Karlsruhe Institute of Technology

Institute for Beam Physics and Technology
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# Mixed-refrigerant cooled 10 kA current leads for superconducting applications

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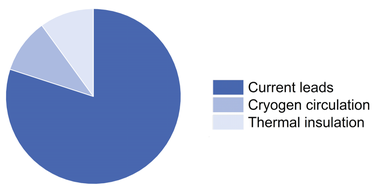
## Motivation – cooling demand of current leads

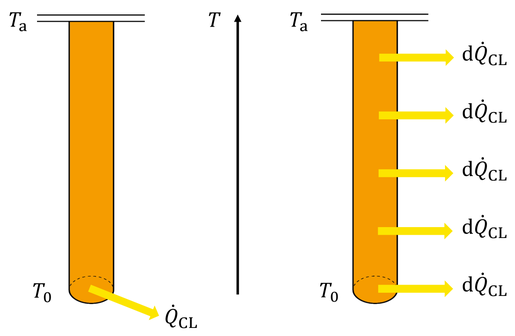
- Current leads (CL) impose heat load on cryogenic system
- Current leads are a main sources of power input for cooling[1]

DC cables and bus bars




**Operating costs** can be **reduced** by about **50 %**

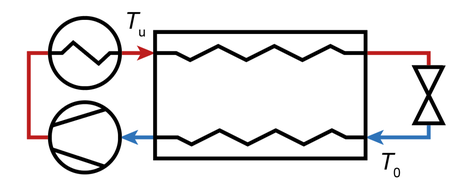
- Theoretical power demand for cooling of conduction cooled (CC-CL) and continuously cooled (∞-CL) current leads




$P_{CC-CL} = 123$ W/kA[2] | $P_{\infty-CL} = 73$ W/kA[2]

## Cryogenic mixed-refrigerant cycles (CMRC)

- Cryogenic mixed-refrigerant cycles offer scalable cooling power at $T \leq 100$ K
- CMRC-CLs promise reduction of power demand for cooling by 2/3 compared to CC-CLs



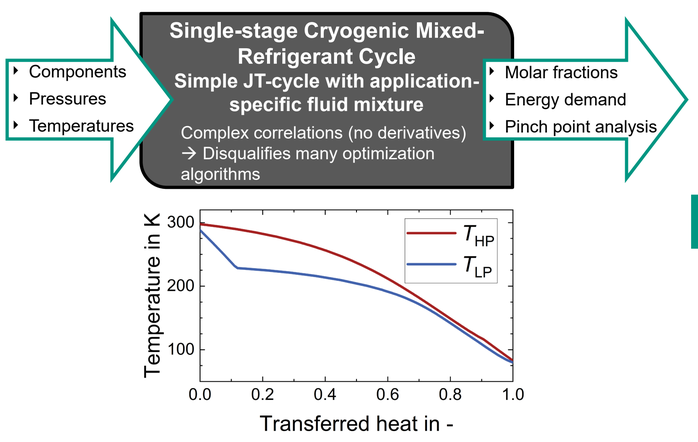


- **Comp**act **A**ccelerator **S**ystem**s** test stand (COMPASS)[3]
  - Infrastructure for experimental studies of i. a. CMRC-CLs
  - Two independent CMRC providing approx. 100 W and 500 W of cooling power, resp.

Commissioning in **Q4/2024**

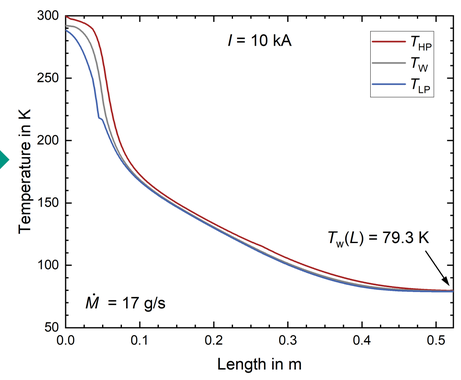
## Optimization of operating conditions

- Optimization with HPC algorithm[4] using **Differential Evolution**[5]
- Consideration of $T$-dependent joule heating
- Optimization parameter:
  - $T_{LP,in} = 80$ K
  - $p_{HP,in} = 20 \ldots 25$ bar
  - $p_{LP,in} = 1 \ldots 5$ bar
  - $\eta_{comp} = f(p_{ND}, \Pi)$




## Detailed modelling of CMRC-cooled current leads

- Simulation results: single-stage CMRC-cooled current lead

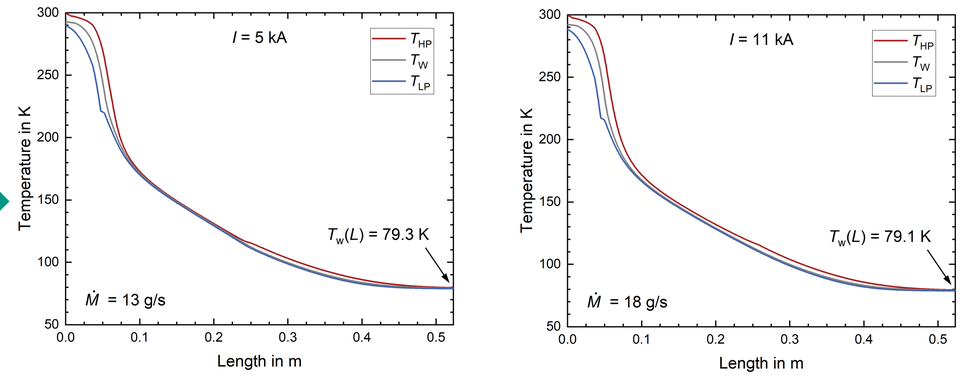



| Parameter | CMRC-CL | CC-CL |
|---|---|---|
| Wall temperature at cold end | 79.3 K | 79.3 K |
| Current capacity | 10 kA | 10 kA |
| Mass flow mixed-refrigerant | 17 g/s | - |
| Heat load due to ohmic losses | 70.2 W | 424 W |
| Power demand* | 2.1 kW | 8.1 kW |
| Carnot-Efficiency | 35 % | 15 % |

*compared to Cryomech AL600 cryocooler

Reduction of **power demand** compared to CC-CL by **74 %**

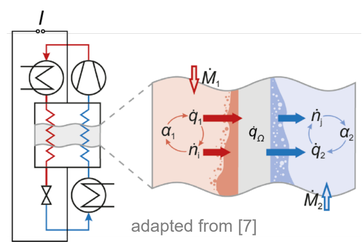
- CMRC-cooled current lead under variable operation conditions




**Adaption** of the mass flow to the operation conditions

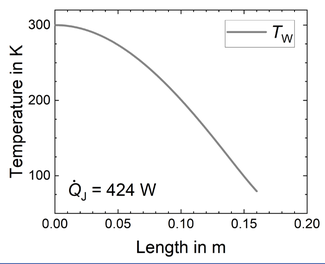
## Numerical model for current lead calculation

- Numerical model for heat exchanger calculations[6]
  - Solution of conservation equations
  - Empirical correlations for $\alpha$, $\Delta p$ and $\varepsilon$
  - Heat source term for ohmic losses[2]




adapted from [7]

## Reference case: conduction cooled current lead



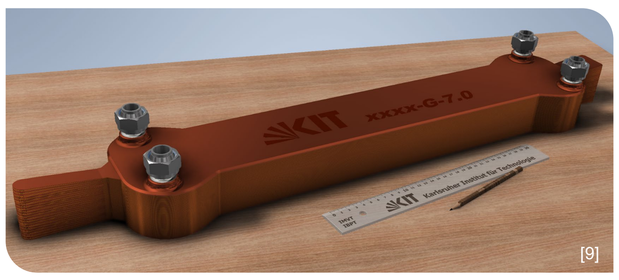

- Solution of 1-D $T$-field equation for conduction cooled part of current lead

$$\frac{\partial}{\partial x}\left(\lambda(T) \cdot A \cdot \frac{\partial T}{\partial x}\right) + I^2 \cdot \frac{\rho(T)}{A} = 0$$

- Reference case: operation with Cryomech AL600[8]

- Final design of CMRC-CL prototype for COMPASS

| Key figures of CMRC-CL prototype | |
|---|---|
| Current capacity | 10 kA |
| Dimensions (L x W x H) | 564 x 90 x 56 mm |
| Pressure level | PN30 |
| Total area for heat transfer | 4.69 m² |




[9]

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[3] J. Arnsberg, M. Stamm, and S. Grohmann. "Design of a High-Current Cryogenic Test Stand for Compact Accelerator Systems". In: 26th IIR International Congress of Refrigeration - Refrigeration Science and Technology Proceedings. 26th IIR International Congress of Refrigeration. Vol. 1. Paris, France, Aug. 21, 2023, pp. 231–239. DOI: 10.18462/iir.icr.2023.0290.
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[5] R. Storn and K. Price, "Differential Evolution—A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces", Journal of Global Optimization, 11, 341-359, 1997.
[6] D. Gomse, „Development of heat exchanger technology for cryogenic mixed-refrigerant cycles", PhD thesis, Karlsruhe: Karlsruhe Institute of Technology, 2019.
[7] D. Gomse, S. Grohmann, „Heat transfer and pressure drop in the main heat exchanger of a cryogenic mixed refrigerant cycle", en, 2018. ICEC27-ICMC 2018, Oxford, England, September 3-7 2018.
[8] https://bluefors.com/products/gifford-mcmahon-cryocoolers/al600-gifford-mcmahon-cryocooler/, last visit: 21.06.2024.
[9] Courtesy of G. Rabsch, Institute for Micro Process Engineering (IMVT), Karlsruhe Institute of Technology (KIT), 27.06.2024.