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OPERATIONAL EXPERIENCE WITH THE EUROPEAN XFEL SRF LINAC

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Abstract

The European X-ray Free Electron laser (EuXFEL) is a 3.4 km long research facility which generates ultrashort X-ray flashes of outstanding brilliance since 2017. Up to 27000 electron bunches per second are accelerated in a 1.3 km long superconducting radio frequency (SRF) linac to a maximum energy of 17.6 GeV. Within this time, operational experience with a pulsed RF machine has been gained and new operation modes simultaneously delivering electron bunches to 3 different SASE undulator beamlines have been successfully implemented. Recent activities on increasing the linac availability, power efficiency and duty cycle are discussed.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL), operated at the Deutsches Elektronen-Synchrotron (DESY) is a research facility which provides its users ultrashort X-ray flashes of photon energies up to 30 keV by 3 different SASE beamlines. Centerpiece of this facility is the 1.3-km-long particle accelerator consisting of 776 Tesla-type superconducting RF cavities. The accelerator is divided into 4 accelerating sections which are the Injector (I1), two bunch compression sections L1 and L2 plus the main linac L3. The maximum achievable beam energy is 17.6 GeV at a 10 Hz repetition rate delivering up to 27000 bunches per second. A facility overview is presented in [1-2] and shown in Fig. 1. The individual RF stations in sections L1 to L3 are composed of 4 cryomodules, each housing 8 cavities. Each RF station is driven by a 10 MW multi-beam klystron. Within this architecture the vector sum voltage of 32 cavities is controlled by a Low-Level Radio Frequency (LLRF) control system, based on a Micro Telecommunications Computing Architecture (MicroTCA.4) [3]. High precision control of the accelerating fields inside the cavities is essential to achieve the required beam energy and arrival time stability. Furthermore, the system has to be flexible in order to cope with variations of bunch patterns, linac energy requirements and bunch compression settings. Overall, availability, parameter reproducibility, and long-term stability are key aspects in achieving the high demands from the photon users. Developments in the direction of improving operability and automation are continuously ongoing. An overview about past LLRF system developments can be found in Ref. [4], further investigations in order to reach the maximum gradients for individual cavities are described in Ref. [5].

This contribution summarizes the operational experience of the superconducting accelerator over the last two years. Linac operation modes are described in the following section, reporting on the machine availability and experience in daily operation. The next section gives an outline in the machine performance and the attempts to foster and improve the operability and reliability. This is followed by new developments introduced to improve the flexibility of the machine operation as well as the efforts to reduce the energy consumption for the RF part of the machine. Finally this paper discusses the next steps in machine development towards the extension of the RF pulse to continuous wave (CW) operation.

LINAC OPERATION

Figure 2 presents the annual operation hours of the European XFEL since the beginning of regular user operation. Typically the machine runs for 7000 hours/year, and the user delivery has steadily ramped up to a planned 5000-hours/year in 2024. Improvements in automation and operational experience has resulted in requiring less time for machine setup and tuning. Figure 2 also shows the draft outlook for the upcoming 2 years, including a longer shutdown period in the second half of 2025.

Typical photon delivery operations run on a weekly cycle. Mondays are reserved for tuning and setup of the SASE parameters requested for the remainder of the week (agreed upon at the end of the last weekly cycle). This time is also used for routine adjustment of linac parameters which may have drifted during the previous weeks operations. If deemed necessary, access to the accelerator tunnel (where most of the accelerator systems are housed) is also scheduled during this time, typically for 2–4 hours, for more significant repairs and maintenance. Non-critical maintenance requests are collected until there are sufficient in number or criticality to schedule an access. Typically this happens every 3–4 weeks. In addition to these short maintenance periods, two longer shutdowns are scheduled per year (typically summer and winter). These are mandatory for the German safety authority for testing of the interlock systems, and are also used for more major works, routine maintenance and service tasks.

Depending on the requested photon energy, the machine is typically operated at three electron beam energy configurations of 11.5, 14 and 16.3 GeV. The final photon energy is tuned by variable gap undulators. The configuration of the injector sections including L1 and L2 usually remains the same for different final electron beam energies (2.4 GeV at the exit of L2). The final electron beam energy is achieved by the setup of the main linac L3. The two lower energies (11.4 and 14 GeV) are achieved by running the RF stations at a reduced RF voltage, whereas the 16.3 GeV beam energy is achieved by running the stations at their maximum voltage. In all cases, the RF stations are typically run at an

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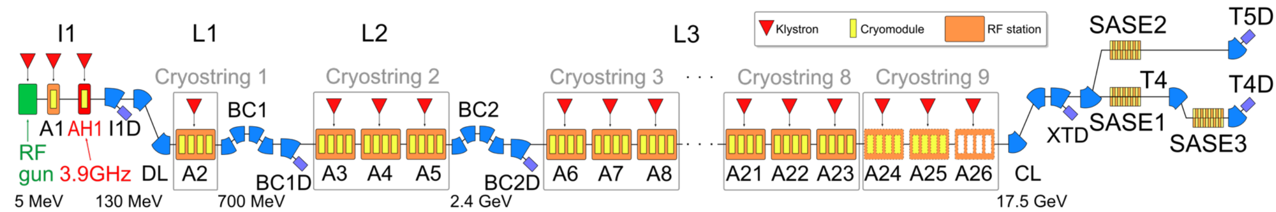

Figure 1: Schematic view of the RF stations, cryo strings and the accelerator sections of the European XFEL.

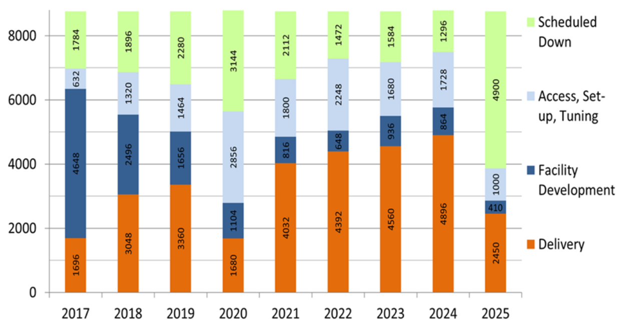

Figure 2: Annual distribution of the machine operating hours for the last years and a draft outlook for the upcoming period.

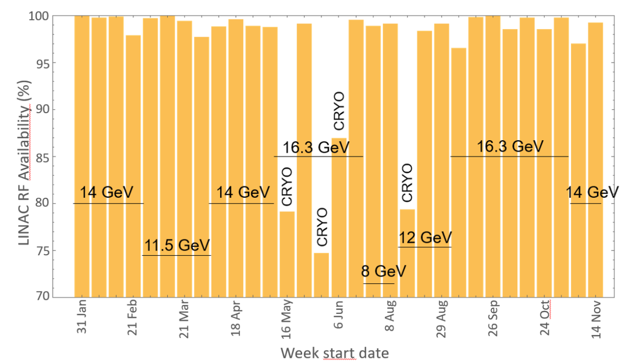

Figure 3: Linac availability for the user runs in 2022 at different voltage configurations.

off-crest phase, providing margin for redundancy, should an RF station fail. More details about the configuration modes can be found in Ref. [4].

The linac energy is setup using a Linac Energy Manager (LEM), which arranges the distribution of energy to the individual RF stations by their off-crest phases [5]. In case of a failure of one RF station, the final beam energy can still be achieved by rearranging the energy distribution. For low-voltage operation conditions it is also possible to shift individual RF stations off-beam, e.g. delaying the RF pulse such that the RF does not contribute to beam acceleration. This allows for parallel RF station maintenance and studies, facilitating additional opportunities for testing new developments. Since the cavities are still tuned on resonance, the resulting beam loading is compensated by neighbouring RF stations. These "off-beam" stations are now typically shutdown completely to save energy if not required. (See discussions on energy saving later in this paper.)

Linac Availability

The accelerator availability is one of the most critical aspects for operations since it determines how many usable photon pulses are delivered to the user experiments. In 2022 the machine availability during 4200 hours of X-Ray Delivery was approximately 96.6% excluding cryogenic system (cryo-system) cold compressor failures and 93.3% when including them. Failures of the cryo-system are rare events, but generally require up to 48-hour to recover from.

For the same period, the availability of just the SRF linacs[1] is about 96.6% for 2022. The SRF linac availability per calendar week is presented in Fig. 3. By far the largest contribution are the four cryoplant trips: the availability of the linacs increases to 99% if they are excluded.

Figure 3 also indicates the different voltage configurations the machine was operated at during the year. The fraction of operation time at high voltage increased from 21% in 2021 to 38% in 2022.

Each interruption is tracked automatically in a database and then reviewed to understand the root cause, if necessary, mitigation actions are implemented. An overview of the downtime distribution according to root-cause subsystem is given in Fig. 4

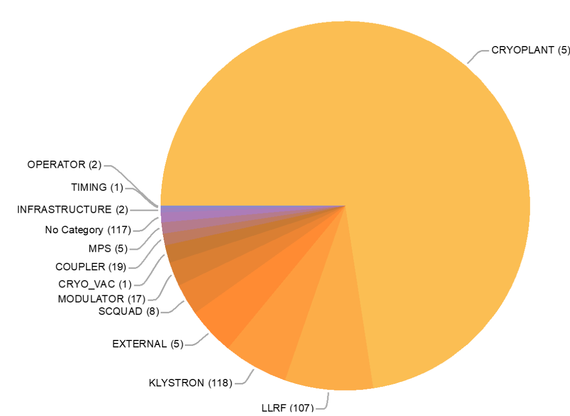

Figure 4: Total SRF linac downtime for 2022 distributed over subsystems. The number of events logged is given in parenthesis.

Usually operation in low voltage configuration of L3 reduces the number of trips and leads to lower radiation in the

[1] Defined as the availability of RF to accelerate beam.

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tunnel due to from dark current. Radiation is of particular interest since all electronics are located inside the accelerator tunnel within shielded racks. Typical kinds of events associated with radiation are single event upsets (SEUs) which are either dealt with via redundant systems or 'self resetting' systems. Generally radiation induced faults require a crate power cycle or CPU reboot which can be performed remotely. Only in a few rare cases, communication to the crate is lost, and a reboot requires tunnel access. Thanks to the energy margin in the main linac (redundancy) these interventions can usually be taken care of during a monday maintenance period as discussed previously.

For any given trip it is important to minimise the mean time to recover. RF system trips typically create a short beam interruption which is either immediately recovered by automation, or has to be acknowledged by the machine operators. In both cases a final state machine (FSM) checks and resets (allowed) states before ramping the station back up to its operating point. This reduces the overall downtime significantly with over half of the trips being recovered in less then 2 minutes, as shown in Fig. 5

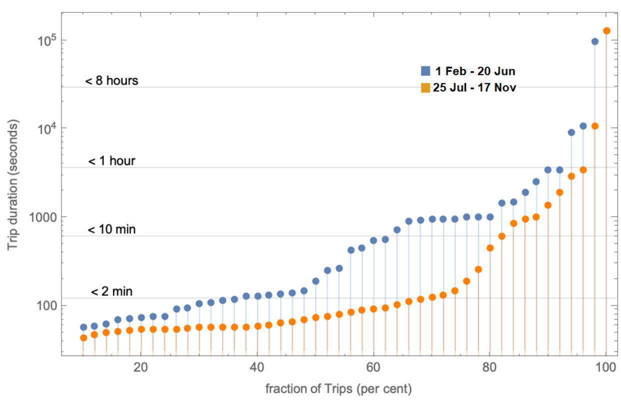

Figure 5: Fraction of the total number of trips recovered in less than a given recovery time for 2022. In the first half of the year, ~ 40% of trips were recovered in less than 2 minutes, compared to nearly 70% in the second half.

The maximum energy reach of the linac is defined by the operation voltage limits of the individual RF stations. These are in turn general limited by the experimentally determined quench voltage of the SRF cavities [5], whereby the maximum operating voltage is set to be ~ 0.5 MV/m below that limit. For a few RF stations, the limit is set by the dark-current-induced radiation measured in the tunnel. In these cases, an administrative limit is set at 500 µSv/h average neutron rate. During operations, radiation levels as well as trips caused by quench events (trapped by the LLRF quench detection system) are closely monitored for any signs of degradation to the SRF cavities. If degradation is suspected, a dedicated study is generally performed, and if necessary the maximum voltage of that RF station reduced. In some extreme cases (mainly due to a sudden activation of a significant field emitter in a cavity), that cavity is identified and completely detuned. Currently there are 26 out of the total of 776 cavities operationally detuned, 20 of them were already detuned during module testing before installation or during the maximum gradient studies campaign [6]. Since then, an average of 1 cavity per year has been detuned. Table 1 summarises the detuned cavities.

Table 1: Cavities Completely Detuned

Date	# Cavities	Reason
2017	9	CM test not passed*
2018/2019	11	gradient max.
2019	1	Field emitter
2020	2	Field emitter
2021	1	Field emitter
2022	1	Field emitter
2023	1	Field emitter
Total	26	

* 4 cavities are detuned because of coupler issue

RF OPERATION

Operating the RF system of such a complex machine requires a careful combination of several subsystems in order to achieve the required high performance and high availability. A large degree of automation and fast data processing is essential to fulfill the given specifications.

RF Stability and Performance

Among other sub components, the beam stability for the FEL strongly depends on the stability of the accelerating RF fields [7]. The LLRF system which is responsible for measuring and regulating the RF fields is a complex system of precision RF field measurement, data processing and a variety of combined control algorithms fulfilling the necessary amplitude and phase requirements of 0.01 percent amplitude and 0.01 deg phase stability [8,9]. In addition to the regular LLRF feedback loops and automation algorithms, the system is backed by a fast intra-train feedback system [10] which further reduces the final beam arrival time jitter down to sub 10 fs. In order to maintain this performance the system has to be highly automated and supported by routine checks of the stability of key parameters [11]. Furthermore, active compensation of parameter drifts arising from environmental conditions and constant monitoring of the regulation performance is done. All cavities are equipped with piezo tuners which keep the cavities on resonance by an automation procedure monitoring the detuning curves of each cavity. Frequent routine checks and adjustments of the trigger frequency motor tuners are performed to shift the piezos back into the optimal dynamic range. This procedure is called piezo relaxation and usually takes place if the cavity operation gradient has changed. An automated daily scan of the most critical LLRF parameters collects and summarizes any deviations from nominal settings to a short report. This is a very helpful mechanism to condense the large number of properties for detection of potential

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failures or mis-configurations. Depending on the severity, the problem will be solved immediately or postponed to the next maintenance opportunity. Within the given vector sum (VS) regulation architecture, the correct VS calibration is necessary to preserve the correct RF field measurement. Misalignment of the individual cavity vectors being measured will lead to a wrong computation of the VS and therefore a mismatch between the measured beam energy compared to the computed energy gain according to the RF system. Environmental influences such as temperature and especially humidity changes lead to miscalculation of the probe signal over time. In addition, measurement errors induced by the LLRF system due to digitization etc. could induce such a miscalibration. Therefore a weekly check of the individual beam transients helps to detect these kind of errors [12]. All RF pulsed waveforms and important controller data are continuously monitored and stored for ≥ 10 days for offline analysis. In case of unclear events a post-mortem analysis is possible. This is advantageous compared to the additional event-driven data storage used for the trip analysis and categorisation mentioned previously. Applications of machine learning (ML) and fault detection can make use of this data as described in Ref. [13]. Fast detection of issues and (as a next step) failure prediction is a goal of such a ML-based approach.

Operation of Multiple Beam Regions

Commonly the XFEL accelerator accommodates several user beamlines and experiments simultaneously within one RF pulse [14]. This demands independent RF tuning knobs for to manipulate beam properties like bunch compression, chirp and arrival time. This feature was originally developed for the FLASH facility [15] and later transferred to the European XFEL. The original version of this application was limited to providing just 3 different scalar RF settings per pulse which was considered insufficient for future applications.

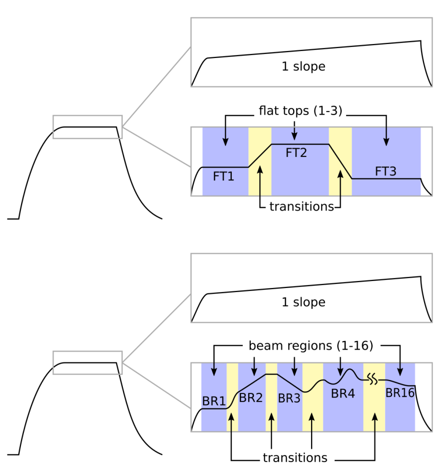

Figure 6: Previous version (top) and new (bottom) of the multiple beam regions concept.

With the upgrade of the mechanism a change in the LLRF server architecture was necessary. From the LLRF perspective an RF station can be operated in a so called scalar mode which supports a single linear variation (in time) of both amplitude and phase over the entire RF pulse flattop. This mode is used for the majority of RF stations in the XFEL main linac where just a common energy gain across all the bunches is needed. The second mode of operation is the so-called table mode, where the LLRF controller supports a predefined 9 MHz sample table for the entire RF flattop, and which is subdivided into (up to) 16 contiguous beam regions of arbitrary length. The locations and lengths of the 'beam regions' are defined and distributed prior to the RF pulse by the main timing system. The user input is done using a bunch pattern builder, which specifies the number of bunches and their destination per beam region. Generation of the RF set point table is handled by a middle layer server which now fills in the beam region areas with the user requested set points (in phase and amplitude). In stations L1 and L2 these set points are generally defined by beam attributes such as total beam voltage and chirp, which are then transferred in corresponding amplitude and phase settings in the tables. The tables can be any arbitrary waveform (see Fig. 6) within certain physical limitations. The tables are transmitted back to the LLRF controller server which fills in the 'gaps' between then beam regions (referred to as transition regions) with the necessary values to achieve the desired RF transition. The combined set point trajectory is then checked to make sure it does not exceed physical limitations of the RF system (most notably the klystron forward power, which is approximately proportional to the square of slew rate of the requested voltage divided by the cavity bandwidth). This functionality introduces a higher complexity to the LLRF controls and the high-level control server, but provides a much greater level of flexibility as well as a cleaner interface between LLRF parameters (amplitude and phase) and meaningful beam parameters (energy, chirp, arrival time etc). Having this flexibility in place lays the foundation for the next steps in adaptive algorithms to iteratively optimize the intra-pulse beam parameters based on learning from earlier pulses. Repetitive regulation errors on arrival time or energy can be reduced using a beam-based iterative learning control. The typical cavity waveforms for probe, forward and reflected amplitudes are shown in Fig. 7. Beam loading compensation and beam region transition effects are visible in the first area of the flattop region.

Reducing the Energy Consumption

Large accelerator facilities such as the XFEL have a high electric power demand. Efficient usage and sustainability is in common interest for all accelerator subsystems. In case of the RF system, modulators which provide the high voltage (HV) pulse for the klystrons are the main consumers. In a pulsed machine this HV is provided for a limited time in which the accelerating field in the cavities is built up (i.e. during the fill time) and maintained (flattop) for a short period where beam acceleration takes place. In the XFEL

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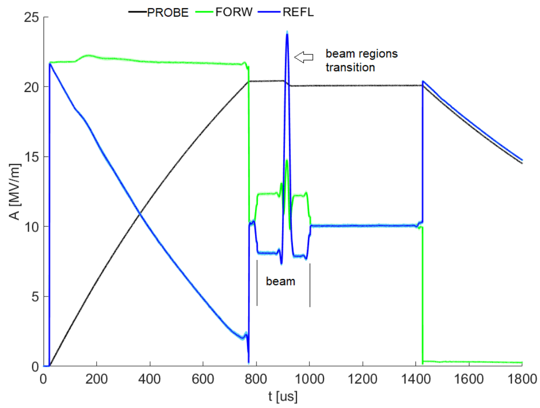

Figure 7: typical RF pulse waveforms for forward, reflected and transmitted amplitude. Beam loading compensation and RF step transition regions are visible at about 900 µs after pulse start. The included plot shows the zoomed version of the transition window.

case a typical HV pulse is about 1.7 ms long and recurs with a repetition rate of 10 Hz. Due to the limited bandwidth of the system this ideally rectangular pulse has a rising and falling edge. The actual drive signal provided by the LLRF starts with a delay to match the stable part of the modulator pulse. A sketch of this typical pulse structure is shown in Fig. 8.

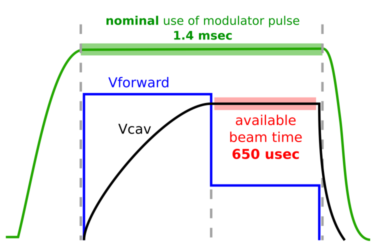

Figure 8: nominal pulse structure for an RF pulse. The RF drive to the cavity start after the modulator HV has reached its plateau.

This timing structure is optimized for regulation performance, sufficient control margin and peak power to charge the cavities fast such that the usable flattop time is maximized. In the following sections, different approaches are outlined describing the possibilities of optimization with respect to AC power consumption, without compromising regulation performance. For certain conditions the combination of these approaches is possible and intended. Changing of the loaded quality factor (Q_L) is another option to influence the LLRF pulse structure, but is not discussed here.

Reduction of the klystron high voltage As mentioned previously, the machine is operated in two different RF voltage regimes, depending on the required beam energy. The low-energy setup significantly reduces the individual cavity gradients and thus the necessary forward power. In this state, the RF stations are operated with unnecessary large power margin, and a reduction of the modulator high voltage is then possible. In terms of regulation requirements the operating point on the klystron saturation curve would be similar to the high-energy setup. A change of the modulator voltage causes changes in regulation loop phase and gain. The LLRF system has to compensate this effect by an automation algorithm which makes this change transparent to the underlying model-based controller. Boundary conditions are the beam loading compensation and transition times in multi-beam-region operation (as discussed above) which require sufficient control margin. A positive side effect of the reduced high voltage is the possible increase in klystron lifetime and a reduction of high-voltage-related trips, increasing the machine availability on average as compared to high-energy operation [16].

Extend usage of the modulator pulse Shortening the modulator pulse also reduces the AC power consumption. Since the cavity filling duration is determined by the loaded quality factor and forward power, it cannot be shortened without changing one or other of these properties. However it is possible to reduce the delay between start of the modulator pulse and the LLRF pulse such that the raising edge of the modulator pulse can already be used to charge up the cavities. In addition, the forward power requirements during the flattop are significantly lower compared to the filling time. Even when the modulator pulse is on the falling edge, there would be sufficient power margin for control and beam loading compensation. Making use of both the leading and falling edges of the modulator pulse, the modulator pulse length can be shortened by up to 200 µs to about 1.5 ms as it is shown in Fig. 9, without compromising the RF flattop pulse length [17].

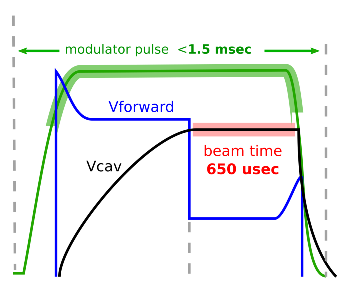

Figure 9: Extended RF pulse structure. The RF drive to the cavity starts and stops during the modulator high-voltage transition times.

The challenge in this approach is dealing with the large variation in loop gain and klystron phase during the rising and falling edges. Usually operation during the stable flattop phase of the modulator pulse is straightforward from the controls perspective, ensuring linear system behaviour. In the transient regions of the modulator pulse, careful characterization and modelling of the amplifier is required, enabling the LLRF system to manipulate the drive signal such that a

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linearized behaviour essential for the controller performance is achieved.

As a side note, this approach can also be employed to extend the RF flattop, opening up the possibility for longer bunch trains, albeit with no energy saving.

Shaping of the modulator pulse As already mentioned above, the power requirements during fill time are significantly larger then during the flattop. Maintaining the pulse flattop and compensation of the beam loading (typically in the order of 1 mA) lowers the forward power requirements to about 1/4 of the the fill time value. This opens up the possibility to further modify the modulator pulse and lower the high voltage after the filling time, better matching the shape of the RF pulse provided by the LLRF system as shown in Fig. 10. The XFEL pulse step modulators (PSM) are capable of providing arbitrary moderate rates of change of the high voltage output. As with the pulse shortening discussed above, the primary issue is the non-linearity and in particular the large klystron phase change caused by the non-constant high voltage, which then needs to be compensated for by the LLRF drive signal. This design significantly increases the complexity of the regulation loop. Furthermore, the initial setup time is increased include time for system modelling. A trade off between possible power savings and control margin has to be found. RF stations which require a higher power overhead for multiple beam regions are not suited for this kind of modification during regular operation. Finally, fast switching between various high-voltage operation modes is not possible, also from the modulator setup perspective [18].

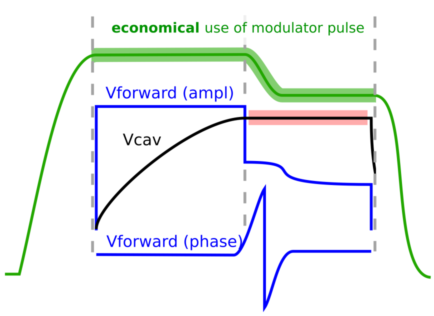

Figure 10: Shaped RF pulse structure. The modulator high voltage is tailored to the possible power overhead reduction during the RF flattop.

TOWARDS CW AND LONG-PULSE OPERATION

Accelerator development is mainly driven by challenging user demands. For an FEL the key performance indicators for the electron beam are typically maximum achievable energy, the number of lasing bunches per second and their spacing, the peak bunch current and the slice emittance. The achievable parameter space is limited by accelerator constraints such as the peak and average RF power, as well as the AC power consumption, cryogenic load and average beam power. The European XFEL is currently operated as a pulsed machine which generates electron bursts of a high bunch repetition rate, however the average duty cycle of the machine is only 0.6%. Prospects of increasing this up to 100% continuous wave (CW) are currently being evaluated with respect to a possible major facility upgrade after 2030. Several working groups have been set up to evaluate options, with a goal of producing a conceptual design report by the end of 2026. This includes continued R&D programmes on the necessary technologies to support the upgrades. The assumed constraints are that as much of the existing machine and its supporting infrastructure should be reused (or maintained), and that the existing high-energy so-called 'burst mode' should still be supported. This essentially constrains the possible parameter space in terms of average power loads as the duty cycle increases. In particular the maximum average cryogenic load at 2 K limits the maximum achievable energy, as shown in Fig. 11, where it can be seen that for a full CW machine the energy will likely be limited to ≤ 8 GeV.

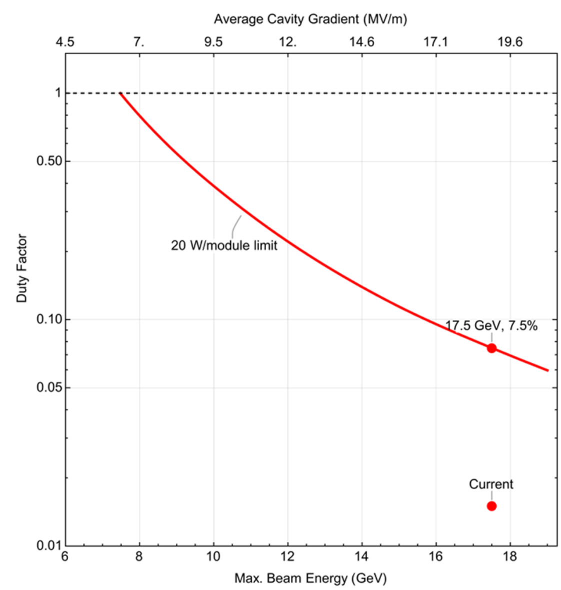

Figure 11: Maximum achievable beam energy and gradient, compared to the duty factor. The 20 W/cryomodule limitation is defining the trade off for the current machine.

CW Operation Considerations

The cryomodules and corresponding systems installed for the XFEL have been designed to be operated in pulsed mode. An upgrade proposal to a CW capable machine will require an upgrade of the the bunch compressor linacs (L1 and L2) with CW optimized cryomodules to maintain the beam energy provided to the main linac (L3). These 16 modules will need to run with similarly high voltages as the current pulsed machine, but with a 100% duty cycle. The CW optimised modules must therefore have a reduced dynamic load (higher Q_0 of the SRF cavities) as well as a cryomodule design which can support the required increased cooling, similar to those already developed for LCLS-II HE [19-20]. The original cryomodules would be installed at the end of the existing main linac, extending it by 4 RF stations and adding additional energy reach. The extended main linac would necessarily have to run at a maximum of ~ 7 MV/m as shown in Fig. 11. In addition, installation of CW-capable RF sources sufficient to drive 1 RF station are considered to preserve the current waveguide distribution and RF control architecture. The overall higher cryogenic losses of this layout will also need a doubling of the current 2 K cooling capacity, requiring an additional cryogenic plant, which is a major cost driver. Finally a CW-capable photo-injector including the RF gun would have to be installed as a second injector to the XFEL. In this scenario, the machine could in principle be operated in both, pulsed and CW mode by (remote) switching of the RF sources and motorized adjustments of the loaded quality factor (Q_L).

This proposal requires extensive R&D work which is currently ongoing on all of the mentioned fields, e.g. SRF CW photo-injector [21], as well development of high Q_0 high voltage SRF cavities, CW-ready cryomodules and development of CW LLRF systems. There is also an extensive program of CW module testing including RF power sources and waveguide components at the available module test stands at DESY.

Long-Pulse Operation

One consequence of Fig. 11 is the possibility of achieving high electron beam energies at reduced duty cycle. One relatively new and interesting regime is running 100 ms-long pulses at low repetition rates (1 Hz). This has the potential for delivering very high bunch rates per second at high energies, possibly up to 17 GeV. This "midway point" in the operating space would be fundamentally based on the CW upgrade, but additional key issues (such as achieving very high Q_L in the existing linac) bring specific challenges that need to be addressed. Simultaneously maintaining all these scenarios including the existing high-energy burst mode may prove intractable however, and remains the subject of R&D.

High-Duty-Cycle (HDC) Operation Aspects

In addition to the key accelerator modifications discussed above, the individual subsystems like diagnostics, controls, timing and LLRF also need to be taken into account. An increase of the Q_L to match the RF source capabilities has a strong impact on the field regulation in terms of regulation bandwidth and susceptibility to microphonics detuning. Special regulation strategies have to be developed to maintain the resonance frequency by piezo actuators [22, 23]. The current operation in vector sum control is challenging for this very narrow bandwidth operation. Considerations of having smaller RF sources driving one cavity each might be better suited, however this has strong implications on the overall RF architecture and capabilities. All electronics and RF sources are located in the accelerator tunnel which puts restrictions on available space, radiation hardness and maintenance possibilities. With the various SRF module test facilities on site as well as dedicated study time on the European XFEL, DESY has commenced on a rich and varied R&D programme to address the remaining outstanding questions, hopefully leading to final design decisions for the options which will be summarised in the CDR.

SUMMARY AND OUTLOOK

Since more then 6 years the European XFEL is continuously operating as an outstanding user facility with an annual operating time of 7000 h. During this period the user beam delivery has been increased to more than 4500 hours. Continuous development, performance and the increase use of automation are the key points to maintain and improve beam quality delivered to the user experiments. Close monitoring of certain cavity operating conditions allows to track and identify potential degradation of single cavities which has resulted in detuning roughly one cavity per year since the start of user operations. The new implementation of multiple beam regions has increased the flexibility and independence of machine parameter tuning for the different SASE beamlines and opens the possibilities for new adaptation mechanisms using beam-based information. The reduction of the power consumption becomes even more important. Attempts to reduce the total AC power requirements of the RF systems have been developed and are now being routinely implemented. This has a strong impact on the RF field regulation mechanisms. Depending on the operation conditions, combinations of the approaches can be applied reducing the overall power requirement per RF station by 20 – 30%. This will be a significant contribution to increase the sustainability of the facility. Finally the potential future CW operation upgrade option of the European XFEL has been discussed. There is a strong user request to increase the number of photon pulses per second. Machine implications and limitations are given. A new task force has been established to propose a conceptual design for high duty cycle operation of the European XFEL, to be completed in 2026, providing input into a major facility upgrade at the turn of the decade.

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