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SOLVING THE USB COMMUNICATION PROBLEM OF THE HIGH-VOLTAGE MODULATOR CONTROL SYSTEM IN THE EUROPEAN XFEL

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Abstract

Since the commissioning of the modulators in the European XFEL in 2016, it happened from time to time that the modulator control system hung up. The reason for the problem was unknown at that time. Initially, the MTBF (Mean Time Between Failure) was 104 days, which was so rare that other problems with the RF system clearly dominated and were addressed first. Over the next 2 years, the error became more frequent and occurred on average every 18 days. After the winter shutdown of the XFEL in 2020, the problem became absolutely dominant, with an MTBF of 2 days. Therefore, the fault was investigated with top priority and was finally identified. Two units of the control electronics communicate via USB 2.0 with the main server. Using special measurement technology, it was possible to prove that weak signal levels in the USB signal led to bit errors and thus to the crash of the control electronics. This article describes the troubleshooting process, how to measure the signal quality of USB signals and how the problem was solved in the end.

INTRODUCTION

The European XFEL is equipped with 26 RF stations [1]. One RF station can generate up to 10 MW of RF power with a pulse width of 1.7 ms and a repetition rate of 10 Hz. The stations are operated with 0.7 to 6.5 MW. The failure of an RF station leads to a reduction in the electron beam energy of 600 to 700 MeV, which stops the generation of the X-ray pulses in the undulator sections. The failure of one station therefore interrupts operation of the free-electron laser as a whole.

Each RF station consists of a multibeam klystron, high-voltage pulse modulator and pulse transformer, RF waveguide power distribution and several other subsystems. While a number of childhood diseases were eliminated after the commissioning of the European XFEL in 2016 [2], a fault that occurred from time to time in the high-voltage modulators played only a minor role. The modulators generate the high-voltage pulses for the klystrons with an amplitude of 6.3 to 9.2 kV, which are transformed upwards by a factor of 12 by a pulse transformer. So, 75 to 110 kV are available for the klystron operation. The initially unknown error led to the failure of a modulator, which could be fixed by a manual power cycle of the control system. When the error occurred, the GUI of the control system displayed a red spider, which is why this error was internally called the red spider. This error message is always displayed when the communication between the two electronic boards and the server controlling the modulator is disturbed (Fig. 1).

Figure 1: High voltage modulator, GUI and control system.

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However, it was completely unclear what had disturbed the communication. In the first two years of operation, the failure occurred 3 to 4 times per year (MTBF = 104 days). The failures were documented but not followed up. This then changed in the two subsequent years of 2018 and 2019. The fault now occurred 20 times per year (MTBF = 18 days) and the investigation began. It was very difficult as the fault occurred completely unpredictably on more than half of the 26 modulators. From January 2020, the probability of the fault occurring increased tenfold and it occurred on average every second day.

THE TROUBLESHOOTING

Various approaches have now been taken to isolate the problem. We tried to find out if there was a difference between the 17 modulators that were affected and the 9 that were not. However, no difference could be found, e.g., in age, software status, cable connections. A few months later, the error also occurred in 4 of the 9 modulators that were not affected until March. At the same time, the suspicion was investigated that an EMC (electromagnetic compatibility) problem could have become more severe from January onwards and thus led to the accumulation of faults. However, there were no indications and EMC measurements did not reveal any unusual stress in the vicinity of the modulators. Since the USB cables themselves had already been replaced with another type in the past, this was initially ruled out as the cause. However, it was decided to use a USB analyser to analyse the data traffic between the electronic boards and the server in the hope of detecting communication problems. The USB analyser was inserted between the board and the server and the USB data ran through it so that it could record what was happening. We took a board that was particularly susceptible to the error and established the USB connection to the server via the USB analyser. The error then disappeared.

USB COMMUNICATION

To understand the problem, some background information on USB technology is necessary. The first USB standard 1.0 was introduced in 1996. It was already possible to transfer data at a low speed of 1.5 Mbps. With the successors 1.1, 2.0 and following, the data rate was increased further and further. The USB communication of the modulator control system based on USB 2.0 with a data rate of 480 Mbps. In principle, however, all USB interfaces are downward compatible. For example, a USB 2.0 interface can switch from high-speed to full-speed if the other USB interface cannot offer more than full-speed (Table 1). In this case, the data rate, but also the levels, are used according to the full-speed specification. It is important to note that USB communication is always bidirectional. Each USB interface sends and receives data [3].

Table 1: Two of the USB Data Transmission Modes

Mode	Full-Speed	High-Speed
Bit Rate	12 Mbps	480 Mbps
Amplitude	0 V to 3.3 V	± 0.4 V

After the error no longer occurred with the USB analyser, the following working hypothesis was made: The actual cause of the communication error, are more bit errors than the error correction can fix. If the analyser is now between the electronic board and the server, it acts like a repeater. It reads the incoming USB signals without errors and regenerates them in better quality than the original signals. As a result, no more bit errors occur.

This working hypothesis had to be tested. This requires a complex measurement setup consisting of an oscilloscope with a bandwidth of 2.5 GHz, a special board for the signal taps and appropriate software, which is offered by some manufacturers. With the help of this measurement setup, eye diagrams of the signals can be recorded, which can be used to assess the signal quality (Fig. 2).

Such an eye diagram consists of the superposition of several hundred to several thousand bits recorded by an oscilloscope. Basically, one can say that the wider the eye is open, the better the signal quality. Theoretically, the eye opening of a USB 2.0 signal should be 800 mV. But due to amplitude noise, the eye opening is reduced in practice. If you also consider the attenuation of a connected USB cable, the vertical eye opening is further reduced. We compared different USB devices and noticed two things. First, the eye diagram of the modulator server and the boards is 5 to 9 % less wide open vertically than other typical USB devices. Secondly, the cable used at the time reduced the eye opening, by a further 8 to 11 %. As a general rule, reducing the eye-opening leads to an increased bit error rate. For a typical USB application, the resulting bit error rate would probably not be a problem, as it does not have to run error-free for a long time.

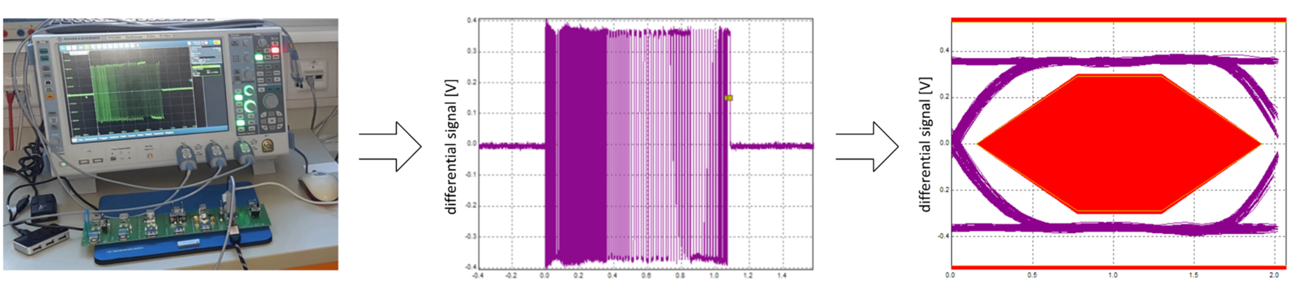

Figure 2: USB signal measurement setup, recorded bit test sequence and the corresponding eye diagram.

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In our case, however, it led to a communication error every one or two months, which caused the failure of a modulator and thus the entire RF station. This results to a MTBF of 2 days for 26 RF stations. The USB analyser opened the eye so much that no more bit errors occurred. The same effect can also be achieved by reducing the cable attenuation.

THE SOLUTION

The problem was understood and as a first measure we installed USB repeaters with the standard 2.0 in all modulators that showed the error. After the repeaters were installed, the error no longer occurred.

However, the repeaters are active components with unknown lifetime and which therefore carry a potential risk of failure. Therefore, we looked for a USB cable with lower attenuation to achieve a large eye opening without repeaters that could fail. This was not easy, as most manufacturers do not specify the attenuation, but we finally found a cable that has a barely measurable insertion loss. Figure 3 shows an eye diagram of a USB signal at the end of the transmission with the original cable at the top and with the new cable at the bottom. The eye is about 10 % more open vertically.

In December 2020, all modulators were then equipped with these cables. In the next 4 months, no more errors occurred and the problem seemed to be finally solved, but the problem showed up again 7 times between May and August.

We then took another measure. We used a USB repeater that can transfer data at a maximum of full speed (Table 1). This forces the USB 2.0 interfaces in the electronic boards and the server to reduce the data rate and increase the level. Each bit thus becomes longer by a factor of 40 and the voltage level is increased by a factor of 4.125. This makes the eye correspondingly larger and thus the signal-to-noise ratio is significantly improved, which makes a bit error much less likely. The data rate of 12 Mbit/s is sufficient for the communication within the control system. In August 2021, the USB 1.1 repeater was installed in all modulators and no red spider has been seen since in operation.

SUMMARY

The fault was found after a long search and proven with suitable measurement technology. Measuring the USB signals is a difficult task and can only be done with a suitable USB measuring device. Basically, the use of USB interfaces for the communication of control systems in a user machine does not seem to make sense. However, based on the knowledge gained, a way could be found to make the data transmission very reliable. By lowering the data transmission from high-speed to full-speed on purpose and using low-attenuation USB cables, the signal quality was improved so much that the error has not occurred again in the last 12 months of operation.

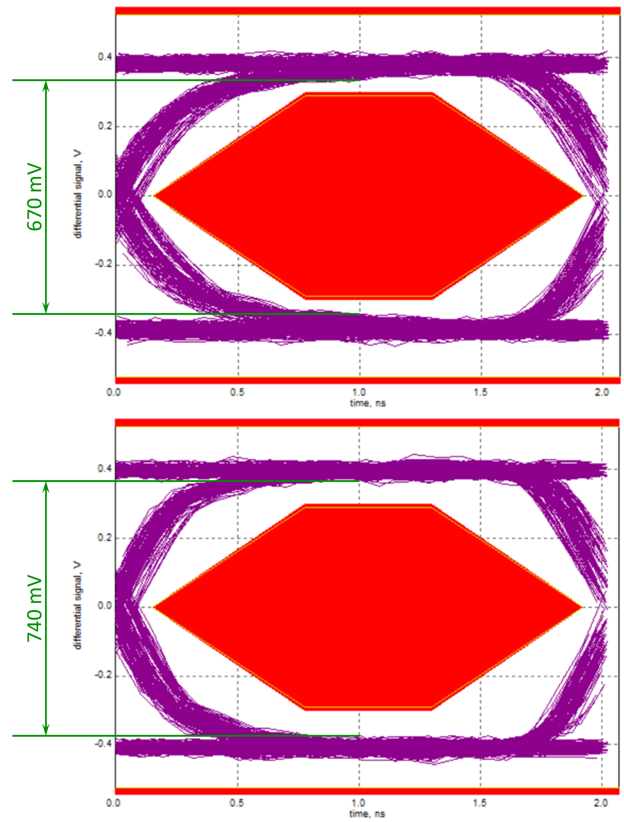

Figure 3: Top - Eye diagram with the USB cable previously used in the modulator control system. Below - Eye opened wider due to the much lower attenuation of the new USB cable.

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