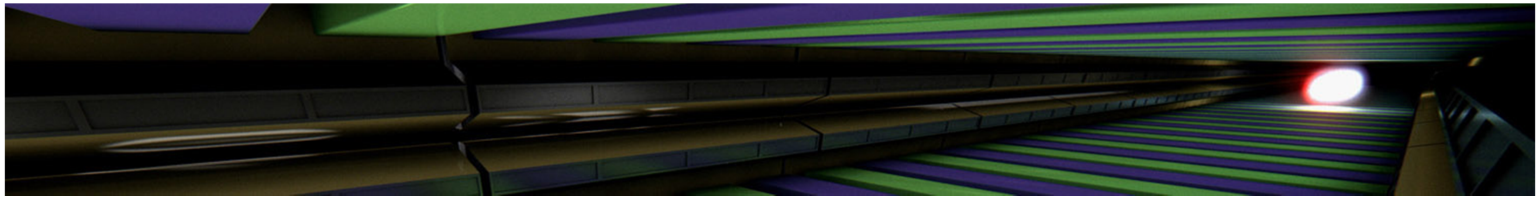


Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

TESLA Technology Collaboration Meeting

IHEP, Beijing, China, 5-8 December 2011

X.L. Wang, W. Maschmann, J. Eschke, O. Sawlanski,
R. Klos, K. Jensch, B. Petersen

Many other involved colleagues

DESY

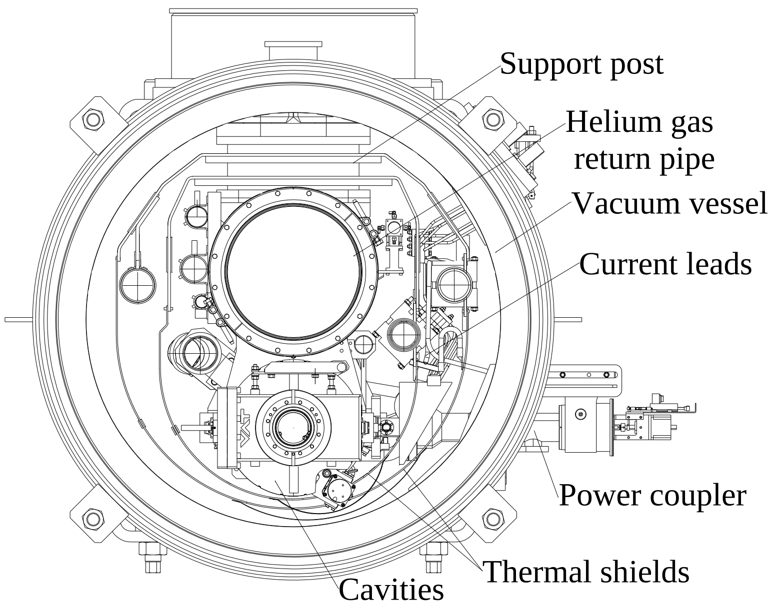
HELMHOLTZ ASSOCIATION

Overview

- Introduction.
- Thermal analysis.
- Heat load measurements.
- Results and discussion.
- Conclusions.
- Sources and references.

Introduction

- **Based on The TESLA/TTF-Type III design.**
- **10 Hz pulsed operation.**
- **One Cryomodule consists of: 8 1.3 GHz 9-cell Nb cavities (2 K), 1 magnet package (2 K), two thermal shields (5/8 K and 40/80K), 8 main RF couplers, 3 support posts.**
- **12 m length and 7.8 t total weight.**



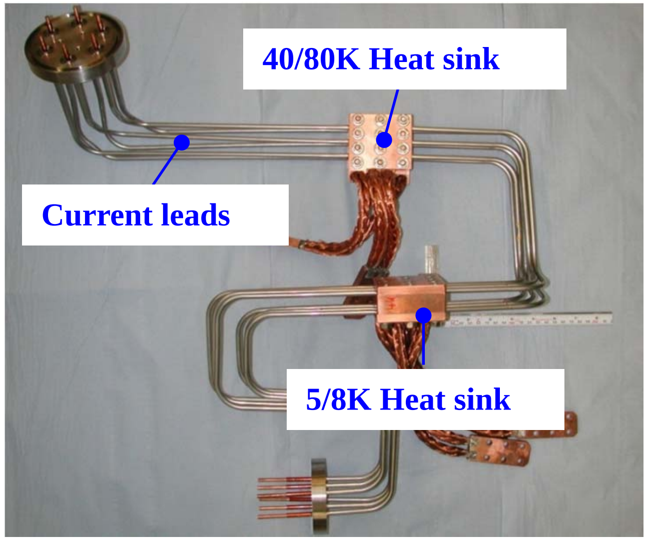
Thermal analysis

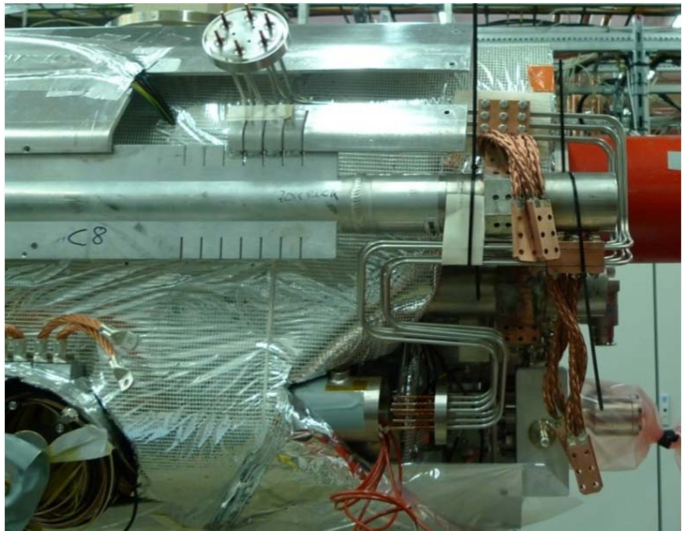
Heat transfers by

- Current leads.
- Power couplers.
- Support posts.
- Multilayer insulation (MLI).

Heat transfer by current leads

- Conduction cooled current leads with two heat sinks and developed by CERN.
- Heat transfer mechanisms:
  - Conduction through brass and copper; heat generated by current and material properties changes with temperature.
  - Negligible axial conduction through SS, Kapton tube and the helium gas and contact thermal resistances.
- A numerical model is developed by using Matlab.
- A analytical model is used to validate numerical results in appropriate limits.



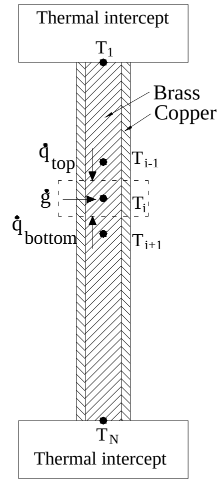


Heat transfer by current leads

Design parameter of the current leads

Level	T_H, K	T_C, K	L, m	D_b, mm	t_{cu}, mm	Copper RRR
40/80 K	300	70	0.50	3	0.60	120
5/8 K	70	5	0.38	3	0.13	120
2 K	5	2	0.48	3	0.60	120

D_b: Diameter of the brass, t_{cu}: Thickness of copper plating.



Comparisons from analytical and numerical models

(One lead, constant thermal conductivity and electrical resistivity)

Model	q, W (300-70 K)		q, W (70-5 K)		q, W (5-2 K)	
	0 A	60 A	0 A	60 A	0 A	60 A
CERN A	1.35	2.50	0.38	0.54	0.023	0.045
DESY A1	1.33	2.34	0.35	0.60	0.028	0.044
DESY N1	1.33	2.33	0.35	0.60	0.028	0.045
DESY A2	1.75	2.76	0.42	0.66	0.028	0.045
DESY N2	1.75	2.75	0.42	0.66	0.028	0.045

- **A:** Analytical solutions
- **N:** Numerical solutions
- **'1'** and **'2'** denotes respectively the solutions with neglecting and considering heat conduction of the brass

- CERN A and DESY A1 fit very well.
- Heat conduction through the brass had been neglected in CERN design.
- The analytical and numerical results have a good agreement.

Heat transfer by current leads

Heat loads by current leads

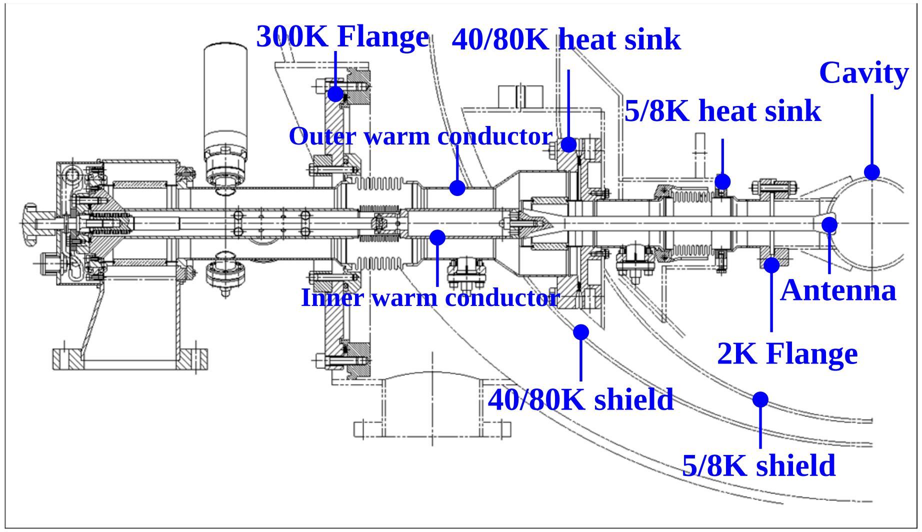
Ts, K	Ti, K	Q (Six leads), 0A/50A, W		
		2K	5/8 K	40/80 K
40	2-10-50-300	0.77/0.84	1.88/2.26	11.88/14.82
50	2-10-60-300	0.77/0.84	2.13/2.58	11.10/14.34
60	2-10-70-300	0.77/0.84	2.36/2.90	10.50/14.04
70	2-10-80-300	0.77/0.84	2.56/3.23	9.96/13.74
80	2-10-90-300	0.77/0.84	2.77/3.63	9.48/13.44

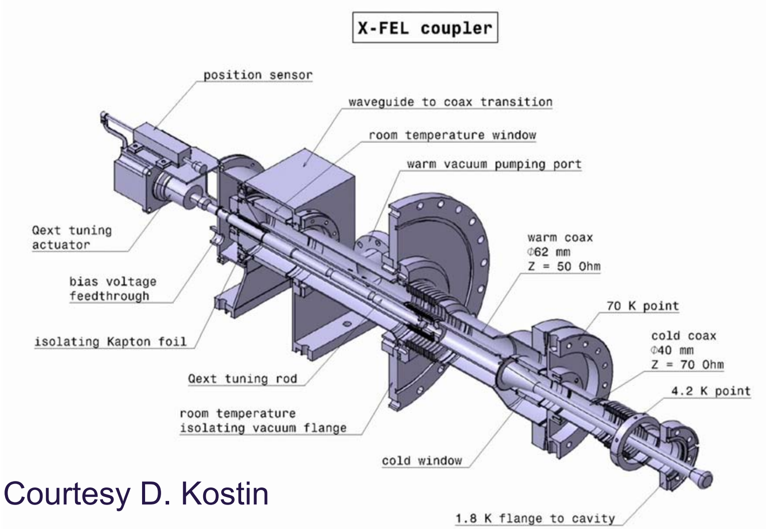
Ts: Shield temperature, Ti: Thermal intercept temperature

- 2 K static one: ~1 W — 2 K dynamic one: ~ 0.1 W
- 5/8 K static one: ~2-3 W — 5/8 K dynamic one: ~0.4-0.9 W
- 40/80 K static one: ~10-12 W — 40/80 K dynamic one: ~3-4 W

Heat transfer by power couplers

- Eight power couplers in one module.
- Conductors made up of SS tubes coated by the copper.
- Two thermal sinks at 5/8 K and 40/80 K levels.
- Heat transfer mechanisms:
  - Conduction through the inner and outer conductors.
  - Heat generation by the RF power coupler.
  - Radiation heat from the antenna to 2 K and 5/8 K levels.
- The numerical model is similar with that of current leads.





Courtesy D. Kostin

Heat transfer by power couplers

Basic parameters of the power coupler

Conductor	Segment	D, mm	L, mm	tss, mm	tcu, µm	Copper RRR	Components
Outer conductor 40/80 K	1	71	203	0.25	10	10	SS bellow
	2	62	79	1.5	10	10	SS tube
	3	92	65	1.5	10	10	SS tube
Inner conductor 40/80 K	1	23	209	2	30	10	SS tube
	2	26	155	0.15	30	10	SS bellow
	3	23	100.6	2	30	10	SS tube
Outer conductor 5/8 K	1	40	66	1.5	10	10	SS tube
	2	46.5	186	0.2	10	10	SS bellow
Outer conductor 2 K	1	46.5	9.5	1.25	10	10	SS tube
	2	40	17.1	1.5	10	10	SS tube

Comparisons with DESY previous model (M. Dohlus, Proc. LINAC 2004)

(One coupler, static, q_{cp1}: Present, q_{cp2}: Previous)

Level	T_C,K	T_H,K	q_{CP1}, W	q_{CP2}, W	Conductor
2 K	2	4	0.01	0.02	Outer conductor
5/8 K	4	70	0,2	0.2	Outer conductor
40/80 K	70	300	1.4	1.1	Outer conductor
	70	300	0.9	0.8	Inner conductor

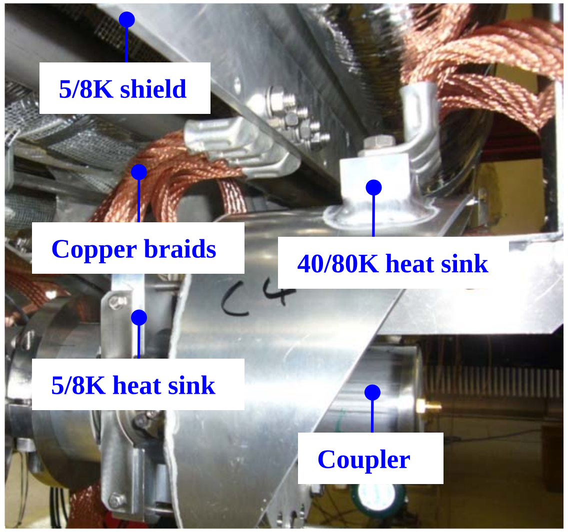
The other comparison with Fermi model (T. Peterson, TESLA report, 1993)

2 K level, identical parameters, error of about 10%.

Heat transfer by power couplers

Static Heat loads by power couplers

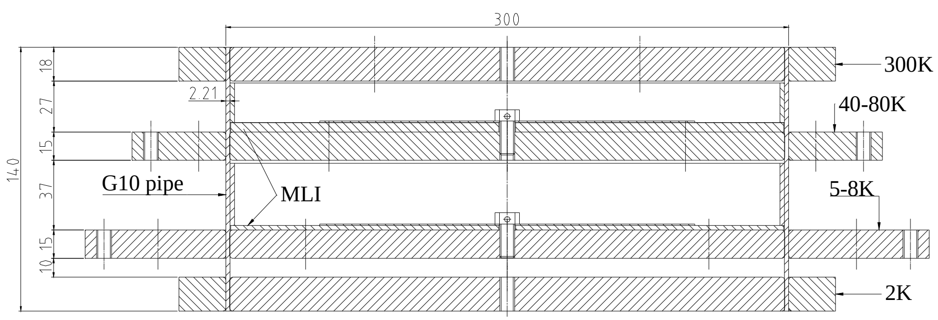
Ts, K	Ti, K	Q (Eight couplers) , W		
		2 K	5/8 K	40/80 K
40	2-10-60-300	0.48	1.20	18.24
50	2-10-70-300	0.48	1.52	17.92
60	2-10-80-300	0.48	1.84	17.12
70	2-10-90-300	0.48	2.16	16.48
80	2-10-100-300	0.48	2.96	15.84

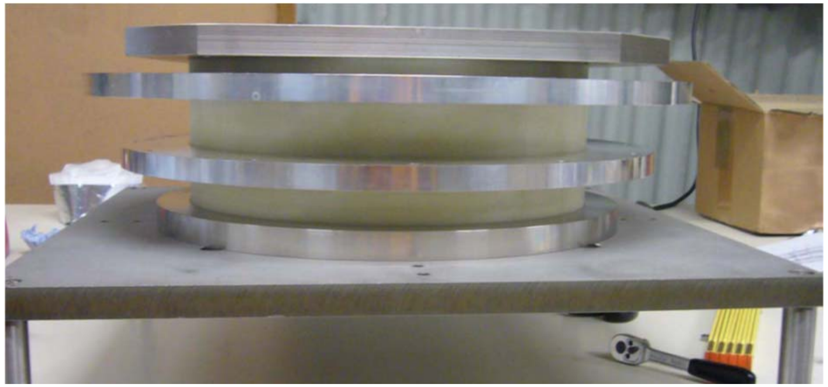


- 2 K static one: ~0.5 W
- 5/8 K static one: ~1-3 W
- 40/80 K static one: ~16-18 W

Heat transfer by support posts

- Three support posts in one module.
- Two thermal sinks at 5/8 K and 40/80 K levels.
- Heat transfer mechanisms:
  - Conduction through G-10 tube.
  - Radiation heat from the MLI (Negligible)
- The numerical model is similar with that of the current leads.
- The analysis model is used to validate the numerical results.
- Cryocomp properties version 3.0 provides three kinds of G-10 with various conductivities depending on the angles between the thermal gradient and the fiber direction.
- The maximum conductivity G10 is taken.





Heat transfer by support posts

Comparisons with INFN previous model (S. Barbanotti, INFN/TC-08-01)

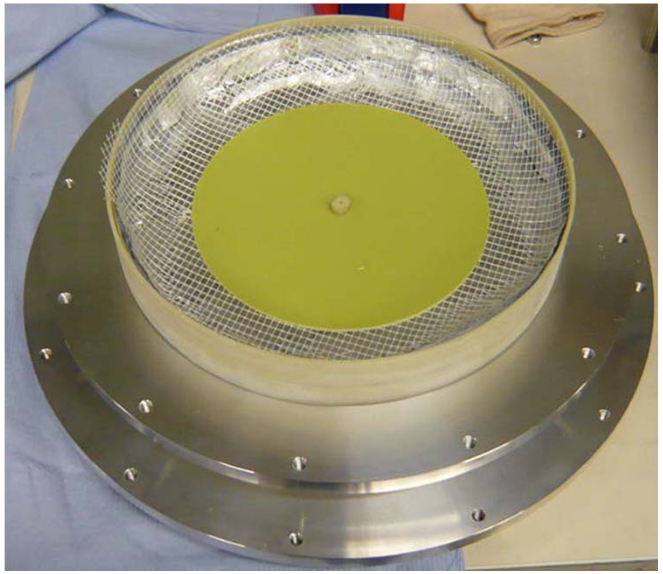
(One support post, q_A: DESY analytical, q_N: DESY numerical)

Level	T_C,K	T_H,K	q_{INFN}, W	q_A, W	q_N, W
2 K	2	5	0.041	0.035	0.035
5/8 K	5	70	0.865	0.93	0.94
40/80 K	70	300	9.906	11.51	11.52

Heat loads by support posts

Ts, K	Ti, K	Q (three posts), W		
		2 K	5/8 K	40/80 K
40	2-10-40-300	0.42	1.05	36.87
50	2-10-50-300	0.42	1.56	36.18
60	2-10-60-300	0.42	2.10	35.40
70	2-10-70-300	0.42	2.73	34.56
80	2-10-80-300	0.42	3.42	33.60

- 2 K: ~0.5 W
- 5/8 K: ~1-3.5 W
- 40/80 K: ~34-37 W



Heat transfer by the MLI

- 30 layers at 40/80 K and 10 layers at 5/8 K.
- Surface areas: 30.9 m^2 at 40/80 K and 26.4 m^2 at 5/8 K.
- Heat transfer mechanisms:
  - Conduction through the solid.
  - Radiation heat.
  - Conduction through residual gas (Negligible $P<10^{-3}$ Pa).
- Difficulty to calculate accurately.
- Reviewed empirical results from CERN and NASA.

Heat transfer by the MLI

Empirical results of heat fluxes

2 K: Negligible, 5/8 K: 0.05 W/m², 40/80 K: 1.5 W/m² (many openings).

Empirical formulas adapted to empirical heat fluxes

$$q = \frac{C_S (\overline{N})^{2.56} T_m}{N_S + 1}(T_H - T_C) + \frac{C_R \varepsilon_{RT}}{N_S}(T_H^{4.67} - T_C^{4.67})$$

(T. Nast, Multilayer insulation system)

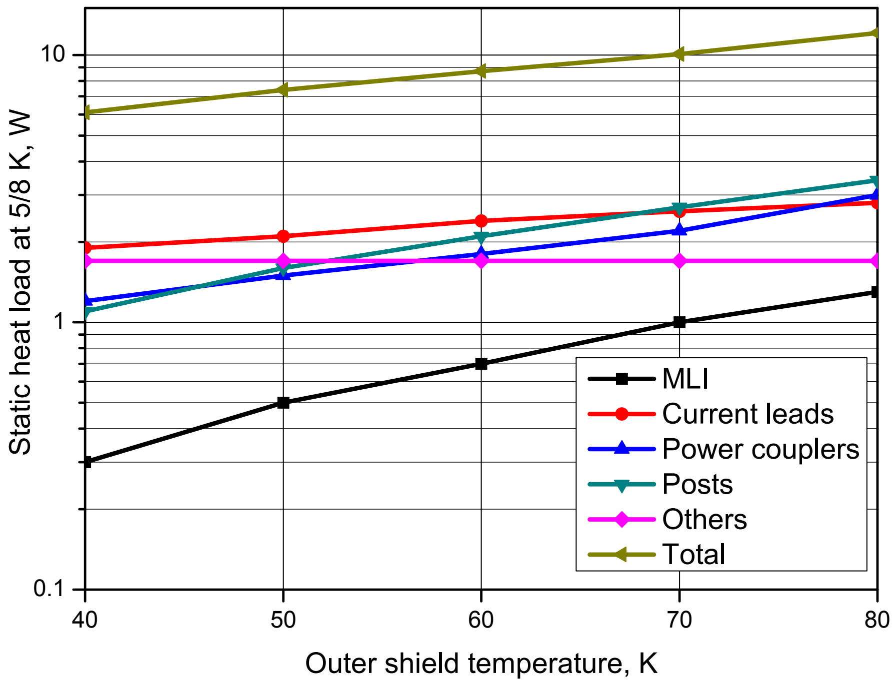
Level	q, W/m²	N_S, layers	$\overline{N}$, layers/cm	T_H, K	T_C, K	ε_{RT}
5/8 K	0.05	10	19.0	80	10	0.03
40/80 K	1.5	30	37.4	300	80	0.03

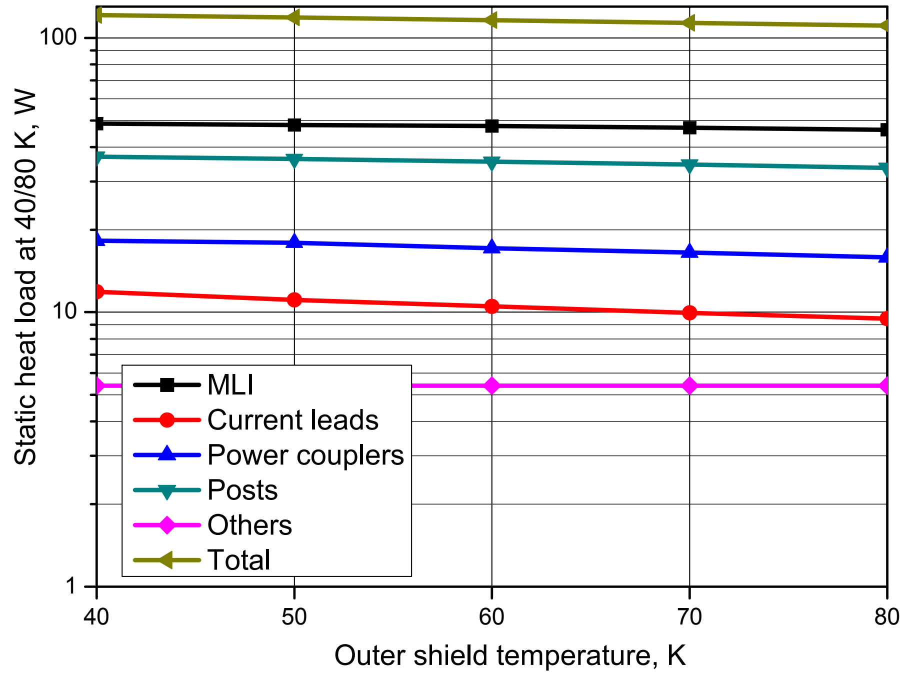
Heat loads by the MLI

Ts, K	Ti, K	Heat load Q, W		
		2 K	5/8 K	40/80 K
40	2-10-40-300	-	0.3	48.7
50	2-10-50-300	-	0.5	48.2
60	2-10-60-300	-	0.7	47.7
70	2-10-70-300	-	1.0	47.1
80	2-10-80-300	-	1.3	46.3

- 2 K: -
- 5/8 K: ~0.3-1.3 W
- 40/80 K: ~46-49 W

Thermal analysis summary





Others including heat loads from HOM absorbers, cablings, etc. is extracted from refrigerator budget, where 2 K: 0.4 W, 5/8 K: 1.7 W, 40/80 K: 5.4 W.

- 2 K: 2.1 W.
- 5/8 K: 6-12 W strongly depending on the 40/80 K shield temperatures.
- 40/80 K: 110-120 W slight effected by the 40/80 K shield temperatures.

Heat load measurements

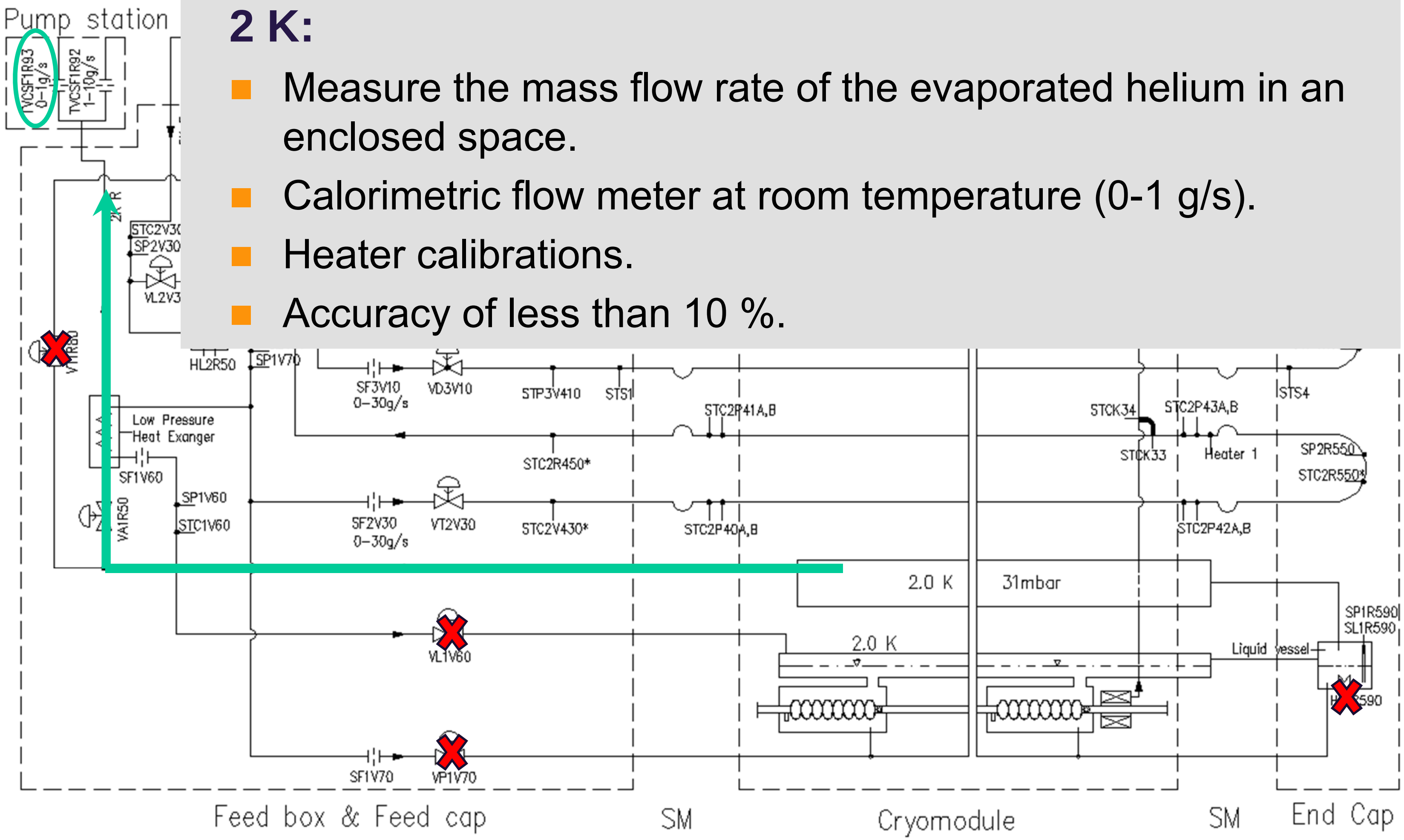
Test	Cold mass vendor	Assembly	Time
PXFEL2_1	Felguera, Spain	CEA, Saclay	Jun. 2011
Dummy test	DESY	DESY	Feb. 2011
PXFEL3 (B)	Thales, France	DESY	Nov. 2010
PXFEL3 (A)	Thales, France	DESY	Sep. 2010
PXFEL2 (B)	Felguera, Spain	CEA, Saclay	Jun. 2010
PXFEL2 (A)	Felguera, Spain	CEA, Saclay	May 2010
PXFEL1	IHEP, China	DESY	Jul. 2009

- Tested at Cryomodule test bench (CMTB).
- Four modules and seven measurements plus dummy test.
- PXFEL2_1: New MLI at 40/80 K shield.
- PXFEL3 (B): Disconnected the 40/80 K thermal intercept of current leads.
- PXFEL2 (B): T sensors at sliding muff range calibrations.
- Dummy test: pure heat load of CMTB without the module.

Methodologies and instrumentation

2 K:

- Measure the mass flow rate of the evaporated helium in an enclosed space.
- Calorimetric flow meter at room temperature (0-1 g/s).
- Heater calibrations.
- Accuracy of less than 10 %.

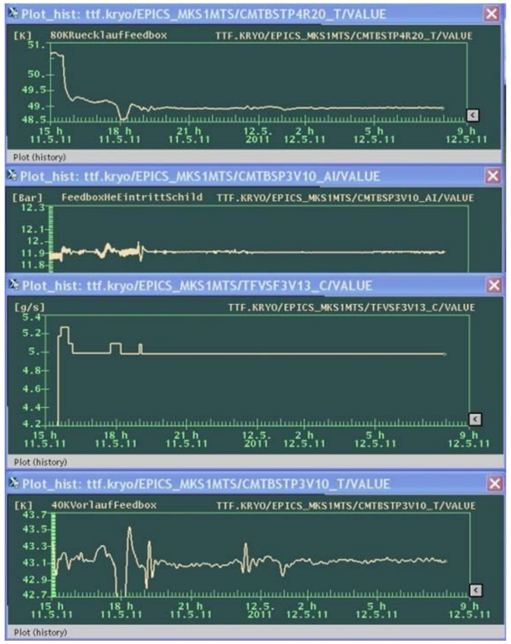


Methodologies and instrumentation

5/8 K and 40/80 K: Enthalpy balance

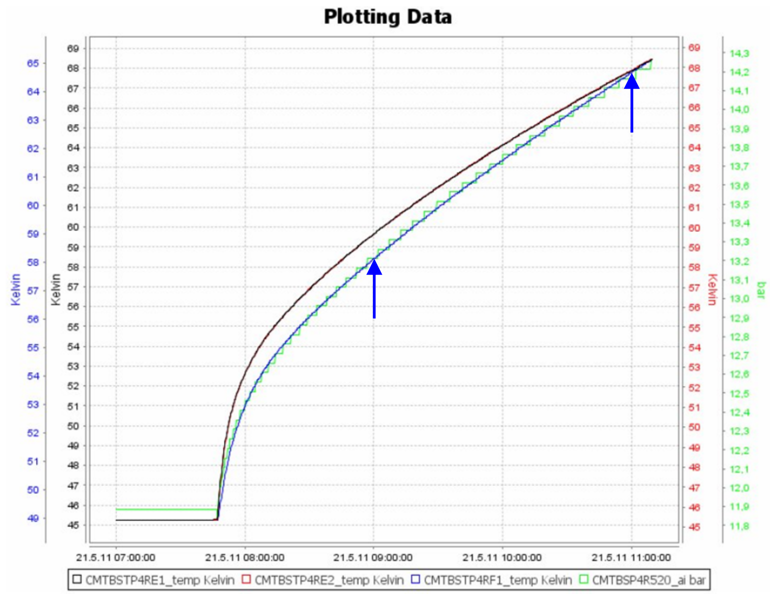
For Helium $\dot{Q} = \dot{m}_{He} C_{pHe} \Delta T_{He}$

For Cold mass $\dot{Q} = m_c C_{pc} \Delta T_c / \Delta t$ **for cross check**



Pure heat load of **99 W**

At 40/80 K

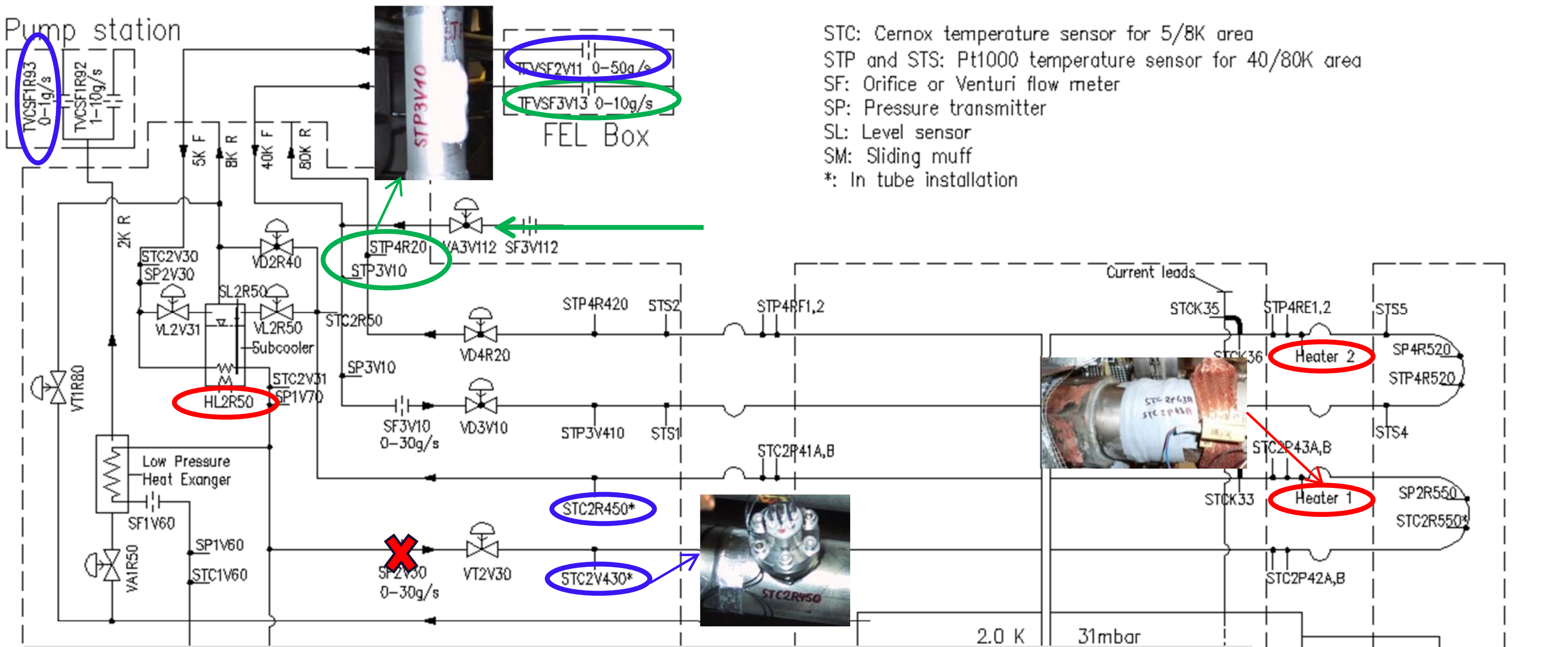


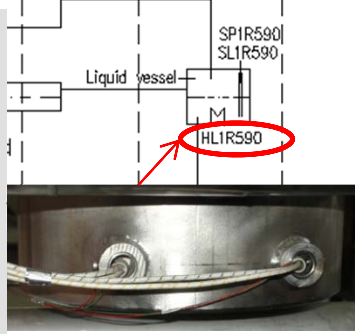
Cold mass: AL of 388 kg and helium of 0.5 kg.

Averaged T increase: 58.9 K to 66.3 K within 2 hours.

Heat load of **94 W**

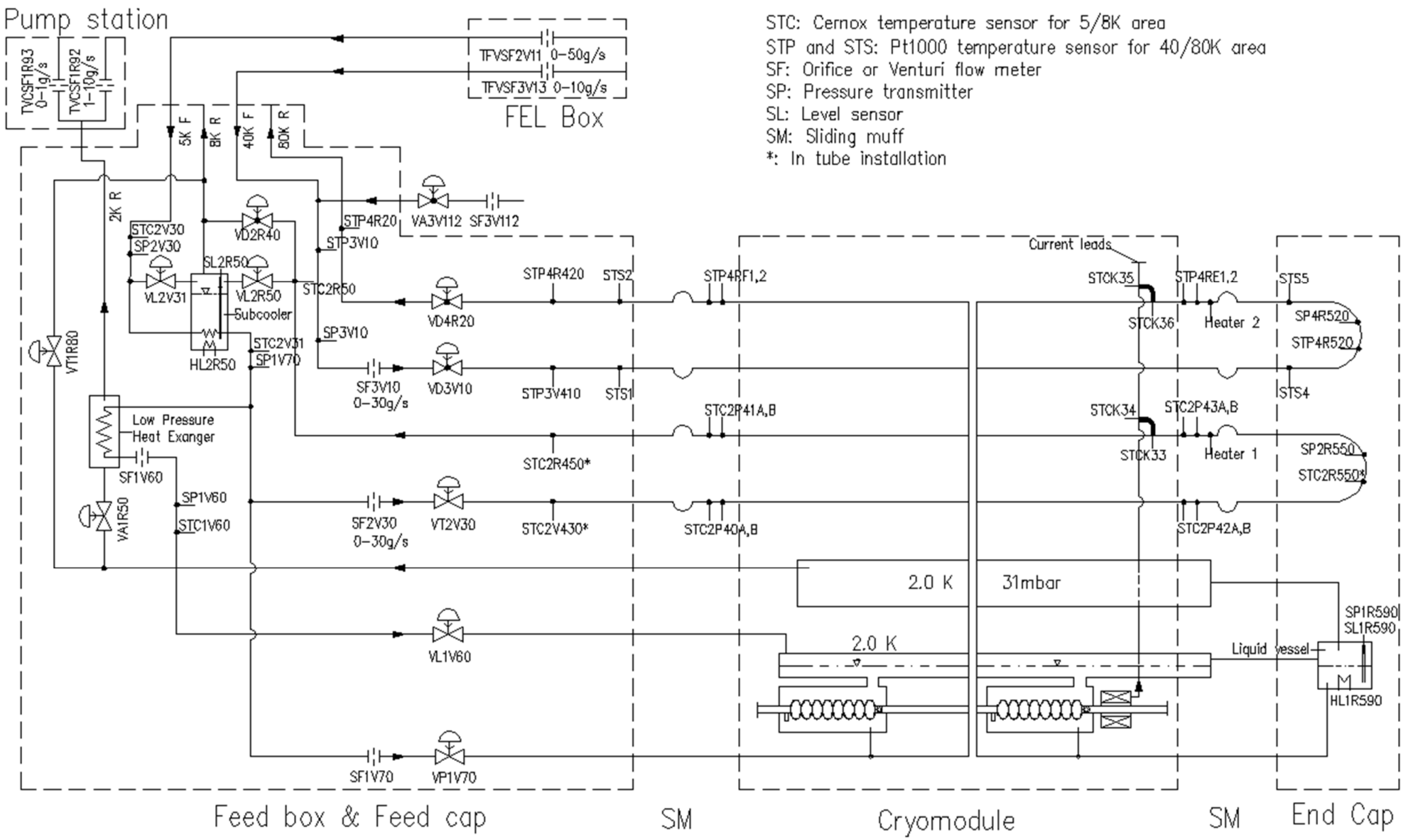
Methodologies and instrumentation



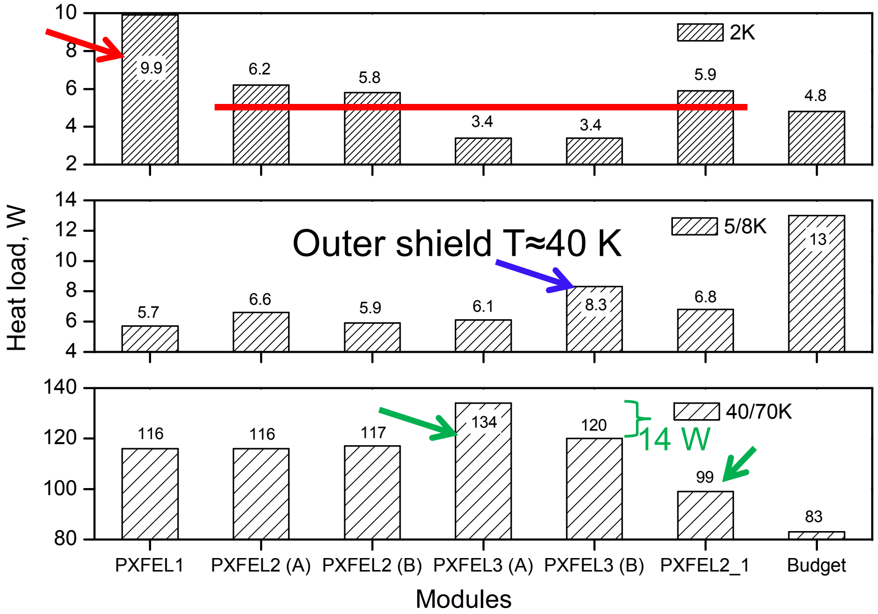


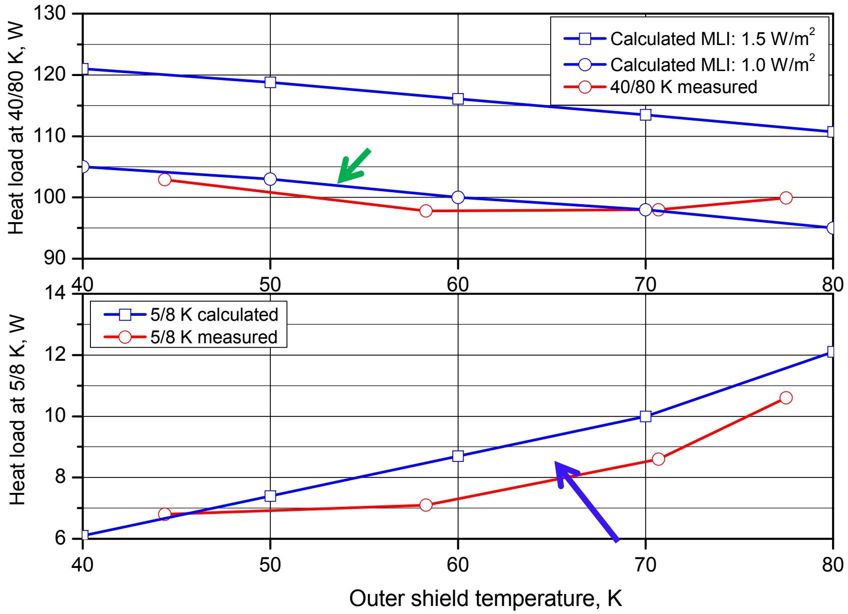
- 40/80 K: Pt1000 (on tube installation), Venturi flow meters.
- Warm flow input to change outer shield T from 40-80 K.
- 5/8 K: Cernox^{TM} (in tube installation), Ventur flow meter.
- Heater calibrations for all circuits.
- Accuracy of less than 10 %.

Methodologies and instrumentation



Results and discussion

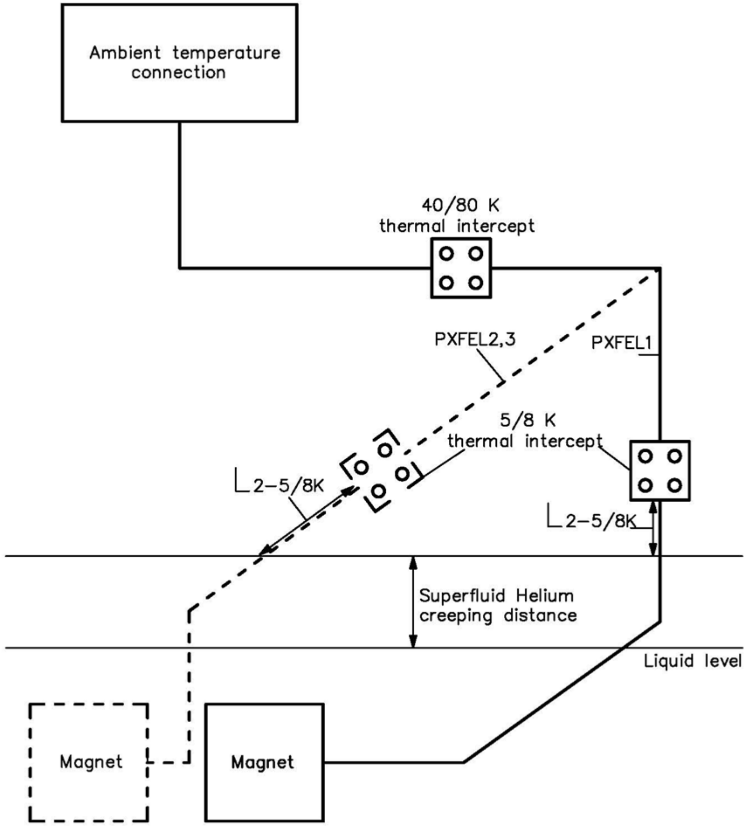




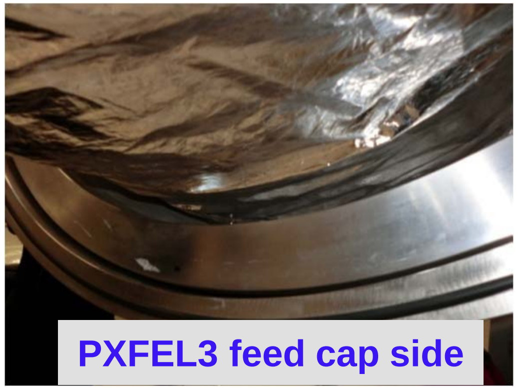
- 2 K: PXFEL1 quite higher than others. Differences from others (due to installation skill of current leads)
- 5/8 K: PXFEL3 (B) higher than others.
- 40/80 K: ΔQ=14 W from PXFEL3. Calculated: 12 W, fit reasonably
- 40/80 K: PXFEL3 (A) higher than others.
- 40/80 K: PXFEL2_1 lower than others.

- 5/8 K: Reasonable agreements. Strongly effected by outer shield T.
- 40/80 K: Could fit well with assumption of 1 W/m^2 through the MLI for PXFEL2_1.

Results and discussion



Layout of current leads causes quite high 2 K heat load of PXFEL1 **(Confirmed)**



PXFEL3 feed cap side

PXFEL3 end cap side

Tuner misalignment causes higher 40/80 K heat load of PXFEL3 **(Guess)**

PXFEL2_1

New MLI at 40/80 K shield in PXFEL2_1 improves the thermal performance **(TBC)**

European XFEL

Conclusions

Static heat load summary of PXEFL modules

Level	Measured	Calculated	XRB	Factor	XRC
40/80 K	100-120	100-120	83	1.5	125
5/8 K	6-11	6-12	13	1.5	20
2 K	6	2.1	4.8	1.3	6

XRB: XFEL refrigerator budget, XRC: XFEL refrigerator capacity

- 40/80 K: **100-120 W** depending on the performance of MLI.
- 5/8 K: **6-12 W** depending on the outer shield temperatures.
- 2 K: **3.5-6 W** depending on the installation skills of current leads.
- Measured and calculated values have a good agreements at 5/8 K and 40/80 K.
- Big deviation at 2 K caused by underestimation of cabling heat load and the installation skills of current leads.
- Specified refrigerator capacity still could cover the heat load at 2 K and 40/80 K (Even come to limit) and have enough margin at 5/8 K.

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End

Thank you for your attention!