Karlsruhe Institute of Technology

Cooling technology for HTS power applications

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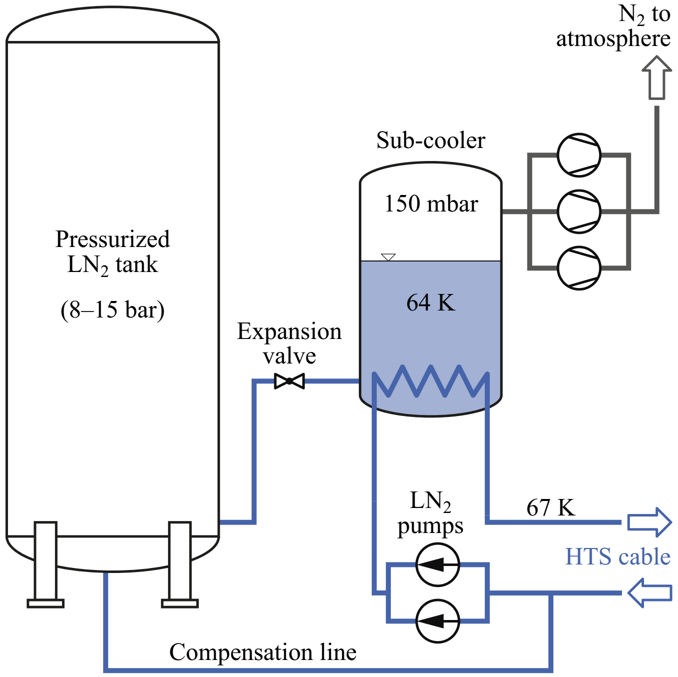
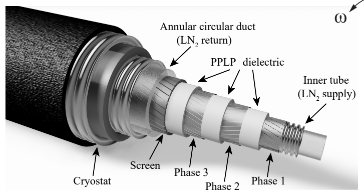
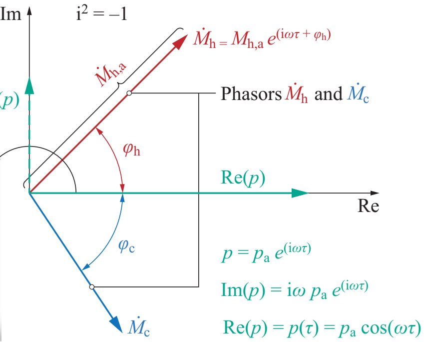
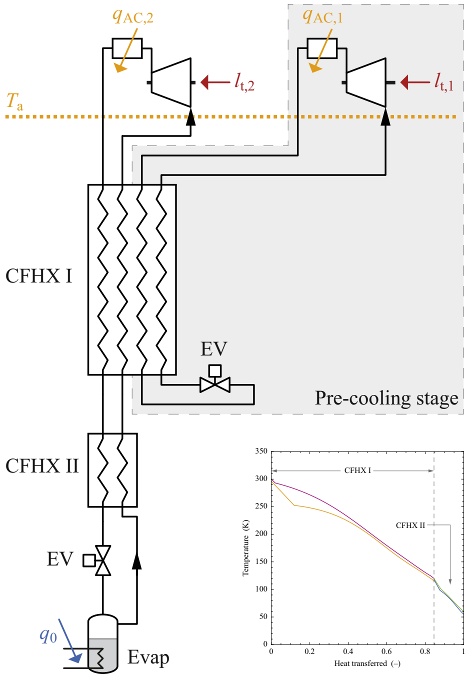
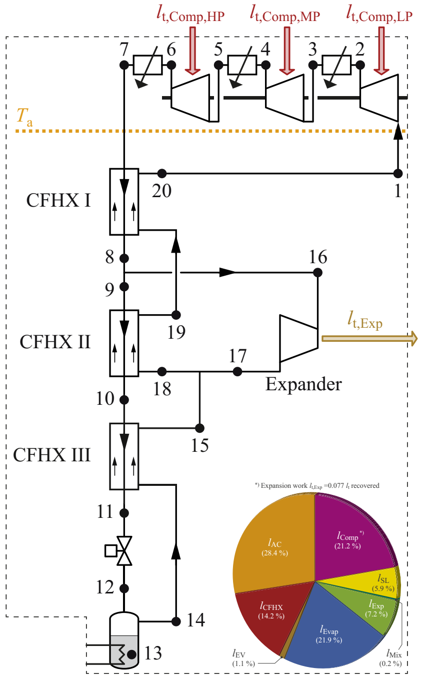










Outline

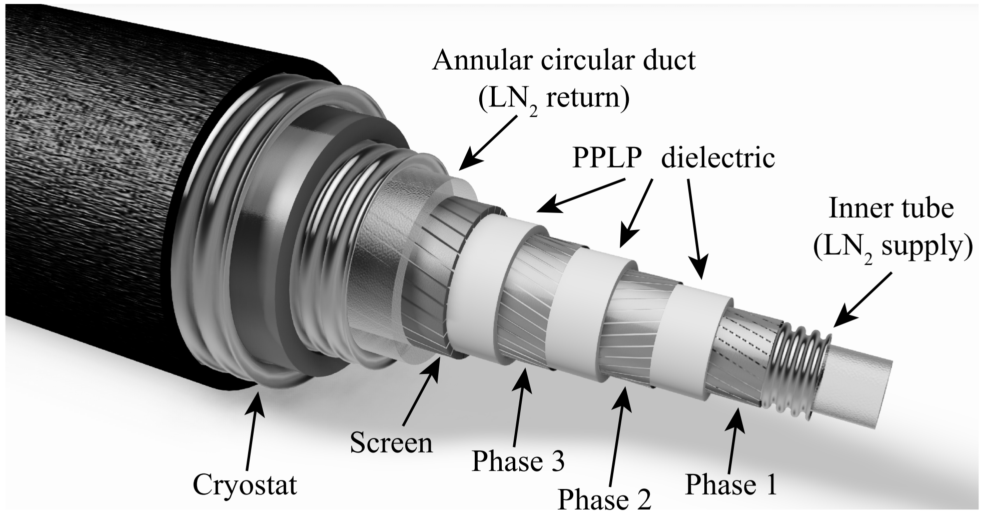
- Taking into account different backgrounds of the course participants, the *aim* of this course is
  - to ***provide*** an ***overview*** of existing HTS cooling technologies
  - to ***explain*** their ***technological differences***
  - to ***discuss*** future development ***potentials***
- Therefore, the course is structured in the following sections
  - Technology overview
  - Cryocoolers
  - Cryoplants (refrigerators)
  - Development potentials
  - Summary

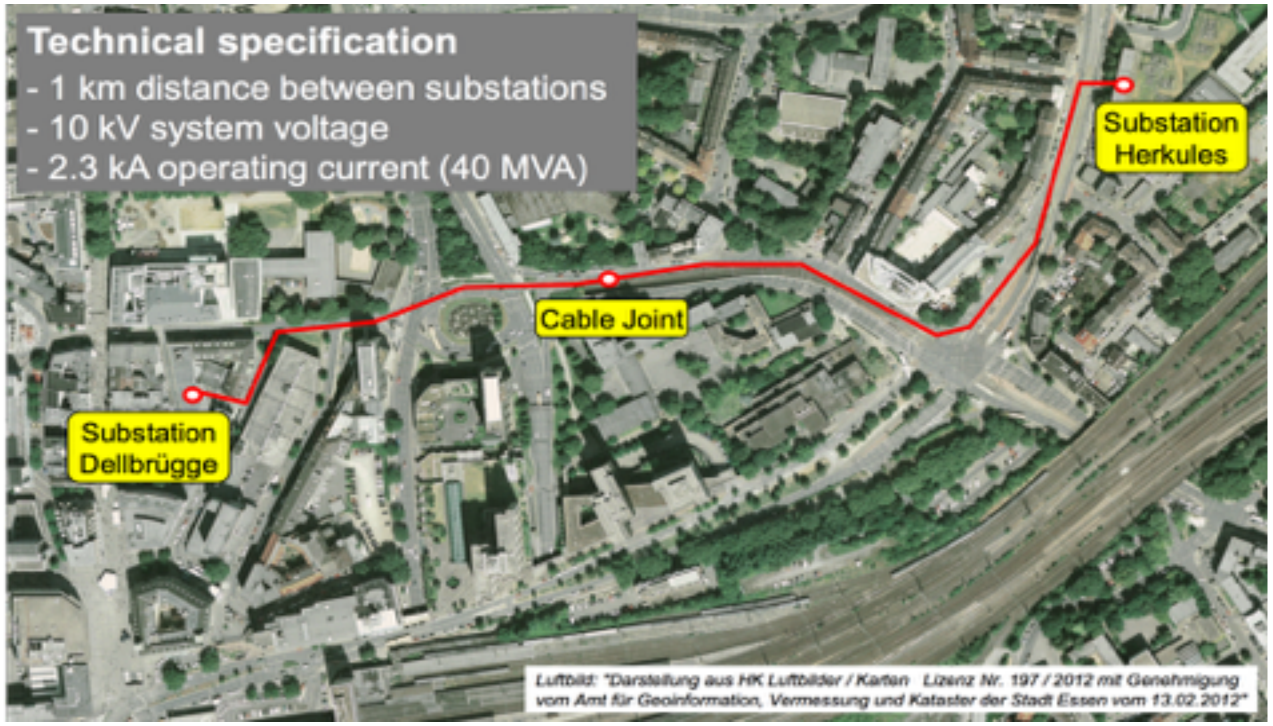
Cooling technology for HTS power applications

TECHNOLOGY OVERVIEW

Three-phase HTS power cables

- Example
  - *AmpaCity* project
  - Partners RWE, Nexans, KIT
  - Cable length $L = 1000\,\mathrm{m}$
  - Voltage $U = 10\,000\,\mathrm{V}$
  - Nominal current $I_\mathrm{N} = 2\,300\,\mathrm{A}$
  - Nominal capacity $P_\mathrm{N} = \sqrt{3} \cdot U \cdot I_\mathrm{N} = 40\,\mathrm{MW}$





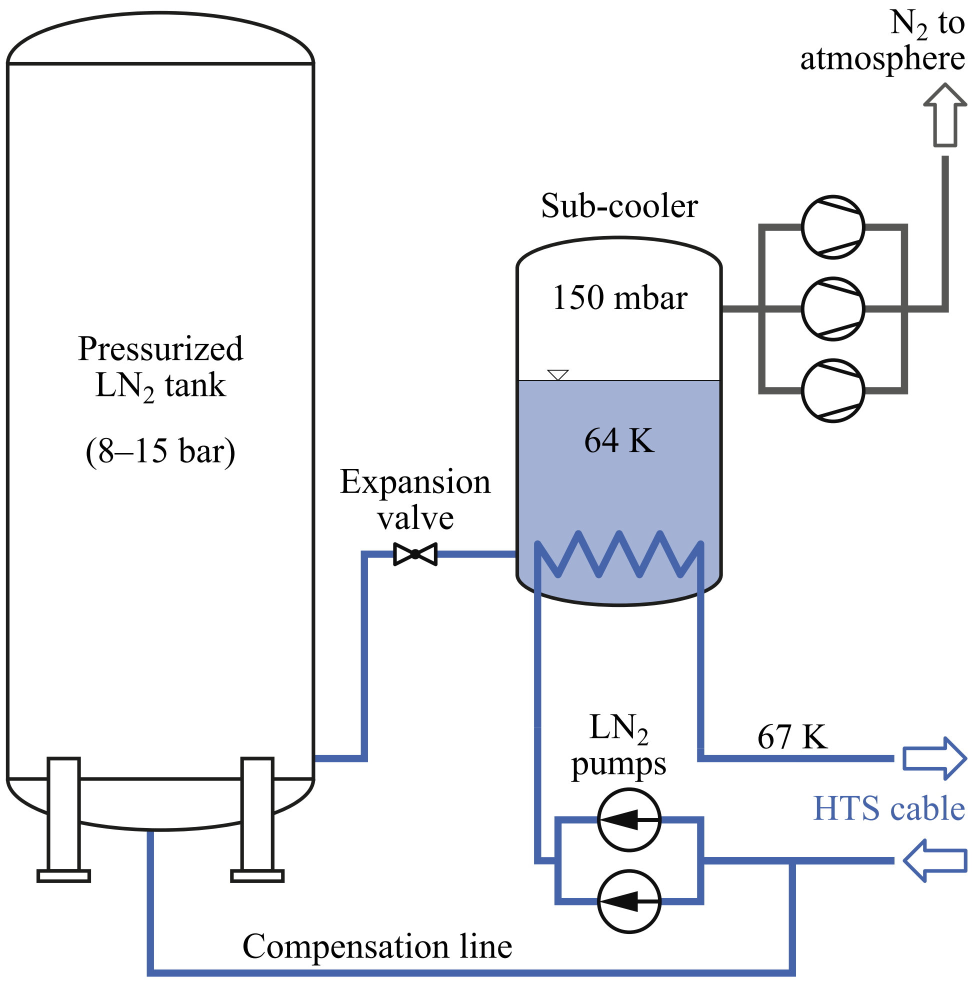
Luftbild: "Darstellung aus HK Luftbilder / Karten Lizenz Nr. 197 / 2012 mit Genehmigung vom Amt für Geoinformation, Vermessung und Kataster der Stadt Essen vom 13.02.2012"

Cable installation route in downtown Essen, Germany

Official start of field test on April 30, 2014

Cooling unit in the AmpaCity project

- Specification¹⁾
  - Sub-cooled LN_2 cooling of the HTS cable
  - Open LN_2 cooling cycle
  - Each one redundant LN_2 and vacuum pump
  - Nominal cooling capacity $\dot{Q}_{0,\mathrm{N}} = 4\,\mathrm{kW}\ @\ 67\,\mathrm{K}$
  - Nominal LN_2 consumption $\dot{M}_{\mathrm{LN_2,N}} = 110\,\mathrm{kg/h}$



1) Herzog, F.; Kutz, T.; Stemmle, M.; Kugel, T.: Cooling unit for the AmpaCity Project – one year successful operation. IWC 2015, Matsue - Japan

Cooling methods

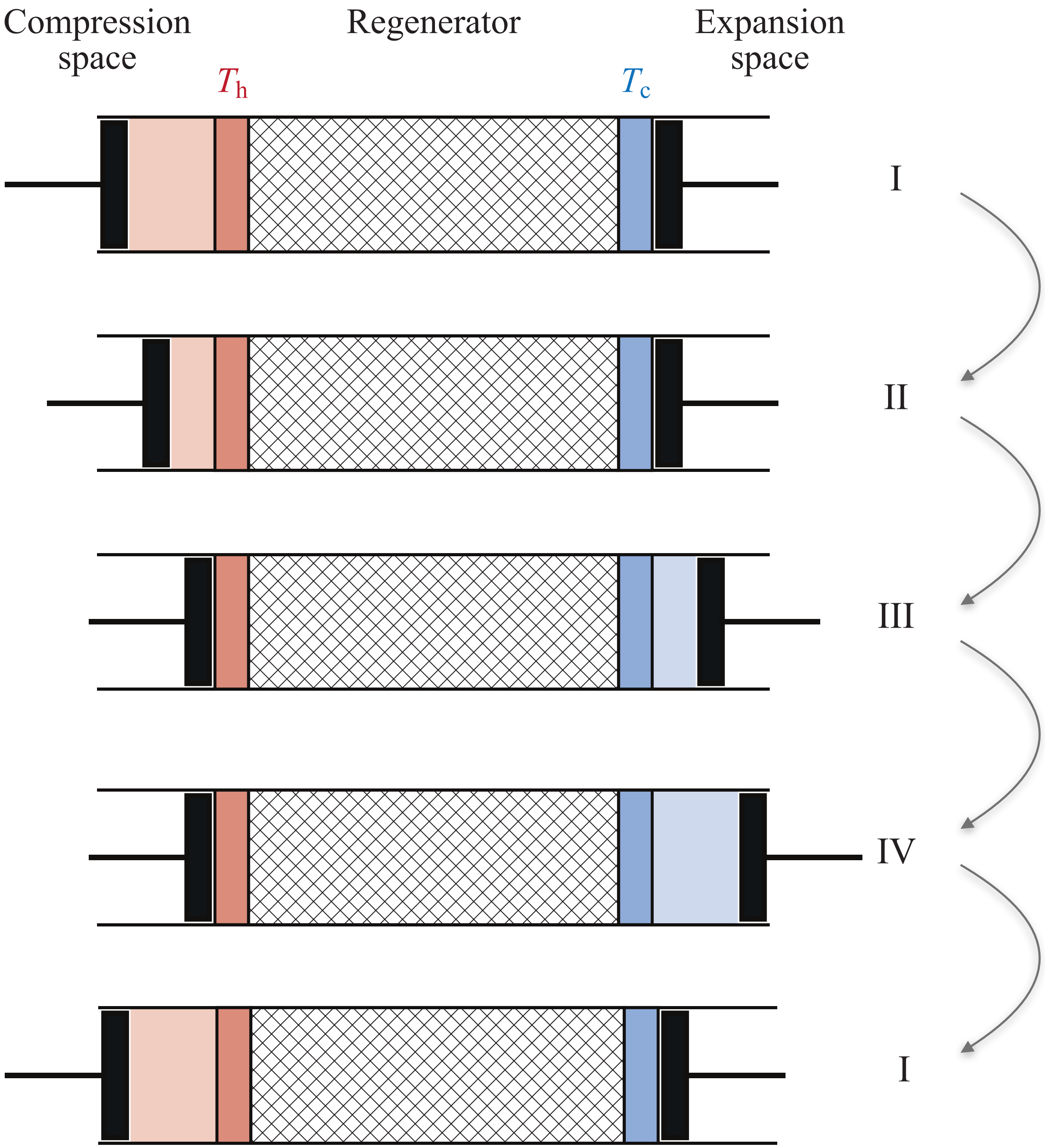
General overview

	Open cycle	**Closed cycle**	
		Cryocooler	Cryoplant (refrigerator)
Principle	Evaporation of LN_2 obtained from air separation units (ASU) Air composition: - 78.09 Vol% N_2 - 20.95 Vol% O_2 - 0.934 Vol% Ar + CO_2, Ne, He, Kr, H_2, Xe, O_3, Rn + Water, HCs, CFCs, dust, …	Oscillating regenerative process	Continuous recuperative cycle
Capacities	Any range	Small	Large
Temperatures	$T_{\mathrm{min}} > T_{\mathrm{tr,N2}} = 63$ K	Any down to ~2 K	Any down to ~1 K
Operation supplies	Electricity LN_2	Electricity (Cooling water)	Electricity (Cooling water)
Other criteria	Investment cost, operating cost, reliability, space requirements, noise, maintenance etc. are ***project-dependent***		

Cooling technology for HTS power applications

CRYOCOOLERS

Principle of Stirling cryocoolers



Steps in a Stirling cycle

I→II: The gas is in the compression space. During *isothermal* compression, heat is removed at T_h

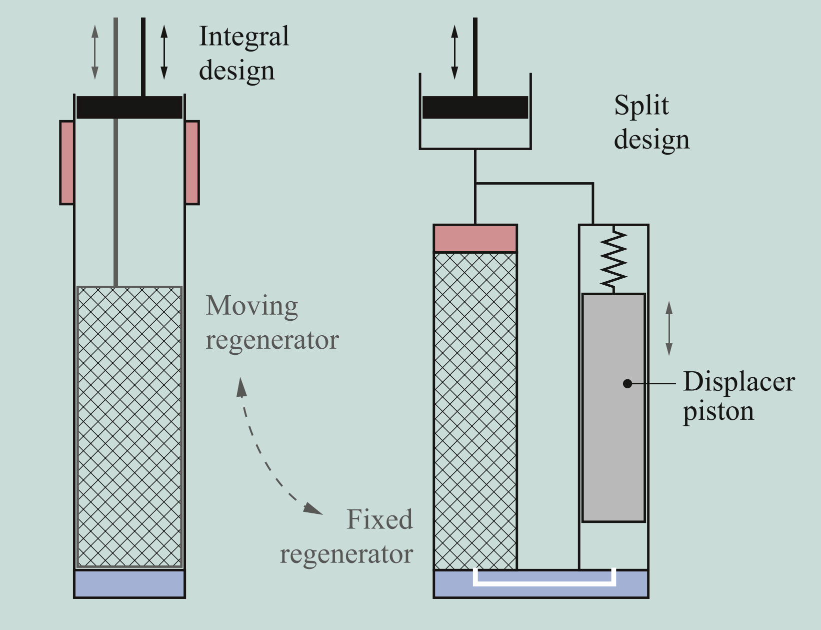
II→III: Isochoric displaced ($V = \text{const.}$) of the gas through the regenerator, cooling the gas down to T_c

III→IV: The gas is *isothermally* expanded in the expansion space, absorbing the heat Q_c at T_c

IV→I: Isochoric displacement back in the compression space, warming the gas up to T_h while cooling the regenerator

Cryocooler types

Stirling



Integral Stirling

- Build-in 90° phase shift

\+ High efficiency, low weight

– Vibration, noise, lifetime

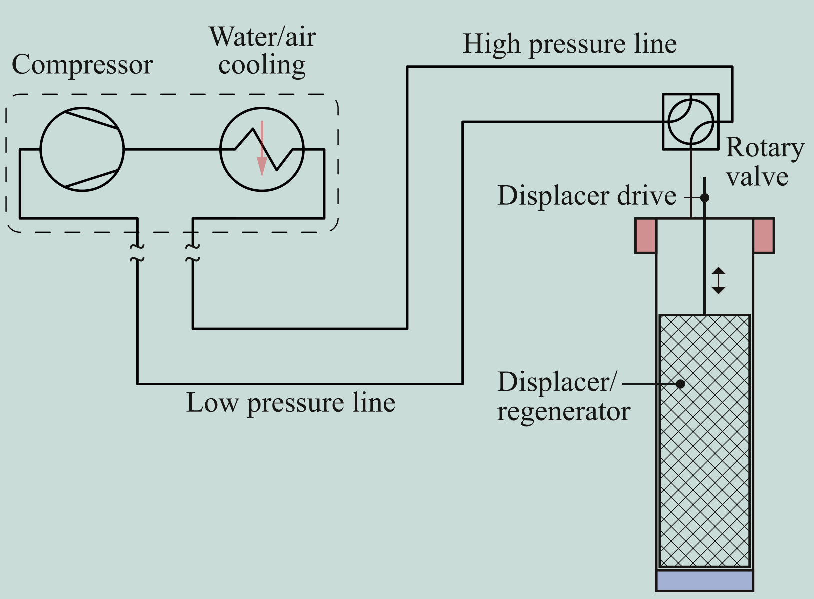
Split Stirling

- Resonance frequency depending on load and ambient temperature

\+ Low vibration and noise

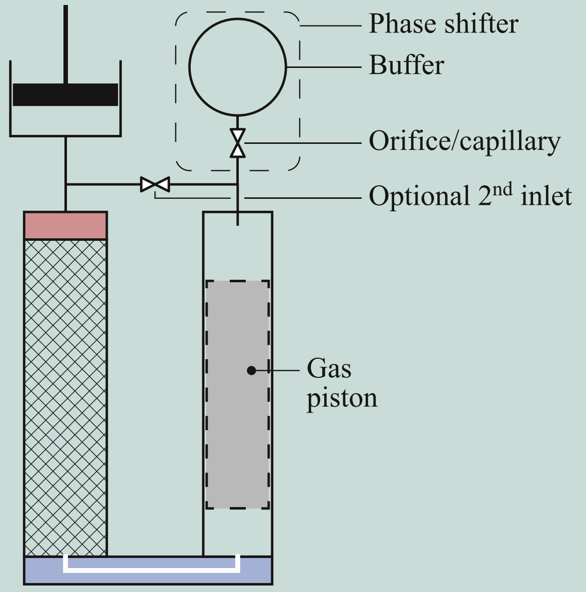
– Less efficient

Gifford-McMahon



- Continuously working compressor unit (air/water cooled)
- Compression and expansion by switching to high-pressure and low-pressure lines (amount of fluid contained changes)

Pulse tube



- Replacement of the displacer piston by a gas piston (wear, reliability)
- Control of the phase shift between mass flow and pressure waves by orifice or capillary combined with a buffer vessel
- Thermodynamically equivalent to Stirling cycle

Cryocooler types (examples)

Stirling

0.5-4 W
@ 77 K

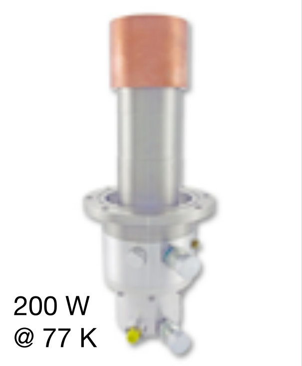
Source: http://www.aim-ir.de/

Source: http://www.stirlingcryogenics.com/

1000 W
@ 77 K

Gifford-McMahon

Source: http://www.shicryogenics.com

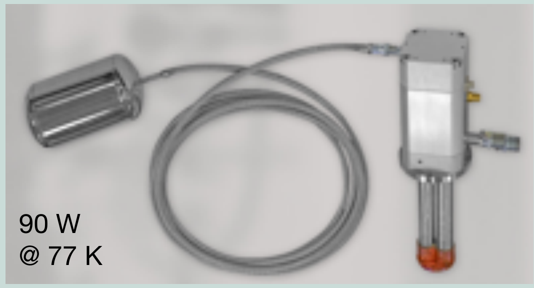


200 W
@ 77 K

140 W
@ 77 K

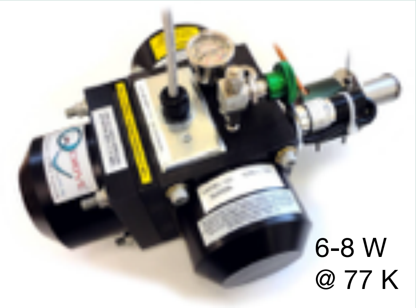
Source: https://leyboldproducts.oerlikon.com/

Pulse tube



90 W
@ 77 K

Source: http://www.cryomech.com/



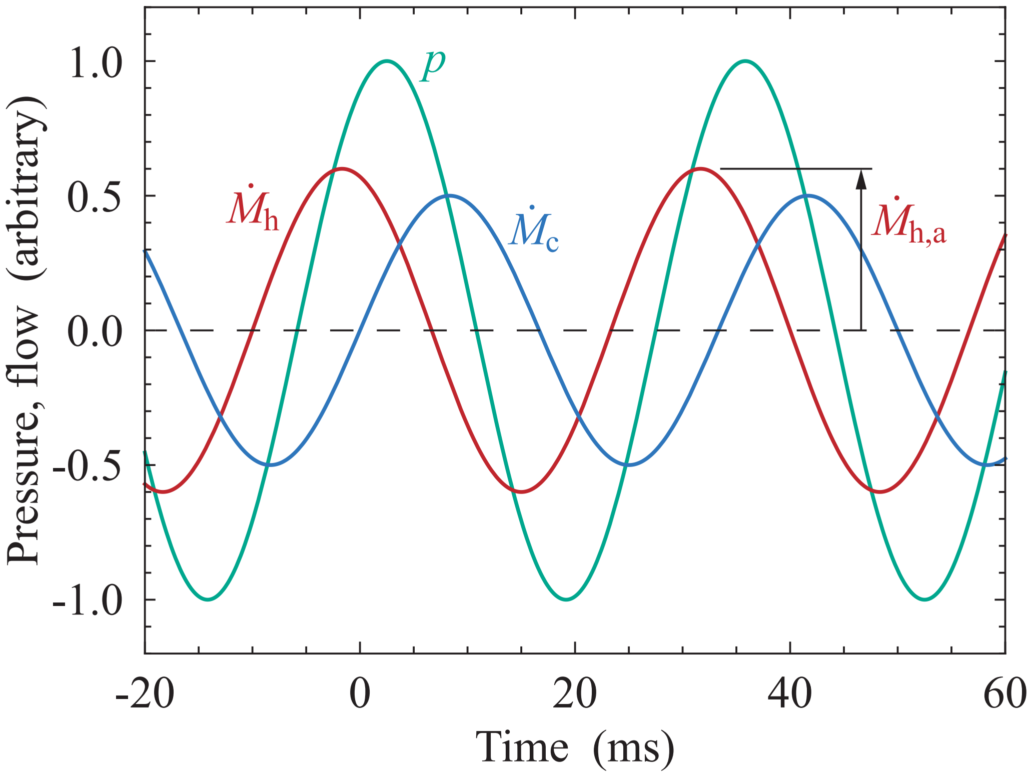
6-8 W
@ 77 K

Source: http://www.chartindustries.com

150 W @ 77 K

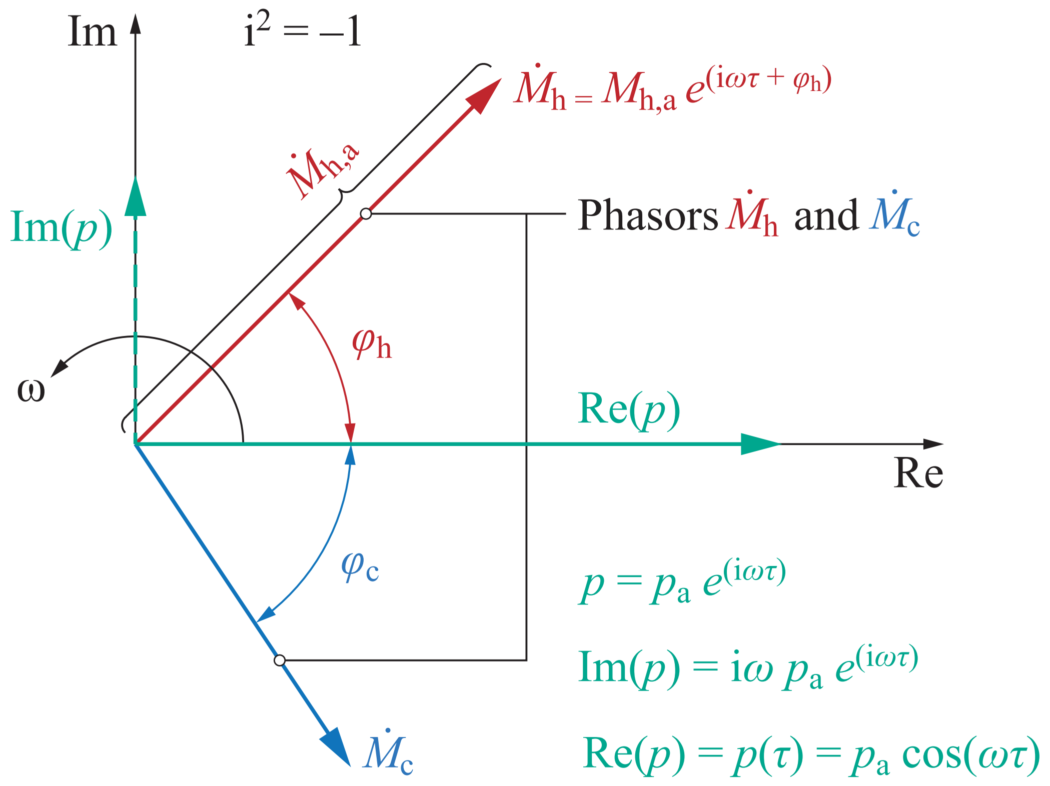
Thermodynamic modelling

- Time domain



  - Sinusoids
  - Math: Differential equations

- Frequency domain



$$p = p_a\, e^{(i\omega\tau)}$$

$$\mathrm{Im}(p) = i\omega\, p_a\, e^{(i\omega\tau)}$$

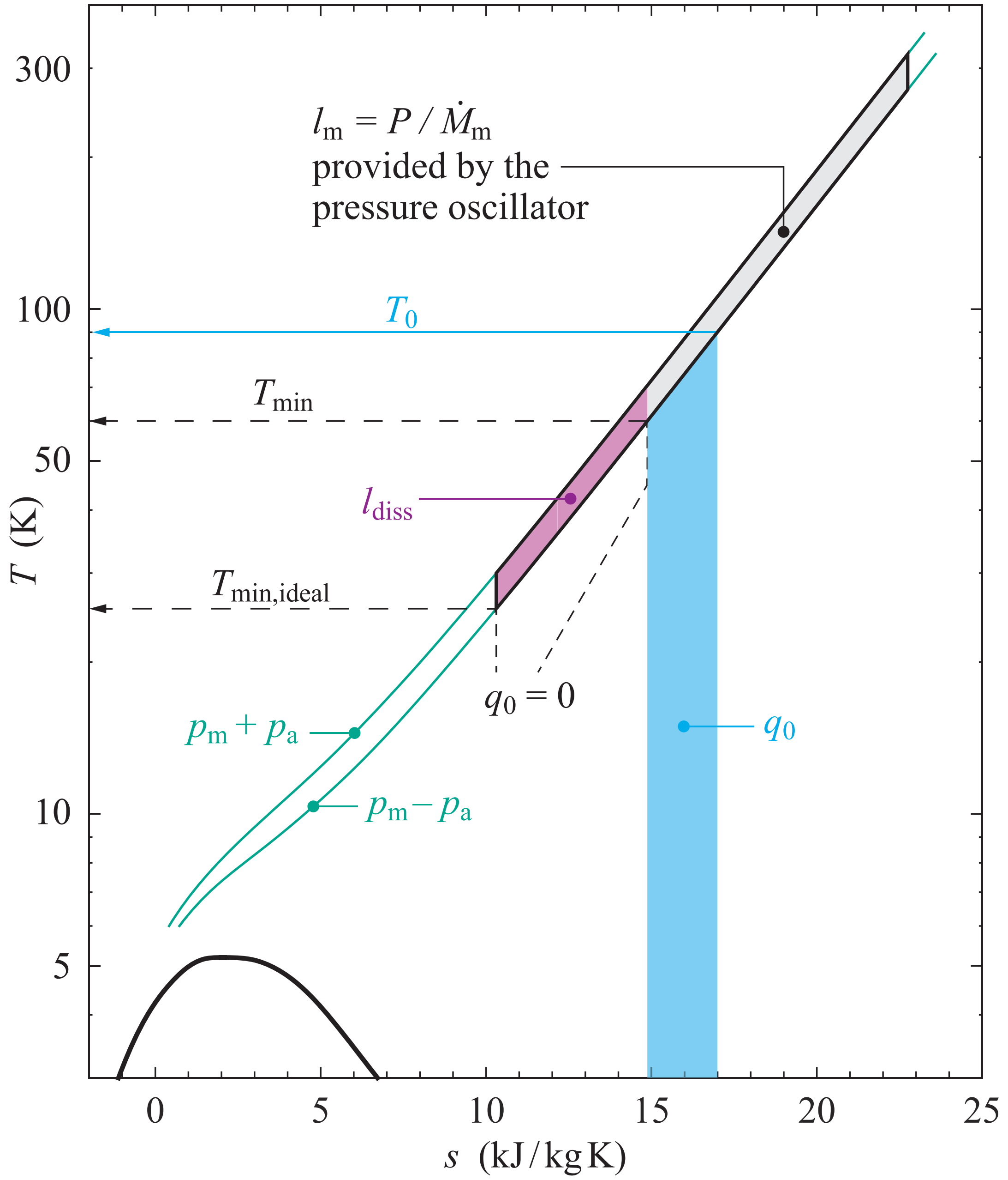
$$\mathrm{Re}(p) = p(\tau) = p_a \cos(\omega\tau)$$

  - Phasors ($\tau = 0$, complex space)
  - Math: Algebra, real and imaginary parts

- ***Acoustic power*** of the pressure oscillator for the real gas EOS $p\,v = Z\,R\,T$
  - $$P = \frac{1}{2}\, Z\, R\, T_m\, \dot{M}_a\, \frac{p_a}{p_m} \cos\left(\varphi_{\dot{M}p}\right)$$

Illustration of cryocooler operation

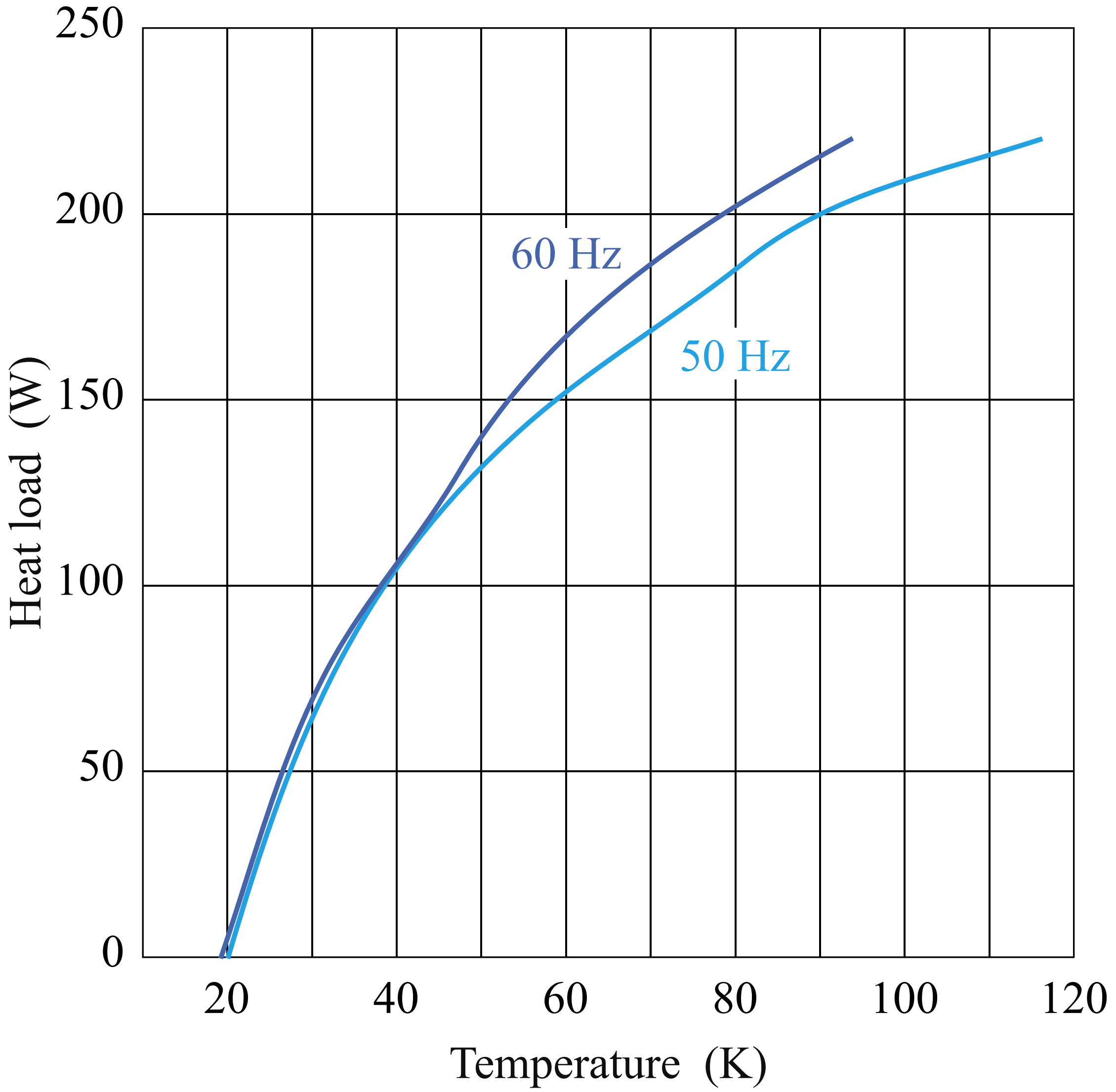
- T, s – diagram (simplified)



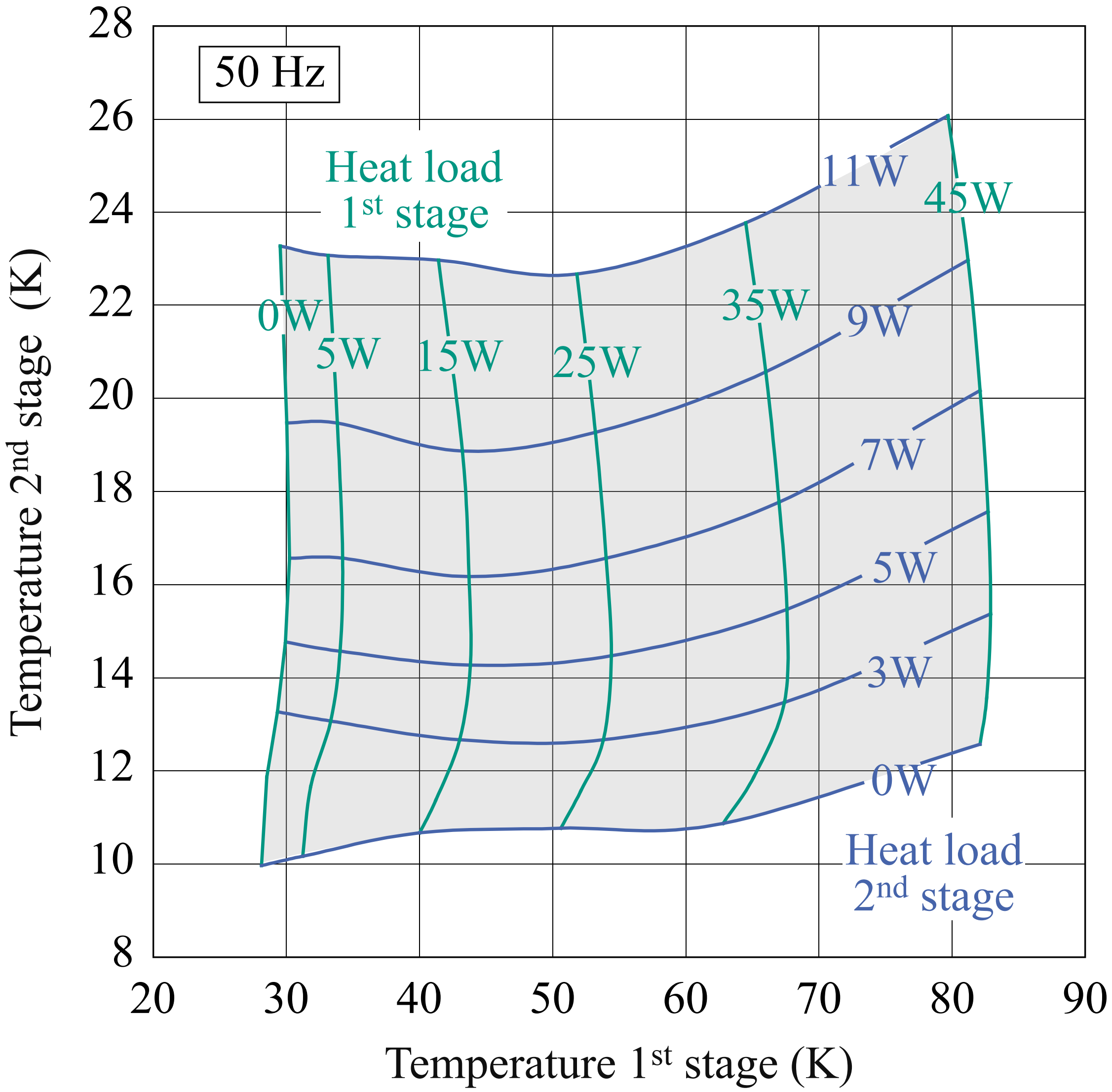
- Consider P as the average ***acoustic power*** provided by the pressure oscillator, causing pressure oscillations $p_m \pm p_a$
  - Minimum temperature $T_{min,ideal}$ of the ideal cryocooler cycle at zero load $q_0 = 0$
- Additional entropy production due to gradients in $\{T, p\}$ in a *real* cryocooler
  - Minimum temperature T_{min} of the real cryocooler at zero load $q_0 = 0$
- Cooling power q_0 available at $T_0 > T_{min}$
  - Work available to compensate the entropy difference between absorbing / dissipating the heat q_0 between T_0 / T_h
  - The higher the temperature T_0, the larger the cooling capacity q_0
  - ***Strong dependence*** $q_0 = f(T_0)$

Exemplary performance plots

- Single-stage cryocoolers



- Two-stage cryocoolers

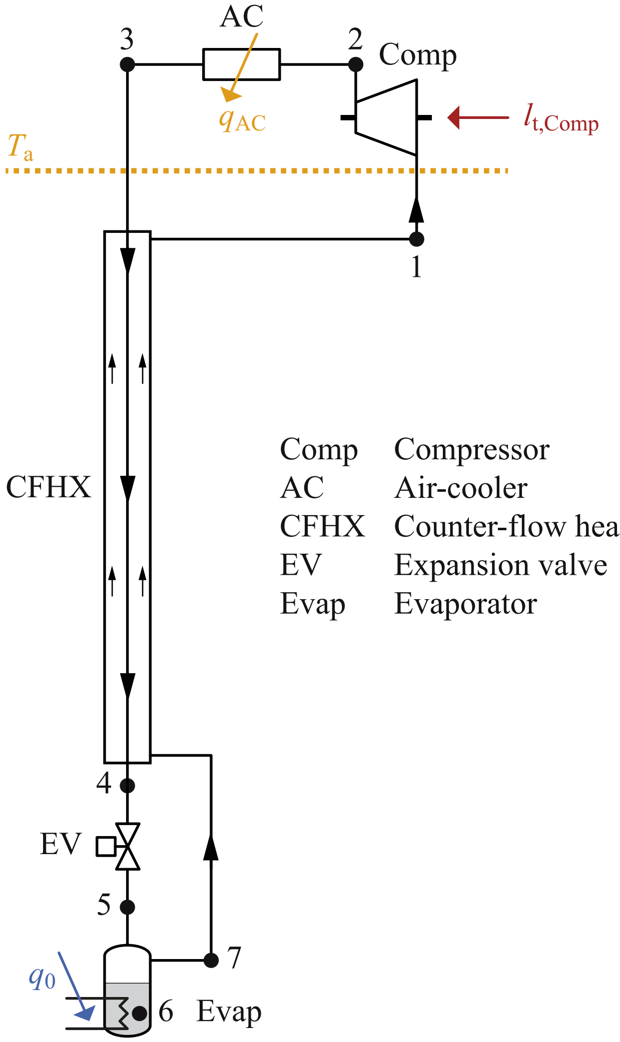


Cooling technology for HTS power applications

CRYOPLANTS (REFRIGERATORS)

Linde-Hampson cycle

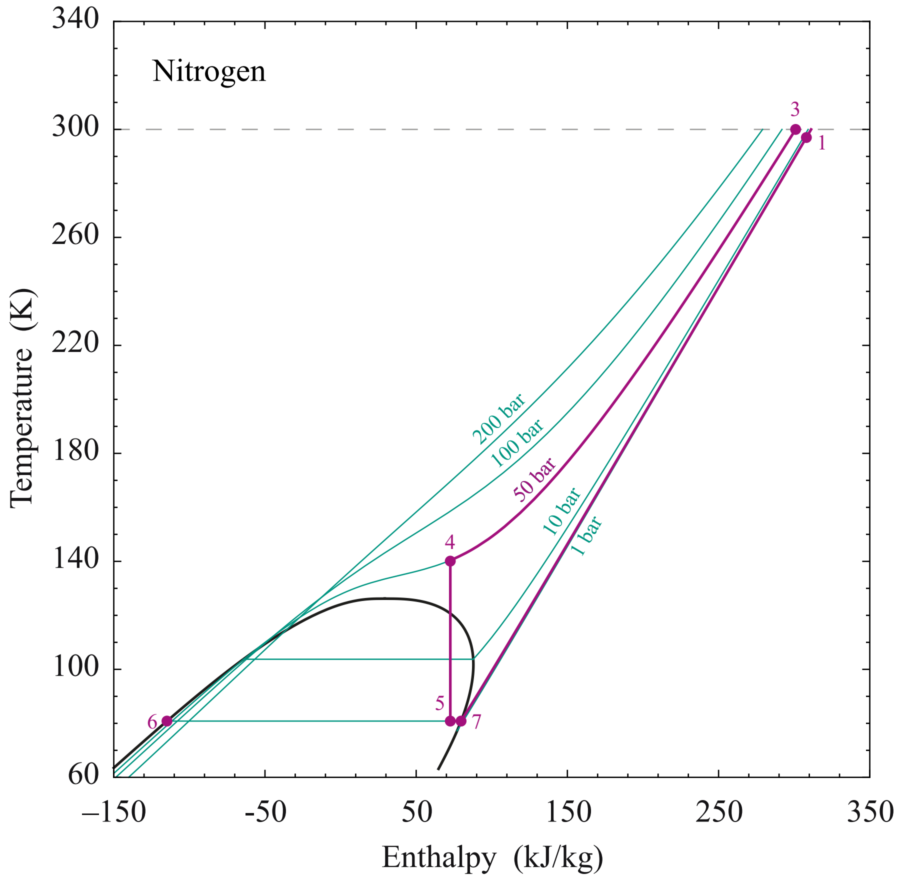
Layout



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

- *Simplest* configuration
- Positive Joule-Thomson coefficient $\mu_{JT} = \left(\partial T / \partial p\right)_h$ required

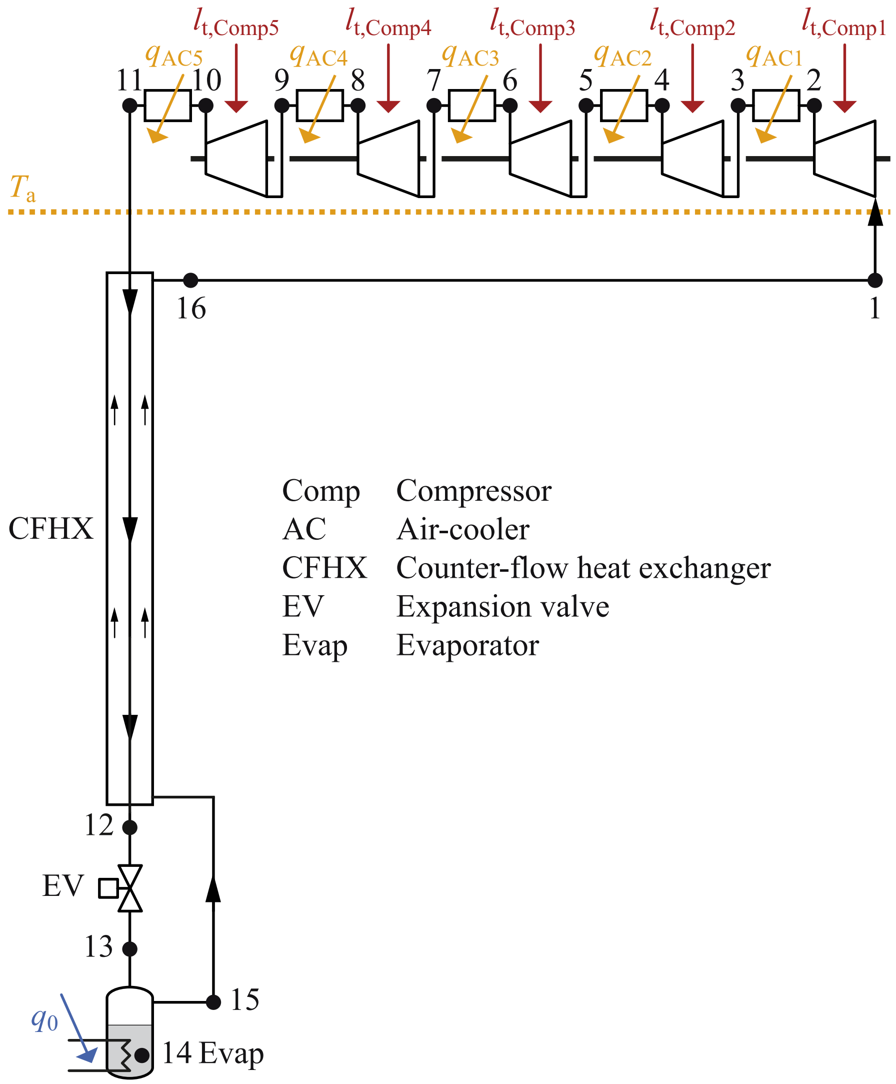
Process in T, h-diagram



- Very low cooling capacity $q_0 = h_7 - h_5$
- Very low efficiency $\eta = q_0 / l_t$
- Warm process part at $T > T_a$ not shown

Linde-Hampson cycle

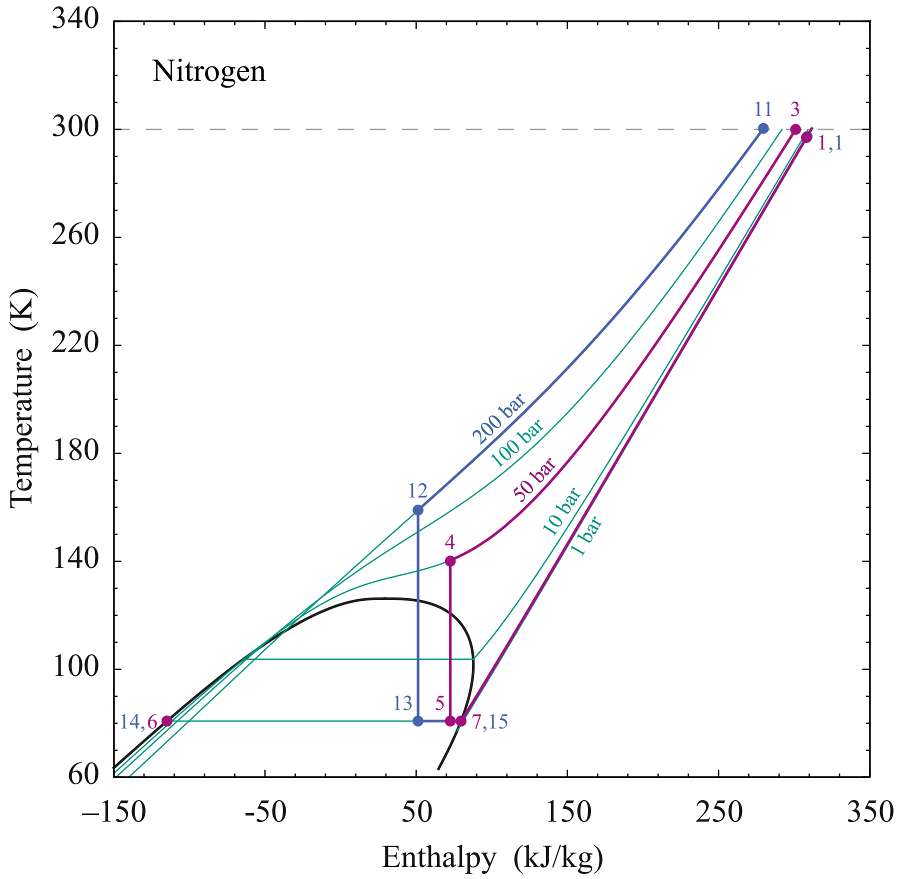
Layout



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

- Multi-stage compression to e.g. $p_{\mathrm{H}} = 200$ bar
- Different number of stages depending on compressor technology (flow rates)

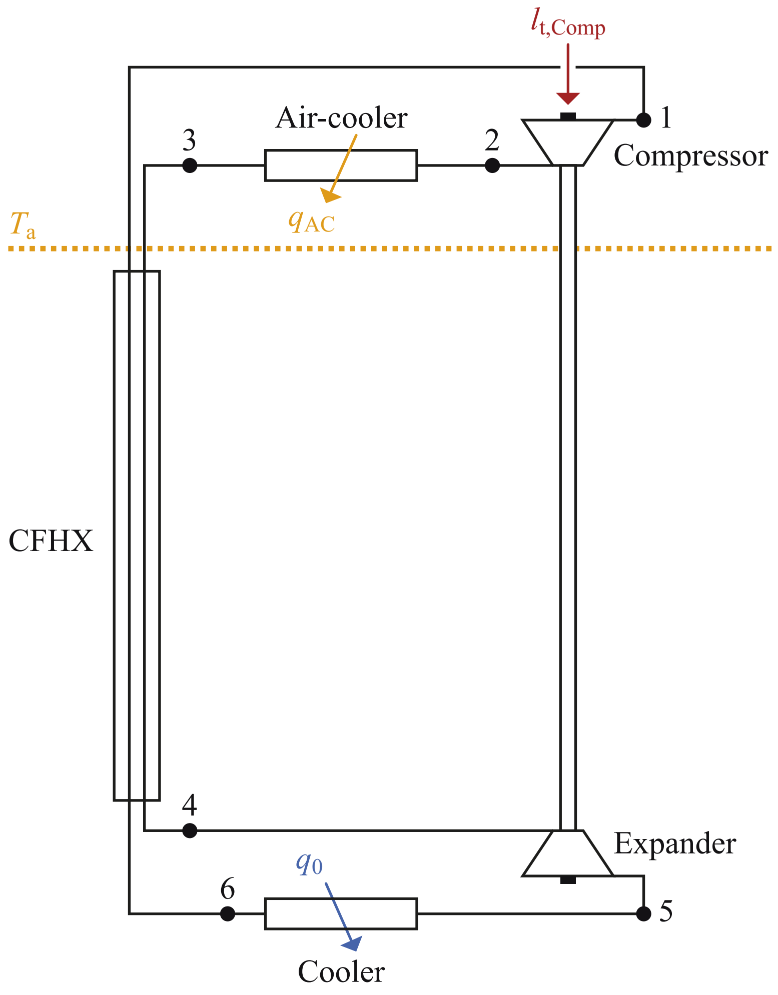
Process in T, h-diagram



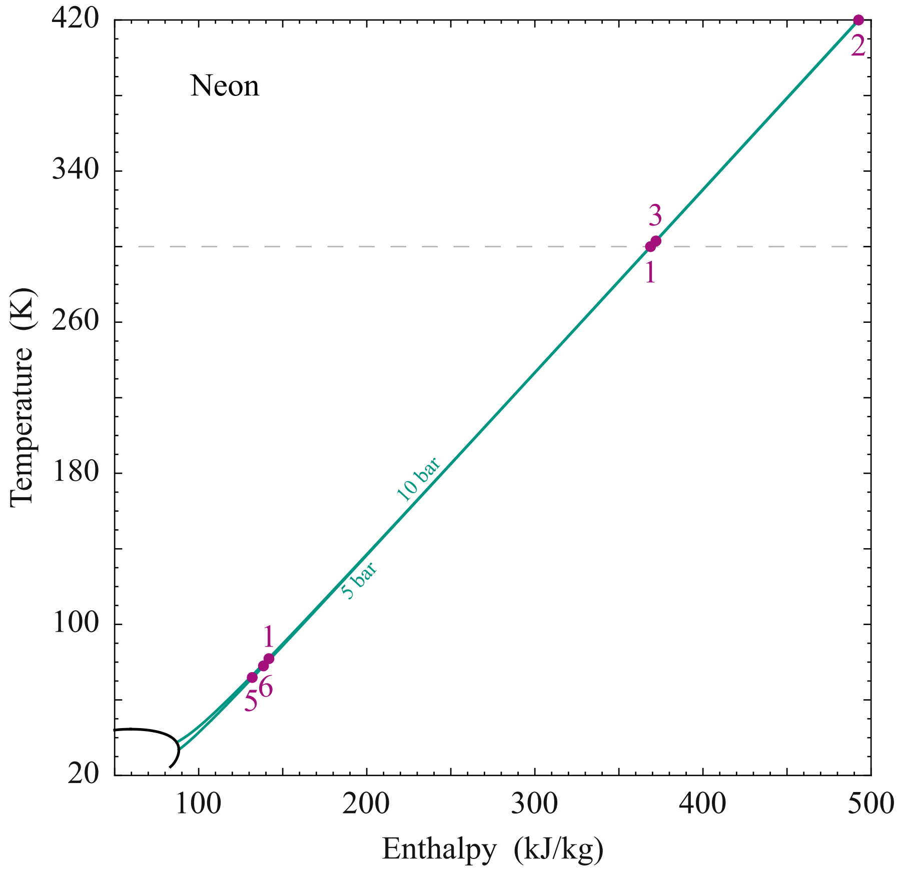
- Higher specific cooling capacity $q_0 = h_7 - h_5$
- Still low efficiency $\eta = q_0 / l_{\mathrm{t}}$
- Warm process part at $T > T_{\mathrm{a}}$ not shown

Brayton cycle

Layout



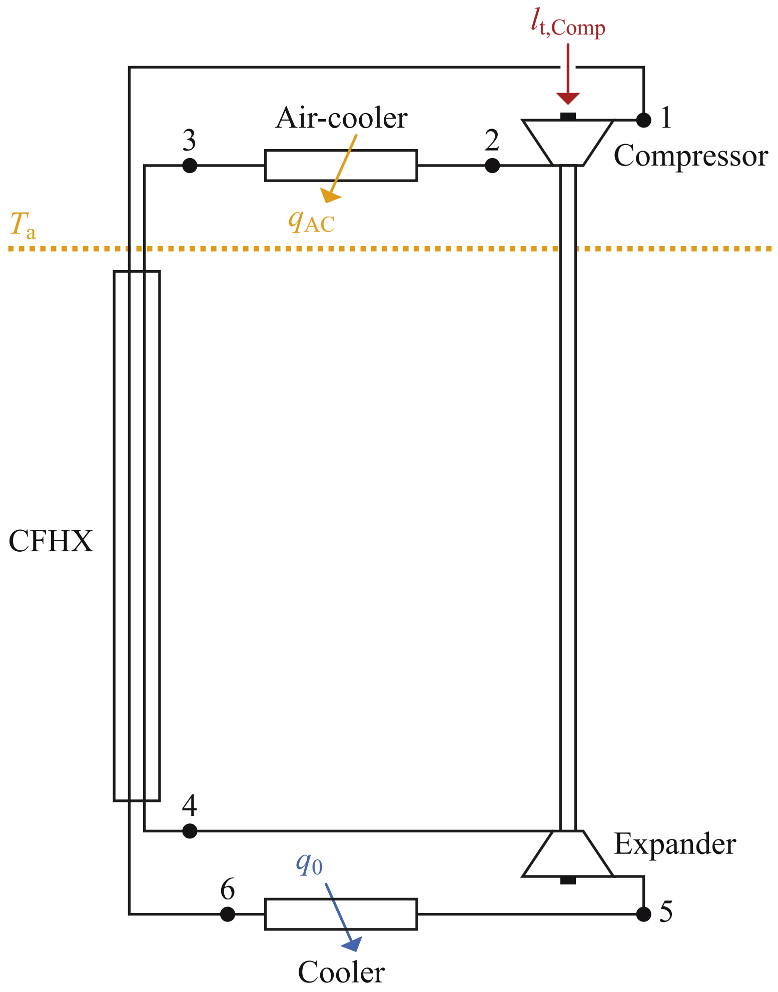
Process in T, h-diagram



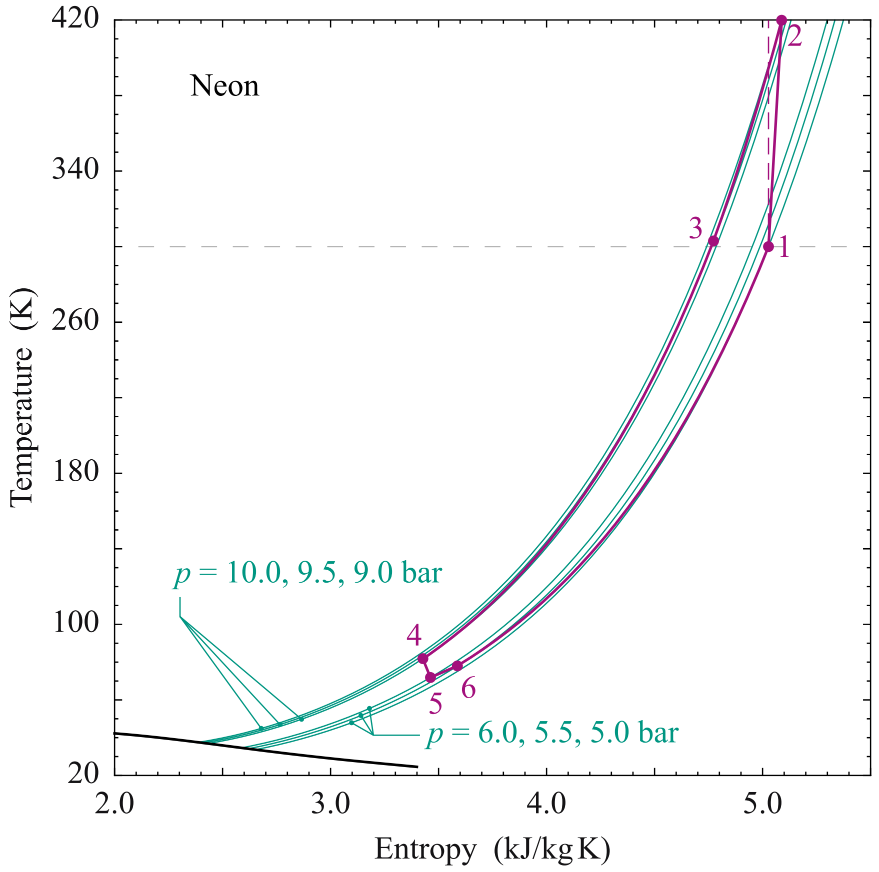
- Expansion of ***single-phase*** working fluid in super-heated region (e.g. Ne)
- Recovery of expansion work

Brayton cycle

Layout



Process in T, s-diagram



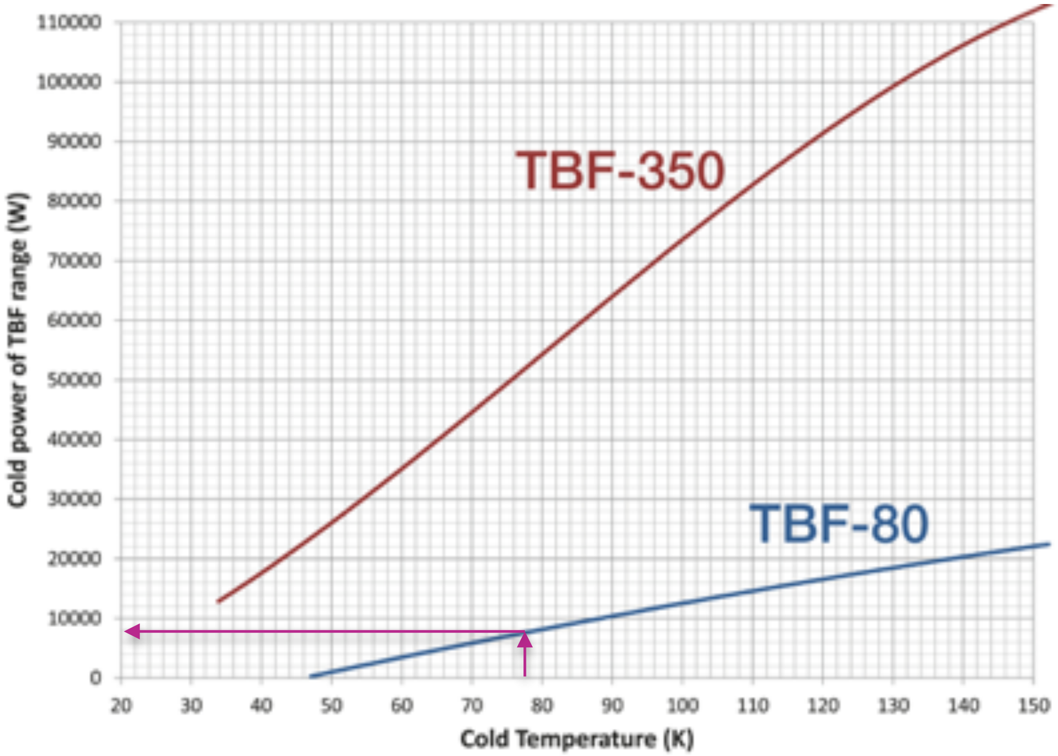
- Expansion of ***single-phase*** working fluid in super-heated region (e.g. Ne)
- Recovery of expansion work

- Efficient due to turbo-expander, but cost factor of cold turbo-machinery
- Costly and rare working fluid (0.0018 Vol% in air)

Turbo-Brayton refrigerator

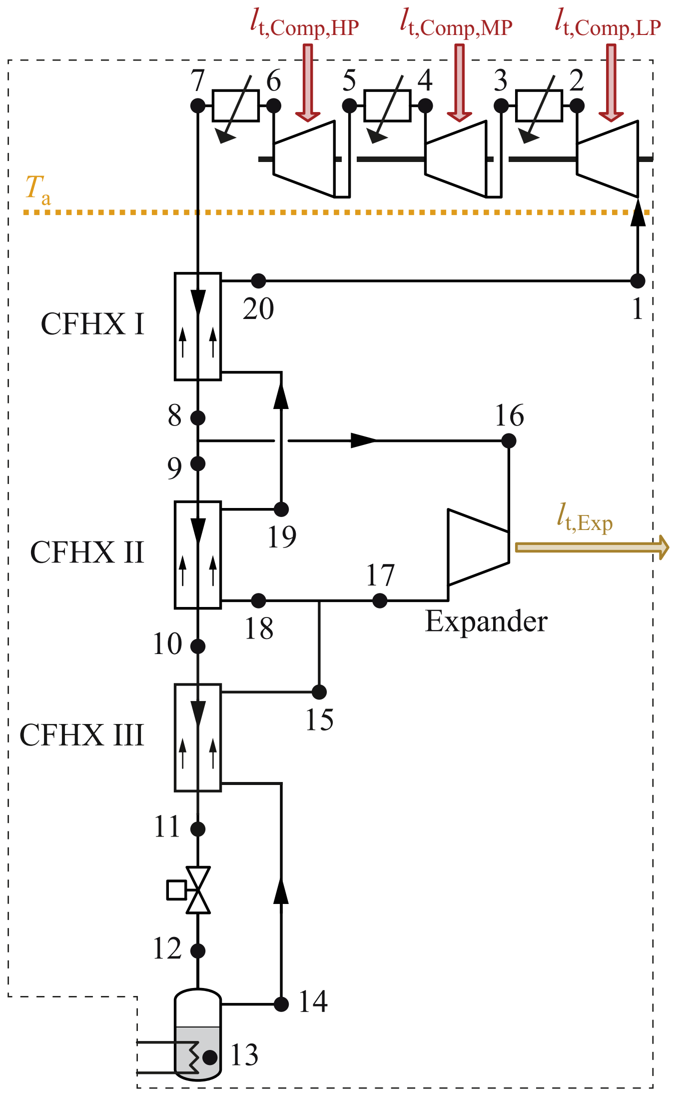
- Commercial system available (Air Liquide)
- Applications
  - Gas (re)liquefaction (HCs, air gases)
  - Cryogenic gas purification/separation
  - Smallest unit suitable for HTS power applications

Source: http://www.airliquideadvancedtechnologies.com/



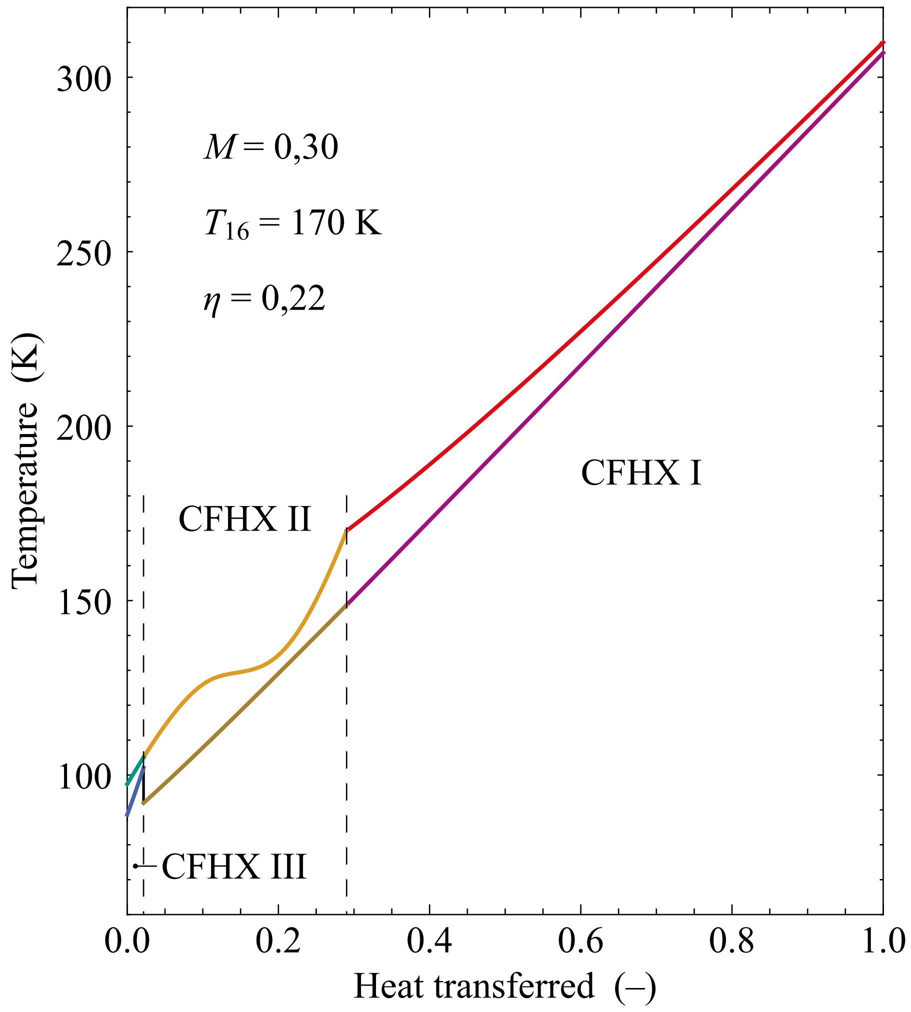
Claude cycle

Layout



- Single-phase expansion of ***partial flow*** in super-heated region
- Pre-cooling of remaining flow

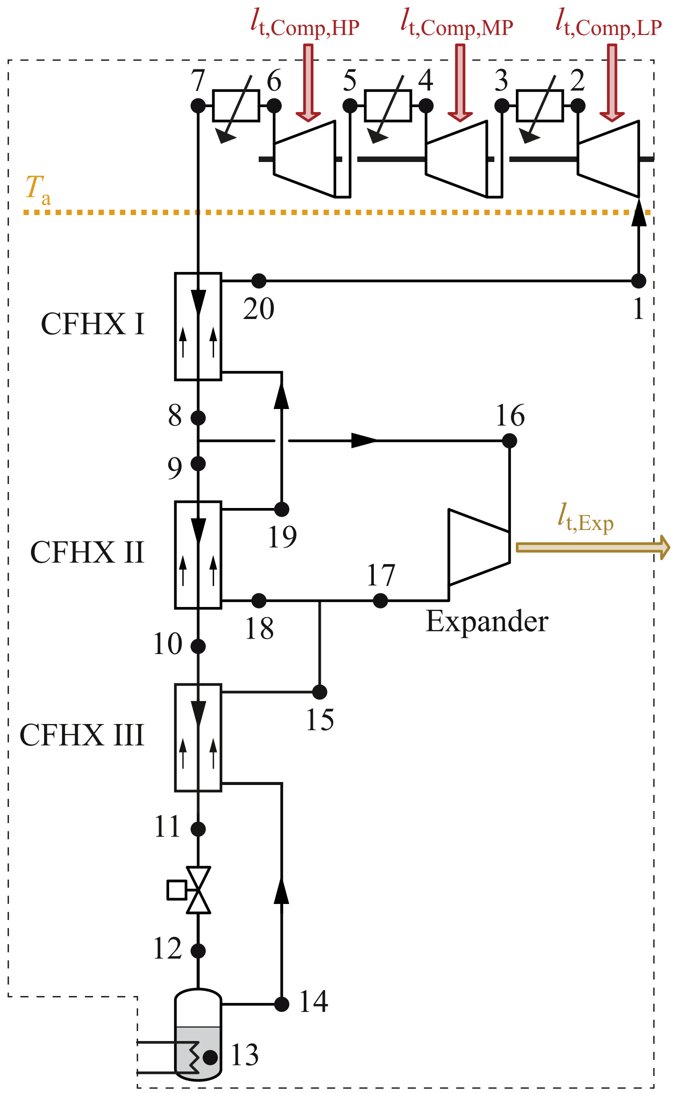
Temperature profiles in CFHX I–III



- Efficient due to turbo-expander, but cost factor of cold turbo-machinery
- Pinch-points to be considered

Claude cycle

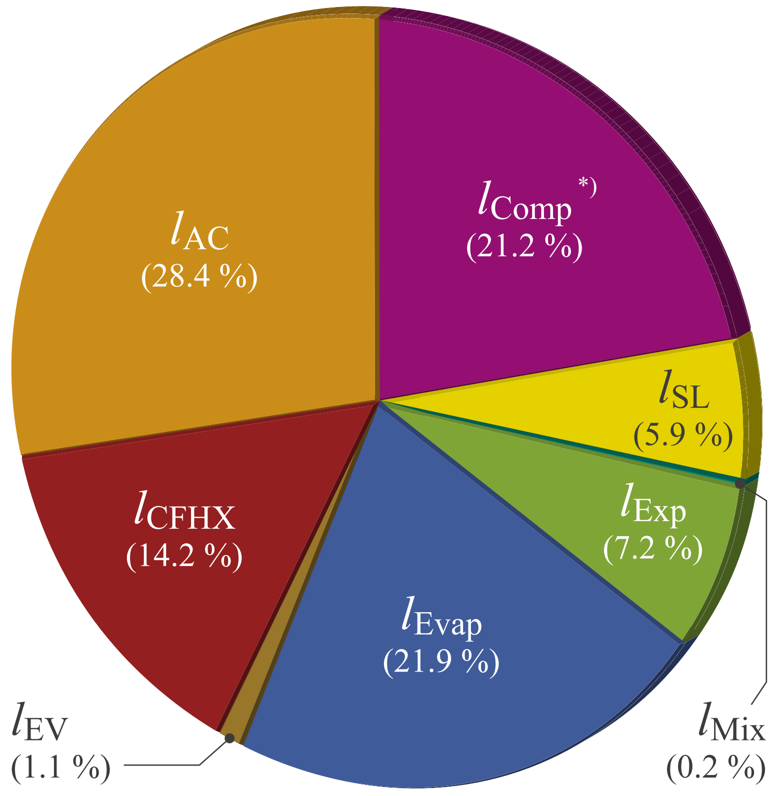
Layout



- Single-phase expansion of partial flow in superheated region
- Pre-cooling of remaining flow

Sources of energy demand

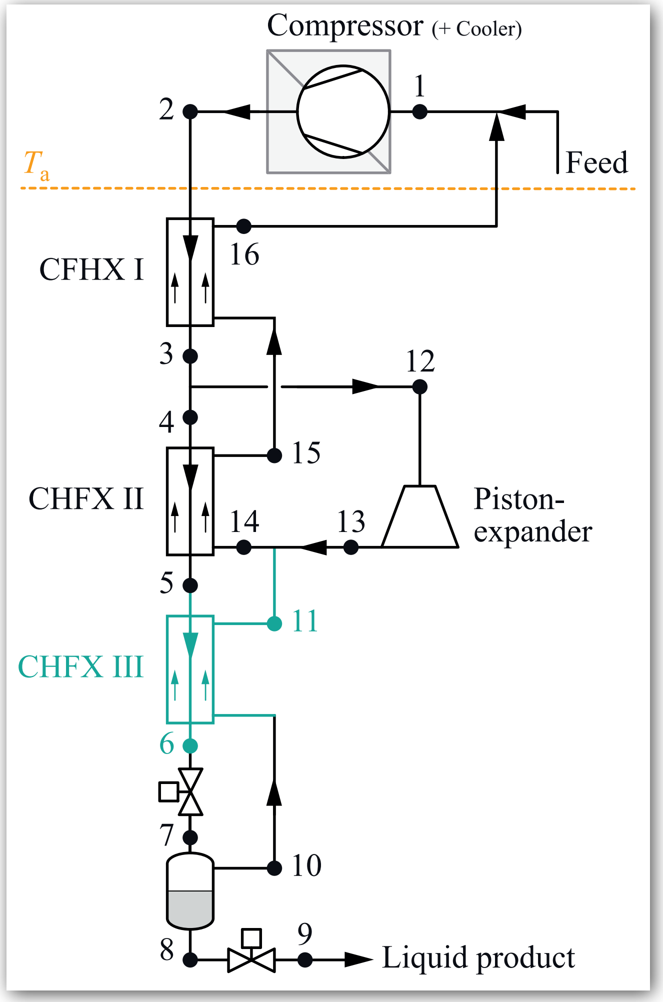
- Example process with N_2, $T_a = 300$ K, $p_1 = 1$ bar, $p_7 = 40$ bar, $\Delta p_{ij} = 0.5$ bar, $\eta_{Comp} = 0.7$, $\eta_{Exp} = 0.8$, $\Delta T_{min} = 3$ K in all heat exchangers
- Most efficient operating point at a cold flow $M = 0.3$ und $T_{16} = 170$ K (expander flow $1–M$)



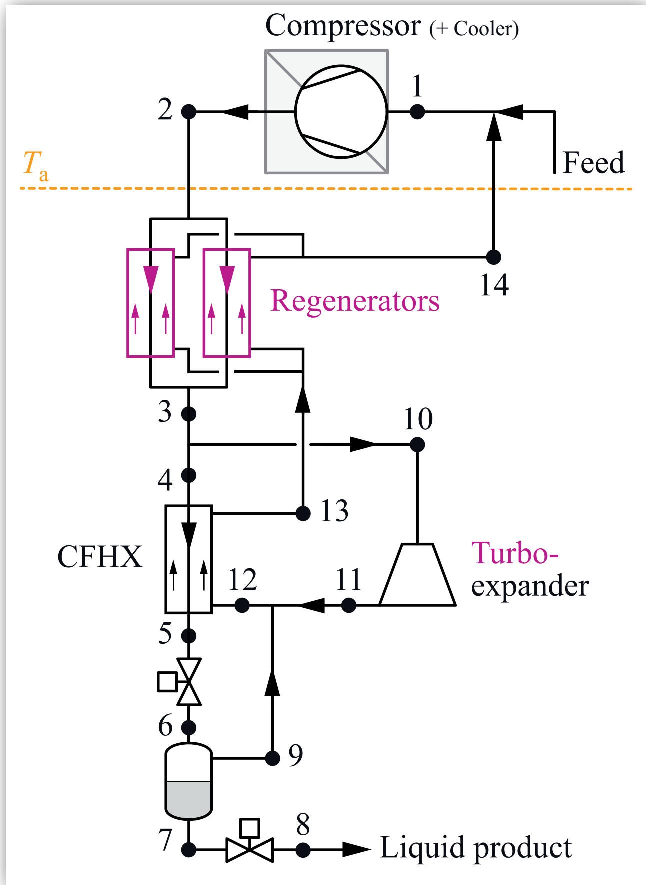
*) Expansion work $l_{t,Exp} = 0.077\ l_t$ recovered

Variants of the Claude cycle

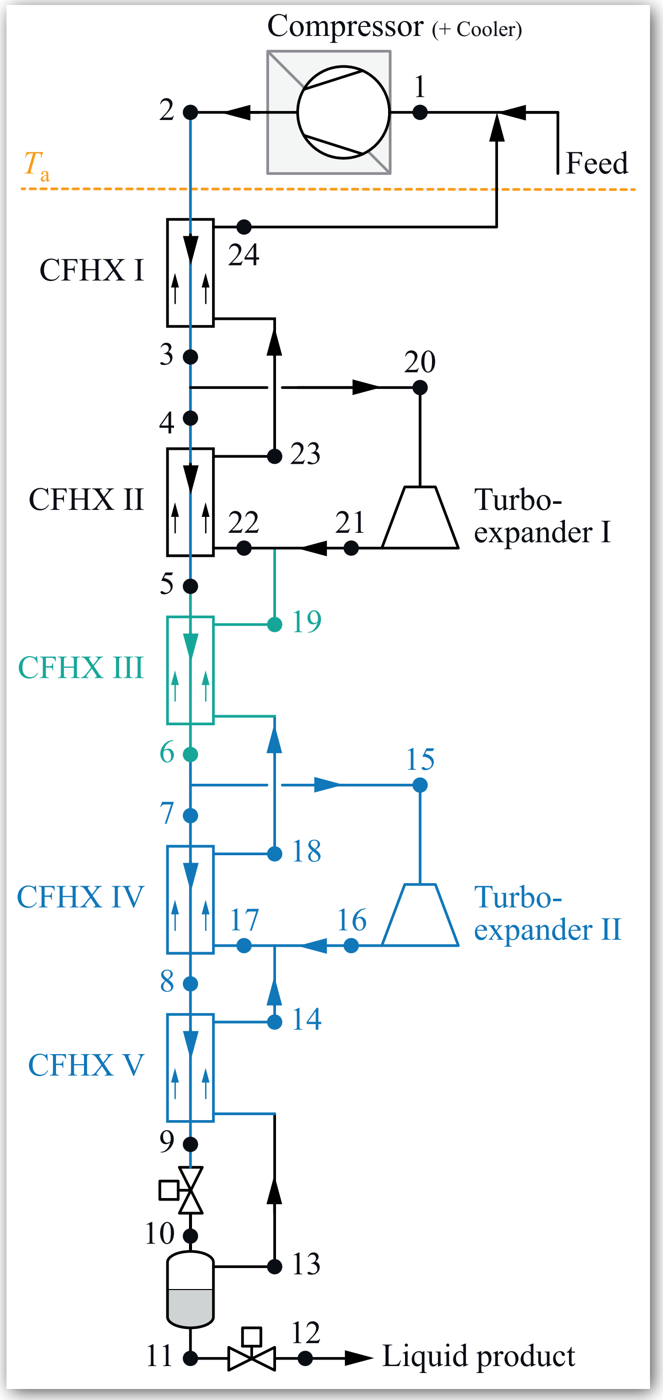
- Claude cycle



- Kapitza cycle



- Collins cycle



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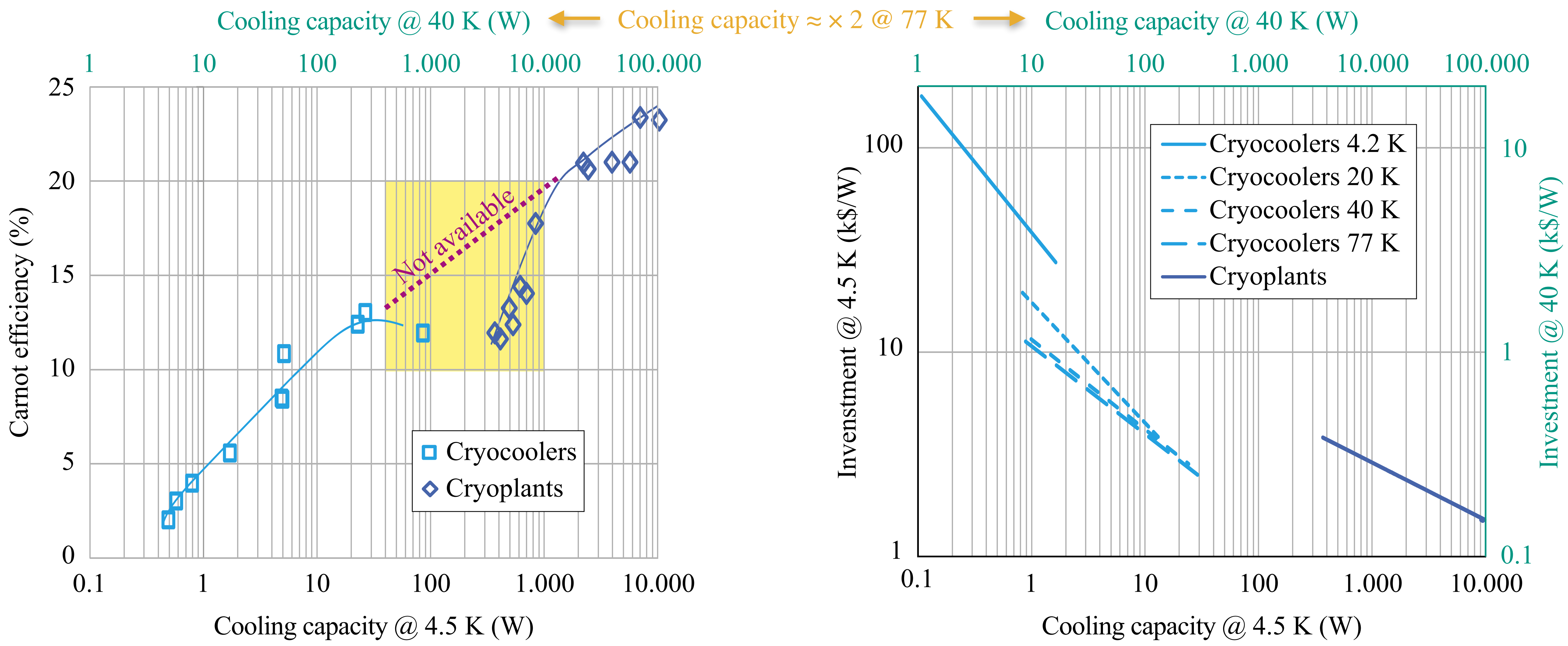
Cooling technology for HTS power applications

DEVELOPMENT POTENTIALS

Technology comparison

- Efficiency
- Specific investment cost

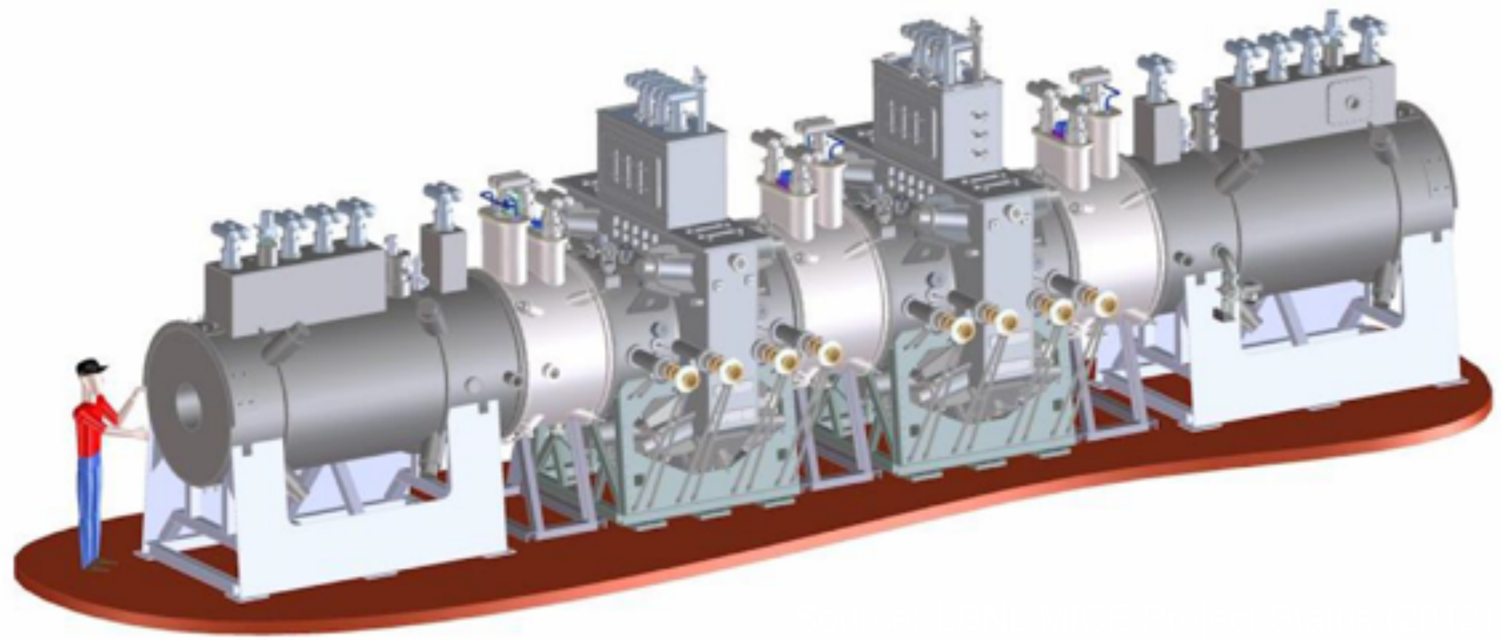


Source: Decker, L.: Overview on cryogenic refrigeration cycles for large scale HTS applications. International Workshop on Cooling System for HTS Applications (IWC-HTS), October 14-16, 2015, Matsue, Japan

- We can conclude that ***either technology*** has ***limitations*** in the HTS power application range

Makeshift solution at 4 K

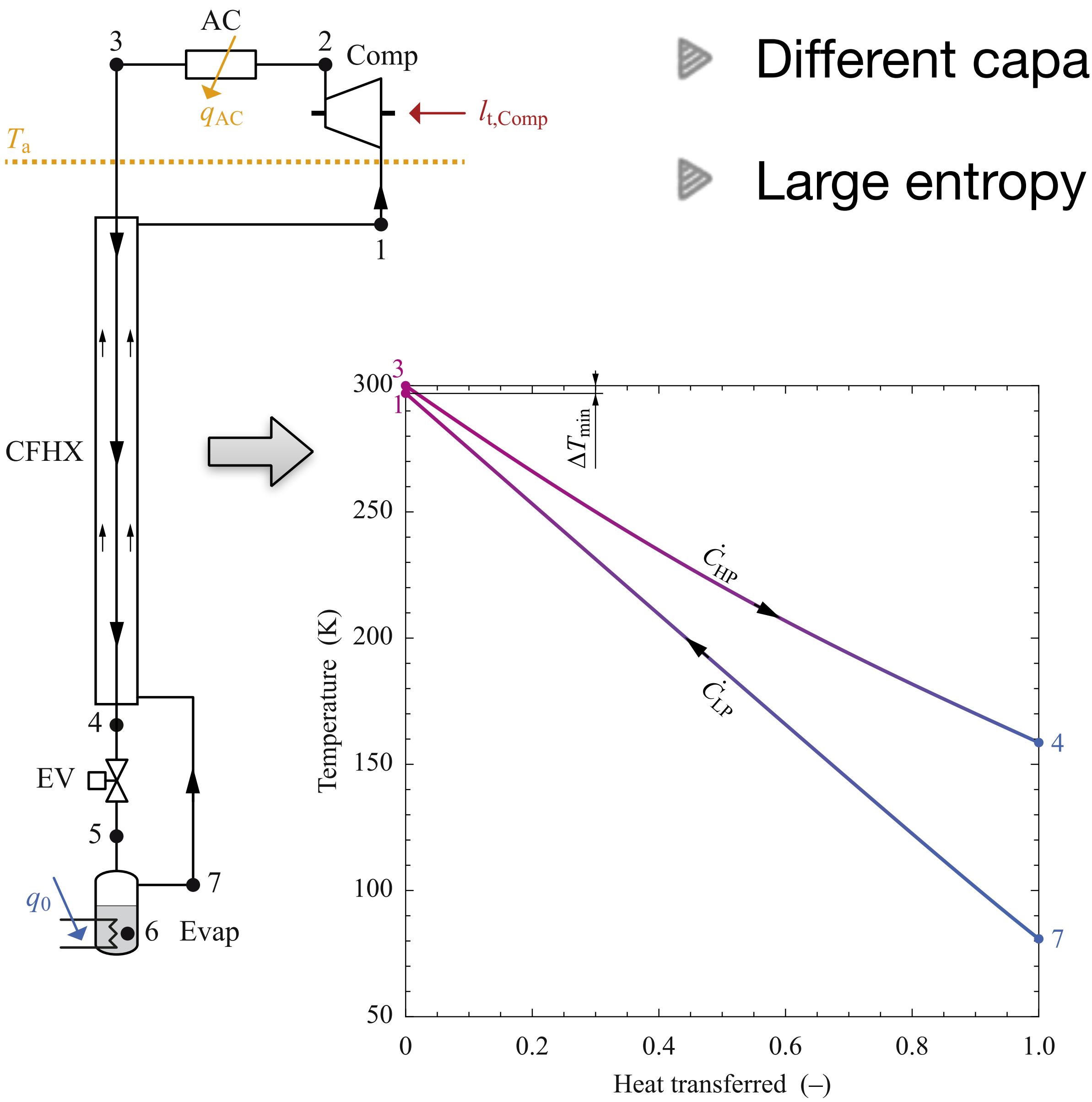
- *Excessive* cryocooler use on a superconducting magnet and RF cryostat



- **25** GM cryocooler on one cryostat
  - Cooling power: $\dot{Q}_0 = 37.5\ \mathrm{W}\ @\ \underline{4.2\ \mathrm{K}} \rightarrow (25 \times 1.5\ \mathrm{W}\ @\ 4.2\ \mathrm{K})$
  - Power consumption: $P = 180\ \mathrm{kW}\ (25 \times 7.2\ \mathrm{kW})$
  - Specific power consumption: $P^* = 4800\ \mathrm{W/W_{Cooling\ power}}$
  - Other issues: Space, vibrations, noise, reliability, maintenance, …
- Comparison to recuperative cycle (Collins process)
  - Specific power consumption: $P^* = 250 \ldots 400\ \mathrm{W/W_{Cooling\ power}}$

Back to the Linde-Hampson cycle

Reason for poor efficiency



- Different capacity flows $\dot{C} = \dot{M} \cdot c_p(T, p)$ yield increasing ΔT
- Large entropy production $\Delta s_{irr} = \int \frac{T_h - T_c}{T_h \cdot T_c} \mathrm{d}q$

1st Law

2nd Law

Technical options

- Aim: $\dot{M}_{HP} \cdot c_{p,HP} = \dot{M}_{LP} \cdot c_{p,LP}$ in order to keep ΔT_{min} along the CFHX

I) Adaptation of flow rates $\dot{M}$

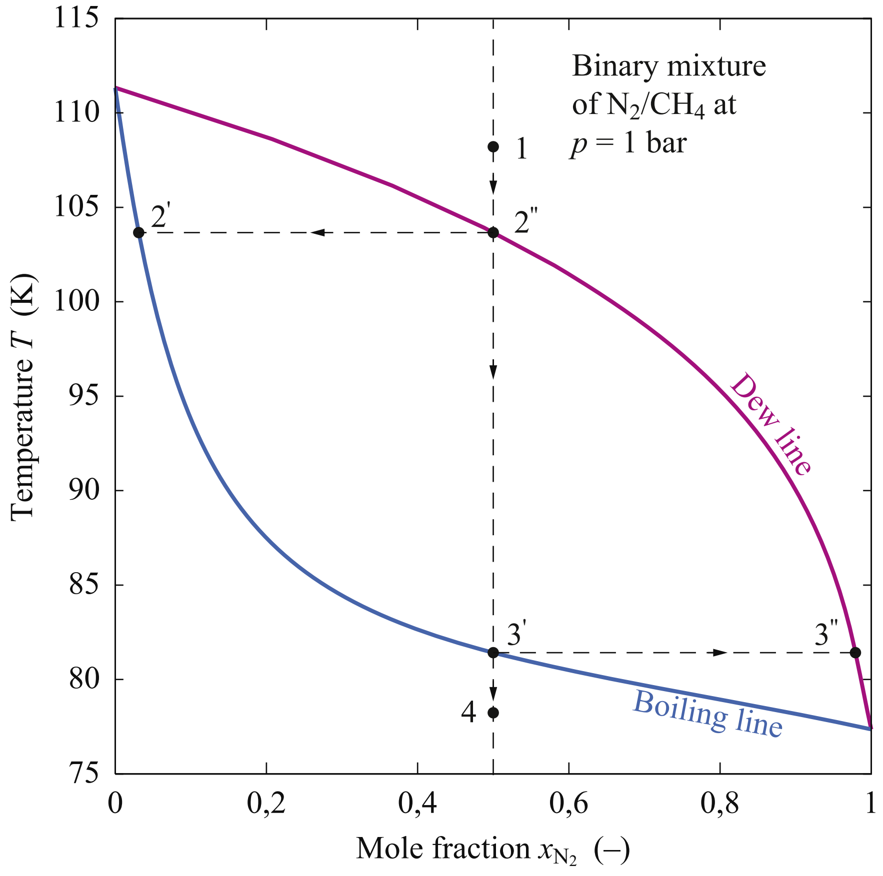
- The Claude cycle includes this solution in CFHX II

II) Manipulation of spec. heat capacities by using ***wide-boiling refrigerant mixtures***

- Mixed refrigerant cycle (MRC)

Phase behavior of zeotrope mixtures

Phase diagram (example)



- Different concentrations of saturated liquid and vapor phases

Closed condensation $1 \rightarrow 4$

(1) Single-phase super-heated vapor

(2) Saturated vapor $2''$; first liquid drop $2'$

- High-boiler CH_4 has lower vapor pressure and condenses first

(3) Saturated liquid $3'$; last vapor bubble $3''$

(4) Single-phase sub-cooled liquid

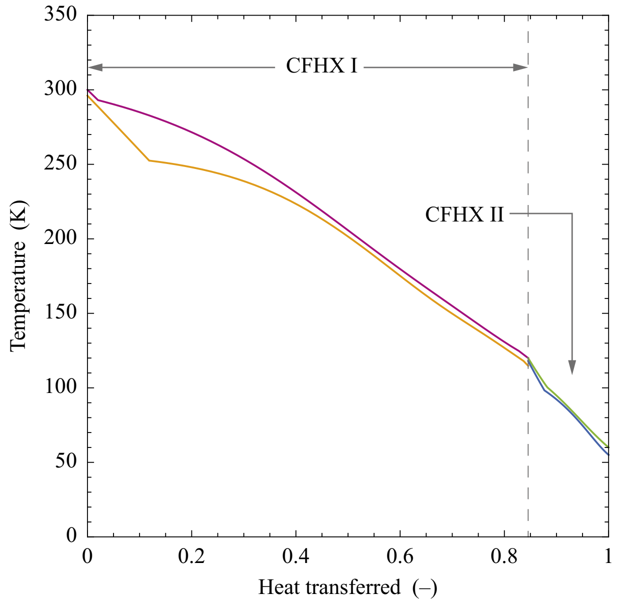
- Equivalent for heating/boiling from $4 \rightarrow 1$
  - Low-boiler N_2 has higher vapor pressure and evaporates first

Basics (ideal mixtures)

- Dalton's law $p_i = y_i \cdot p$
- Raul's law $p_i'' = x_i \cdot p_{sat,i}$
- Equilibrium $p_i = p_i''$

Effects of using refrigerant mixtures

- Partial condensation and evaporation (HP and LP sides), respectively, of mixture components along the CFHX
  - High-boiling components condense/evaporate at the warm end
  - Low-boiling components condense/evaporate at the cold end



- Reduced entropy production Δs_{irr} during heat transfer
  - Manipulation of capacity flows $\dot{C} = \dot{M} \cdot c_{\mathrm{p}}(T, p)$ through the specific heat capacities of the condensing/evaporating components i (phase change implies $c_{\mathrm{p,\,i}} \rightarrow \infty$)
  - Minimization of temperature gradients in the CFHX

- Reduced entropy production Δs_{irr} during throttling
  - Higher Joule-Thomson coefficients $\mu_{\mathrm{JT}} = (\partial T / \partial p)_{\mathrm{h}}$ at lower temperature
  - Lower Δp required for the same ΔT

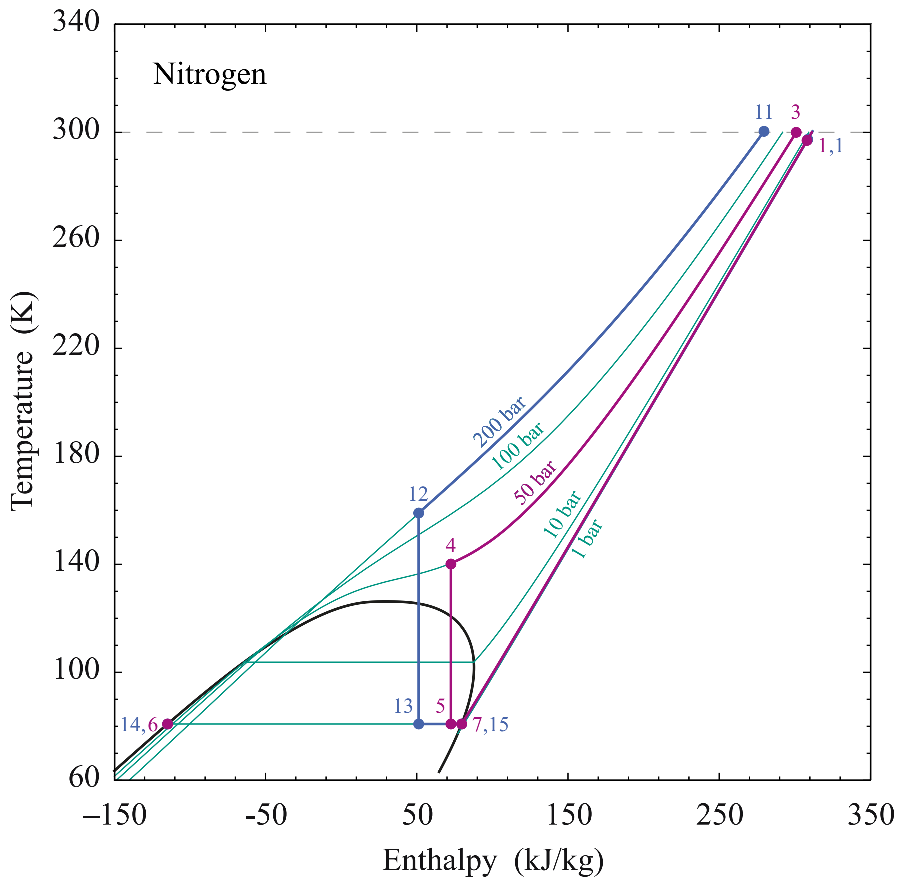
Throttling in the Linde-Hampson cycle

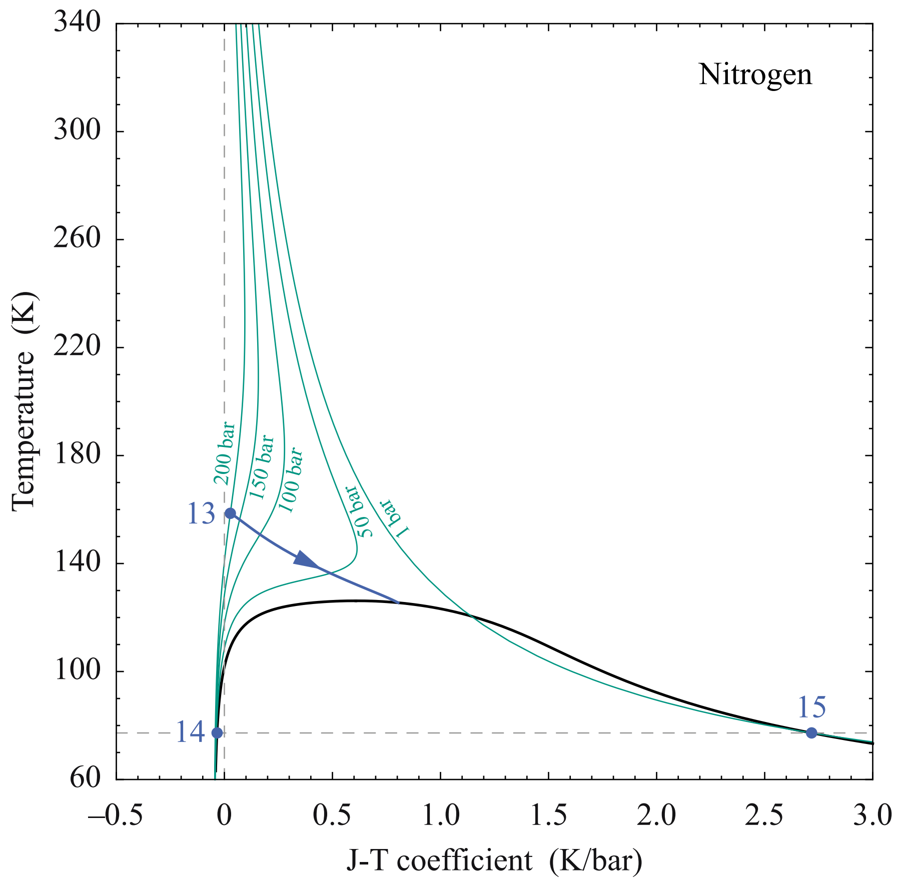
Example process

- Higher specific cooling capacity at higher pressure
  - ▷ Necessity of c. 200 bar in case of N_2

Joule-Thomson coefficient of N_2

- $\mu_{JT}\uparrow$ bei $T\downarrow$
  - ▷ Better pre-cooling (T_{12}) with mixtures
- $\mu_{JT}\uparrow$ bei $p\downarrow$
  - ▷ Lower pressure needed as well





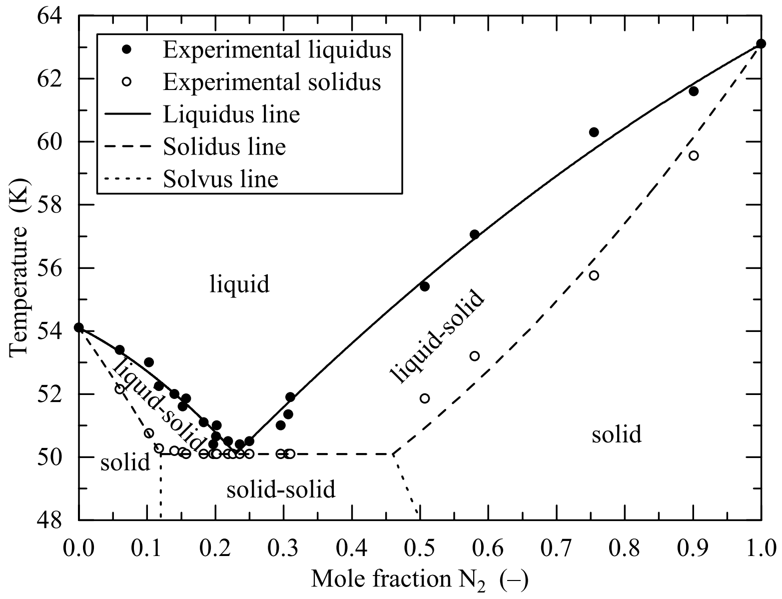
Low-temperature limits of MRCs

State-of-the-art

- MRCs are ***widely used*** in natural gas liquefaction since the 1970s
  - C3MR process (C3 pre-cooling)
  - DMR process (double MR process)
  - MFC process (mixed fluid cascade)
- Typical use of hydrocarbon mixtures ($C_1 \ldots C_5$) at $T > 100$ K
  - $T_{nb,CH4} = 112$ K
- Low-temperature limits
  - Achievable temperature influenced by lowest boiling component
  - Some reduction of boiling temperatures $T_b(p)$ by addition of intent gases (N_2, …)
  - $\underbrace{y_i \cdot p}_{p_i} = x_i \cdot p_{sat,i}$, i.e. $T_b = f(p_i)$
  - Low-temperature limit determined by *freezing* of high-boilers and oil

Theoretical limit for HTS application

- Classical limit of vapor compression cycles given by the ***triple point*** of N_2
  - $T_{tr,N2} = 63$ K
- N_2/O_2 binary mixtures, however, have freezing points as low as ~50 K
  - Eutectic point at 50.1 K and 77 mole-% O_2

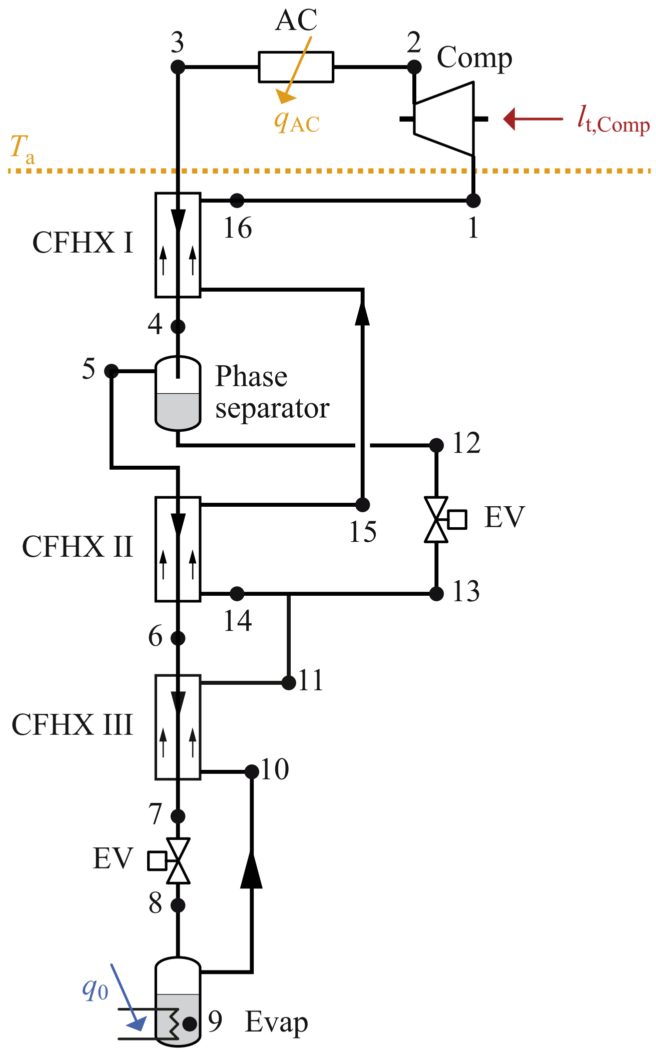


Data source: Ruhemann, M. et al.: Zustandsdiagramme niedrig schmelzender Gemische; II. Das Schmelzdiagramm Sauerstoff-Stickstoff und das Zustandsdiagramm Stickstoff-Kohlenoxyd. *Phys. Z. Sowjetunion* 1935, 8, 326.

- Data for ternary $Ne/N_2/O_2$ mixtures not yet available (⇨ studies at KIT)

Prevention of freeze-out

Kleemenko cycle



Principle

- Similarity with the Claude cycle, but ***phase separator*** and ***expansion valve*** instead of the expander
- Separation of high-boilers (e.g. C_5, C_4) as well as oil at ~250…270 K

\+ Concentration-dependent freezing point

– No complete separation

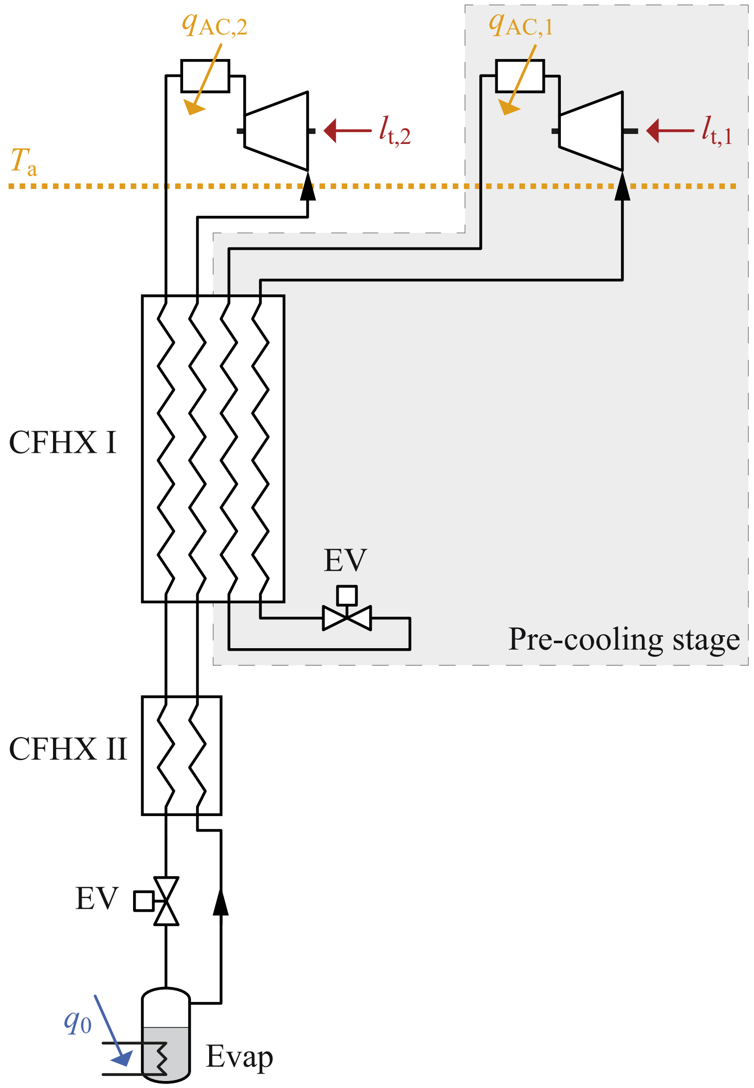
Various process configurations

- Several phase separators, especially for low-temperature operation

– Complexity, …

Cryogenic mixed refrigerant cascade (CMRC)

Layout

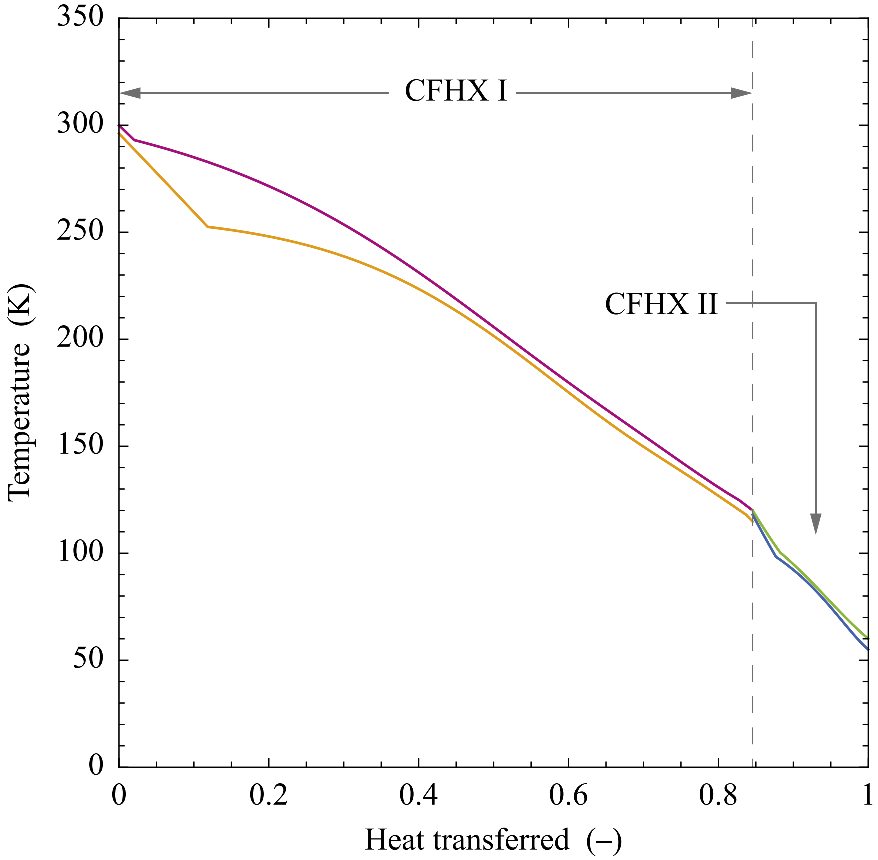


Principle

- Separate pre-cooling and second stage

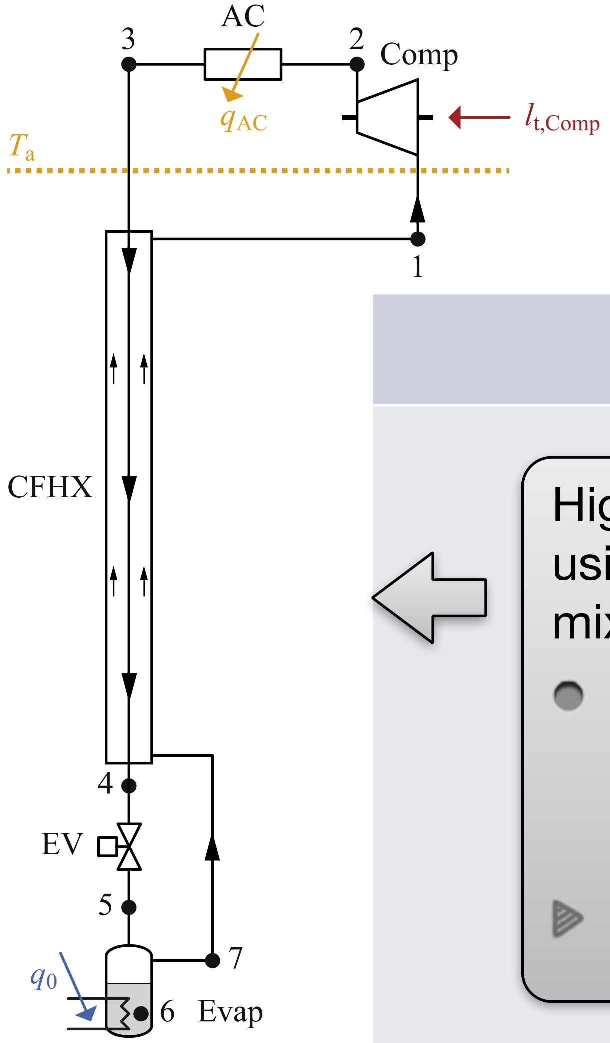
\+ No high-boilers and no risk of freeze-out in the second stage

Example temperature profiles

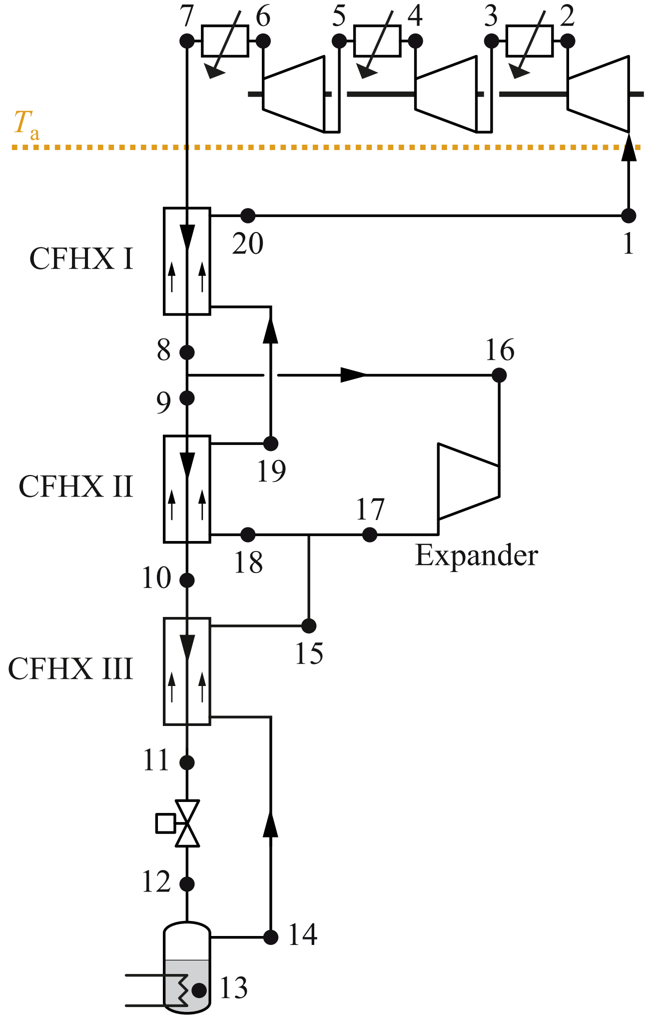


Approaches for cooling system improvements

- Linde-Hampson process



- Claude process



Options for efficiency increase

← Higher efficiency by using refrigerant mixtures (MRC)

- *„Molecular Engineering“*
- ▶ Negligible cost

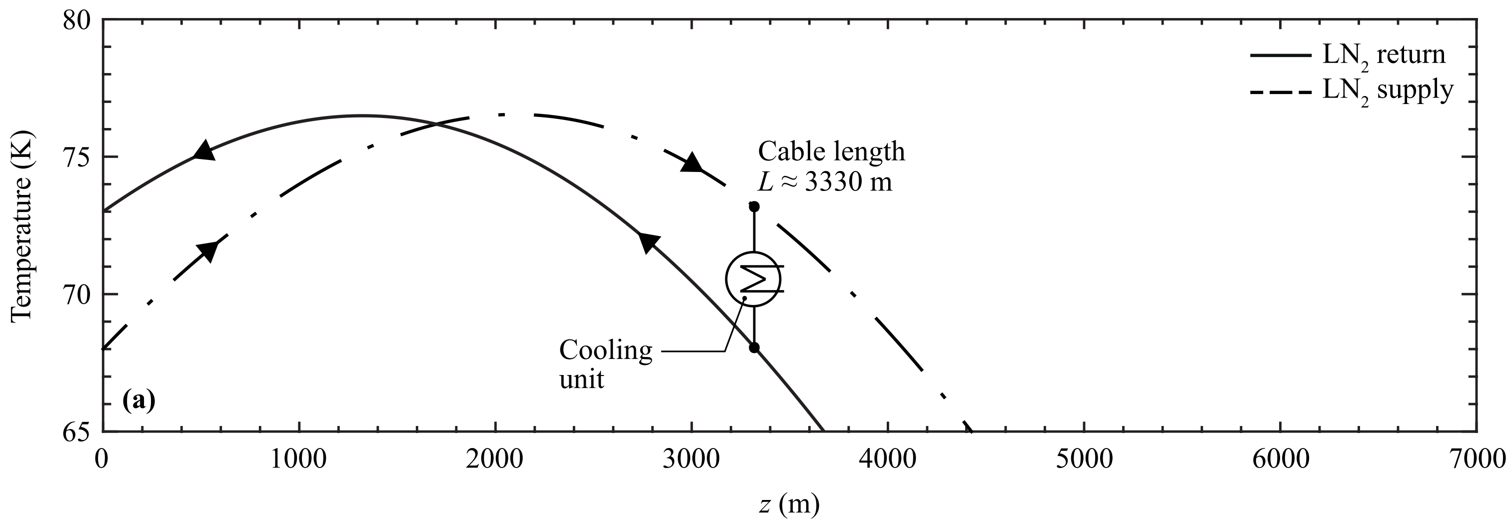
Higher efficiency by increased system complexity →

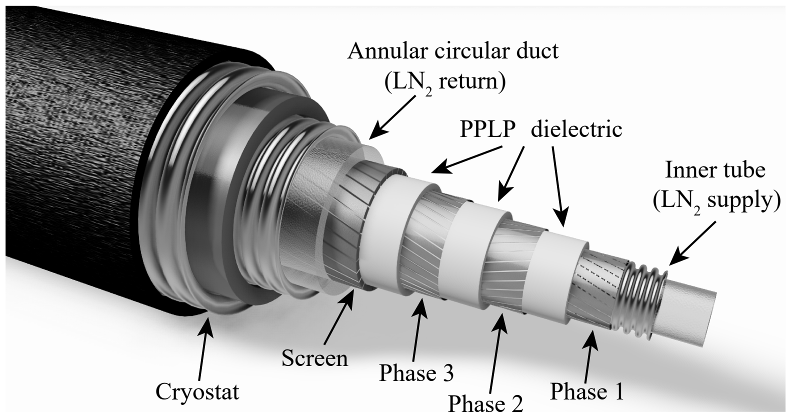
- Cold expander
- Number of HX ↑
- Control ↑
- 🟥 Investment cost ↑

↓ Use of standard refrigeration technology

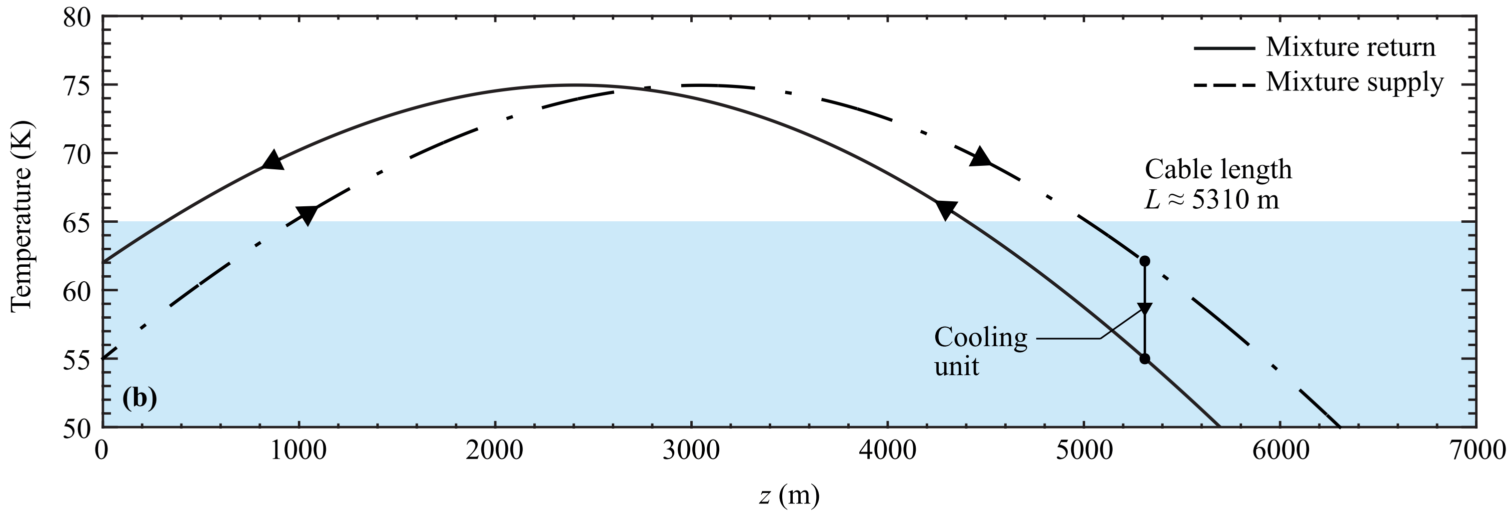
Potential HTS mixture applications

- Use of wide-boiling refrigerant mixtures in closed cycle cooling units
  - Longer power cable lengths by re-cooling units at the far cable end





- Potential use of O_2/N_2 mixtures as cooling liquid in HTS power cables



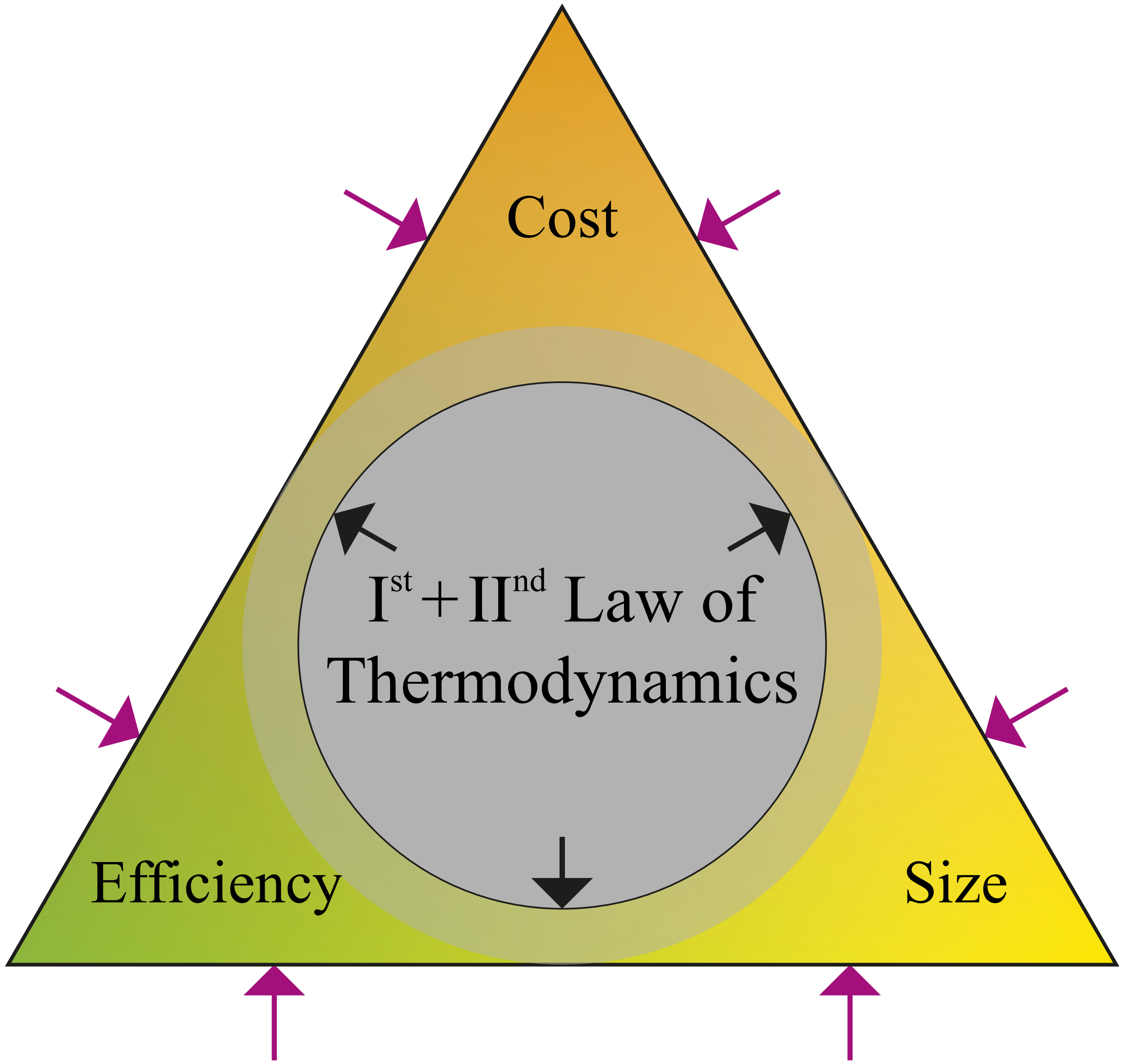
Source: Shabagin, E.; Heidt, C.; Strauß, S.; Grohmann, S.: Three-dimensional modelling of temperature and pressure profiles in concentric three-phase HTS power cables. *Cryogenics* 2016 (to be published).

  - ***Open issues:*** Material compatibility, safety, …

Cooling technology for HTS power applications

CONCLUSIONS

Conclusions



HTS application requirements