RF-BASED ENERGY SAVINGS AT THE FLASH AND EUROPEAN XFEL LINACS

J. Branlard*, V. Ayvazyan, A. Bellandi, C. Christou, M. Diomede, T. Froehlich, S. Göller, H. Schlarb, C. Schmidt, V. Vogel (Fogel), M. Vogt, N. Walker
Deutsches Elektronen-Synchrotron DESY, Germany

Abstract

Several measures were developed and deployed at the pulsed linacs FLASH and European XFEL operated at DESY in order to reduce the energy consumption of the RF systems. A staged implementation of several techniques allowed energy savings up to 25% for both facilities, at the cost of reducing the RF overhead and increasing the complexity of the low-level radio frequency (LLRF) system. However, through tool development and automation, the energy saving linac configuration could be implemented without compromising the RF stability, maximum beam energy, accelerator availability and with minimal impact on the setup time.

INTRODUCTION

One third of the European X-ray Free Electron Laser (EuXFEL) accelerator energy consumption comes from generating the radio frequency (RF) fields necessary to accelerate the electron beam. Over the last couple of years, multiple efforts to optimize the energy consumption translated into significant energy and cost savings. A first initiative to lower the HV drive of the accelerator high-power sources (klystrons) was introduced at EuXFEL in 2022, removing the unused klystron power overhead, while preserving enough margin for field regulation. This first step already provided 10-15% savings [1]. As a second step, modifications of the high-power modulator shape combined with a more sophisticated use of the available klystron power allowed to bring the savings up to 25%, without compromising the beam quality necessary for photon science. A similar effort at the Free Electron Laser in Hamburg (FLASH) was carried out, optimizing the modulator high-voltage (HV) shape with tighter margins around the RF pulse for all accelerating stations including the RF gun. Altogether, the RF power consumption could be reduced by 200 kW, also corresponding to a 25% saving. A conceptual description of these techniques is presented in the first section of this report, including their impact on the RF and some insight on the technical solution. The second and third sections present the energy saving achieved at FLASH and EuXFEL, followed by a conclusion.

CONCEPTUAL DESCRIPTION

The approaches presented here to achieve energy saving by shaping the modulator HV can be applied separately or together to combine their benefit.

Profiling the Modulator Shape

The most direct approach to reduce the power consumption is to lower the modulator HV, denoted as circle 1 in Fig. 1. Both FLASH and EuXFEL have different energy working points requiring different klystron power levels. Changing the HV set point affects the power level where klystron saturation occurs. One can then experimentally find the minimum HV settings that will guarantee the maximum klystron power required to cover typical operation scenarios, with the caveat that not all modulator voltages result in a stable klystron working point. Optimizing the modulator HV will effectively reduce the RF overhead necessary for field regulation. Accurate resonance control using piezo and efficient field control using on-resonance cavity filling with the LLRF system is essential to efficiently use the available RF power [2], hence allowing for maximum HV reduction (i.e. operating just a few percent from klystron saturation).

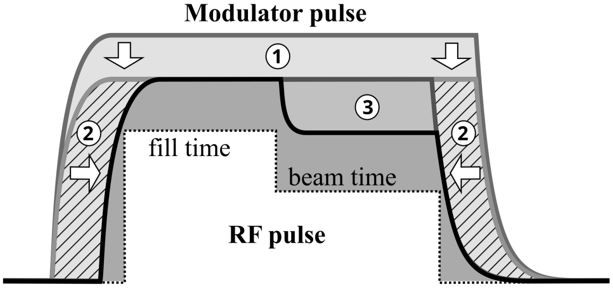

Figure 1: Different stages of modulator HV pulse shaping (solid line): lowering the HV (1), shortening the modulator pulse (2), introducing a step in the second half of the pulse (3). The dotted line illustrates the RF pulse scheduled during the modulator pulse.

The next step in profiling the modulator pulse focuses on its time duration. In the original high power settings, the width of the modulator HV pulse is chosen so that a stable plateau is reached and kept for the entire duration of the RF pulse, including some margins before and after. Some power savings can hence be achieved by reducing, more or less aggressively the duration of the HV pulse, eating up the margin before and after the pulse. For reference, the duration of the fill time and beam time (or flat top) are listed in Table 1 for both facilities. This point is illustrated Fig. 1 circle 2. The reduction in pulse duration is combined with a change of trigger delays so that the savings are distributed before and after the RF pulse. Due to the non-symmetrical shape of the modulator pulse (i.e. soft knee at the end of the fill time against an abrupt drop at the end of the pulse), the

---

* julien.branlard@desy.de

Table 1: SRF Pulse Duration for FLASH and EuXFEL

Facility	**Fill** (µs)	**Flat** (µs)	**Total** (µs)
FLASH	500	630	1130
EuXFEL	750	650	1400

pulse can typically be shortened more at the beginning of the RF pulse rather than at the end. Another argument in that favor is that the first part of the RF pulse is used to fill the cavity, as opposed to the second half of the pulse dedicated to beam acceleration where field stability is paramount.

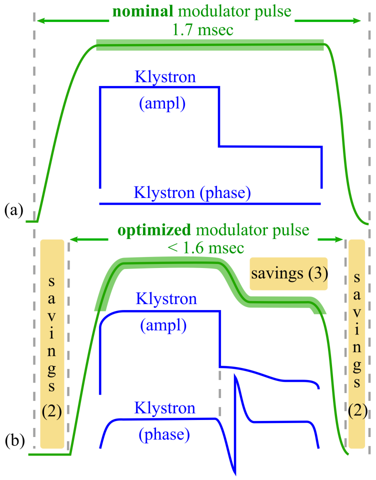

Figure 2: Schematic representation of the modulator pulse (green) scheduled around the RF pulse (blue), for the unmodified case (a) and for the shorter modulator pulse including a step down during the beam time (b). If left uncorrected, the resulting change in gain and phase of the klystron output signal over the course of the RF pulse make field regulation extremely challenging.

Finally, a third approach can be applied to further lower power consumption by making use of the fact that the RF power required during the second half of the pulse is significantly lower than that required during the cavity fill time (typically one fourth). This comes from the way FLASH and EuXFEL are operated, with low to moderate beam loading (up to 1 mA). This means that the RF overhead during the beam time (second half of the RF pulse) is larger than necessary. One can then introduce a step down in the modulator profile, as denoted by circle 3 in Fig. 1. EuXFEL is equipped with pulse step modulators, consisting of 24 700V-modules that can freely be configured or shifted in time to generate such slopes. FLASH on the contrary is equipped with bouncer modulators with a built-in resonator circuit to flatten out the decay of the capacitor bank [3]. This older design does not allow generating a step in the modulator pulse. As a consequence, the RF power saving corresponding to point 3 could only be implemented at EuXFEL. The next section highlights the negative impact of these approaches on the RF klystron output pulse, as well as the countermeasure implemented in the LLRF system.

Impact on the RF Signal

As mentioned earlier, changing the modulator HV will affect the klystron gain and phase. This is illustrated in Fig. 2. In the upper plot, Fig. 2 (a), the entire RF pulse (blue) fits within the flat section of the modulator pulse (green). In Fig. 2 (b), the modulator pulse length is reduced and includes a step down during the beam time. The RF pulse now starts during the rising edge (“knee”) and finishes during the falling-edge of the modulator pulse. These changes introduce strong variations in the amplitude gain (up to 50%) and phase (up to 360 deg) of the high power chain. Without compensation, this RF pulse cannot be used for beam acceleration.

Dynamic Output Vector Correction

A scalar output vector correction (OVC) was already present in the LLRF firmware. This single constant correction is applied in amplitude and phase to the entire RF pulse. Typical applications include slow drifts compensation (hours, days) in the high power chain. This scalar (or static) OVC can also be used to compensate for the loop phase and gain changes resulting from lowering the modulator HV (Fig. 1 circle 1) but it cannot cope with varying changes over the course of the pulse (Fig. 1 circle 2 and 3). A new firmware block was then introduced providing complex multiplication at the output of the drive signal chain. Based on a lookup table, each sample point of the LLRF drive can be rotated individually in phase and scaled in amplitude.

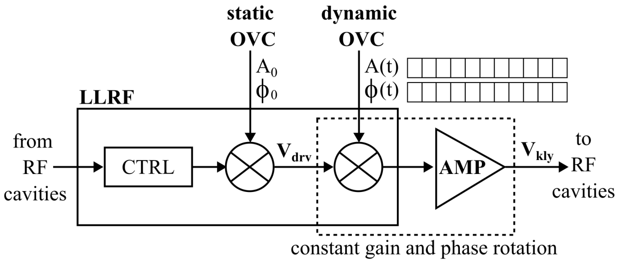

Figure 3: The dynamic output vector correction ensures that the combined effect of the LLRF drive modulation and the high power amplifier results in a constant input-output gain and phase rotation.

As illustrated in Fig. 3, this newly introduced array, referred to as Dynamic OVC (DOVC), allows to compensate for predetermined amplitude and phase non-linearities in the signal chain down stream of the LLRF, whether coming from the klystron itself (klystron non-linearities) or resulting from profiling the modulator pulse as described above.

To define the DOVC tables, the signal at the output of the klystron V_{kly} and the LLRF drive forward signal V_{drv} are measured. The complex ratio $G = \frac{V_{\mathrm{drv}}}{V_{\mathrm{kly}}}$ is computed and low-pass filtered. The correction table is then $T_{\mathrm{linear}} = \frac{G_{\mathrm{target}}}{G}$, where G_{target} is the desired gain between the klystron input and output, which can be chosen arbitrarily. Note that if the characterization is performed with a non-empty DOVC

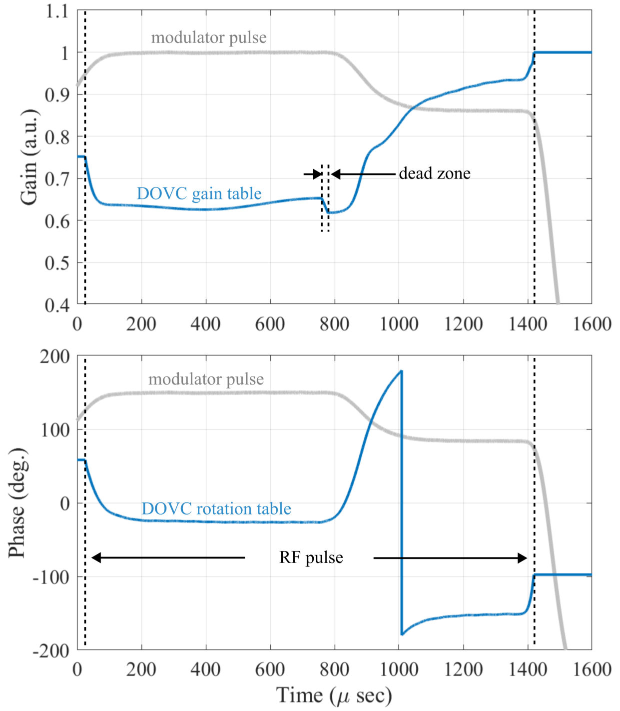

Figure 4: Example of gain and phase lookup tables for the dynamic OVC.

table, the old table T_{old} is scaled to compute the new one $T_{\mathrm{new}} = T_{\mathrm{linear}} T_{\mathrm{old}}$. In practice, and since the amplifier is not linear, only a fraction of the correction T_{frac} is applied. The correction is measured and applied iteratively until the table converges,

$$T_{\mathrm{frac}} = C_{\mathrm{f}} T_{\mathrm{linear}} + (1 - C_{\mathrm{f}}) T_{\mathrm{old}}, \tag{1}$$

with $C_{\mathrm{f}} \in [0 - 1]$. As a safety measure and to avoid driving the klystron in saturation, the gain table is clamped in amplitude. Furthermore, a *dead zone* was introduced during the transition from fill time to beam time where the forward power drops significantly, possibly inducing gain spikes. Instead, the table gain correction is interpolated between the two edges of this region (typically 10-20 µs). An example of the DOVC gain and rotation lookup tables is given in Fig. 4. The correction for the modulator step starting around 800 µs can clearly be seen on the gain and on the phase tables. The phase and gain rolls induced by the modulator rising edge during the first 50 µs and falling edge around 1400 µs are also explicit. Since the table size is larger than the actual RF pulse, the last value is held till the end of the buffer.

A graphical interface was developed to ease this measurement, visualize and apply the DOVC tables. The corrections tables are applied in firmware as real and imaginary components (I and Q) but are displayed to the user as amplitude and phase. The tool lets the user measure and apply correction continuously, in particular when setting up a new station, since the gain correction can vary significantly as the high power operating point is increased. Some exception handling measures were built in, namely to disable the continuous update mode if the RF level drops below a certain threshold or once the field controller operates in feedback mode. With this tool, a station could be updated with a new DOVC table in a matter of minutes.

POWER SAVINGS AT FLASH

In spring 2024, the RF drive signals for the 1.3 GHz stations were optimized: the modulator pulse length for the superconducting cryomodules were shifted 30 µs later so that a fraction of the HV rise time was used during the beginning of cavity filling. The loss of HV was compensated by modulating the RF drive and optimizing feedback gain scheduling. In addition, the modulator pulse lengths for the normal conducting RF gun and for the seven superconducting cryomodules ACC1 - ACC7 were shortened, as listed in Table 2. Note that in most cases, two cryomodules are powered with a single klystron so that the RF stations are referred to by their combined name (e.g. ACC2/3, corresponds to 16 cavities). Additionally, the HV setting for the RF gun was lowered from 8800 to 8550 V. The third harmonic RF station was left unmodified. The power consumption before and after optimization is presented in Table 2, showing a total power saving of 206 out of 825 kW, corresponding to 25% savings.

Table 2: FLASH Modulator Settings and Power Consumption before and after Optimization

RF Station	**Pulse Length** msec		**Power** kW		**Savings** kW	%
	before	after	before	after		
Gun	1.6	0.85	166	95	71	42.8
ACC1	1.6	1.3	134	104	30	22.4
ACC2/3	1.6	1.3	192	152	40	20.8
ACC4/5	1.6	1.3	141	112	29	20.6
ACC6/7	1.6	1.3	192	156	36	18.8
TOTAL			**825**	**619**	**206**	**25.0**

With this configuration, a user run in May 2024 could be carried at a record beam energy of 1365 MeV [4], with nominal pulse length and optimal RF performance.

POWER SAVINGS AT EUXFEL

High- and Reduced-Energy Configurations

In its present state, the EuXFEL can reach a maximum energy of 17.5 GeV but high-energy user runs typically call for 16.3 GeV beam energy, leaving enough RF reserve to compensate for the failure of a single RF station. This station is kept on, at its maximum gradient but set off-beam as a hot spare. Some user runs require lower beam energies, ranging from 11.5 to 14 GeV and special study modes require even lower energies (≤ 8 GeV). As an example, user runs in 2023 were allocated 8 weeks at energies 11.5 GeV and lower, 12 weeks at energies around 14 GeV and 12 weeks at

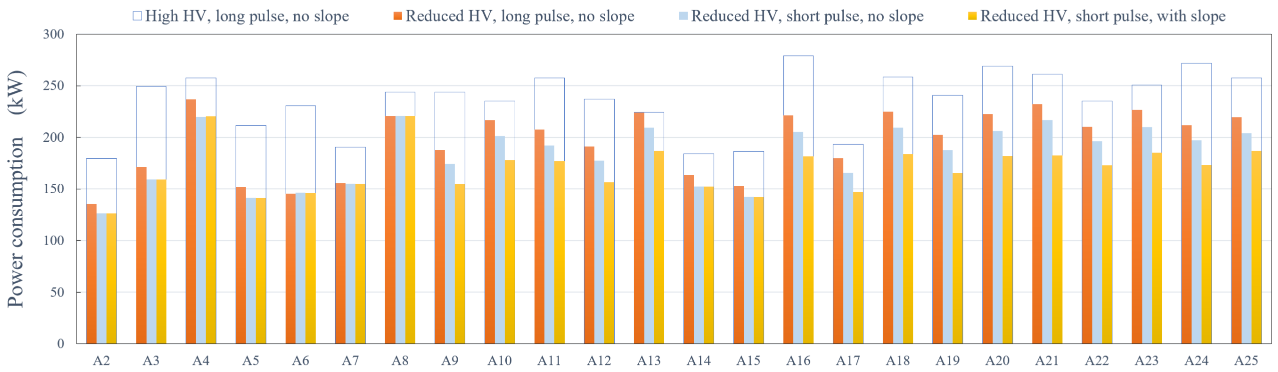

Figure 5: Energy savings across all modulators of the EuXFEL linacs, showing the benefits of the three successive approaches.

energies at 16.3 GeV. To simplify the machine setup, it was decided to provide two gradient configurations: a so-called high-energy setup for runs of 14.5 GeV and above and a reduced-energy setup for all requests below 14.5 GeV. For a given configuration, changing the accelerating phase will allow for small beam energy adjustments, scaling with the cosine of the off-crest phase. For reduced-energy runs, up to 5 stations can be left over as reserve which is more than needed. Typically, four out of five are then switched off, saving approximately 200 kW per station. Turning a station back on can be done on demand and takes about half an hour. Note that reducing the machine repetition rate, for example to 5 Hz instead of 10 Hz, would cut the RF consumption by half but also decrease the production of photons by half. This is certainly not the desired goal.

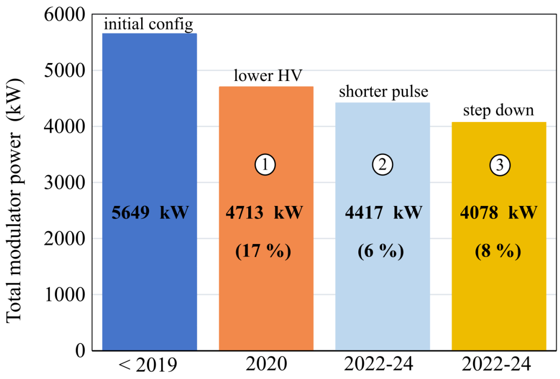

Figure 6: Total energy savings achieved over time, showing the benefits of the the successive implementation and deployment of the different approaches, circle 1 to 2. The percentage savings are calculated with respect to the previous step.

Lowering the Modulator High-Voltage

As a first attempt to save energy, the modulator HV was lowered for the reduced-energy configuration, corresponding to circle 1 in Fig. 1. Depending on the RF stations, this first step was successfully implemented in 2022 in the RF stations of the main linac (L3) at EuXFEL [1], and already provided 10-15% power savings. A second iteration of this approach extended to the entire accelerator pushed the savings to 17%, essentially removing all unused power overhead. One should stress that this HV reduction still allows reaching maximum energy for all user runs. The klystron gun arc rates also reduced with the decreased HV, from 10.7 in 2019 down to 3.6 arcs / month in 2022. Since no pulse length reduction had been done at that time, the RF pulse still fits entirely within the flat steady-state zone of the modulator pulse, so that the gain change induced by this step can be compensated for with static OVC.

Second Optimization Phase

The optimization steps corresponding to circle 2 and 3 in Fig. 1 were subsequently implemented later in 2022, first as a six-month test phase on two high-performance stations, each operating with a klystron from a different vendor. The modulator pulse was shortened from 1700 to 1580 msec forcing the RF to start and finish during the transient time of the modulator pulse, and the modulator shape was modified by introducing a 10-20% drop in the second half of the pulse where the RF drive level is lower. After this successful test phase, the optimization was rolled out in 2023 on 10 out of 20 stations in the main linac (L3), providing an approximate saving of 500 kW [5]. During the pilot phase, it could be confirmed that the optimized configuration, while increasing setup time and the complexity of the LLRF system did not impact the availability and quality of the beam. Another 7 stations in L3 were configured similarly during the startup in January 2024.

The power consumption of all modulators in the linacs (L1, L2, L3) for the successive energy saving steps are shown in Fig. 5. The empty bars denote the consumption from the initial configuration, while the filled bars reflect the power saving measures. The two injector RF stations (the normal conducting RF gun, the first cryomodule A1 and the third harmonic AH1) were not modified for power saving. Reducing the HV brought on average 17% saving, reducing the pulse length an additional 6% and introducing the step down contributed to an additional 8%. One should mention that a step was not introduced in the bunch compression sec-

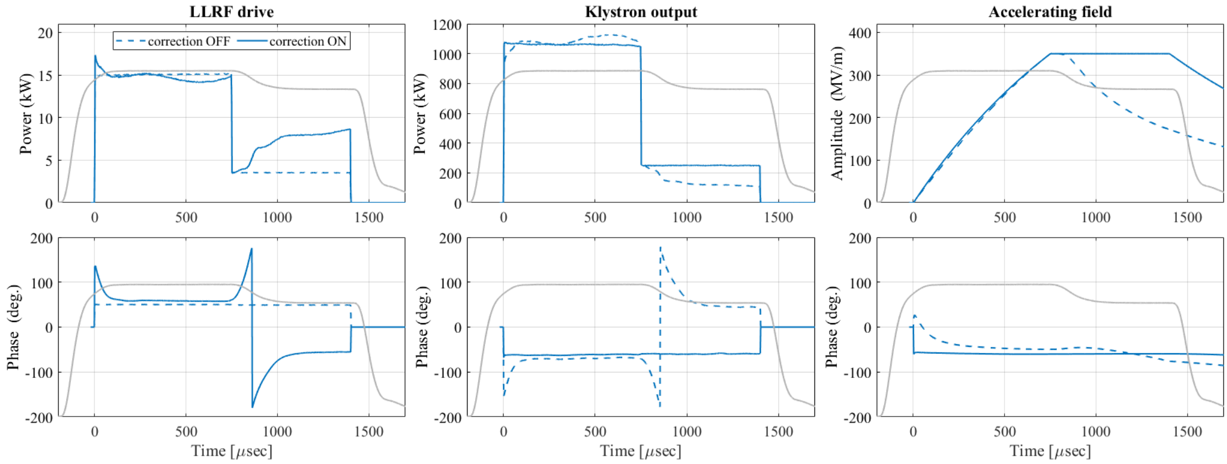

Figure 7: Impact of the dynamic output vector corrections on the LLRF drive, klystron output and accelerating gradient. The modulator shape is shown in the background for reference. Data taken in July 2023 on station A21.

tion (stations A2 to A5) to keep the maximum RF overhead for beam-based feedback algorithms, nor in stations A14 and A15 where the HV was already drastically lowered. A further step down would bring the klystron to an unstable regime. It is also worth mentioning that stations A6, A7 ad A8 were not yet optimized due to a temporary technical problem. The total power saving is summarized in Fig. 6.

Figure 7 illustrates the impact of the DOVC correction seen on the LLRF drive, on the klystron output and on the resulting accelerating field. The modified modulator shape is overlayed in grey for reference. On the left most plot, one can see the gain modulation (top) and the phase roll in the LLRF drive (bottom) when DOVC is on. As a consequence, the klystron output amplitude and phase (middle plots) are flat throughout the pulse. Only with DOVC on is the cavity gradient flat during the beam time (right most plots). One should emphasize that without DOVC, the phase roll in excess of 180 deg at the output of the klystron would result in a sign flip of the system gain, preventing any feedback operation. With DOVC on, the non-linearities are completely transparent to the controller, so feedback operation can be applied as usual.

CONCLUSION

Motivated by an energy saving effort focused on the RF power consumption, several methods were implemented and successfully deployed both at FLASH and at the EuXFEL, effectively reducing the power consumption without compromising the available accelerating gradient nor its stability for beam operation. Both machines have been running in the optimized configuration since at least 6 months and several user runs, including some at maximum energy, were carried out. These approaches can be combined, leading up to 25-30% of power reduction, which, in the case of EuXFEL, amounts to more than 1.5 MW compared to the operation mode in 2019. This new operation mode required an update of the LLRF firmware and development of new automation tools to characterize the introduced high-power gain and phase non-linearities and to compute the required compensation applied to the RF drive signal. As a positive side effect, one should emphasize that the techniques developed to compensate non-linearities in the high-power chain can also be used to extend the available beam time if used without modulator pulse length reduction. This development perfectly fits with the EuXFEL R&D road map towards longer pulses and high duty-cycle operation.

ACKNOWLEDGEMENTS

This work was funded in the context of the R&D program of the European XFEL.

REFERENCES

[1] M. Bousonville *et al.*, “Energy saving measures in the high-power RF system of the European XFEL”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 2006–2008. `doi:10.18429/JACoW-IPAC2023-TUPL117`

[2] V. Vogel *et al.*, “Optimization of klystron drive signal and HV shape to reduce energy consumption during operation of the European XFEL”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1806–1808. `doi:10.18429/JACoW-IPAC2023-TUPL018`

[3] R. Wagner *et al.*, “The bouncer modulators at DESY”, in *Proc. IET’09 European Pulsed Power Conference*, Geneva, Switzerland, Sept. 2009, pp. 1–4. `https://ieeexplore.ieee.org/document/5332206`

[4] V. Ayvazyan *et al.*, “Reaching design electron energy at FLASH after linac upgrade”, presented at the LINAC’24, Chicago, IL, USA, Aug. 2024, paper TUPB003, this conference.

[5] C. Schmidt *et al.*, “Operational Experience with the European XFEL SRF Linac”, in *Proc. of SRF’23*, Jun. 2023, Grand Rapids, MI, USA, pp. 43–50. `doi:10.18429/JACoW-SRF2023-MOIXA06`