DEVELOPMENT OF PROGRAMMABLE BIPOLAR MULTI kHz KICKER DRIVERS FOR LONG PULSE SUPERCONDUCTING ELECTRON LINACS

J. L. Teichgräber*, W. Decking, J. Kahl, F. Obier,
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, Hamburg, Germany

Abstract

Superconducting cavities allow for long RF-pulses, which enable the acceleration of thousands of electron bunches within one RF-pulse. Due to transient effects, e.g. coupler kicks, eddy currents, wakefields or gun properties the beam trajectory can change along the pulse train. To compensate for this, kicker systems based on high-current operational amplifiers (OA) have been developed for the free electron lasers European XFEL and FLASH at DESY in Hamburg. Here, we present the layout of the kicker system, the setup of the pulse electronics and operational results with beam.

INTRODUCTION

During the commissioning the European XFEL used 500 bunches per train [1]. It was later shown that the full specified 2700 bunches in a 600 µs bunch train can be produced at 10 Hz repetition rate. Due to the architecture of the current photo injector laser only completely filled bunch trains can be generated. If the machine is set up with 4.5 MHz bunch repetition rate but an experiment needs a reduced repetition rate the unwanted bunches need to be dumped after the accelerator section. This leads to a high firing rate of the six dump kickers. The continuous use of the dump kickers leads to an accumulation of orbit deviation along the bunch train. This is probably caused by eddy currents in the six simultaneously used stripline kickers [2]. The horizontal orbit deviation leads to the reduction of the SASE intensity after each change in dump kicker repetition rate. A solution to this problem has been successfully tested using programmable bipolar multi kHz kicker drivers with the air coil kickers.

PROBLEM DESCRIPTION

The orbit deviation already showed up during commissioning. In Fig. 1 a deviation of 25 µm is observed for a 100 µs bunch train. The steep curve on the left can be explained by the fact that a large number of bunches was dumped before the shown bunches were used. Then the eddy currents decline due to the reduced dump kicker repetition rate. One solution to this problem could be the transverse intra bunch train feedback system. But using this expensive high bandwidth system for this purpose in addition to correcting various other orbit errors would be increasingly difficult and might bring it to its limit. In this paper a system is presented that uses a commercially available OA to directly drive the air coil kickers shown in Fig. 2.

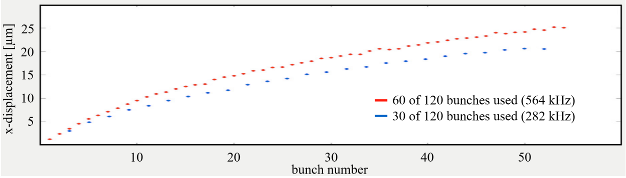

Figure 1: Orbit Deviation in the undulator section of SASE 1. The machine is set up with 1128 kHz repetition rate. The first block of the bunch train is dumped completely. This figure shows the comparison between dumping every second bunch and dumping three of four bunches.

Figure 2: One meter long air coil around the ceramic beam pipe for horizontal correction.

SYSTEM DESCRIPTION

The location of the error source is known and it was decided to do the correction as close to the source as possible. In addition, two kickers are placed in such a way that amplitude and phase in the horizontal plane can be corrected independently. One is placed before and one behind the dump kicker section. The kicker compensation relies on BPM readings from the SASE section.

In the current state the system consists of several different components. The actual kicker is a 1-meter long air coil made of copper strand and a durable polymer. The kicker is built around the ceramic vacuum tube with a thin sputtered metal layer. The kicker magnets are identical to the long pulse beam distribution kickers. The connection from the pulser to the kicker is realized by ten parallel approximately fifteen meter long RG213 cables to reduce resistance and inductance of the connection while having standard connectors. The current towards the kickers flows through the inner conductor while the cable shield is used as the return path. A simplified schematic is shown in Fig. 3. The pulser is basically a powerful OA by Apex Microtechnology [3] which is connected to the pulser output and used as a variable current source. The return current of the kicker is connected to a shunt resistor and the resulting voltage is fed into the negative input of the amplifier. Thus the output current is determined by the voltage applied to the positive amplifier input. To decouple the signal source from the pulser an instrumentation amplifier AD8421 is used at the input of the pulser. A differential input was implemented for increased

---

* jan.lukas.teichgraeber@desy.de

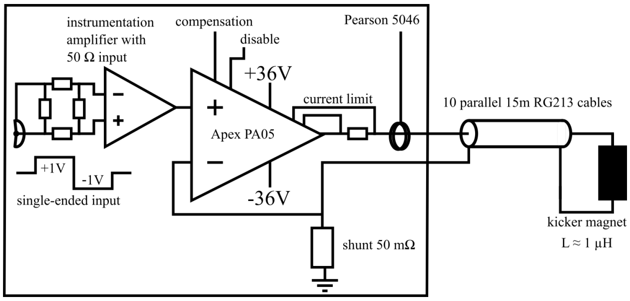

Figure 3: Simplified schematic of the pulser and the kicker.

noise immunity but it is currently not in use. The input signal is generated in a MTCA crate by a DAC on a SIS8300-L2 card made by Struck Innovative Systeme GmbH. As already stated the calculation of the input signal relies on BPM readings in the relevant SASE sections. The most important reason to use an OA is to get good zero crossings without a massive increase in system complexity.

From a signal quality point of view it would be advantageous to integrate the DAC in the pulser but for simplicity the MTCA DAC is used. With electromagnetic compatibility (EMC) in mind the system was tested and the results have been within the specifications. Before the final EMC optimisations some high frequency noise from the dump kickers, which are located in the same rack, was visible on the current pulse.

The system has been tested with a 10 Hz repetition rate and 1 ms long 30 A pulses which results in a 1% duty cycle. To realize safe operation a current limit of 42 A is implemented by a resistor at the amplifier output. To make sure that a current pulse cannot be longer than 1 ms the amplifier is disabled between bunch trains. The testing was necessary because the safe operating area (SOA) of the amplifier suggests that ohmic loads should be used to reduce heat generation in the amplifier. The problem is not the average power but the instantaneous power generated during current pulses through the mainly inductive load. The system speed is limited by several factors. First of all, the maximum usable voltage of the amplifier is ±50 V. Since the load is mostly inductive the supply to output voltage differential is large. That means that the voltage drop and thus the losses occur in the OA and not it the magnet. The data sheet recommends not more then 15V supply to output differential at 30A output current. Measurements as in Fig. 4 show that the output voltage is 6V and the used supply voltage is ±36 V. The resulting differential is 30 V and thus higher then the recommended 15 V. The peak power is 30 V multiplied by 30 A is 900 W. Since an increase in voltage would have increased losses further we settled for ±36 V. Weeks of testing showed that the amplifiers can withstand this stress. Furthermore the usual current pulse does not exceed 20 A and 600 µs. Typically the necessary current is a linear or exponential function.

It was found that in addition to the 1 µH magnet inductance we get 500 nH from the cables and 500 nH from the pulser. Thus approximately 2 µH of inductance have to be driven.

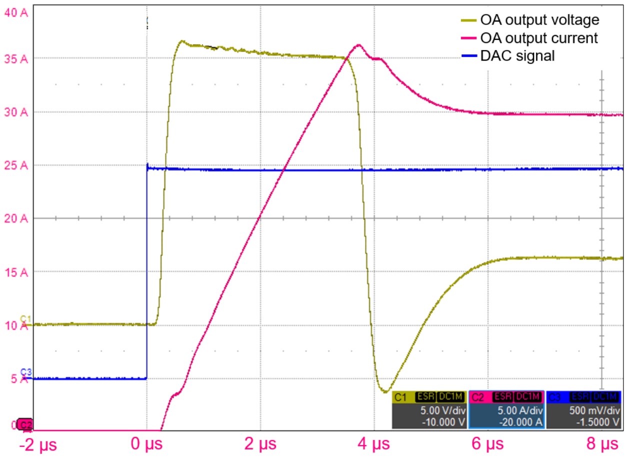

Figure 4: Fastest possible rise time to 30 A is 3 µs. It takes another 3 µs to settle to a stable level. This results in a full power bandwidth of approximately 100 kHz. This picture is from a lab test with ten parallel 20 meter long RG213 cables.

The resistance of the kicker is negligible while the cables and the pulser including the shunt and the amplifier resistance add to approximately 0.6 Ω, while the amplifier makes up the biggest part of this resistance. Final measurements in the XFEL showed that the maximum current of 30 A can be reached within 2 µs with a settling time of approximately 2 µs depending on the current step.

$$dt = L\frac{dI}{U} \tag{1}$$

Eq. (1) with L = 2 µH, 36 V and 30 A gives an estimation of 1.66 µs and is thus in good agreement with the measured results. It might be possible go get an even higher bandwidth by increasing the supply voltage. Unfortunately steep edges send the OA in saturation and are followed by some oscillation. While it was tried to get higher speeds with the shown components it always leads to more ringing. It is possible to tweak the frequency response by tuning an RC-network connected to the OA. A trade-off has to be done. In Fig. 4 it was tuned to reach a flat top as fast as possible. If necessary it can be tuned in a way that the overshoot disappears completely, but the bandwidth is reduced drastically.

To further illustrate the behaviour of the system and typical bunch trains the Fig. 5 - 7 have been added to the paper.

OTHER USE CASES

After the system has been installed and successfully corrected the eddy current distortions, other use cases were found. In the injector a horizontal and a vertical system with shorter kickers has been implemented and due to the low beam energy the necessary current is smaller. The magnet length is reduced to 15 cm for each orientation. The cables are shorter and the necessary current is smaller, thus RG58 cables are sufficient. The purpose of the system placed directly after the gun is to compensate the gun input coupler kicks which vary along the RF pulse. Due to the so called

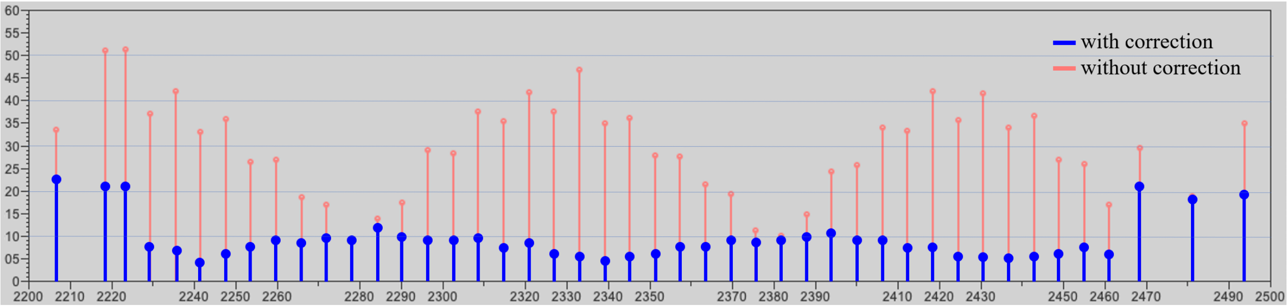

Figure 5: Peak to peak orbit jitter [µm] along BPMs in the undulator section. The betatron oscillation is significantly reduced.

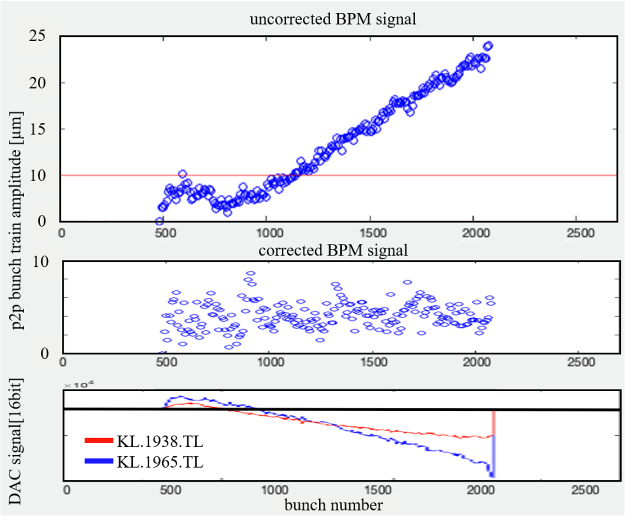

Figure 6: Up to 40 µm deviation measured by a BPM in the undulator section. By applying the correction the systematic error vanishes almost completely. The remaining error is less then ±4 µm arbitrary noise. The third picture shows the signal generated by the DAC which in fed to the pulser.

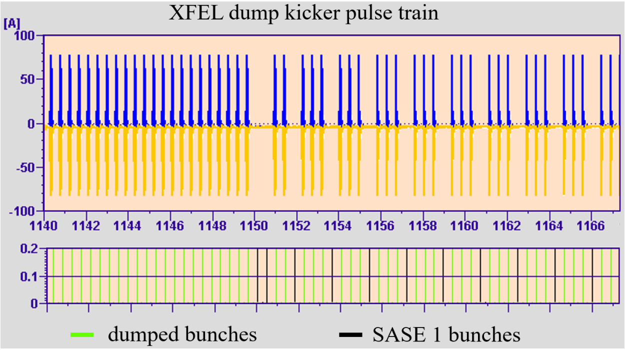

Figure 7: Example of a typical bunch train behind the dump kicker section. SASE 1 and SASE 3 bunches can be interleaved arbitrarily.

dog leg behind the injector section which was supposed to allow for the use of two separate guns, it is important to arrive at this position with a stable orbit. Otherwise the bunches are bent differently along the bunch train which leads to uncorrectable errors in the following accelerator section. But even without the dog leg it is beneficial to do the correction as close to the source as possible.

The successful implementation of the system in the XFEL lead to the decision to add it to FLASH as well. Currently it is planed to add eight magnets with 100 A OAs and two magnets with 30 A OAs in the injector during the ongoing FLASH2020+ upgrade. As in the XFEL injector there is always a horizontal and a vertical system combined for all FLASH magnets. The FLASH injector kickers can either by used for orbit correction or alternatively as dark current kickers by switching the connection to another pulser.

CONCLUSION

Using powerful OAs to drive correction kickers is a relatively low cost solution to a variety of different errors that can occur in long pulse linacs. It was successfully tested in the European XFEL and will be implemented in FLASH.

ACKNOWLEDGEMENTS

The authors would like to thank L. Fröhlich for useful discussions and help in the creation of this paper.

REFERENCES

[1] W. Decking, S. Abeghyan, P. Abramian, *et al.* ”A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator.” *Nat. Photonics*, vol. 14, no. 6, pp. 391–397, 2020. `doi:10.1038/s41566-020-0607-z`

[2] F. Obier, W. Decking, M. Hüning, and J. Wortmann, “Fast Kicker System for European XFEL Beam Distribution”, in *Proc. 39th Int. Free Electron Laser Conf. (FEL'19)*, Hamburg, Germany, Aug. 2019, pp. 353–356. `doi:10.18429/JACoW-FEL2019-WEP013`

[3] Apex Microtechnology Power Operational Amplifier - PA05, `https://www.apexanalog.com/resources/products/pa05u.pdf`