FEASIBILITY OF CW AND LP OPERATION OF THE XFEL LINAC

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Abstract

The European XFEL superconducting linac is based on cavities and cryomodules (CM) developed for TESLA linear collider. The XFEL linac will operate nominally in short pulse (sp) mode with 1.3 ms RF pulses (650 μs rise time and 650 μs long bunch train). For 240 ns bunch spacing and 10 Hz RF-pulse repetition rate, up to 27000 bunches per second can be accelerated to 17.5 GeV to generate uniquely high average brilliance photon beams at very short wavelengths [1]. While many experiments can take advantage of full bunch trains, others prefer an increased to several μ-seconds intra-pulse distance between bunches, or short bursts with a kHz repetition rate. For these types of experiments, the high average brilliance can be preserved only with duty factors much larger than that of the currently proposed sp operation.

In this contribution, we discuss progress in the R&D program for future upgrade of the European XFEL linac, namely an operation in the continuous wave (cw) and long pulse (lp) mode, which will allow for more flexibility in the electron and photon beam time structure.

INTRODUCTION

In summer 2011 we began tests with pre-series XFEL cryomodules in order to define limits in the cw and lp operations for the XFEL linac. We conducted up to now, four runs, each approximately one week long, with four pre-series cryomodules. All tested cryomodules differed somewhat from the XFEL series cryomodules, mainly because many cavities they housed were equipped with old type, low heat conduction HOM-coupler feedthroughs and with their thermal connections to the 2-phase helium line. We have presented some of the tests results along with new components needed for these two operation modes (high thermal conduction feedthroughs, beam line absorbers, all superconducting photo-injector, LLRF and new RF-source) in [2, 3, 4 and 5] during last four years.

In short, the goal of our studies is to prove feasibility of the XFEL cw operation at gradients $E_{acc} \leq 7$ MV/m and lp operation at higher E_{acc}, with duty factors (DF) scaled roughly proportional to $(7/E_{acc})^2$. The studies, proposed in 2005/2006, were motivated by the duty factor potential, which can be anticipated for linacs based on the superconducting technology. Unlike XFEL, other short wavelength FELs, proposed or under construction at that time, were based on room temperature technology and thus their DFs are very low, considerably below 0.1%.

For the sp operation, XFEL linac cavities will be fed by pulsed klystrons, which maximum pulse duration is 1.38 ms and thus possible largest nominal DF is 1.38 % at 10 Hz repetition rate. With new operation modes we expect to gain significantly in DF at cost of operation at lower gradients; however this can still allow for very short wavelengths, as it is discussed in [6].

There are technical and practical constraints for the upgraded DF range.

LIMITATIONS FOR DF

Heat Load at 2K (1.8K)

One of technical constraints is the heat load (HL) budget for present type of XFEL cryomodules, which in total (static plus dynamic load) should not exceed 20 W/cryomodule. The limit results from diameter of 2-phase He transport tube and from its approximately 160 m length between feed- and end-cup (12-cryomodule long cryogenic strings in main linac).

Upgrade of the Cryogenic Plant

To keep high quality of electron bunches, as for the present linac configuration and nominal operation, we will need to replace first seventeen cryomodules (136 cavities) with new ones, modified for cw operation at E_{acc} between 11 and 16 MV/m. The new cryomodules will have larger diameter 2-phase helium tube allowing for enhanced HL. Twelve out of seventeen replaced cryomodules can be re-installed at the end of the XFEL main linac (ML). In this scenario, the XFEL linac will consist of 113 cryomodules (904 cavities). Table 1 displays capacity of the present and upgraded cryogenic plant, and the total HL at 2 K and 1.8 K for the 113-cryomodule linac. One should note that the capacity of upgraded cryogenic plant will be similar to that of the existing CEBAF cryogenic refrigerator at JLab.

Table 1: Cryo-plant Capacity and HL for Two Operations

sp operation (2K)		cw/lp operation (1.8K)	
Cap. [W]	HL [W]	Cap. [W]	HL [W]
2450	1175	4980	3320

ISBN 978-3-95450-126-7

RF-power Source

New RF-power sources will be needed for the cw and lp operations. We plan to install one source per cryomodule in the tunnel, which means the sources should be very compact. The required power per cryomodule will be ca. 100-120 kW. The sources should allow efficient operation, especially for the lp mode. These two properties, compactness and the lp mode efficiency, were arguments to initiate an R&D program for high power Inductive Output Tube (IOT). An IOT amplifier is very compact, as compared to present solid state amplifiers and it takes power from the mains only when it delivers RF-power, which makes it superior to cw-operating klystrons. The program was carried out at CPI Company in USA, in frame of the EUROFEL project. The first prototype was delivered to DESY in 2009 and is routinely used for the cw/lp cryomodule tests we will discuss later. The second prototype was ordered in 2012. Specification for the second tube is listed in Table 2. The tube will be delivered to DESY in fall 2013.

Table 2: Parameters of the Second IOT Prototype

	Unit	Spec
f	[MHz]	1300
Pout	[kW]	> 100
Gain	[dB]	> 22
η	[%]	> 60
V_{beam}	[kV]	47-49

Cavity End-group

Originally, TESLA collider cavity and its auxiliaries were designed in early 90's for DF of ca. 1%. In that design, cavity end-groups, containing Higher Order Mode (HOM) and Fundamental Mode (FM) couplers, are placed outside Liquid Helium (LHe) vessel (Fig. 1). The design enabled substantial saving on production costs, which was the main argument in the case of 22000 cavities needed for TESLA, but made end-groups more sensitive to energy dissipation in couplers and to heat leaks. The design proves since many years its capability to operate in cryomodules in sp mode at gradients up to 40 MV/m. In vertical tests, unequipped TESLA cavities immersed in superfluid helium, without LHe vessel and HOM feedthroughs, demonstrate gradients in cw mode up to 45 MV/m. When they are equipped with HOM antennae, achieved gradients in vertical tests are up to 40 MV/m for duty factors ~30%. When TESLA cavity is assembled in a cryomodule, only its body is immersed in superfluid

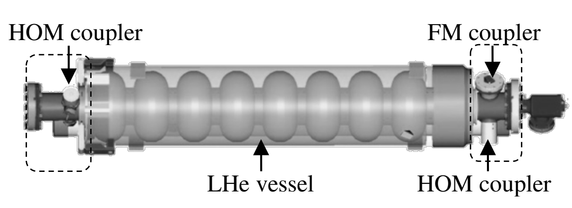

Figure 1: TESLA cavity. End groups are marked with dash lines.

helium. The end-groups are cooled by means of heat conduction only. The DF limit resulting from the TESLA cavity design is that heating of end-groups must not lead to quenching of cavity. The main sources of heat are antennae in HOM couplers exposed to residual magnetic field of the accelerating mode. New high thermal conduction feedthroughs were developed and will be used for all XFEL cavities to improve heat transfer from the HOM couplers. In addition, all feedthroughs will be connected directly to 2-phase tube with copper braids.

New cw-operating cavities will be equipped with modified HOM couplers, in which shorter antennae will be partially hidden and less exposed to the magnetic field.

TESTS WITH PRE-SERIES CRYOMODULES

As already mentioned, we have conducted several cw/lp operation tests with pre-series cryomodules, which in many cases had worse thermal conditions for the end-groups as compared to XFEL series cryomodules. We expect that the serial CMs should perform better both in the cw and lp operation mode. We will discuss here two experiments in which we measured dynamic heat load vs. DF and E_{acc}. We should underline that in all conducted experiments no abnormal behavior like quenching, field emission, multipacting were observed.

Dynamic Heat Load vs. DF

The test was conducted at 2K. The cavities operated at 5.6 MV/m. Q_{load} for all cavities was adjusted to $1.5 \cdot 10^7$. In the tested cryomodule (PXFEL3_1) only three out of eight cavities were equipped with new feedthroughs and new thermal connections. The dynamic heat load (DHL) was measured for DF = 38, 60, 75 and 100% (cw). The test took 14 h. Over the whole test time the cryomodule performed very stable.

Figure 2 shows measured DHL in that experiment. We measured reference DHLs for E_{acc} = 0 MV/m at the

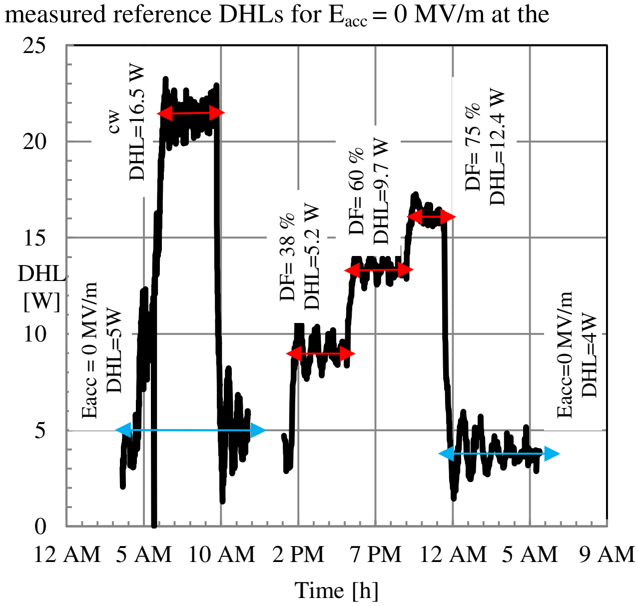

Figure 2: (Color) 2K DHL vs. DF at 5.6 MV/m. Reference levels, at E_{acc} = 0 MV/m, are marked in blue.

ISBN 978-3-95450-126-7

beginning and at end of the cw-test, and at the end of the whole run. They amounted to 5 W and 4 W respectively. Knowing performance in vertical tests of all cavities housed in PXFEL3_1 cryomodule, we could estimate DHL at 2K for all DFs. The cavities have shown in vertical tests rather high intrinsic Qs, which calculated mean value is <Qo> = $2.2 \cdot 10^{10}$. The estimated dynamic heat load (EDHL) is displayed in Table 3. The difference between measured and estimated DHL can be attributed to heating of 16 end-groups. Last row of the table displays this additional heat per end-group.

Table 3: EDHL and End-group Heat Load at 2K vs. DF

DF	[%]	38	60	75	100
EDHL	[W]	4.2	6.5	8.3	10.7
Heat / end-group	[W]	0.07	0.23	0.29	0.41

Figure 3 illustrates conclusion from the test, scaled for operation at 1.8 K. For 20 W total heat load (THL, red line), including DHL and measured static load of 4.5 W, one can expect to operate XFEL at 6.1 MV/m in cw mode and at 11.5 MV/m for 38% DF (black line). Furthermore, the scaling indicates that operation at E_{acc} = 7 MV/m will be achievable for DF ≤ 80%. We think, that for serial XFEL cryomodules, which have better cooling of end-groups, the gradient for cw operation should be higher than 6.1 MV/m.

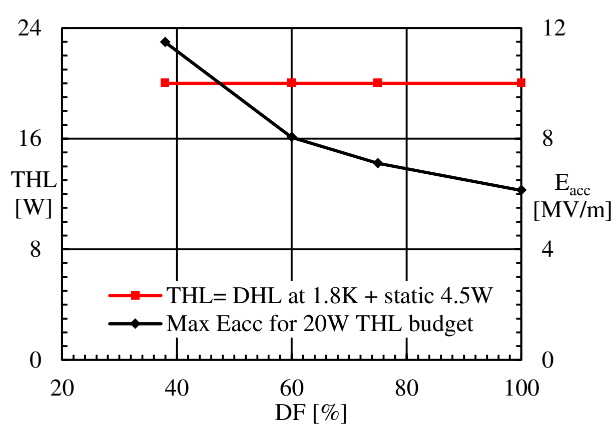

Figure 3: (Color) Achievable gradient E_{acc} at 1.8 K vs. DF (black line) for 20 W THL (red line).

Dynamic Heat Load vs. E_{acc}

The second test we want to discuss here, was conducted at 2 K and DF = 20%. In that test we measured DHL vs. E_{acc}. As in previous test Q_{load} of all cavities housed in tested cryomodule (PXFEL2_3) was adjusted to $1.5 \cdot 10^{7}$. The mean value of intrinsic Q for cavities in that cryomodule was $2.0 \cdot 10^{10}$. The test was conducted for E_{acc} = 7.4, 9.0, 9.8, 10.5 and 10.7 MV/m. Also in this test, in which cavities operated ca. 13 h, we did not observe abnormal behavior of the tested cryomodule. The measured DHL load is shown in Figure 4. Estimated DHL and the additional heat attributed to single end-group are listed in Table 4. In PXFEL2_3, only two cavities were equipped with new feedthroughs and new thermal connections.

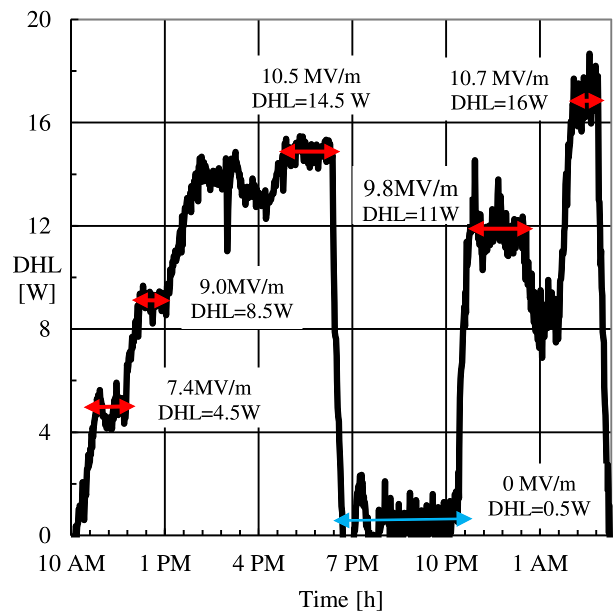

Figure 4: (Color) 2 K DHL vs. E_{acc} for DF = 20 %. Reference level at E_{acc} = 0 MV/m is marked in blue.

Table 4: EDHL and End-group Heat Load at 2K vs. E_{acc}

E_{acc}	[MV/m]	7.4	9.0	9.8	10.5	10.7
EDHL	[W]	4.5	6.8	7.8	9.3	9.8
Heat /end-group	[W]	0.01	0.1	0.2	0.32	0.39

Scaling of this test result allows prediction for operation at 1.8 K. For the scaling, as for the first test, we took into account static heat load of 4.5 W. The prediction is shown in Figure 5. Here, the result led to conclusion that cw operation at 7.4 MV/m, with margin of 2 W below the budget, would be feasible. On the other hand, according to this test, the lp operation at approximately 11MV/m seems possible for DF ≤ 24 %.

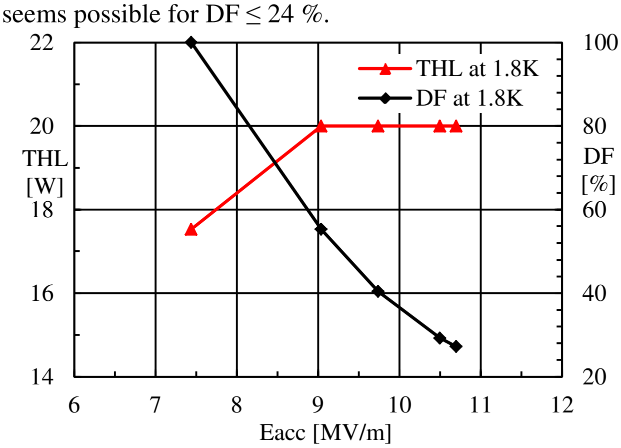

Figure 5: (Color) Achievable DF at 1.8 K vs. E_{acc} (black line) for THL ≤ 20 W (red line).

ISBN 978-3-95450-126-7

UPGRADE SCENARIO

We will briefly discuss here the previously mentioned upgrade scenario, with 136 new cw-operating TESLA-like cavities in the injector section (IS) and 12 CMs relocated to the end of ML. The scenario offers the most flexible operation. Other scenarios, for example using present IS, will require less investment but will allow for less flexibility in the time structure of the electron and photon beam. In the proposed upgrade, the electron beam, right before it enters second bunch compressor (BC2, see Fig. 6), will reach 2 GeV energy in cw/lp operations, as it does for the nominal sp operation. This shall enable all three types of operation, with no or minor modification of the linac optics.

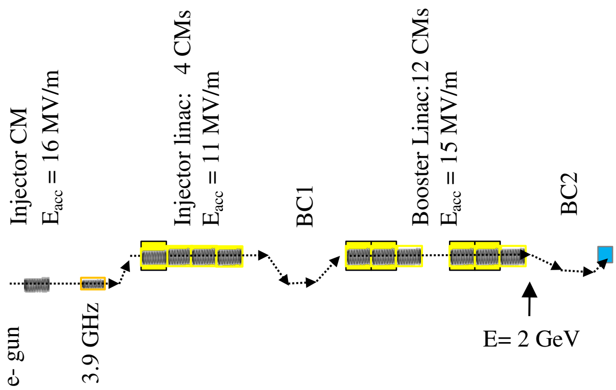

Figure 6: (Color) Sketch of the injector section. Required gradients E_{acc} and number of CMs in each sub-section are depicted in the sketch.

We have summarized in Table 5 possible DFs for the discussed scenario, taking into account less favorable results of the presented tests.

Table 5: DFs for all Operation Modes vs. E_{acc} of ML

Mode	Energy [GeV]	E_{acc} ML [MV/m]	RF-pulses Length [ms]	RF-pulses Rep. Rate [Hz]	DF [%]
sp	17.5	23.5	1.38	10	1.38
cw	6.9	6.1	-	-	100
lp	10	10	350	1	35
lp	14	15	150	1	15

For all three cw/lp operation examples listed in the table, DFs are remarkable larger than for the nominal mode. Operation at E_{acc} of 6.1 MV/m in ML, resulting in the electron beam final energy of 6 GeV, should be possible for cw mode. At E_{acc} of 10 MV/m in ML, electron beam will have final energy of 10 GeV. The maximum expected DF for this gradient is 35 %. Accordingly to the modeling discussed in [6], 1 Å wavelength can be generated as a third harmonic with 0.5 nC bunches, when normalized slice emittance is not larger than 0.7 mm·mrad. The lasing at higher harmonics seems possible with a proper phase adjustment between undulator segments, leading to suppression of the first harmonic. This very attractive lasing mode was demonstrated experimentally for longer wavelength and needs to be proven experimentally for 1 Å. Last row of the table shows projection for lp operation at E_{acc} of 15 MV/m, not demonstrated yet in our experiments. With this gradient, electron beam will reach final energy of 14 GeV, for which wavelength of 1.5 Å was achieved at LCLS. The maximum projected DF at this gradient is 15 %.

SUMMARY AND FUTURE PLANS

All experiments conducted since 2011 are encouraging and show feasibility of operation modes at substantially larger DFs.

We will continue this kind of tests with serial XFEL cryomodules, hoping to gain statistics for components of the ML. As an intermediate goal, we would like to test serial CMs at 1.8 K to prove experimentally if operation at the lower temperature is beneficiary and if projection of results acquired at 2 K to 1.8 K is justified. Furthermore, operation at higher than 10.7 MV/m gradients has to be demonstrated in the near future.

In parallel, we will continue R&D programs on LLRF, piezo tuners [7] and on 1 mA-class, Nb/Pb superconducting photo-injector, which is an indispensable component for new operation modes. The injector project, which began in 2004/2005, gained recently more attention and is currently partially supported by the European EuCard 2 program and by German ARD funds.

ACKNOWLEDGMENTS

Authors would like to thank all colleagues at NCBJ, WUT, TUL and DESY for their scientific, engineering and technical support in the R&D programs presented here.

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