SECOND CW AND LP OPERATION TEST OF XFEL PROTOTYPE CRYOMODULE

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Abstract

In summer 2011, we performed the first test of continuous wave and long pulse operation of the XFEL prototype cryomodule [1], which originally has been designed for a short pulse operation. In April and June 2012, the second test took place, with the next prototype. For that test, cooling in the cryomodule was improved and new LLRF system has been implemented. In this contribution we discuss results of the second test of these new types of operation, which can in the future extend flexibility in the time structure of the electron and photon beams of the European XFEL facility.

INTRODUCTION

The XFEL cryomodules are based on TESLA collider cryomodules [2] and as such, they still have many features of that original design from early 90's. The TESLA cryomodules have been compromised to keep the cost possibly low. In these 8-cavity containers, unlike for example, in 2-cavity HERA cryomodules, only cells of cavities are immersed in the superfluid liquid helium (LHe). The energy dissipated in their superconducting surface is transferred to the LHe bath thru ~3 mm thick high purity Nb wall. The situation is very different for so-called end-groups, the end-beam tubes with attached input couplers and/or HOM couplers, located outside the LHe vessels. Energy dissipated in the end-groups is transported to the helium bath via much longer distance and much higher thermal resistance, which depends on the heat conductivity of niobium the end-groups are made of. The losses are often enhanced on the HOM antennae, which are made of niobium and should stay superconducting for an operation. The TESLA cavity and cryomodule designs prove to operate very successfully in the XFEL nominal short pulse mode, when the duty factor (DF) does not exceed 1.3 %, RF-pulses are ca. 1.3 ms long and their rep-rate is 10 Hz. This operation is demonstrated since many years at FLASH, which linac comprises 56 TESLA cavities.

A continuous improvement in the performance of superconducting 9-cell TESLA cavities, especially the remarkable increase of the intrinsic quality factor, and minor cooling improvements for the end-groups, should make possible operation of the XFEL cryomodules in continuous wave (cw) mode at gradients up to ~7.5 MV/m and in the long pulse (lp) mode up to the XFEL nominal gradient E_{acc}= 23.4 MV/m. These estimated gradients result from splitting of the XFEL linac in to 12-cryomodule long cryogenic strings, which leads to the maximum allowed total 2K (1.8 K) heat load (HL) per cryomodule of 20 W. For the nominal operation, the estimated maximum 2 K heat load is ca. 11 W. The maximum gradient of 23.4 MV/m in the lp-mode seems to be achievable for up to 100 ms long RF-pulses.

The new operation modes will allow for more flexibility it the time structure of both the electron and photon beam. In the nominal operation, the intra RF-pulse bunch-to-bunch spacing is 220 ns. The new operation modes will offer significantly larger bunch spacing, of the order of few microseconds, keeping the average XFEL brilliance superior to other facilities. The enlarged spacing is advantageous. For example, it allows for less expensive detectors. Further, in the new operation modes, the photon burst rep-rate can be in the kHz range. This will make optical lasers for pump-and-probe experiments less technically challenging, still providing ca. 1000 photon-bursts in the cw operation and ca. 100 at the maximum electron beam energy in the lp runs. For the nominal short pulse operation, one will have only 10 bursts /s.

PREPARATION OF THE SECOND TEST

Thermal improvements in cryomodule

Two thermal improvements were done in cryomodule PXFEL3_1, which was foreseen for the tests in 2012. Each made cooling of the HOM antennae more effective. At first, five cavities could be equipped with prototypes of the high conduction HOM feedthrough, in which low conduction standard alumina window was replaced with the sapphire window and the niobium antenna was brazed to the inner-conductor pin. Secondly, all sixteen HOM feedthroughs were thermally connected, with copper strips, directly to the 2 K tube.

Cavity performance and Q_{ext} of input couplers

Prior to the cw/lp studies, the cryomodule was tested in the nominal mode. For that test, Q_{ext} of all input couplers had been set to $3{\cdot}10^6$. The test showed malfunctioning of two cavities. Cavity No 7 had strongly detuned HOM coupler and could be operated cw up to 4 MV/m. At this gradient, the out-coupled power was already 24 W, from which 20 % was dissipated in the cable, contributing significantly to the total HL at 2 K. Cavity No 8 showed strong electron emission, leading in the cw operation to enhanced HL and to quenching already at 9.3 MV/m.

For the cw/lp tests Q_{ext} of all cavities was set to $1.5{\cdot}10^7$, which corresponds to the 3 dB resonance width of 87 Hz.

RF distribution system and IOT amplifier

The RF-power distribution system was re-arranged in 2012 to make switching between a 10 MW klystron (used for nominal test) and the IOT amplifier for the cw/lp operation less time consuming. The new waveguide arrangement was not sufficiently balanced and reflected ca. 5% (1%) RF-power in the lp (cw) mode. A better balancing requires very careful RF-characteristics for all components and thus it is lengthy procedure, which could not be done during the test period. The IOT amplifier is protected with technical interlock, which stops operation when the reflected power at the output exceeds 0.9 kW. In addition during the IOT performance test in February this year, prior the amplifier was attached to the cryomodule, we observed a mismatch of the IOT input circuit, which was not technically understood and thus could not be fixed in-house. The tube will be sent to CPI in November 2012, after the second 120 kW IOT prototype will be delivered to DESY. The waveguide reflection and mismatch of the input circuit limited the IOT output power to ca. 18 kW. Even though, the power was low, with high Q_{ext} of input couplers we could expected to reach gradients up to 11 MV/m.

Low Level RF: VME and µTCA

New LLRF based on the µTCA architecture was used in the studies for the monitoring and for stabilization of phase and amplitude of the accelerating gradient, both in the cw and lp mode. The VME standard, LLRF system used in 2011, was in 2012 employed only once for verification of the stability we achieved with µTCA. The new LLRF system shall operate two feedback loops, for the RF and for piezo-tuners. The later one is meant as an additional compensation of microphonics and it was implemented in April 2012 for the first time. The piezo-bias with DC-voltage only was successfully used in 2011 and 2012 for fine frequency adjustment of all cavities.

Cryogenic plant and vacuum system

The cryogenic plant at DESY supplies with liquid helium (LHe) both the FLASH facility and the cryomodule test hall. The LHe pressure at 2 K can be stabilized for several hours within the range of ±30 µBar, when the total HL does not vary rapidly (no quench). The accelerating mode frequency modulation caused by this pressure variability is ±1.1 Hz. The pressure at 1.8 K is not as stabile. In 2012 we did not attempted to test the cryomodule at 1.8 K. This test is scheduled for the end of this year. In 2011 we observed that dominant modulation of the field amplitude was at frequencies 47-50 Hz. Further investigation, after the first cw/lp studies had been finished, showed that the modulation was caused by vacuum pumps located close to the middle of the cryomodule. The pumps, which are needed only for cool-down, were switched off during the test in 2012.

CW OPERATION

Several dynamic HL tests for cw/lp operations were conducted in April and June 2012. The dynamic HL is calculated as difference between actual heat dissipation in cryomodule and heat capacity of the superfluid helium flowing through a cryomodule. It takes always a while to balance that difference, which oscillates vs. time around its final value. Prior to the dynamic HL tests in 2011 and 2012 we measured the static HL for the investigated cryomodules. For PXFEL3_1, the static HL at 2K was 4.5W. It was lower by 3W than static HL of the cryomodule tested in 2011. Here we present the result for one of the 2012 cw tests at 5.6 MV/m. Table 1 shows conditions for the test. The result is shown in Figure 1.

Table 1: Conditions for the dynamic HL test at 2K

Condition /Parameter	Value/Status
Number of cavities in operation	7
$< E_{acc} >$	5.6 MV/m
Q_{ext}	$1.5 \cdot 10^7$
RF-power / Input coupler	550 W
RF-feedback	off
Piezo-feedback	on

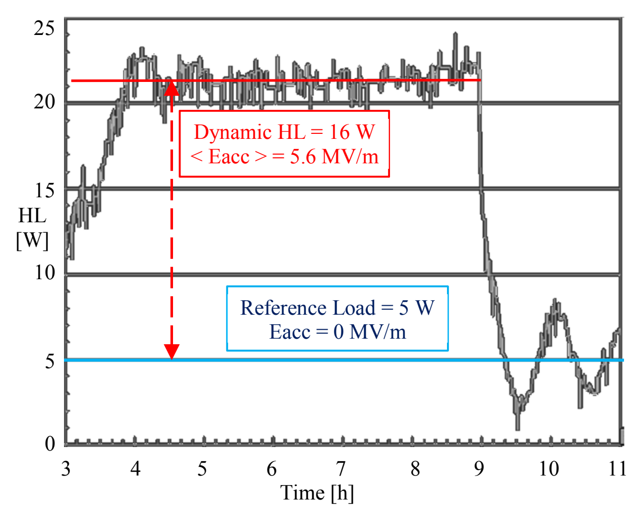

Figure 1: (Colour) Dynamic HL measured at 5.6 MV/m.

The measured 2 K dynamic HL at $<E_{acc}>$ = 5.6 MV/m was 16 W. The operation was very stable over more than 5 hours. Knowing intrinsic quality factors of cavities assembled in PXFEL3_1 from the vertical tests, we could estimate dynamic HL, which shall be 13.7 W. The 2.3 W difference between the measured and estimated HL can be attributed to enhanced dissipation in the 14 end-groups of 7 active cavities.

Projecting this result on 8 cavities operating at 1.8 K and assuming the same static loss of 4.5 W, one might expect that XFEL cryomodules can operate cw at ~7 MV/m, staying within 20 W budget for the total HL per cryomodule.

LP OPERATION

We performed also several lp tests in 2012. For some of these tests we could operate only 6 cavities and two cavities No 7 and 8 were detuned off resonance. In other lp tests cavity 8 operated at slightly lower gradient.

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Dynamic Heat Load vs. DF

In one of the lp experiments, we measured dynamic HL vs. duty factor at 8.1 MV/m. The tested DF range was from 15-47 %. In that experiment we set the rise time of RF-pulse to 100 ms to avoid overvoltage in the high voltage supply. 1/3 of the rise time was added to the RF-pulse flattop duration to calculate an effective DF. Conditions for the experiment are shown in Table 2. Figure 2 summarizes the result. For DF between 15-30% the measured dynamic HL is slightly lower than the estimated value. For DF higher than 30%, the measured dynamic HL is higher than the estimated one and the difference increases with DF. For DF=47% the difference is 3.4 W, which is 280mW/end-group. Again, projecting the result on 8 cavities at 1.8 K, it seems possible to operate XFEL cryomodules at 20 MV/m with DF=14% and the pulse rep-rate of 1 Hz, keeping the 20 W budget for total HL.

Table 2: Conditions for the dynamic HL test vs. DF

Condition /Parameter	Value/Status
Number of cavities in operation	6
$< E_{acc} >$	8.1 MV/m
Q_{ext}	$1.5 \cdot 10^7$
RF-pulse repetition rate	0.7 Hz
RF-power / Input coupler	1200 W
RF-feedback	off
Piezo-feedback and bias	on

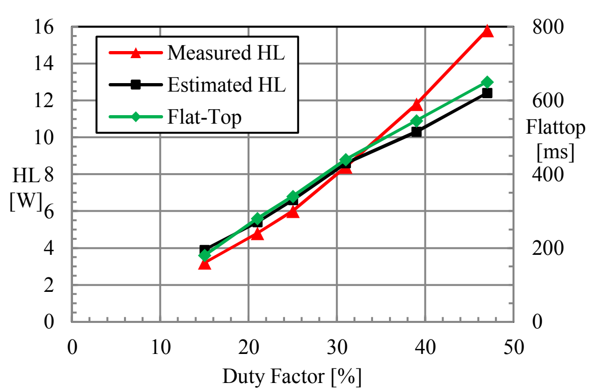

Figure 2: (colour) Measured and estimated dynamic HL, and flattop vs. effective duty factor at $<E_{acc}>$ = 8.1 MV/m.

Maximum gradient vs. DF

We set 6 good performing cavities at 10.5 MV/m and cavity No 8 at 8.1 MV/m. The RF-power was 18 kW, close to the IOT limit. The cryomodule operated for more than two hours very stable. The DF was 17%, flattop 200 ms and rep-rat 0.7Hz. The measured dynamic HL was 5.3W and it was higher than the estimated value by 0.8W, which is 64 mW/end-group. The test proved that XFEL cryomodules should run at 21 MV/m with 140 ms flattop and DF=17%, keeping total HL below 20W.

LLRF

As mentioned already, we used mainly μTCA LLRF electronics, which performed very reliable, both in the cw and lp mode. Amplitude and phase of the vector sum (VS) for 8 cavities operating cw at 3.5 MV/m could be stabilized by the RF-feedback (piezo feedback was off) to $6.5 \cdot 10^{-5}$ and 0.0098° rms respectively (see Figure 3). When the RF-feedback was switched off, standard deviation for the VS amplitude and phase was $1.5 \cdot 10^{-3}$ and 0.5° respectively.

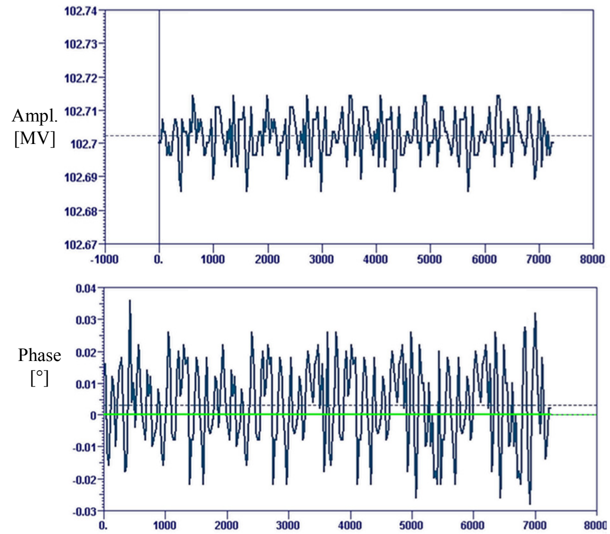

Figure 3: Amplitude (upper) and phase (lower) for cw mode when the RF-feedback was on. The whole range of horizontal axes is 1 s and the displayed units are arbitrary.

Similar stability was achieved for the lp operation. We also observed that the piezo-feedback suppressed microphonics by at least factor of 2, however we were not able to integrate operation of the piezo- and RF-feedback simultaneously.

FINAL REMARKS

The cw and lp operation test result are encouraging. These operations seem to be possible, even though the total HL/cryomodule is rather limited for the XFEL linac. We still do not have the final proof, and following has to be demonstrated or measured in the near future:

1. Lp operation at gradients ~20 MV/m.
2. HL for operation at 1.8 K at higher gradients.
3. Integration of the piezo- and RF-feedback.

We are planning to conduct these experiments in fall 2012 and in 2013.

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REFERENCES

[1] J. Sekutowicz et al., "Cw and lp operation test of XFEL-like cryomodule", IPAC12, New Orleans, USA, 21-25 May, 2012.

[2] R. Brinkmann et al. (editors), TESLA TDR, DESY-Report-2001-23, 2001.

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