CW Cryomodule testing at DESY - differences from pulsed tests

J. Sekutowicz

DESY/SLAC

Outline

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3. Differences in parameters and in cool-down
4. Complementarity of results
5. Example of the sp and cw/lp test
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1. Introduction

General remarks

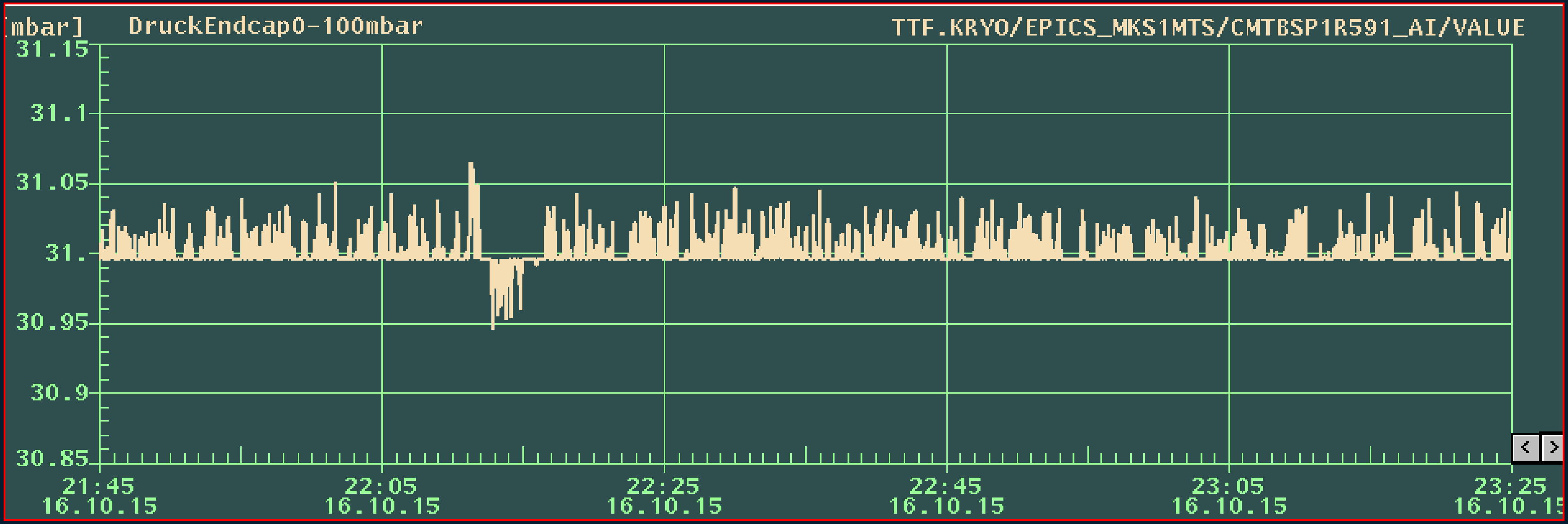
- We test E-XFEL CMs (prototypes and production) at CMTB in the cw/lp mode always after they were conditioned and tested in the sp mode.

- The cw/lp operation is mainly:
  - to measure dynamic heat load vs Eacc and/or DF
  - to test performance of the FPC- and HOM couplers for these modes
  - to test performance of the slow and fast tuners for these modes
  - to study and adapt the E-XFEL LLRF for cw/lp operation
  - to study cool-down procedures and their impact on Qo.

- In this presentation, recent (preliminary!) test results for the XM4 cryomodule are used as an example.

1. Introduction, cont.

- Many previous and XM4 cw/lp tests could be conducted without LLRF (RF- and piezo feedback). It was and is possible because:
  - Helium pressure at CMTB is very stable, usually better than ±50µBar, which cause small Δf of ±2.5 Hz.



  - Microphonics caused by vacuum pumps is has been significantly suppressed by placing the pumps on a foam mat.

2. Differences in the test equipment

	Short pulse	Long pulse	CW
RF-source	10 MW Klystron	105 kW IOT	
Peak Pin/cavity	-> 750 kW	-> 12 kW	
Duty Factor	-> 1.4%	-> 100%	
Rep. rate	10 Hz	usually 1Hz	-
Max. RF-pulse length	1.4 ms	-> cw	

The same RF-distributions system is used for both tubes. The RF-power at CMTB is theoretically “equally” distributed between cavities.

2. Differences in the test equipment, cont.

- LLRF used for the sp test is a copy of what will be used for the E-XFEL accelerator.

  The LLRF used for the cw/lp operation is in an R&D stage.

  - The R&D LLRF program has been initiated at DESY to integrate the RF- and piezo feedback, and to compensate the Lorentz Force Detuning at loaded Qs ≥ 10^7. This seems complicated especially for the lp mode.

  - The goal is to reach the sp mode spec for the vector sum stability; 10^{-4} and 0.01° for amplitude and phase respectively.

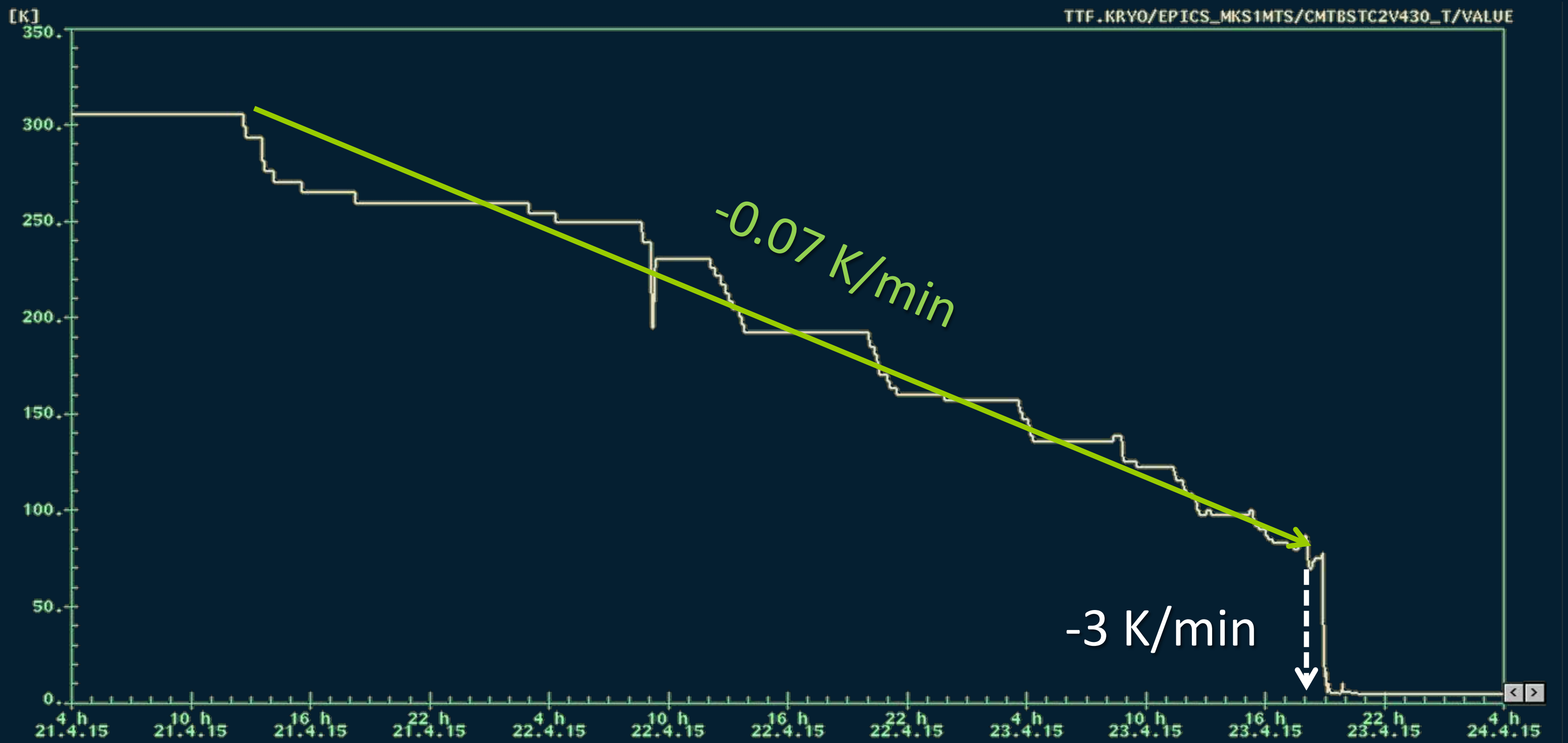
Loaded Q and T

	Short pulse	Long pulse	CW
Q_{load}	$3.0\text{-}4.6 \cdot 10^6$	$1.5 \cdot 10^7$	$1.5 \cdot 10^7$
Δf_{3dB}	283 Hz->	87 Hz	87 Hz
Filling time	->750 µs	up to 150 ms	-
Flattop	650 µs	up to 850 ms	-
Max Eacc	-> 40 MV/m	19 MV/m	15 MV/m
Max LFD	-1600 Hz	-361 Hz	-225 Hz
Temperature	2K	1.8 K and 2 K	

2. Differences in parameters and in cool-down

Cool-down:

- For sp test, we always apply the "fast" cool-down DESY procedure
- For cw/lp tests, we apply first the fast cool-down. Slow cool-down was performed for LG cavities (XM-3) and is planned for XM4.



4. Complementarity of the results

Short pulse tests

- High available P_{in} allows for FPCs and cavities conditioning, and to determine max Eacc for every cavity.
- Low Q_{load} makes sp tests less sensitive to microphonics.
- LFD needs more attention due to high gradients.
- Calorimetric measurements of Qo is challenging, because the dynamic cryo-loads are rather small (few watts).

Long pulse/cw tests

- High Q_{load} makes tests more sensitive to microphonics (observed in the past).
- Low Pin (few kWs), in general, does not cause an electron activity in FPCs nor quenches in cavities. Less radiation.
- Measurements of cryoload gives reasonable results already at low Eacc.

5. Example of the sp and cw/lp test

XM4 is the first production cryomodule installed at CMTB for cw/lp test.

Courtesy D. Kostin)

It was fast cooled down in May 2015:

- 300 K->80 K with rate - 0.07 K/min
- 80 K-> 4.2 K with rate - 3 K/min

XM4, cont.

- It houses 8 TESLA cavities made of polycrystalline Nb.
- All HOM couplers are equipped with high conduction feedthroughs.
- During tests at AMTF in 2014, four FPCs (Cav# 1, 2, 3, 4) were heavily overheated and burned. This happened due to improper assembly of inner conductors of warm parts . All 4 warm parts have been exchanged.
- Two HOM couplers have detuned filters:

Cav#1 HOM2 Qext = 6.9E10

Cav#2 HOM1 Qext = 1.4E10 !!

Short pulse test (D. Kostin)

cavity	FE onset [MV/m]	$X>10^{-2}$ [MV/m]	$E_{acc.max}$ [MV/m]	$P_{in.max}$ [kW]	$X_{max.G}$ [mGy/min]	$X_{max.D}$ [mGy/min]	Limit	E_{oper} [MV/m]	Op.Limit
1.CAV00626	33.5	33.5	33.5	420	0.3	10^{-5}	BD_FE	31.0	PWR
2.CAV00607	32.0	34.8	34.8	530	0.01	10^{-5}	BD_FE	31.0	PWR
3.CAV00556	23.0	—	31.1	390	0.007	10^{-5}	BD_FE	30.6	BD
4.CAV00597	23.0	29.9	34.5	470	0.09	5×10^{-4}	BD_FE	29.9	XRAY
5.CAV00606	36.5	—	39.0	685	0.002	2×10^{-5}	BD_FE	31.0	PWR
6.CAV00621	—	—	24.4	220	—	—	BD	23.9	BD
7.CAV00592	—	—	22.0	180	—	—	BD	21.5	BD
8.CAV00594	30.0	—	35.1	480	4×10^{-4}	4×10^{-4}	BD_FE	31	PWR

- Cav#1 P_{HOM2} = **17 W at E_{acc} = 33.5 MV/m**, Cav#2 P_{HOM1} = **90 W at E_{acc} = 34.8 MV/m,** which for DF of ca. 1% does not lead to thermal issue in the cable, but may cause a discharge in connectors.
- The lowest X-ray onset is at 23 MV/m. The lowest quench gradient is at 22 MV/m.

Short pulse test, cont.

2 K	static	dynamic		comment
<E_{acc}> [MV/m]		15	20.5	
Cryo-losses [W]	8 ÷ 9	1.01	2.02	all 8 cavities tuned
Q_0		2.4×10^{10}	2.3×10^{10}	

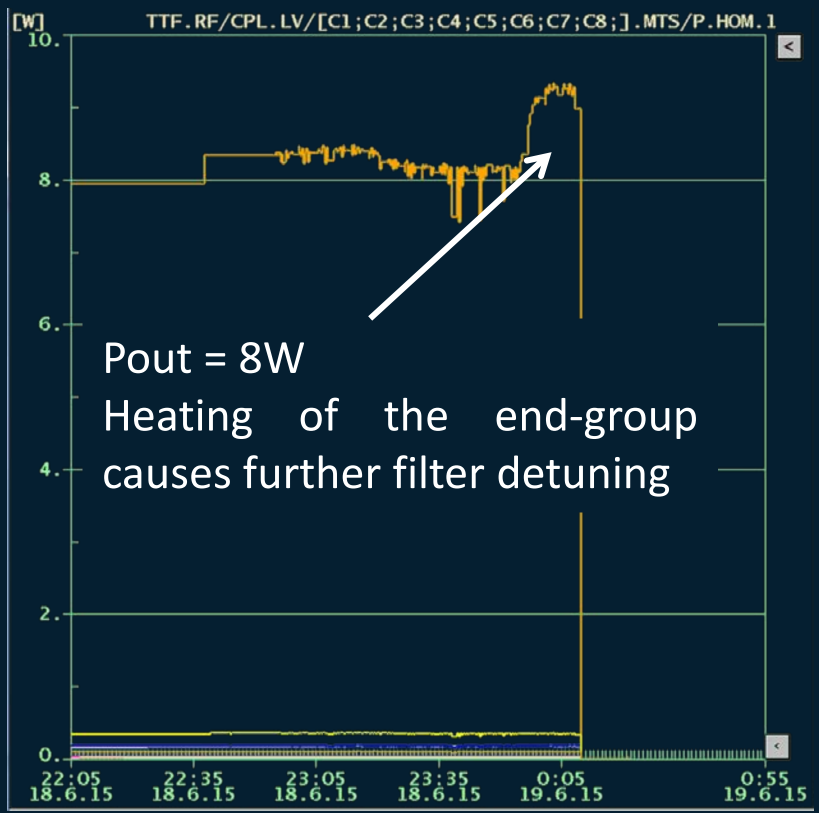
Q_o seems high (small heat load)

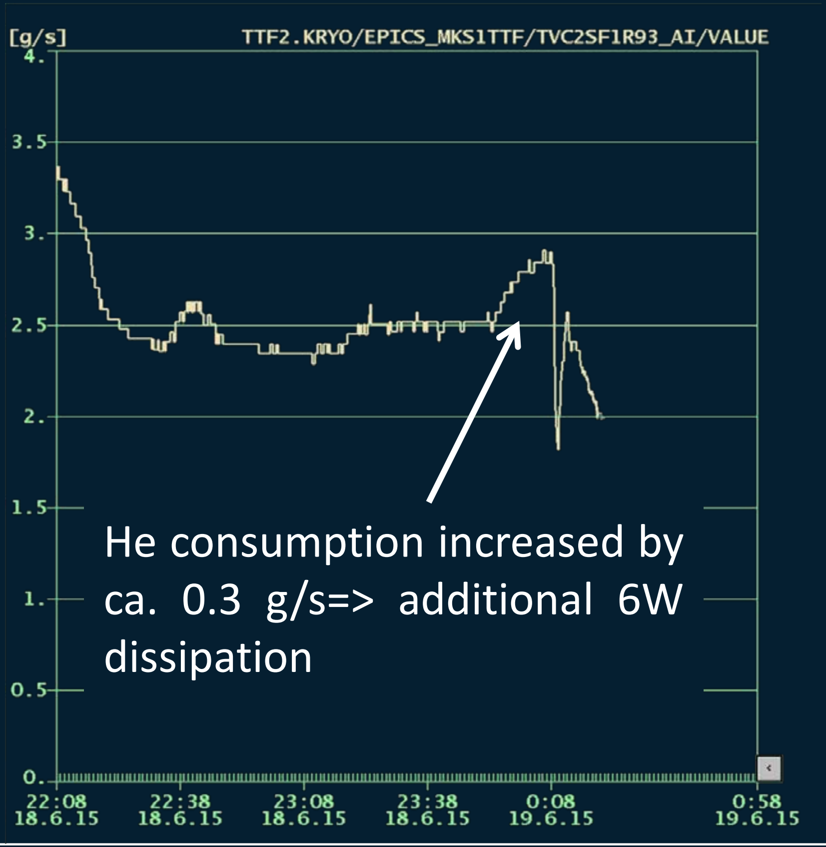
These values do not match the vertical test values, which are lower.

cw/lp test

I. Thermal issues, not detected in the sp test

- Heating of the HOM1 coupler of cavity 2.
  Cav#2 can operate stable cw up to 8 MV/m. Heating of the end group at 11+MV/m:

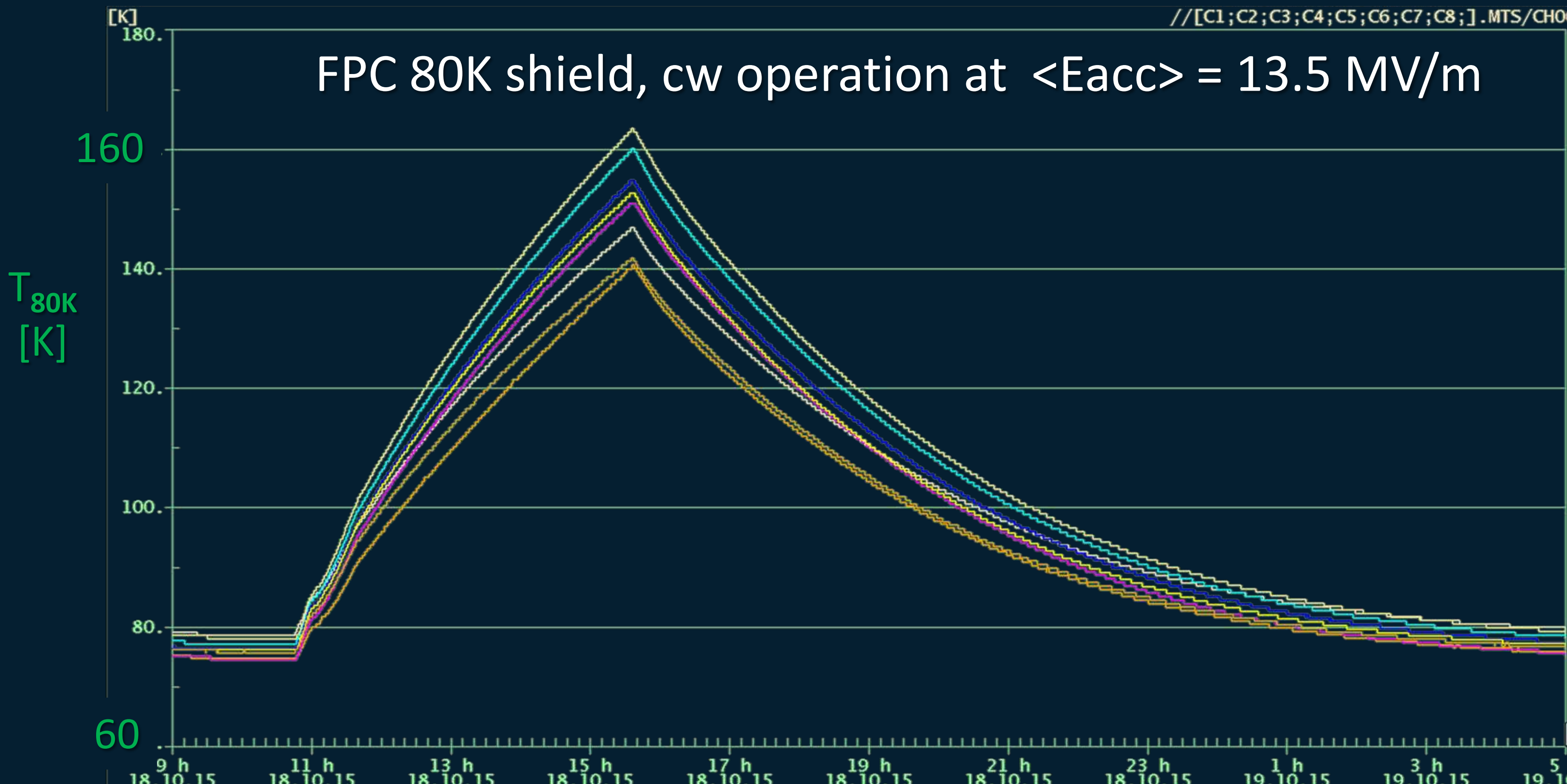




cw/lp test, cont.

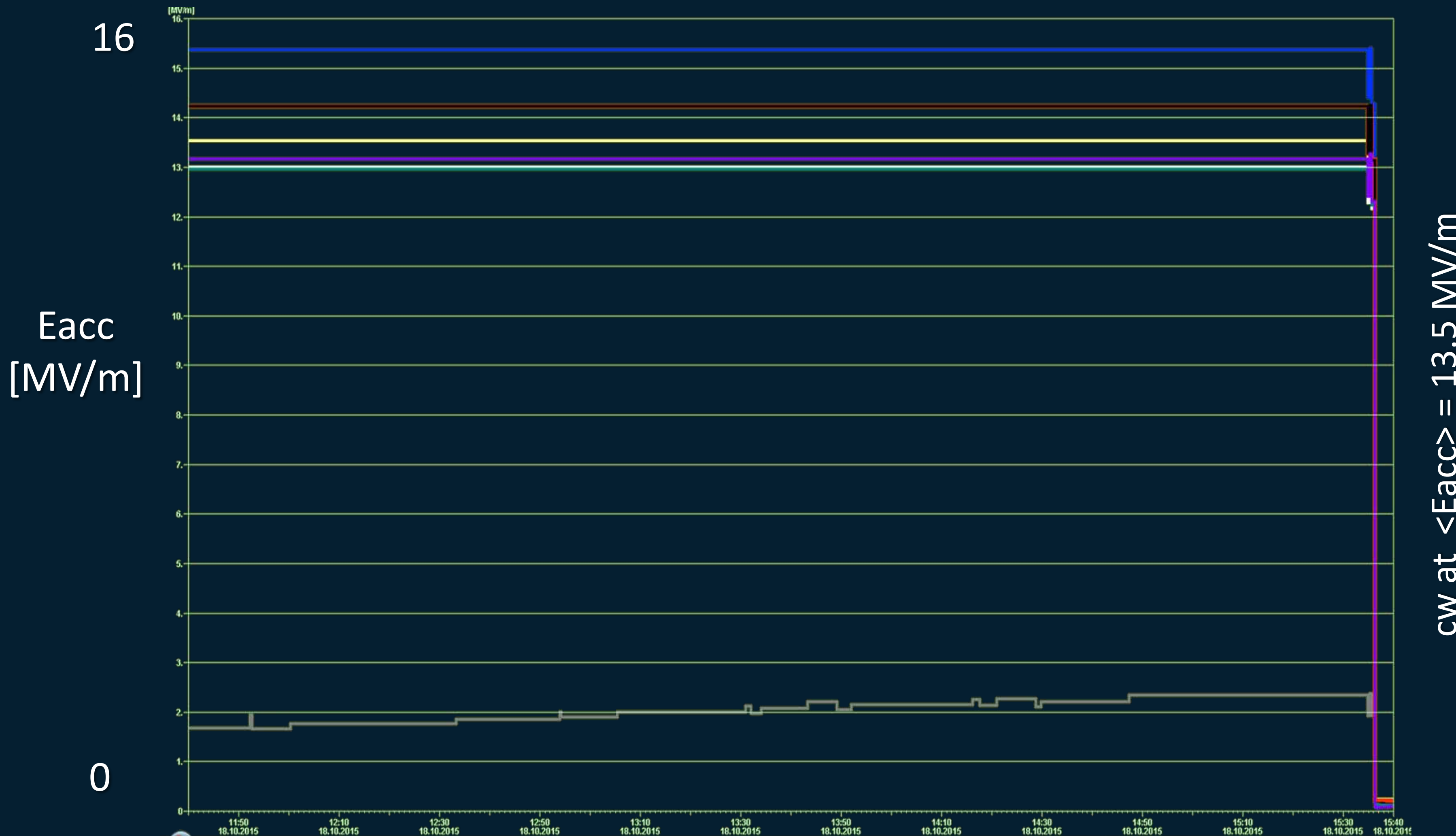
II. Thermal issues, not detected in the sp test

- Heating of FPCs causing change of Q_{load}. It is a very slow thermal process:



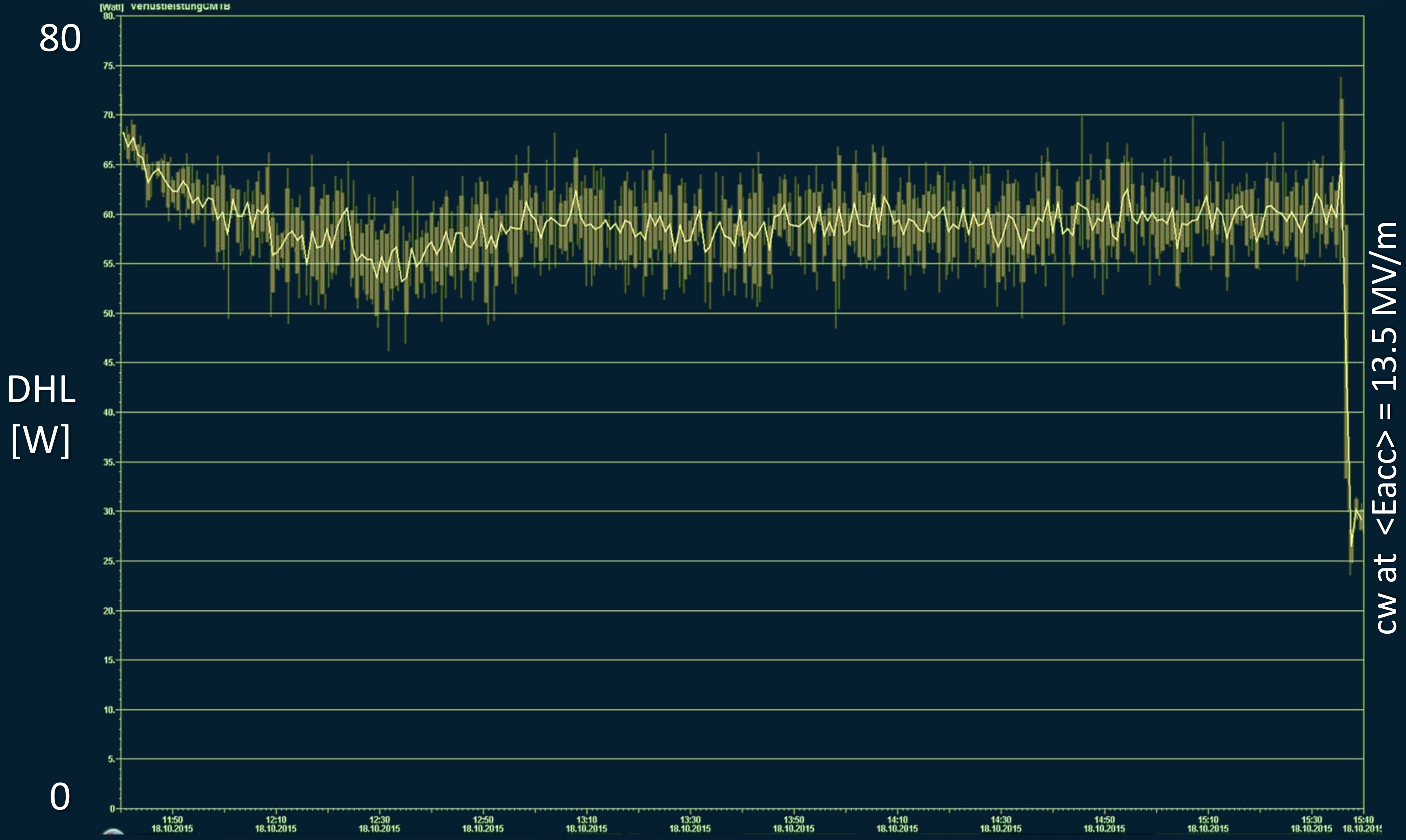
cw/lp test, cont.

- Over more than 4 hours Eacc stays constant



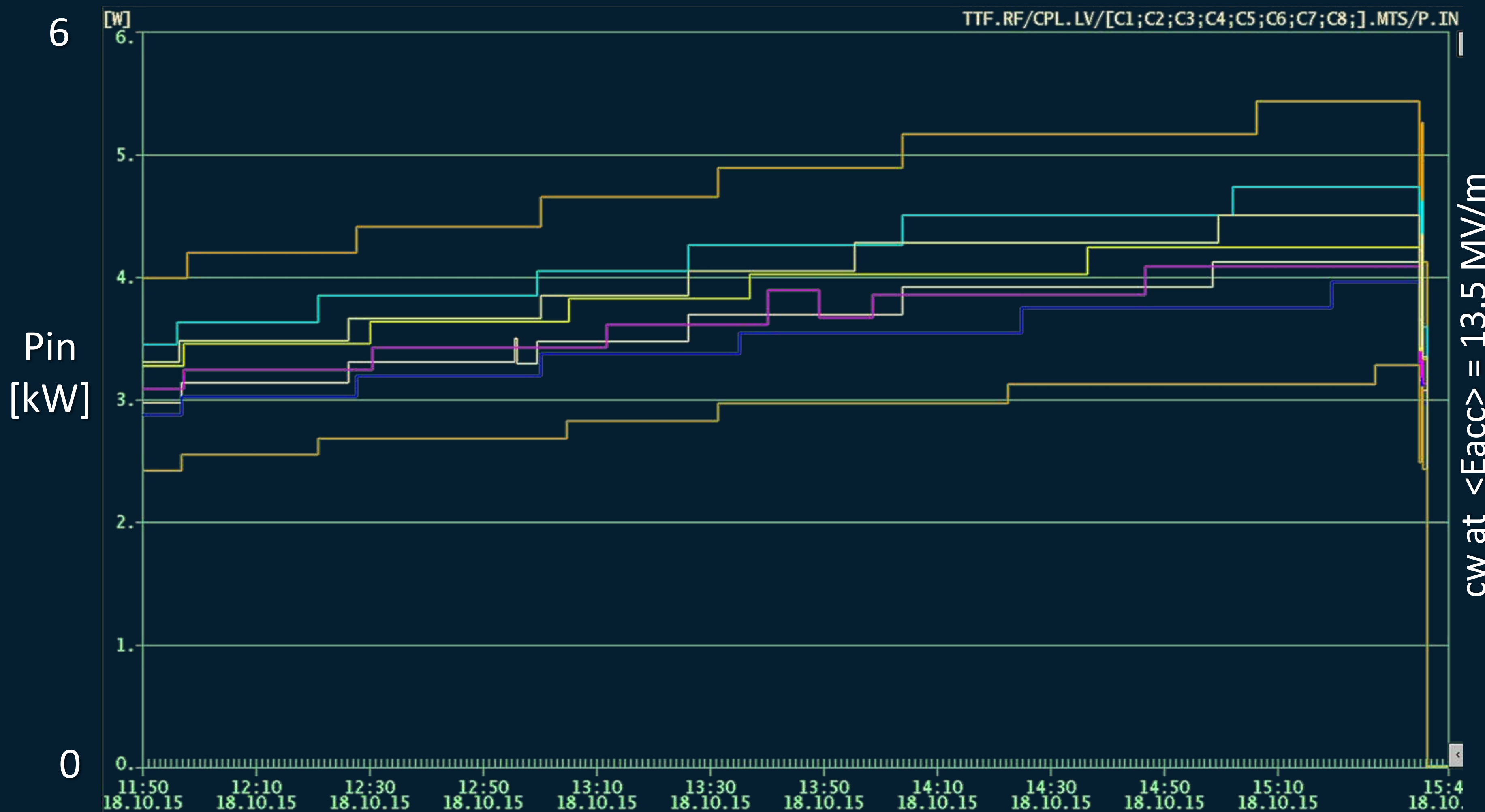
cw/lp test, cont.

- Dynamic Heat Load (DHL) stays constant



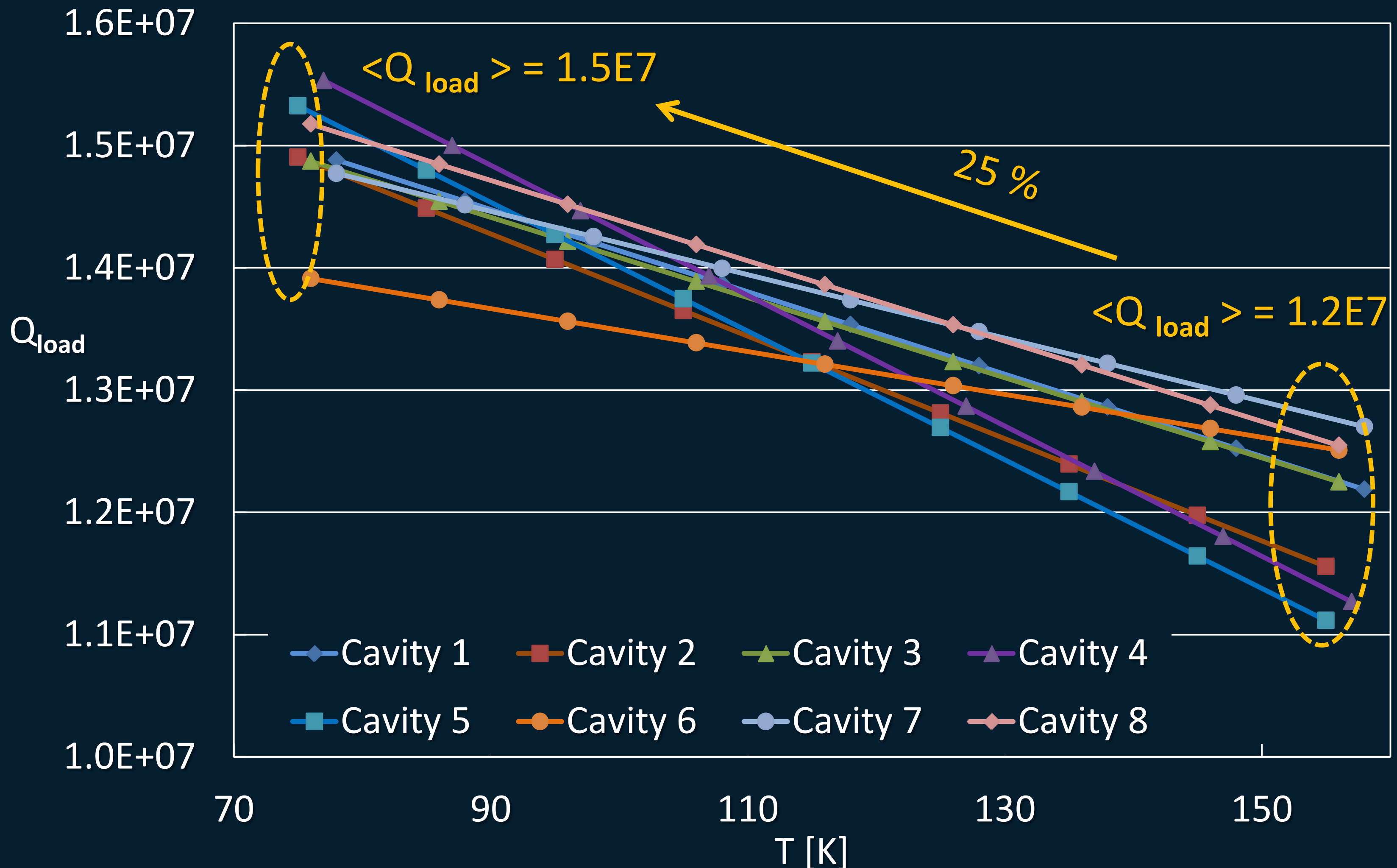
cw/lp test,cont.

- The input power Pin increased significantly (by ca. 30%) during the 4h test:



cw/lp test, cont.

- Linear approximation of the measured Q_{load} vs T_{80K}



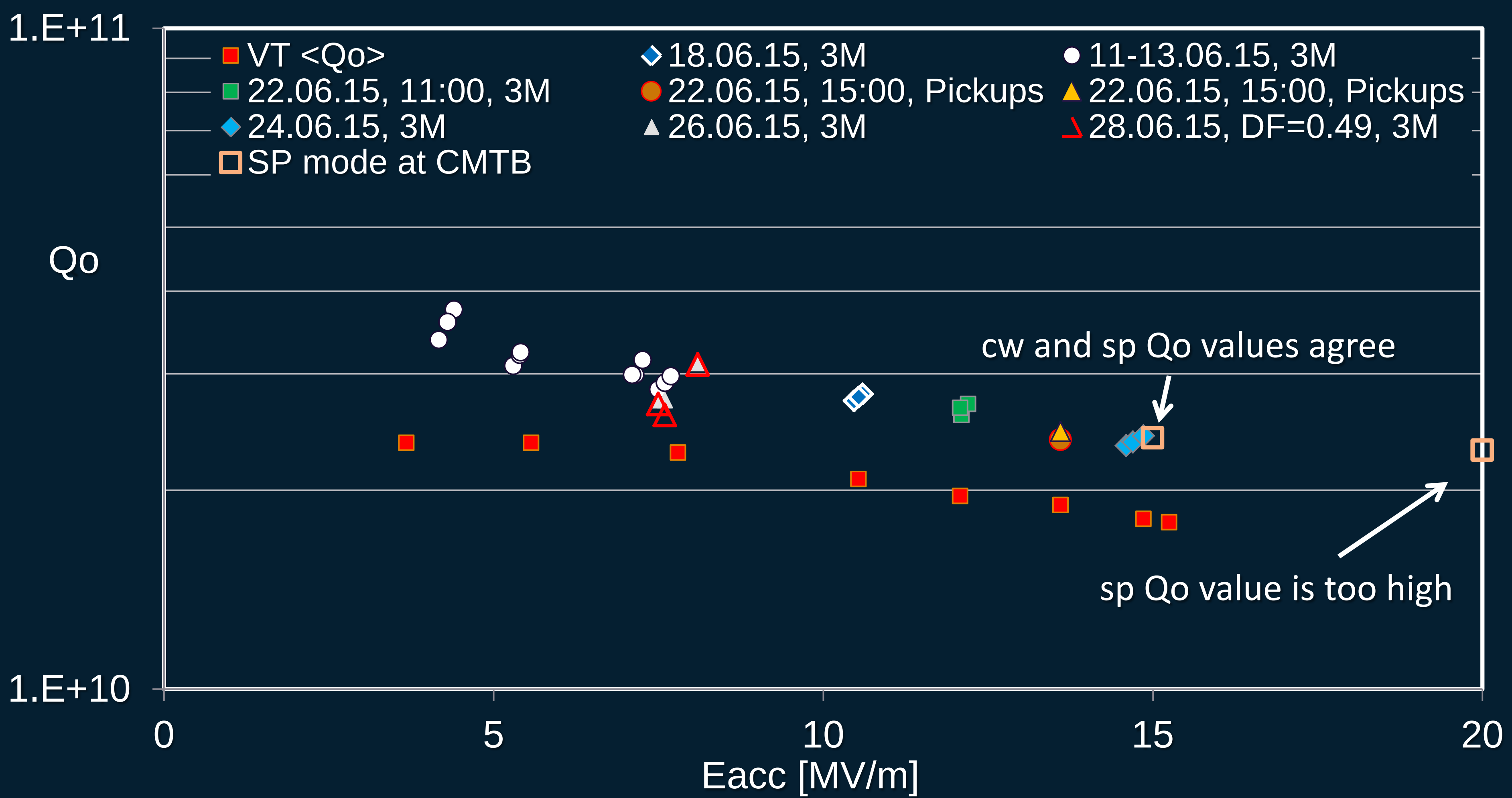
cw/lp test, cont.

III. Qo test; general remarks

- For the cw/lp operation, measured DHL is significantly larger than the DHL measured in sp mode, for which the DF is ~ 1%.
- In general, the accuracy of the calorimetric measured DHL is better for large DHL.
- In most runs 3 methods were used to determine E_{acc} (to minimize an error):
  a. Read out of pickups which were calibrated for the sp mode.
  b. P_{in} for each cavity (the directivity of the waveguide couplers is crucial).
  c. IOT output power (P_{IOT}*0.95/8).
- We calibrated with the end-cup heater the DHL measurement. The calibration has confirmed values measured when RF was on.

cw/lp test, cont.

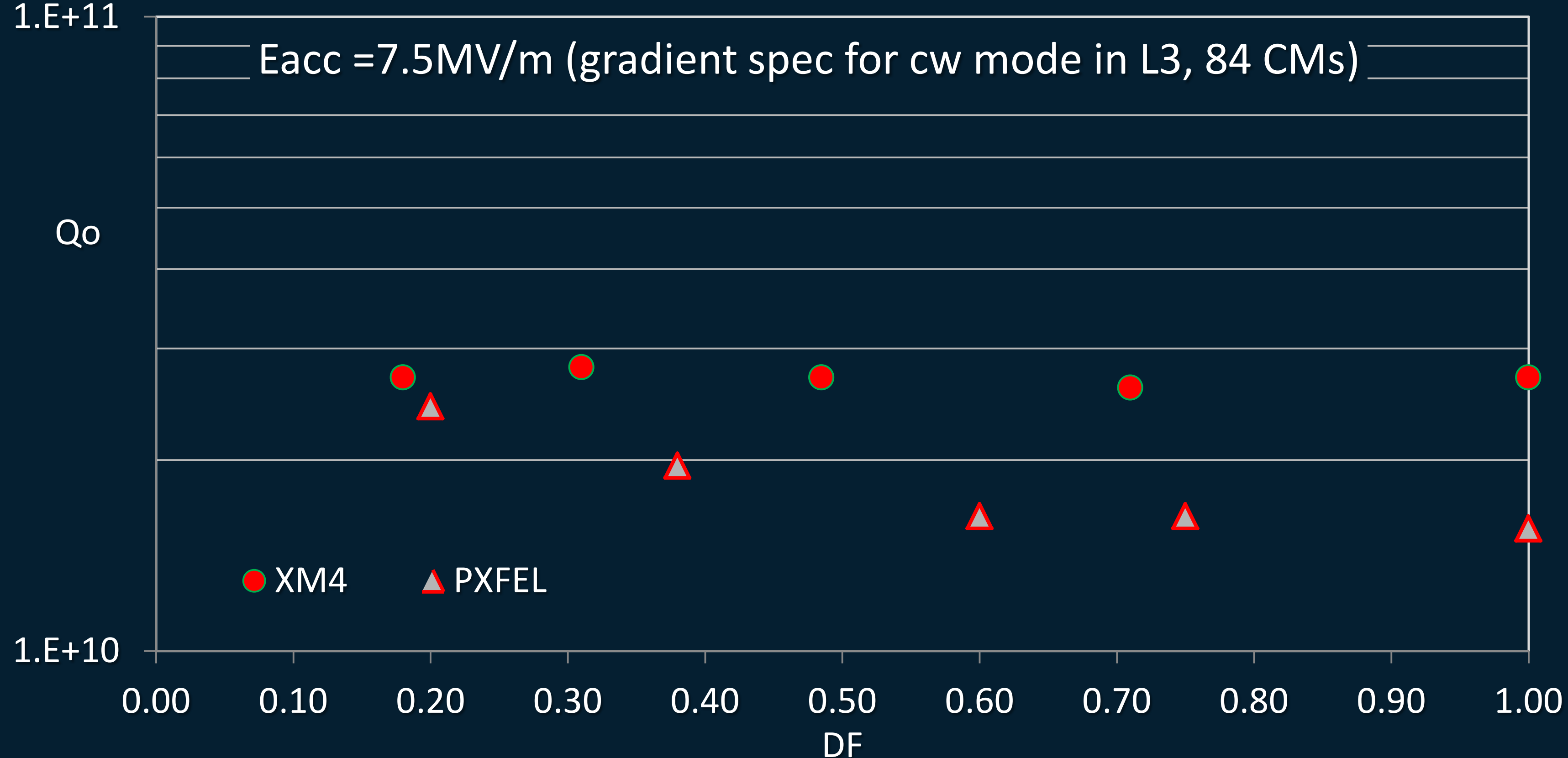
Qo vs. Eacc



cw/lp test, cont.

IV. Indication of the end group heating

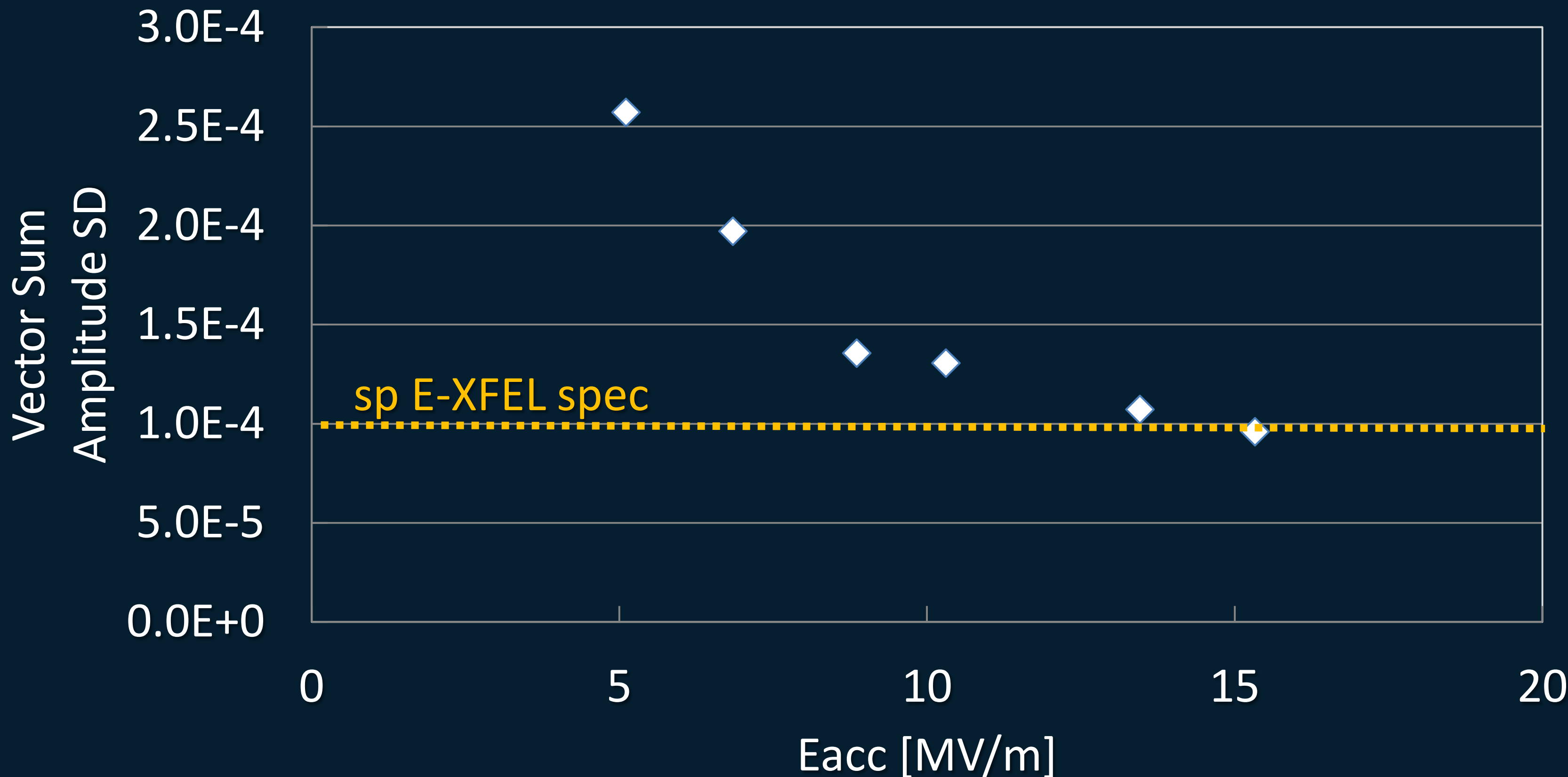
- Production E-XFEL CMs do not have temperature sensors on HOM couplers.
- Test of the Qo vs DF can help to “detect” heating of end groups (a cavity or CM):



cw/lp test, cont.

V. VS amplitude stability vs Eacc for Q_{load} of 1.5E7 (cw mode)

The VS amplitude stability in cw mode has been demonstrated. In this test the RF-feedback, Piezo-bias and Integral part of the piezo-feedback were on.



1. SP and cw/lp tests are complementary and give together more complete picture of a CM performance.

2. E-XFEL CMs are first conditioned and tested with high peak power klystron in SP nominal mode and then thermally conditioned and tested with 105kW IOT in the cw/lp mode.

3. We have observed two thermal issues when a CM operates in cw mode, which may constrain the cw operation of an accelerator:

    a. Heating of FPCs causing Q_{load} drop, which in turn causes that the LLRF rises the input power to keep the gradient, and thus increases the heating. The process can be stopped by remotely adjustable Q_{load} or with "pre-heating" of the FPCs. The latter will need some hours to stabilize thermally the system, after the input power was changed to match new setting e.g. beam current or Eacc.

b. End-group heating caused by HOM coupler which rejection filter is not properly tuned. This can limit the operational gradient of a cavity.

4. Dark current? There is a progress on these measurements. Nick Walker is helping to get the sp AMTF data calibrated. Once the AMTF system will be calibrated, we will install one at CMTB. The remaining open question is the phasing of cavities for the dark current measurement.

5. The statistics DESY has for cw/lp tests is still rather poor, especially for the production CMs, but for the E-XFEL cavities the statistics is 8 times better, so observed phenomena and performance of cavities are more sound.

I want to express my gratitude to all Colleagues supporting and contributing to the cw/lp experiments:

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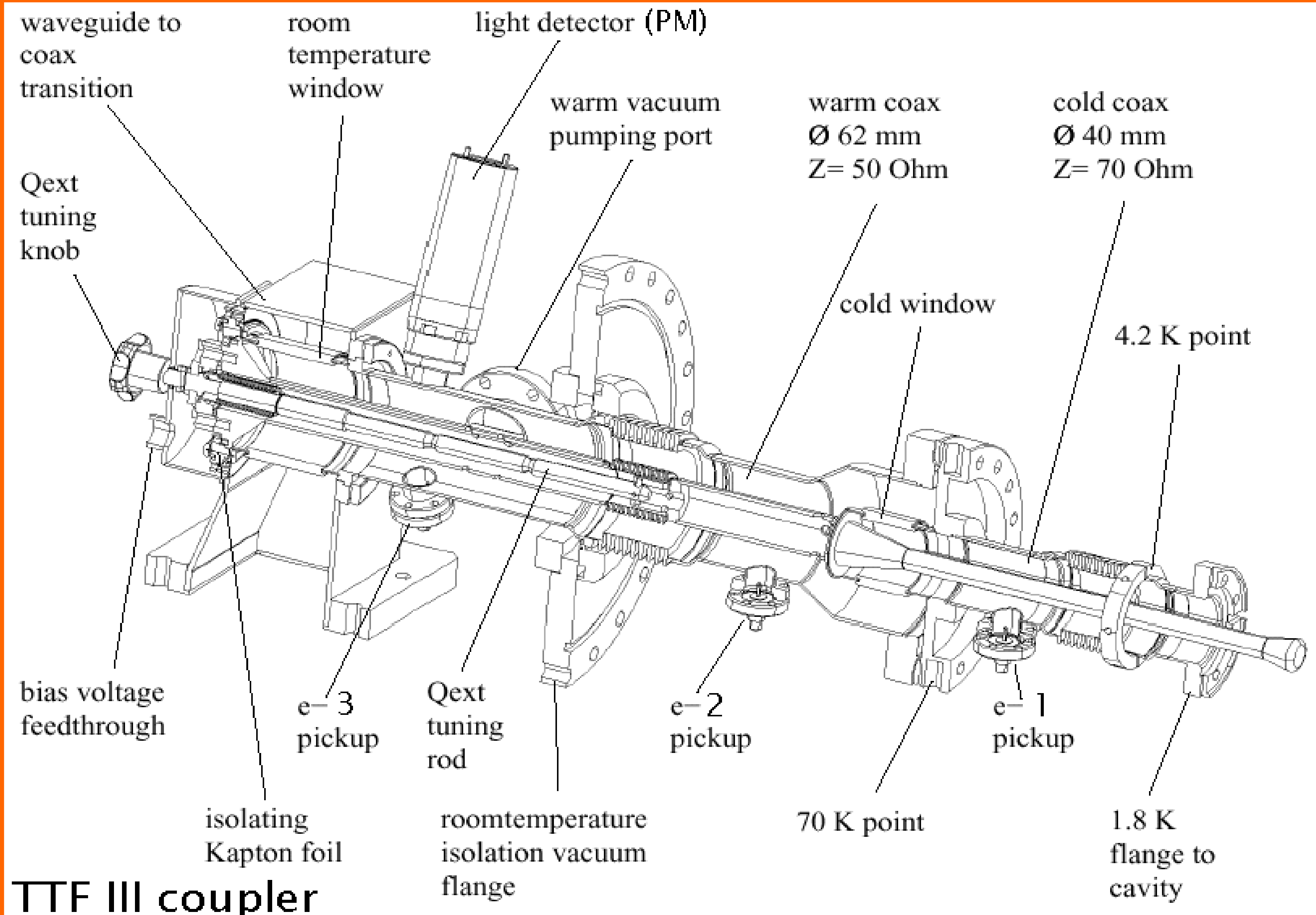
WUT: K. Czuba

IFJ-PAN: S. Myalski, M. Sienkiewicz, M. Wiencek

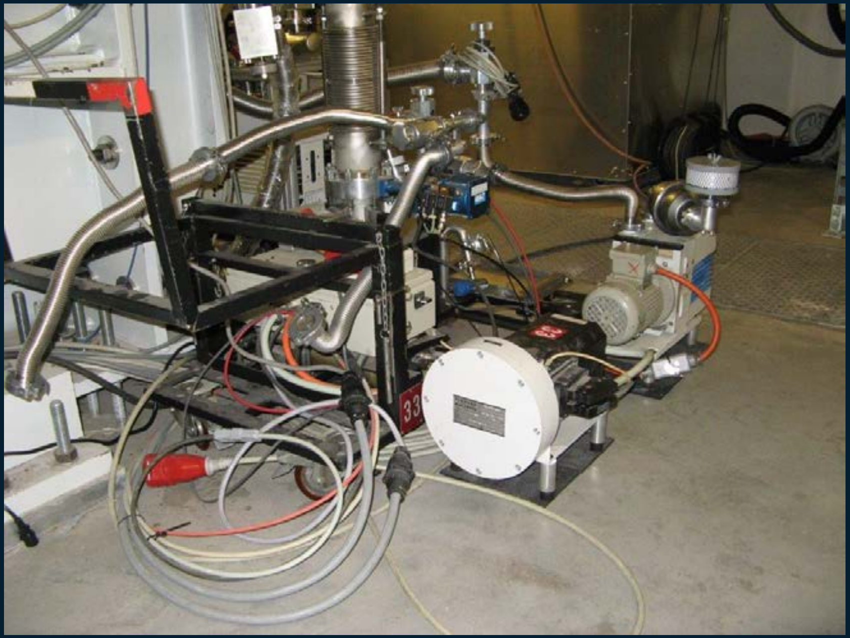
Thank you for your attention

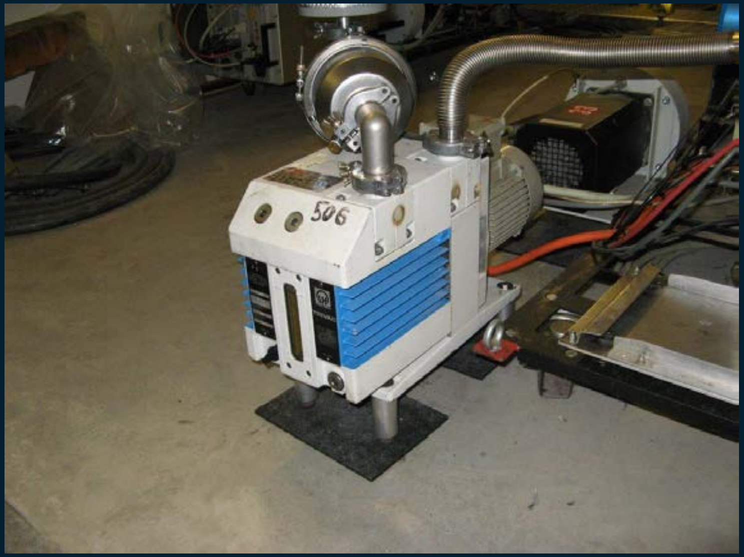
Backup: E-XFEL FPC



TTF III coupler

Backup: gradients for stability test 16/17.10.2015 (pumps)





Backup: LP shape