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THE PATH TO HIGH DUTY CYCLE AT EUROPEAN XFEL: CRYOMODULE DEVELOPMENTS

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Abstract

The European XFEL is in operation since 2017 with a maximum energy of 17.5 GeV in short-pulse (SP) mode, consisting of 0.65-ms long bunch trains at 10 Hz repetition rate. The accelerator can deliver up to 2700 electron bunches every 100 ms, with a spacing between bunches of 220 ns. After eight years of successful operation the accelerator team, with strong support from the EuXFEL strategy process, is working to define an accelerator upgrade scenario for possible implementation in the next decade. The main goal of the upgrade is to facilitate more bunches per second with larger bunch spacing while maintaining the high energy of the beam, a world record amongst FEL machines. Possible scenarios include continuous-wave (CW) and long-pulse operating modes, collectively referred to as high duty cycle (HDC). This paper describes the different operating modes under investigation and the R&D activities ongoing at DESY to support the upgrade. The main focus of the paper is on the cryomodule and cavity design modifications, while also giving a brief introduction of the other challenging aspects connected to the upgrade.

HIGH DUTY CYCLE (HDC) AT EuXFEL

The current EuXFEL 'burst mode' (or 'short pulse', SP) provides up to a 600 µs beam pulse with a maximum electron beam energy of 17.3 GeV, at a pulse repetition rate of 10 Hz, corresponding to a beam duty cycle of 0.6%. With a bunch repetition rate of up to 4.5 MHz, the EuXFEL is currently capable of producing up to 27000 bunches per second. A more detailed description of the EuXFEL linac and its operation can be found in [1]. As a possible future upgrade to the facility, the potential of higher average bunch rates from running at higher duty cycles, up to and including 100% (continuous wave, CW), is actively being studied. A cost-effective proposal which reuses the existing SRF linac cryomodules was already proposed in [2] and still forms the basis of the current approach: The cryomodules in the injector and bunch compressor linacs (L1, L2) will be replaced with new CW-optimised cryomodules, with the originals being relocated to the end of the main accelerating linac (L3) to boost the energy reach. The upgrade also foresees a new SRF CW 1-MHz photoinjector, the installation of low-power CW RF sources, new LLRF systems, and an additional cryoplant, effectively doubling the current 2 K cooling capacity.

A primary constraint on the maximum beam energy is the increased cryogenic 2 K dynamic load associated with the higher duty cycle. The upgraded cryogenic infrastructure will provide a total of 5 kW cooling capacity at 2 K, approximately half of which will be available for the main linac (L3). Figure 1 shows how the beam energy can be traded for duty cycle assuming a fixed (L3) cryogenic load.

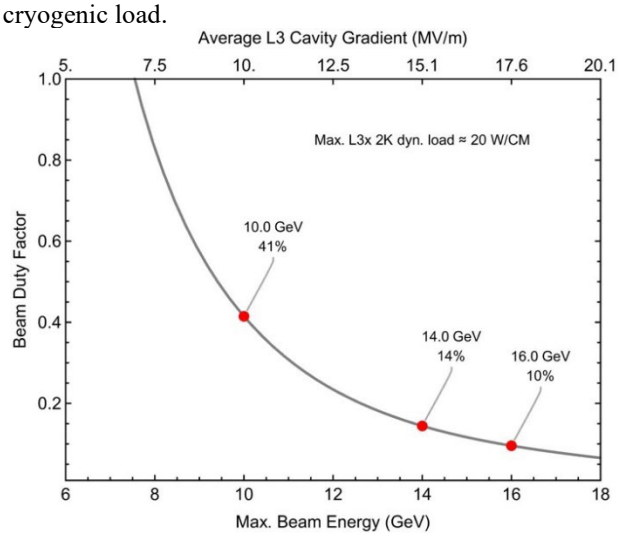


Figure 1: Beam duty cycle versus maximum beam energy assuming a constant (maximum) 2 K dynamic load in the L3 linac. The top horizontal axis gives the average required accelerating gradient. The three highlighted working points were identified as use cases for further study. Full CW operation is possible below 7.5 GeV.

Table 1 gives the top-level parameters corresponding to the operation points shown in Fig. 1. Running with duty cycles of $D < 100\%$ requires pulsing the RF. A 1-Hz pulse repetition rate is currently considered with RF (beam) pulses ranging from 100-430 ms, so-called Long Pulse (LP) mode. The choice of LP pulse lengths and low repetition rate is primarily driven by the much longer fill times required for the very narrow bandwidth cavities (typically tens of milliseconds).

The reduction in dynamic cryogenic load is achieved by reducing the average gradient to about 8 MV/m in the L3 linac, where the maximum load is constrained by the design of the existing cryomodules (in particular the diameter of the two-phase pipe). For the bunch compressor linacs, the accelerating gradients are fixed by the compression parameters and do not change with the maximum beam energy. Hence new CW-optimised cryomodules capable of CW operation at higher accelerating gradients must be installed. Table 2 gives the main top-level requirements for these new modules.

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Table 1: HDC Top-Level Parameters for Selected Working Points

	CW	LP		
Duty Cycle	**100%**	**41%**	**14%**	**10%**
Energy (GeV)	7.5	10	14	16
Bunch rate ($s^{-1}\times10^3$)	1000	410	140	100
Pulse length (ms)	-	100	150	430
Rep. rate (Hz)		1	1	1
Bunch charge (pC)	100	100	100	100
est. AC power (MW)	5.1	4.1	3.2	3.1

Table 2: CW-Optimised Cryomodule Requirements for L1 and L2

Cavity gradient	$\geq$	20 MV/m
Cavity Q_0	$\geq$	3×10^{10}
2K dynamic load /module	$\leq$	120 W
Cavity Q_{LOAD}		6×10^7
Cavity RF P_{FOR}	~	3 kW

The choice of average gradient (20 MV/m) in L1 and L2 is sufficient to provide a beam energy of 2 GeV at the exit of the bunch compressors with an off-crest phase of 40 degrees (considered a likely maximum) and an additional 5 % overhead for redundancy. A value of $Q_0 \geq 3\times10^{10}$ is specified for the cavities in order to keep the CW 2 K dynamic load per cryomodule at the ~120 W level. Both gradient and Q_0 numbers represent minimum requirements.

The upgrade also requires the installation of CW-capable RF sources in all linac sections. In order to reduce the RF power requirements, the Q_{LOAD} of the cavities needs to be increased by a large factor over the current burst mode value of 4.6×10^6. For the CW-optimised cryomodules a value of $Q_{LOAD} = 6\times10^7$ has been specified, which results in a forward RF power of approximately 3 kW per coupler, assuming 20 MV/m and 100 μA beam current with on-crest acceleration. This requires a modification to the existing antenna design of the EuXFEL coupler, which can only achieve $Q_{LOAD} = 10^7$. Furthermore, the copper coating will be made thicker to allow for larger average RF power. For the existing linac (L3), although an in-situ modification of the current couplers is feasible, it is neither particularly practical, nor guaranteed to work. Therefore, external stub-tuner devices are being investigated, which can be integrated into the waveguide system. The current specification for the L3 cavities is $Q_{LOAD} \geq 2\times10^7$. The average RF power per coupler remains ≤ 1.2 kW for the entire range of energy and duty factor considered, and is therefore well with the current limit of 4 kW.

The choice of RF power source and its configuration remains one of the main open questions. Several options are being studied based on CW klystrons, Inductive Output Tubes (IOT) and Solid-State Power Amplifiers (SSPA). Furthermore, the trade-offs between single-cavity regulation (one amplifier per cavity) and so-called vector-sum regulation (8 or 16 cavities per amplifier) are also being considered.

The many challenges and open questions are currently being studied as part of the on-going HDC Feasibility and Options Study (FOS), which will culminate in a major technical report in the first half of 2026. The FOS report will lay the technical foundations for both the next years' R&D plan as well as providing technical input to the full EuXFEL facility upgrade Conceptual Design Report, which is currently foreseen in 2028.

TOWARDS AN HDC CRYOMODULE

The design of the EuXFEL 1.3 GHz cryomodule needs to be modified to fulfil the new requirements for CW and HDC operation.

The modifications are driven by the new gradient and quality factor defined for the HDC superconducting cavities given in Table 2. These values determine the new dynamic heat load for the cryomodule, which is the main parameter affecting the design of the whole assembly. Dynamic heat loads up to ~120 W are expected when running the accelerator in CW mode.

The HDC cryomodule design is based on the EuXFEL series 1.3 GHz cryomodule, and modifications are only foreseen for components that do not satisfy the new requirements. The HDC cryomodules have to be compatible with the existing ones (same vessel diameter, same position of piping, etc.) and with the existing neighbouring components in the EuXFEL accelerator, i.e. feed and end caps and string connection boxes [3]. The tooling and installation equipment should also be kept in use as far as possible.

The following paragraphs summarise the main modifications planned for the different cryomodule components, starting from the individual cavities up to the whole assembly.

Superconducting Cavities

The HDC requirements for the upgraded 1.3 GHz cavities of $Q_0 \geq 3\times10^{10}$ at $E_{acc} \geq 20$ MV/m (Table 2) cannot be achieved using the established EuXFEL cavity surface treatment [4]. Currently at DESY, the so-called medium temperature (Mid-T) heat treatment is being pursued as a means of achieving these goals. When compared to the standard EuXFEL surface treatment, experience from several labs has indicated that Mid-T baked cavities (250°- 350° C for typically 3h in ultra-clean high vacuum oven) show higher values of Q_0 (up to ~5×10^{10} at ~20 MV/m) and a characteristic so-called anti Q-slope (positive Q_0-versus-E_{acc} slope), but often at the expense of lower quench fields (20-25 MV/m). Results of the on-going DESY R&D have demonstrated for the first time several cavities showing the classic High-Field-Q-Slope (HFQS) above 25-30 MV/m. Typically these cavities did not reach their breakdown ('quench') limit but were limited by the rapid reduction in Q_0 and the lack of available forward power. DESY has since shown that an additional application of the standard Low-T bake (130 ° C for 24 h) successfully cures this HFQS, resulting in single-

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cell cavities achieving Q_0~3×10^{10} up to nearly 40 MV/m [5]. This combination of Mid- and Low-T bake is currently the most promising approach for the HDC cavities.

The latest results achieved at DESY with Mid-T/Low-T treatment combinations on different single-cell cavities can be seen in Fig. 2. The results include cavities made of different niobium materials. The recipe works on fine-grain, large-grain and single-crystal niobium, indicating that the Mid-T/Low-T process is independent of the niobium grain structure.

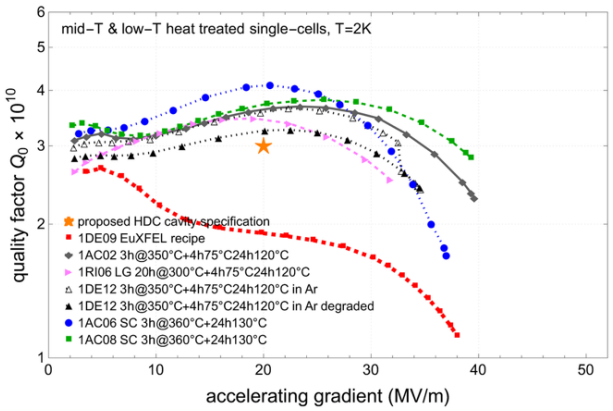


Figure 2: Quality factor versus accelerating gradient of single-cell cavities treated with Mid-T/Low-T process. A cavity treated with the standard EuXFEL recipe is shown in red for comparison.

The next step is the transfer of the recipe from single to nine-cell cavities. For this purpose, new nine-cell cavities will be ordered soon based on a revised specification for cavity fabrication and treatment.

Additional studies are also ongoing to understand more of the underlying physics processes. For example, flux trapping mechanisms of Mid-T treated cavities are subject of investigations as well as the dependency of the cavity performance on the cool-down velocities and the quality factor degradation that may occur following a quench. More details about R&D activities and studies on single-cell cavities and material samples at DESY can be found in [6, 7].

Field emitted electrons, due to particulate contamination of the inner cavity surface, cause a reduction in quality factor and the emitted dark current can limit the cavity performance. In CW operation, it may result in higher radiation levels in the accelerator tunnel, when compared to the present burst mode. The higher radiation can lead to activation and damage to the electronics installed in the tunnel. Therefore, the cleanliness requirements of the cavity surface preparation and string assembly are stricter compared to the initial EuXFEL cavity and module production.

High Order Mode (HOM) Couplers

Overheating of the HOM antennas at the cavity was already an issue in previous cryomodules for the Tesla Test Facility TTF and the FLASH accelerator. The connector and cooling of the HOM antenna was optimised during the prototype phase of the EuXFEL production and no overheating was observed with the modified design [8]. A higher repetition rate (HDC or CW) will increase the RF power dissipated at the HOMs and overheating could reappear. This effect will be studied in the ongoing cryomodule tests at the Accelerator Module Test Facility (AMTF) at DESY to decide if the cooling needs to be improved.

Helium Tank and Two-Phase Pipe

The design of the EuXFEL cavity tank is the result of years of technological development and is still state-of-the-art for this component. For example, the choice of an internal bellows has highly reduced the risk of damages to such a delicate component during all stages of manufacturing, assembling and testing.

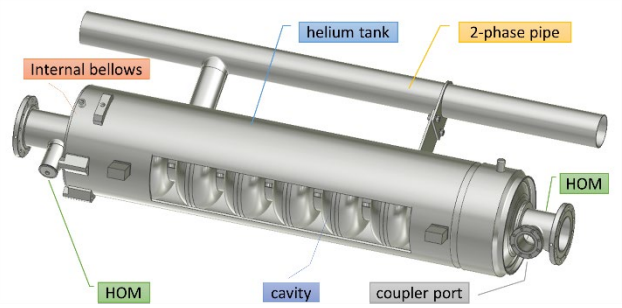


Figure 3: EuXFEL cavity, He tank and two-phase pipe

Moreover, the helium tank is a critical part of the manufacturing certification of the cryomodule as a pressure vessel and should be modified only if strictly necessary.

Two components are sensitive to changes in the maximum heat load of the cavity: the cavity chimney and the two-phase pipe itself. The main cavity parts can be seen in Fig. 3.

Cavity chimney Calculations show that the cavity chimney with the present internal diameter of 56.3 mm can transport up to 20 W without exceeding the liquid helium heat conduction limit. Tests performed at HZB [9] and DESY show higher values: at HZB a TTF-like cavity tank sustained a heat load of 30 W without any noticeable increase in the helium temperature nor instabilities in the cavity. Similar values have been reached at DESY.

The HDC cryomodule should reach 120 W per cryomodule, corresponding to less than 20 W per cavity. Therefore, the diameter of the cavity chimney does not need to be modified. Tests are planned at AMTF to validate these values for the HDC cavities and further study the heat load limit of a single cavity tank.

Two-phase pipe The two-phase pipe has in the present EuXFEL design an inner diameter of 72.1 mm. The pipe transports the liquid and vapour helium to the cavities and provide the evaporating surface to keep the temperature of

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the helium bath surrounding the accelerating cavities constant.

Cryogenic calculations show that the liquid and gas helium velocity at this surface is a critical parameter to guarantee stable cryogenic operation (no vibrations, no instabilities), while dissipating 120 W of dynamic heat load in the eight cavities. An increase of the two-phase pipe diameter would guarantee stable operation with higher heat loads. Presently, different values of the inner diameter (up to 100 mm) are under investigation in the calculations and one of them will be implemented in the next HDC test cryomodule and tested in the AMTF.

The calculations also show that the total length of the two-phase pipe, i.e. the number of cryomodules supplied by the same Joule-Thompson valve and forming a cryogenic string, is an important parameter to determine the maximum heat load that can be dissipated per cryomodule while keeping stable operation. Conservative assumptions require one JT valve per cryomodule to stay in the stable regime. The installation of one valve per module will be investigated in the next cryomodule being modified and prepared for extensive testing in AMTF.

Couplers

A few modifications are planned at the fundamental power coupler (FPC) of the existing EuXFEL cryomodule design [10] to allow CW operation.

First, the copper plating thickness of the warm part inner conductor is increased from 30 to 150 μm to reduce the heating of the inner conductor for input RF powers up to at least 5 kW.

Secondly, the cold part antenna is shortened by 8 mm to increase the Q_{LOAD}, still allowing pulsed operation.

At the existing cryomodules in L3, the Q_{LOAD} can also be increased modifying the FPC cryomodule outer flange shifting the FPC 10 mm outwards. This modification also requires minor changes at the thermal shields, to avoid collisions between the coupler 70K window and the shield itself when moving the antenna.

Two sets of modified couplers (thicker copper plating and modified cryomodule outer flange) have already been assembled and tested [11].

Superconducting Magnet

From the operational point of view the existing EuXFEL superconducting magnet [12] is absolutely sufficient for the HDC linac and does not need to be replaced.

However, the mechanical connection of the magnet tank to the two-phase pipe causes significant space constrains that can prevent the required increase of the two-phase pipe diameter while preserving the bottom part of the 5-8K shield.

LCLS-II (and SHINE) developed a conduction cooled superconducting magnet [13] that requires neither a helium tank nor a direct connection to the piping system. Preliminary investigations show that the LCLS-II magnet could fit in the existing EuXFEL cryomodule design.

The LCLS-II magnet has a further advantage: the split design of the magnet allows the installation outside of the clean room. This would reduce the risk of contamination during string assembly, since the whole quadrupole unit [14] could be replaced by a longer piece of beam pipe and a Beam Position Monitor (BPM), which are easier to handle in the clean room.

Fully Equipped Cavity String

Eight HDC cavities with helium tank and improved coupler and one superconducting magnet are the main components of the new cavity string. The following paragraphs briefly summarise the additional components needed in a fully-equipped cavity string and the impact of the HDC upgrade on these components.

Tuner assembly with piezo Currently, no modifications are foreseen for the tuner mechanical components. The tuning range and cavity stiffness are neither affected by the new cavity recipe nor the new operating mode. The availability of the motor assembly (a special EuXFEL production) and the tuning range of the piezo components to compensate for microphonics in longer pulses are the remaining open points. Typical microphonic levels of the EuXFEL series cryomodules are already under investigation at DESY and additional studies are planned at the AMTF.

Magnetic shield The sensitivity of the HDC cavities to external magnetic fields is under investigation. In case a higher sensitivity than the standard EuXFEL cavities is observed, a second magnetic shielding and better magnetic hygiene need to be implemented. The design and the magnet hygiene practices implemented for the LCLS-II cryomodules can be used as baseline for the magnetic shield modifications and to improve handling.

Coupler cooling The cooling of the main input coupler is a critical aspect to reduce its overheating during CW or HDC operation. Figure 4 shows a first improved design of the coupler thermalisation. The modifications of the 40-80 K cooling mainly aim to decrease the temperature gradient between the coupler itself and the 40-80K cooling circuit. The new design has a thicker aluminium plate and a better connection to the coupler flange than the previous EuXFEL coupler shield. First tests at the AMTF with the modified cryomodule XM99 already show smaller thermal gradients along the component. The 5-8 K thermalisation has also been modified to improve cooling, but also has two additional functions: first, the new cooling part can be installed before coupler conditioning at the dedicated test stand and stays in place during the whole cavity string assembly, significantly reducing the risk of damage and contamination during the process. Secondly, the new cooling system has also been designed to allow assembling the cryomodule with the beam pipe under vacuum (see later paragraph in this paper).

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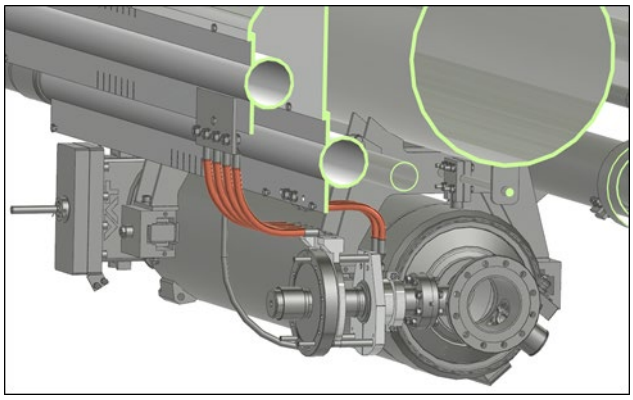


Figure 4: Coupler cooling connections.

A fundamental decision was taken about the 5-8 K thermal shield: LCLS-II and SHINE decided to remove it to allow more space for the components inside the cryomodule, despite expected higher static heat loads. The EuXFEL HDC cryomodule should keep the 5-8K thermal shield. First design studies confirm that an increase of the two-phase pipe diameter to 100 mm will still allow the installation of the complete 5-8 K thermal shield.

PROTOTYPES FOR THE HDC MODULE

First Modifications of a EuXFEL Cryomodule

The series EuXFEL cryomodule XM99 was modified in 2024 to allow first tests of some critical components for the HDC upgrade. The modifications include:

- One modified coupler cooling assembly including additional thermal sensors at coupler 4.
- Additional thermal sensors at the HOM of cavity 4 and 5 (the best performing cavities of this spare cryomodule).
- Additional cryogenic instrumentation: a thermal sensor close to a cavity chimney, pressure sensors inside the two-phase pipe at cavity 5 and 8.
- Additional vibrations sensors connected to the tuner main body at cavity 4 and 5.
- One 60 W heater attached to each cavity tank, to simulate increased heat load.
- Removal of the bottom part of the 5-8 K thermal shield.

A first test run with the modified XM99 cryomodule took place at one of the horizontal cryomodule test stands (XATB2) in the AMTF hall in winter 2024/25. The cryogenic tests were not conclusive (problems with the level measurement system did not allow testing at the required level of liquid in the two-phase pipe), but some preliminary conclusions can be drawn:

- The 5-8 W static heat load was significantly higher than in previous tests. More measurements are needed to determine the exact value, but the increase is not negligible and cannot only be related to the test stand conditions. The removal of part of the thermal shield plays here a significant role.
- First tests using the heaters at the cavity tank to simulate high 2 K dynamic heat load show that stable cryogenic operation is possible with dynamic heat loads at single cavities higher than 15 W. Further tests are planned with higher power and with RF operation.

The cryogenic diagnostic system at the test stand was modified in spring 2025 to address the level problems and the cryomodule tests are ongoing at the time of the writing.

Cryogenic Modifications of a EuXFEL Module

The EuXFEL pre-series cryomodule XM-3 and the series cryomodule XM50.1 will be used as next test cryomodules toward an HDC prototype module. The main focus on these modules will be the cryogenic modifications of the two-phase pipe. The disassembly of the cryomodule XM-3 will start shortly and the main components are being purchased. The modifications will include:

- A new two-phase pipe with internal diameter 97.4 mm. This change will require also new Titanium bellows and Titanium-Stainless Steel transition joints.
- Integration of a Joule-Thompson valve and a small level vessel in the two-phase pipe.
- Additional instrumentation, still to be defined.

First HDC Prototype Cryomodule

The cryomodule XM99 will also be used as the first HDC prototype cryomodule. The focus for this cryomodule will be on the cavity string.

The module after disassembly and refurbishment will integrate 8 new cavities treated with the Mid-T bake recipe. The procurement is being finalised and the naked cavities ready for their first acceptance test are expected at DESY in 2026. The Mid-T treatment will be performed at DESY. The cavities are planned to be integrated in the helium tank and ready for string installation by end of 2028.

The cryomodule string will be assembled following the procedure optimised by LCLS-II-HE and SHINE to minimise contamination of the beam pipe, i.e. the inner cavity surface, by reducing the cavity string venting cycles. Tooling is being modified and procedures developed to perform the assembly with the new procedure and to allow the tuner installation with the beam pipe under vacuum. XM50.1 will be the first cryomodule to test the whole procedure.

The cryomodule will also get a new two-phase pipe, a JT-valve, modified coupler cooling parts and additional sensorics, depending on the results obtained in the next years with the first two test cryomodules.

TESTING PROTOTYPE CRYOMODULES

Available Test Stands

The portfolio of DESY for testing superconducting cavities and cryomodules includes:

- Two vertical cryostats each testing up to four 1.3 GHz cavities simultaneously at temperatures down to 1.4 K.

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- Two cryomodule horizontal test stands (XATB2 and CMTB) for testing 1.3 GHz cryomodules in CW and pulsed RF mode.
- One 3.9 GHz cryomodule test stand for pulsed cryomodule tests and CW single cavity tests (a 3.9 GHz amplifier is available).

Cryogenic modifications are ongoing and planned in 2026 at the XATB2 test stand. The cryogenic design will be modified to simulate the cryogenic distribution of a string of cryomodules installed in the EuXFEL linac.



Figure 5: the horizontal cavity test stand XATBH under refurbishment

A single cavity horizontal test stand XATBH as shown in Fig. 5 is in the final steps of refurbishment and will allow testing of single 1.3 GHz and 3.9 GHz cavities with the main input coupler at 2K. Tests of tuners, magnetic shields, alignment components and other cryomodule components will also be possible at this newly available test stand which will be connected to the horizontal test stand XATB1.

CRYOGENIC MODIFICATIONS AT L3

The EuXFEL cryomodules currently operate with a maximum 2 K total heat load of ~13 W per cryomodule. In CW or HDC operation this value will increase for the L3 cryomodules up to ~30 W.

The L3 cryomodules should remain unchanged for the HDC upgrade. Calculations are being performed to verify whether additional Joule-Thompson valves are required between the modules to guarantee smooth operation with higher heat load [15].

Preliminary conservative results show that up to 20 valves might be needed in L3 to keep the velocity of helium in the two-phase pipe within the range of stable operation and avoid oscillations.

The additional valves will be mounted at the end of the cryomodules, while still installed in the tunnel. Looking at some very preliminary sketches, is looks possible to install the valve at the end of the cryomodule and connect it to the existing 2 K forward and two-phase pipe. The module connections will have to be opened to access the piping and for the installation.

A dedicated R&D program needs to be implemented to investigate this topic, once the need of additional valves is confirmed. The R&D program will include hands-on installation tests on a mock-up of the cryomodule in the tunnel. The risk of contamination of the installed component should also be analysed and minimised.

CONCLUSIONS

An R&D program is ongoing at DESY to define the upgrade scenario for the EuXFEL accelerator to be implemented in the next decade. One of the key components of the upgrade are the CW-optimised cryomodules to be installed in the first part of the linac.

A new cavity treatment is under development to guarantee Q_0 values of 3×10^{10} at accelerating gradients up to 20 MV/m. Promising results with single cells are now being transferred to 9-cell cavities.

Prototype cryomodules are being assembled and first tests are ongoing to qualify the CW-optimised components and verify the modifications needed to the existing design.

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