PARAMETRIC STUDY FOR THE COOLING OF SUPERCONDUCTOR CURRENT LEADS (HTS CLs)

Monika LEWANDOWSKA[1], Rainer WESCHE[2]

(1) West Pomeranian University of Technology, Szczecin, Poland
(2) EPFL-CRPP, Villigen PSI, Switzerland

Outline

- CLs key features
- Model
  - – Cooling options
  - – Design parameters of the analyzed current lead
  - – Basic assumptions
    - HTS part
    - HEX part
  - – Method of solution
  - – Input parameters range
  - – Cooling power requirements
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- Conclusions

HTS CLs key features

PRO:

– No Joule heating in HTS part

→ lower heat leak at cold end

→ significant reduction of cooling power (by a factor 3)

CON:

– Higher investment costs

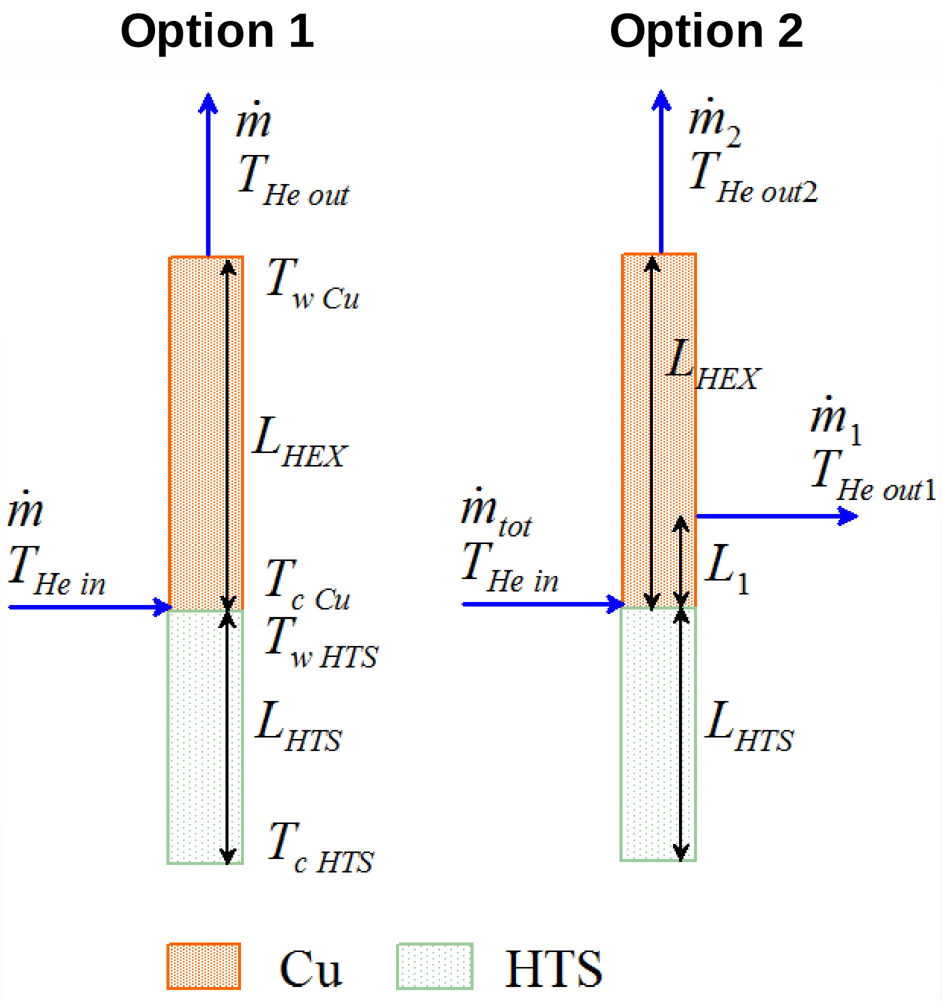
70 kA HTS CL [1]

[1] Heller R, Darweshsad MS, Dittrich G, Fietz WH, Fink S, Herz W, Hurd F, Kienzler A, Lingor A, Meyer I, Noether G, Suesser M, Tanna VL, Vostner A, Wesche R, Wuechner F, Zahn G. *Experimental results of a 70 kA high temperature superconductor current lead demonstrator for the ITER magnet system*, IEEE Trans Appl Supercond **15**, 1496 (2005)

Cooling options

Forced –flow cooled. Helium is warmed up to the RT.

Conduction Cooled.



Forced –flow cooled. At length L_1 part of the helium mass flow is diverted. The remaining helium is warmed up to the RT.

Conduction Cooled.

Copper contact region is not taken into consideration → $T_w \equiv T_{w\,HTS} \approx T_{c\,Cu}$

Design parameters of the current lead

Analysis based on the outline design of the 18 kA HTS CL for EDIPO [2], adjusted to operating current of 20 kA.

[2] Wesche R, Bagnasco M, Bruzzone P, Felder R, Guetg M, Holenstein M, Jenni M, March S, Roth F, Vogel M. *Test results of the 18 kA EDIPO HTS current leads*. Fusion Eng Des (2011) in press

Main input parameters:

Parameter [Unit]	Value
HTS part	
I/O diameter of the cylinder [mm]	59.8/45.8
Cylinder length [mm]	405
Number of AgMg/Ag/Bi-2233 stacks	22
Stack width [mm]	4.2
Stack height [mm]	$1.9n_t/8$
Averaged value of the perpendicular magnetic field [mT]	70
HEX part	
Copper RRR	50
Number of strands	118440
Strand diameter [mm]	0.1
Inner diameter of the embedding tube [mm]	84.9
Helium pressure [MPa]	1
Warm end copper temperature [K]	300

HTS module – Basic assumptions

Number of AgMg/Ag/Bi-2233 tapes in each stack:

$$n_t(T_w) \approx \frac{I}{22\, f_s I_c(70\ \mathrm{mT}, T_w)}$$

f_s = 0.65 - safety factor

Critical current for a single tape:

$$I_c(70\ \mathrm{mT}, T) = 0.5\left[I_c(60\ \mathrm{mT}, T) + I_c(80\ \mathrm{mT}, T)\right]$$

$$I_c(B,T) = 0.9 I_c(B,0)\left[1 - \frac{T}{T_c(B)}\right]^{\alpha}$$

Parameter [Unit]	Value
T_c (60 mT) [K]	95.45
T_c (80 mT) [K]	94.56
I_c(60 mT, 0)/I_c(sf ,77 K)	6.705
I_c(80 mT, 0)/I_c(sf ,77 K)	6.31
I_c(sf ,77 K) [A]	110
α	1.5

Bruker HTS GmbH. Data sheet BHTS current lead application tape. http://www.bruker-est.com/

Heat leak at the cold end of the CL:

$$\left|\dot{Q}_0(T_w)\right| = \frac{A_{steel}}{L_{HTS}} \int_{4.5K}^{T_w} k_{steel}(T)\,dT + \frac{A_{HTS}}{L_{HTS}} \int_{4.5K}^{T_w} k_{HTS}(T)\,dT$$

HEX part – governing equations

Steady state energy balance equations:

$$\frac{d}{dx}\left[k_{Cu}(T_{Cu})\frac{dT_{Cu}}{dx}\right]+\frac{I^2\rho_{Cu}(T_{Cu})I^2}{A^2}-\frac{H_{eff}\,p_{w,eff}}{A}\left(T_{Cu}-T_{He}\right)=0$$

$$\dot{m}_{He}C_{p,He}(T_{He})\frac{dT_{He}}{dx}=H_{eff}\,p_{w,eff}\left(T_{Cu}-T_{He}\right)$$

x – coordinate directed along a strand, m

I – operating current, A

ρ_{Cu} – copper electric resistivity, Ω m

k_{Cu} – copper thermal conductivity, W/(m K)

$A = N_{str}\,A_{Cu}$ – cross section strands in a direction perpendicular to x, m^2

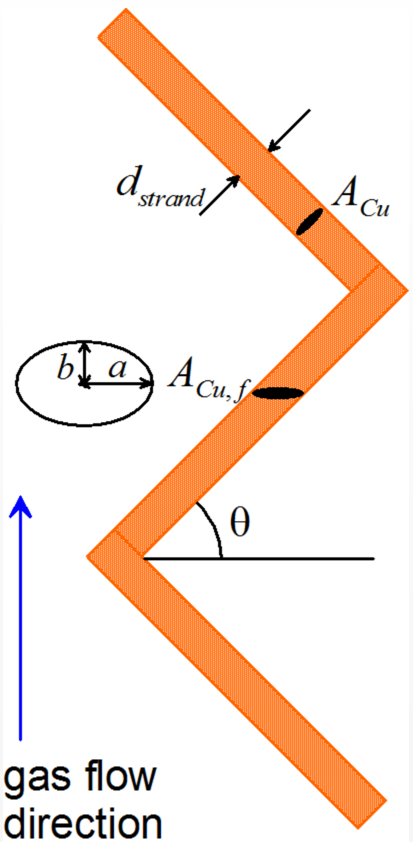
A_{Cu} – cross section of a single strand in a direction perpendicular to x, m^2

$\dot{m}_{He}$ – helium mass flow rate, g/s

$C_{p,He}$ – helium specific heat at constant pressure, J/(kg K)

HEX part – Heat transfer [3]

$$L_{HEX} = L_{str}\sin\theta = \frac{L_{str}}{\Psi}$$ length of HEX



$$A_f = A_{tube} - N_{str} A_{Cu,f}$$ flow area

$$A_{Cu,f} = \Psi \pi d_{str}^2 / 4 = \Psi A_{Cu}$$

$$p_{w,f} = N_{str}\, p_{Cu,f} = \left[\frac{3(1+\Psi)}{4} - \frac{\sqrt{\Psi}}{2}\right] N_{str}\pi d \approx 1.21 N_{str}\pi d$$

$$p_{w,eff} = N_{str}\pi d$$

wetted perimeter

$$\mathrm{Nu} = \left(0.4\,\mathrm{Re}^{1/2} + 0.2\,\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0.4}$$

$$H(\dot{m}_{He}, T_{He}) = \mathrm{Nu}\, k_{He} / D_h$$

correlation for the laminar flow in a packed bed [4]

Effective heat transfer coefficient:

$$H p_{w,f} L_{HEX} = H_{eff}\, p_{w,eff} L_{str} \quad \Rightarrow \quad H_{eff} \approx 0.86 H$$

[3] Anghel A., *Heat transfer from fluid to a wire bundle*, PSI Technical Physics internal report (1992)

[4] Gamson B.W., Thodos G.E., Hougen O.A., *Heat Mass and Momentum Transfer in the Flow of Gases Through Granular Solids*.Trans. AIChE **39**, 1 (1943)

Problem to be solved

$$\frac{d}{dx}\left[k_{Cu}(T_{Cu})\frac{dT_{Cu}}{dx}\right]+\frac{I^2\rho_{Cu}(T_{Cu})}{A^2}-\frac{H_{eff}\,p_{w,eff}}{A}\left(T_{Cu}-T_{He}\right)=0$$

$$\dot{m}_{He}C_{p,He}(T_{He})\frac{dT_{He}}{dx}=H_{eff}\,p_{w,eff}\left(T_{Cu}-T_{He}\right)$$

Boundary conditions:

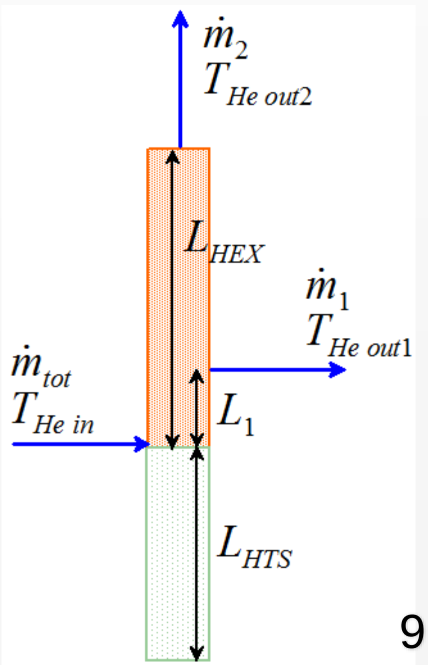
$$T_{Cu}(0)=T_w$$

$$\frac{dT_{Cu}}{dx}(0)=\frac{\left|\dot{Q}_0(T_w)\right|}{k_{Cu}(T_w)A}$$

$$T_{He}(0)=T_{He,in}$$

Additional conditions for the Option 2:

- continuity of the temperature and heat flux at $x=\Psi L_1$
- $\dot{m}_{He}=\dot{m}_{tot}$ for $x<\Psi L_1$ and $\dot{m}_{He}=\dot{m}_2$ for $x>\Psi L_1$



Solution method [5]

The HEX part of a CL is divided into many short segments of length Δx.
Neglecting the variation of $\Delta T = T_{Cu} - T_{He}$ and the temperature dependence of the material properties (k_{Cu} , ρ_{Cu} , $C_{p,He}$) within a single segment we get the recurrence solution equations:

$$T_{Cu_{i+1}} = -\frac{1}{2k_{Cu}(T_{Cu_i})A}\left[\frac{I^2\rho_{Cu}(T_{Cu_i})}{A} - H_{eff}\,p_{w,eff}\,\Delta T_i\right]\Delta x^2 - \frac{\dot{Q}_i}{k_{Cu}(T_{Cu_i})A}\Delta x + T_{Cu_i}$$

$$\dot{Q}_{i+1} = \dot{Q}_i + H_{eff}\,p_{w,eff}\,\Delta T_i \Delta x - \frac{I^2\rho_{Cu}(T_{Cu_i})\Delta x}{A}$$

$$T_{He_{i+1}} = T_{He_{i+1}} + \frac{H_{eff}\,p_{w,eff}\,\Delta T_i}{\dot{m}_{He}C_{p,He}}\Delta x$$

- Integration procedure repeated for various mass flow rates until $T_{Cu} = 300$ K and $\dot{Q} = 0$ W is reached at the warm end of HEX

  → optimum mass flow rate and optimum HEX length
- Solution independent of the segment length for Δx = 10^{-5} m (or smaller)

[5] Wesche R., Fuchs A.M., *Design of superconducting current leads*, Cryogenics **34**,145-54 (1994)

Range of input parameters

- **Option 1**

  T_w = 40 to 75 K

  $T_{He,in}$ = 5 K to (T_w - 5 K)

- **Option 2**

  T_w = 47 to 73 K

  $T_{He,in}$ = (T_w - 8 K) to (T_w - 2 K)

  L_1 = 3, 4 and 5 cm

  $\dot{m}_2 / \dot{m}_{tot}$ = 0.05 to 1

Cooling power requirements

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Ideal refrigerator input power required to cool the whole binary HTS CL

- for the cooling option 1:

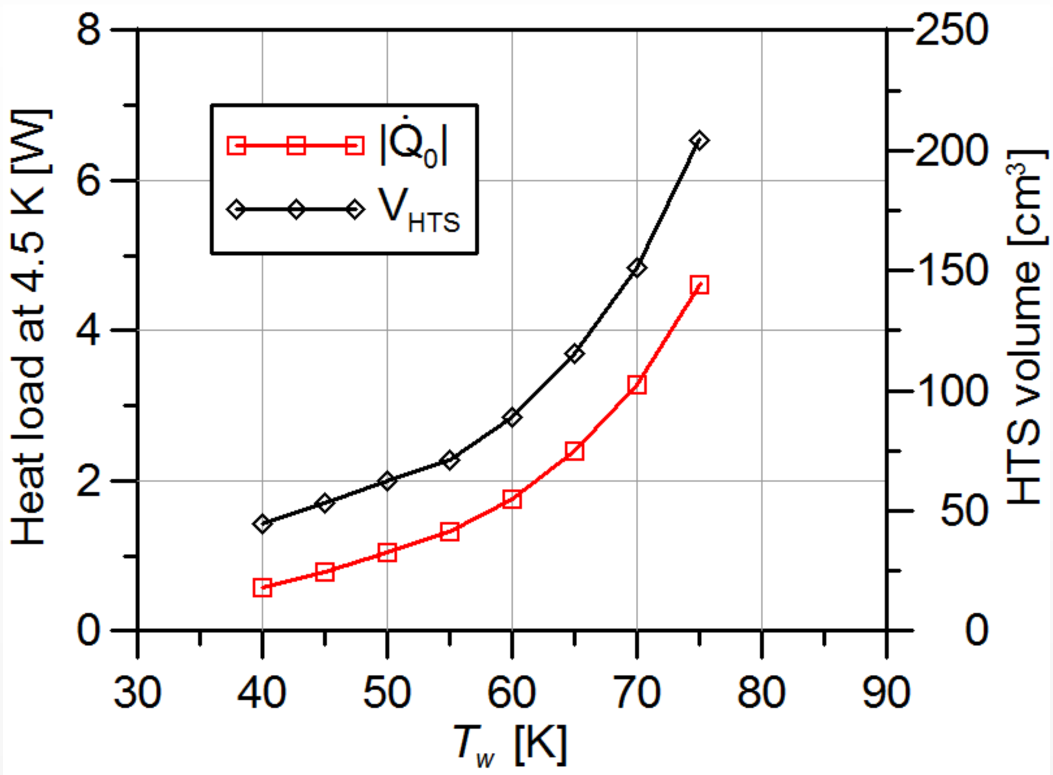
$$P_{ideal,1} = \frac{T_{\max} - T_0}{T_0}\left|\dot{Q}_0\right| + \dot{m}\left\{T_{\max}\left[s(T_{\max}) - s(T_{He,in})\right] - \left[h(T_{\max}) - h(T_{He,in})\right]\right\}$$

- for the cooling option 2:

$$P_{ideal,2} = \frac{T_{\max} - T_0}{T_0}\left|\dot{Q}_0\right| + \dot{m}_1\left\{T_{\max}\left[s(T_{He,out1}) - s(T_{He,in})\right] - \left[h(T_{He,out1}) - h(T_{He,in})\right]\right\} + \dot{m}_2\left\{T_{\max}\left[s(T_{\max}) - s(T_{He,in})\right] - \left[h(T_{\max}) - h(T_{He,in})\right]\right\}$$

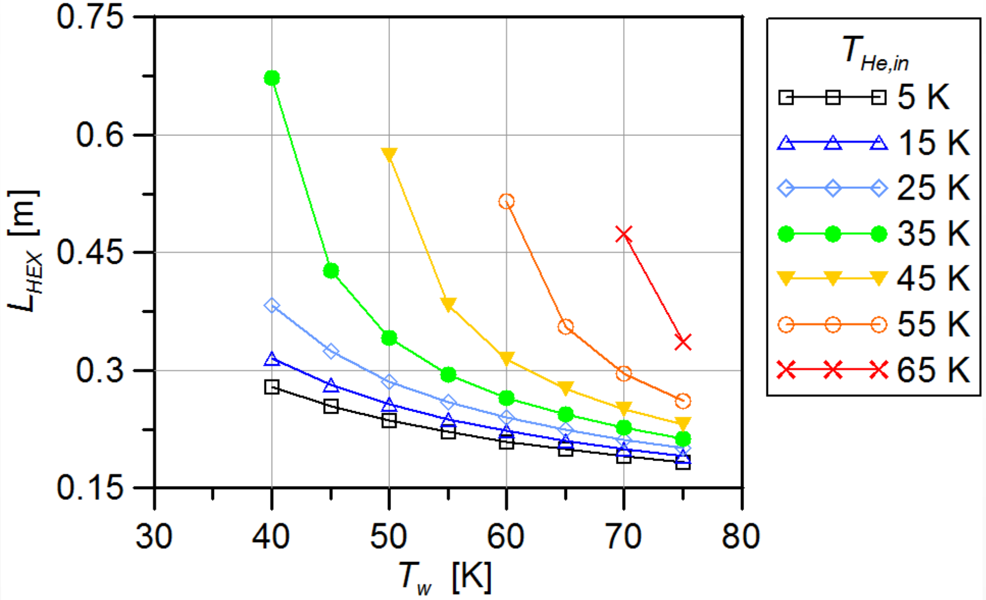
h - helium specific enthalpy, J/kg
s - helium specific entropy, J/(kg K)
T_0 = 4.5 K
$T_{\max}$ = 300 K

Results (I)
Heat leak at the cold end

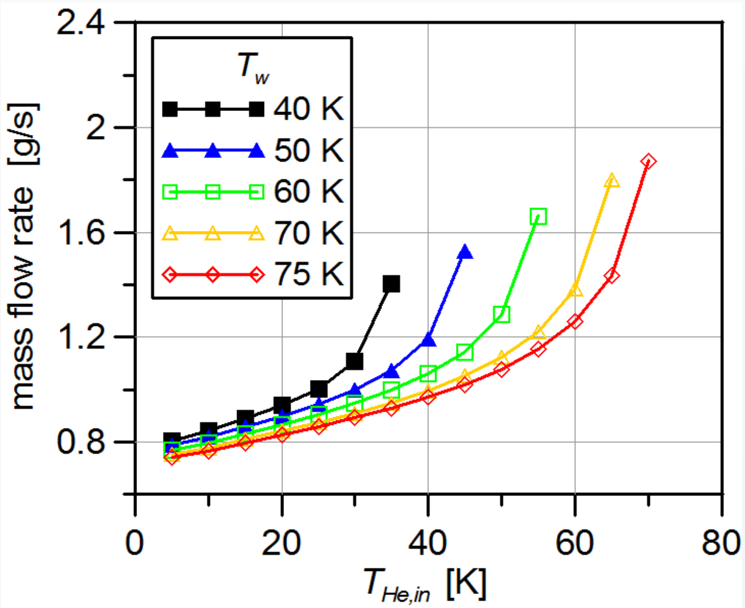


Heat load at the cold end of the HTS CL and the required volume of 0.405 m long HTS tapes as a function of the temperature at the warm end of the HTS part.

Results (II)
Cooling Option 1

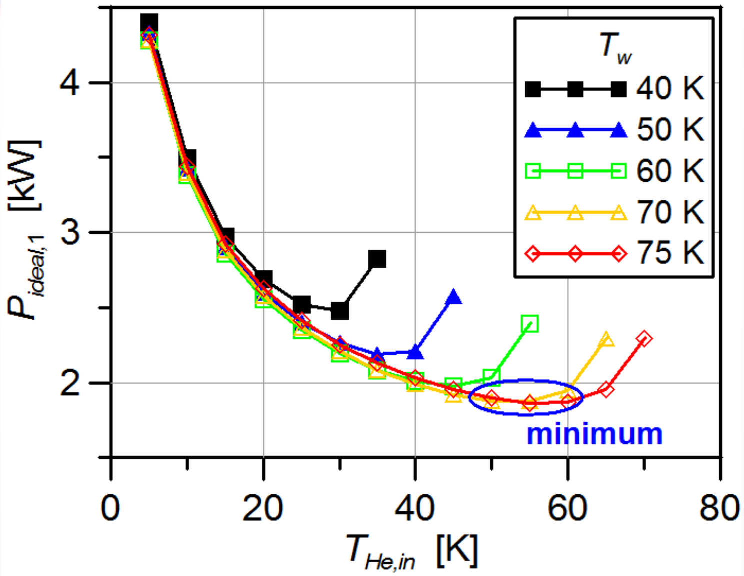


Optimum length of the HEX part



Optimum helium mass flow rate required to cool the HEX

Results (III) Cooling Option 1 - summary



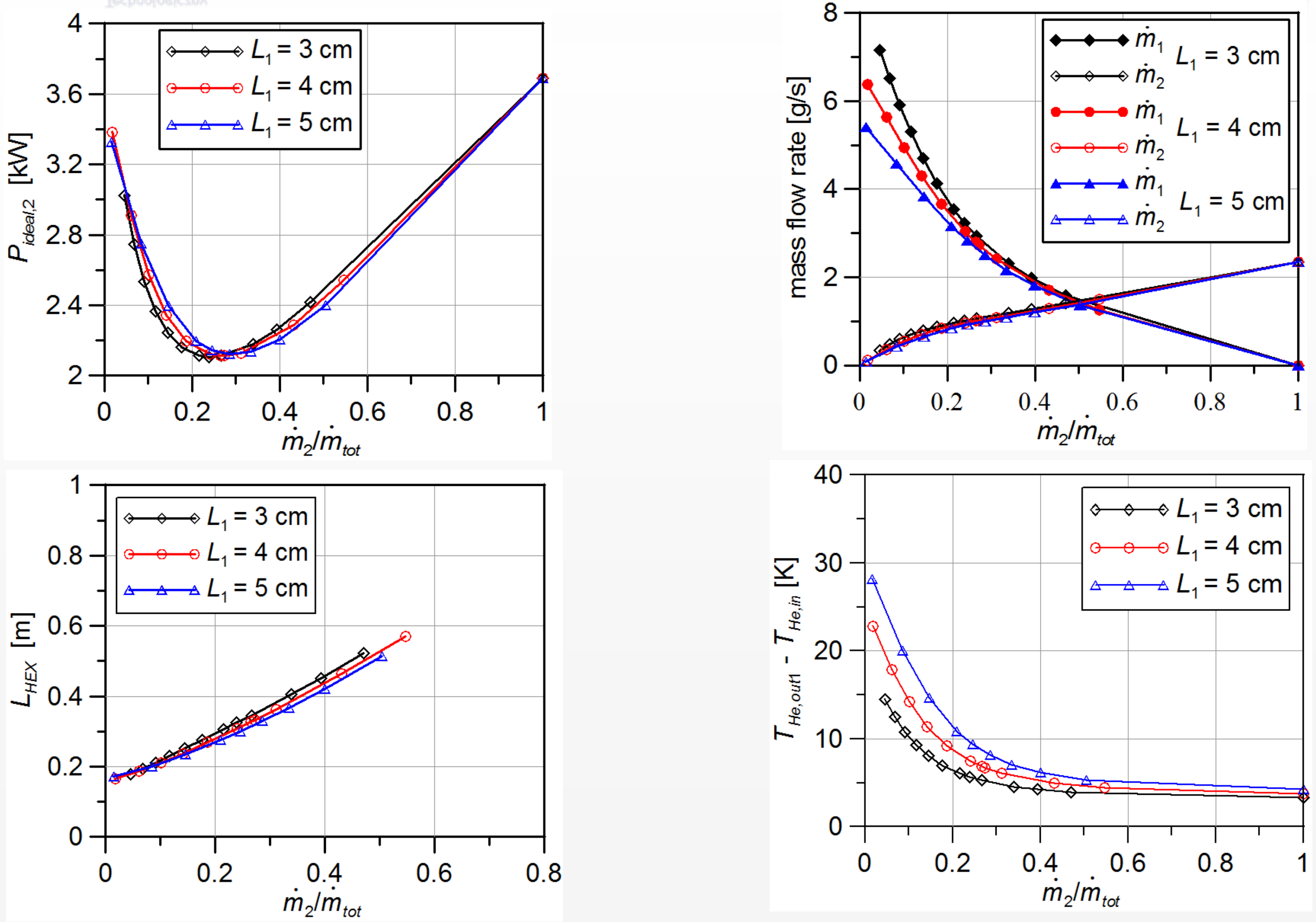
Ideal refrigerator input power necessary to cool the whole CL

Optimum cooling conditions for different values of the temperature at the warm end of the HTS part

T_w [K]	$T_{He,in}$ [K]	$\dot{m}$ [g/s]	L_{HEX} [m]	$P_{ideal,1}$ [kW]
50	37	1.1116	0.3605	2.191
60	45	1.1442	0.3141	1.992
70	53	1.1759	0.2832	1.889
74	56	1.1834	0.2722	1.876
75	57	1.1896	0.2707	1.884

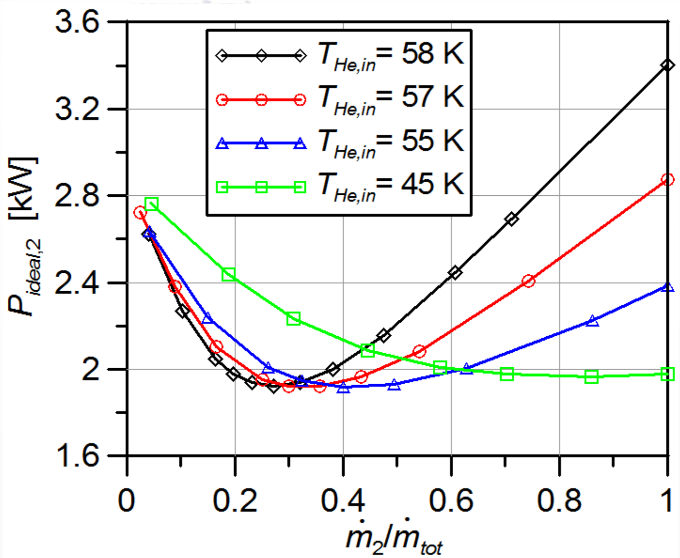
Results (IV) - Option 2

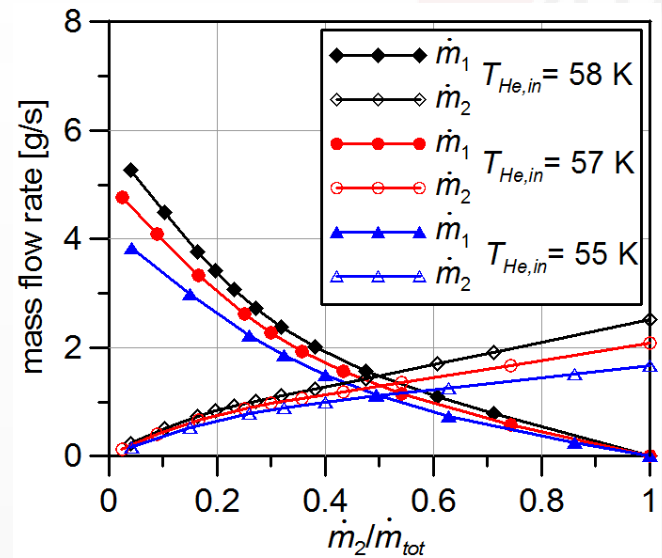
T_w = 50 K, $T_{He,in}$ = 48 K

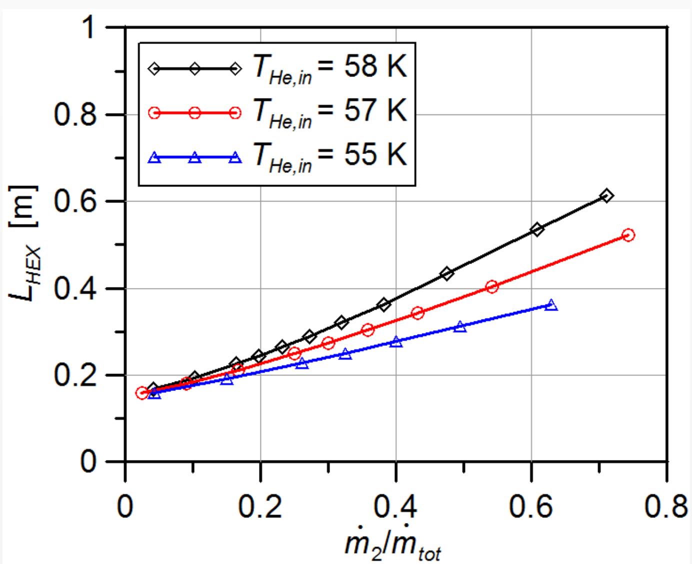


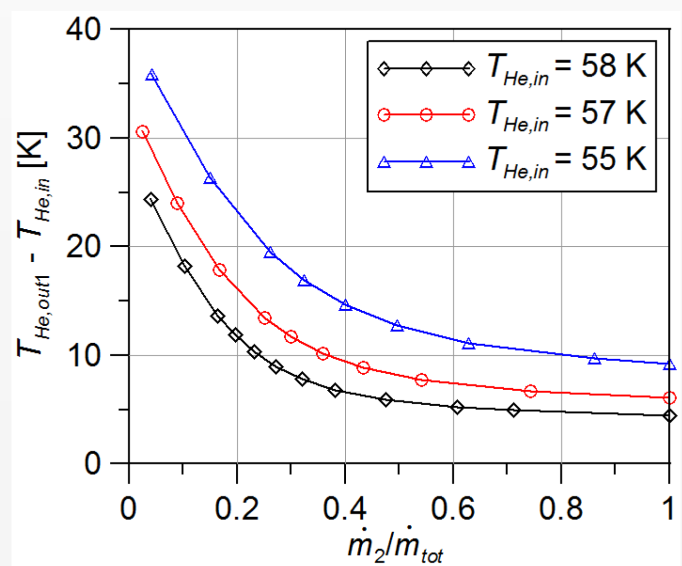
Results (V) - Option 2

T_w = 60 K, L_1 = 4 cm









Results (VI)
Summary

Optimum cooling conditions for different values of the copper temperature at the cold end of HEX

OPTION 2

T_w [K]	$T_{He,in}$ [K]	$\dot{m}_{tot}$ [g/s]	$\dot{m}_2$ [g/s]	L_{HEX} [m]	$T_{He,out1}$ [K]	$P_{ideal,2}$ [kW]
50	47	3.10	1.0119	0.3262	55.45	2.122
60	56	2.75	1.0111	0.2826	68.83	1.930
70	65	2.55	1.0106	0.2540	82.67	1.831

OPTION 1

T_w [K]	$T_{He,in}$ [K]	$\dot{m}$ [g/s]	L_{HEX} [m]	$P_{ideal,1}$ [kW]
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Results (VI)
Summary

Optimum cooling conditions for different values of the copper temperature at the cold end of HEX

OPTION 2

T_w [K]	$T_{He,in}$ [K]	$\dot{m}_{tot}$ [g/s]	$\dot{m}_2$ [g/s]	L_{HEX} [m]	$T_{He,out1}$ [K]	$P_{ideal,2}$ [kW]
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Results (VI)
Summary

Optimum cooling conditions for different values of the copper temperature at the cold end of HEX

OPTION 2

T_w [K]	$T_{He,in}$ [K]	$\dot{m}_{tot}$ [g/s]	$\dot{m}_2$ [g/s]	L_{HEX} [m]	$T_{He,out1}$ [K]	$P_{ideal,2}$ [kW]
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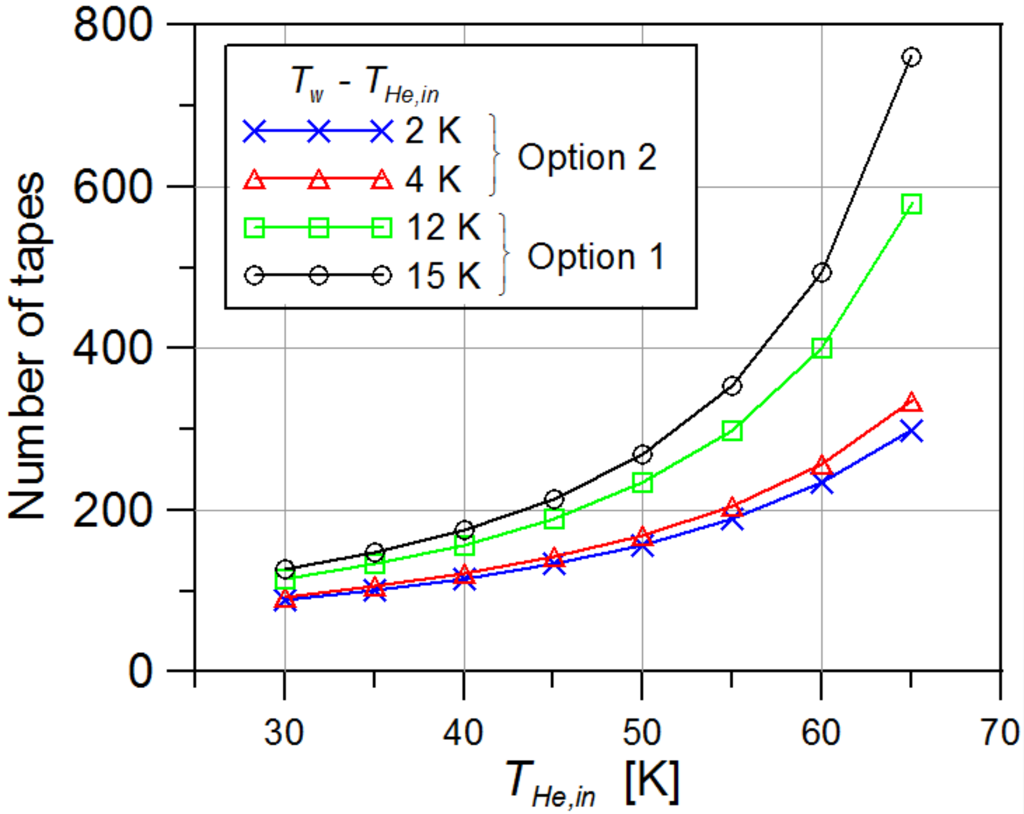
Results (VII)



The required number of HTS tapes as a function of the helium inlet temperature for various values of the temperature at the warm end of HTS part.

Summary and conclusions

- Comparative analysis of the two cooling options for the HEX part of the 20 kA HTS CL has been performed.
- **Option 1**
  - **PRO:** simple operating control
  - **CON:** T_w much higher than $T_{He,in}$
- **Option 2**
  - **PRO:** T_w only 2 – 4 K higher than $T_{He,in}$

    → possible reduction of T_w at a given $T_{He,in}$

    → possible reduction of the required number of HTS tapes
  - **CON:** complicated operating control

    → further more detailed investigation necessary

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Question Time

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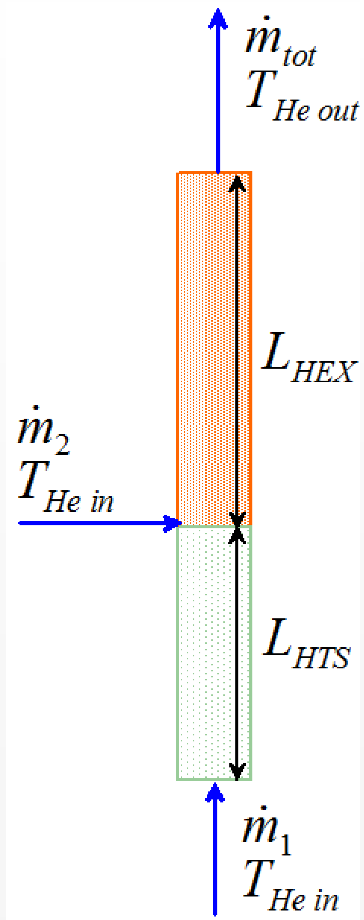
Thank you for your attention

Option 3 - model

$$\frac{d}{dx}\left[k_{steel}(T_s)\frac{dT_s}{dx}\right]-\frac{H(T_{He})p_{w,s}}{A_s}\left(T_s-T_{He}\right)=0$$

$$\frac{d}{dx}\left[k_c(T_c)\frac{dT_c}{dx}\right]-\frac{H(T_{He})p_{w,c}}{A_c}\left(T_c-T_{He}\right)=0$$

$$\dot{m}_1 C_{p,He}(T_{He})\frac{dT_{He}}{dx}=H(T_{He})p_{w,s}(T_s-T_{He})+H(T_{He})p_{w,c}(T_c-T_{He})$$



Indices *c* and *s* are related to the conductor (cylinder + HTS stacks) and steel tube, respectively.

Effective thermal conductivity of the conductor

$$k_c(T)=\frac{A_{steel}k_{steel}(T)+A_{HTS}k_{HTS}(T)}{A_{steel}+A_{HTS}}$$

Ideal refrigerator power required to cool the whole HTS CL

$$P_{ideal,3}=\frac{T_{\max}-T_0}{T_0}\left(\dot{Q}_{s0}+\dot{Q}_{c0}\right)+\dot{m}_{tot}\left\{T_{\max}\left[s(T_{\max})-s(T_{He,in})\right]-\left[h(T_{\max})-h(T_{He,in})\right]\right\}$$

Option 3 - results

Input parameters	T_w [K]	$P_{ideal,3}$ [kW]	$\lvert\dot{Q}_0\rvert$ [W]	$P_{ideal,1}$ [kW]
$\dot{m}_1$ = 0.002 g/s $\lvert\dot{Q}_{s0}\rvert$ = 0.039 W $\lvert\dot{Q}_{c0}\rvert$ = 0.934961209421591 W	54.83	4.365	1.350	4.375
$\dot{m}_1$ = 0.0072 g/s $\lvert\dot{Q}_{s0}\rvert$ = 0.0049 W $\lvert\dot{Q}_{c0}\rvert$ = 0.314399106219985 4 W	54.78	4.326	1.348	4.375
$\dot{m}_1$ = 0.00852 g/s $\lvert\dot{Q}_{s0}\rvert$ = 0.0009 W $\lvert\dot{Q}_{c0}\rvert$ = 0.213968232905647 2 W	54.85	4.318	1.351	4.375

- Cooling power consumption only about 1% lower than in the Option 1 for the same T_w and $T_{He,in}$ = 4.5 K.
- Lower heat leak at the cold end
  → possible application in cases when a high heat load in HTS part, e.g. due to AC losses, is expected