Heat loads measurements at the XFEL cold linac

Measured static and dynamic values at 2K, 5-8K, 40-80K

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Outlook

01 Methods of heat load calculation

02 Single cryomodule static and dynamic heat loads at AMTF
- at 5-8K , 40-80K and at 2K

03 Static and dynamic heat loads at the XFEL linac
- at 5-8K , 40-80K
- at 2K

04 5Hz and 10Hz operation

05 Summary

Heat load calculation: methodology

For the single cryomodules and the XFEL linac

- Heat load estimated for three different temperature levels:
  External shield: 40-80 K Internal shield: 5-8 K Cavity environment: 2 K

- **Static heat load calculation at 5-8 K and 40-80K**
  - Stable flow
  - Calculate heat loads from flow and delta enthalpy

$$\dot{Q}_{s,5/80K} = \dot{m}\Delta h = \dot{m}(h_{out}(p_{out}, T_{out}) - h_{in}(p_{in}, T_{in}))$$

- **Static heat load calculation at 2K**
  - Stable flow, turn off magnets and RF, subtract heaters
  - For XFEL linac, heat loads from flow and delta enthalpy
  - For single cryomodules in the AMTF hall: warm flowmeters after compressor used, close the JT valve and measure amount of evaporated LHe at constant pressure (isothermal).

$$\dot{Q}_{s,2K(XFEL)} = \dot{m}\Delta h = \dot{m}(h_{out}(p_{out}, T_{out}) - h_{in}(p_{in}, T_{in}))$$

$$\dot{Q}_{s,2K(AMTF)} = L\dot{m} \qquad \mathrm{L} = 23.40\ {}^{J}/_{g}\ @\ 2\ K\ ,31\ mbar$$

- **Dynamic heat load calculation at 2K, 5-8 K and 40-80K**
  - Same method as static measurement, with RF
  - Subtract average static component from total value

$$\dot{Q}_d = \dot{Q}_{total} - \dot{Q}_s$$

Static and dynamic heat loads (HL) measured in AMTF

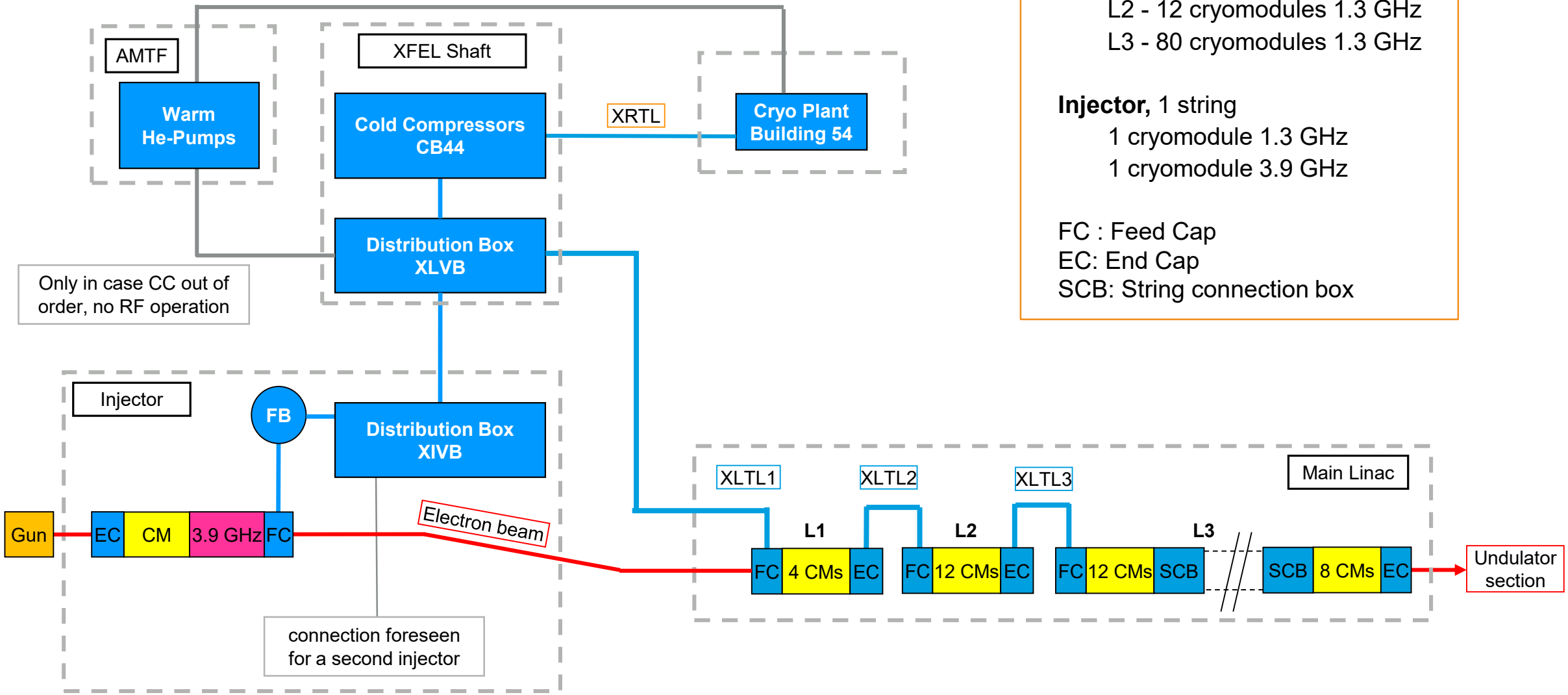
40-80 K, 5-8 K and 2 K circuits

- Three test stands available for cold test of single XFEL cryomodules
- Average value of all 103 tested cryomodules (CM)at the three test stands (2014 – 2015)
- 2K dynamic loads value at average cavity gradient of 23 MV/m

Circuit	Average static HL/ CM	Average dynamic HL/ CM
40-80 K	93 W	n.a.
5-8 K	11 W	n.a.
2 K	5.6 W (Isothermal)	4.2 W

XFEL overview

From the point of view of the heat load calculations



XTL, 9 strings
- L1 - 4 cryomodules 1.3 GHz
- L2 - 12 cryomodules 1.3 GHz
- L3 - 80 cryomodules 1.3 GHz

Injector, 1 string
- 1 cryomodule 1.3 GHz
- 1 cryomodule 3.9 GHz

FC : Feed Cap
EC: End Cap
SCB: String connection box

XFEL static heat loads at 40-80K, 5-8K and 2K

Measurement at the XLVB box

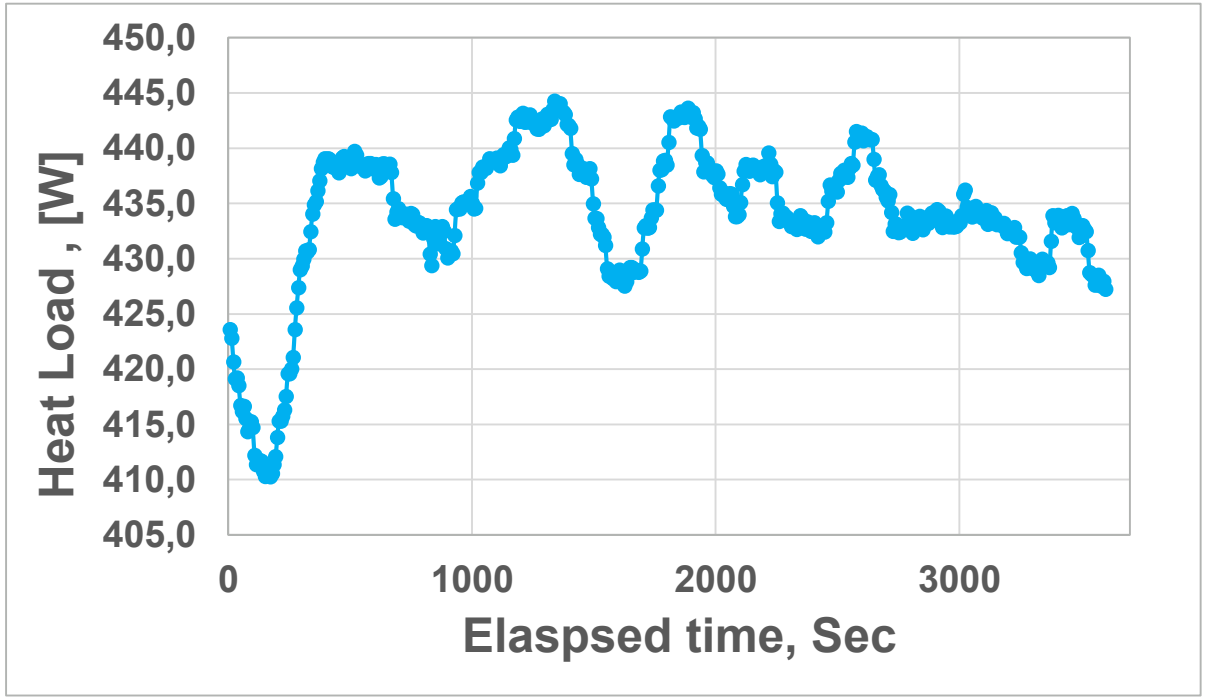
- Measurement performed for the entire linac, including transfer lines, cryogenic boxes and caps
- The values are an average on time periods from 2020 till 2022
- Choice of thermal sensors verified with different methods

Circuit	Average static HL (W)
40-80 K	9800 W
5-8 K	800 W
2 K	587 W

Contributions to the 2K static heat load

2K bath (cavities and magnets) isothermal contribution

- Measurement performed with the AMTF method.
- XFEL injector included
- Heat load estimated: **430 W**
  - XFEL has 97.5 cryomodules, the static HL/CM is **4.4 W**
    - one 3.9 GHz CM counts for half a 1.3 GHz CM
  - XFEL Linac 2K isothermal static load: 96 X 4.4 = **423 W**

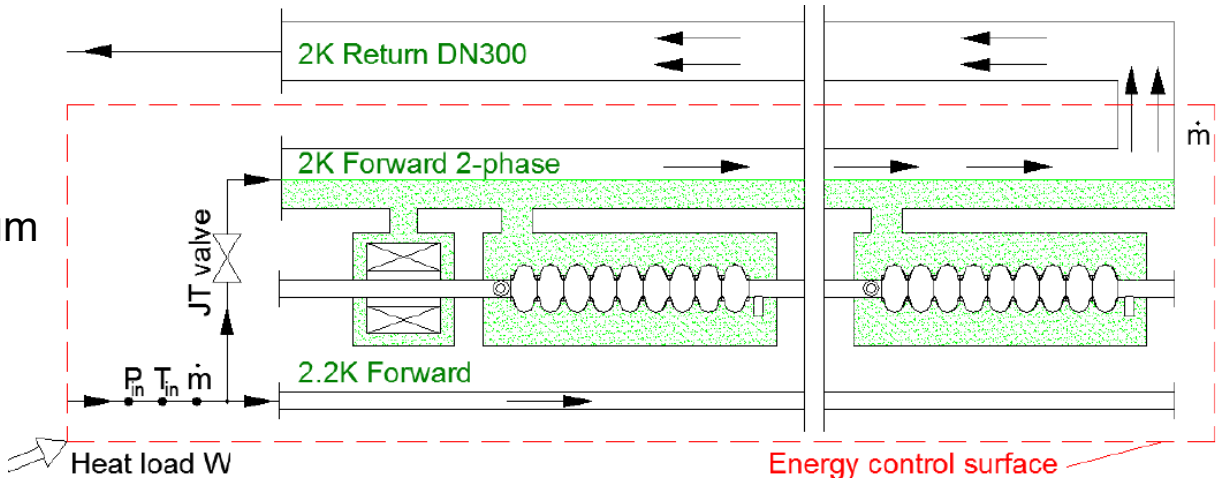


Contributions to the 2K static heat load

2K return pipe contributions

- 2K return pipe (Gas Return Pipe, DN300) contribution:
  - Instead of outlet T and P, we consider the enthalpy of helium in the saturates state (25.04 J/g)

$$\dot{Q}_{Total} = \dot{m}(h_{sat,V} - h_{in}(p_{in}, T_{in}))$$



- The above equation is applicable only if the inlet and outlet enthalpies are measured at same height.
  - Inlet P and T measured 17.6 m above tunnel → contribution of hydrostatic head (**173 J/kg**) to be included

$$\dot{m} * (25.04 - h_{in} - 0.173) = (24.867 - h_{in}) = \dot{Q}_{Total}$$

- Static HL without 2K return pipe: 515 W

Contributions to the 2K static heat load

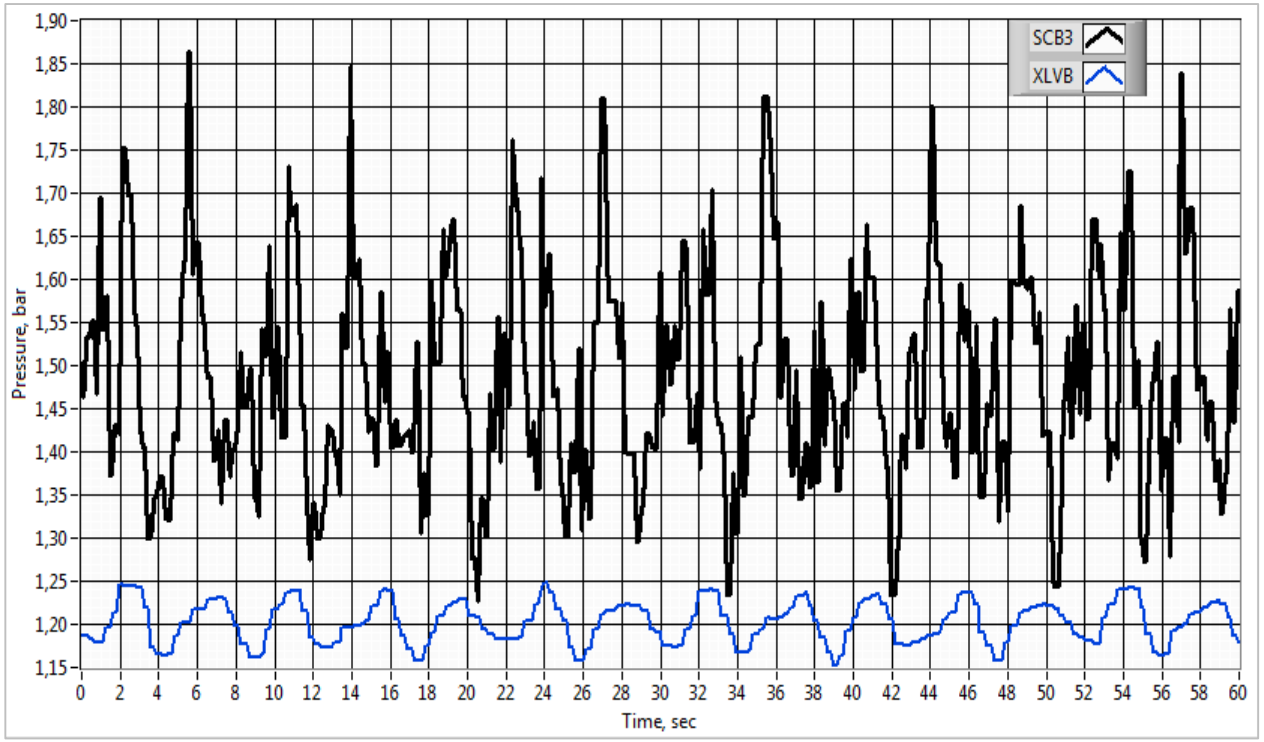
Summary

Components	Heat load (W)
Total heat load at XLVB	587
Heat load 2K bath (Isothermal)	423
Heat load without 2K return	515
Heat load 2K forward (DN40)	515 – 423 = 92
Heat load 2K return (DN 300)	587 – 515 = 72

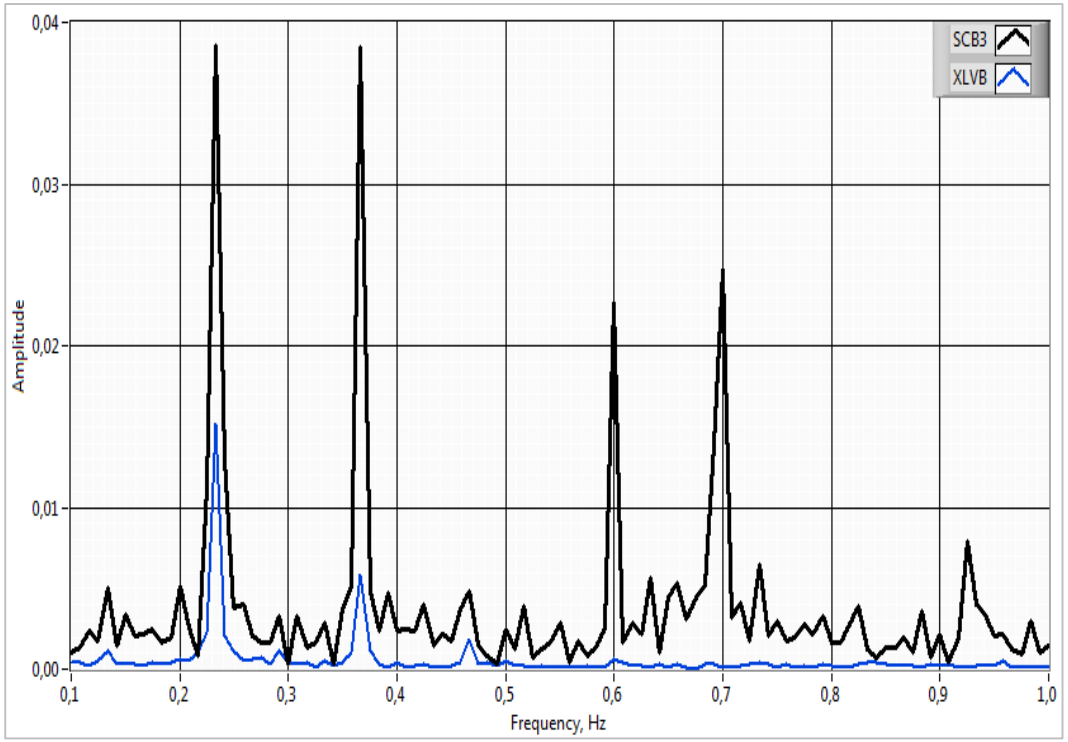
Contributions to the 2K static heat load

Summary

Pressure fluctuations at the 2K forward pipe



FFT spectrum of pressure oscillations

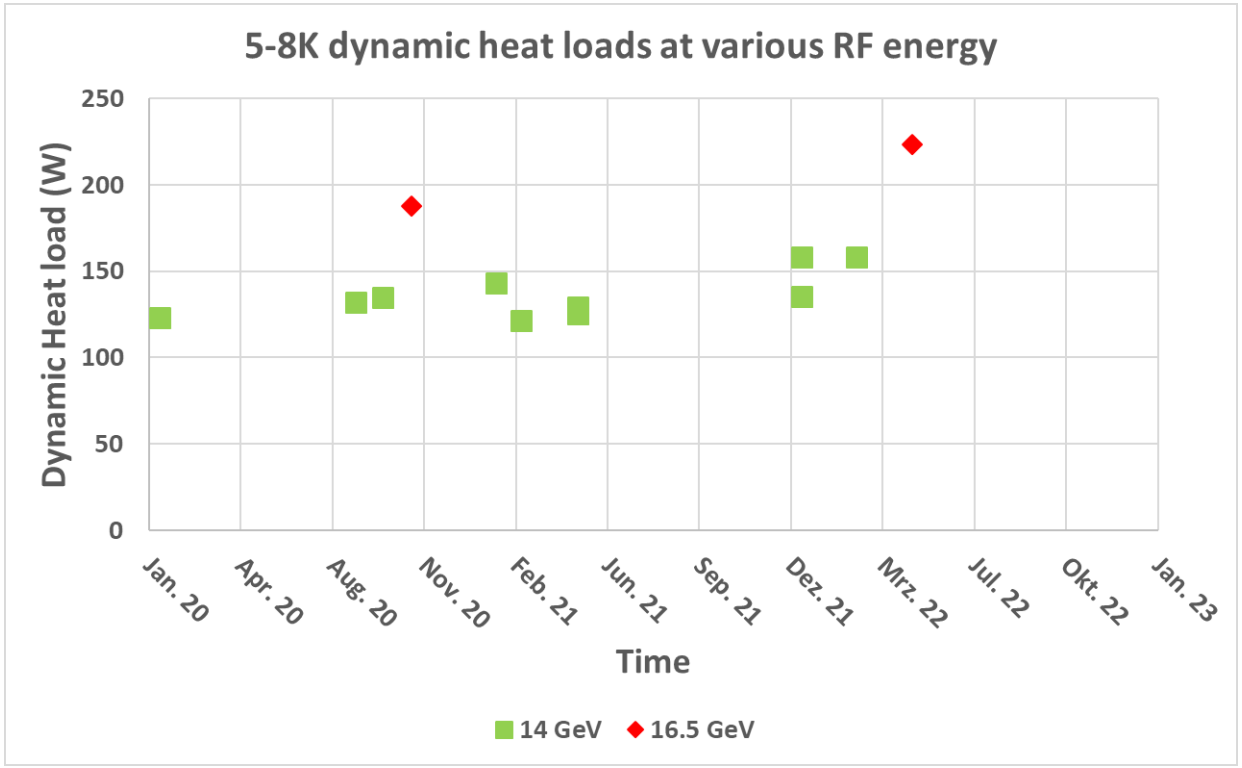


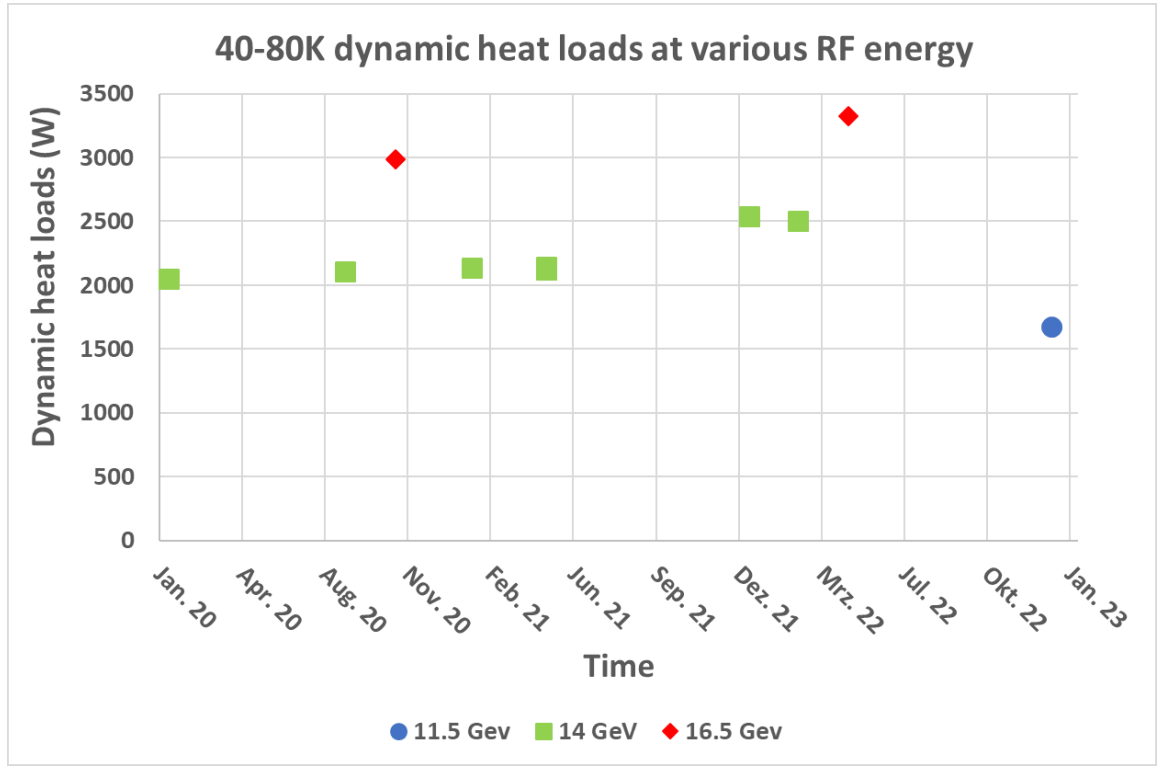
Major frequencies are around 0.22 and 0.37 HZ which are too slow to result from thermal acoustic oscillations.

XFEL dynamic heat loads at 5-8K and 40-80K circuits

Summary

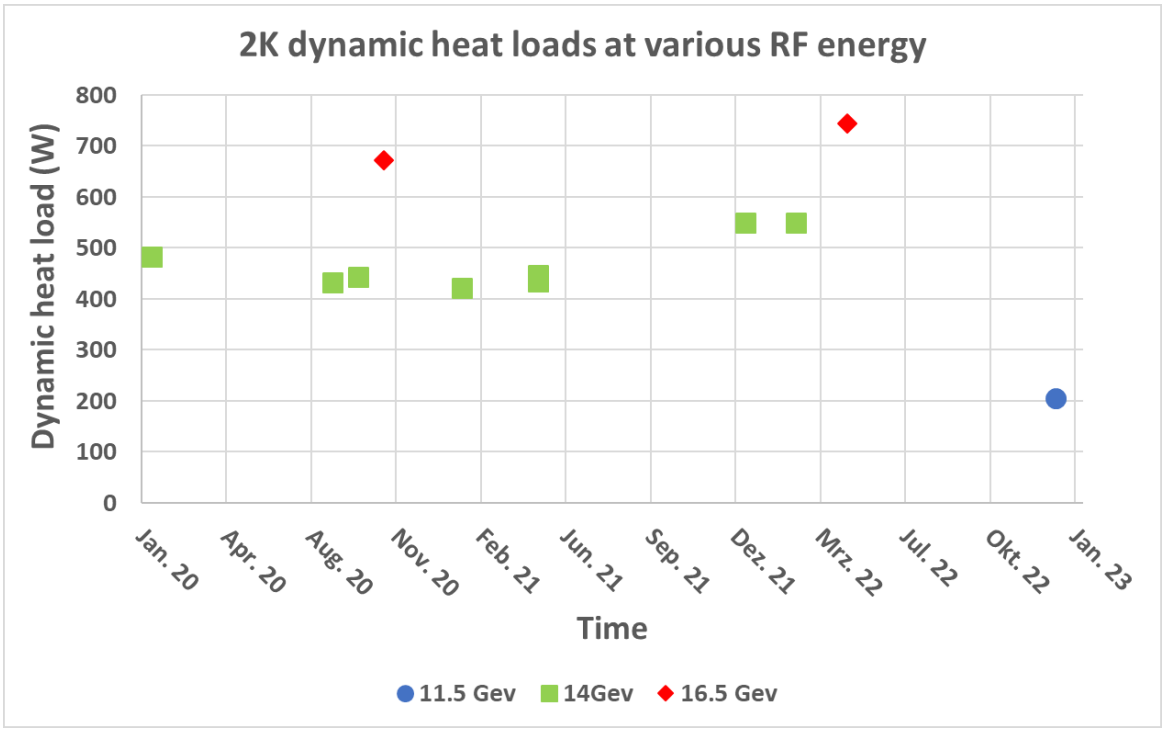
Circuit	Dynamic HL at various RF energy (XTL)		
	11.5 GeV	14 GeV	16.5 GeV
5-8 K	n.a.	140 W	210 W
40-80 K	1700 W	2300 W	3200 W

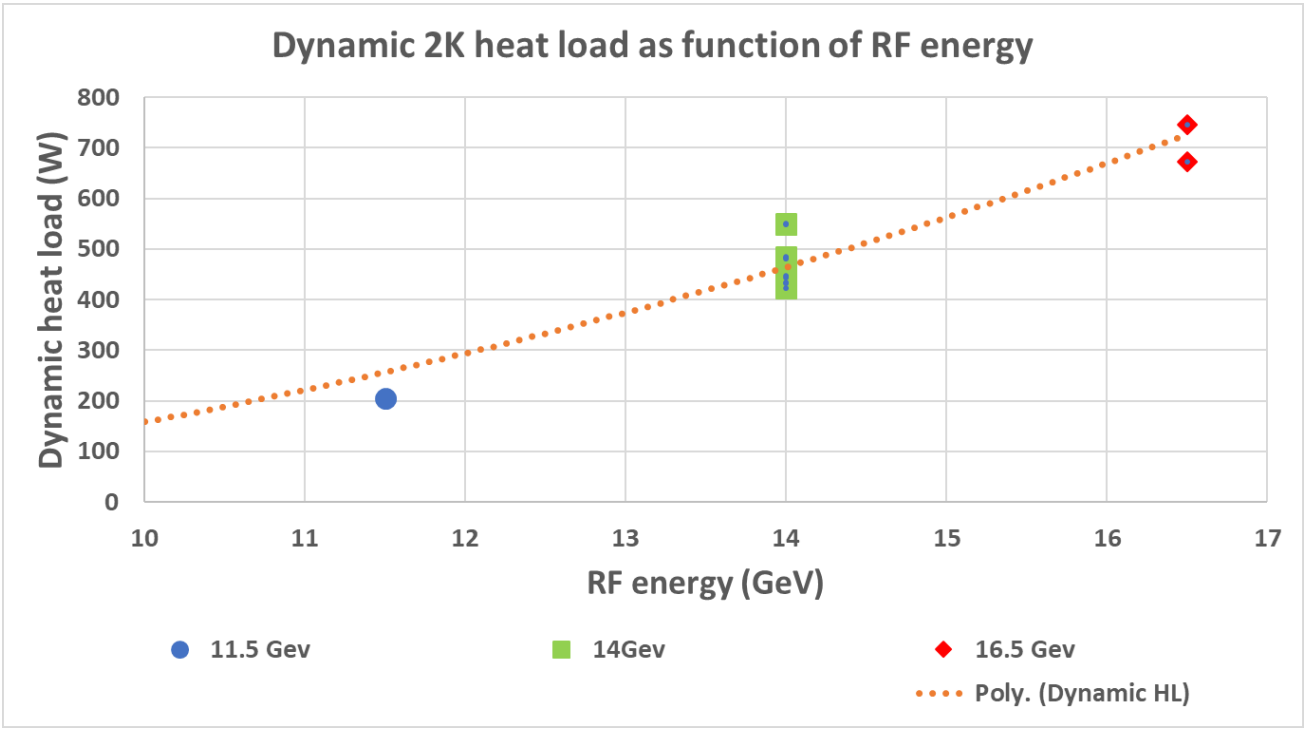




XFEL dynamic heat loads at 2K

Circuit	Dynamic HL at various RF energy (XTL)		
	11.5 GeV	14 GeV	16.5 GeV
2 K	200 W	470 W	700 W





2 K Heat load per cryomodule (CM)

XFEL Linac

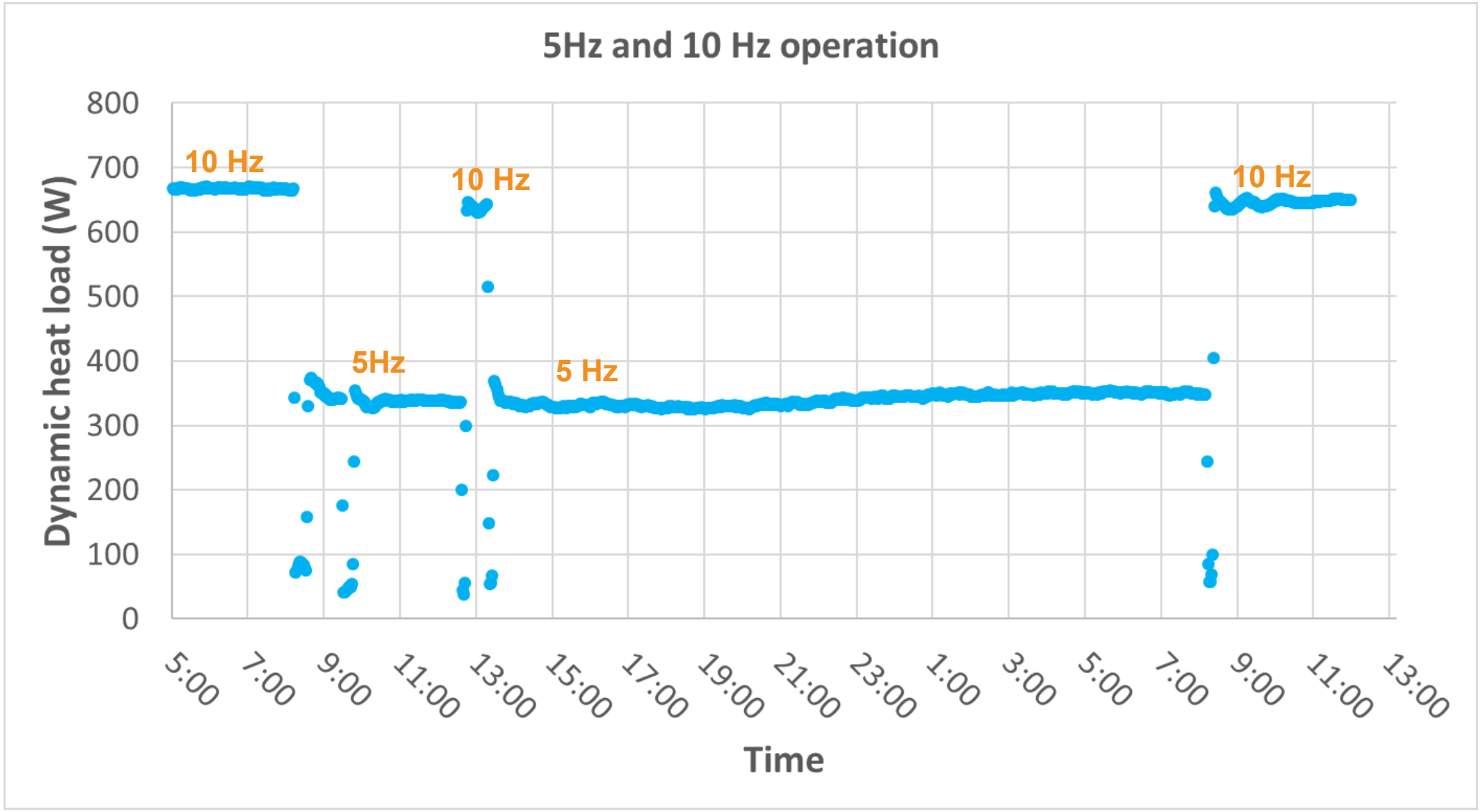
Circuit	Average static HL / CM (W)	Average dynamic HL / CM (W)		
		11.5 GeV	14 GeV	16.5 GeV
2 K	**4.4***	**2.1**	**4.9**	**7.3**

* Isothermal heat load per cryomodule without 2K forward and 2K return line

- Uncertainty related to heat loads calculation is expected to be around +**10 %**
  - Measurement uncertainty due to instrumentation inaccuracy and measurement methods
  - e.g. due to leaky valves

Heat loads during repetition rate test: 5Hz and 10Hz

Comparison of heat loads (17.01.2023 – 18.01.2023)



Summary

Static and dynamic heat loads

Static and dynamic heat loads measured at XLVB for entire XFEL Linac (Including TL, FC&EC, SCB)

Circuit	Average static HL (W)	Average dynamic HL (W)		
		11.5 GeV	14 GeV	16.5 GeV
40-80 K	9800	1700	2300	3200
5-8 K	800	n.a.	140	210
2 K	587	200	470	700

- TL = Transfer Lines (XLTL1-3, 2KF, 2KR)
- FC & EC = Feed and End caps
- SCB = String connection boxes

XFEL Linac Heat load per cryomodule (CM)

Circuit	Average static HL / CM (W)	Average dynamic HL / CM (W)		
		11.5 GeV	14 GeV	16.5 GeV
40-80 K	102.1	17.7	24	33.3
5-8 K	8.3	n.a	1.45	2.2
2 K	4.4*	2.1	4.9	7.3

Uncertainty around +10 %

* Isothermal heat load per cryomodule without 2K forward and 2K return line

Thank you

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