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OPTIMIZATION OF KLYSTRON DRIVE SIGNAL AND HV SHAPE TO REDUCE ENERGY CONSUMPTION DURING OPERATION OF THE EUROPEAN XFEL

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Abstract

Currently 26 RF stations are in operation at the European X-ray Free Electron Laser (XFEL) and all RF stations can deliver sufficient power to support 600 µs beam pulse with an energy up to 17 GeV. These beam parameters require a power consumption of about 4.9 MW for high-power RF. Of course, the simplest way to save power is to reduce the XFEL repetition rate, but with some additional work and research, and without modifying any hardware, we can save the modulator power, without any impact on the XFEL performance. To reduce the power, we offer two methods that can be used together or separately. The first one is to make full use of the available power of the klystron during the rise and fall time of the HV pulse, and partial use of the available power during cavity filling by using phase and amplitude compensation. As a result, we can reduce the length of the HV pulse, because we fill the cavities with energy earlier. The second one is to slowly reduce the klystron HV during flattop. In total we can reduce the power consumption up to 30%, at the cost of making the low-level RF control more complicated as it needs to deal with large phase and amplitude changes. To solve this problem, we propose a new feature, dynamic output vector correction (OVC). In this report we will present some of experimental results from the klystron test stand and from several XFEL RF stations.

INTRODUCTION

Currently, XFEL has three laser beam lines, each of which provides high quality beam to users [1]. At the moment the klystrons high voltage (HV) pulse has a length of 1700 µs and the RF pulse a length of 1400 µs, out of which only 600 µs can be used for the beam acceleration. In XFEL we use two types of 1.3 GHz multibeam klystrons (MBK) and both of them have a high DC to RF efficiency in saturated regime of more than 60%. During the cavity filling time the levels of the klystrons output power are 15% below the saturated power to provide margin for feedback regulation; during flat top we need about three times less power depending on the bunch repetition rate and bunch charge. Figure 1 shows a typical RF pulse shape compared to the klystron output power when it works in the regime close to saturation during the HV pulse. It can be seen that we can use a klystron power of up to 180 µs during the HV rise time of 260 µs [2] to fill the cavities in a regime close to saturation. The klystron phase roll can be compensated by the RF drive signal. In addition, up to 50 µs may be used during the HV fall time. During flat top the HV level can be reduced by up to -30% of the nominal value, limited by the requirement of cavities gradient regulation.

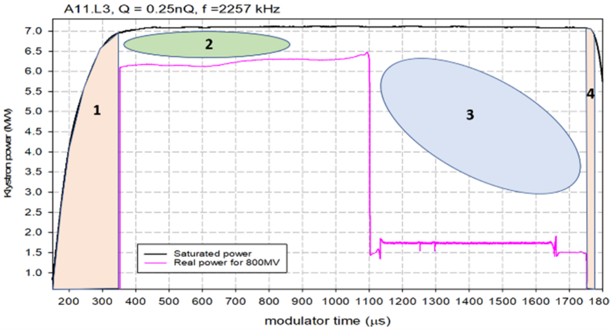


Figure 1: Area 1 - unused power during HV rise time, 2 unused power during part of filling time, 3 unused power during flat top, 4 unused power during HV fall time.

MAX USE OF MODULATOR POWER

The first test of reducing the HV during the pulse was made on the klystron test stand [3], using a bouncer type of modulator; for this type of modulator a linear slope of 15% of nominal voltage can be made during the HV pulse.

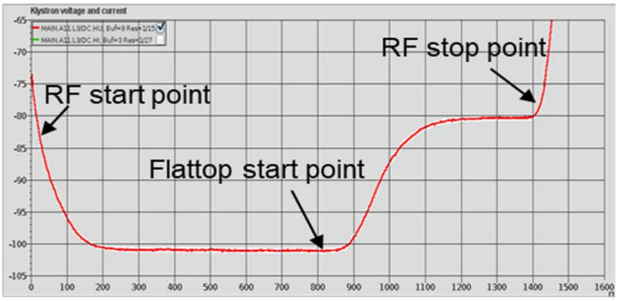


Figure 2: Part of klystron cathode voltage pulse shape versus time with HV slope during cavities flat top.

In XFEL the HV modulators that drive the klystrons are pulse step modulation (PSM) modulators. The modulator consists of 24 power modules. These modules are connected in series and generate a high voltage pulse. Each module is controlled individually by the modulator control system. Therefore, the HV pulse shape can be adjusted within certain limits. The system allows to setup changes within time frames of 100 µs. The voltage can be reduced within each timeframe by 30% of the initial timeframe voltage. The klystron HV shape during testing is show on Figure 2. The klystron RF output power during the rise, fall and slope of the HV will be lower than at normal operation, but still large enough to be used for filling cavities. The level of output power versus HV for two types of XFEL klystrons are shows on Figure 3.

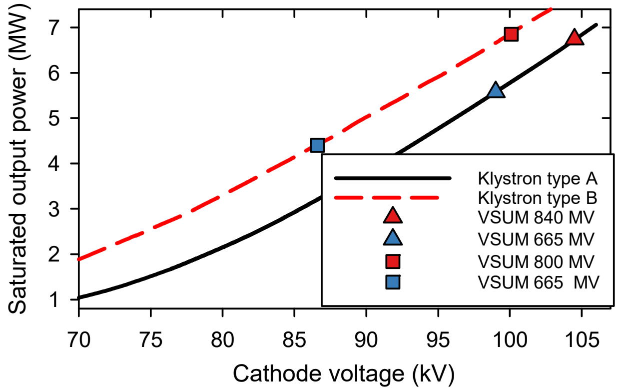


Figure 3: Saturated output power as a function of cathode voltage for klystrons types (A) and (B) for different vector sum (VSUM) of the cavity voltages.

OPERATION CLOSE TO SATURATION

To compensate the power drop during the rise of the HV, the klystron must be in a regime close to saturation for some time. In this regime we cannot control the power level, but we can fully control the phase.

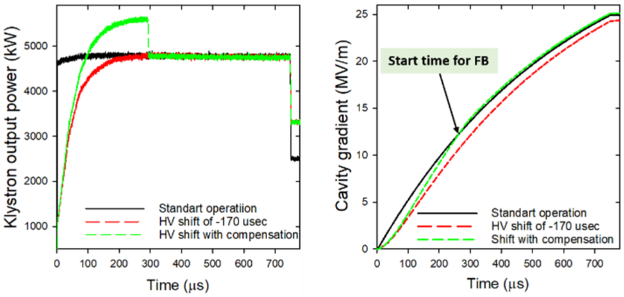


Figure 4: (Left) Klystron output power, black: normal operation, red: with 170 µs HV shift, green: 170 µs shift with compensation. (Right) Cavity filling curves.

The time during which the klystron must be close to saturation can be defined based on the calculation of energy directed into the cavities until the moment when the measured gradient in the cavities will be equal to the expected value. The methods of amplitude compensation for the rise and fall times are different, because during the rise time the klystron operates close to saturation, while during the fall time it must operate in a linear mode to allow for beam loading compensation and gradient control. To fully compensate a gradient drop during HV rise time we need about 300 µs. Figure 4 shows the klystron power in the normal regime, in the regime using the part of HV rise time and in the regime using HV rise time with compensation and the gradient in the cavities corresponding to these cases. Figure 5 shows the klystron saturated input power versus cathode voltage for two types of klystrons.

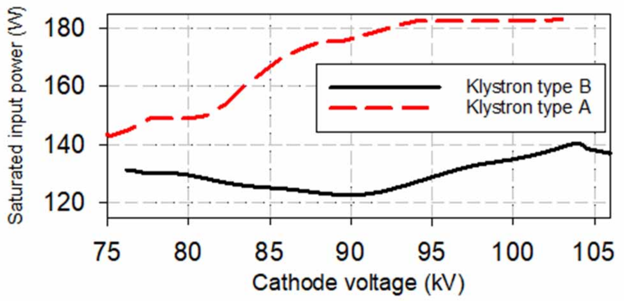


Figure 5: Saturated input power versus cathode voltage for two klystrons types used at XFEL.

LOW-LEVEL RF REGULATION

Control of the RF power normally takes place on the low-power level before the amplification of the signals [4]. The low-level RF system is stabilizing the RF field in the superconducting cavities with feedback and feed-forward algorithms. The repetitive disturbances are particularly suppressed by adaptation of the system input drive, using the known system response from previous pulses. The feedback control algorithm employs tables for feed-forward, set-point and feedback gain settings to allow time varying of those parameters. Variations in loop phase and loop gain are compensated for in both feedforward and feedback modes. An external algorithm, output vector correction, following system parameter changes corrects the loop phase and loop gain between RF pulses. Operation close to klystron saturation results in a strong dependency of loop gain on the output power of the klystron. Operation during the modulator's high voltage rise and fall time and during high voltage pulse shaping after filling to the flat top transition time results in large loop phase changes of more than 180 degrees. The effects of feedback control during klystron operation near saturation at the beginning of the RF pulse and compensating for large phase changes during the HV rise and fall time are shown in Figure 6.

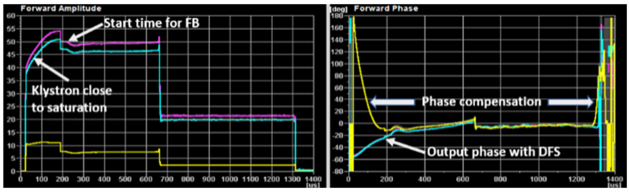


Figure 6: Klystron input (yellow) and output (blue and magenta) amplitude and phases waveforms. Phase and amplitude compensation for rise and fall times only.

To compensate for all of these “negative” effects, the OVC algorithm was extended to use tables instead of scalar values to allow for a variation in system loop gain and loop phase parameters over time. During amplitude compensation the input power changes from a level that is close to saturation to linear regime, which produces an additional phase shift. An external script measures the required compensation error, computes and writes the OVC tables which are applied at the output of the feedback chain. More details about the implementation and application of the table-based OVC will be presented in a future proceeding.

STUDY RESULTS

Experimental tests to reduce power consumption were carried out first on a klystrons test stand [5] and then on two XFEL RF stations, A11.L3 equipped with klystron type (B), at operating voltage 665 MV and 800 MV and station A21.L3 klystron type (A), at operating voltage 665 MV and 840 MV.

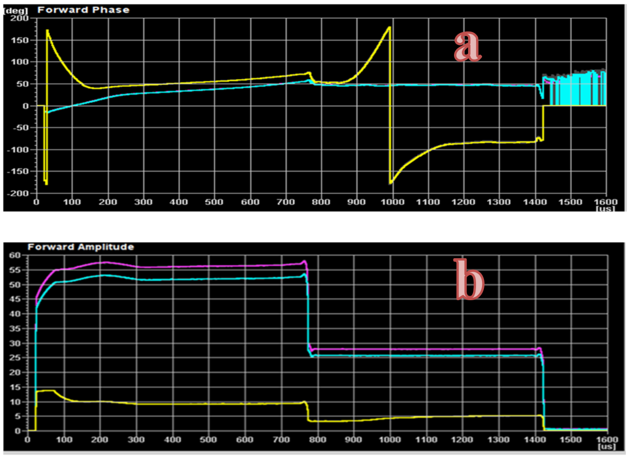
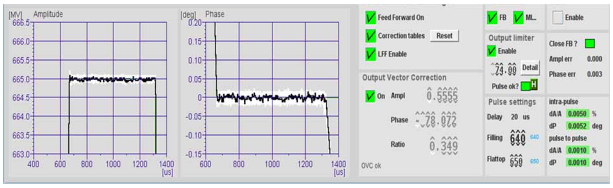


Figure 7: (a) Klystron input (yellow) and output (blue and magenta) phases shapes, (b) Klystron input power (yellow) and output power (blue and magenta) during the test of A11.L3, HV slope level -22%, voltage level 800 MV.

Figure 7 shows the waveforms of I/O phase and power during the power saving test on the XFEL RF station A11.L3, by using part of the HV rise and fall time of the HV the pulse length was reduced to 1510 µs compared to 1700 µs in normal regime. The phase roll as well as power level dropping during rise, fall and HV slope times were compensated by changing the input phase and power. The power saving test at voltage level of 665 MV and HV slope of 16% was 20.7%, the test at voltage 800 MV with the HV slope of 22% showed 24.6% power saving. It can be seen that to achieve a flat phase at the output of the klystron, a large phase change at the input of the klystron is required, but the frequency bandwidth of the used klystrons will allow them to be successfully compensated. Figure 8 shows the stability of amplitude and phase during test at station A21.L3. In addition to the short test (~24 hours), a long test was performed with a beam loading at a voltage level of 665 MV. The measured stability of the gradient and phase of the cavities did not differ from the values measured during normal operation (dA/A = 0.01% dP = 0.01 deg.). During the 665 MV test, not only did we use the power during the rise and fall, but the fill time was also reduced by 100 µs, which allowed us to reduce the HV pulse length to 1400 µs and we were able to save as much as 29.6% of the modulator power. When tested at 840 MV with a nominal filling time, the power savings were 20.5%, but in this test the length of HV pulse was 1580 µs.



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dA/A 0.0050 %
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pulse to pulse
dA/A 0.0010 %
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Figure 8: Stability of amplitude and phase in the cavities during power saving test at XFEL station A21.L3.

CONCLUSION

The modern large user facilities based on SC linear accelerators use several MW AC line power for RF production. Reducing energy consumption is very important. Using the dynamic frequency shift [6] feature together with an amplitude and phase compensation during the HV rise and fall times as well as during the HV shape slope introduced during the flat top length of 650 µs, the AC line power consumption of the XFEL linac RF can be reduced as much as 20%-30% depending on klystrons types and required RF cavity voltage. On the other hand, the reduced power consumption comes at the cost of an increased complexity for the RF control, longer setup times and also the need to introduce a new feature, dynamic OVC, in the existing low-level RF control system. A test on the klystron test stand and the tests of two XFEL RF stations have shown that this can be done reliably and efficiently without any degradation of beam quality. Another application is to use the same approach to increase beam pulse length for user operations.

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