Solving the USB Communication Problem of the High-Voltage Modulator Control System in the European XFEL

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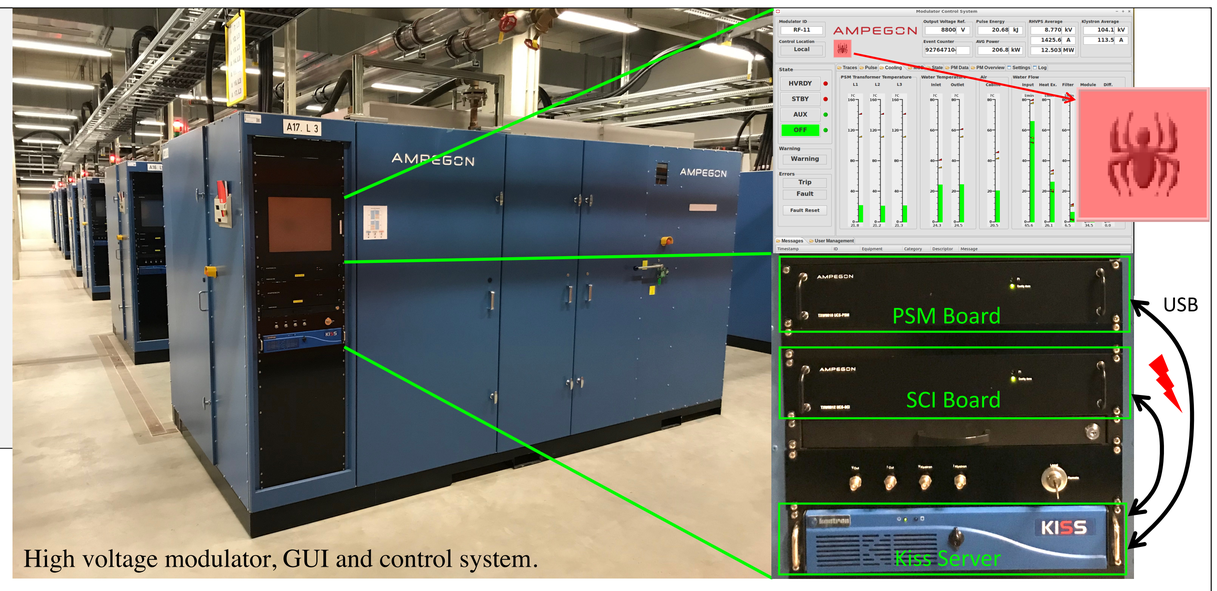
Introduction

- The European XFEL is equipped with 26 RF stations.
- Each RF station consists of a multibeam klystron, high-voltage pulse modulator and pulse transformer, RF waveguide power distribution and several other subsystems.
- 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.
- This means that any modulator failure will also lead to the failure of the entire XFEL.

Red Spider

- An initially unknown error led to the failure of a modulator.
- 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 PSM or SCI board and the server controlling the modulator is disturbed.
- At the beginning of the XFEL operation, the error occurred very rarely, but then the probability of occurrence increased and from 2020 onwards it became very annoying.



High voltage modulator, GUI and control system.

Period	2016 to 2017	2018 to 2019	1 January to 17 August 2020
Number of occurrence	7	40	121
Mean time between failure	104 days	18 days	2 days

The Troubleshooting

Since the cause of the error was completely unclear, we pursued different approaches:

- We tried to find out if there was a difference between the 17 modulators that were affected and the 9 that were not.
  ⟹ But no difference could be found, in age, software status, cable connections, etc.
- It was investigated whether an electromagnetic disturbance had become larger.
  ⟹ There were no indications and EMC measurements did not reveal any unusual stress in the vicinity of the modulators.
- 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.
  ⟹ Surprisingly, the error no longer occurred.

USB Communication

To better understand the issue, here is some information about USB communication:

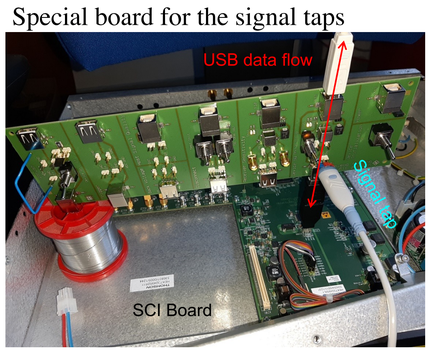
- The first USB standard 1.0 was introduced in 1996.
- It was already possible to transfer data at a low speed of 1.5 Mbps.
- With the successors 1.1, 2.0 and following, the data rate was increased further and further (see table).
- The USB communication of the modulator control system based on USB 2.0 with a data rate of 480 Mbps.
- In principle, 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.
- In this case, the data rate, but also the levels, are used according to the full-speed specification.

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

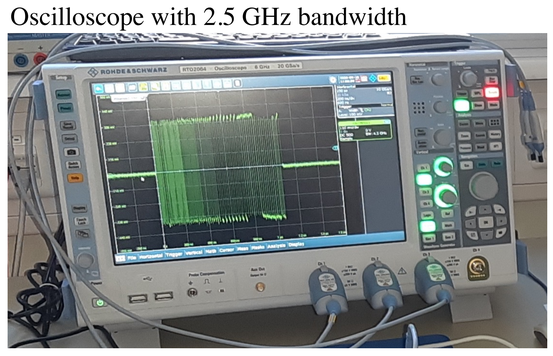
Working hypotheses: the USB analyser improves the signal quality, which reduces the bit error probability and thus prevents the communication error.

Verification of the hypothesis: This requires a measurement setup consisting of an oscilloscope with 2.5 GHz bandwidth, a special board for the signal taps and the appropriate software.

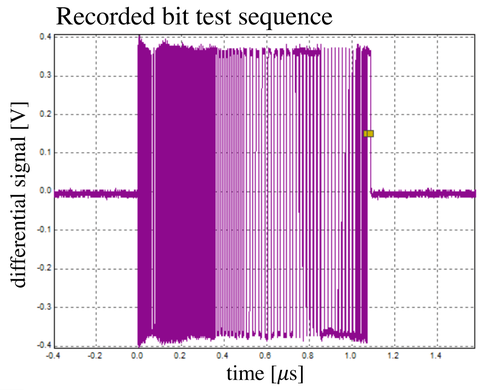
Special board for the signal taps



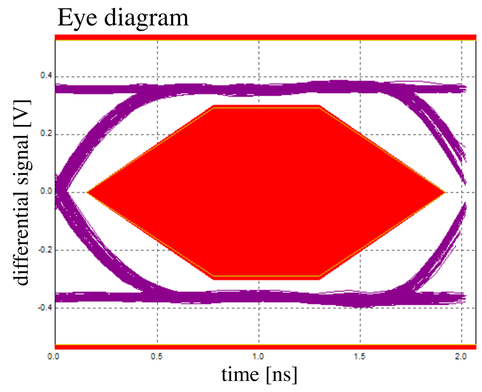
Oscilloscope with 2.5 GHz bandwidth



Recorded bit test sequence



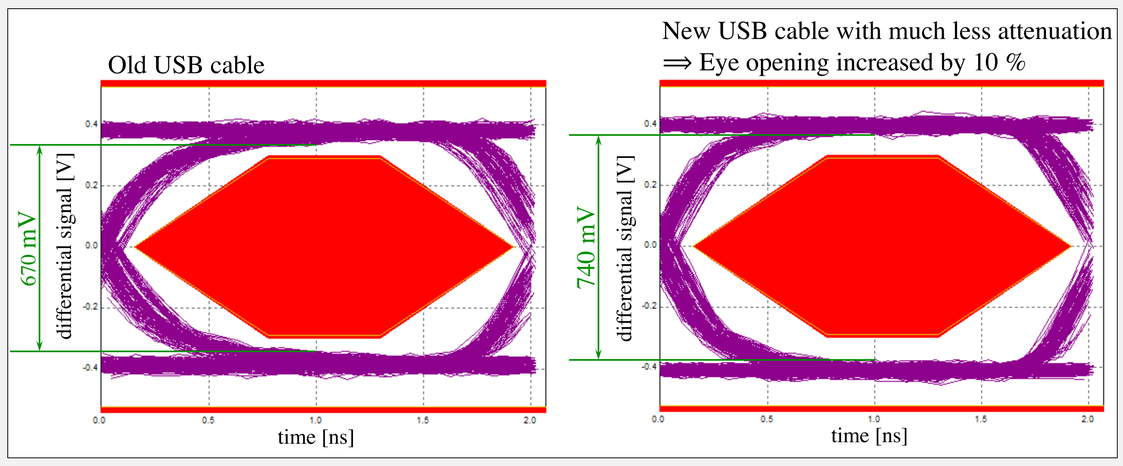
Eye diagram



- By superimposing all bits of the test sequence, an eye diagram is created.
- The wider the eye is open, the better the signal quality.
- It turns out that the eye diagram of the modulator server and the boards is 5 to 9 % less wide open vertically than with other typical USB devices. On the other hand, the cable used at that time reduced the eye opening by another 8 to 11 %.

Measurement 1

After these findings, we used a USB cable with lower attenuation and thus increased the eye opening.



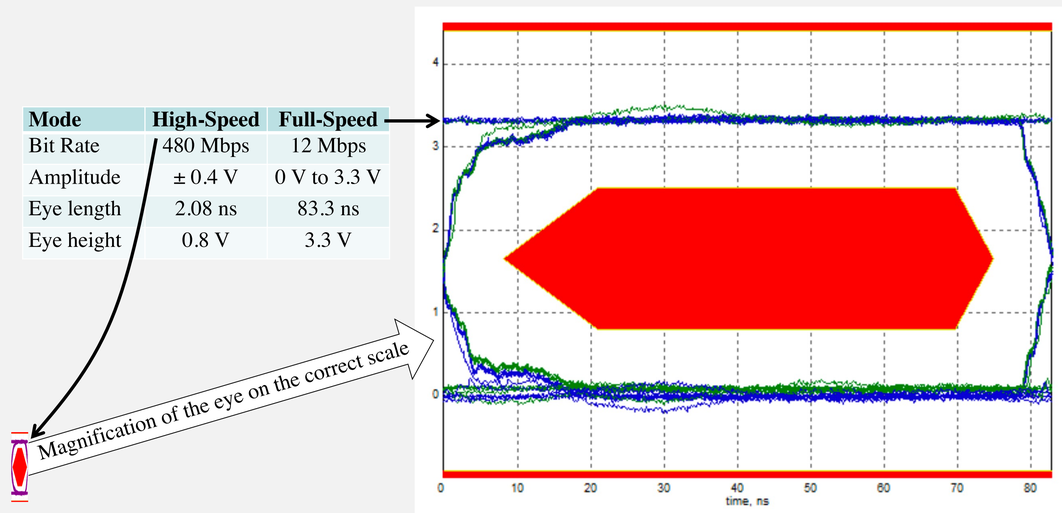
This worked at first. The error did not occur again for a good 4 months. But then the red spider returned.

Measurement 2

Then we decided to make the eye even bigger.

- To do this, we used the backwards compatibility of the USB standards (see above).
- A repeater was inserted that can only handle full-speed.
- This reduces the data rate and increases the level of the data transmission.
- Each bit becomes 40 times longer 4.125 higher. ⟹ Much bigger eye opening.

Mode	High-Speed	Full-Speed
Bit Rate	480 Mbps	12 Mbps
Amplitude	± 0.4 V	0 V to 3.3 V
Eye length	2.08 ns	83.3 ns
Eye height	0.8 V	3.3 V



Summary

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.

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