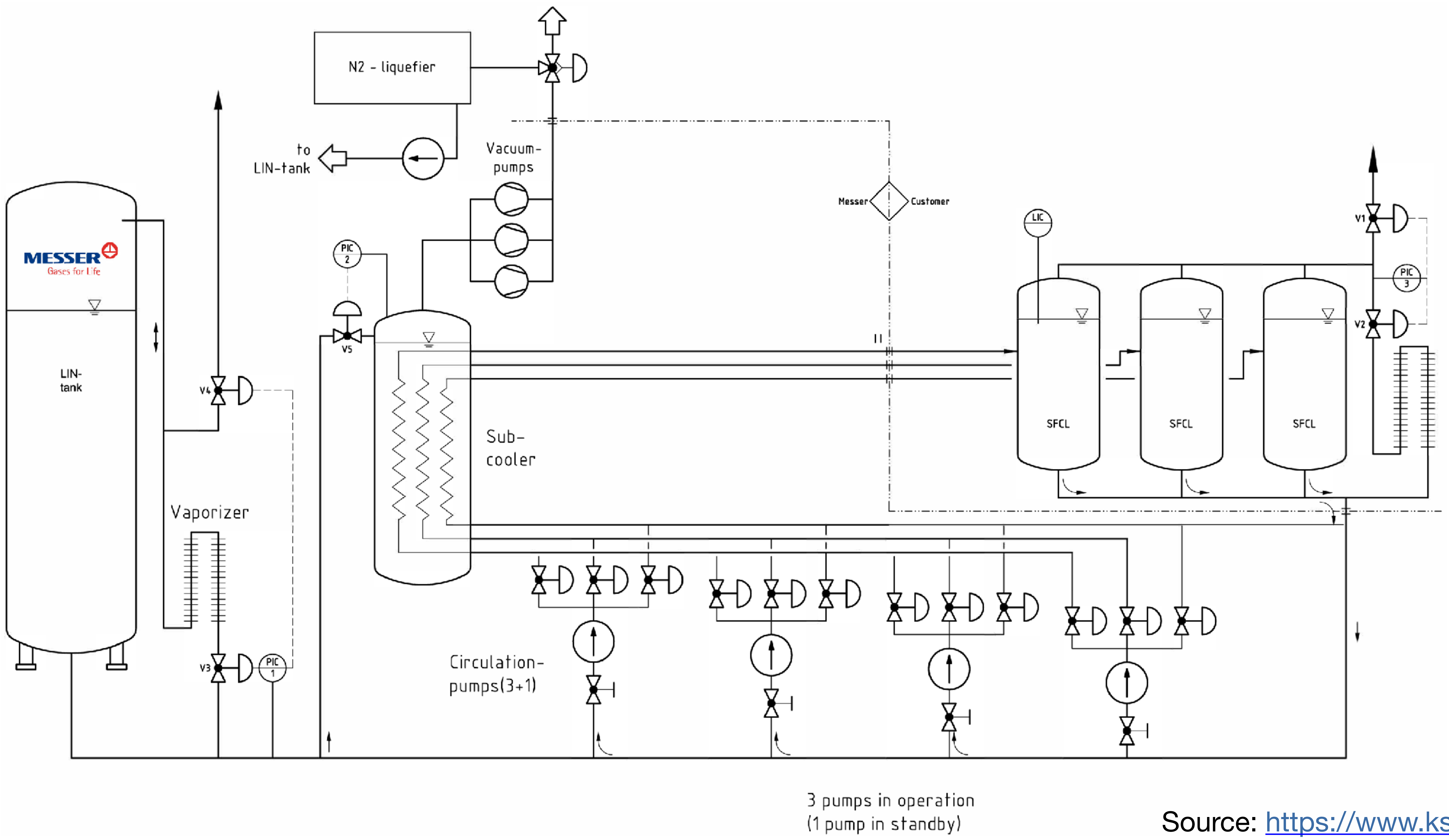
Parameter	Value
Amount of HTS	235 km
Total weight	142 t
Thereof LN_2	**94 t**



Source: https://www.ksp.kit.edu/site/books/series/karlsruher-schriftenreihe-zur-supraleitung-3/

Cooling of 380 kV SFCL

- Conceptual cooling layout by F. Herzog, Messer



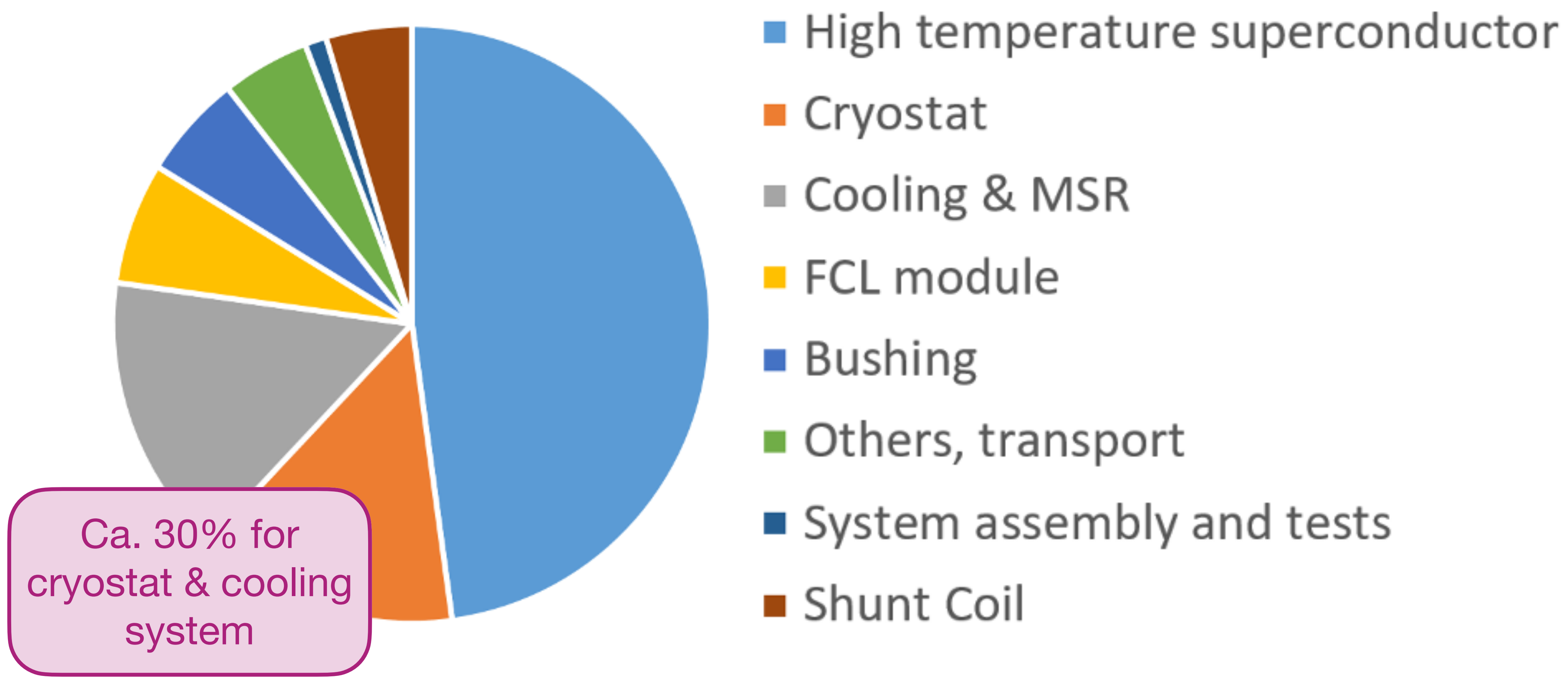
Coolant	LN_2
Tank operating pressure	5 to 8 bar
Cooling power	**18 kW @ 68 K**
SFCL supply temperature	< 71 K
SFCL return temperature	~ 77 K
Coolant circulation	3 x 30 kg/min
Average LN_2 consumption	~ 120 kg/h @ 4.5 kW

Source: https://www.ksp.kit.edu/site/books/series/karlsruher-schriftenreihe-zur-supraleitung-3/

Economic feasibility

Capital expenditure (CapEx)

	Minimum	Medium	Maximum
Total invest	19.0 M€	25.8 M€	37.5 M€



Operating expenses (OpEx)

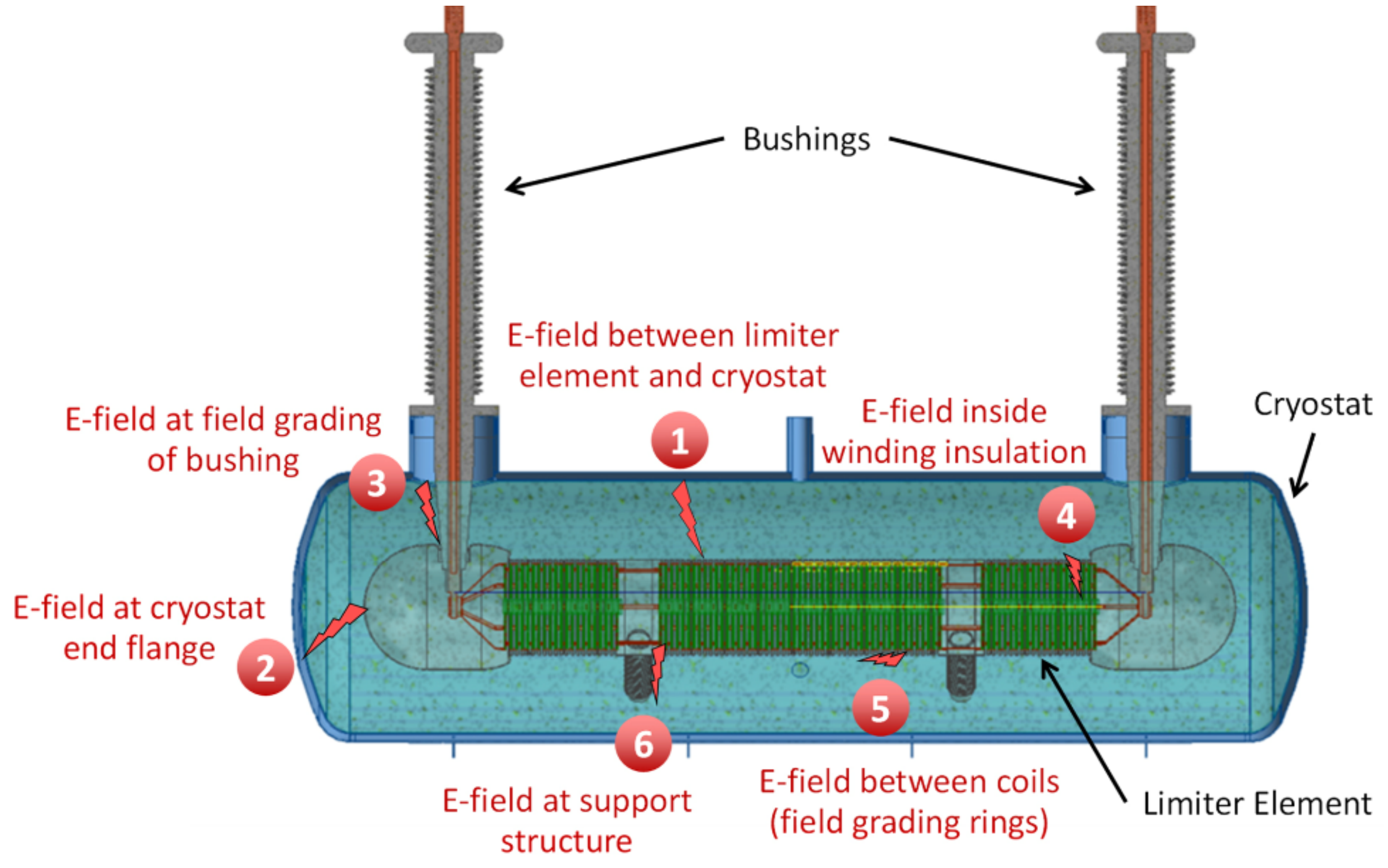
Load factor	0.7	1
AC loss	**786 MWh**	2057 MWh
Current lead thermal	104 MWh	104 MWh
Current lead ohmic	40 MWh	65 MWh
Cryostat	119 MWh	119 MWh
Others	8 MWh	8 MWh
Pumps	18 MWh	18 MWh
Total energy loss per year	1075 MWh	2371 MWh
Cost per year for losses	**315.000 €**	**695.000 €**

Source: https://www.ksp.kit.edu/site/books/series/karlsruher-schriftenreihe-zur-supraleitung-3/

There are **no technical showstoppers** for the further development of 380 kV / 5 kA resistive type SFCL

380 kV SFCL outlook

- **New R&D project** on key technologies for 380 kV SFCL **(Start: March 2025)**
  - Economic assessment — TenneT
  - Technical design — Siemens energy
  - Cryogenic bushing — HSP
  - High voltage design — Technology Arts Sciences TH Köln
  - Current limiting module — KIT Karlsruhe Institute of Technology



STATE-OF-THE-ART COOLING SYSTEMS

State-of-the-art cooling systems

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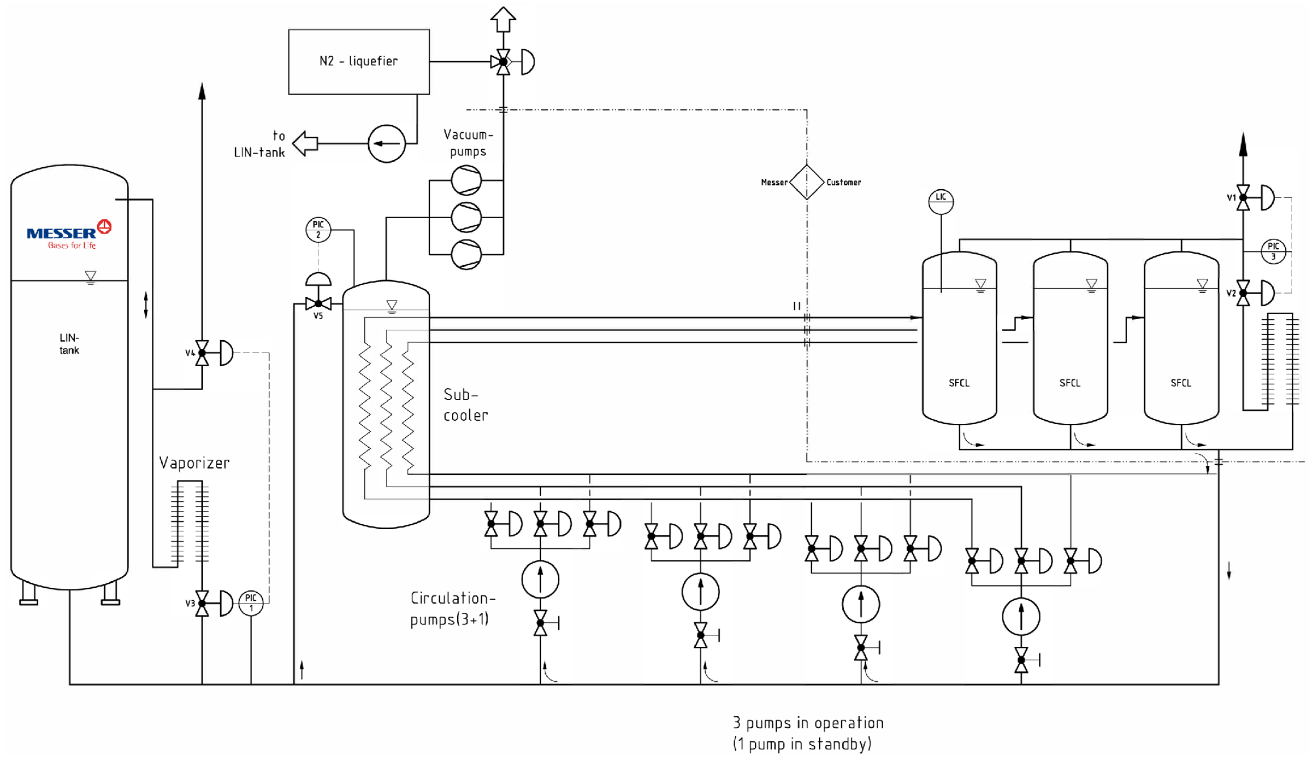
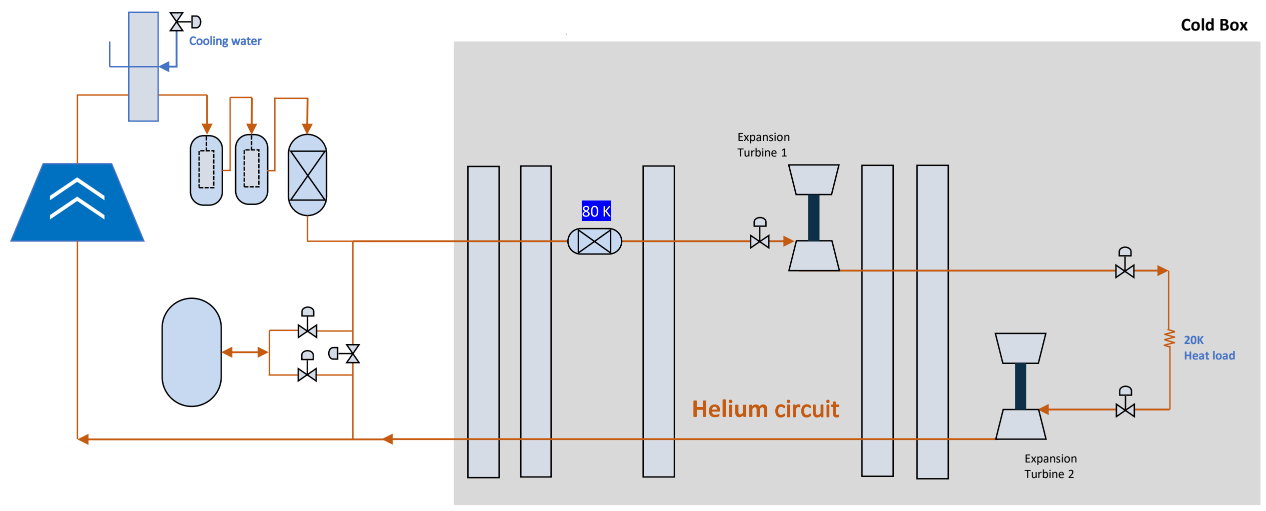
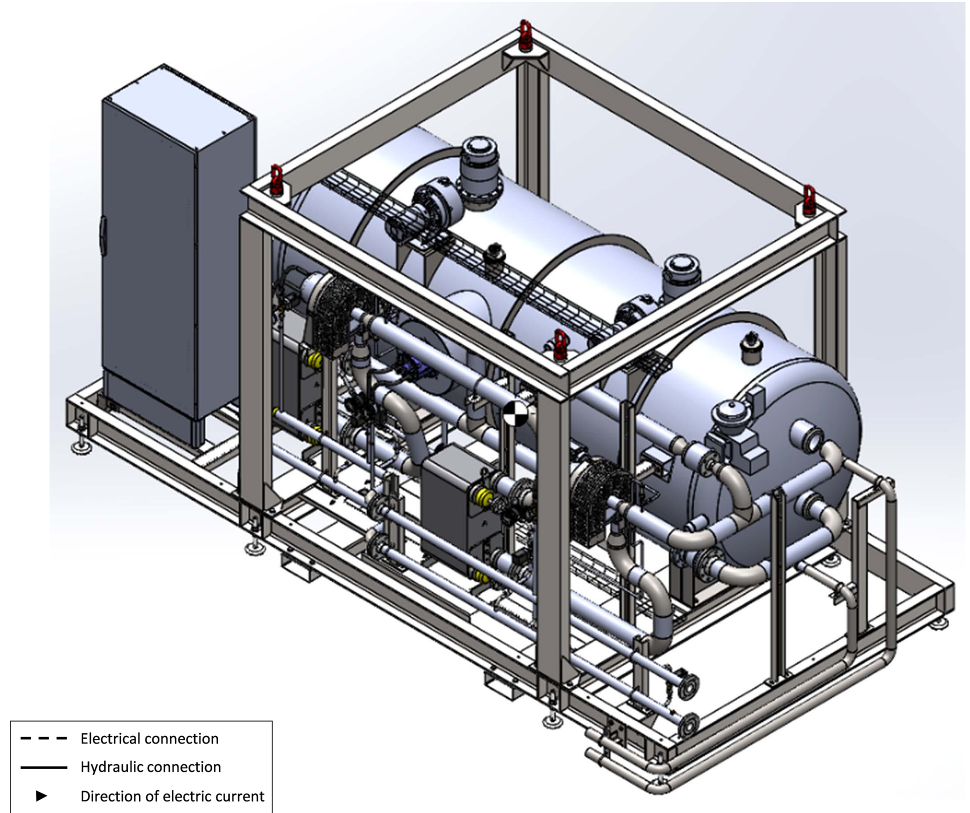
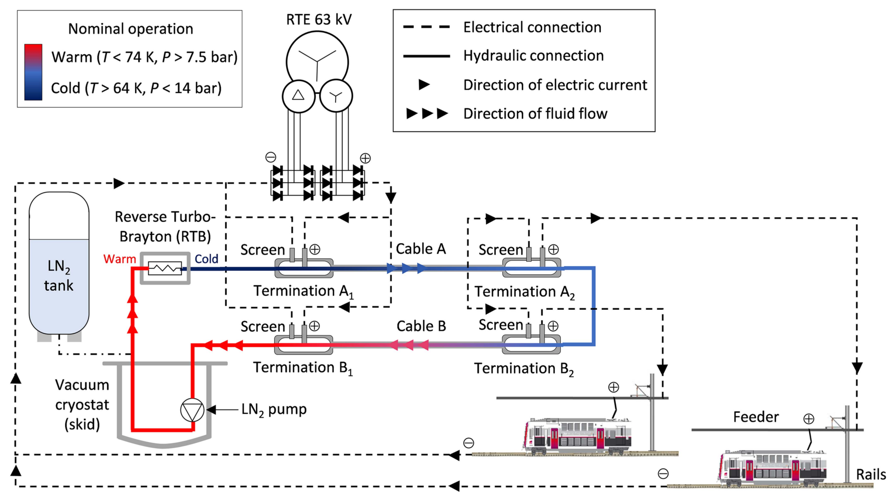
- **Most common solution:** LN_2 sub-cooling with Turbo Brayton cooler





Project	Cooling power	Temperature
SuperLink	30 kW	64-74 K
SuperRail	2 kW	67 K
Trimet	2 × 6 kW	77 K
	1.2 kW	20 K
SuperOx SFCL	3 × 2 kW	70 K
380 kV	18 kW	68 kW



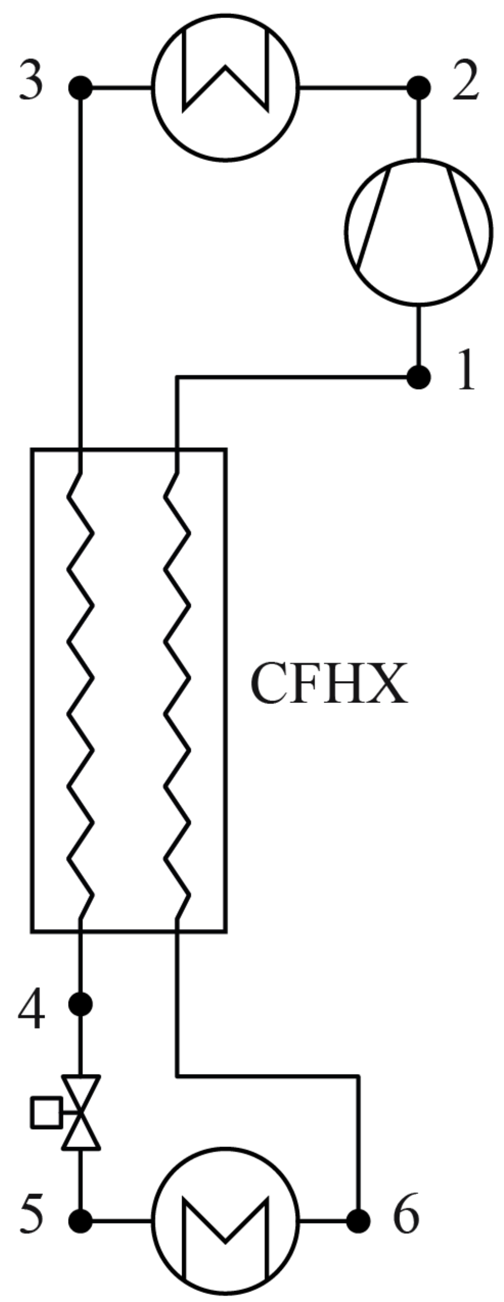


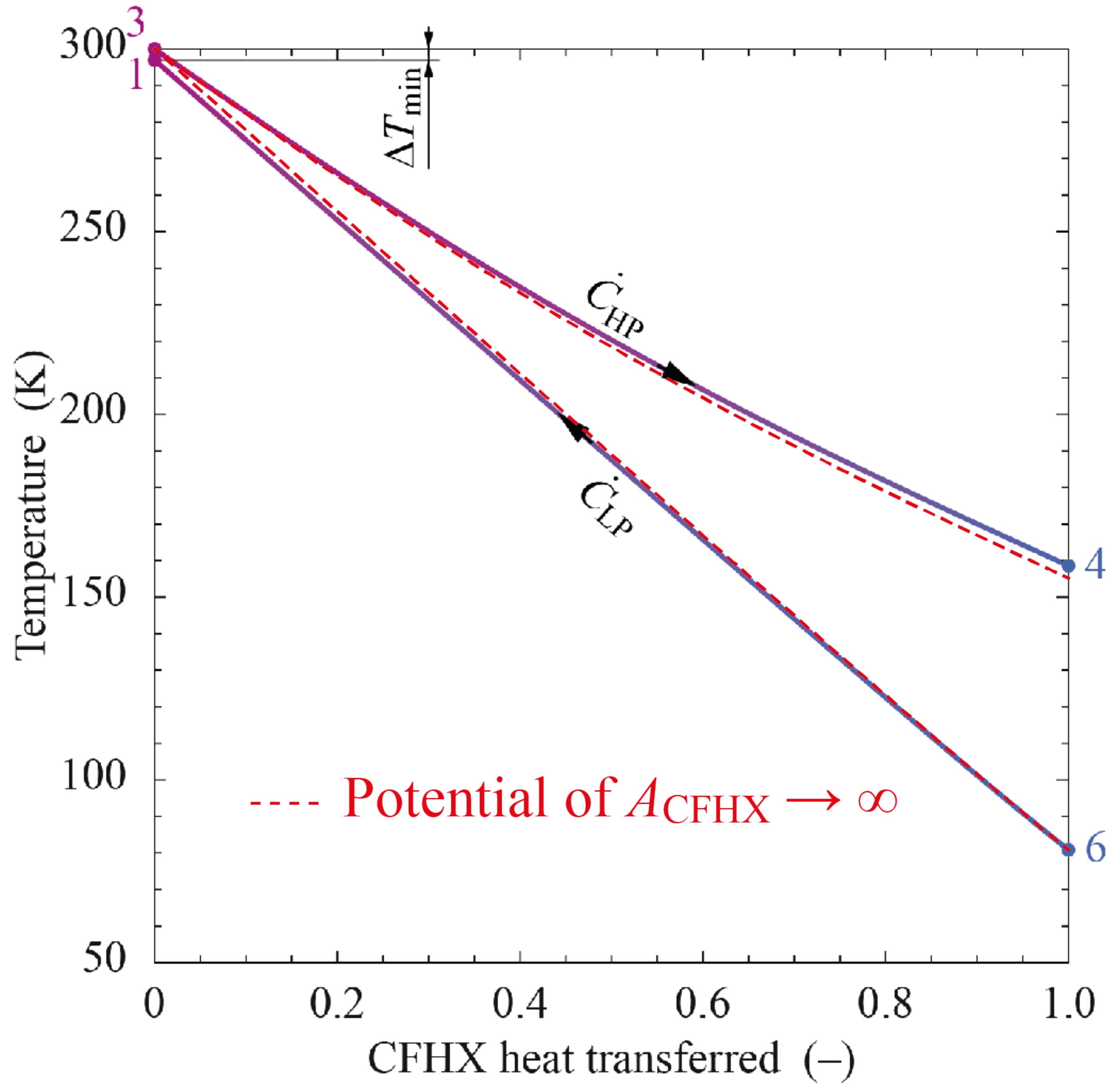
How to overcome common issues?					
Availability	Cost	Space requirements	LN_2 logistics	Efficiency	Reliability

The role of the refrigerant

The simplest cycle (Level 1 System complexity)

- Linde-Hampson cycle operated with e.g. N_2
  - Does not work {He, Ne} due to $\mu_{JT}(RT) < 0$





Reasons for low efficiency

- Different capacity flows $\dot{C} = \dot{M}\, c_p(T, p)$ yield increasing ΔT ⇐ First Law

- Entropy production by **heat transfer**

$$\dot{S}_{irr,\Delta T} \propto \frac{T_h - T_c}{T_h\, T_c}\, dq \qquad \Leftarrow \text{Second Law}$$

… further impact on irreversibility

- Entropy production by **expansion**

$$\dot{S}_{irr,\Delta p} \propto -\frac{v}{T}\, dp \qquad \Leftarrow \text{Second Law}$$

i.e. the specific volume v_4 is relevant

Limitations of the Turbo-Brayton cycle

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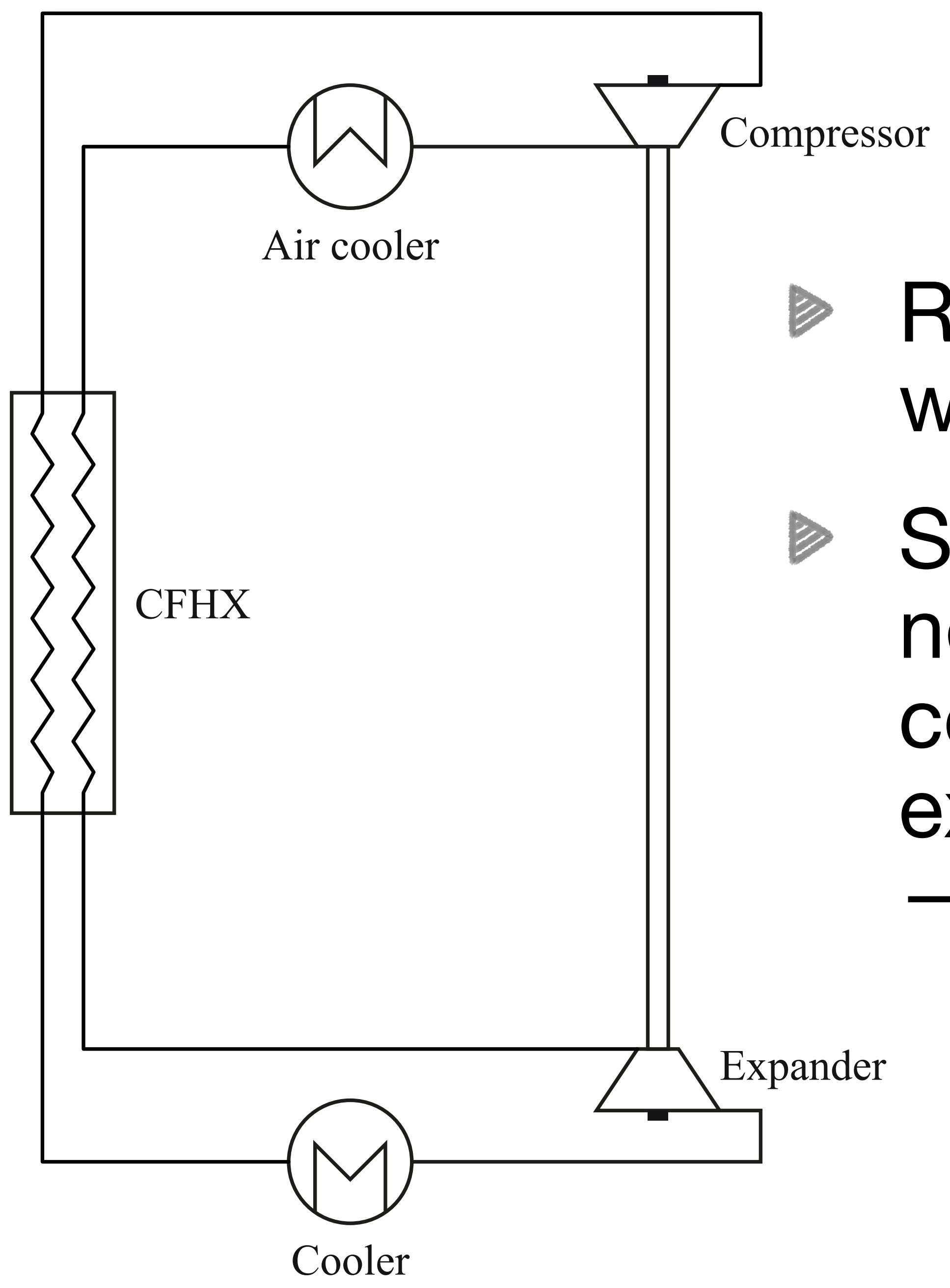
Process modification (Level 2)

- Replace expansion valve by turbo expander
  - Operation with {He, Ne} possible independent of Joule-Thomson coefficient μ_{JT}



  - Recovery of expansion work possible
  - Single-phase operation necessary to avoid condensation in the expander
→ Application of {He, Ne}

Characteristics of the working fluids

- {He, Ne} show nearly **ideal gas behavior** in the application range
  - Very good match of temperature profiles in the CFHX due to $c_p \neq f(p)$
- However, the ideal gas behavior implies the **least efficiency** of all refrigerants!
  - Largest isentropic coefficient
  - Use {He, Ne} only at very low temperature
- Single-phase operation yields the **lowest power density**
  - **Heat transfer coefficients** about **E-02 smaller** compared to vapor/liquid phase change
  - Very large heat exchangers determine **space requirements** in HTS power applications

Alternatives for cooling system improvement

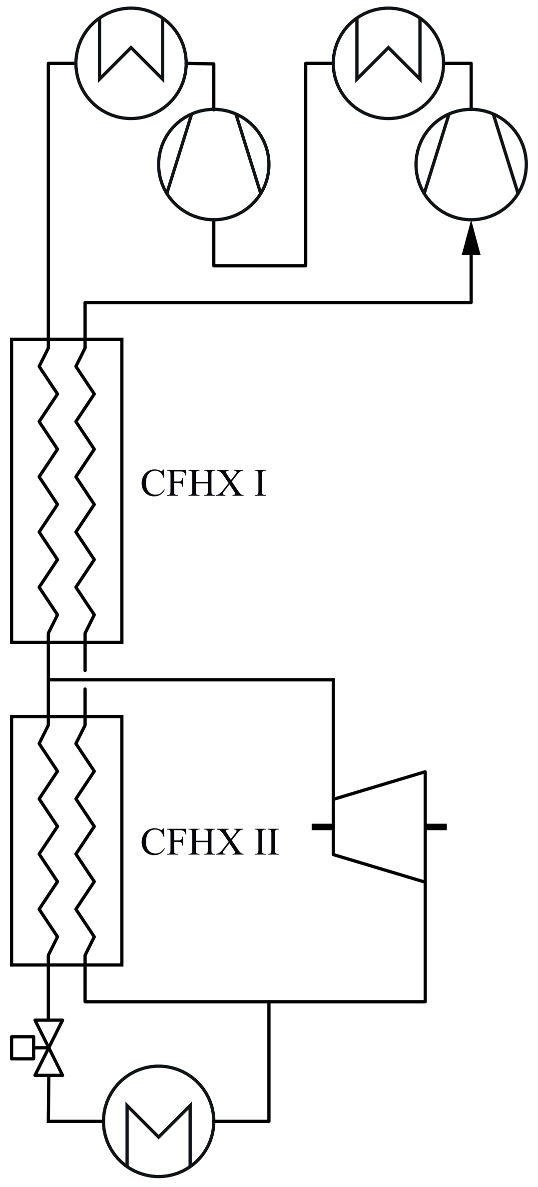
Level 3 | Cooling task with $\{\dot{Q}_0\,;T_0\}$ | Back to Level 1

1

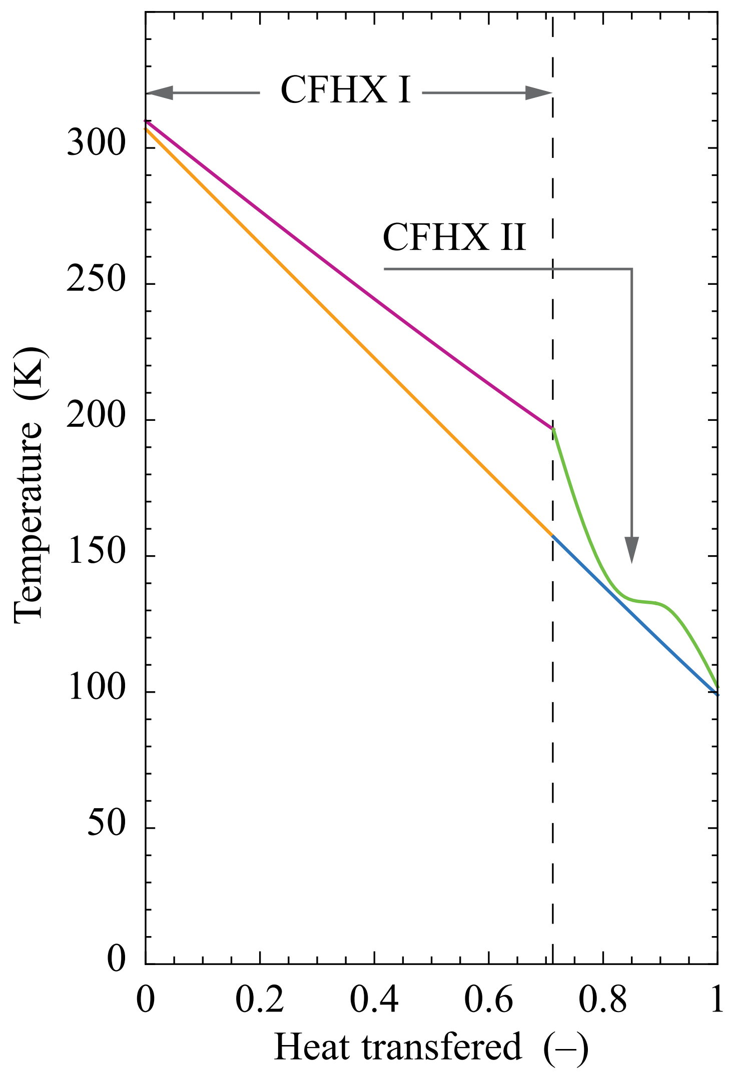
Pure refrigerant that is the best match to requirements

Optimize efficiency by **more complex process topology**

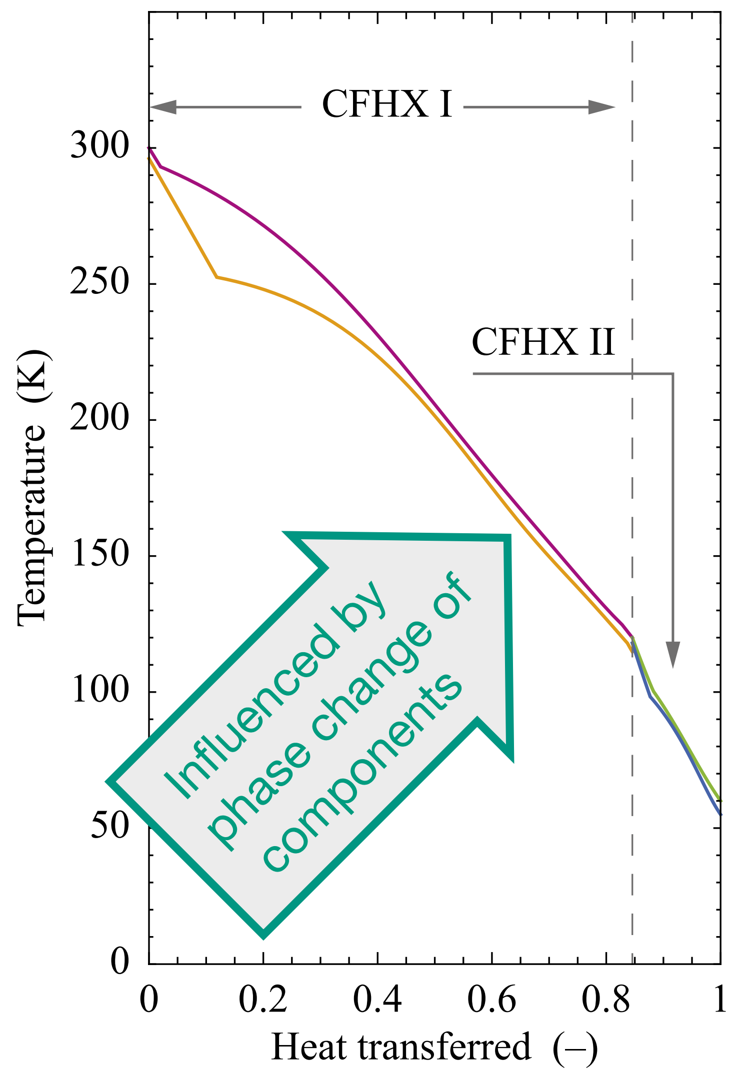
Process design

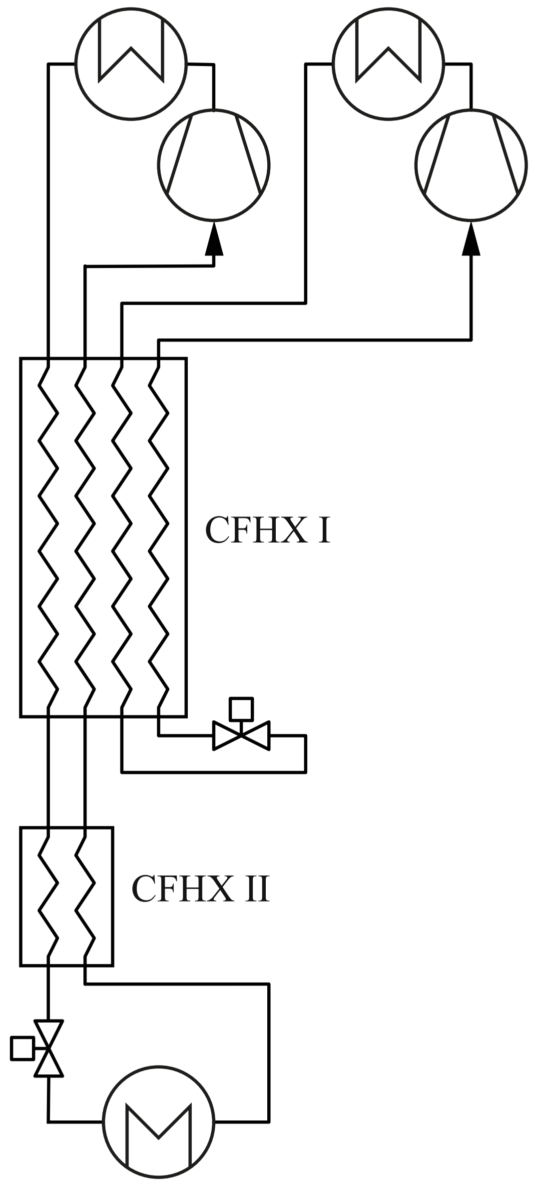


- **Example:**
  Claude cycle with **pure nitrogen**



- **Example:**
  Linde-Hampson cascade with **wide-boiling mixtures**





2

Design desired **refrigerant behavior**

Simple process with high efficiency

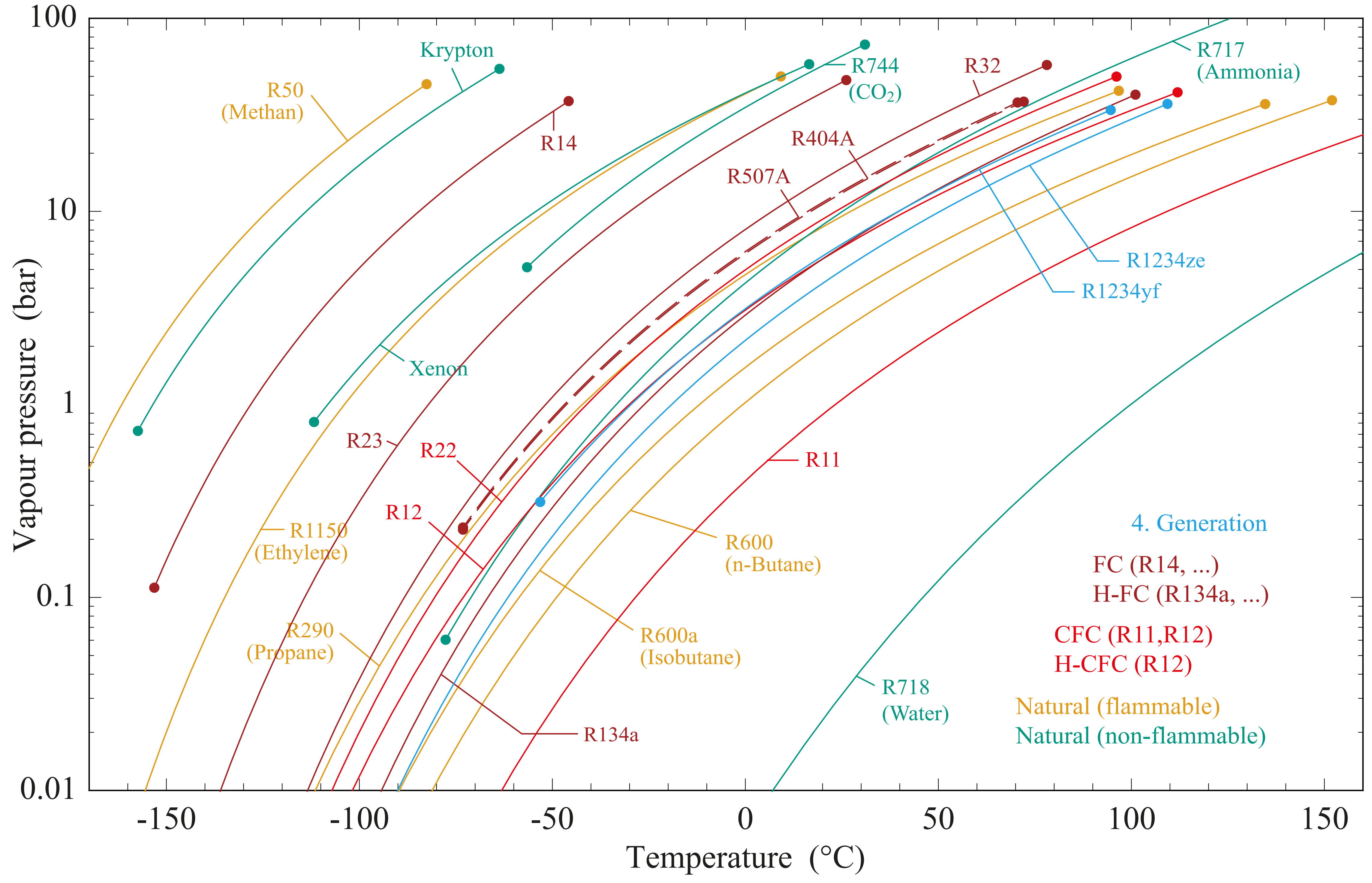
Refrigerant design

Historical perspective of refrigerant design

Karlsruhe Institute of Technology

- The **refrigerant** is the **key component** in any cooling system!
  - In principle, there is one „ideal“ refrigerant for each application/process topology

- In the past, refrigerants have been **synthesized** to optimize the efficiency of all kind of applications
  - All synthetic refrigerants have been causing **ecological problems → restriction, phase-out**
    - Ozone depletion, global warming, PFAS



- The only **sustainable** approach is the use of **natural refrigerant mixtures**
  - **Large increase of parameter space** (number of components, concentrations, pressure levels, …)
  - The use of **flammable components** (HCs) is **inevitable → safe handling** in closed cycles ✔

CMRC: AN EMERGING CRYOGENIC TECHNOLOGY

- Cryogenic Mixed-Refrigerant Cycles

Development levels of CMRC technology

3 CMRC-cooled **applications**

- Current leads/terminations for superconducting magnets/power cables
- Cooling stations for superconducting power cables
- Technology transfer to non-superconducting applications

2 **Heat exchanger** technology and **system modeling**

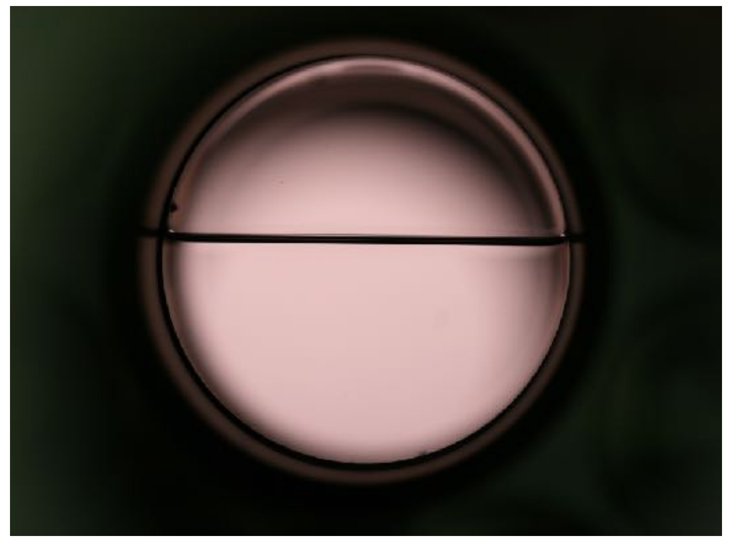
- Development of modeling frameworks
- Evaluation and validation of transport correlations
- Prototyping and testing

1 **Properties** of cryogenic fluid mixtures

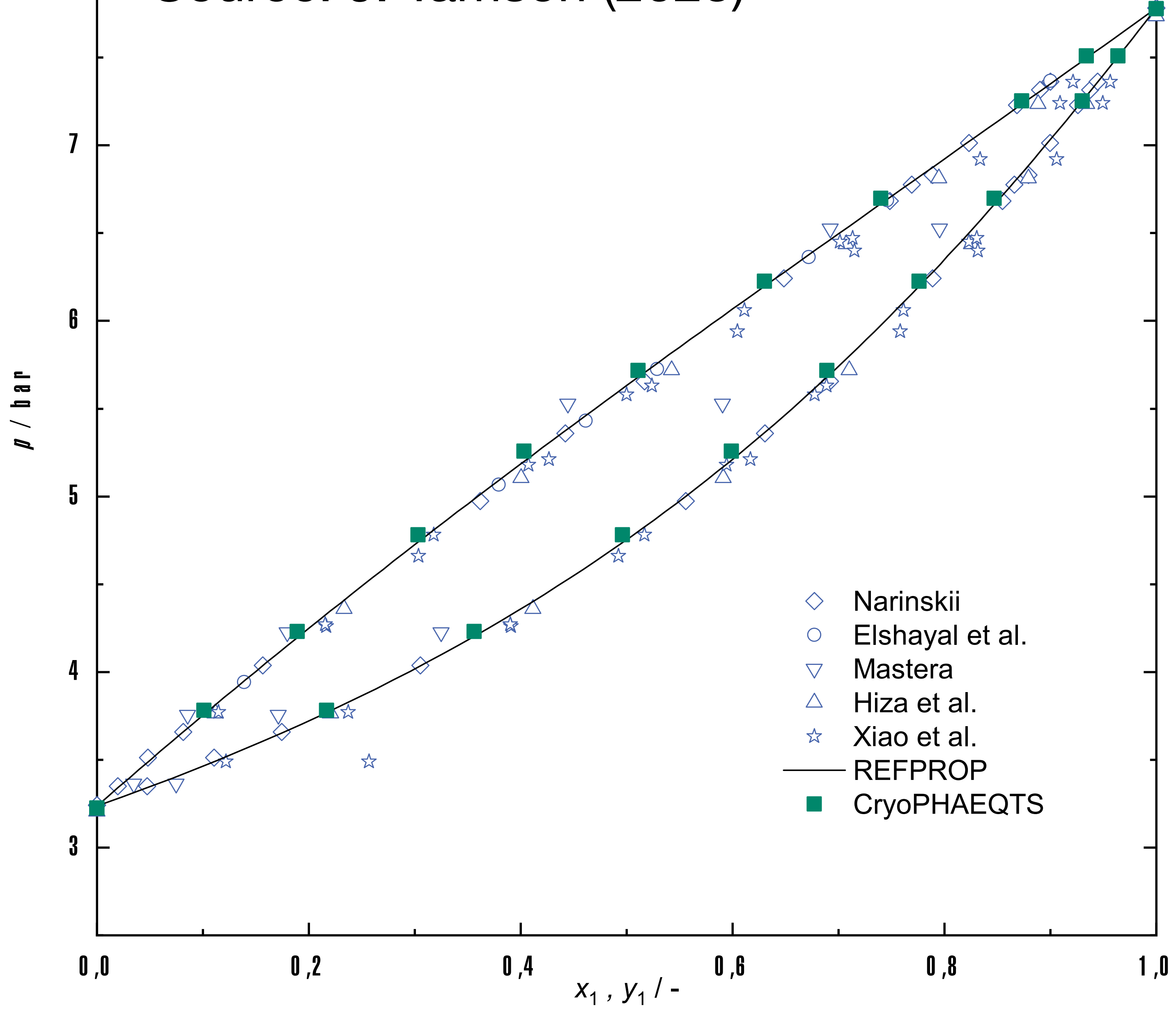
- Measurement of fluid state and transport properties
- Modeling of phase behavior by equations of state (EOS)

1 Properties of cryogenic fluid mixtures

- Cryogenic phase equilibria test stand (CryoPHAEQTS)
  - Validation/development of equations of state (EOS) for cryogenic fluid mixtures
  - Operation within $T = 8 \ldots 300\,\mathrm{K}$ and $p = 0 \ldots 150\,\mathrm{bar}$



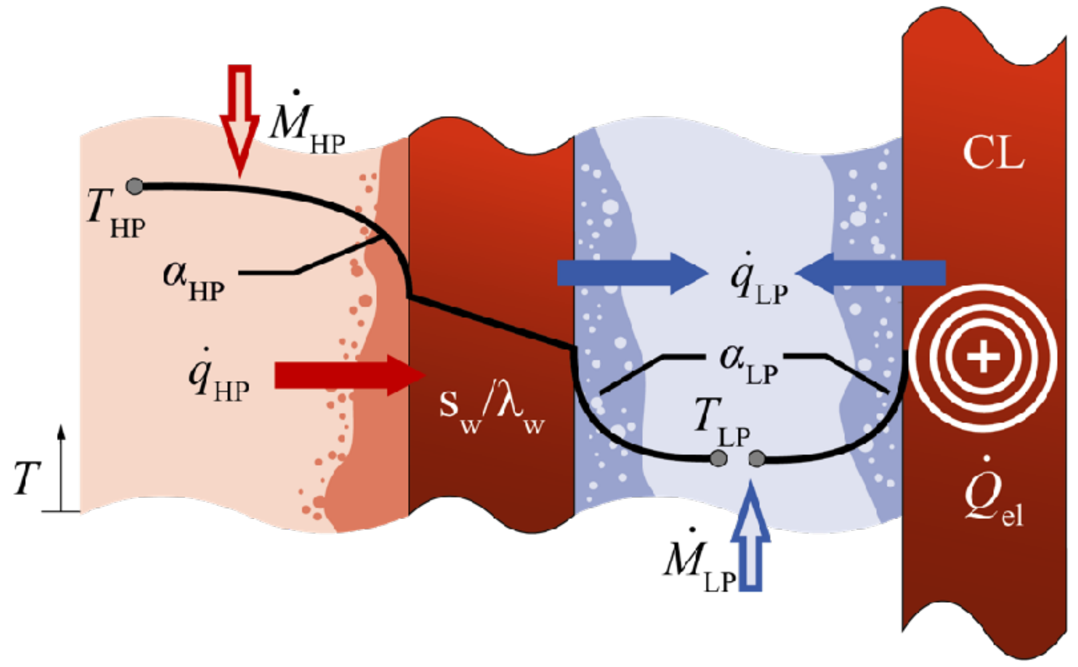
Example:
Ne-He phase equilibrium measurements
Source: J. Tamson (2023)



2 Heat exchanger tools and technology

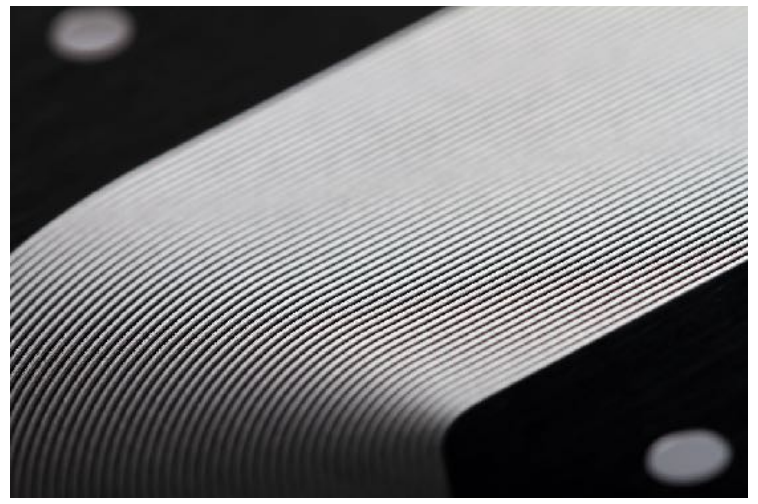
Modeling framework

- **Classical ε-NTU** models **inappropriate** due to changing fluid properties
- Extensive numerical framework
  - Compatible with numerous correlations
  - Single- and **two-phase flow**
  - Pure fluids and **zeotropic mixtures**
  - Longitudinal and parasitic heat loads
  - Inclusion of **electric modeling**



Prototype development and testing

- **Micro-channel** heat exchangers with **diffusion-bonded** metal foils
  - **Large spec. surface** $A_{HX}/V_{HX} \approx 10^3 \ldots 10^4\ m^2/m^3$ i.e. $\geq$ E+01 compared to plate heat exchangers
  - **Clean technology** suitable for cryogenic systems



First CMRC-CL prototype
Cu (2021)

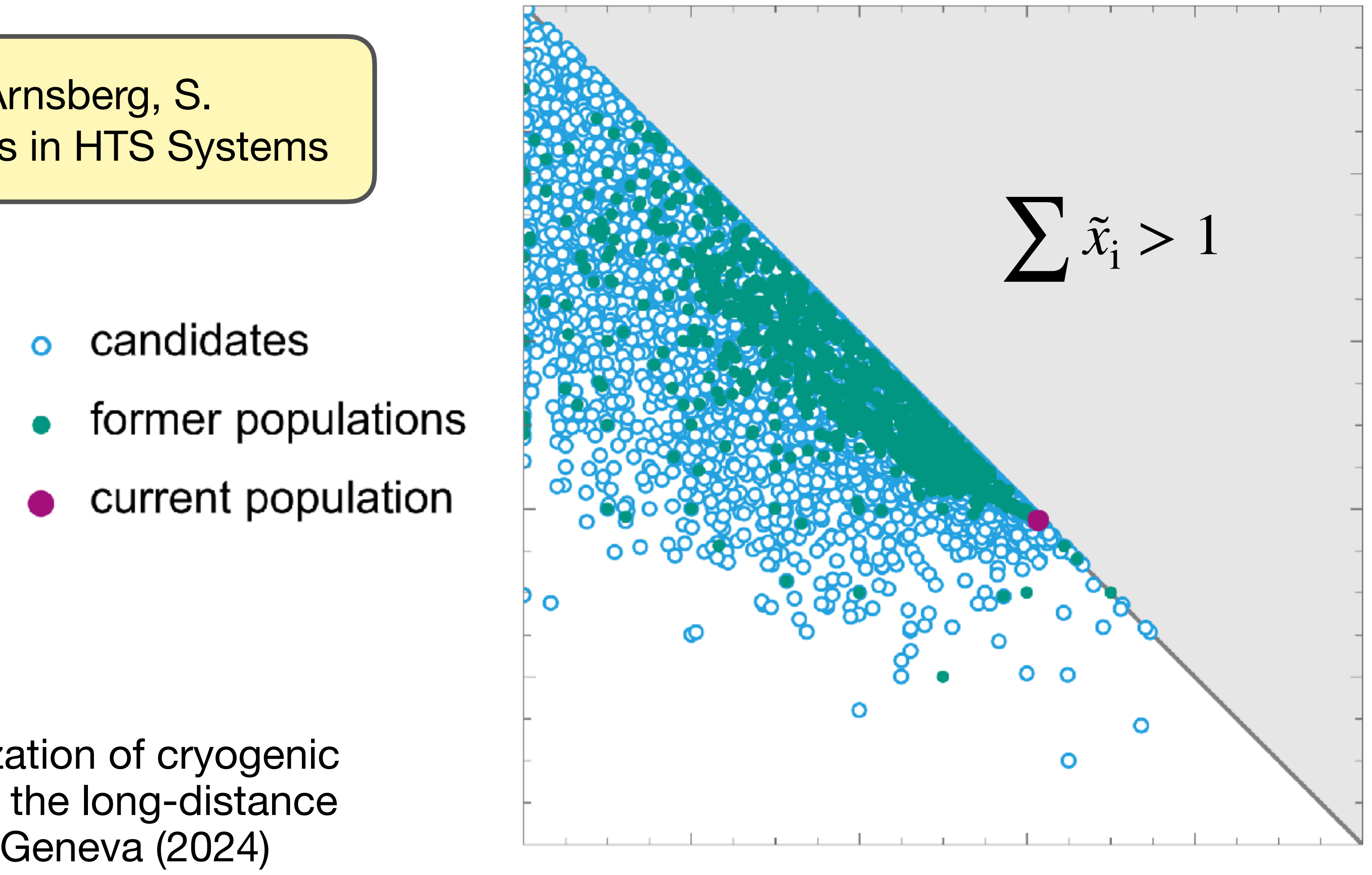
First CFHX prototype
SST (2019)

2 Refrigerant design by genetic algorithm

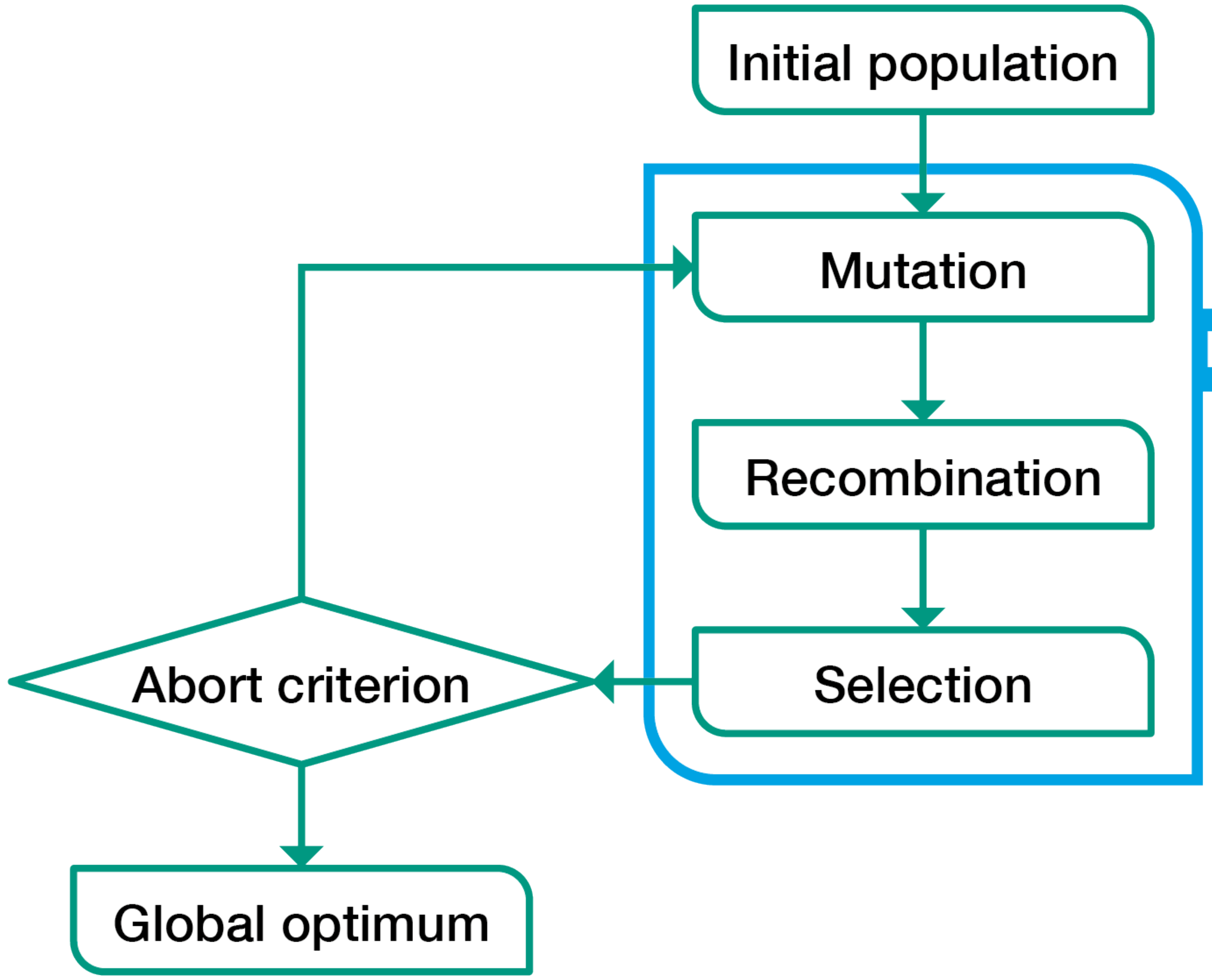
Karlsruhe Institute of Technology

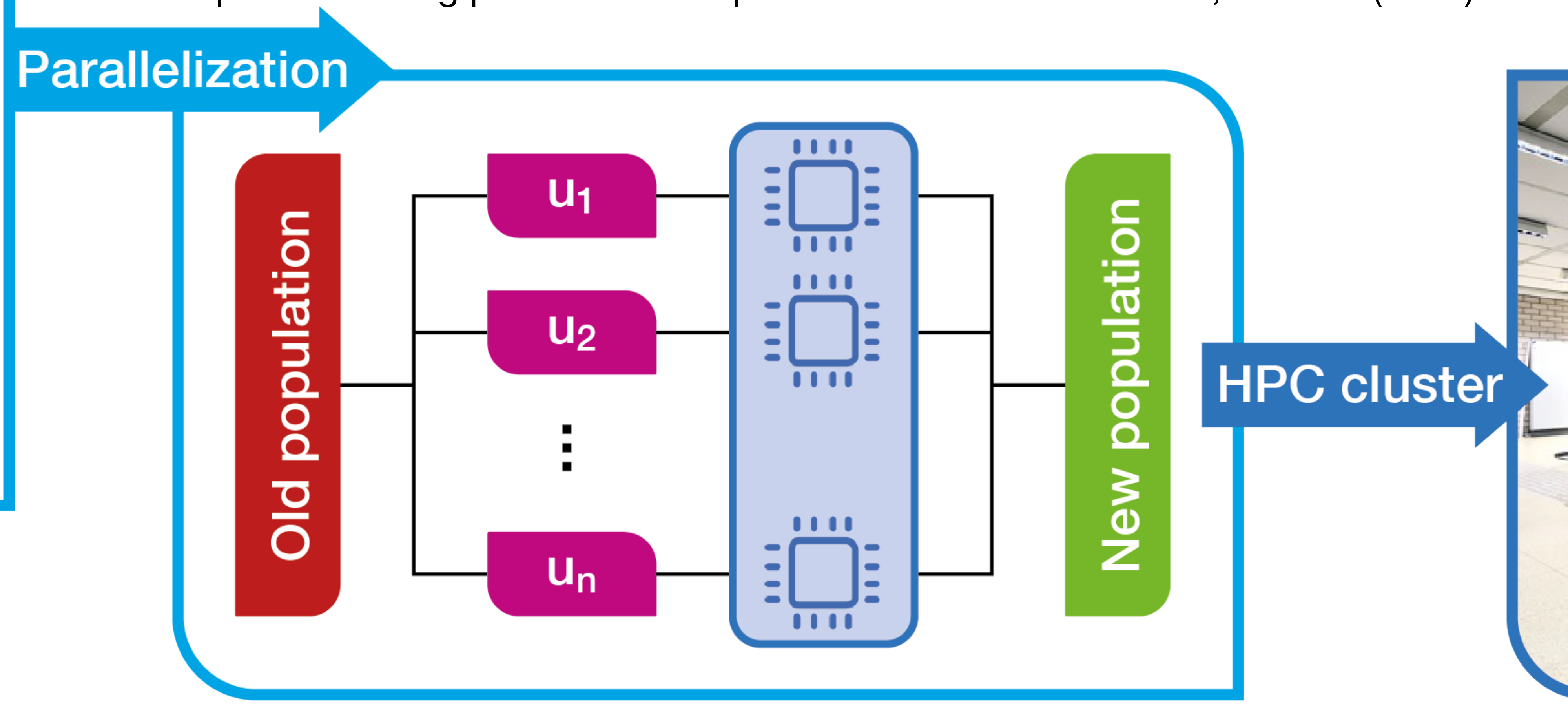
- Differential Evolution (DE)
  - No derivatives needed
  - Global optimization → „Exploration & Exploitation“

More details in 2nd poster session on Friday: F. Boehm, J. Arnsberg, S. Grohmann: Application of Cryogenic Mixed-Refrigerant Cycles in HTS Systems



Source: F. Boehm, W. Batista de Sousa, S. Grohmann: Optimization of cryogenic mixed-refrigerant cascades for intermediate cooling stations of the long-distance superconducting power cable SuperLink. ICEC29/ICMC 2024, Geneva (2024)

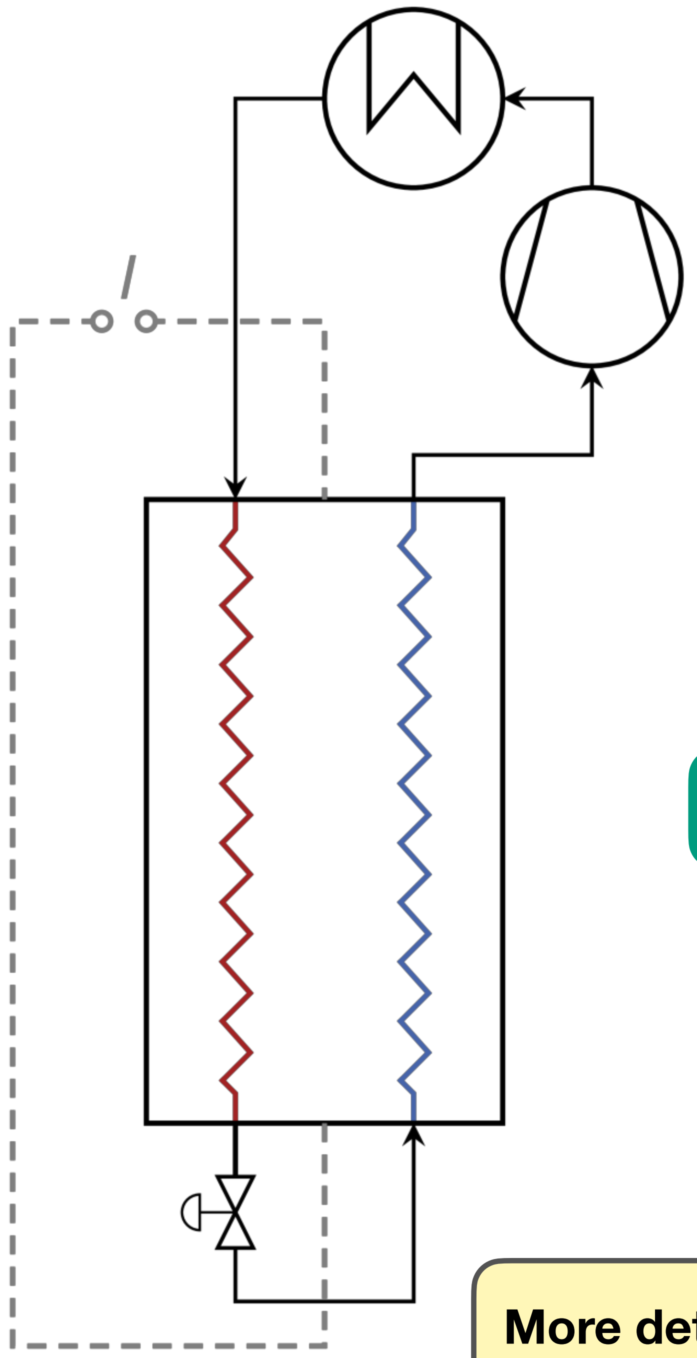


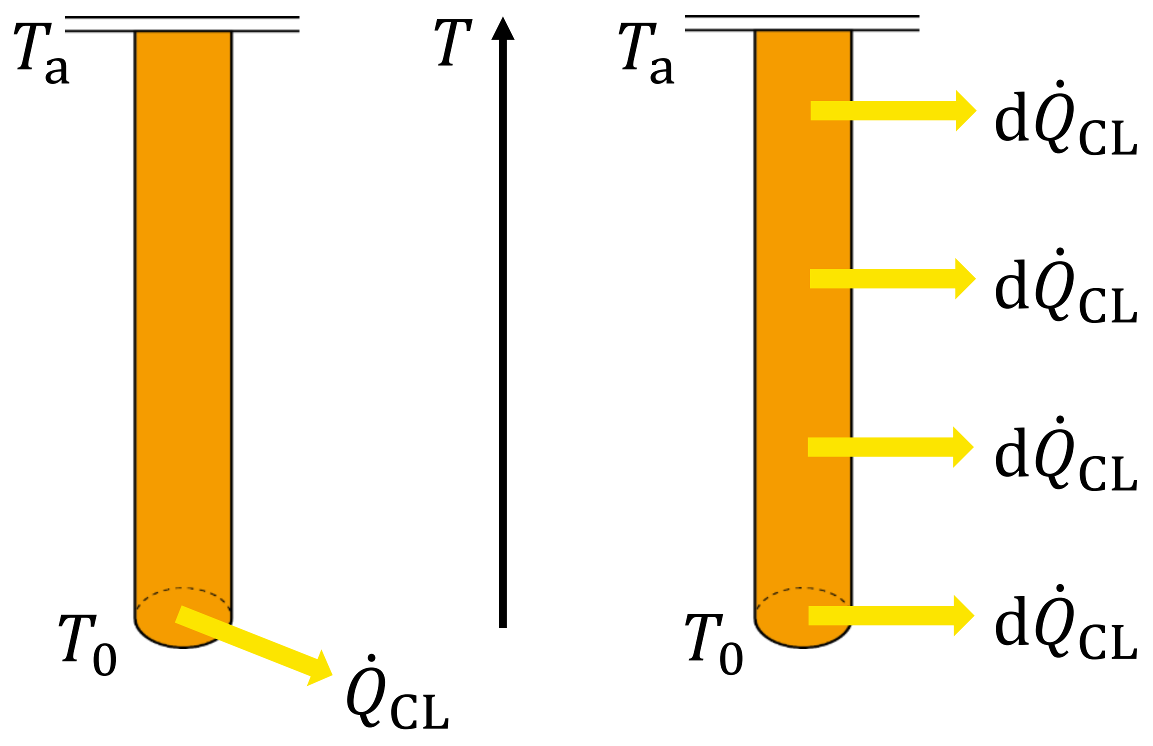


3 Sc. current leads/power cable terminations

Theoretical power demand

- Cooling of conduction cooled (CC-CL) vs. continuously cooled (∞-CL) current leads





$P_{CC-CL} = 123\ \mathrm{W/kA}$

$P_{\infty-CL} = 73\ \mathrm{W/kA}$

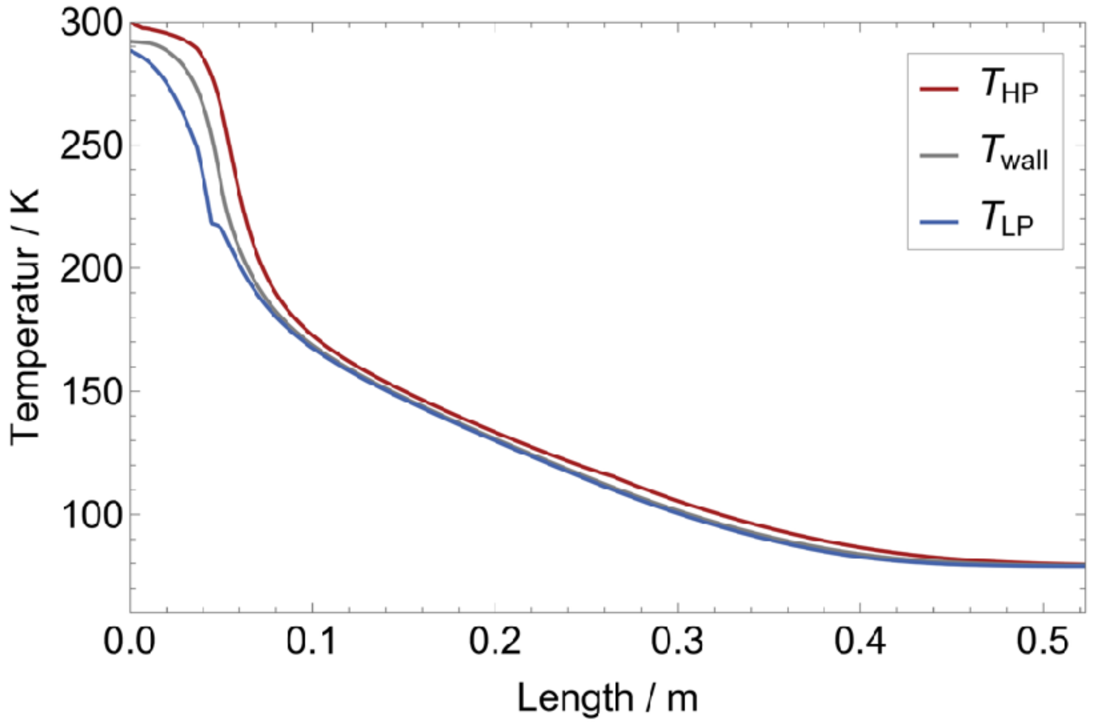
Energy saving 40%

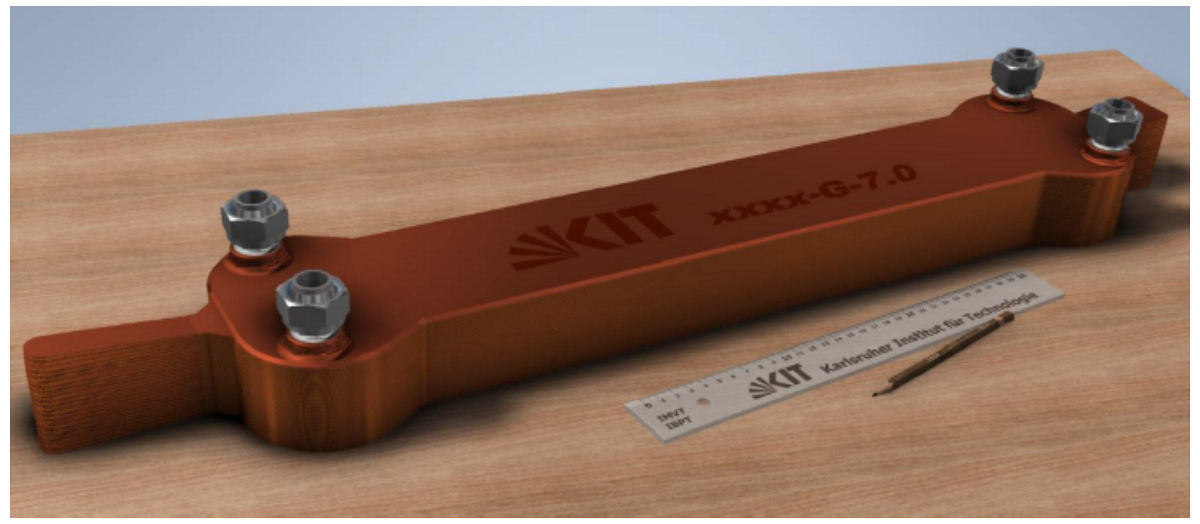
More details in 2nd poster session on Friday: F. Boehm, J. Arnsberg, S. Grohmann: Application of Cryogenic Mixed-Refrigerant Cycles in HTS Systems

Real system comparison

Parameter	CC-CL	CMRC-CL
Temperature at cold end	79.3	79.3
Design current	10 kA	10 kA
Mass flow of mixed refrigerant	-	17 g/s
Heat load due to ohmic losses	424 W	70 W
Total power demand	8.1 kW	2.1 kW
Carnot efficiency	**15 %**	**35 %**

Energy saving 75%

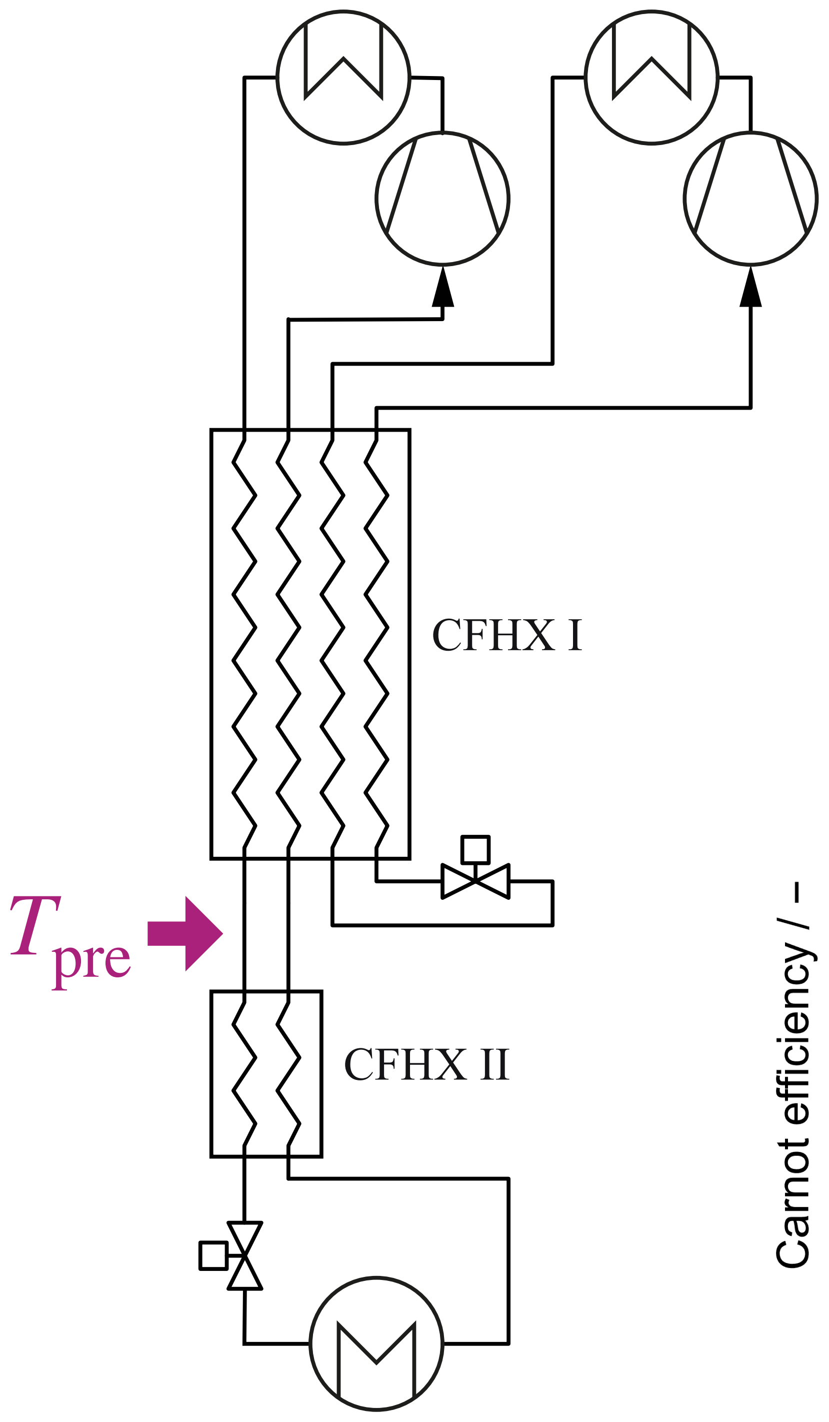




Source: J. Arnsberg, F. Boehm, S. Grohmann: Mixed-refrigerant cooled 10 kA current leads for superconducting applications. ICEC29/ICMC 2024, Geneva (2024)

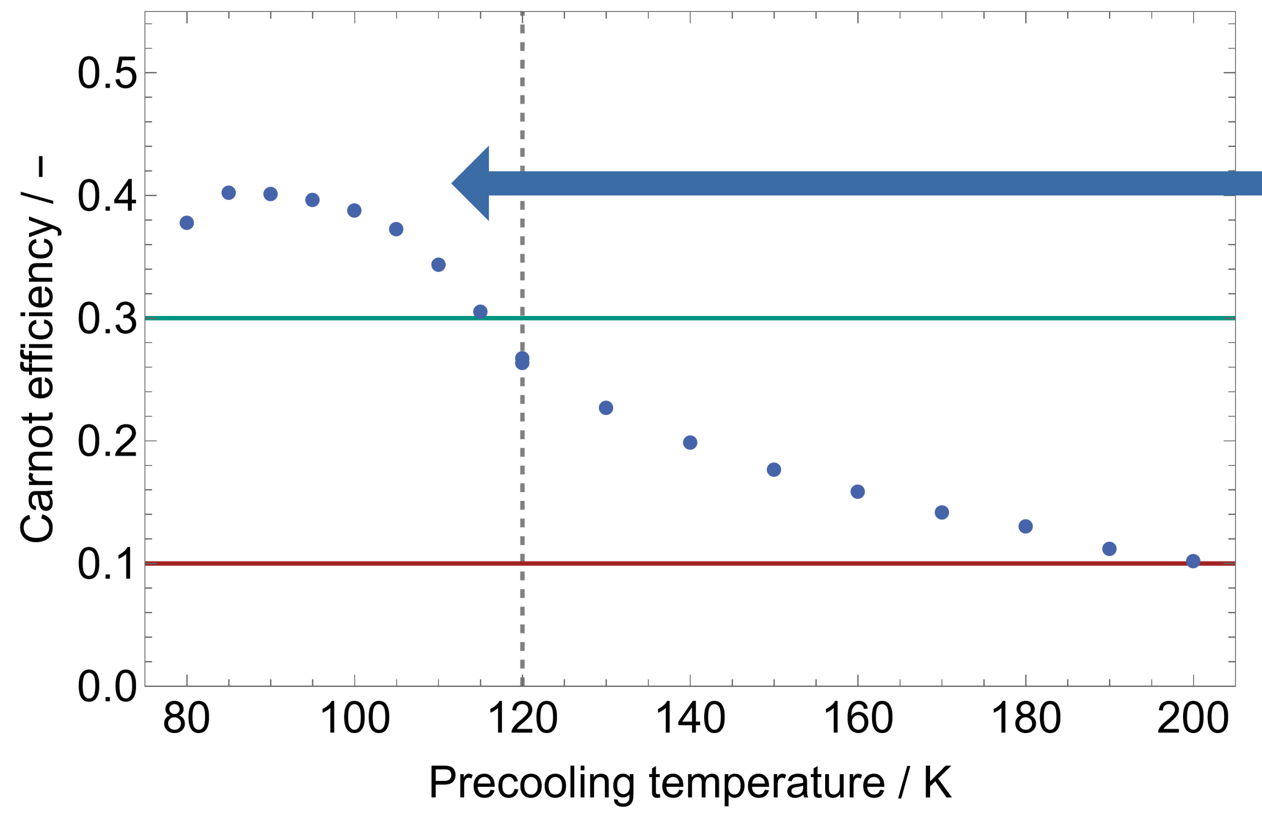
3 HTS power cable cooling stations

- **Example:** Cooling station with **30 kW @ (64…74) K** for SWM SuperLink
  - CMRC cascade with optimization of pre-cooling temperature



Fixed parameters	
Cooling temperature T_0	64…74 K
Ambient temperature T_a	293.15 K
$\Delta T_{min,a}$ to ambience	5 K
$\Delta T_{min,CFHX}$ in CFHX	2 K
Compressor efficiency η_{is}	0.7

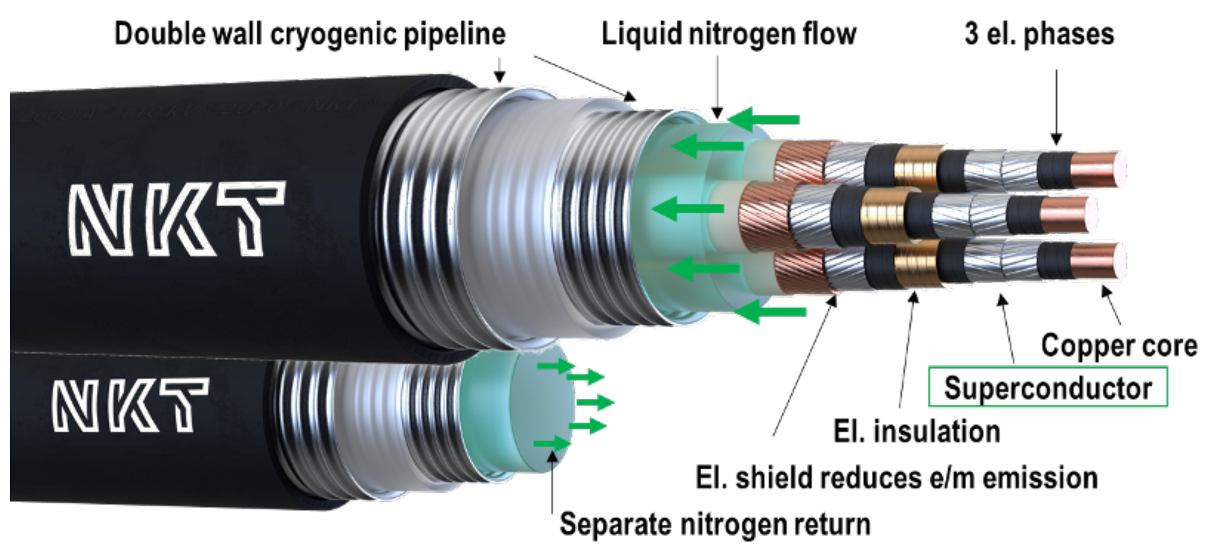
Optimization parameters	
Pre-cooling temperature T_{pre}	80…200 K
Low-pressures p_{LP}	1…20 bar
High-pressures p_{HP}	10…60 bar
Component concentrations	0…1

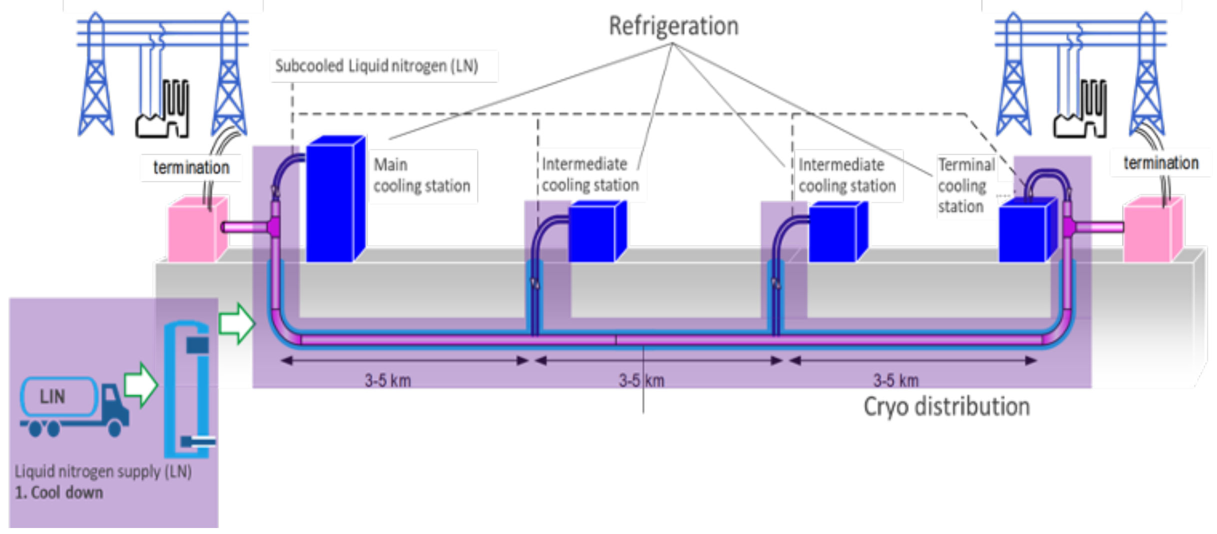


CMRC reaching **40% Carnot !**

Turbo Brayton ≤ 30% Carnot

Cryocooler ~10% Carnot





More details in 2nd poster session on Friday:
F. Boehm, J. Arnsberg, S. Grohmann: Application of Cryogenic Mixed-Refrigerant Cycles in HTS Systems

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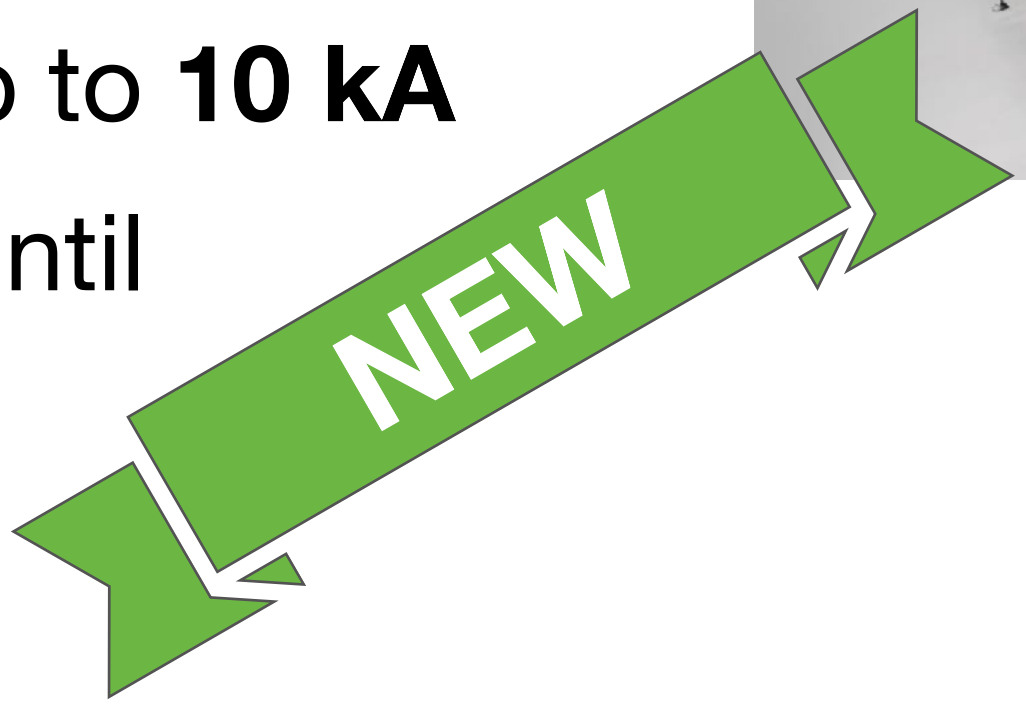
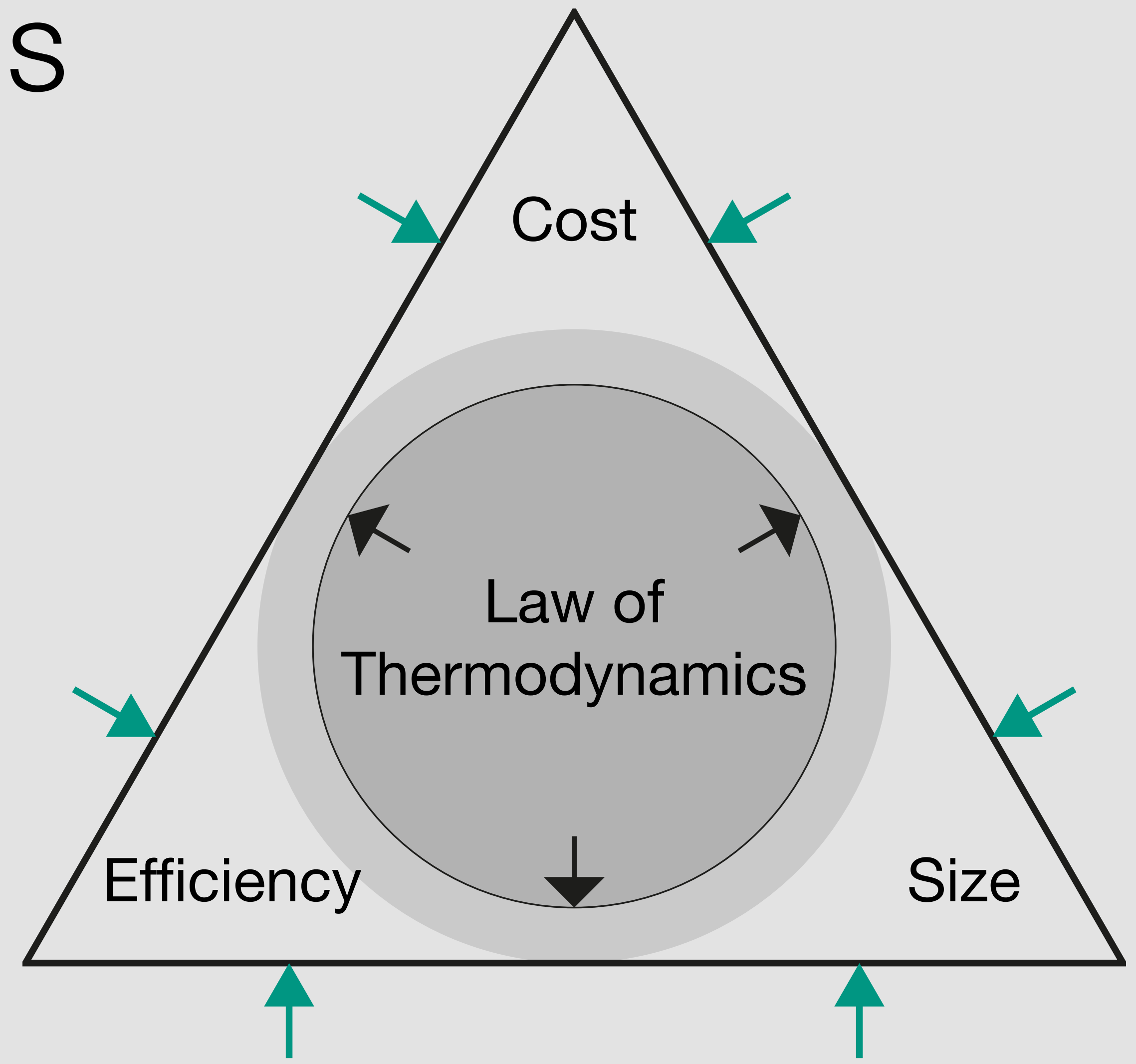
3 COMPASS test facility

- **Comp**act **A**ccelerator **S**ystems Test **S**tand
  - Platform for **prototype developments** up to **TRL6**
  - Single or cascade operation of **two CMRC circuits**
  - **Cryocooler** for LTS operation down to **4 K**
  - **Power supply** up to **10 kA**
  - Commissioning until the **end of 2024**



Conclusions

- **HTS power applications** require **10s of kW** cooling power at ***T* < 77 K**
- State-of-the-art is **LN_2 sub-cooling** with **Turbo Brayton** (He cooling at T < 63 K)
- Emerging **CMRC technology** for cryogenic applications
  - Increase of **energy efficiency**
    - Current leads up to **factor 4**, i.e. **75% energy saving**
    - LN_2 sub-cooling stations with **40% Carnot**
  - **Sustainable** using only natural refrigerants
  - **Scalable** to required **cooling power** range
  - High **compactness** due to two-phase operation
  - **Maintenance-free** operation possible by design
  - **Moderate cost** of simple process topology with **standard components** from refrigeration industry



THANK YOU FOR YOUR ATTENTION !