LIMITS FOR THE OPERATION OF THE EUROPEAN XFEL 3.9 GHz SYSTEM IN CW MODE

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Abstract

Future upgrades of the European XFEL (EXFEL) facility may require driving the linac at higher duty factor, possibly extending to CW mode at reduced gradients. A preliminary analysis for the accelerator modules has been presented in the EXFEL TDR, but no precise assessment has been performed so far for the present 3.9 GHz system design. By making use of data collected during the commissioning and operation phase of the EXFEL injector system, we discuss here an estimate for the limits of CW operation of the present system and a plan for its possible experimental verification with existing available cavities and the EXFEL spare module.

EXFEL FUTURE UPGRADE SCENARIOS

Future scenarios for the EXFEL long term upgrades are discussed in the Technical Design Report [1] and elsewhere [2], either for an increased duty cycle up to 30 Hz or for operation with hundreds of ms pulses at 1 or few Hz (Long Pulse, LP, mode, with duty factors in the range approximately 10%–50%), or even in pure Continuous Wave (CW). A substantial amount of R&D activities is ongoing since 2007 for various components to assess a possible upgrade plan of the facility. A few 1.3 GHz accelerator modules have been tested at high duty cycles at the CMTB facility in DESY to assess its technical feasibility [3, 4].

However, for the third harmonic system needed at the EXFEL injector, no dedicated R&D activity has started up to now to explore the limitations of the present design towards the achievement of high duty operation.

AH1 AT THE EXFEL INJECTOR

The EXFEL third harmonic system (module AH1) is in operation at DESY since December 2015, providing the necessary capability for the longitudinal beam phase space manipulation in the injector linac, after the L–Band photoinjector gun and the first 1.3 GHz accelerator module (A1), acting as a booster module.

The 8-cavity AH1 module is able to provide 40 MV of third harmonic voltage to compensate the RF curvature due to the long bunch length at the injector, non-linear dispersion effects in the compression beamlines and wake fields effects in the main linac. Nominal operation of the EXFEL present 3.9 GHz infrastructure with 1.3 ms long pulses, 650 μs flat top and 10 Hz repetition rate is used for the acceleration of trains of up to 2700 bunches per RF pulse.

A second 3.9 GHz system, identical to AH1, is currently in preparation at DESY in order to provide the availability of a complete spare component for the facility. Furthermore, during the cavity production stages 4 additional cavities have been prepared, in order to provide readily available components in the case of cavities failing to meet the specifications during the module production and assembly. Capabilities for testing the individual spare cavities exist at the Accelerator Module Test Facility (AMTF) in DESY [5], which is also being prepared for the tests of the complete spare module unit.

The availability of these components allows to develop a R&D and testing plan to perform a similar activity performed on the accelerator modules in order to address the present 3.9 GHz system limitations.

It should be noted that the LCLS-II project has introduced several modifications to the present EXFEL third harmonic system in order to comply with the foreseen CW operation mode of the facility. Changes affected the cavity, coupler and cryomodule design [6]. The present paper concerns the prospect and limits of using the present EXFEL design towards higher duty cycle operation and outlines a possible program to assess them experimentally, similarly to what is currently done at DESY for the 1.3 GHz modules.

PROSPECTS AND LIMITS

All upgrade scenarios for the EXFEL 1.3 GHz main linac rely on the minimal number of modifications to be performed to the module RF distribution system installed in the tunnel, in order to limit the cost, the workload and the downtime of the facility. Therefore, vector sum operation of all cavities in the module is preserved, and a single IOT is foreseen to feed each installed cryomodule. On the contrary, for the third harmonic module several factors would suggest to change its RF distribution system and opt for an individual cavity powering in case of LP or CW operation. First, only one linac module would require adaptation. Secondly, solid state technology is able to offer CW sources of power that would be sufficient to drive a single cavity to the expected gradients. Finally, cavities at these frequencies have a higher sensitivity to any mechanical perturbation, thus require increasing the reserve power needed for microphonics compensation, and make vector sum operation more challenging.

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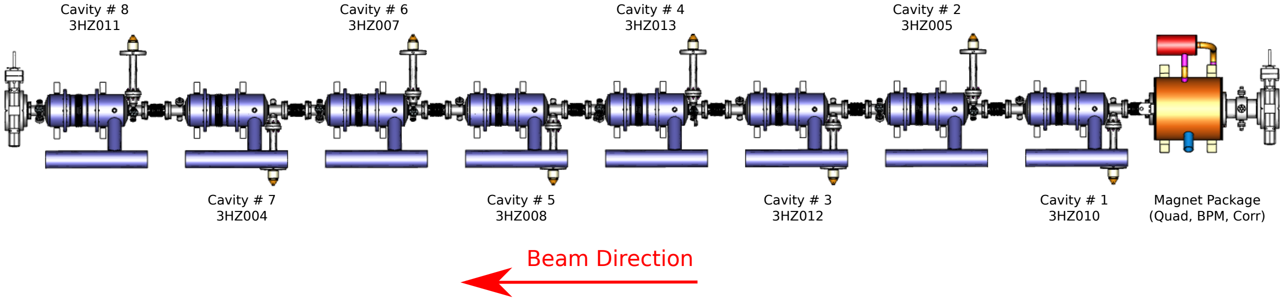

Figure 1: Cavity string of the AH1 module at the EXFEL injector. Coupler alternate sides to compensate dipole kicks.

Cryogenic Limitations

Heat transport from the cavity to the 2-phase pipe One of the limitations to take into account for the assessment of an increase of the cavity duty factor is related to the Helium II heat transport within the helium vessel. Heat conduction carries the RF power dissipated on the cavity internal wall to the liquid surface, maintaining superfluid condition. In the present cavity design the helium vessel is connected to the 2 phase 2 K line by a short (≈ 13 cm) connecting pipe (so-called "chimney") with an internal diameter of 56 mm. A conservative estimate for the critical heat flux density to maintain a temperature difference of few tens of degree is approximately 1 W/cm^2 (even if higher values, up to 1.2 W/cm^2 where measured at HZB), thus resulting in a cavity maximum RF dissipation of aproximately 25 W (neglecting additional load coming from the conductively cooled end-groups).

Figure 2 shows the heat deposited from RF dissipation on the cavity wall, for the design Q_0 value of 10^9 and for the average Q_0 measured during the fabrication of all EXFEL 3.9 GHz cavities [7]. For gradients with an upper limit in the range from 12.5 to 17.6 MV/m (depending on the achieved Q_0 value) the RF dissipation remains below the heat transport limit.

Module heat transport limit A second limitation is that the vapor transported in the 2-phase pipe over the liquid surface should be limited to speeds below 4 m/s, in order not to trap and carry liquid droplets and drive flow instabilities. This imposes an overall limit on the overall heat load allowed along the 76.1 mm outer diameter 2-phase pipe of the XFEL design. For the nominal EXFEL strings of 12 modules (approximately 160 m length between the feed and end caps) this limit amounts to ≈ 240 W (20 W/module) [2]. For the shorter string (approximately 25 m, two modules) of the current EXFEL injector (one 1.3 GHz module and one 3.9 GHz module) we can at first assume the same limit of 240 W, with approximately 120 W/module, i.e. setting a limit of 15 W/cavity. The corresponding upper limits on the cavity gradients would reduce to the range 9.6-13.7 MV/m. In the absence of additional heat sources, this results in a total voltage approximately in the range from 25 to 35 MV for the 8 cavity module at the EXFEL injector.

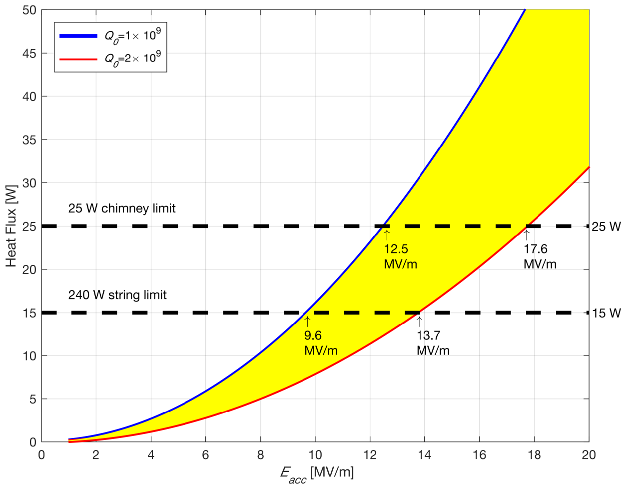

Figure 2: Heat flux generated by the cavity by RF, for two cases of Q_0 values (nominal specification and average of the EXFEL production). R/Q is 750 Ω. Gradients with upper limits in the range between 12.5 and 17.6 MV/m would be compatible with heat transport to the 2-phase pipe. In order to keep the overall heat load on the two module string below 240 W these upper limits reduce to the range 9.6-13.7 MV/m.

Additional heat sources The increase of the duty cycle will however lead to additional heat loads in the cavity end regions, which are outside the helium vessel and are only conductively cooled. In particular, the HOM RF antenna, could become a strong contribution, even if in the present design a heat sink is directly connected to the 2-phase line. Like for the 1.3 GHz accelerator modules, this effect for the 3.9 GHz module needs a careful analysis with dedicated experiments, in order to quantify its relevance. A further limitation comes from the capability of the present coupler design (which do no include the later changes developed for the LCLS-II [6]) to sustain the additional power losses at high duty cycles or CW operation. In particular the design changes foreseen by the LCLS-II imply the use of shorter bellows and thicker copper coatings in the warm coupler part. A possible solution, in case of strong limitations, would be the in-situ replacement of the warm coupler parts in the EXFEL module, operation that does not require a complete disassembly of the cavity string from the module.

RF Operation

RF power sources Solid State Amplifier (SSA) technology is able nowadays to deliver kW-class CW power amplifies in the 3.9 GHz range. A preliminary market investigation showed at least two potential suppliers for a 1 kW device with the necessary characteristics.

RF Power coupler The AH1 module uses the FNAL fixed antenna design and is equipped with 3-stub tuners at each cavity. During the technical commissioning stage , a full scan of the stub positions has been performed, demonstrating the capability to reach a $Q_L > 10^7$ at all cavities. The CW operation of these devices may incur in heating problems at the stub tuner position, which need to be experimentally investigated. This could be explored to allow operation in LP/CW mode, without the necessity to physically exchanging the cold antenna length of the coupler (which would require the complete module disconnection and disassembly). A further concern is the heat deposition in the coupler components at high duty cycles, which could lead to strong heating of the inner conductor of the warm part. For the LCLS-II design FNAL increased the copper coating thickness of this part (150 μm with respect to 30 μm for the pulsed version) and used fewer bellows convolutions to sustain a 2 kW traveling wave load. Possibly these components could be substituted in-situ to allow operation at high duty cycles. Figure 3 shows the accessible accelerating gradient E_{acc} on the Q_L-P_f plane. Gradients in excess of 10 MV/m can be achieved with a forward power below 1 kW/cavity and Q_L values in the range from the nominal value of the EXFEL pulsed linac up to 10^7.

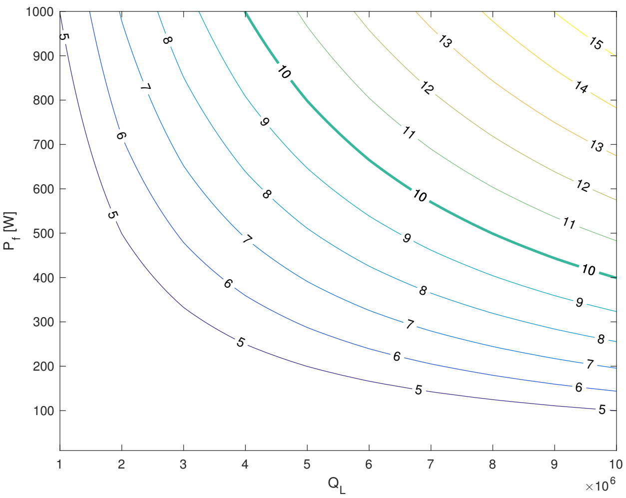

Figure 3: Achievable accelerating gradient E_{acc} (in MV/m) in the Q_L-P_f plane. Gradients above 10 MV/m can be achieved with Q_L in the range 4×10^6-10^7 and a forward power to the cavity in the 400-1000 W range.

LLRF topics for CW When operating in CW, the loaded quality factor (Q_L) of SRF cavities is typically set to higher values than in short pulse, nominal mode, to maximize the power coupling into cavities, hence lowering the required CW RF power to reach nominal cavity gradients. In the case of 1.3 GHz, the Q_L is adjusted to 1.5×10^7 from the pulsed mode nominal value 3×10^6, bringing the required RF power down to 2.6 kW for 12 MV/m per cavity. A drawback of this weaker coupling is a reduced cavity bandwidth leading to a higher sensitivity to external mechanical vibrations or cryogenic pressure fluctuations. The LLRF system has to be adapted to actively compensate for microphonics, using piezo feedback and active noise cancellation techniques. These principles were demonstrated experimentally in the case of 1.3 GHz cavities [8, 9] but not yet at 3.9 GHz, where the frequency sensitivity to external disturbance is known to be a factor of 9 higher than at 1.3 GHz. Moreover the Cold Tuner Design of the EXFEL third harmonic cavities is not presently equipped with piezo capabilities, and a study is needed to assess the possibility of driving these cavities to high duty cycles and the need to introduce piezo actuators. The complexity is increased due to the use of 3-stub tuners in the case of the present 3.9 GHz cryomodule. The influence of ponderomotive oscillations observed at 1.3 GHz remains also to be investigated at 3.9 GHz.

POTENTIAL PROGRAM

The spare third harmonic module of the EXFEL injector is in its final preparation stage. At first the test program will qualify it at AMTF for the operation in the present facility, in pulsed mode (1.3 ms RF pulses, 10 Hz). A testing program towards the assessment of LP or CW operation is under consideration, to assess all required changes to the test cave. Four additional cavities have been manufactured, in order to provide spare components in case of cavities failing to meet the specifications and for readily available units during the module assembly. All the spare cavities meet the nominal performance specifications and are stored in clean conditions for immediate use. A horizontal cryostat at DESY is capable to test single 1.3 and 3.9 GHz cavities in conditions comparable to the module installation. We propose this configuration to perform LP and CW tests of the complete cavity package and, critically coupled tests of single dressed cavities before coupler assembly. A LP or CW RF station is presently not available at the AMTF, but would represent a minor investment and technical effort, considering the scale of the testing facility. LP/CW tests on the spare cavities and cryomodule would provide important insight on the feasibility of extending the EXFEL operation to higher duty cycles, and the needed measures to be implemented for the operation of the third harmonic components.

CONCLUSION

The availability of the spare components of the EXFEL third harmonic system (1 full module and 4 additional cavities) allows to setup a test plan to assess the prospects and limitation of driving the present design to higher duty cycles, as foreseen by future upgrades of the facility.

REFERENCES

[1] R. Abela et al., “XFEL: The European X-Ray Free-Electron Laser - Technical Design Report”, DESY-06-097, DESY, Hamburg, 2006.

[2] J. Sekutowicz et al., “Feasibility of CW and LP operation of the XFEL Linac”, In *Proc. of 35 Free–Electron Laser Conf. (FEL13)*, New York, NY, USA, Aug 2013, pp.189–192.

[3] J. Sekutowicz et al., “CW and LP operation test of XFEL-like cryomodule”, In *Proc. of International Particle Accelerator Conference (IPAC’12)*, New Orleans, LA, USA, May 20-25, 2012, pp. 2215–2217.

[4] J. Sekutowicz et al., “Second CW and LP operation test of XFEL prototype cryomodule”, In *Proc. of 12 Linear Acc. Conf. (LINAC12)*, Tel Aviv, Israel, Sep 2012, pp.516–518.

[5] C. G. Maiano et al., “Validation of the superconducting 3.9 GHz cavity package for the European X-Ray free electron laser”, *Phys. Rev. Accel. Beams*, **20**:042005, Apr 2017.

[6] I. Gonin, T. Khabiboulline, A. Lunin, N Solyak, “Simulation of 3.9 GHz CW coupler for LCLS-II project”, In *Proc. of International Conference on RF Superconductivity (SRF2015)*, Whistler, BC, Canada, Sept. 13-18, 2015, pp. 1066–1069.

[7] P. Pierini et al., “Fabrication and vertical test experience of the European X-Ray free electron laser 3.9 GHz superconducting cavities”, *Phys. Rev. Accel. Beams*, **20**:042006, Apr 2017.

[8] L. Branlard et al., “LLRF System Design And Performance For XFEL Cryomodules Continuous Wave Operation”, In *Proc. of International Conference on RF Superconductivity (SRF2013)*, Paris, France, Sep. 23-27 2013, pp. 1129–1131.

[9] R. Rybaniec et al., “FPGA based RF and piezo controllers for SRF cavities in CW mode”, *IEEE Transactions on Nuclear Science*, accepted for publication.