STATUS UPDATE OF CONTINUOUS WAVE AND LONG PULSE TESTS ON XM46.1 AND X3M2.

POSTER #71

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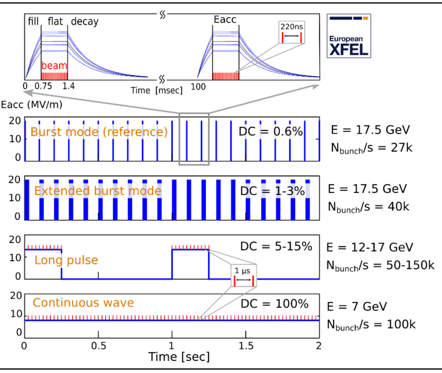
Abstract

The foreseen European XFEL **High Duty Cycle** upgrade requires driving the accelerator either in **Continuous Wave (CW)** or in **Long Pulse (LP)** mode of operation. In the Long Pulse mode of operation, the duty factor of the RF pulses is higher than 5% as opposed to the actual value of 1.4%. Therefore it is required to adapt the control system to operate with the new pulse parameters and, at the same time, preserve an RMS stability of the accelerating field of 0.01% in amplitude and 0.01° in phase. In the injector, where the maximum accelerating gradients will be realized, the accelerating cavities will operate at 20 MV/m with a loaded quality factor in the order of 6e7. Therefore tests with similar gradients, conducted at the CryoModule Test Bench (CMTB) on **XM46.1** are presented along with RF stability measurements. Additional tests on the 3.9 GHz third harmonic module **X3M2** are presented as well. The current third harmonic module used at European XFEL lacks piezoelectric tuners. Therefore the tests are crucial to determine whether a modification of the cryomodule is required.

SP / LP / CW

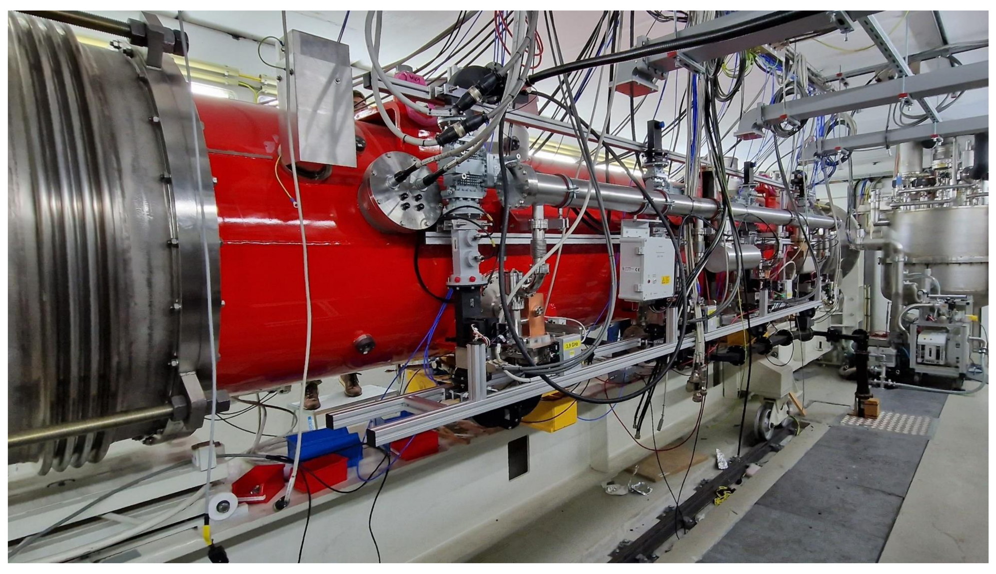
The European XFEL currently operates in **short pulse** (SP) also called burst mode (~1msec RF pulses i.e. ~1% duty factor), allowing for maximum energy (17.5 GeV) with $27x10^3$ bunches/sec. On the other end of the spectrum, the **continuous mode** (CW) would allow up to 10^6 bunches/sec but at a beam energy of 7-8 GeV. R&D programs are currently looking at **extending the burst mode** (i.e. 2-3 msec pulses at max energy with minimal hardware changes) and **long pulse** (LP) operation corresponding to 5-15% duty factor. LP provides more bunches/sec than short pulse at a higher energy than CW. All these scenarios have to keep a **constant dynamic heat load.**



X3M2 : spare 3rd harmonic XFEL cryomodule

Investigation of CW operation of the spare third harmonic cryomodule

- X3M2 is the spare 3.9 GHz cryomodule (8 cav.)
- Goal is to assess the limitations of the module for CW / LP operation
- Characteristics
  - Blade frequency tuner,
  - 3-stub tuners Q_L / phase
  - No piezo !
- Tested in pulsed mode
  - 8 cavities vector sum
  - Klystron
- Tested in CW / LP
  - Single cavity regulation
  - SSA



X3M2 in XATB1 (Accelerating Module Test Facility)

Challenges for CW operation

- **Challenge 1**
  - Heating of HOMs prevents CW operations at gradients above 5 MV/m

CAV	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 Limit
7	5.0	HOM1 overheating
8	8.0	Power Limit

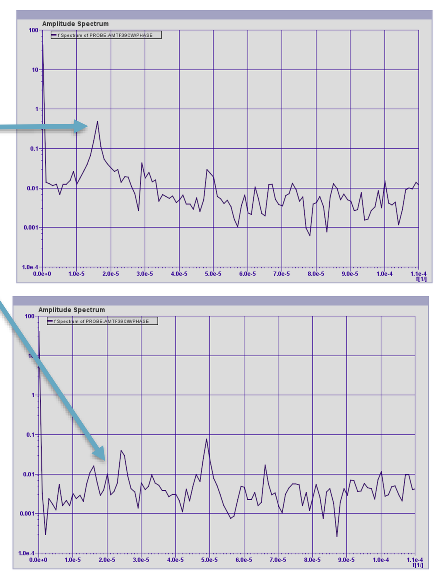
- **Mitigation**
  - Problem was suspected after site acceptance tests *
  - New HOM antenna design ? (as done for 1.3 GHz)
  - Learn from LCLS-II / SHINE modified design

* Reference: "LIMITS FOR THE OPERATION OF THE EUROPEAN XFEL 3.9 GHz SYSTEM IN CW MODE", C. Maiano et al. in proceedings of IPAC 2017

- **Challenge 2**
  - 18 Hz oscillations, excited by 4K cooling circuit, investigation on-going
  - Confirmed with RF and with external seismometer

18 Hz microphonics

Suppressed when changing the pressure inside the 4K cryo circuit

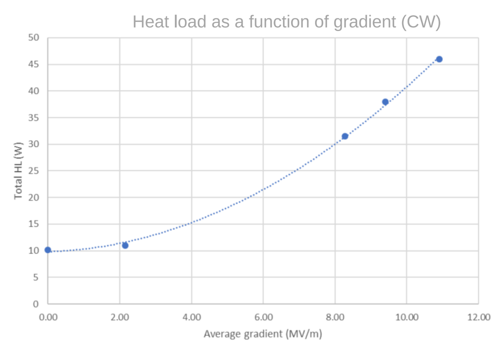


- Check if visible also at XFEL (Dec. 2023)

XM46.1 : XFEL series cryomodule

How XFEL series cryomodules designed for pulse operation perform in CW / LP?

- XM46.1 is a series XFEL cryomodule with some modifications for CW operations
  - Thicker coupler coating
  - Q_L tuning range extended towards higher range (i.e. can reach 6e7)

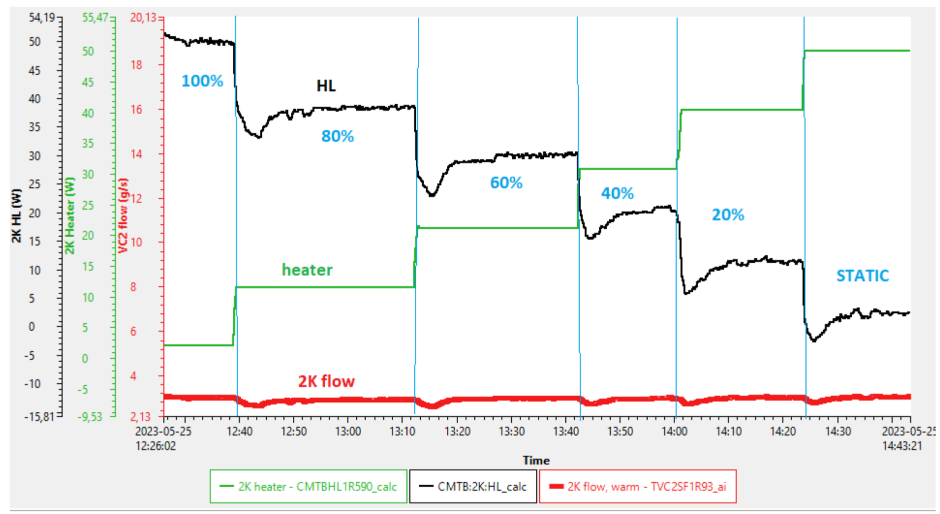


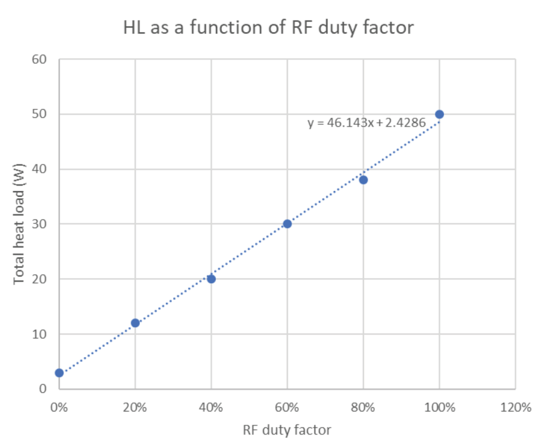
The dynamic heat load increases quadratically with gradient.

XM46.1 at CMTB

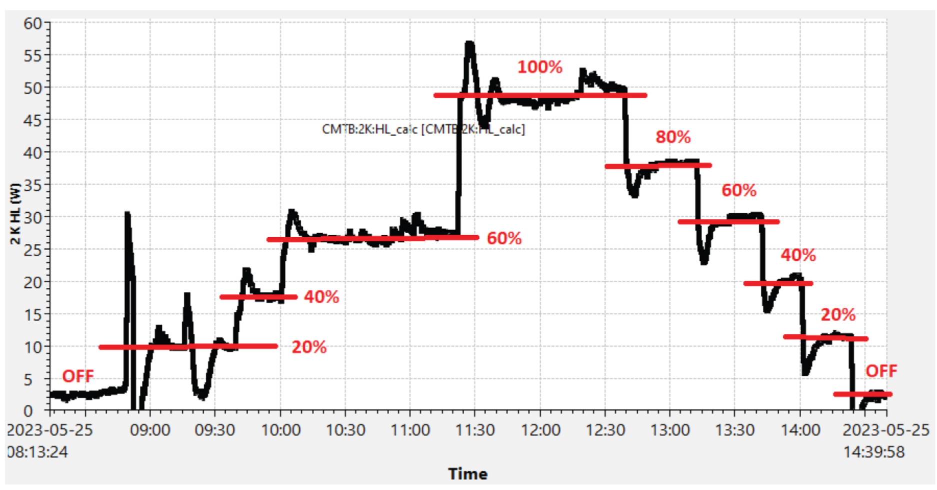
Heat load measurement as a function of RF duty factor

- Heat load measurements are performed by measuring the heater compensation to a gradient change, while keeping a steady helium flow
- The LLRF drive is open loop, pulse shape parameters are adapted to drive at the requested RF duty factor





A linear relationship between dynamic heat load and duty factor is an indication that the cavity end groups are not over heating



Other tests

- Q_L range

	C1	C2	C3	C4	C5	C6	C7	C8
QL min [x10^6]	2.5	<0.5	2.0	4.4	0.9	1.1	2.5	2.3
set QL [x10^6]	**3.3**	**3.3**	**3.3**	**4.4**	**3.4**	**3.2**	**3.3**	**3.2**
QL max [x10^6]	7.2	5.4	11.8	13.3	14.5	18.8	8.2	13.7

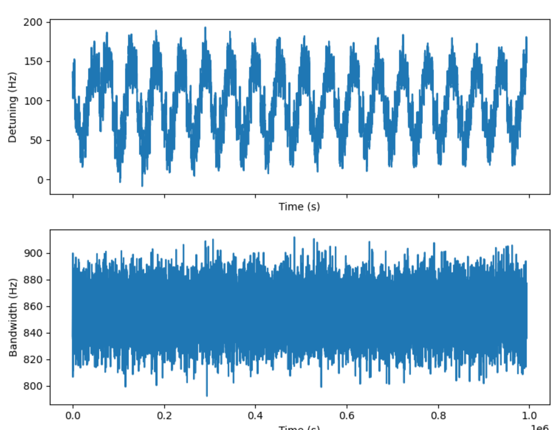
- LFD coefficients

	C1	C2	C3	C4	C5	C6	C7	C8
LFD [Hz/(MV/m)^2]	**-0.37**	**-0.49**	**-0.35**	**-0.40**	**-0.34**	**-0.43**	**-0.37**	**-0.45**

- Quench gradient in (1msec) pulse

	C1	C2	C3	C4	C5	C6	C7	C8
Quench gradient [MV/m] *	**24.6**	**20.7**	**22.5**	**27.0**	**21.7**	**23.2**	**23.0**	**25.7**
Gradient limiter [MV/m]	23.6	19.7	21.5	26.0	20.7	22.2	22.0	24.7

- Closed loop performance
  - Results are unsatisfactory
  - Main limitation comes from 18 Hz oscillation (see above)

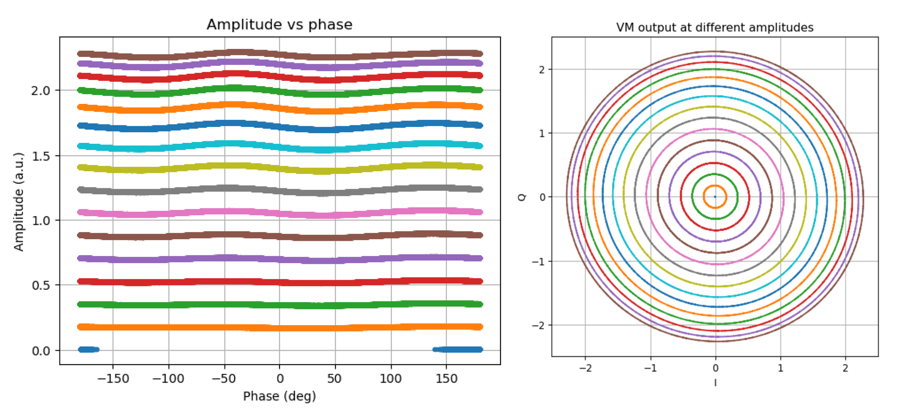


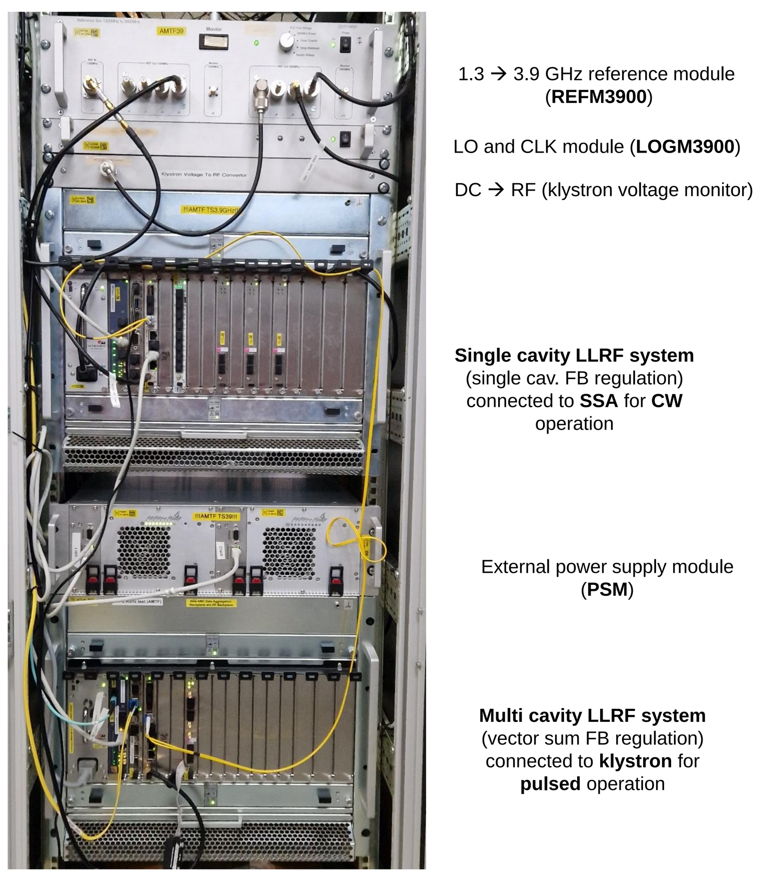
Parameters open loop
Amplitude std 2.63%
Phase std 4.95 deg.
Detuning std 40 Hz

Parameters closed loop
Amplitude std 0.06%
Phase std deg 0.04 deg.
Detuning std 40 Hz

Impact of 18 Hz cryo-induced oscillations on detuning

- VM non-linearities



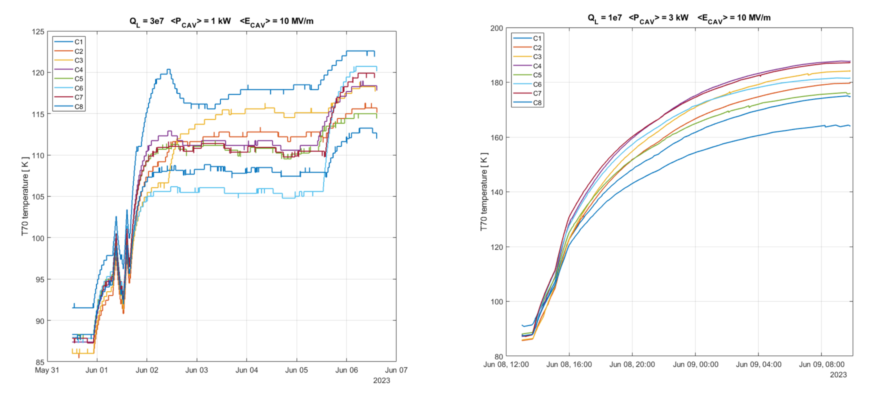


Dual LLRF system at AMTF for the third harmonic system

Coupler heating when running in CW / LP

- We expect CW operation at input powers up to 4 kW per coupler
- We measured coupler heating in CW at 1 kW and 3 kW
- At Pin = 3 kW, a delta T = 90K was observed, corresponding to a max coupler temperature of 190K which is still acceptable
- The Q_L = 3e7 test was not stable and needs to be repeated
- Higher forward power tests to come

Average input power	RF duty factor	Coupler temperature increase	Steady state temperature reached	QL	Average gradient	Delta QL due to temperature increase
700 W	50%	7K	100K	3e7	7 MV/m	
3 kW	100%	90K	190K	1e7	10 MV/m	13% (0.87e7)
1 kW	100%	30K	120K	3e7	10 MV/m	

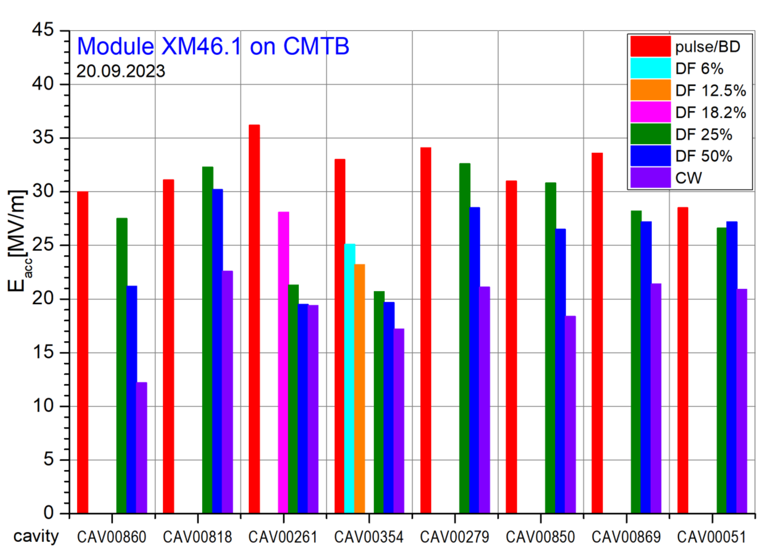


Coupler heating at the 70K temperature sensor for 1 kW and 3 kW input power

Quench gradient in pulsed versus CW operation

- Cavities driven in **SEL**, one at time
- Investigation of the quench gradient in CW compared to normal XFEL-like pulsed operation
- Cavities are XFEL series production (no special treatment for CW operation)
- **On average, for DF of up 25%, cavities can reach 90% of the pulse quench limit !**

<Ecav(DF=25%)> = 27.5 MV/m
<Ecav(DF=100%)> = 30.3 MV/m



Summary and Outlook

DESY is currently exploring new modes of operation for a possible upgrade of the European XFEL accelerator, to increase the effective number of bunches delivered per second, while preserving a beam energy as high as the cryoplant can allow. At the two tests facilities (CMTB and AMTF) cryomodules at 1.3 GHz and 3.9 GHz are tested in CW and LP mode of operation to identify their limitations in terms of coupler power, temperature, stability against microphonics, gradient and dynamic heat load. Solid state amplifiers and inductive output tubes are used as power sources. Numerous tests are planned for the near future, including experimenting with single cavity regulation options with 8 SSAs per cryomodule, pushing Q_L to higher values (≥ 6e7) and exploring single cavity regulation options with 8 SSAs per cryomodule.

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