Development potential of mid-scale cooling systems for HTS applications

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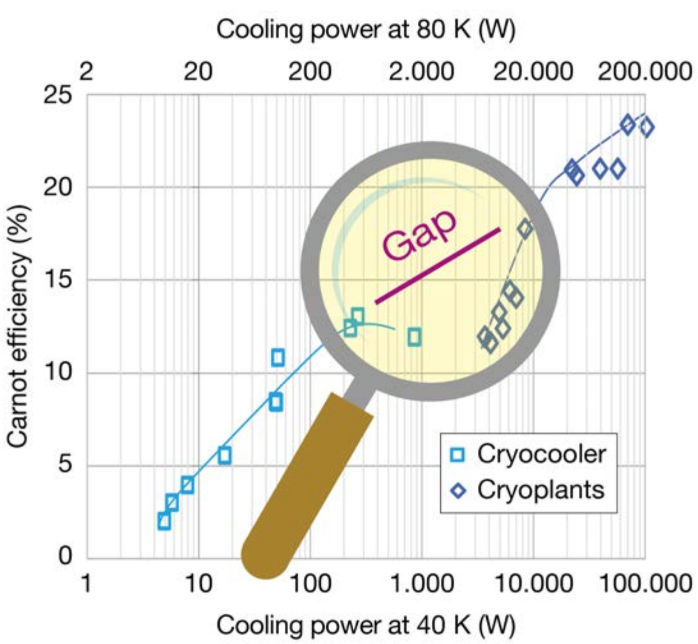

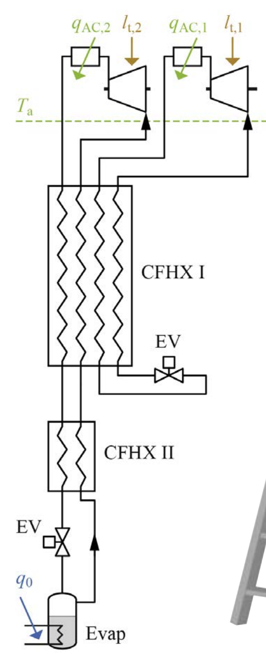

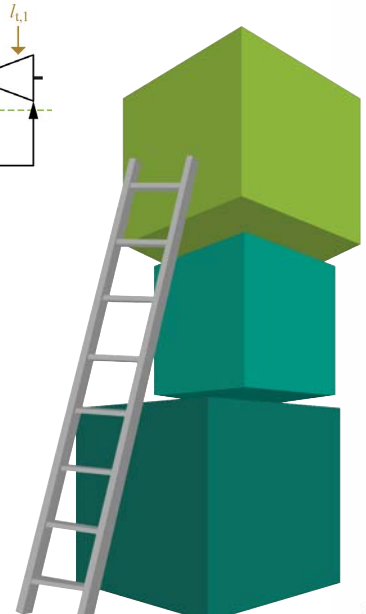

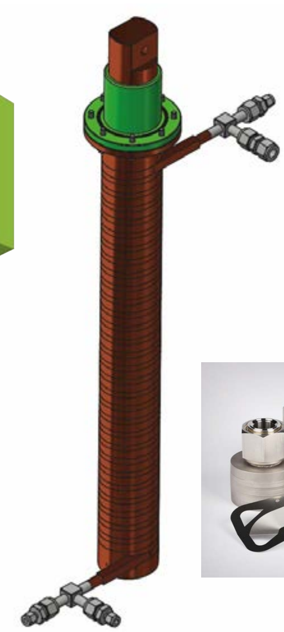

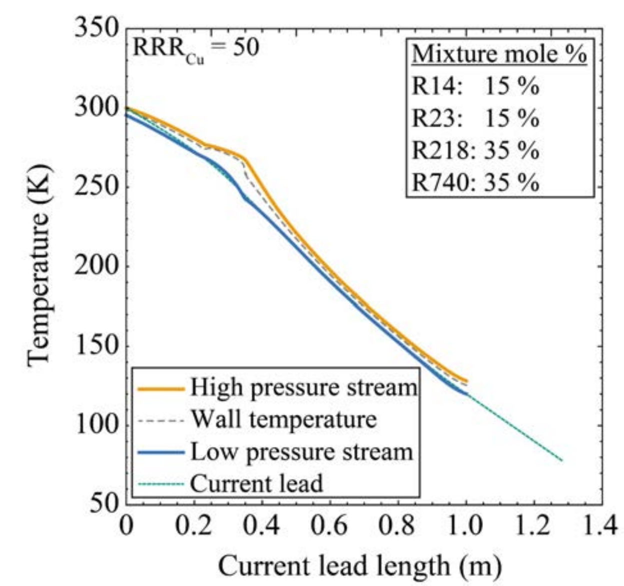

Outline

A) Cooling requirements in HTS applications

B) State-of-the-art cooling technologies

C) Development potential of mid-scale cooling systems for HTS applications

D) Conclusions

A) COOLING REQUIREMENTS IN HTS APPLICATIONS

Cooling requirements

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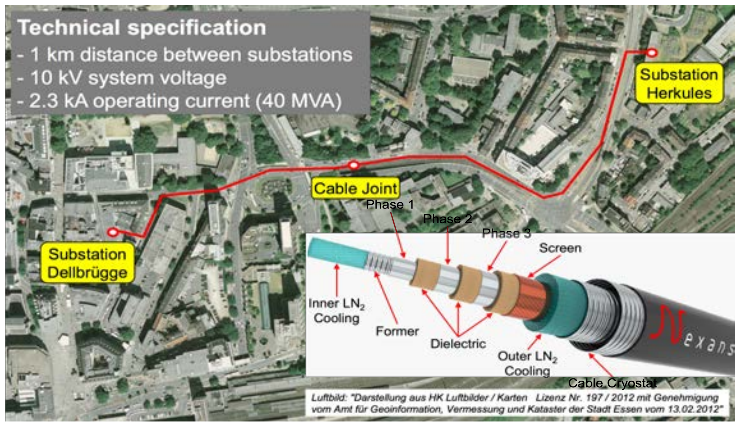
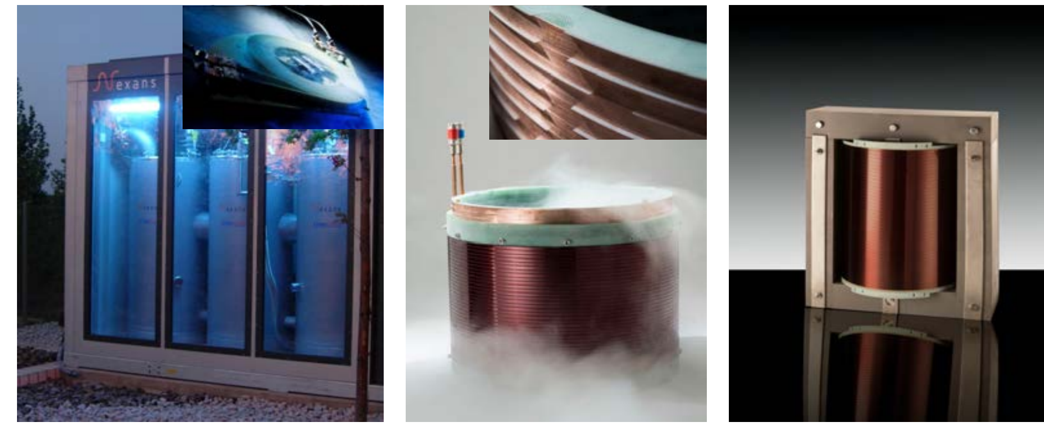
- **Examples** of HTS power applications



Sc. power cable, AmpaCity project

Sc. hydrogenerator, GE



Sc. fault current limiters and transformers, KIT, Nexans

Sc. wind turbines, Suprapower project

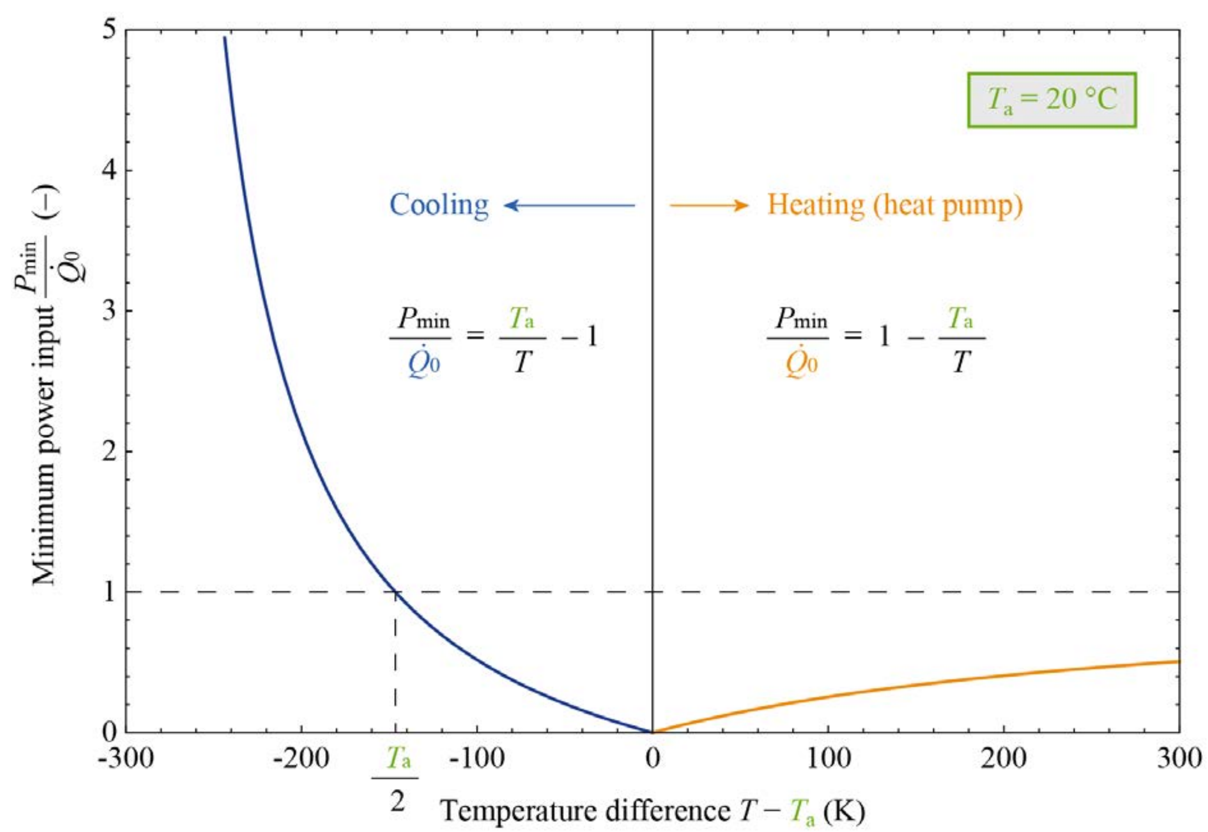
Sc. industrial DC magnet heater, Bültmann, Theva

Sc. ship propulsion, Siemens

HTS power applications require **10^3…10^4 W** cooling power below **80 K**

Thermodynamic requirements

- Cooling cycles requires **power input** in order to **create and sustain** low operating temperatures that are different from the ambient temperature T_a
- The power input is required due to **two fundamental Laws**
  - I. Law of Thermodynamics: Energy conservation
  - II. Law of Thermodynamics: Energy transformation
  - Thermodyn. **work function**: $P_{ij} = \left(\dot{H}_i - \dot{H}_j + P_{t,ij}\right) - T_a\left(\dot{S}_i - \dot{S}_j\right) \rightarrow P = \sum P_{ij} = T_a \sum \dot{S}_{ij,irr}$ (per unit time)
- Minimum power → **Carnot cycle**
  - **Idealised** thermodynamic cycle of **zero power density**
  - Power demand of **real-world** cryogenic processes/cycles is **by factors ~4…20 larger**
  - Slide 12



B) STATE-OF-THE-ART COOLING TECHNOLOGIES

State-of-the-art of cooling technologies

	Open process	Closed processes	
	LN_2 cooling	Cryocooler	Cryoplant
Thermodynamic principle	Evaporation of liquid nitrogen (LN_2)	Oscillating regenerative process	Continuous recuperative cycle
Operating principle	▶ Liquefaction in air separation units ▶ LN_2 distribution to applications	Direct local cooling of HTS applications	
Power range	Any	**< 10^3 W** @ 80 K	**> 10^4 W** @ 80 K
Temperatures	$T_{tr,N2}$ = 63 K < T_{min}	T_{min} < 63 K	
Supplies	LN_2, electricity	Cooling water, electricity	

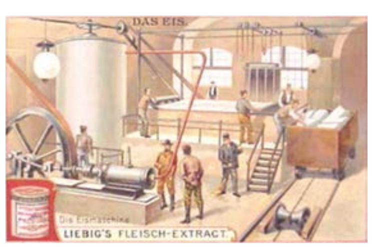
Technology gap of closed processes at **10^3…10^4 W** cooling power @ 80 K

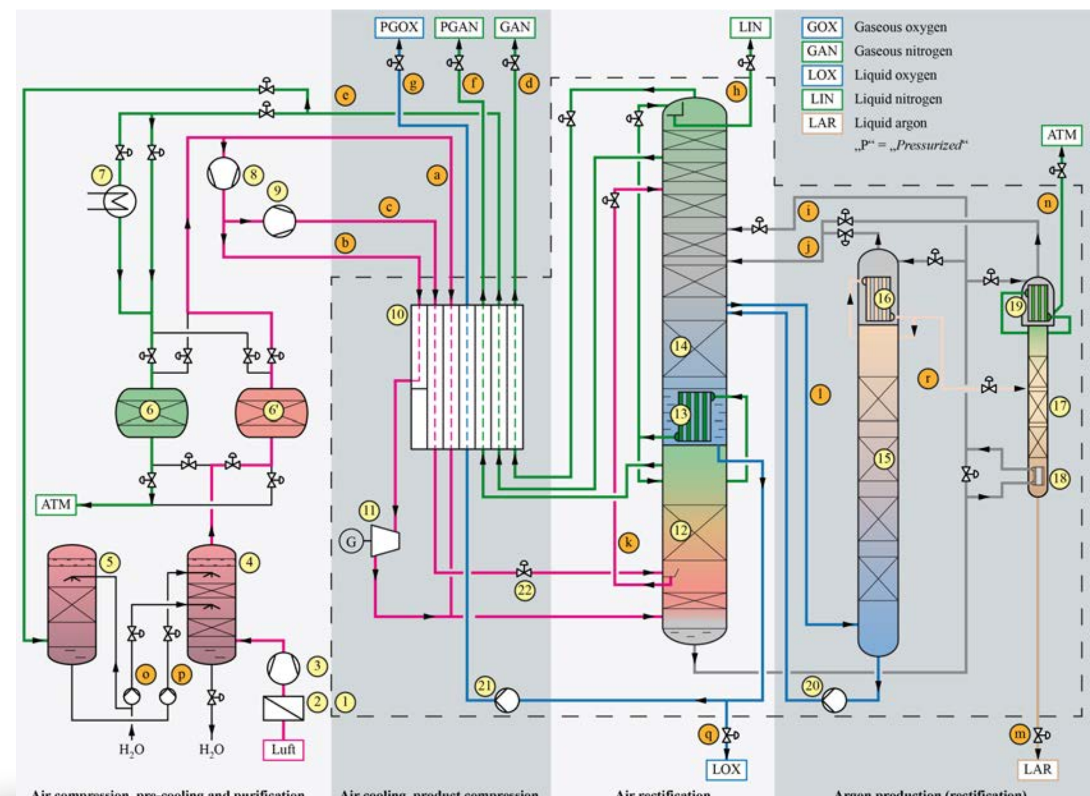
Open process – LN_2 technology

- **Air separation units** (ASU) are operated mainly for oxygen (O_2) production
  - Large capacities with high levels of process integration and efficiency
  - Liquid nitrogen (LN_2) and nobel gasses as by-products
  - Concentration ratio in air → $N_2 : O_2 \approx 4 : 1$ → low price of LN_2
- LN_2 distribution chain



  - „Iceman principle“



Economic where possible, but **not desired/possible** in many HTS applications

Closed process 1 – Cryocooler technology

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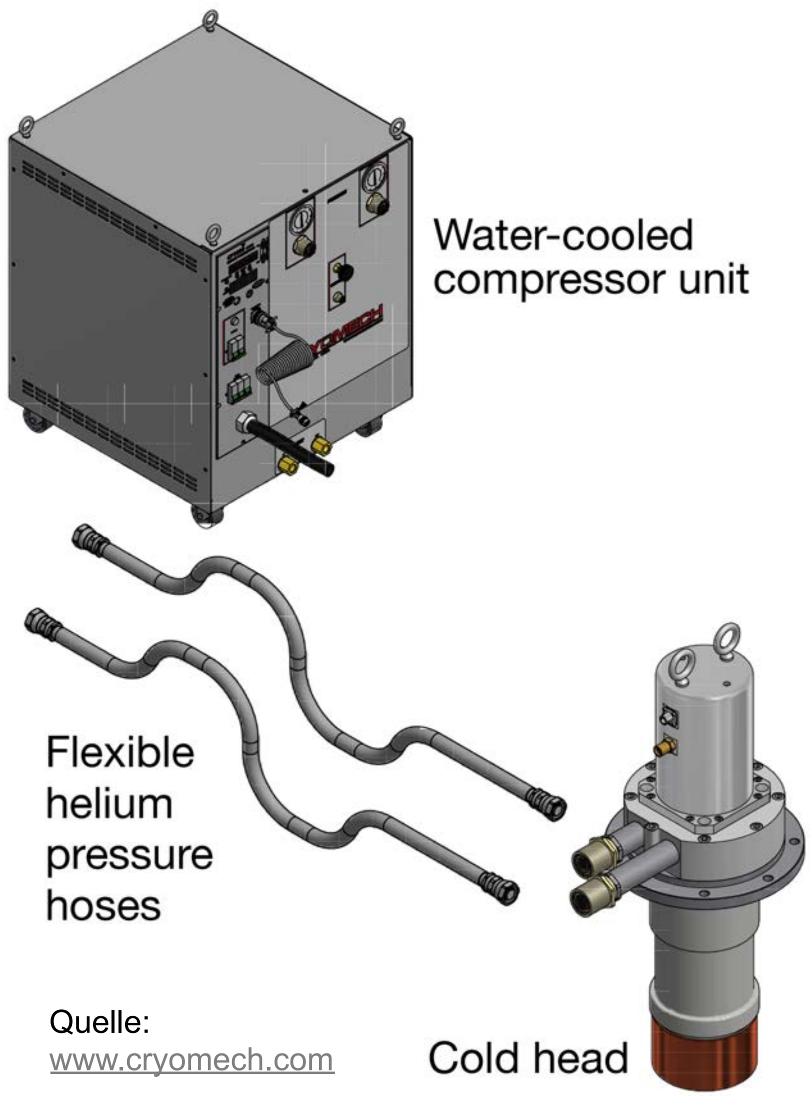
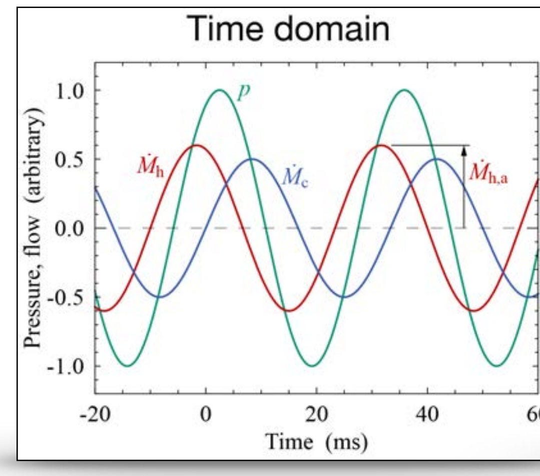
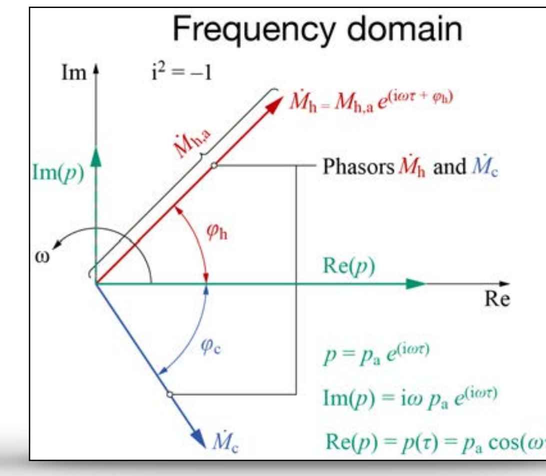
- Example: GM-cryocooler



Quelle: www.cryomech.com

- Characteristics
  - Oscillating process, **no cycle!**





- ☹ Low potential for upscaling
- 😐 Limited efficiency

… however

- ☺ Relatively simple way to achieve low temperature
- 😐 Maximum power c. 600 W @ 80 K

Multiple cryocooler needed for cooling of mid-scale applications

Cryocooler use in mid-scale applications

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LTS Example

- Muon Ionization Cooling Experiment MICE

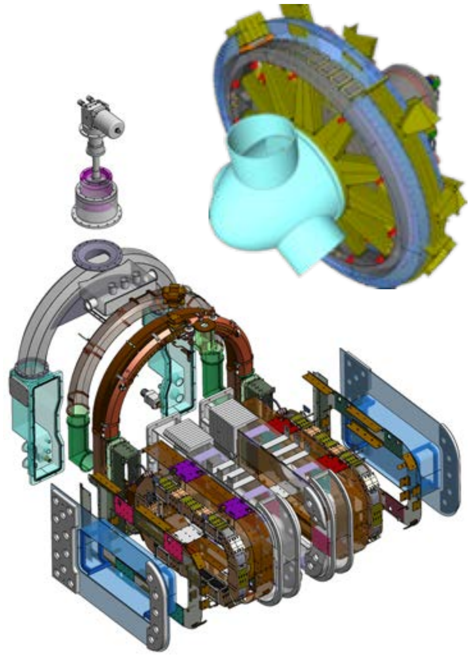
Source: LBNL MICE Project Status (2012)

- 25 GM cryocooler on one cryostat
- Cooling power:

$$\dot{Q}_0 = 37.5 \text{ W @ } 4.2 \text{ K} \rightarrow \left(25 \times 1.5 \text{ W @ } 4.2 \text{ K}\right)$$

HTS Example

- 10 MW superconducting offshore wind turbine – SUPRAPOWER

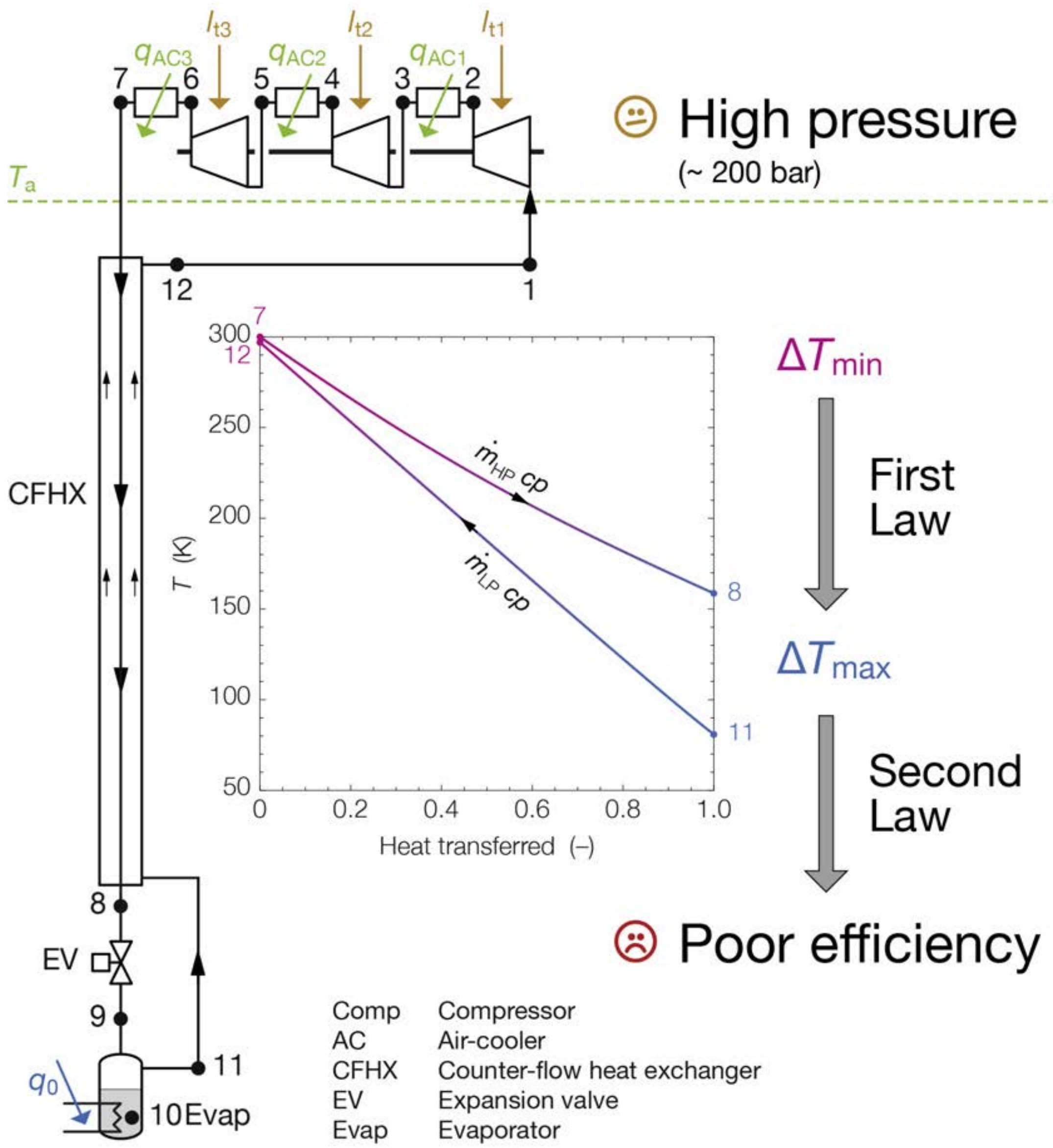


- 48 MgB_2 coils operated at 20 K
- 1 GM cryocooler for each 2 modules
- Conduction cooling coils – cryocooler

***N* > 20 units:** No cost advantage of cryocoolers compared to cryoplants

Closed process 2 – Cryoplant technology

Simplest cycle

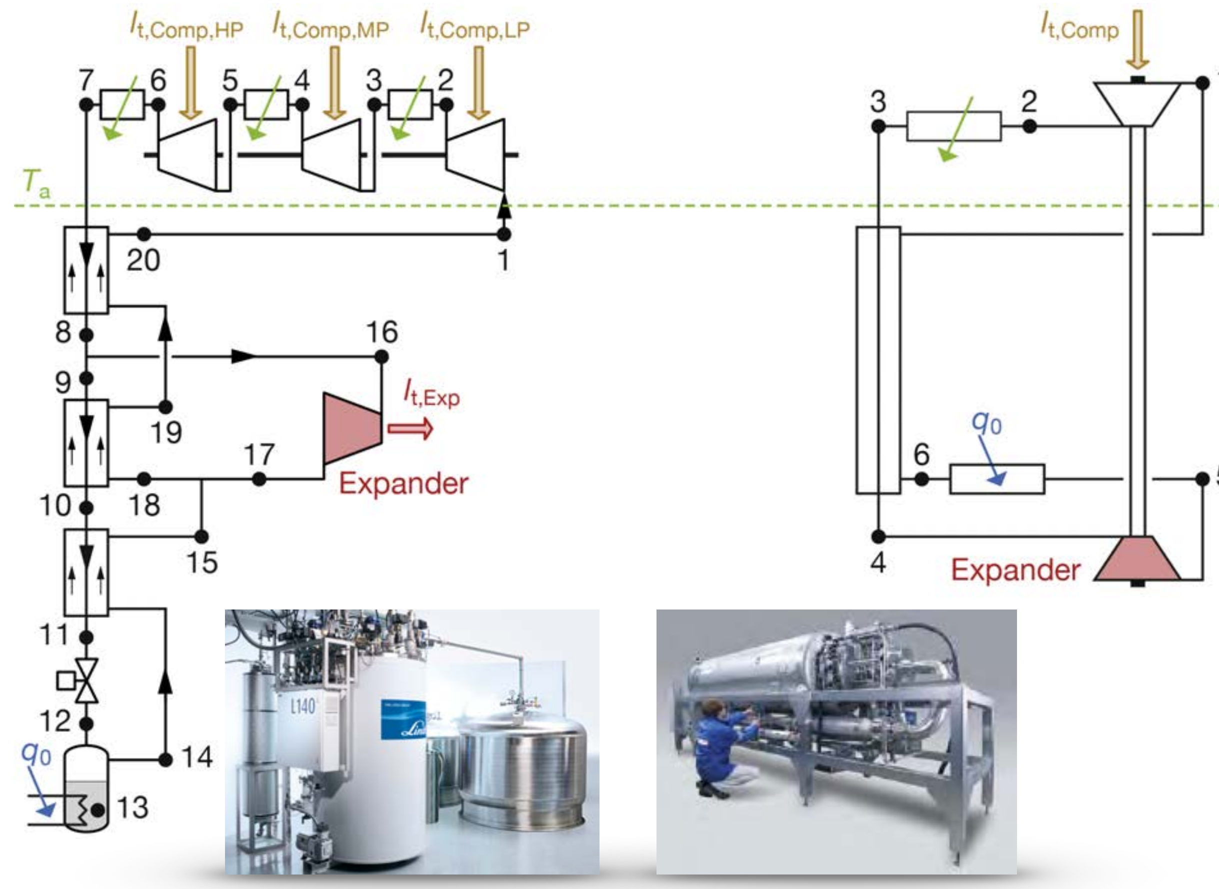


😐 High pressure
(~ 200 bar)

☹ Poor efficiency

Comp	Compressor
AC	Air-cooler
CFHX	Counter-flow heat exchanger
EV	Expansion valve
Evap	Evaporator

Industrial cryoplants

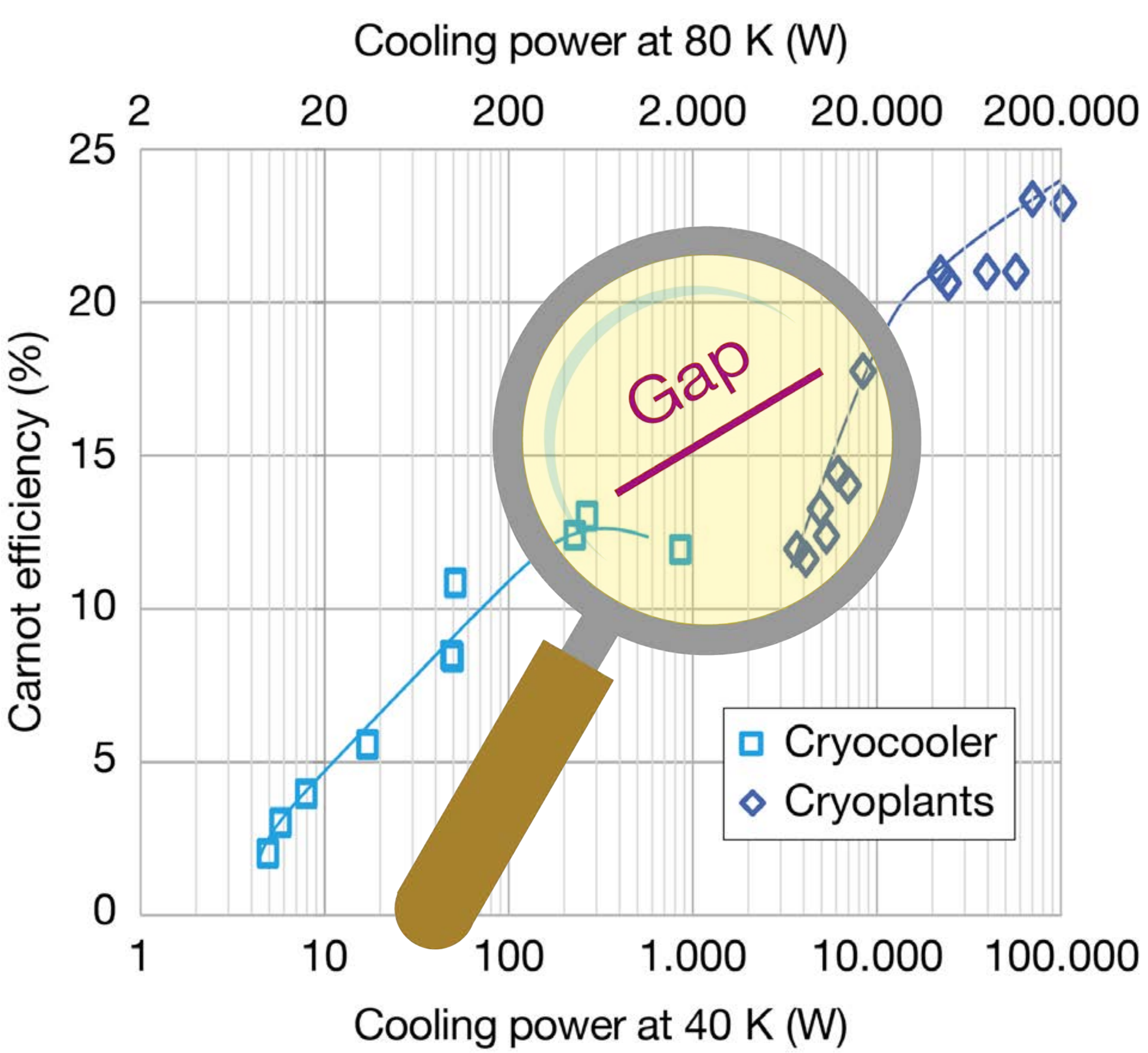


- 😊 High efficiency, moderate pressures
- 😐 Need of cold turbo-machinery
- ☹ High cost (typically ≥ 1 M€)
- ☹ Low potential for down-scaling

Cryoplant **cost** is **uncompetitive** for mid-scale cooling of HTS applications

Closed processes – comparison

- State-of-the-art



Data source: Decker, L.: Overview on cryogenic refrigeration cycles for large scale HTS applications. International Workshop on Cooling System for HTS Applications (IWC-HTS), October 14-16, 2015, Matsue, Japan

- We saw why the gap exists.

↓

- Is there any alternative?

C) DEVELOPMENT POTENTIAL OF MID-SCALE COOLING SYSTEMS FOR HTS APPLICATIONS

The key player in thermodynamic processes

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- Common (non-cooling expert) terminology

Cryocooler
„*Cryogen-free* cooling“

Cryoplants
„*Mechanical* cooling“

- There is helium in each cryocooler!
- A cryoplant is not a gearbox!

- The **key player** in every cooling system is the **working fluid** with
  - its **state & transport properties**, and
  - its **changes of state** during the thermodynamic process/cycle

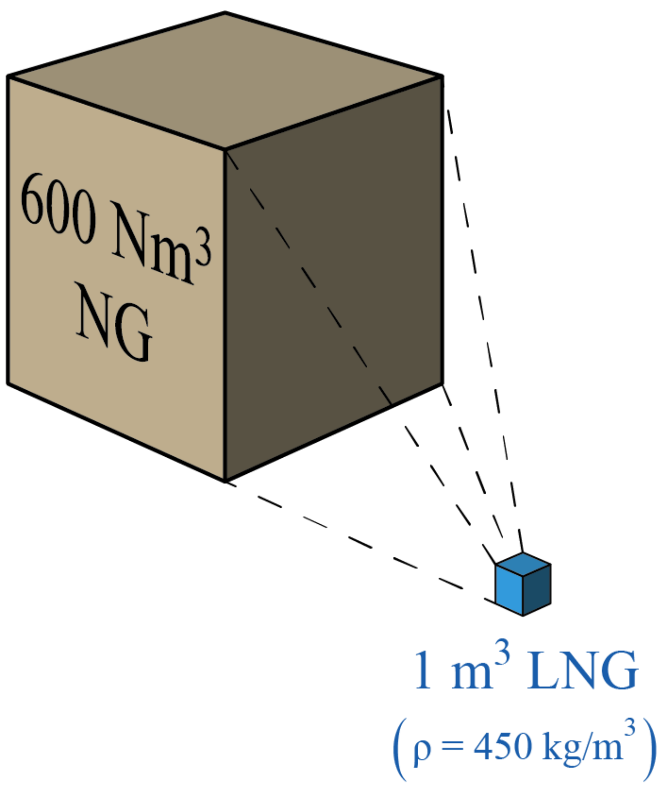
!!!

- **Beyond** the pure fluids in **the periodic table**, fluid properties can be **manipulated** by **mixing of several working fluids** in order to **„design“ specific properties**

Concept of **mixed-refrigerant** cycles (MRC) = **molecular engineering**

Example of MRC in gas industry

- Liquefaction of natural gas → LNG
  - Example: Statoil LNG Plant in Hammerfest, Norway (Snøvit)
  - Production capacity 4.3×10^6 t/a ← Large scale
  - Main component CH_4 → normal boiling point $T_{nb} = 112$ K ← „High" temperature



Status of MRCs in cryogenics

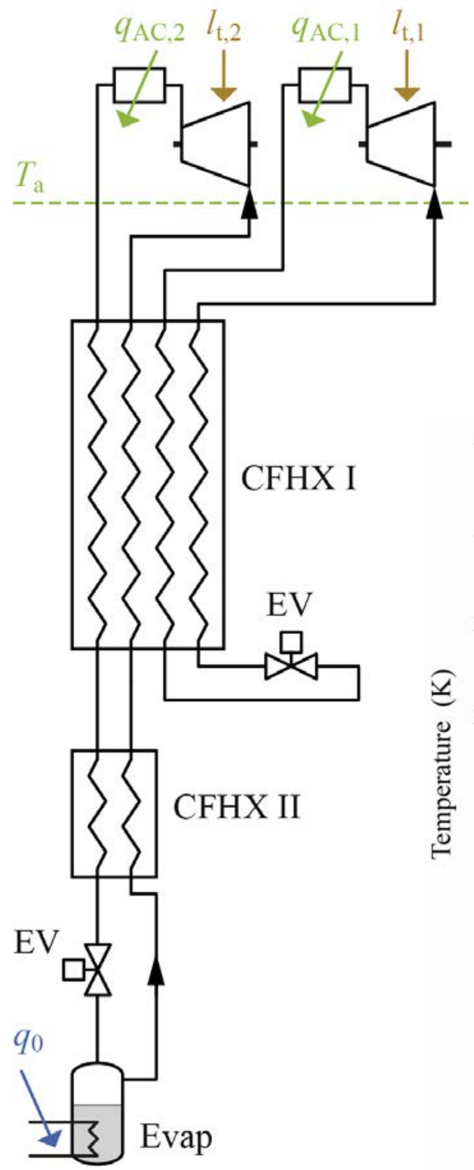
- Apart from some laboratory demonstrations, there is **no commercial application** of MRCs in cryogenics yet, i.e. at $T < 100\,\mathrm{K}$
- Reasons:
  - Lack of **fluid property data** (cryogenic mixtures)
  - **Lacking need** (applications/market) that motivate such a development

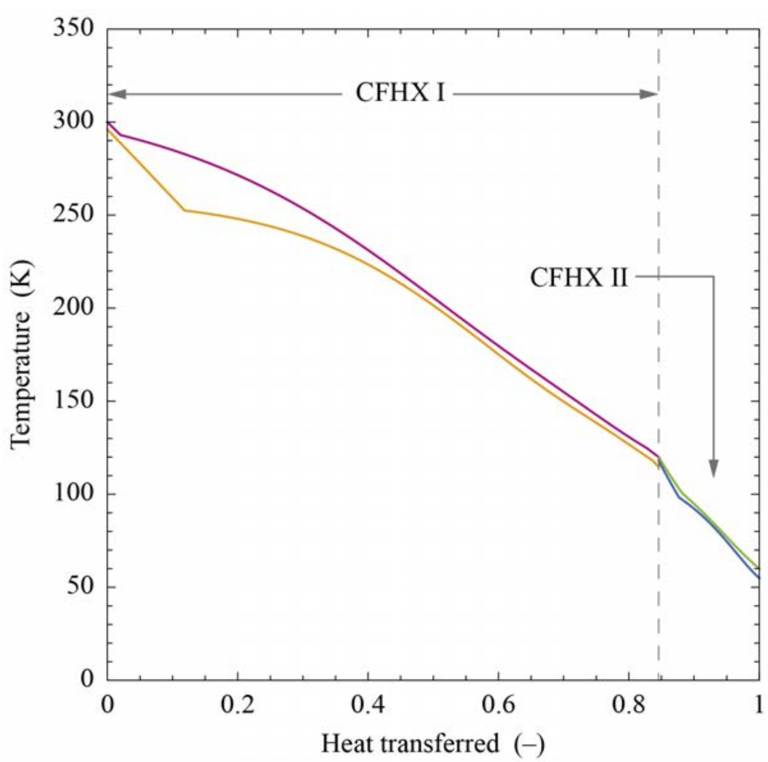
  This situation has changed with HTS application (see gap ↑) !

- The **technical benefit** of MRCs **increases** with **decreasing temperature**
  - Power input (I[st] + II[nd] Law): $P = T_\mathrm{a} \sum \dot{S}_\mathrm{irr}$
    - Entropy production due to ΔT: $\dot{S}_\mathrm{irr} \propto \frac{T_1 - T_2}{T_1 \cdot T_2}$
    - Entropy production due to Δp: $\dot{S}_\mathrm{irr} \propto -\frac{v}{T}\,\mathrm{d}p$

Potential of MRCs in cryogenics

- Example of a **<u>cryogenic</u>** mixed-refrigerant cycles (**<u>C</u>**MRCs)





- **Wide-boiling mixtures** for adaptation of capacity flow rates
  - Application-specific **design of fluid properties**
  - 2nd stage mixture properties yet to be verified

- **<u>Main advantages</u>**
  - No cold turbo-expanders
  - Inexpensive standard-refrigeration components
  - Scalable
  - Good cycle efficiency
  - Very good thermal integration

  Application efficiency

Thermodynamic Laws → **Only option** for **generic** technology improvement!

Development levels of CMRC technology

3 CMRC-cooled **HTS applications**
- Prototype of 10 kA current leads

2 CMRC **heat exchanger** development
- Modeling framework
- Prototyping and testing
- Evaluation of transport correlations

1 **Properties** of cryogenic **fluid mixtures**
- Measurement of fluid state and transport properties
- Modeling of equations of state (EOS)

1 Properties of cryogenic fluid mixtures

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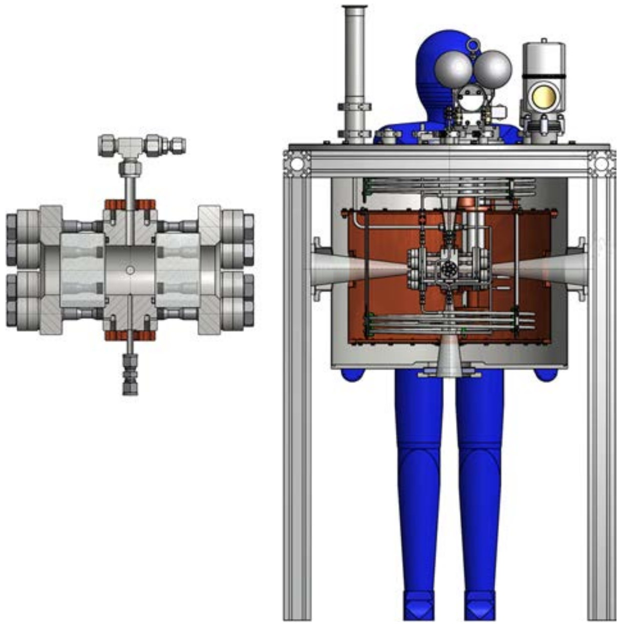
1 Properties of cryogenic fluid mixtures

- **Systematic screening** of **non-flammable** refrigerant mixtures
  - Investigation of mixtures with 4th generation refrigerant R1234yf for pre-cooling stage
  - **Equations of State** (EOS) and **process modelling**
  - Hydrocarbons not excluded as high-boiling components in HTS power applications

- New **Cryo**genic **Pha**se **Eq**uilibria **T**est **S**tand (CryoPHAEQTS)
  - Temperature range **15 – 300 K**, maximum pressure **15 MPa**
  - **ALL mixtures**, incl. flammable/oxidising fluids (ATEX compliant)
  - Preparations for optical measurements
    - Dynamic light scattering (DLS) for measurement of thermal diffusivity, diffusion coefficient, speed of sound / sound attenuation
    - Surface light scattering (SLS) for measurement of viscosity and surface tension



Unique facility to study low-temperature thermodynamic fluid properties

1 Properties of cryogenic fluid mixtures

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- CryoPHAEQTS laboratory at KIT

CryoPHAEQTS laboratory (Status 10/2019)

Equilibrium cell and cryocooler

2 CMRC heat exchanger development

2 **Heat exchanger** development
- Modeling framework
- Prototyping and testing
- Evaluation of transport correlations

1 **Properties** of cryogenic fluid mixtures
- Measurement of fluid state and transport properties
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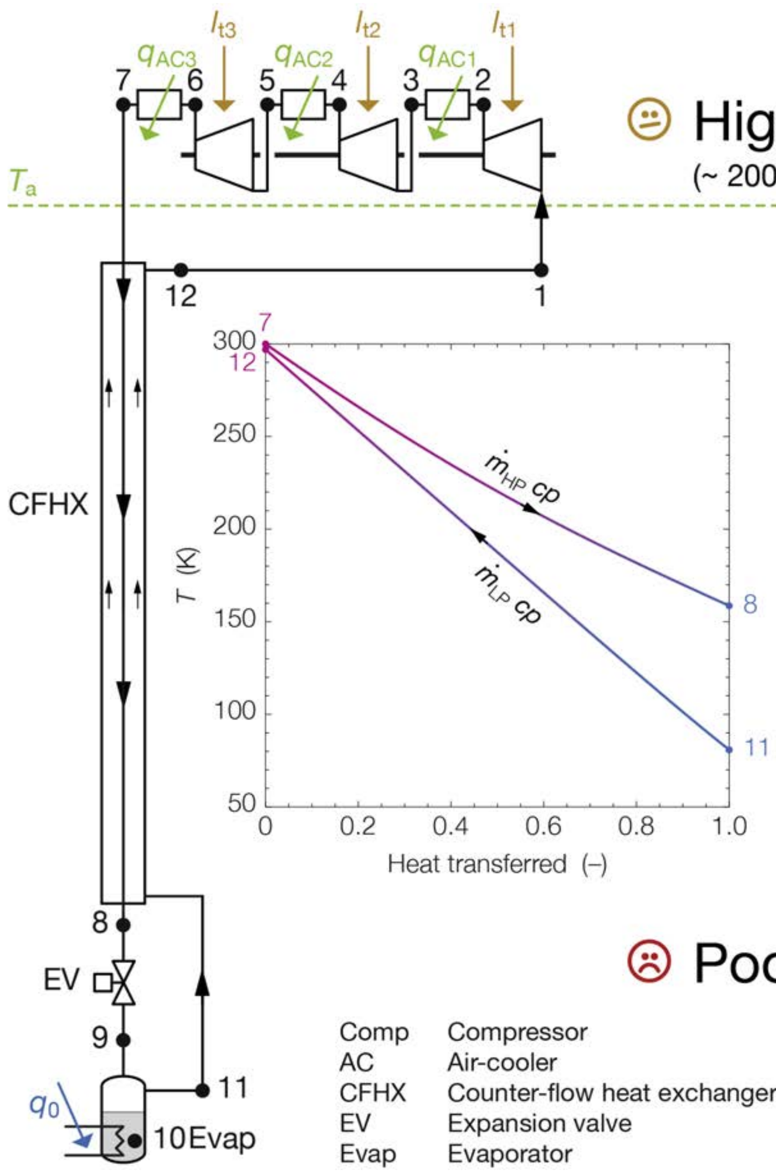
2 Importance of heat exchanger technology

Simplest cycle, pure fluid



😐 High pressure
(~ 200 bar)

ΔT_{min}

First Law

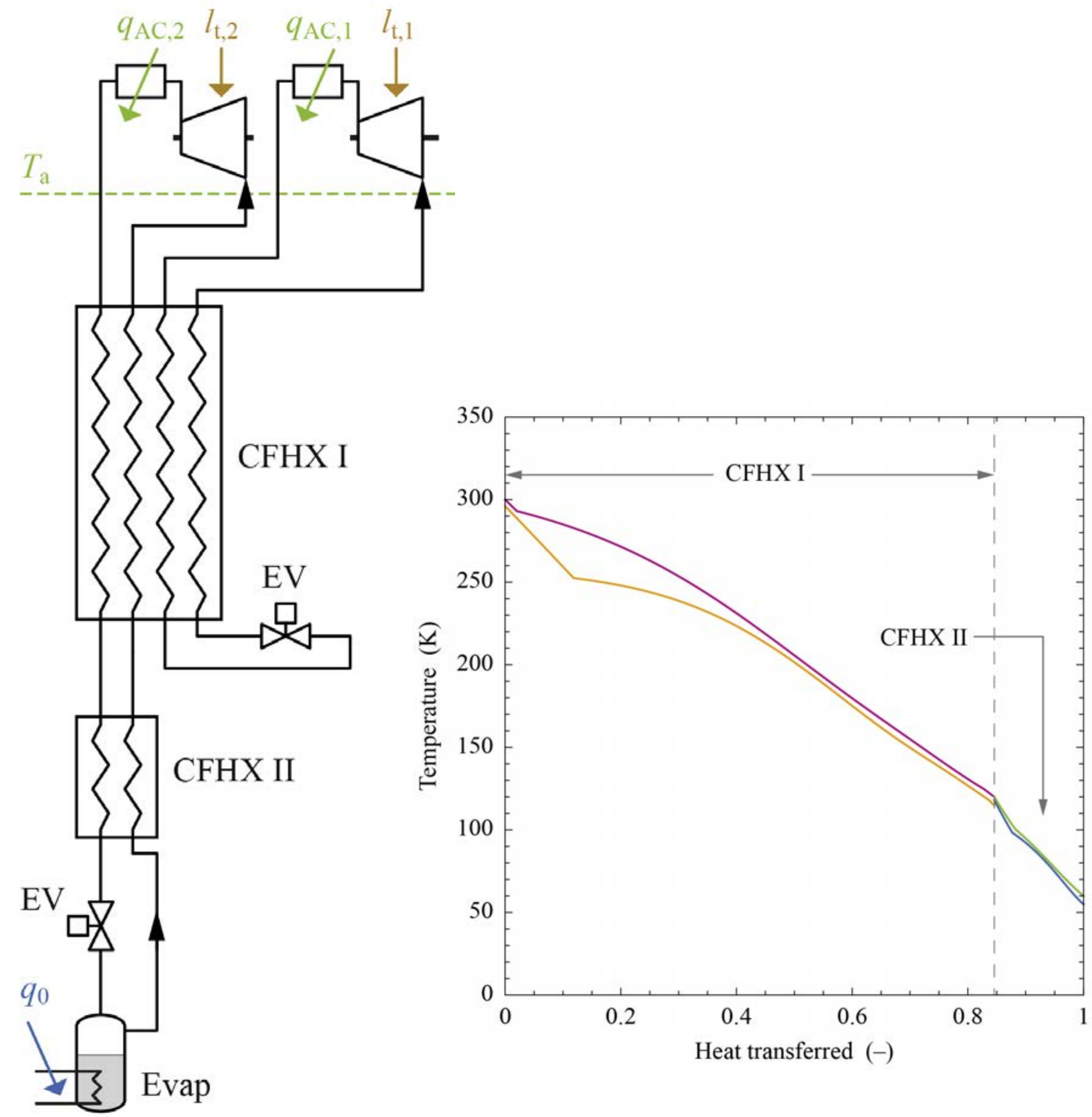
ΔT_{max}

Second Law

☹ Poor efficiency

Comp	Compressor
AC	Air-cooler
CFHX	Counter-flow heat exchanger
EV	Expansion valve
Evap	Evaporator

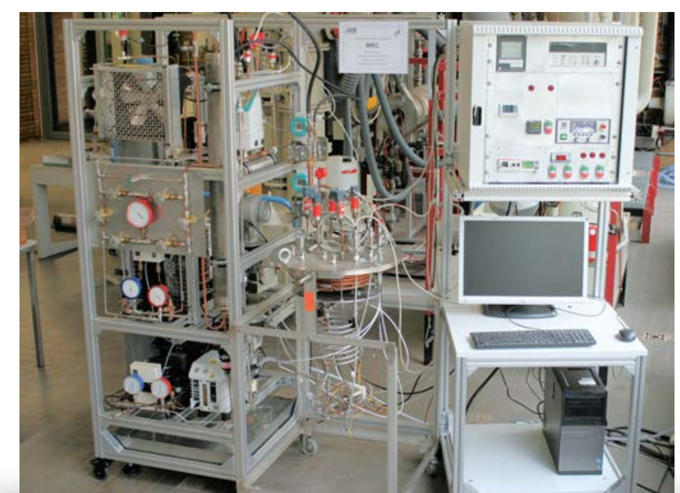
CMRC



💬 CMRCs **require** a new heat exchanger technology (no benefit in classical cycles)

2 CMRC heat exchanger development

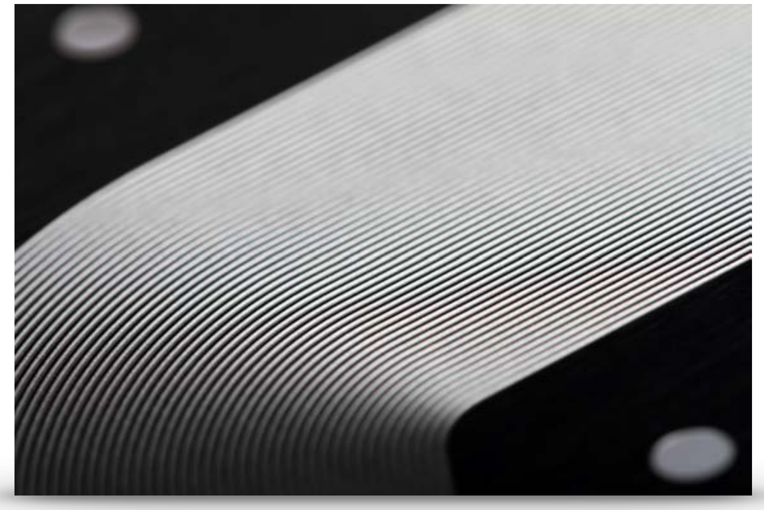
- Modeling framework for CMRC heat exchangers
  - Classical ε-NTU models inappropriate due to non-constant fluid properties
  - Development and publication of **matured 1D numerical framework**
    - Compatibility with numerous correlations for both single- and two-phase flow of pure fluids and zeotropic mixtures, as well as longitudinal and parasitic heat loads
- Prototype development and testing
  - High efficiency due to small gradients → **large heat transfer surfaces**
  - Development of **micro-channel** CMRC heat exchangers
  - Testing in **MRC test stand**

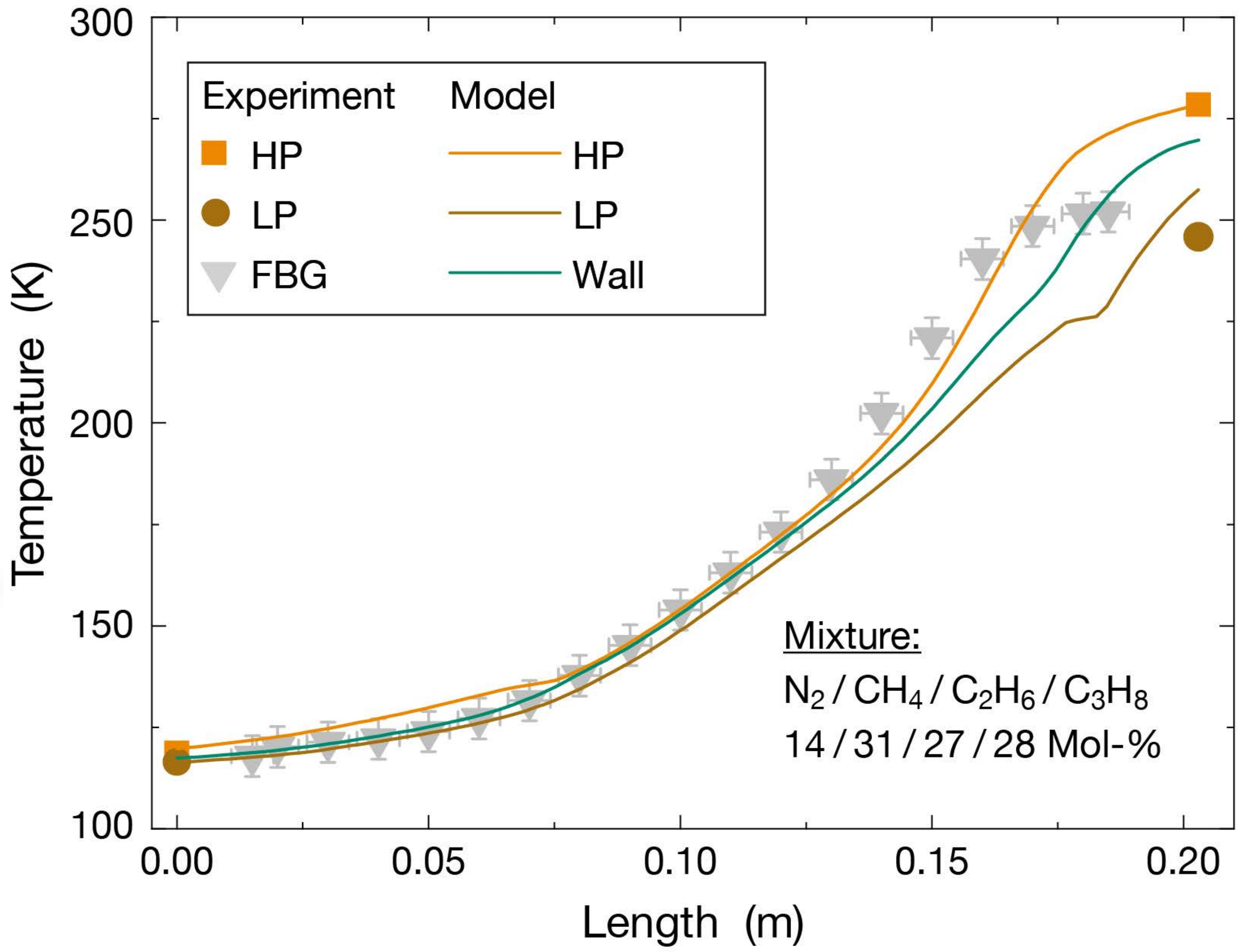


Development of **design tools** and **novel heat exchanger technology**

CMRC heat exchanger development

- Test results of the micro-channel heat exchanger prototype
  - 60 diffusion bonded metal foils
  - Each with 50 parallel channels
  - Hydraulic channel diameter 320





Source: Gomse, D.: Development of heat exchanger technology for cryogenic mixed-refrigerant cycles. PhD dissertation, KIT (to be published)

3 CMRC-cooled HTS applications

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- Prototype of 10 kA current leads

2 **Heat exchanger** development
- Modeling framework
- Prototyping and testing
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1 **Properties** of cryogenic fluid mixtures
- Measurement of fluid state and transport properties
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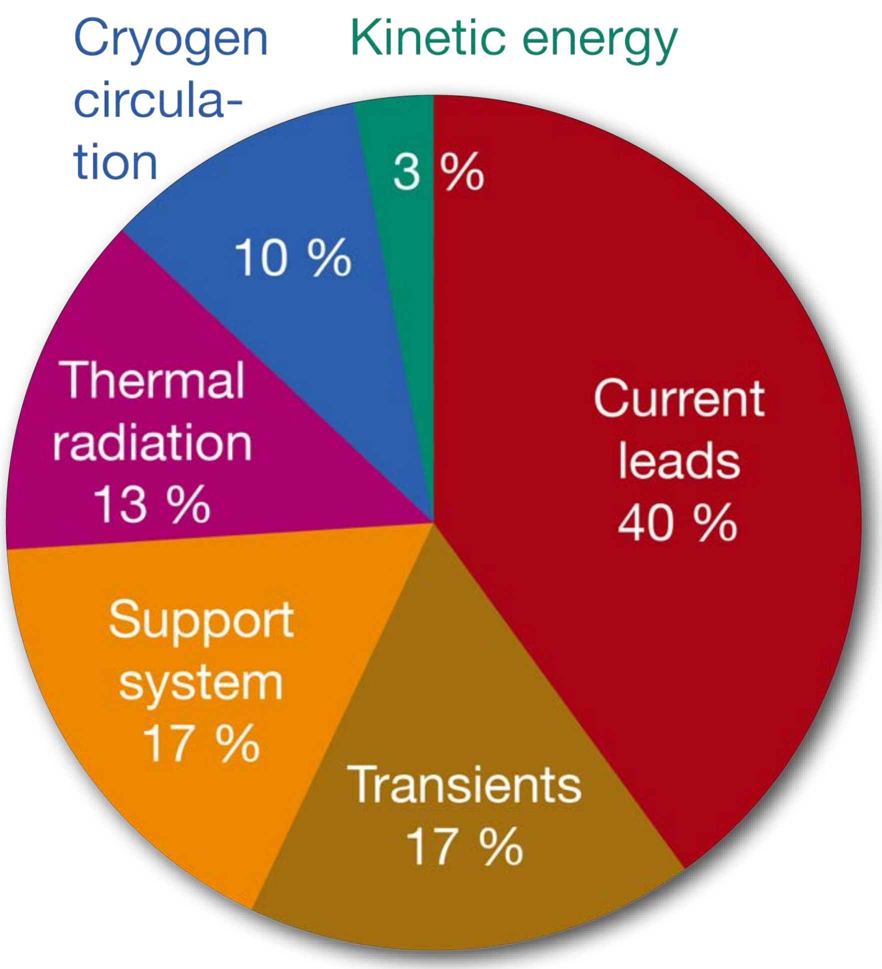
3 Sources of power input for HTS cooling

Rotating machines

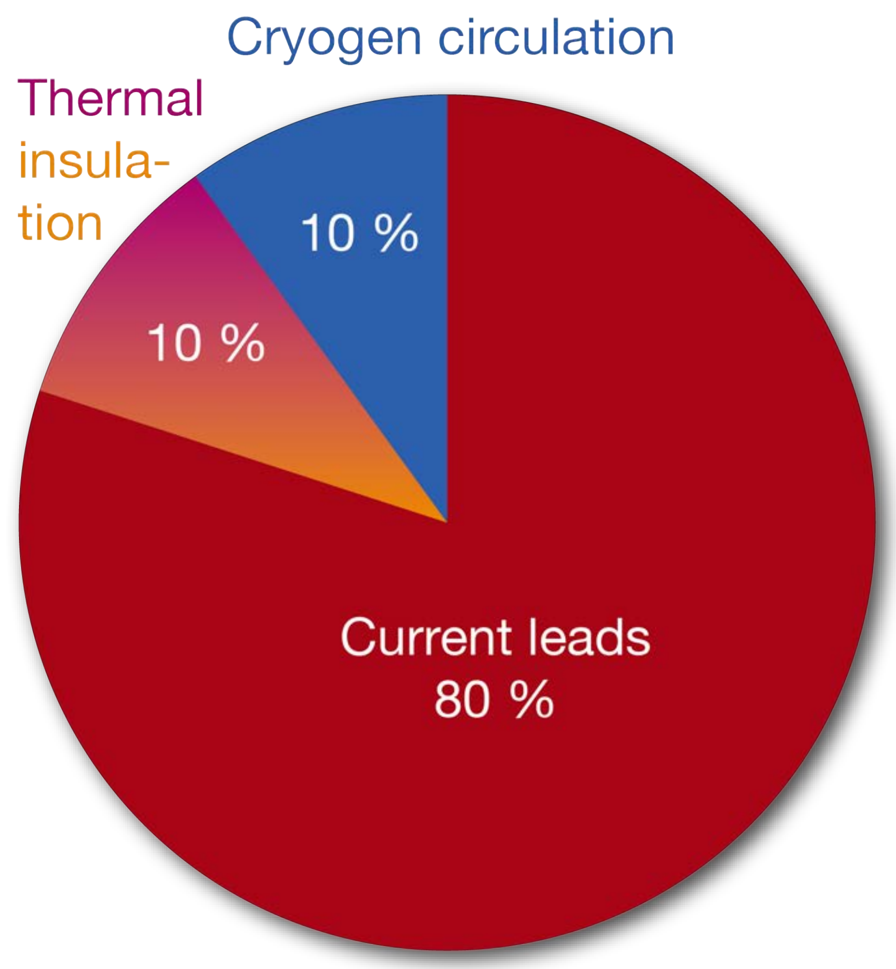
- Typical values



Data source: Tabea Arndt, Siemens AG, ASC 2018

DC cables and bus bars

- Typical values



3 CMRC-cooled HTS applications

- **Largest heat loads** are typically caused by **current leads**
- **Large temperature gradient** between room-temperature $(T \approx 300\,\mathrm{K})$ and the HTS operating temperature $(T \leq 80\,\mathrm{K})$
- **State-of-the-art solutions**

- Conduction-cooled current leads
  - ☺ Lowest technical effort (1 stage)
  - 😐 Limited capacity (cryocooler)
  - ☹ Lowest efficiency (full load at cold end)

- Multi-stage-cooled current leads
  - ☹ Highest effort (3 to 4 cooling stages)
  - 😐 (Partly) scalable capacity
  - 😐 Good efficiency

- **Future solution → →**

- **CMRC-cooled current leads**
  - ☺ Low technical effort (1-2 stages)
  - ☺ Full scalability
  - ☺ Highest efficiency (continuous heat absorption at the source)

HTS current leads are predestinated applications for **CMRC technology**

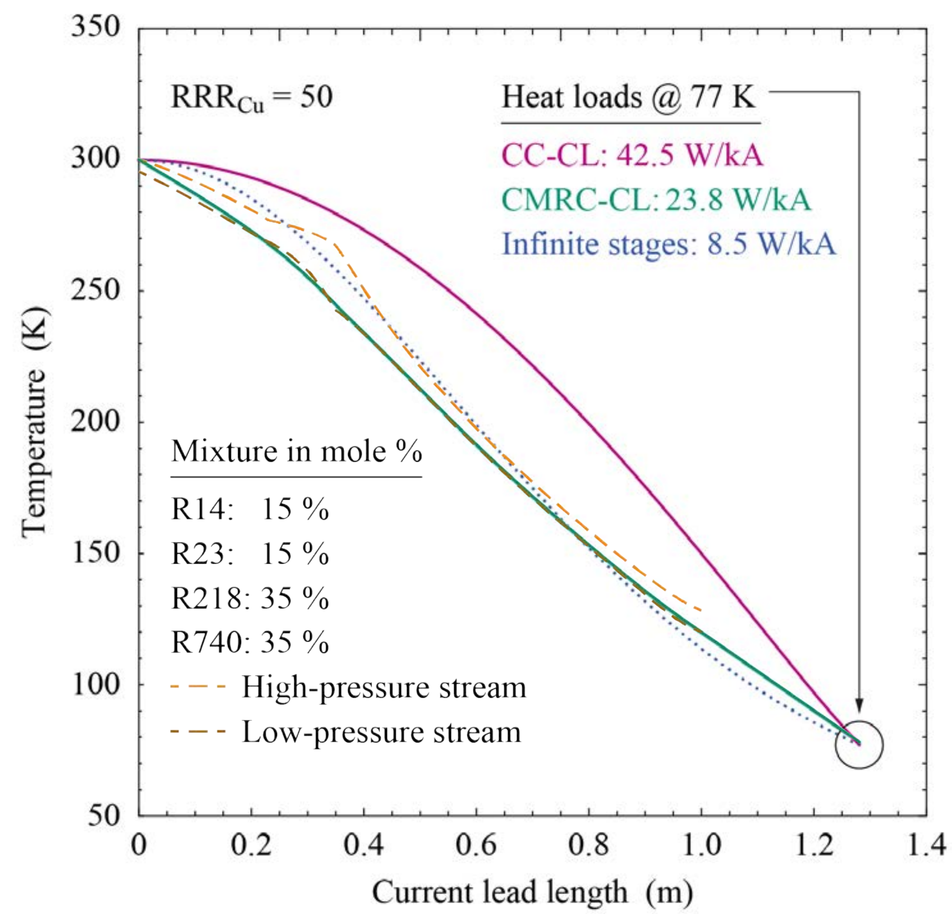
CMRC-CL prototype (10 kA, classical HX)

- Prototype development of one pair of 10 kA current leads
  - Classical tube-in-tube heat exchanger design
  - Cooling with cryogenic mixed-refrigerant cycle (CMRC)
  - Prototype design completed

- Simulation results

  - ***Reduction of heat load*** at the cold end ***by 45 %*** compared to conduction-cooled current leads (CC-CL, GM cryocooler)

  - **Reduction of overall power input** (resistive losses + cooling system) to **1/3**



Only feasible due to **fundamentally new approach** in cryogenic technology

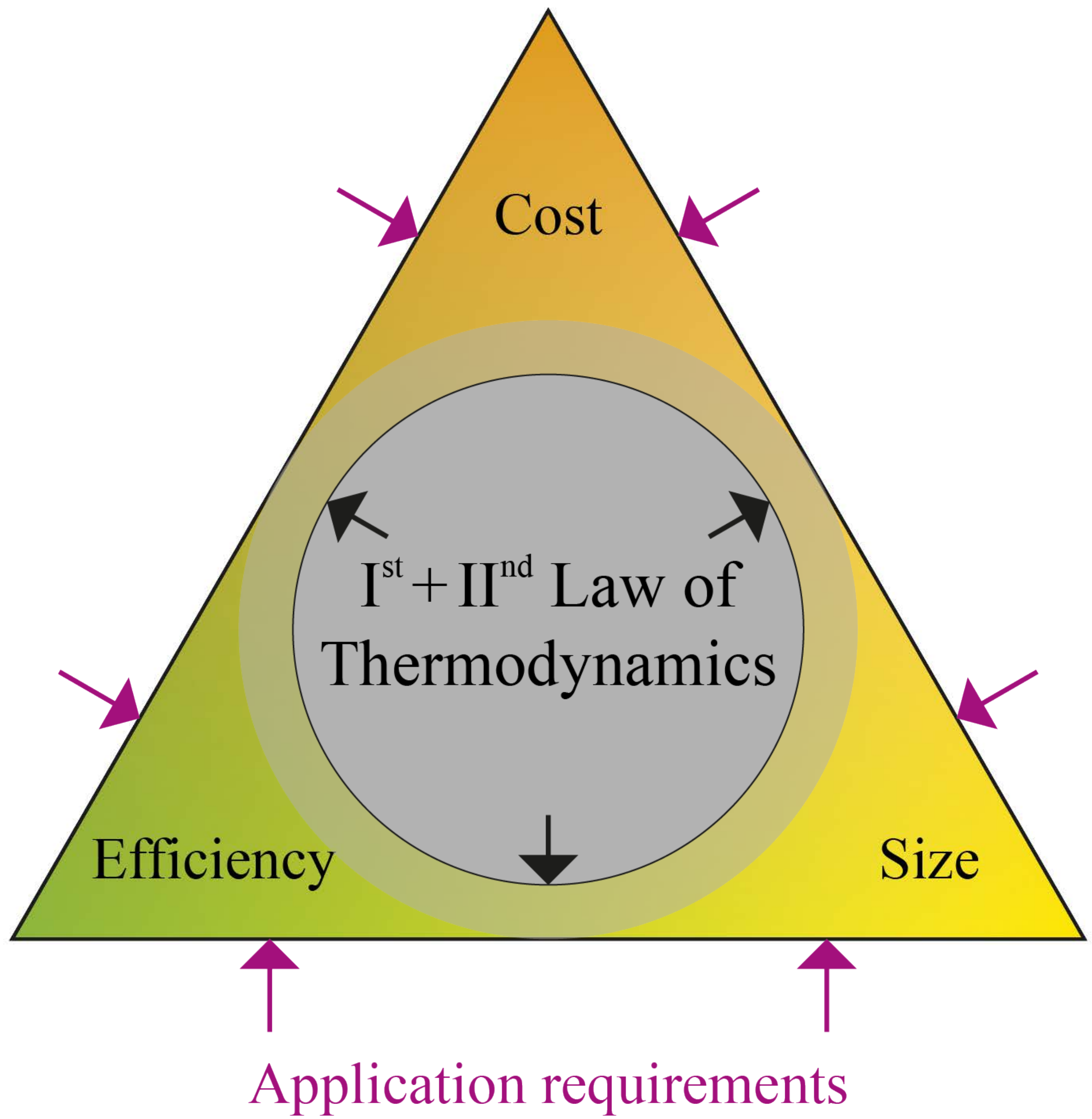
3 CMRC-CL prototype (10 kA, classical HX)

- Technology and efficiency comparison for the total power ⟶ $P_\mathrm{i} = P_\mathrm{el} + P_\mathrm{cool}$

	Resistive losses P_el (W)	Power input P_cool (W)	P_i / $P_\mathrm{i,GM}$ (%)
GM (conduction cooled)	400	7000	100
CMRC (same length)	360	2200	35
CMRC (1/2 length)	172	5400	75

D) CONCLUSIONS

Conclusions



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Thank you for your attention!

Steffen Grohmann