TEST RESULTS OF COMPONENTS FOR CW AND NEAR-CW OPERATION OF A SUPERCONDUCTING LINAC*

J. Sekutowicz, M. Ebert, F. Mittag, DESY, 22607 Hamburg, Germany
P. Kneisel, TJNAF, Newport News, 23606 Virginia, USA
R. Nietubyć, A. Sołtan INS, 05400 Świerk/Otwock, Poland

Abstract

The European XFEL will use superconducting (sc) TESLA cavities operating with 650 µs long bunch trains. With 220 ns bunch spacing and 10 Hz RF-pulse repetition rate, up to 27000 high quality bunches/s will be delivered to insertion devices generating unprecedented high average brilliance photon beams at very short wavelength. While many experiments can take advantage of full bunch trains, others prefer an increased intra pulse distance of several µ-seconds between bunches, or short bursts with a kHz repetition rate. With the nominal RF-pulse structure these features will lead to a substantially reduced number of bunches per second and therefore to significantly lower average brilliance. We discuss here an R&D program aiming at an upgrade of the European XFEL in the far future, namely an operation in the cw and/or near-cw mode. The program profits from the continuous improvement in performance of TESLA cavities, which allows for longer RF-pulses in comparison to the current design. We present test results of a SRF electron injector and a new RF-power source, and additionally some modification of the HOM damping scheme, which will avoid the necessity of re-assembly of the XFEL accelerator for the upgraded operations.

INTRODUCTION

The sc linac of the European XFEL facility [1] will deliver very short bunches of σ_z = 25µm at maximum energy of 14.5 GeV. The nominal operational gradient of ~650 sc TESLA cavities will be ~24 MV/m. The possible future cw or near-cw operation shall offer more flexibility in the beam time structure. It should maintain the high average brilliance of the present nominal operation, having significantly increased spacing between subsequent bunches. Figure 1 shows an example of the possible beam time structure; number of bunches/s vs. beam energy, under assumptions that spacing between bunches is 4 µs and that a new SRF electron injector can deliver maximum 50000 bunches/s. At the maximum energy, the number of 1nC bunches is 21250 and it is limited by the duty factor (DF) of the linac - de facto by the total cryogenic load (CL). Below 10 GeV the number of bunches is limited by the assumed performance of the electron source. For the XFEL-type cryomodule (CM) we have set the CL to 20 W at 1.8K. As a result of that limit, DF is still 8.5% at 14.5 GeV. It is thirteen times higher than the present nominal DF for the short pulse (SP) operation. Both an upgrade of the cryogenic plant capacity (C) by 25% and operation at 1.8 K will be required to accommodate the increased cryogenic load. Table 1 displays the CL for two types of operation of 81 CMs (new option since 2010).

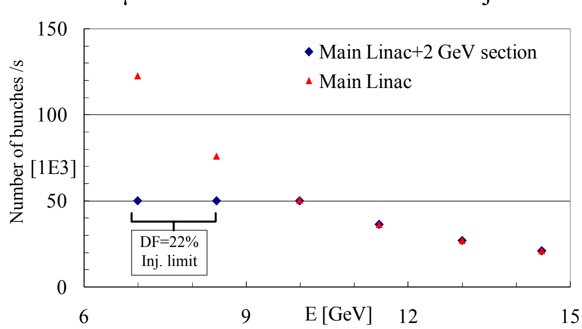

Figure 1: Number of 1nC bunches/s vs. beam energy.

Table 1: Cryoplant Capacity and CL for two Operations

	SP OPERATION (2K)		NEAR-CW OPERATION (1.8K)	
T RANGE	C [W]	CL [W]	C [W]	CL [W]
2 (1.8) K	2450	1175	3060	2040
5-8 K	4000	2810	5000	3330
40-80 K	30000	12250	37400	25000

CAVITY ACCEPTANCE TEST

All XFEL cavities must pass cryogenic acceptance test at DESY after they are equipped with HOM feedthroughs. This procedure is different from how the TESLA/FLASH cavities were tested in the past since mid 90`s. Here one should note that originally TESLA cavity and its auxiliaries were design for DF<1%. The cw 2K acceptance tests of equipped cavities showed very often thermal instability of the HOM couplers. A recent analysis with ANSYS confirmed that heating of the Nb antenna in the HOM coupler is very much the same in either case; when the cavity is immersed in superfluid helium (vertical test) and when it operates in the cryomodule. In the cw test the heat load of the Nb antenna is roughly 100 times higher than the load during the SP operation. Our experience after many years of SP operation of FLASH cavities is that there is no thermal instability of the HOM couplers we observed during the cw tests. We have estimated that the heat load of HOM couplers will increase at most by a factor of 10 as compared to the SP operation for future cw operation at ~7 MV/m and for near-cw operation at up to 24 MV/m. Accordingly, we have changed the acceptance test from a cw to a 10 % DF pulse test with 5s long RF-pulses (~ 45s RF off). With this change, no thermal instability was observed. Many pulse tests conducted recently proved

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that an equipped TESLA cavity can operate at much higher DF than it was designed for, and that there will be no limitation for the future operation modes for that design. We have also begun to test cavities at 1.8 K. An example of two recently tested cavities, equipped with HOM feedthroughs, in the pulse mode at 1.8 K is shown in Figure 2.

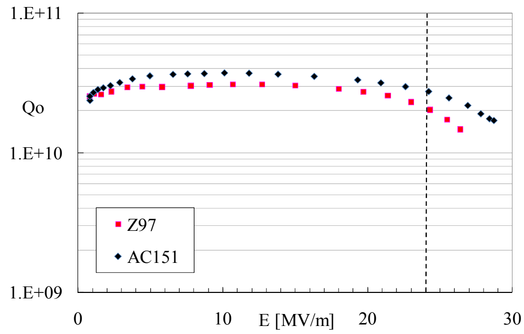

Figure 2: Pulse test at 1.8 K of two TESLA cavities equipped with HOM feedthroughs; Z97 poly-crystal Nb, AC151 large grain Nb. Dashed line indicates XFEL spec.

BEAM LINE ABSORBER

The total deposited HOM power by the nominal XFEL beam will be 3.81 W/CM, if no synchronous excitation will take place [2]. All modes below cut-off will be suppressed by coaxial HOM couplers [3] attached to each cavity. A big fraction (~85%) of the propagating HOM power will be dissipated in the beam line absorbers (BLA). Fig. 3 shows the proposed layout of the BLA [4]. The absorbers will be integrated into the vacuum chambers connecting cryomodules. They will be installed in all interconnections, and at the beginning and end of all linac subsections. The absorption of microwaves takes place in the ceramic ring attached to the brazed copper stub. The stub transfers the dissipated energy to the 40-70 K cryostat shield via an external thermal connection. A stainless steel bellows serves as thermal barrier between the 40-70 K level and the 4 K cold vacuum chamber. In the absorber design we took into account a possible upgrade of the XFEL facility to higher average brilliance by operating it with more bunches. For this case, the BLA power capacity has been specified to 100 W, which will allow for acceleration of up to one million nominal bunches/s. The prototype of the BLA was tested at FLASH twice in 2008 and 2009. The second test was conducted with much more stable linac operation than the first one. The charge/bunch was up to 3.2 nC and the

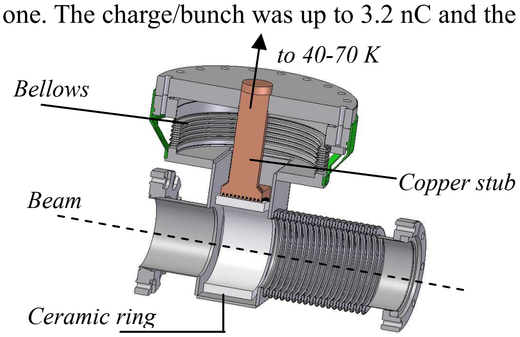

Figure 3: Layout of the beam line absorber.

bunch length was ~1.5 mm. The FLASH linac could be operated with 800 bunches/pulse. An example of the HOM power induced in the cryomodule ACC6 closest to the BLA and the temperatures measured by thermometers attached to the stub and to the cooling tube are shown in Figure 4. In the run (4-8 am) presented here, the numerically estimated power absorbed by the BLA was 255 mW. The maximum observed temperature rise of 2.5 K indicated absorption of 325 mW, which was higher by 27% than the computed value. In the first test, the measured power was lower by 21% than the estimated value. Both tests confirmed the concept of the BLA design and we are fabricating the next prototypes.

The thermal connection of the BLA to the 40-70 K He tube is technically not simple. For the XFEL nominal SP operation, when the dissipation is 3.81 W, the connection can be made of a copper stub, terminated on each end with short braids, eliminating mechanical forces during the cool down and warm up cycles. With this thermal connection the ceramic ring temperature for nominal SP operation is 59 K when the He tube is at 50 K. For the upgraded operation, when dissipation will by at least one order of magnitude higher, this connection is not suitable. The thermal modeling showed that for proposed connection and 30 W dissipated power, the highest temperature on the ceramic ring is 230 K. Higher conductivity connections, for example with an active helium gas cooling, are much more expensive and thus they will be designed and implemented when the XFEL linac will be modified for the new operation mode.

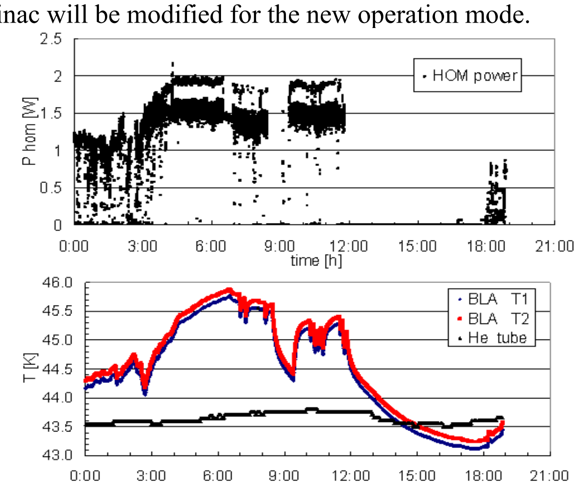

Figure 4: Power deposited in ACC6 and corresponding temperatures measured in 2009.

SRF ELECTRON SOURCE

The new XFEL operation modes will require a new electron source operating at cw. One of the possible options is a SRF hybrid Nb/Pb gun shown in Figure 5. The concept of the hybrid injector with a sc lead cathode was first discussed in 2005 [5] and the progress since then was reported recently in 2010 [6]. The photo-emission properties of lead were studied extensively in parallel. The result of these studies has been summarized in [7]. The conclusion from many quantum efficiency (QE) tests, both at 300 K and 4.2 K, was that such a SRF injector has the potential to deliver ~1 mA current and ~1 nC charge/bunch. The sc Pb cathode, located at the center of the back-wall of the Nb cavity, is deposited by means of a filtered cathodic arc. This method differs from other methods by producing high energy ions impacting on the target. This results in the formation of a relatively clean, dense and uniform coating. Our present goal is to establish a coating technology allowing for the repetitive and reproducible lead deposition in the photoinjector cavities. Figure 6 shows results of 1.6-cell TESLA shape injector cavity tests in 2008 and 2010. Both the baseline test (*B-*) and the test with the Pb spot (*Pb-*) in 2008 gave better results than the recent test in 2010. Unfortunately, the test with the Pb spot in June 2010 was limited by a superfluid leak in the cavity, which led to ionization and discharges. The leak has been localized and fixed. We will continue testing in autumn. Later in this year, the cavity will be used to measure the QE of the coating in a separate cryogenic test. Even though the results are not yet fully satisfactory, the achieved electric fields of the order of 40 MV/m on the cathode in two tests are encouraging and we will continue the R&D program towards better quality of the sc cathodes. In parallel, a second 1.6-cell cavity was coated for the QE and beam quality tests at BESSY, which are scheduled for the end of this year.

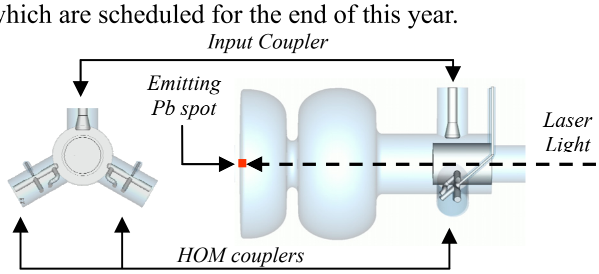

Figure 5: 1.6-cell SRF-injector cavity with 2 HOM couplers and an input coupler.

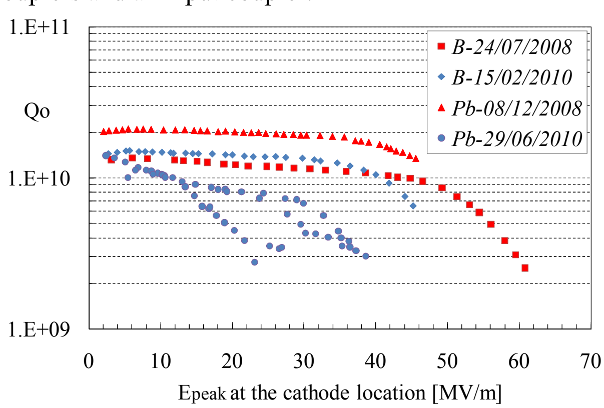

Figure 6: Tests results of the 1.6-cell Nb cavity with (*Pb*) and without (*B*) the lead coating.

RF-POWER SOURCE

New RF-power sources will be needed for the long-pulse and cw operations. To lower both investment and operation costs of a new RF-system, a high power Inductive Output Tube (IOT, tetrode) was developed at CPI Company in frame of the EUROFEL program [8]. The idea behind this development was to have a "modular layout" of the sc linac, in which one RF-source supplies power to one XFEL-like cryomodule, housing eight TESLA cavities. Parameters of the first prototype (see picture below) as specified and then measured at CPI and DESY are listed in Table 2. The tube is still under investigation at DESY. We are planning to test the XFEL-like cryomodule with that tube to learn more about the amplitude and phase stability when a chain of eight cavities, with loaded quality factors of the order of 2E7, is fed by a single IOT amplifier. The experiment is not yet scheduled.

Table 2: Parameters and Picture of the IOT Prototype

	Unit	Spec	Test at CPI/DESY
f	[MHz]	1300	1300
Pout	[kW]	60-120	85 / 80
Gain	[db]	> 21	22.3
η	[%]	> 60	54
V_{beam}	[kV]	36-50	45-48

FINAL REMARKS

The components discussed here are still in a R&D or/and test stage. All of them are essential for the future possible upgrade of the XFEL facility; they can also be very useful for smaller FEL facilities operating with high DF (~10%) or/and cw at lower gradients.

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