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FOUR YEARS OF SUCCESSFUL OPERATION OF THE EUROPEAN XFEL

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Abstract

The European X-Ray Free-Electron Laser (EuXFEL) has been successfully operating for almost 4 years, and routinely delivering 6- to 14-KeV X-rays to users (30 KeV photon energy was demonstrated). At the heart of the machine is the 1.3-km-long 1.3-GHz superconducting radio-frequency linac which can reach a maximum electron energy of 17.6 GeV, and is capable of accelerating up to 2700 bunches per RF pulse at a repetition rate of 10 Hz, delivering beam to 6 experiments via 3 SASE undulator sections. In this contribution, we present the linac operational experience and highlight some recent developments towards monitoring and improving operations and linac availability.

THE EUROPEAN XFEL

The EuXFEL comprises a normal conducting gun, a first 1.3 GHz and third-harmonic accelerating modules (A1 and AH1), a dogleg and chicane; the first linac L1 consists of one RF station (A2) with 32 SRF cavities housed in 4 cryomodules, followed by the first bunch compressor (BC1), the second linac L2 consists of three RF stations (A3-A5); the beam energy at the exit of the second bunch compressor (BC2) is 2.4 GeV going into the main linac L3 with stations A6 to A25. A26 was planned but not installed. The collimator section is followed by three undulator lines. Beam dumps are located at the end of the injector (I1D), after each bunch compressor (B1D, B2D), at the end of the linac (XTD) and at the end of the photon beam lines. A facility overview is presented in [1].

Since the main linac cool down end of 2016, the European XFEL (EuXFEL) has reached several important milestones. In April 2017, the first beam was delivered to the main dump; in May 2017, the first self-amplified spontaneous emissions (SASE) were demonstrated; in September 2017, the first user run took place. The maximum linac energy (17.5 GeV) was reached in July 2018; in October 2018, all three undulator lines (SASE1/2/3) were in operation. In November of the same year, the maximum number of bunches (2699) was accelerated. In January 2019, piezo operation was fully automated (to compensate for Lorentz force detuning), in October of the same year, beam-based feedback demonstrated a beam arrival time stability better than 10 fsec rms [2]. 2019 has also marked the start of parallel user operation in all three beam lines. In February 2020, despite the covid-19 lock down, a 30-keV world record photon energy was achieved, while in May of 2021, the linac RF demonstrated an availability of 100% for a whole week.

This contribution gives a general status report on the operation of the accelerator since its start in 2017, with an emphasis on the superconducting linac and its availability. Machine operating hours are introduced in the introduction. The following section exposes the linac configuration strategy to deliver the various beam energies requested by users. The next section gives a short report on some key components of the accelerator. Section four presents the linac availability and is followed by an outlook on the future of the accelerator.

Overview of Machine Operating Hours

Figure 1 summarizes the machine operating hours since start-up in 2017. The last column depicts the typical or target time distribution. With the exception of 2020, where the global covid pandemic forced a shutdown longer than anticipated, the photon delivery hours have been steadily increasing, the target being around 4400 hours (i.e. ≈ 183 days). The scheduled down time (≈ 10 weeks) would be difficult to reduce further. It includes winter and summer shutdowns, mandatory for the yearly operation approval from the German safety authority (TÜV), routine maintenance activities as well as bank holidays. The increased photon delivery time over the years has been enabled by the reduced commissioning or machine development time. The category labeled “Access, Set-up, Tuning” corresponds to machine setup or tuning after an operation interruption, or between different machine settings, as well as unscheduled access time (whether remote or in-situ tunnel interventions) required to fix faulty subsystems.

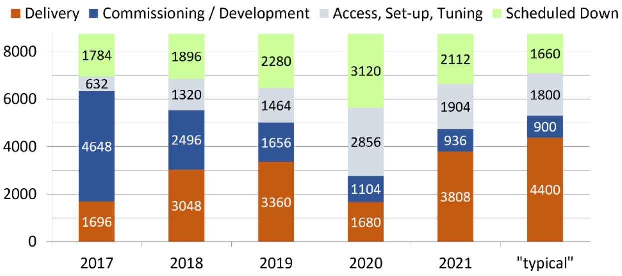

Figure 1: Operation hours distribution from the start-up in 2017. The last column, “typical”, shows the target hour distribution.

LINAC OPERATION CONFIGURATION

Typical user runs require linac energies ranging from 11.5 to 16.5 GeV. The injector section mode of operation is usually kept constant to match the 2.4 GeV energy required at the second bunch compressor. Therefore, the main energy

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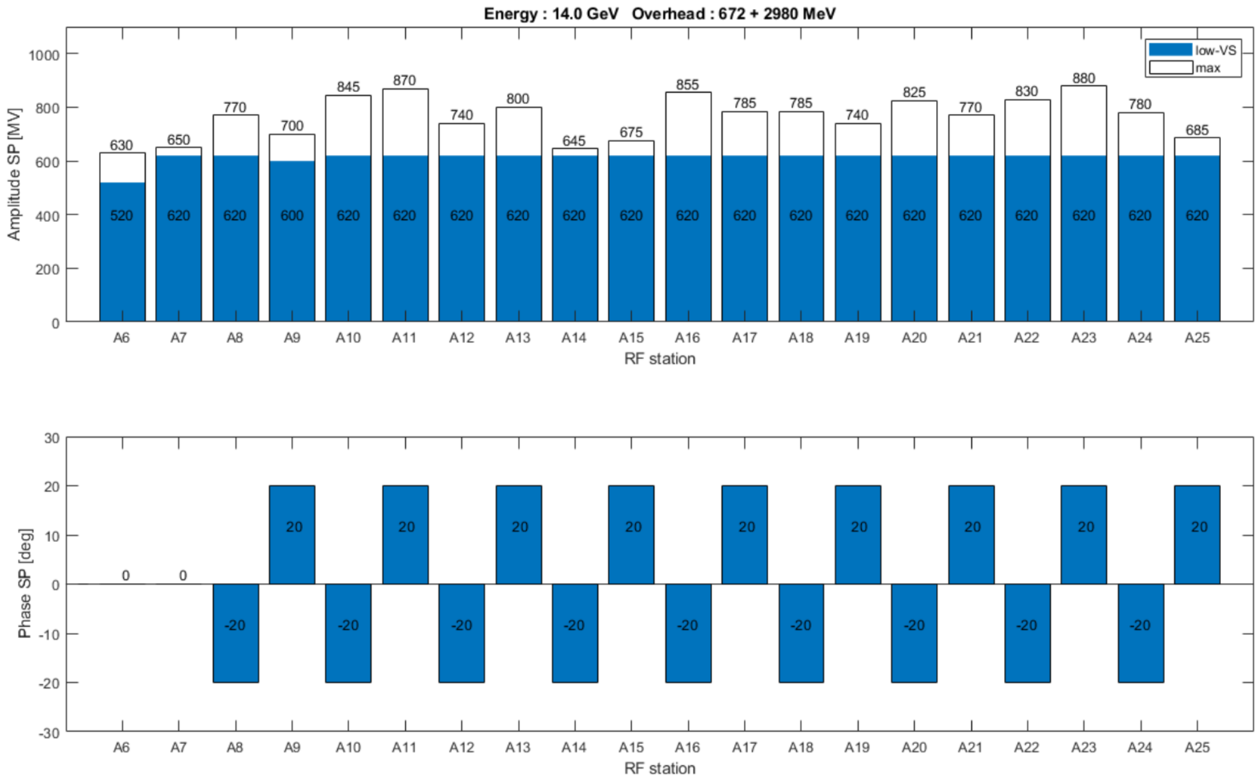

Figure 2: Linac 3 configuration for low- and maximum vector sum operation. A6 and A7 are kept on crest, all other stations are operated off-phase to adjust to the required beam energy. 872 MeV is the energy overhead that can be used by placing the stations on crest without changing the current gradient. 2980 MeV is the energy overhead that can be used by set all stations to their maximum gradient.

modulation is achieved using the stations in L3: RF stations A6 to A25. To accommodate for the different user energy requests in a simplified way, two modes of operation have been defined: the low- and the high-vector sum L3 configurations, shown in blue (respectively white) on Fig. 2.

In the low-VS configuration, most stations are operated at or around 620 MeV (Fig. 2 top), providing a total energy ranging from 11.5 to 14.5, simply by adjusting the phases (Fig. 2 bottom). The alternating phase sign scheme is introduced to minimize the single-bunch energy chirp. The control system allows the beam energy to be modified with a single knob, by suitably adjusting the phases of the RF stations. The energy overhead available by phase adjustment is indicated above Fig. 2. If the energy requested goes beyond the phase margin, then the station gradients need to be increased. Typically, this is done by changing the entire L3 to the so-called high-VS configuration, where all stations are operated at their maximum reliable gradient. This allows for a final energy of 16.5 GeV with enough phase margin to absorb any one station loss.

Should a station fail, it is placed off-beam, and the energy server would rotate all other stations on-crest to absorb the energy loss from the failed station. Keeping the station off-beam (i.e. shifted in time with respect to the machine burst pattern) allows for troubleshooting it and repairing it in parallel to normal beam operation. If the station can be fully recovered remotely (most cases), the station just remains as a spare station until it is placed back on beam. If the failure is more severe and requires a more invasive intervention, a tunnel access is then scheduled at the next opportunity.

OVERVIEW ON SOME ACCELERATOR KEY COMPONENTS

RF Gun

The normal conducting RF gun, in operation since 2015 has demonstrated its design parameters [3]. It is routinely operated at 10-Hz repetition rate, at a gradient of 56 MV/m, corresponding to a klystron power of 6 MW for a total beam region (RF flat top) of 560 μsec. The bunch charge is typically 0.25 nC at a laser repetition rate ranging from 1 to 4.5 MHz. Several automation algorithms have been implemented in the last 4 years: matching the gun resonance frequency during ramp up allows for an efficient trip recovery (< 10 minutes) [4]; RF pulse width modulation is used to fine tune the RF gun frequency beyond what the 0.1 mK cooling water regulation can achieve [5]. A fast RF protection was developped to trigger whenever sudden high reflected power is observed. The faulty pulse is truncated, nominal operation is recovered on the following pulse, hence minimizing down time. The gun cathode was exchanged after the first three years of operation, mostly due to its inhomogeneous emission. The gun operates reliably for pulse lengths up to 540 μsec. Operating at longer pulse length increases the gun trip rate (one trip every two to three days).

Third Harmonic

The EuXFEL has one third-harmonic cryomodule, hosting eight 3.9-GHz SRF cavities, powered by an 80-kW peak-power klystron manufactured by CPI. The cavities are typically operated between 5 and 7 MV/m, are equipped with 3-stub tuners to set the loaded quality factor to $Q_L = 3.3 \times 10^6$ for a corresponding klystron power of 6.3 kW per cavity. The RF pulse shape follows the same profile as for all other SRF cavities: 750 μsec fill time and 650 μsec flat top. The cavities are not equipped with piezo and their sensitivity to helium pressure was measured to be 62.4 Hz/mbar. The measured intra-pulse and pulse-to-pulse RMS stability is better than 0.02 % and 0.02 degree in amplitude and phase respectively. The module has been operating very reliably with no issues since start-up.

Klystrons

Since 2017, only three klystrons have been taken out of the tunnel for repair, two due to a water leak in the solenoid, one due to a problem at the cathode. The klystrons typically deliver 3.33 MW, (resp. 4.97 MW) average power for beam energies up to 14.5 GeV (resp. up to to 17.5 GeV). The weekly average number of klystron events is given in Table 1.

Table 1: Number of Klystron Events per Week

2017	2018	2019	2020	2021
6.32	3.54	2.74	2.96	1.18

A fast reaction system was developed [6] to monitor the high-power signal (input and output of the klystron) and stop the low-level drive in case a break down is detected. The fast reaction time (<800 nsec) of this monitoring system avoids a rise in vacuum, so that the next pulse is fully nominal. Since 2021, a campaign is on-going to optimize the high-voltage modulator settings to lower the strain on the klystrons, to reduce the breakdown rate and possibly extend their lifetimes, while preserving enough RF head room for regulation. Before high-voltage optimization, klystrons were operating around 78% of saturation power (on average). The regime after optimization is expected to be around 85% of saturation power.

Cryogenic System

The initial cool down started in December 2016 and lasted two weeks. The helium pressure during normal operation is very stable: 30 mBar ±0.1 mBar. As a preventive maintenance, the cold compressor motor bearings are exchanged routinely every four months. The down time associated with this cold compressor maintenance is less than 36 hours. Fluctuations in dynamic heat load due to controlled (gradient increase, ramp down) or accidental (interlock) change in linac energy are compensated for using heaters. This counter measure guarantees a constant helium flow, essential for the cold compressors. A controlled failure of the cryogenic system took place in June 2021 to evaluate how fast the cavities would warm up should the helium flow stop, while preserving the cryo pump operation. The test was carried out for 10 hours, the observed increase in cavity temperature was from 2K to 4K for the main linac and from 2K to 9K in the injector. The 3.9-GHz cavity temperature increased the most, up to 15K. The faster increase in the injector was to be expected since it has a significantly shorter cryostring.

Cavities

The 776 SRF cavities (1.3 GHz) are operated on average at 18 MV/m for low energies (11- 14.5 GeV) and at 22 MV/m for high energies (14.5 - 17.5 GeV), corresponding to the low- and high- vector sum configurations introduced in linac configuration section. The gradient spread and corresponding forward power, sampled at beam time, are given in Fig. 3.

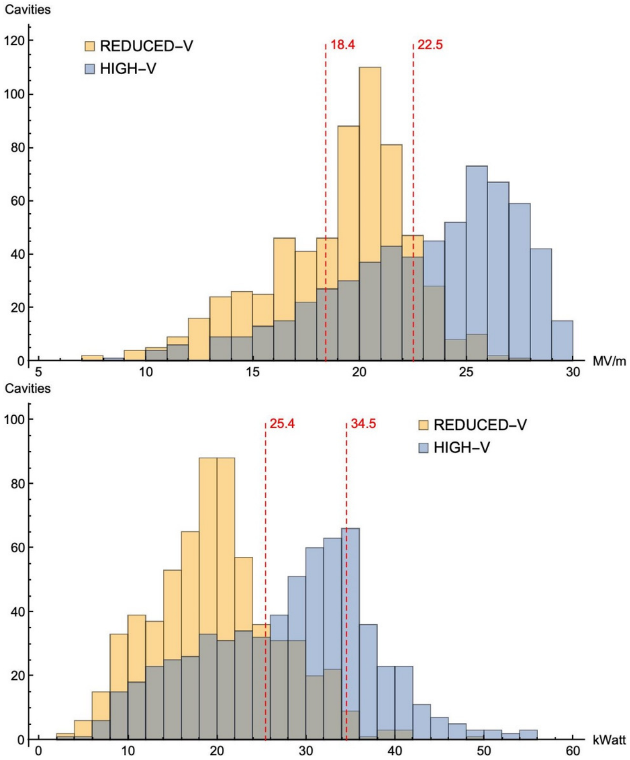

Figure 3: Gradient spread (top) and corresponding coupler power (bottom) for a typical low-voltage (up to 14.5 GeV) and high-voltage (max) configuration. The average gradients are 18.4 and 22.5 MV/m respectively. The coupler forward power is sampled at the beginning of the beam time; the peak power (i.e. during the cavity fill time) is approximately four times higher.

The sensitivity to helium pressure for the 1.3 GHz cavities was measured to be 39.6 ±3 Hz/mBar [7], and the reported pulse-to-pulse RMS stability of the RF pulse is better than 0.01 % and 0.01 degree in amplitude and phase respectively [8].

The motorized external loaded quality factor (Q_L) are set to $(4.6 \pm 0.01) \times 10^6$ and are routinely checked and adjusted when needed. Lorentz force detuning is compensated for by a piezo sinusoidal excitation preceding each RF pulse; a feedback controller adjust the piezo excitation parameters (DC offset, and AC amplitude) to keep the cavities on resonance, typically within ± 10 Hz over the beam time duration. Figure 4 shows a typical detuning and cavity Q_L distribution.

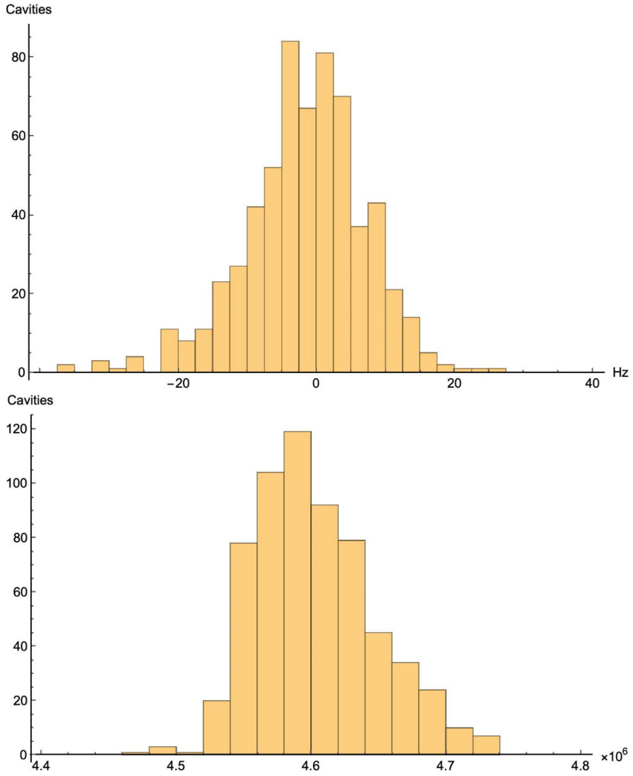

Figure 4: Cavity detuning (top) and loaded quality factor Q_L distribution (bottom) during standard 14 GeV operation. The mean detuning is 0 Hz with 18.5 Hz RMS spread. The mean Q_L is 4.60×10^6 with 0.05×10^5 RMS spread.

As of June 2021, a total of 23 cavities are kept detuned and are not used for beam acceleration. Four cavities are detuned because of coupler over-heating. The corresponding couplers were disconnected from the waveguide. One cavity is detuned due to a specification error in the waveguide distribution system; four cavities are detuned due to excessive field emission or too low quench gradient. These cases were known before installation of the cryomodule in the tunnel. During early operation in 2017, one cavity proved to cause excessive cryogenic losses and was detuned. In 2018, a campaign took place to identify the limiting cavity (due to quench) in each RF station and observe if a higher overall vector sum voltage could be achieved by detuning it. Twelve cavities were detuned through this exercise [8]. Since then, two were tuned back on resonance, since automatic Lorentz force detuning compensation (introduced in 2019) influenced the limiting cavities. More cavities are likely candidates to be retuned for the same reason. The remaining three cavities were detuned during operation in 2019 and 2020 due the onset of a strong field emitter. One of them clearly started emitting during operation. For the other two, it is not clear if the observed field emission was not preexisting since early commissioning, since the tools and the procedure used to decide if a cavity is too strong a field emitter were not set up until 2019. The next section explains the monitoring and the approach with respect to field emitters.

Radiation Monitoring

The radiation observed in the tunnel is mostly from cavity-induced dark current. The accelerator electronics is located in racks inside the tunnel, under heavy concrete shielding blocks, providing approximately a factor of 20 damping for gammas. The radiation level is measured outside of the racks with RadFETs [9], inside of the racks with RadCons [10], and along the linac using the moving robot MARWIN [11], transporting a gamma and neutron detector (PANDORA). Figure 5 shows the neutron readings measured during a routine scan of the accelerator tunnel, at two different energy levels (14.0 and 17.5 GeV).

A new field emitter appearing during operation will be detected as a sudden increase in the measured radiation. Several alarm systems are in place to send notifications (via emails) when this happens. To date, the mitigation strategy consists of scanning with MARWIN the RF station where the new emitter has been reported, and parking the robot at the location of the neutron peak. In most cases, this peak location does not correspond to the location of the field emitter, but rather where the quadruple mounted at the end of each cryomodule is located. Indeed, the emitted dark current is captured and accelerated by neighboring cavities (upstream or down stream) and scattered at the quadrupole due to the energy mismatch, resulting in a radiation shower. Once MARWIN is in place, cavities upstream and down stream of the observed radiation peak are detuned one at a time (≈ 2 kHz). If the detuned cavity was merely accelerating dark current, the observed radiation is only slightly affected. On the contrary, if the detuned cavity was the field emitter, the radiation drops significantly (exponentially with gradient). Once the culprit is found, it is taken out of the vector sum RF control, and detuned by ≈ 30 kHz to minimize its impact on beam transport. This procedure was used for the three strong field emitters detected in 2019.

AVAILABILITY

In May 2019, the linac operations group was created, combining expertise from SRF cavity system, high-power RF, low-level RF controls as well as run coordination, in an attempt to better monitor the availability of the linac and understand how to improve it. The group also helps establishing procedures, improving change and configuration management and fosters accelerator developments and

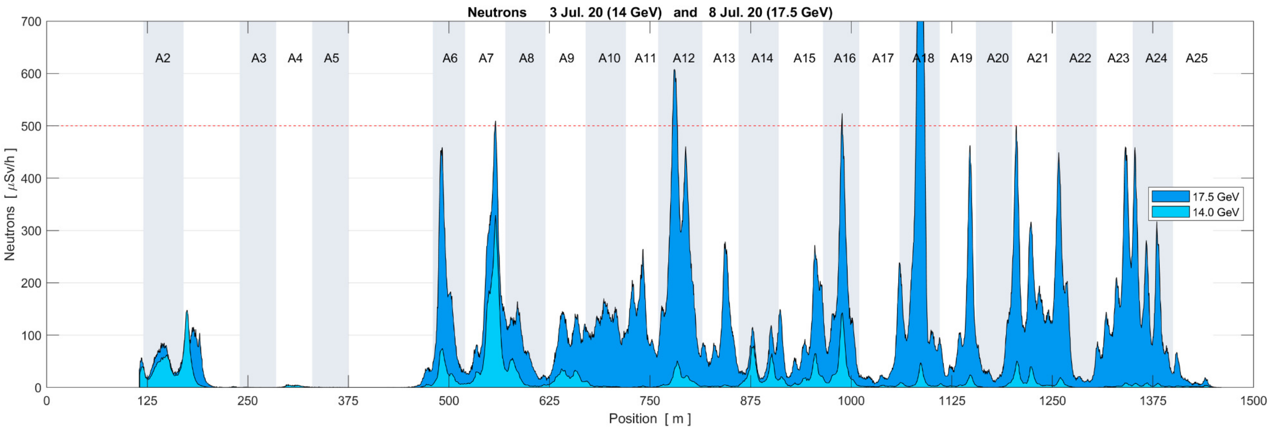

Figure 5: Neutron map of the accelerator at 14.0 and 17.5 GeV. The administrative limit is 500 μSv/h. A12 was operated above its maximum allowed gradient (radiation limited). A18 had a newly detected field emitter. After investigation, the emitting cavity was detuned, returning the overall neutron radiation of the station below the administrative limit.

studies. The first outcome was a tool developed to track all machines trips, identified by a loss of RF in any station. Using the data available in the control system, the tool can track the history of interlocks and identify a time stamp, a recovery time and a likely root cause for the trip. The tool also automatically saves a snapshot of the DAQ data (RF waveforms) for postmortem analysis. All this meta data is saved into a database. The trips are reviewed weekly by the operations team. In most cases, the root causes were correctly identified by the tool; corrections or adjustments are made when needed. The outcome is a careful tracking of the linac down time, accessible online. The tool provides categorized trip root causes (modulator, klystron, couplers, cryogenics, vacuum, LLRF, infrastructure, unknown, etc.) and a database summarizing the trips along with corresponding RF waveforms extracted from the DAQ. Newly developed algorithms exploiting machine learning techniques are also making use of this saved data sets [12].

Around the same time, a systematic review of trips causing more than four hours down time was established, following an industry standard, the so-called eight-disciplines problem solving (8D). This quality assurance approach consists of building a team of expert to analyze the trip, identify its root cause, analyze short reactions, defined long-term solutions and follow up on their implementation. The goal is either to avoid a recurrence of this issue if possible, or minimize its impact on the availability of the machine. The number of 8Ds initiated, still open or closed as a function of year is illustrated in Fig. 6.

It is likely that these 8D reviews along with the systematic tracking and analysis of machine trips performed by the linac operation team helped improve the overall accelerator availability. Operation at the reduced gradient (energies up to 14.5 GeV) show weekly machine availability above 98%, against 95% when the RF stations are operated at their maximum energy. To establish these numbers, an experiment was performed in Fall of 2020, where the linac was operated for seven consecutive weeks at the reduced voltage, followed by five consecutive weeks at the maximum voltage (although the user run only called for two weeks at the highest energy). Lower beam energies were reached from the high voltage setup by increasing the off-crest phase, as explained in in the linac configuration section.

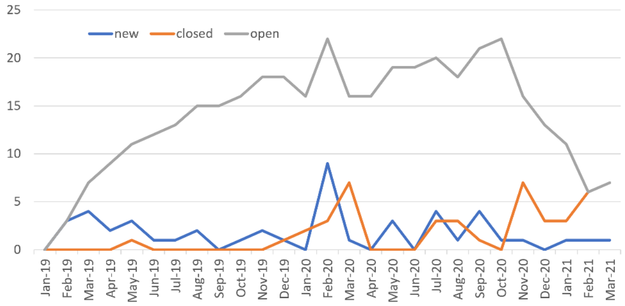

Figure 6: Number of 8D reports started, closed or still open since the implementation of this quality control practice in 2019. Each 8D report triggers a number of follow-up actions that are also tracked. A report is closed when all actions identified during the analysis are implemented or closed
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The total operation time for these 12 weeks is 125.2 hours, out of which 27.9 hours at the reduced voltage and 36.9 hours at the maximum voltage are allocated to down time due to trips, machine ramp down and up, or tunnel access. Details are summarized in Table 2.

Running at the maximum operational gradient implies an increased cavity quench rate, higher field emission, more klystron and coupler events (arcs, sparks) and less regulation headroom, so overall a decrease in availability. During the five weeks maximum energy run, the number of detected cavity quenches was 2.5 quenches per week (compared to <1 at reduced voltage), the detected radiation level from the RadCon increased six times (from 10 to 60 μGy/hr), the number of recovered single events upset (SEU) detected in the low-level electronics located under the concrete shielding inside the tunnel increased nine times (from 6.3 to 56 SEU /week). Recovered SEUs do not have an immediate impact on operation but are probably an indication of long term degradation of electronics in the tunnel.

Emergency Detune

When the global pandemic hit Germany in early spring 2020, it was not clear if the personnel allowed on site would be able to guarantee safe cryogenic operation of the facility. It was therefore decided to place the EuXFEL in a so-called light shutdown. Before the lock down, all 784 SRF cavities (776× 1.3 GHz and 8× 3.9 GHz) were detuned to their safe position, typically, 100-200 kHz below the 1.3 GHz resonance. This safe position avoids mechanical deformation of the cavity should the linac be warmed up in an uncontrolled way, while preventing tuner motor over-usage. To speed the process up, eight operators worked in parallel, but it nonetheless took nearly 16 hours for all cavities to reach their detuned state. This was due to the manual detuning process, to the limitation of simultaneously driving a maximum of four motors per cryomodule to avoid over currents, and finally to several driver failures (power supplies) observed during the detuning, which required tunnel access. The facility remained in light shutdown over March and April 2020. In May, it was decided that remote control of the facility with minimal personnel on site still allowed EuXFEL operation while complying with the COVID-19 safety regulations. Retuning the 784 cavities was organized in a similar way as the detuning, again, requiring close to 16 hours. This experience triggered the need to have a one-push button emergency detuning tool. This tool does not track the actual cavity detuning with RF but only relies on the reported tuner motor position. It assumes availability of the critical subsystems: control system and network access is needed, the motor drivers are powered, the "cryo-OK" safety mechanism (preventing tuner motor operation in case motors are warm) is bridged. This tool was developed and first tested in early June 2021 on the entire linac. Notwithstanding a few cases of motor driver failures requiring a follow up intervention, all cavities could be automatically safely detuned within 45 minutes. Retuning to resonance took the same time.

Table 2: Machine Availability over 7 (5) Weeks of Operation at Reduced (Maximum) Voltage

	unit	reduced-V	max-V	total
availability	%	98.7	95.6	97.9
total operation time	days	90.4	34.8	125.2
number of events		124	176	300
total down time	hrs	27.9	36.9	64.7
trips	hrs	13.5	26.6	40.1
linac off (access)	hrs	10.7	7.6	18.3
ramp up/down	hrs	1.8	1.7	3.5
development	hrs	0.8	0.8	1.9

OUTLOOK

A few milestones are coming up in the near future: the implementation of a new beam regions concept, allowing maximum flexibility when defining and distributing different beam attributes (energy compression, chirp) to different users within a single RF pulse. The fast beam-based feedback will also soon include the bunch compression monitors as input to the feedback controller, in addition to the existing bunch arrival time monitors. An R&D program is on-going to investigate the feasibility and offer solutions to the RF control challenges associated with a continuous-wave upgrade of the European XFEL. A parallel effort focuses on possible options to increase the RF flat-top length available for beam acceleration without changing the installed equipment: adjusting the cavity Q_L and fill time, making full use of the modulator RF pulse including fill- and fall time transitions, investigating non-square modulator pulse widths, etc... Building on the trip database accumulated over the years, new tools are also being developed to perform further analysis and trip categorization, comparing the cavity trace to a model-based predicted behavior. Future uses of the autonomous robot MARWIN are also being discussed. Last but not least, improving or even just maintaining a high linac availability is a continuous effort, especially as the number of user runs requesting maximum linac energy is expected to increase. To this extent, new tool developments are focused on providing more automation, subsystem health monitoring and achieving maintenance prediction.

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