Design, optimization and operational parameters of multichannel cryogenic transfer line for XFEL AMTF

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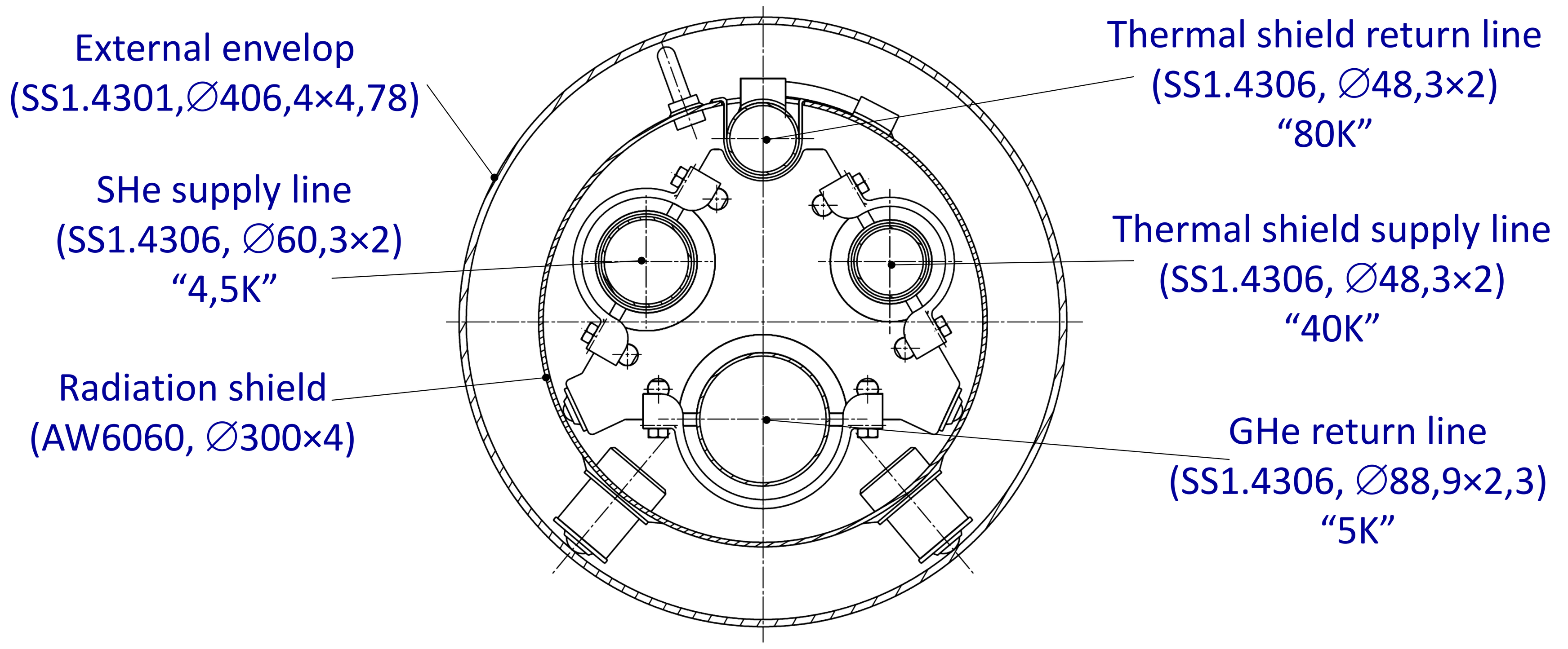
BACKGROUND

European X-ray Free Electron Laser (XFEL) being under construction at DESY in Hamburg, Germany, will be composed of about 100 cryogenic modules, each holding eight superconducting cavities and one superconducting magnets assembly. Before their installation in the XFEL underground tunnel the cavities and cryogenic modules will be tested at their nominal operation conditions in the dedicated Accelerator Module Test Facility (AMTF). The cryogenic system of that facility will be supplied with cryogenic cooling capacity from helium refrigerators located of about 167 m from the AMTF hall. The cooling capacity, that is specified as the sum of 3 kW at 40K, 0,5 kW at 4,5 K and 0,8 kW at 2,0 K, will be provided by means of two cold helium continuous streams: pressurised gaseous helium at 40 K and supercritical helium at 4,5 K. For that reason the AMTF hall will be connected with the helium refrigerators by multichannel cryogenic transfer line XATL1. The line will be located on a pipeline bridge, approximately 8 m in height, and will be exposed to weather conditions.

INTERNAL STRUCTURE OF THE CRYOGENIC TRANSFER LINE



- four process lines,
- two cryogenic circuits at 4,5 K and 40/80 K

The 4,5 K circuit is composed of the SHe supply and GHe lines, whilst the lines of thermal shield return and supply form the 40/80 K circuit. The thermal shield return line is connected with the radiation shield, thermalized at an average temperature of about 80 K, by a number of thermal bridges and it is used for gathering the radiation heat flux from the vacuum jacket, which temperature can vary from 260 K to 310 K due to external whether conditions.

METHOD OF ANALYSIS

To apply Second Law analysis method it is essential to identify all entropy streams generated in a single process lines. As it follows from Eq. 1, there are two basic entropy sources in case of fluid flow which is characterized by the temperature significantly different from the temperature of environment, namely heat transfer and pressure drop.

$$\dot S = \sum_i \dot S_{\Delta T} + \sum_j \dot S_{\Delta p} \quad (1)$$

$$\dot S_{\Delta T} = Q\left(\frac{1}{T_C} - \frac{1}{T_O}\right) \approx Q\frac{\Delta T}{T_C^2} \quad (2)$$

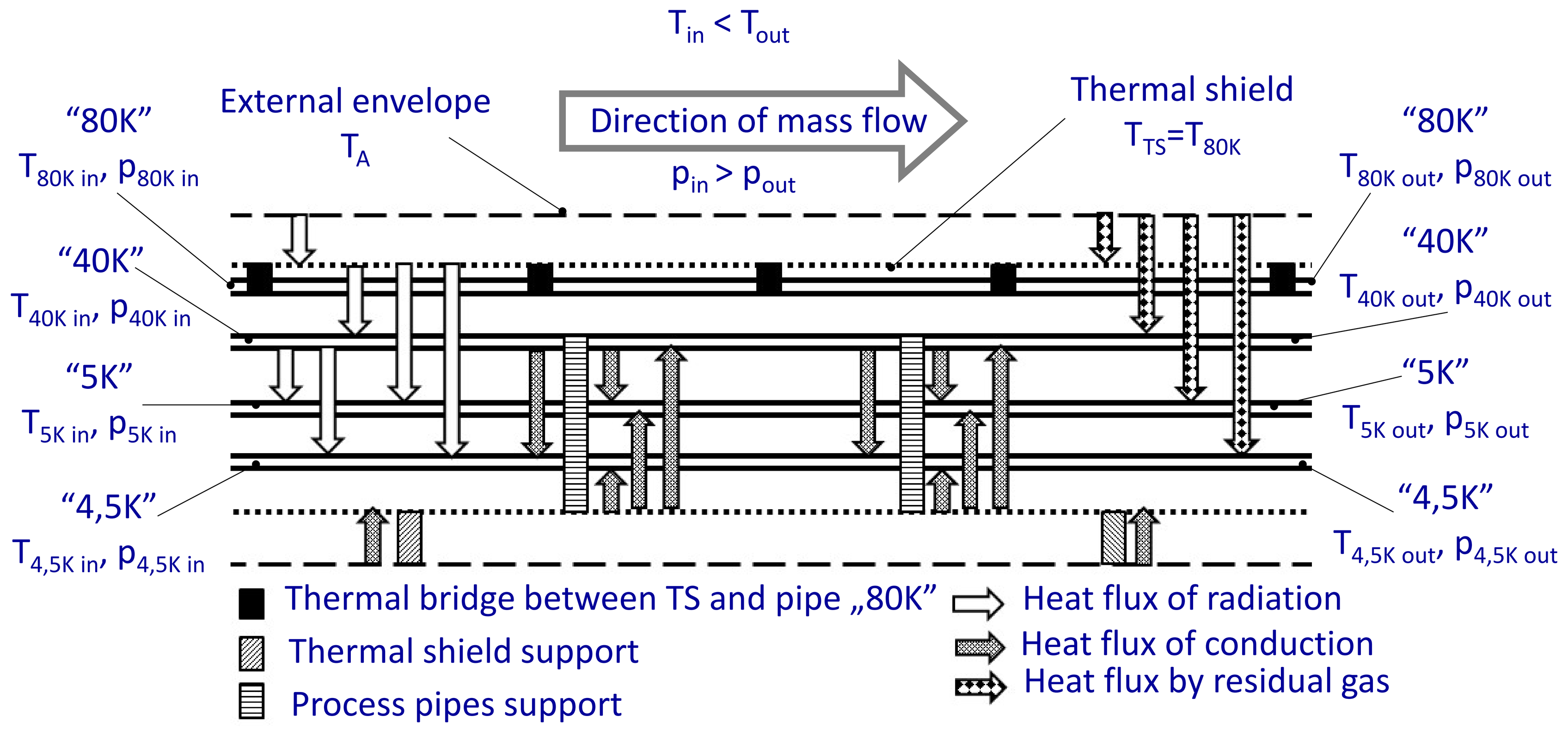
$$\dot S_{\Delta p} = \frac{q_m w^2}{2T_C}\left(\lambda_S \frac{L}{d} + \sum_n \zeta_n\right) \quad (3)$$

$$P_{Ad} = T_A \cdot \dot S \quad (4)$$

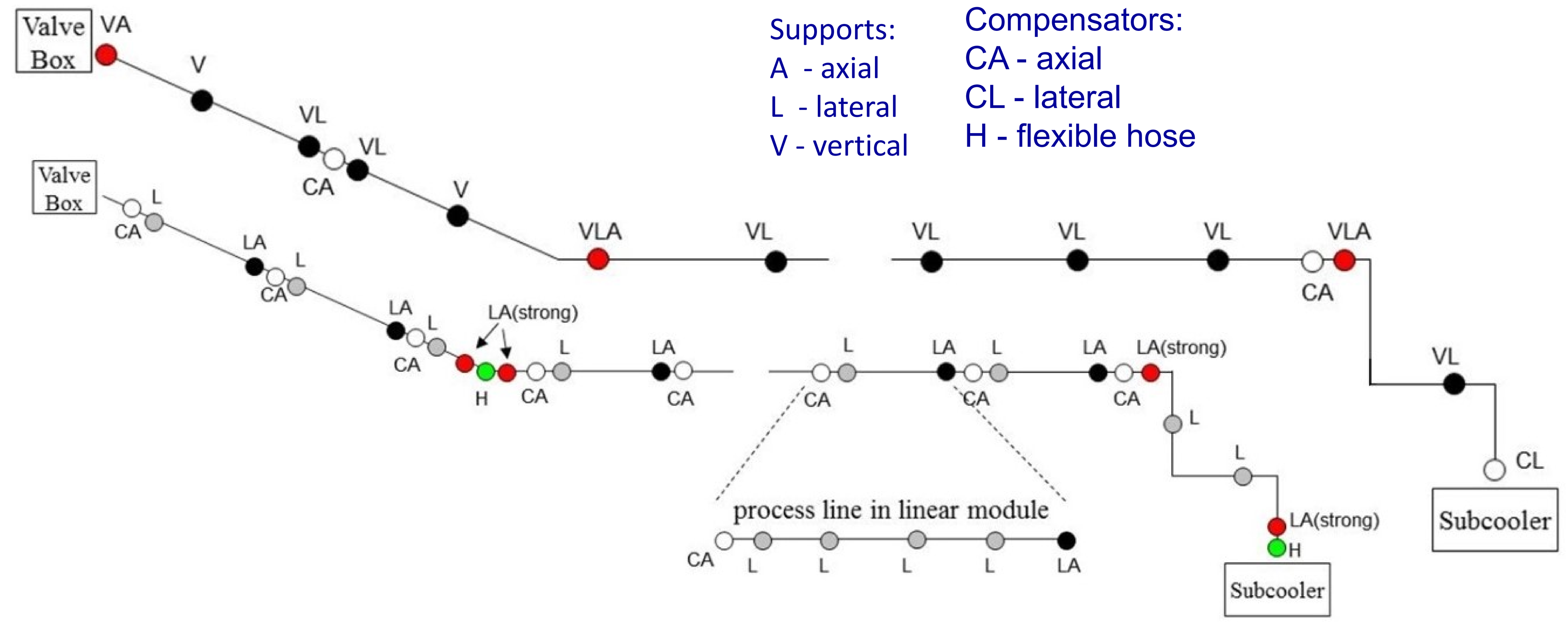
Heat transfer generated entropy can be calculated from Eq. 2. The entropy stream is increasing with the decrease of the process pipe temperature what makes this entropy source especially important in cryogenic conditions. The second entropy source is pressure drop caused by local and linear flow resistivities – Eq. 3

For an integrated entropy generation, additional work necessary to overcome the cryogen flow accompanied irreversibilities can be calculated from Gouya-Stodola theorem described by Eq. 4.

Entropy generation processes are schematically depicted in figure below. Heat fluxes to process pipes and between the pipes are indicated, as well as heat exchange between the pipes of different temperatures. Pressure drop caused by flow resistivities is shown as well.



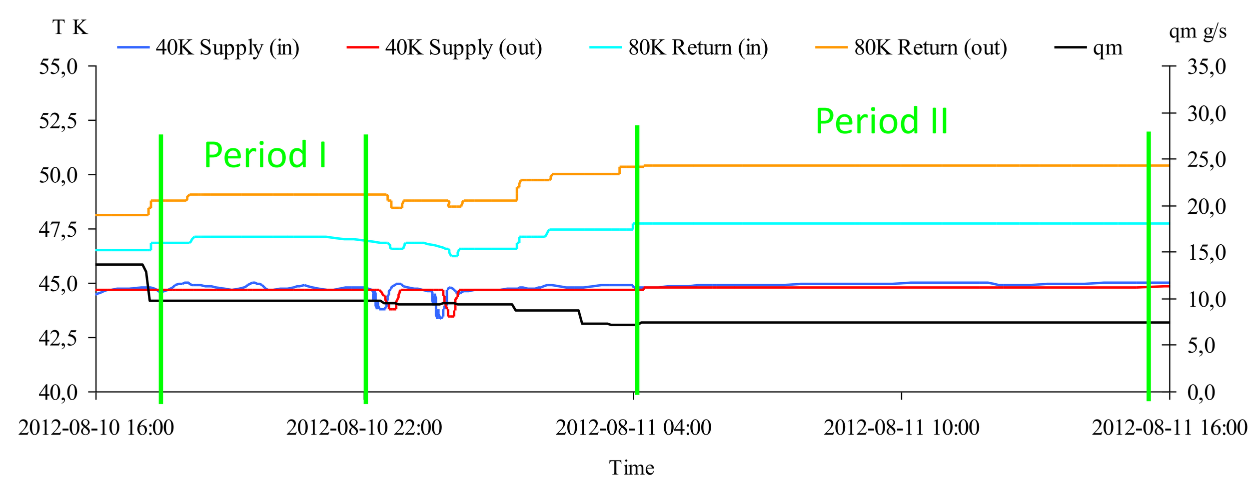
ROUTING AND DESIGN OF SUPPORTING AND THERMAL COMPENSATION SYSTEM

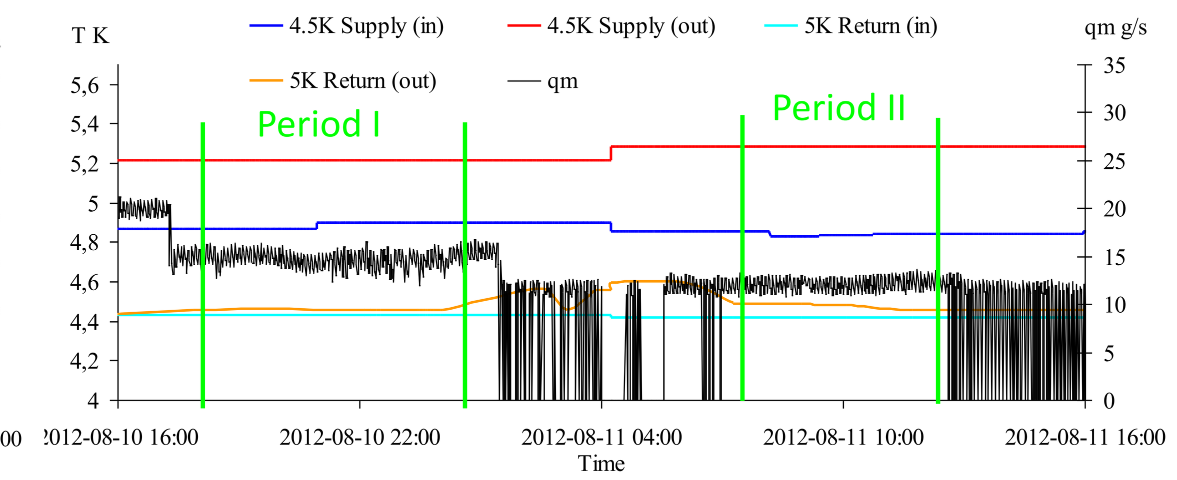


The supporting and thermal compensation system of the external envelope consist of two fixed supports (VLA) which block all the possible movements (vertical, lateral and axial) as well as it includes 21 sliding supports allowing for axial movements only (VL) and 2 sliding supports blocking the line movements only in vertical directions (V). The supporting and thermal compensation system of each process line includes a set of one fixed (LA), four sliding supports (L) and one axial compensator (CA) per each linear module.

THERMAL ANALYSIS BASED ON EXPERIMENTAL DATA

During the measurements an isolation vacuum of XATL1 was of about $1\cdot10^{-6}$ mbar. The mass flow rate was estimated using the inherent flow characteristics of the control valve installed in sub-cooler. The 4,5K/5K circuit is equipped with the Coriolis flow meter installed in sub-cooler . This allowed to carry out the direct measurement of the incoming mass flow.





	q_m	T_{in}	T_{out}	p	h_{in}	h_{out}	ρ	Q	$\dot S_{\Delta T}$	P_{Ad}
	g/s	K	K	MPa	kJ/kg	kJ/kg	kg/m³	W	W/K	kW
40K Period I	9,73	44,79	44,68	1,38	238,87	238,30	14,35	-5,49	-0,03	$-1\cdot10^{-3}$
40K Period II	9,73	44,88	44,76	1,38	239,35	238,74	14,29	-4,53	-0,02	$-1\cdot10^{-3}$
80K Period I	9,73	49,08	59,14	1,29	261,56	314,60	12,25	516,26	43,54	13,70
80K Period II	9,73	50,38	63,77	1,28	268,40	338,90	11,88	524,66	44,24	13,28

	q_m	T_{in}	T_{out}	p	h_{in}	h_{out}	ρ	Q	$\dot S_{\Delta T}$	P_{Ad}
	g/s	K	K	MPa	kJ/kg	kJ/kg	kg/m³	W	W/K	kW
4.5K Period I	14,64	4,89	5,21	0,42	3,84	5,65	127,43	26,43	50,77	2,74
4.5K Period II	14,64	4,84	5,28	0,42	3,62	6,10	128,28	29,95	57,53	3,11
5K Period I	12,06	4,43	4,46	0,10	22,3	22,54	15,38	3,43	8,62	0,47
5K Period II	12,06	4,42	4,48	0,10	22,21	22,74	128,28	6,41	16,10	0,87

Due to very low mass flow q_m of the cryogen, the entropy stream generated by pressure drop is practically negligible. Thanks to the thermal shield which is thermally coupled with 80K process pipe, heat fluxes to 40K process pipe are very low. Additionally 40K process pipe is transferring heat to 4,5K and 5K pipes, what creates a negative entropy stream calculated for this pipe, not compensated by negligible pressure drop.

THERMAL ANALYSIS BASED ON SPECIFICATION DATA

To compare operational parameters of XATL1 line with technical specification requirements, entropy analysis has been performer for the line design data, namely heat fluxes of 0,15W/m to 4,5K and 5K pipes, and 1,5W/m for 40K and 80K pipes.

	q_m	Q	T	p	$\dot S_{\Delta P}$	$\dot S_{\Delta T}$	$\dot S$	P_{Ad}
	g/s	W	K	MPa	W/K	W/K	W/K	kW
4.5K	92,50	24,9	4,5	0,35	0,00	92,84	92,84	7,43
5K	92,50	24,9	5	0,12	0,53	74,70	75,23	6,02
40K	14,20	249	40	1,7	0,00	6,23	6,23	0,50
80K	14,20	249	80	1,68	0,00	8,56	8,56	2,57

CONCLUSIONS

- The entropy generation streams resulting from pressure drops are negligible in comparison with heat transfer induced entropy fluxes,
- There is a possibility of the line design optimisation be reducing the process pipes diameters,
- The measured thermodynamic efficiency of the line, estimated by Second Law analysis and Gouya-Stodola theorem, is of about 3,5% worse from specification parameters

		4.5K	5K	40K	80K	Σ
P_{Ad} – operational data (average of periods I and II)	kW	2,93	0,67	0,00	13,49	**17,10**
P_{Ad} – technical specifications	kW	7,43	6,02	0,50	2,57	**16,52**