# CW operation characteristics of the spare Eu-XFEL third harmonic cryomodule

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HOMSC2025 Workshop, Hamburg, 06-08.10.2025

European XFEL

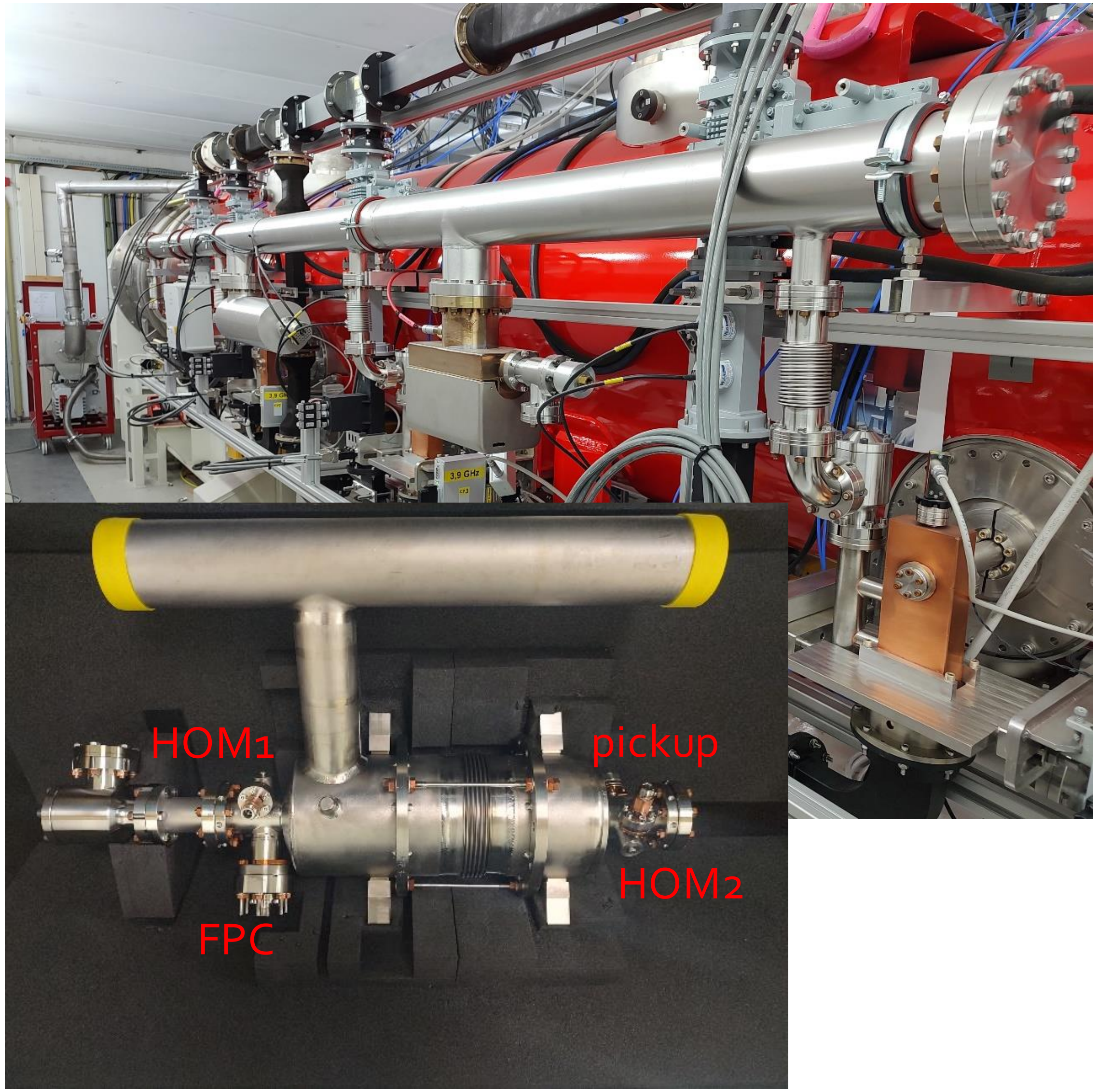
DESY.

# Outline

- 3.9 GHz (spare) cryomodule for the Eu-XFEL - parameters
- 3.9 GHz cavities / cryomodules test
  - SINGLE CAVITY tests in vertical cryostat (2016-17)
  - MODULE PULSE MODE – 0.15 % Duty Cycle (2018)
  - MODULE PULSE MODE – 0.65 % Duty Cycle (2023) -> Eu-XFEL current operating mode
  - MODULE PULSE MODE – 10 % Duty Cycle (2024)
  - MODULE LONG PULSE MODE – 50 % Duty Cycle (2024)
  - MODULE CONTINUOUS WAVE MODE (2023)
- HOM Couplers
  - Maximum gradients
  - HOM1 Coupler Temperature
  - Temperature stability

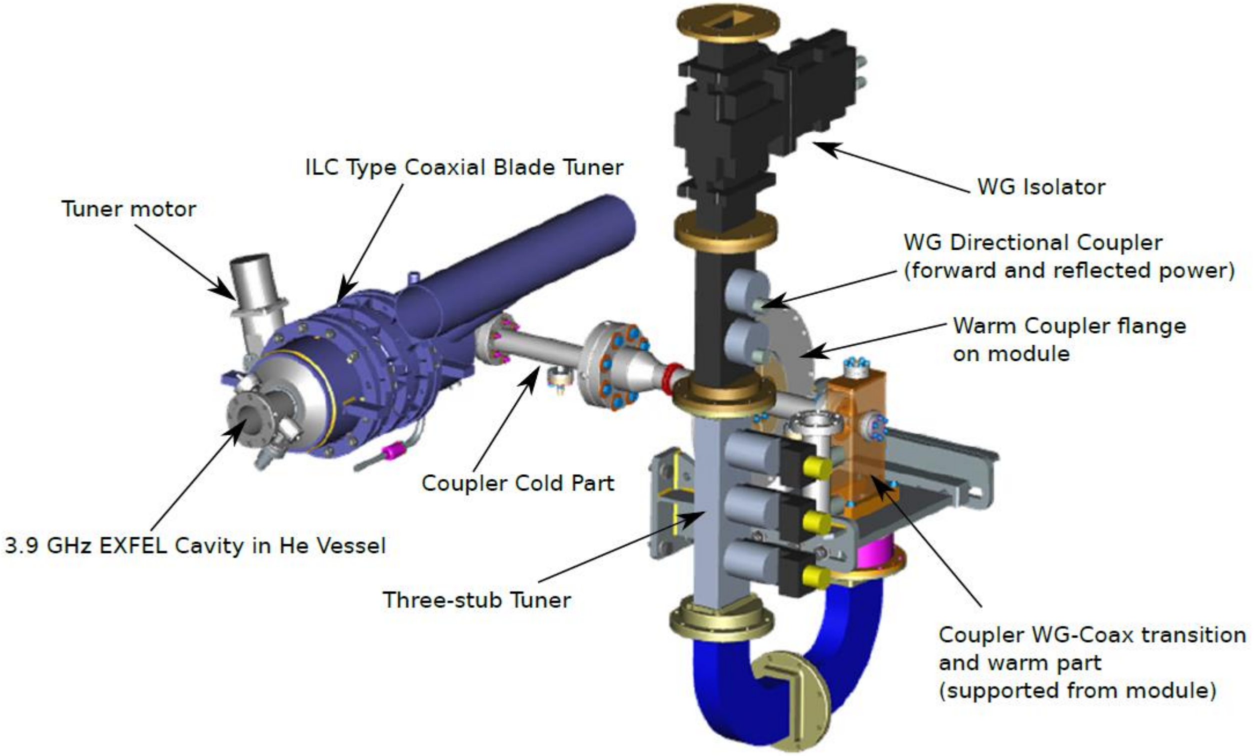
# Third harmonic (spare) Eu-XFEL cavity/cryomodule

| SELECTED PARAMETERS OF 3.9 GHz CAVITIES AND CRYOMODULES | |
|---|---|
| Operating frequency | 3900 MHz |
| Number of cavities per cryomodule | 8 |
| Number of cells per cavity | 9 |
| Active Length of a cavity | 0.346 m |
| R/Q | 750 Ohm |
| G | 280 Ohm |
| Eacc at maximum gain (40 MV) | 14.5 MV/m |
| Ep/Eacc | 2.3 |
| Bp/Eacc | 4.9 mT/(MV/m) |
| Design $Q_0$ | $> 1x10^{9}$ |



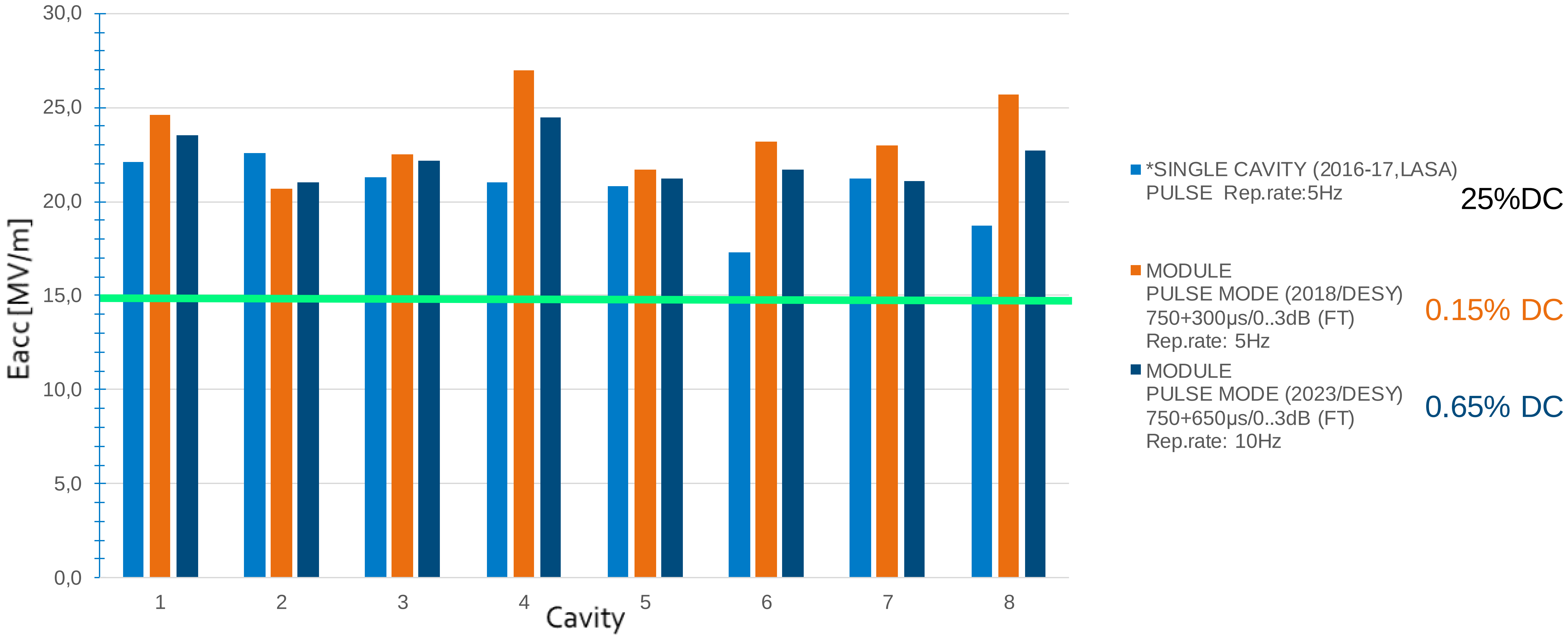
# Third harmonic (spare) Eu-XFEL cavity/cryomodule

| SELECTED PARAMETERS OF 3.9 GHz CAVITIES AND CRYOMODULES | |
|---|---|
| Coupler Type | Coaxial with fixed antenna position |
| Coupling adjustment | 3 stub tuner |
| Tuner Mechanism | Blade Tuner (No piezoelectric transducers) |
| Cold Tuning Range | ≈750 kHz |




Courtesy: C.G. Maiano

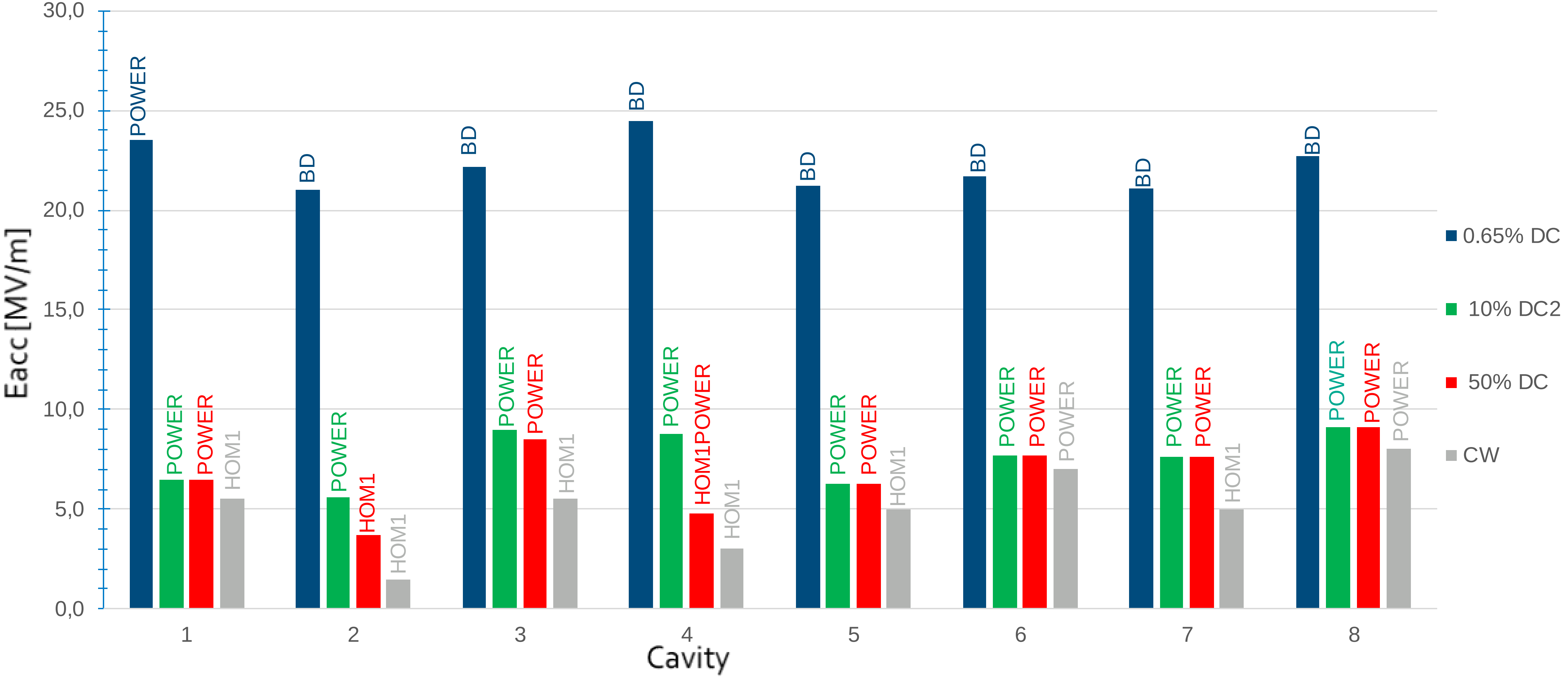
# Comparison: single cavity test vs. cavity in module




**In pulse mode, the results are consistent and exceed the specification.**
**The differences observed are a consequence of another flat-top time and repetition rate.**


*D. Sertore (LASA), P. Pierini (ESS)

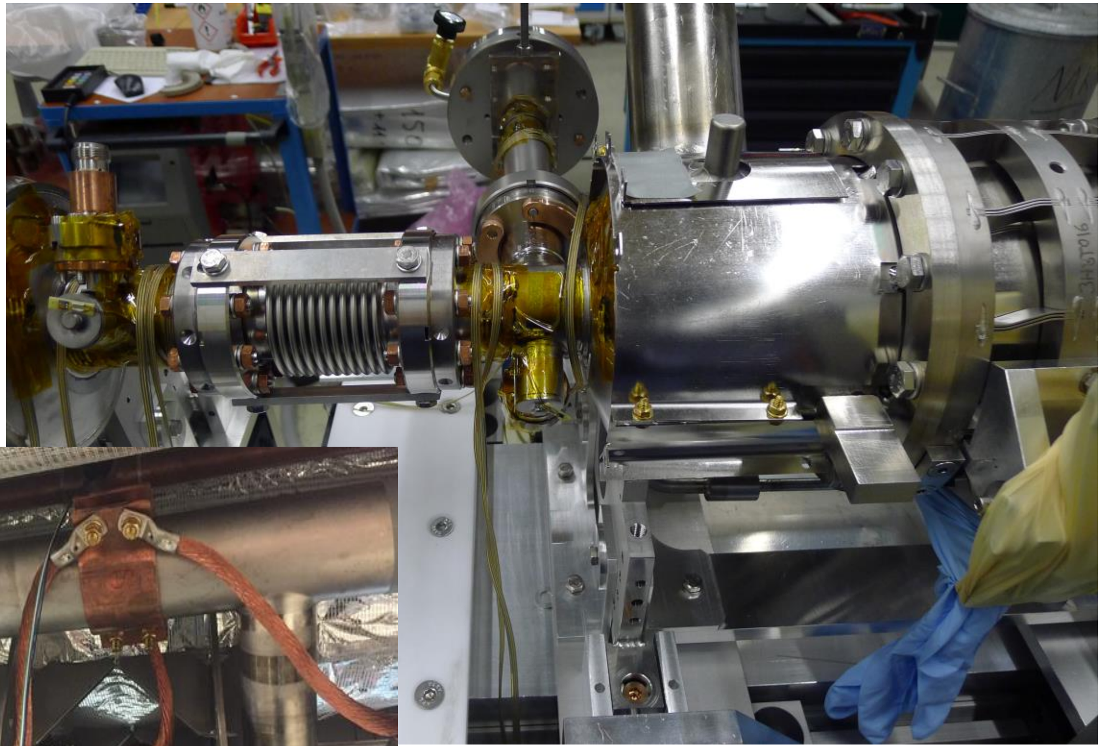
# Comparison (0.65% DC / 10% DC / 50% DC / CW)

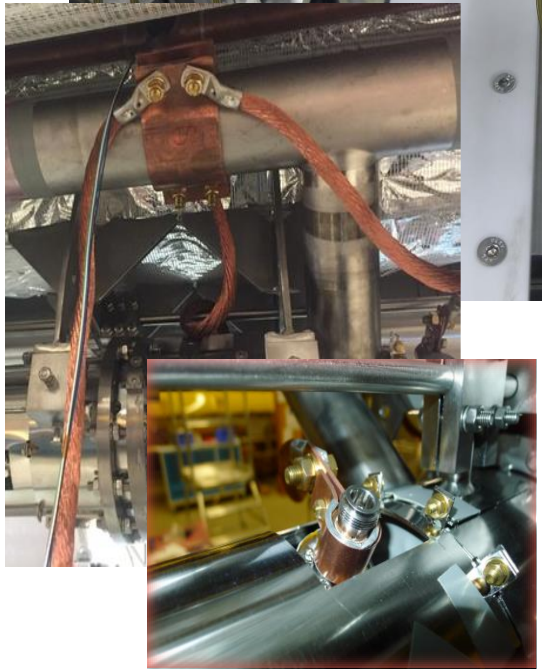


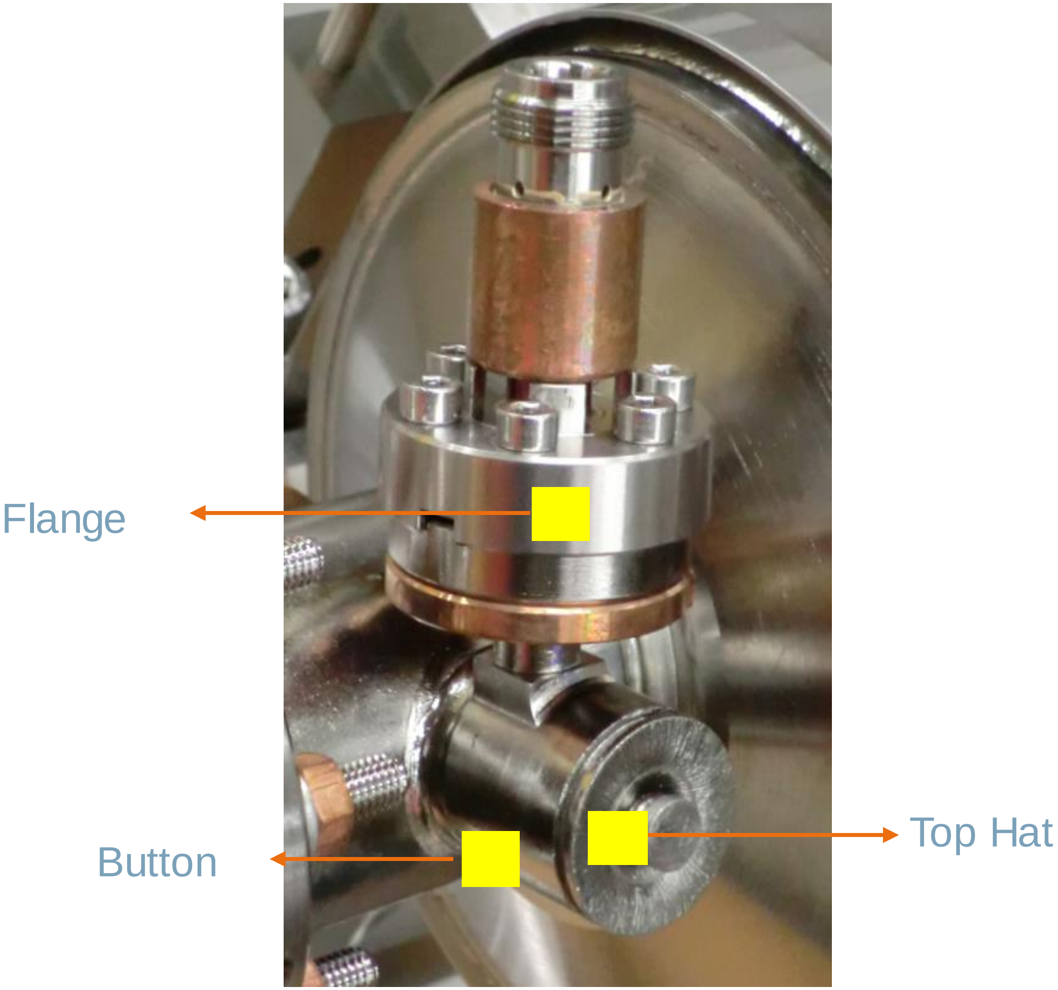

- Limits: cavity quench (BD), amplifier limit (Power), HOM1 overheating (HOM1) and HOM1 Power limit (HOM1POWER)
- Main limitation in the CW mode is a significant rise of the temperature at the first HOM coupler.

# HOM1 coupler overheating

## Temperature measurement








- Temperature sensors connected to both HOM couplers
- Sensors located at „Button" & „Top Hat" showed similar temperature (±0.5K)
- Temperature measured in „Flange" is 2-3K higher (without RF )
- At „ Flange" an avalanche increase of the temperature occurs - >which was limiting Eacc

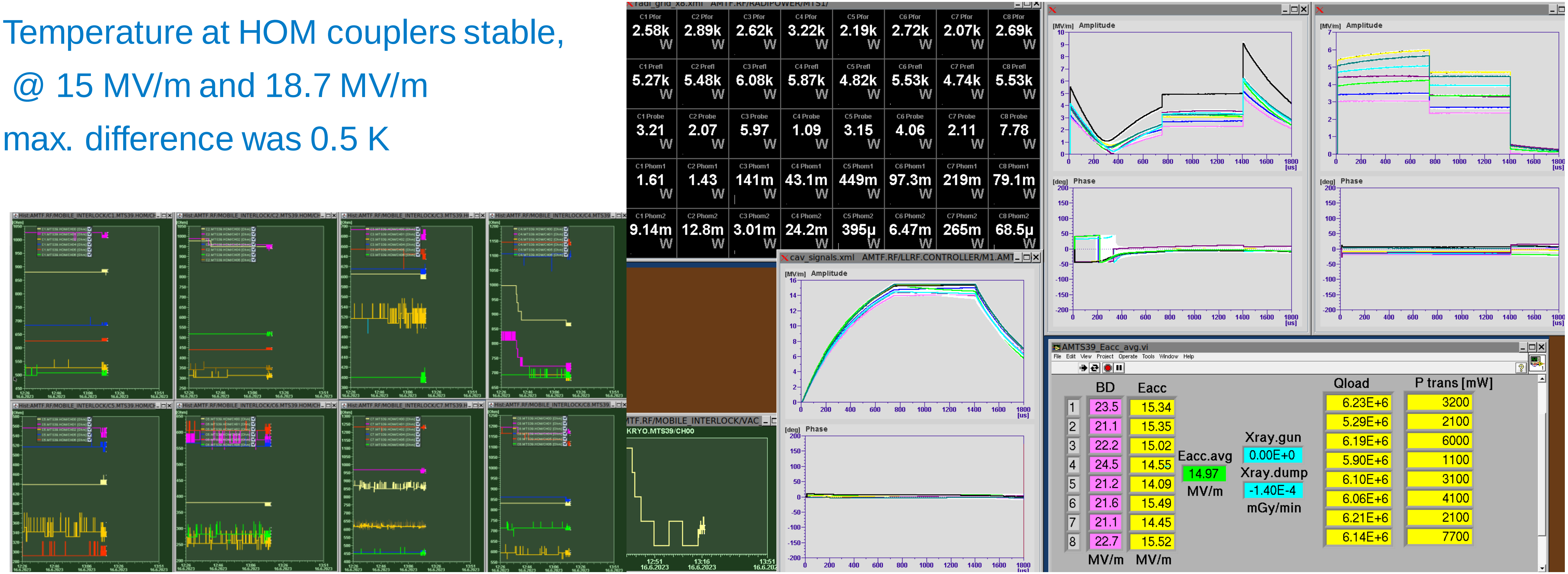
# HOM1 coupler overheating

## DURING THE HEAT LOADS measurement with 0.65% DC

Temperature at HOM couplers stable,

@ 15 MV/m and 18.7 MV/m

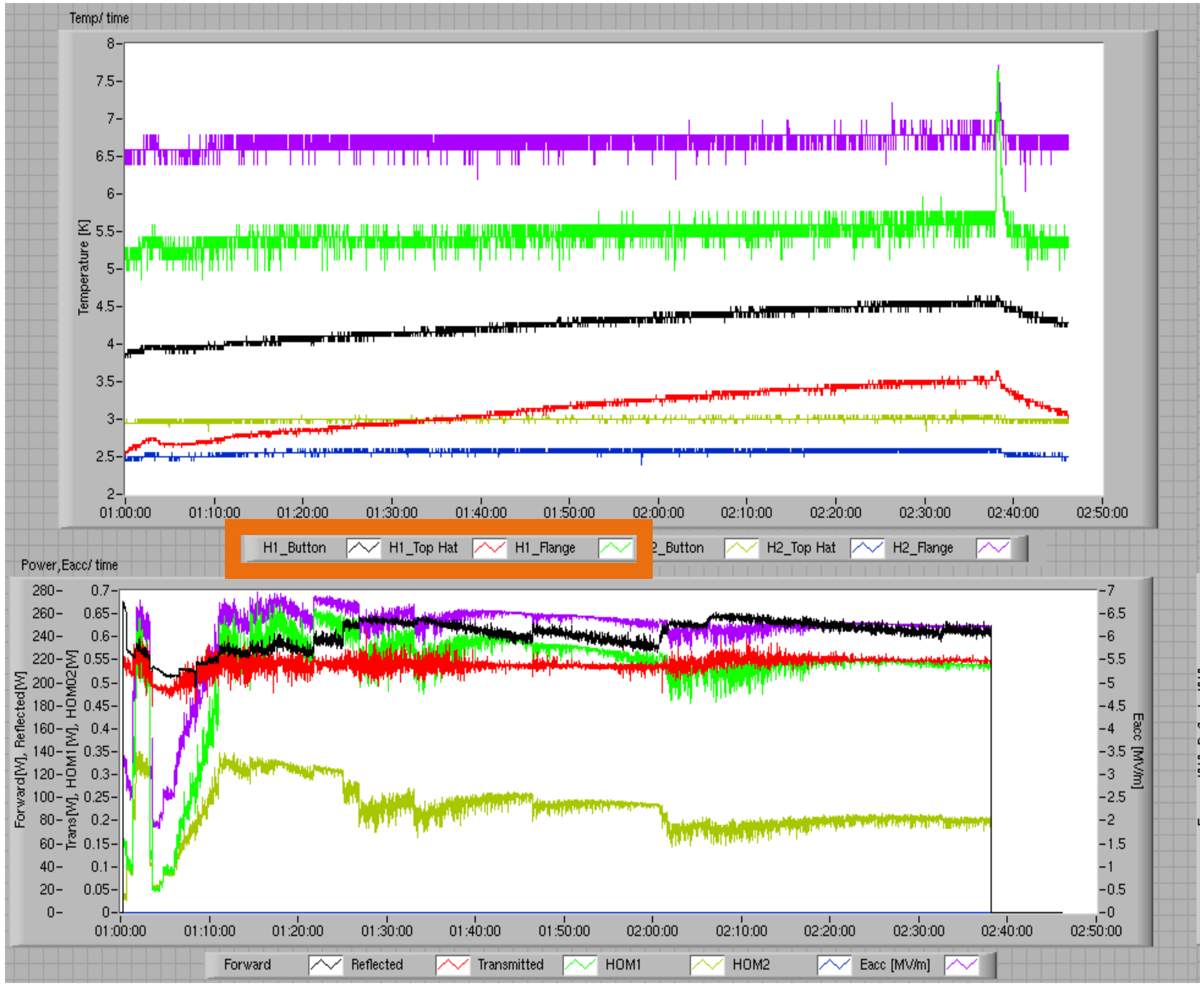
max. difference was 0.5 K



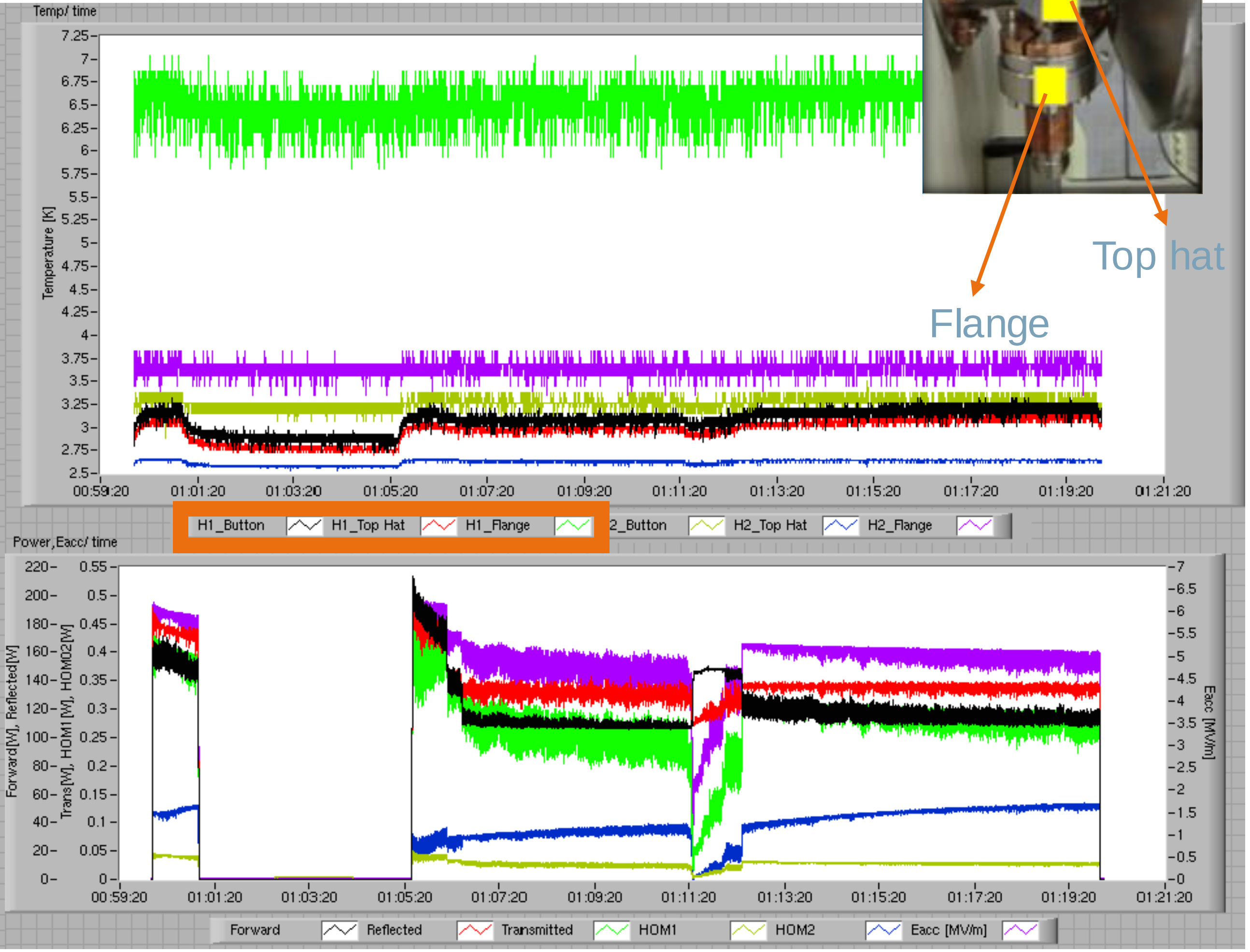

No overheating in 0.65% DC (Eu-XFEL current operating mode).

# HOM couplers overheating in CW mode

Cavity 1 6 MV/m
Temperature increase at HOM1




Cavity 7 5 MV/m
Stable temperatures




An avalange-like increase in temperature was observed only at the first HOM coupler!

# HOM couplers overheating

Check of the quality factors and
**rejection filter tuning**

| Cavity | Qtrans | QHOM1 | QHOM2 |
| --- | --- | --- | --- |
| 1 | 1.2e+10 | 2.2e+10 | 6.1e+12 |
| 2 | 1.9e+10 | 3.6e+10 | 3.1e+12 |
| 3 | 7.0e+09 | 1.6e+11 | 7.9e+12 |
| 4 | 4.2e+10 | 1.1e+12 | 1.6e+12 |
| 5 | 1.1e+10 | 7.1e+10 | 6.7e+13 |
| 6 | 9.5e+9 | 2.7e+11 | 6.1e+12 |
| 7 | 1.4e+10 | 1.4e+11 | 9.9e+10 |
| 8 | 5.9e+09 | 4.6e+11 | 1.2e+13 |

CONTINUOUS WAVE MODE (2023)

| CAVITY | LIMIT [MV/m] | REASON |
| --- | --- | --- |
| 1 | 5.5 | HOM1 overheating |
| 2 | 1.5 | HOM1 overheating |
| 3 | 5.5 | HOM1 overheating |
| 4 | 3.0 | HOM1 overheating |
| 5 | 5.0 | HOM1 overheating |
| 6 | 7.0 | POWER |
| 7 | 5.0 | HOM1 overheating |
| 8 | 8.0 | POWER |

$$Q_x = \frac{(Eacc * L)^2}{(R/Q) * P_x}$$

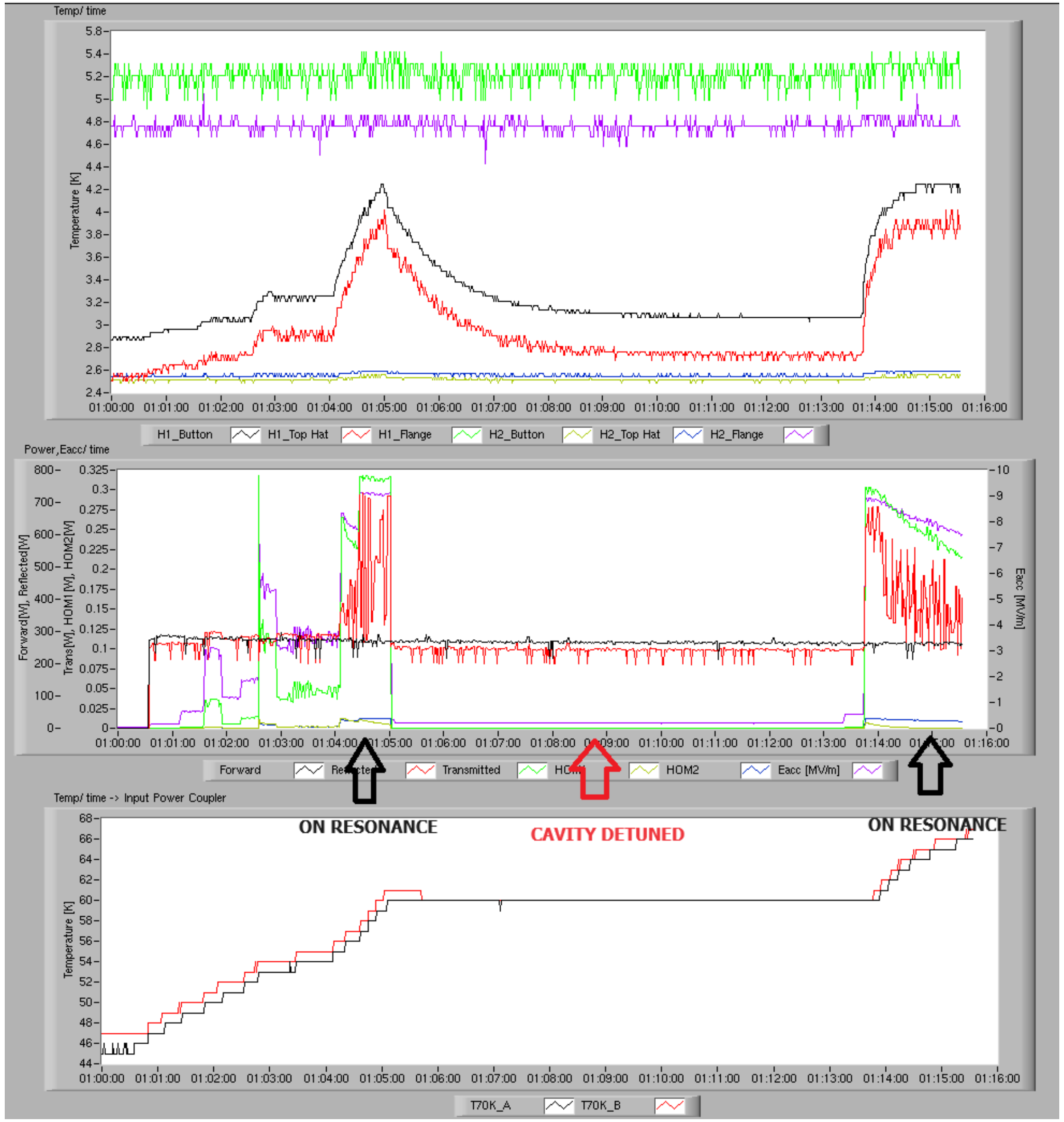
No clear correlation was found between overheating and rejection filter tuning.

HOM2 notch filter better tuned than HOM1 notch filter.

# Maximum power coupled through the HOM1 coupler (1W) @ 50% DC


Frequent tuning required. Detuning increase as the temperature increase. Continuous increase of the power coupled through the HOM1 coupler.

# Heating of HOM1 coupler only when cavity tuned




- **Increase of the temperatures only when the cavity is on the resonance.**
- **Change of the temperature on FPC affects loaded quality factor and the detuning.**
- **Frequent tuning required**

# Modification of HOM coupler/feedthrough at LCLSII / SHINE

**The main finding of the investigations was that inadequate thermal conduction from the inner conductor of the HOM antenna causes localized magnetic-field-induced heating of the niobium tip, which can initiate a quench.**

- Reduced penetration of antenna inside HOM to reduce heating
- Increased wall thickness on the top of HOM can to prevent cracks and vacuum leak
- Modified length of HOM feedthrough

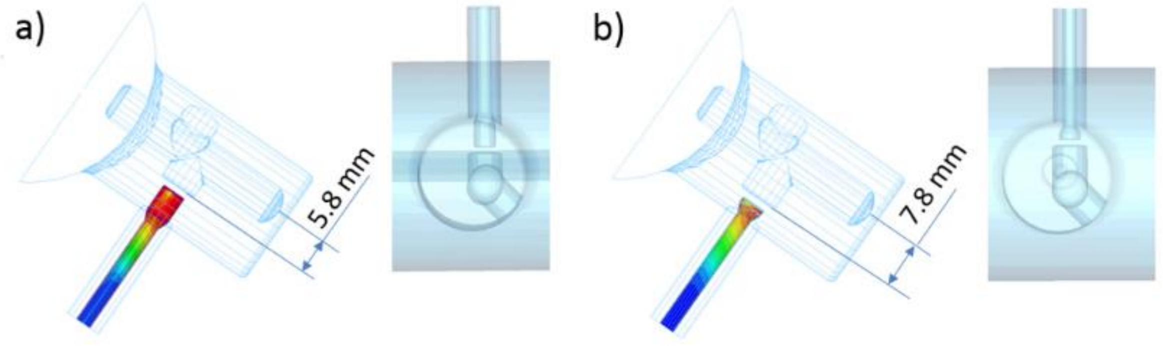



Figure 1: Modifications of the HOM coupler for the 3.9 GHz cavity: a) XFEL design and b) LCLS-II design.

Courtesy: A. Lunin, N. Solyak

*N. Solyak „3.9GHz components design”
*A. Lunin ”Redesign of the end group in the 3.9 GHz lcls-II cavity”
*Yu-Xin Zhang „RF design optimization for the SHINE 3.9 GHz cavity”

# Average accelerating gradient for for different pulse lengths

| | Specification | Single cavity 25% DC | MODULE 0.15 % DC | MODULE 0.65% DC | MODULE 10% DC | MODULE 50% DC | MODULE CW |
|---|---|---|---|---|---|---|---|
| Eacc [MV/m] | 14.5 | 20.6 | 23.5 | 22.0 | 7.2 | 6.5 | 4.7 |
| LIMIT | | BD | BD/Power | BD/Power | Power | Power (HOM1 for cavity 2 and 4) | HOM1 (Power for cavity 6 and 8 |
| AMPLIFIER | | SSA 1 | Klystron | Klystron | SSA 2 | SSA 2 | SSA 2 |

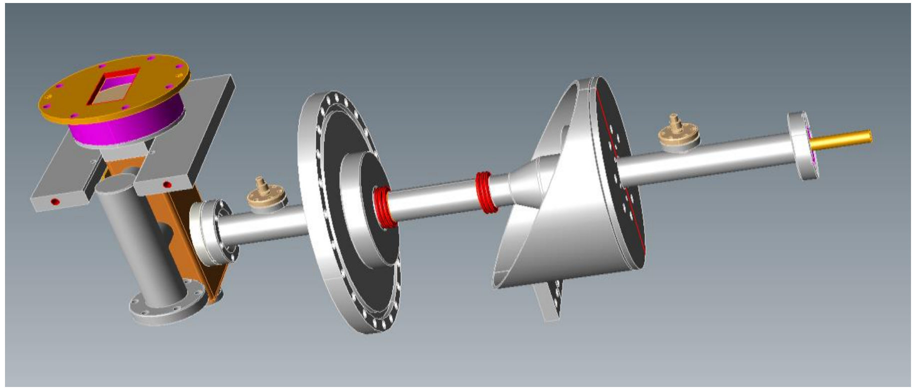
# Summary

- The module behavior in the pulse mode exceeds the specification.
- Maximum accelerating gradient in the CW mode is much lower than in the pulse mode.
- Main limitation in the CW mode is an overheating of the <u>first</u> HOM coupler.
- A modified design of HOM Couplers is required for the CW mode upgrade of the Eu-XFEL.

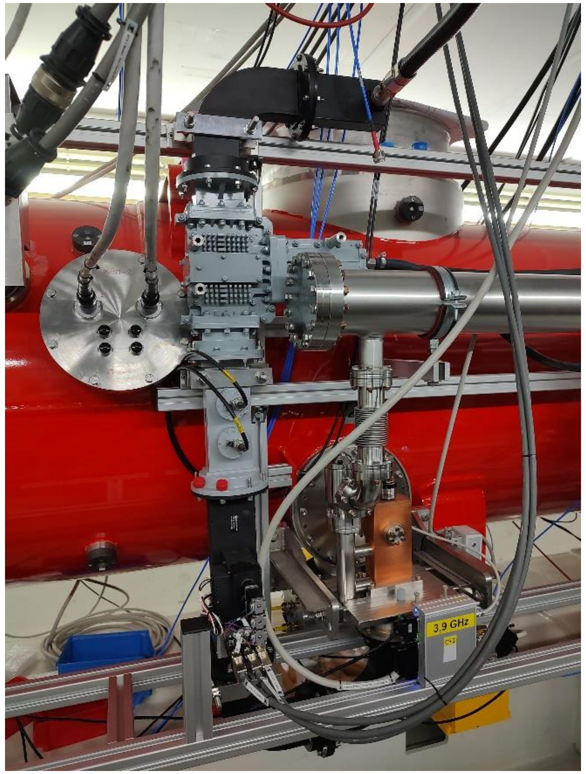
# Qload min / max

FIXED Fundamental Power Coupler (FPC)

Measurement done by adjusting the 3 stub tuners.



Courtesy:N. Solyak




| Cavity | QL min | QL max |
|---|---|---|
| 1 | 1.34e+06 | 9.38e+06 |
| 2 | 5.53e+05 | 5.29e+06 |
| 3 | 1.67e+06 | 1.16e+07 |
| 4 | 3.68e+06 | 1.64e+07 |
| 5 | 8.91e+05 | 1.69e+07 |
| 6 | 9.42e+05 | 1.93e+07 |
| 7 | 2.31e+06 | 8.24e+06 |
| 8 | 1.88e+06 | 1.58e+07 |

Tuning of the loaded quality factor done with 3 stub tuners.