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ACCELERATOR MODULE REPAIR FOR THE EUROPEAN XFEL INSTALLATION

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Abstract

Repair actions of different extent have been performed at 61 of the 100 accelerating series modules for the European XFEL to qualify them for tunnel installation. Four modules could not be repaired in time. CEA Saclay managed to perform three major repairs in parallel to the series module integration, the residual repair actions took place at DESY Hamburg. In this paper we will give an overview on the various technical problems which required being fixed before the tunnel installation and on the repair actions performed.

INTRODUCTION

The 100 superconducting accelerating series modules for the European XFEL [1,2] have been integrated and tested from September 2013 until August 2016 after the three pre-series modules whose integration started one year before. Institutes from six different countries (France, Germany, Italy, Poland, Russia and Spain), organized in 12 different work packages contributed with parts, capacity for work and facilities to the production and the testing of the modules [3].

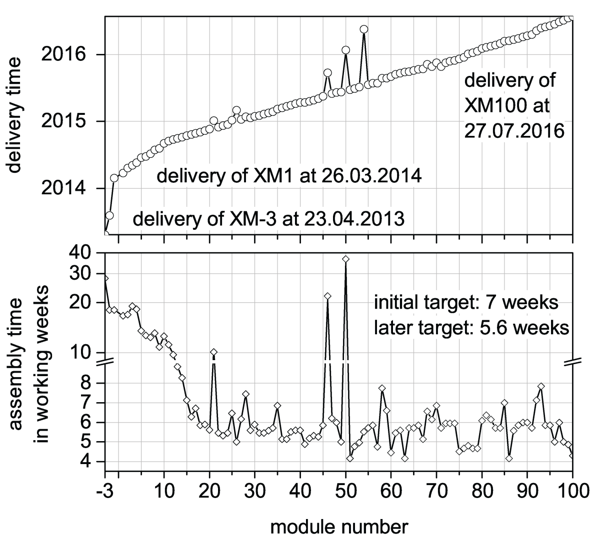

Figure 1: Delivery and assembly times of the modules.

An assembly infrastructure, called the ‘XFEL Village’, at CEA was used by the industrial contractor Alsyom for the integration of the modules under CEA supervision [4,5]. At two lines of seven workstations the components of the modules where integrated. The very challenging goal to produce one module per week has been achieved after the ramp-up phase lasting until module XM15 (Fig. 1). The improvement of the assembly quality and the otimization of the processes was an ongoing effort. Significant gradient degradation from XM6 to XM23, while CEA and Alsyom put all their effort in achieving the one module per week throughput, was overcome by an audit of string and module assembly conducted by CEA on XM26. A simplification of the clean room procedures was introduced at XM54. Thanks to organisational efforts, a 4-day throughput was reached in January 2015 with XM25 and maintained until the end of the production [6].

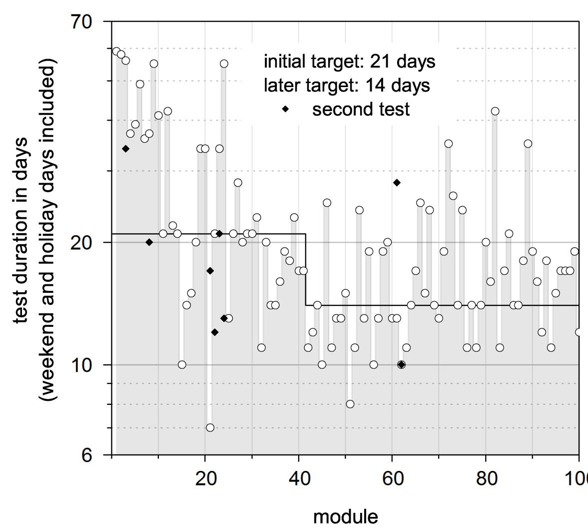

Figure 2: Module testing time.

After transportation from CEA to DESY, the modules have been received at the accelerator module test facility (AMTF) by a Polish team from IFJ PAN, Kraków. The team performed the complete test cycle including incoming inspection, installation to one of the three test stands, cool down, measurements of the cryogenic losses, rf operation of all cavities to determine the maximum cavity gradients and the levels where field emission starts. The initial target of 21 days per test was achieved in the ramp up phase. At the beginning, testing was handicapped by process line leaks, leaks at the connections of the gas return pipe (GRP) of the modules to the test stands, coupler push rod leaks and until about half-time the space for storing modules. Towards the end of the production overheating warm coupler parts became an issue. Performing a process optimization with

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assistance of the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) the IFJ PAN team managed to decrease the testing time to 14 days for the second half of the modules (Fig. 2). After warm up the modules have been handed over to the next work package for wave guide installation and subsequently installed into the tunnel.

Quality control performed at CEA and the AMTF tests revealed faults at 61 modules requiring repair actions of different extent. The repair actions had to comply with the constraints given by the tunnel installation schedule. Consequently, often previously untested repair methods have been used.

MODULE REPAIR ACTIVITIES AT CEA

XM46 had a beam vacuum leak ($10^{-7}\,\frac{\mathrm{mbar\,l}}{\mathrm{s}}$) discovered at the end of the module assembly at Saclay. Introducing Helium against a continuous air flow from the opposite side at the assembled module revealed the leak at cavity 4. The module was disassembled with the string still hanging under the cold mass. The leak check implied tightening of the leaky cold coupler connection at cavity 4. A leak test was performed on the connection by accumulating Helium inside a bag taped around the flange and the connection found leak tight. After reassembly and transportation to DESY the module has been measured at the AMTF and afterwards in more detail at DESYs cryo-module test bench (CMTB) with strong dark current on cavity 6. The module was not accepted for tunnel installation.

At the end of the assembly in Saclay XM50 showed a beam vacuum leak ($10^{-10}\,\frac{\mathrm{mbar\,l}}{\mathrm{s}}$). A first attempt locating the leak in the still assembled module was without success. Consequently the module was disassembled the string still hanging under the cold mass. A bag was taped around each inter-cavity connection, the connections to the gate valves, the DN16 valve and gauges of the quadrupole and around the BPM. A leak signal ($10^{-10}\,\frac{\mathrm{mbar\,l}}{\mathrm{s}}$) was finally detected when injecting helium into the bag around the DN16 valve and gauges of the quadrupole. After closing the gate valve at the quadrupole side, the beam vacuum area of the module was leak tight. The final leak check and the RGA analysis before shipping where conform to the requirements. At the AMTF module test strong field emission was observed. After the warm up a beam vacuum leak ($10^{-7}\,\frac{\mathrm{mbar\,l}}{\mathrm{s}}$) appeared. The module is not accepted for tunnel installation.

After the incoming inspection and the survey check have been performed at the AMTF, the upstream gate valve of XM54 was found defective. Normally the module required a disassembly and the complete string entering a clean room. This was incompatible with the module production running at full speed due to the blocking of workstations and personnel needed elsewhere. For almost one year XM54 was put aside and solutions were evaluated. Then the module was brought to CEA and disassembled with the string still hanging under the cold mass in front of the clean room. The support used for the gate valve assembly inside the clean room was moved on the rail system outside the clean room

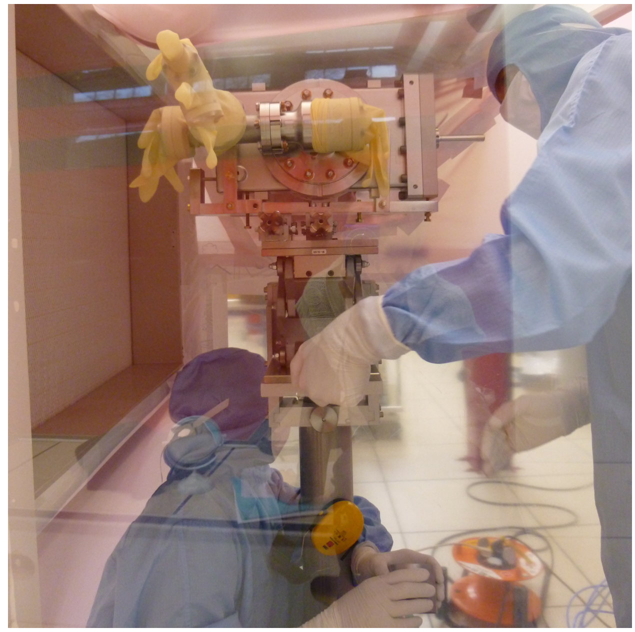

Figure 3: Locan clean room with horizontal laminar flow used for the exchnage of the defective gate valve of XM54.

and a local cleanroom with horizontal laminar flow installed around the upstream end of the module including the gate valve and the support (Fig. 3). The gate valve exchange was controlled by a particle counter. After re-assembly the module has been tested at the AMTF for the first time. The performance of the first cavity is degraded by field emission; all other cavities kept their performance above the (administrative) RF power limitation at 31 MV/m. The module provides an average usable gradient of 30.1 MV/m and is installed in the tunnel.

REPAIR WORK AT THE CANTILEVER SYSTEM IN THE DESY "HALLE 3"

XM-2 is a pre-series module initially not foreseen for the installation in the XFEL tunnel. The assembly at CEA took place in spring 2013. At this time the pressure equipment directive certification requirements from the notified body TÜV Nord where still under evaluation. As a consequence the x-ray inspection of the 2-phase pipe titanium welds was missing at this module for the certification required for tunnel installation. In autumn 2013 the module was tested at AMTF and showed an average gradient of 27.5 MV/m. In 2014 the module was used for tunnel installation tests and then put aside. Due to the good performance we decided in September 2016 to qualify XM-2 for tunnel installation by x-ray inspection of the 2-phase pipe titanium welds and by repairing welds found non-conform. In 29 days the module was disassembled to make the 2-phase pipe accessible for x-ray inspection and repair; X-ray investigation was done, some welds were redone, and finally the module was reassembled. The module obtained the TÜV certification and is now installed in the tunnel.

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XM8 has been assembled at CEA in spring 2014, when the module assembly was still in the ramp up phase. Nevertheless, the 2 K circuit consisting of the 2-phase pipe itself, the warm-up cool-down line and the cavity tanks was never suspicious-looking for any leaks. Connecting the module to the AMTF test stand two leaks appeared. One in the bellows of the coupler 5 push rod and one at the 2 K circuit with a leak rate of $8 \cdot 10^{-8} \frac{\text{mbar l}}{\text{s}}$. In situ exchange of the coupler push rod bellows cured the coupler leak. Separating the process lines to enclose the area where the leak is located revealed the leak location somewhere at 2-phase line and warm up pipe. In October 2014 the module was removed from the test stand without cold test, wrapped to guaranty low humidity and put aside for later investigation and repair as personnel was tight during the ramp up phase. In October 2015 the module has been brought to "Halle 3" for further investigations. Motivated by the experience with leaks at the magnet current leads of XM21 the magnet current leads where examined first without finding a leak in this area. Then XM8 was disassembled to make the 2 K circuit accessible. The leak was found at the capillary on the warm-up cool-down pipe connection at cavity 6 (Fig. 4). The weld was repaired and the following leak check at warm showed no anomalies. The repair took 38 days. In March 2016 the cold test resulted in an average usable gradient of 26.3 MV/m. After the warm up a $10^{-9} \frac{\text{mbar l}}{\text{s}}$ leak has been found again in the 2 K area. The module was put aside for further investigation, presently still ongoing.

End October 2015 the AMTF incoming inspection performed at the module XM69 revealed loose pins at the center post where the cold mass hangs at the outer vessel. Fixing this problem required supporting the gas return pipe by the cantilever in the "Halle 3". This action has been performed within some days. Already beginning December the module has been successfully tested (average gradient 28.9 MV/m) and mid-January 2016 installed in the tunnel.

Different problems arose while testing the module XM93: two helium leaks appeared at the 2 K and 70 K area respectively and cavity 1 could not reach its nominal frequency of 1.3 GHz nor go back to its nominal warm up position once the module was cold. All the problems were solved without disassembling the module; the leaks required some re-welding of the end pipe connections outside the module, while the frequency tuning problem needed some part exchange: the optical inspection performed after warm up revealed multi-layer insulation (from the test stand) trapped in the ball bearing of the tuner motor (Fig. 5). The drive unit was exchanged and the tuner performances measured to verify the results of the repair work. The frequency change operating the tuner motor was within the acceptance values.

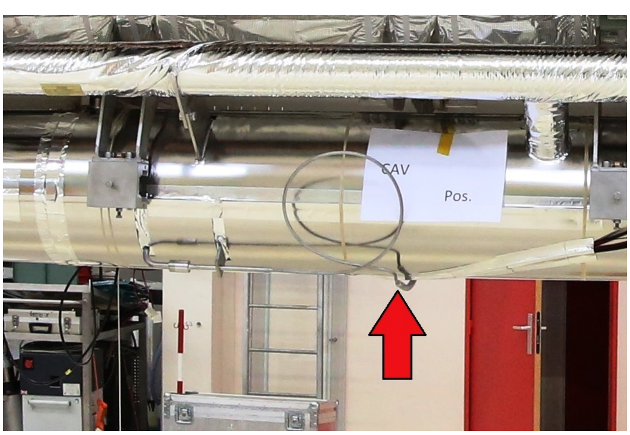

Figure 4: Position of the leak at the XM8 Helium filling line. The photograph shown here was taken at a different module at the CEA assembly line.

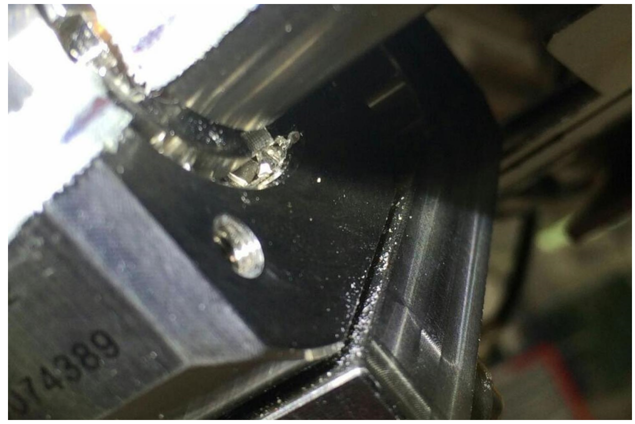
Figure 5: Multi-layer insulation trapped in the XM93 ball bearing of the tuner motor.

The modules XM22, XM24 and XM91 had beam line leaks requiring the disassembly and the complete string entering a clean room. We applied a slim method instead [7]. Furthermore, the problems occurring when testing XM22 and XM24 show exemplary problems occurring at the beginning of the series production and testing:

In January 2015 testing of module XM22 started. A leak found at the A-flange of coupler 2 was repaired in situ by exchanging the O-ring. Due to a leak venting the insulation vacuum caused by a loose fastening nut at a coaxial feed-through the testing had to be interrupted and the module warmed up. The flange with the leaky feed-through was exchanged. After the next cool down a heat load 10 times nominal has been found and the module warmed up for investigation. Finally, a 10^{-9} to $10^{-7} \frac{\text{mbar l}}{\text{s}}$ leak at the beam line appeared. Due to the time delay between the spraying of Helium and the detection inside the beam vacuum volume the leak was expected somewhere at an inner position. We removed the module from the test stand without being tested and stored it in the XFEL tunnel, which was still quite empty at this time. In January 2016 the module was brought back to the AMTF for warm coupler disassembly and subsequently to "Halle 3" for disassembly of the thermal shields permitting access to the string. In March 2016 the HOM #2 feed through of cavity 7 has been found leaky. We decided to try an exchange in a local clean room with the string of cavities still hanging at the cantilever (Fig. 6). To provide access

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to the feed through the tuner was uninstalled. The local clean room has been qualified with particle counters and the feed through exchanged. After reassembly XM22 has been fully tested for the first time in April 2016: All cavities kept their performance w.r.t. the vertical test providing an average gradient of 15.8 MV/m and the heat load measured was within the specification. The module has been installed.

Figure 6: Local clean room at XM22 hanging at the cantilever for HOM antenna exchange.

At the cold test starting February 2015 the module XM24 showed cold leaks at the process lines. By cooling down cryogenic circuits one after the next the 2 K circuit has been found leaky. In addition a thicker Indium seal was used for tightening the GRP adapter connections and the connection two times re-tightening after 6 and 8 hours waiting time. For later modules the work flow was adapted and leaks at GRP adapters prevented. While performing the rf tests, the push rod bellows of coupler 2 became leaky requiring an immediate warm up and in situ exchange before cooling down again and finalizing the rf testing. Due to the various leaks the module has been cooled down four times. During rf testing sparks appeared at coupler 4 caused by a loose capacitor screw. After the last warm up in March 2015 the beam vacuum showed a leak. We stored the module for almost one year in the XFEL tunnel before disassembling it like XM22. The pick-up antenna of cavity 8 was found leaky and exchanged in a local clean room. The second rf test performed in June 2016 showed the same results (average gradient 28.0 MV/m) like the first one. Especially the performance of cavity 8 is only limited to 31 MV/m due to the (administrative) rf power limit. The module is in the tunnel.

In June 2016 the module XM91 already successfully passed the rf test with an average gradient of 28.8 MV/m. After some repair work at warm coupler parts re-establishing the coupler and beam vacuum revealed a $10^{-4}\,\frac{\text{mbar l}}{\text{s}}$ beam line leak. We applied the same repair method like for XM22 and XM24. The HOM #2 feed through of cavity 7 was leaky and exchanged. Due to the tight schedule and the good experience with XM22 and XM24 the module was reassembled and installed in the tunnel without a second test.

COUPLER REPAIR ACTIONS

Before installing modules into the tunnel 69 warm coupler parts required repair actions of different extent at 41 modules [8]. Before the series production we didn't expect this big amount and diversity of problems. The XFEL coupler design is based on a design used at FLASH matured over years. But, the XFEL production was two orders of magnitude lager than previous productions. Here, we survey the most prominent issues, for details see [8].

At the beginning the torque applied to the screw connecting the warm coupler part to the coupler antenna in the cold coupler part was an issue. This was resulting in loose connections and contact problems requiring an in situ re-tightening. Sometimes sparks appeared. Then the warm parts where disassembled and partly replaced in local clean rooms after in situ grinding and cleaning of the rf surfaces. Using screws with higher tensile strength, increasing the torque and operator training solved the problem.

Until XM81 many coupler push rod bellows showed leaks leading to gas flowing into the coupler vacuum preventing further rf operation and forcing a warm up. The leaky bellows where replaced with the modules still on the test stand before cooling down again and resuming rf testing. This repair method is applicable at test stands requiring days for warm up and cool down but not at the XFEL main linac requiring weeks for warm up and cool down. Consequently, these leaks represented a major headache. First suspicions the leaks are caused by material problems or at the bellows manufacturing led to extensive examinations without results. Special repair caps where developed and tested establishing also vacuum outside leaky push rod bellows. Towards the end of the production couplers from a second supplier were assemeled without showing leaks at push rod bellows. Together with investigations of the correlations between the appearance of the leaks and rf power operation this mystery was solved: The XFEL push rod bellows design is slightly different form the one used so far at FLASH; rf can leak through the coupler dielectrics and damage the bellows [9]. Initially, the dielectrics have been installed to enable the application of a DC voltage to supress multipacting. The XFEL couplers never showed multipacting and the dielectrics could be replaced by shorts (metal parts) tightening the rf leak. The couplers from the second supplier had already from the beginning metals parts. All dielectrics at modules newly assembled at CEA, delivered to the AMTF and also already installed in the tunnel [9] where replaced and no leaks of this kind appeared any longer.

The warm parts of couplers from the second supplier showed frequently an overheating. The reason is still under

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investigation. Similar effects were not seen at the processing and testing at LAL [10]. All overheating warm parts have been replaced by parts inconspicuous at the cold test before the modules were finally installed in the tunnel.

Some rare cases of non-conform installations damaged couplers applying RF. Usually warm part disassembly in a local clean room, inspection and re-assembly either with new or cleaned parts fixed the problems.

We established two coupler repair workstations in the AMTF equipped with vacuum pump stands, clean rooms and storage place to comply with the tremendous coupler repair work.

MODULES STILL UNDER REPAIR

Four modules could not be repaired in time; XM8, XM46, XM50 and XM99. The first three have already been discussed above. While testing XM99 end July 2016 a beam line leak ($5 \cdot 10^{-8} \frac{\text{mbar l}}{\text{s}}$) appeared still present after warm up near the gate valve to cavity 1 connection. The screws where retightened. Some weeks later the leak disappeared. A second cold test was performed in June 2017. Unfortunately, a beam line leak ($4 \cdot 10^{-8} \frac{\text{mbar l}}{\text{s}}$) has been detected again.

XM46 and XM50 will be disassembled completely and the cavities re-treated as required, vertically re-measured, the cavities re-grouped to the modules and the modules reassembled and re-tested. In case the leak in the 2 K area of XM8 is at a cavity helium vessel, this module will also be disassembled completely and join the treatment of XM46 and XM50. XM99 will also be completely disassenbeled. Nevertheless, the XM99 cavities do not suite the cavity performance from the other three modules and will not join the cavity re-grouping.

For completeness: The AMTF test of XM92 in May 2016 revealed three overheating couplers which have been echanged. During the preparation for the warm (coupler) re-test in end June, the upstream gate valve has been found defective. We decided to install this module as it is (average gradient 29.3 MV/m).

XFEL MODULE PERFORMANCE

With an average usable gradient of 26.9 MV/m the XFEL modules surpass the design requirement of 23.6 MV/m. Details on the AMTF measurements may be found in [11]. For the tunnel installation we sorted the modules for the optimal use of RF (Fig. 7). Due to special sorting the L2 provides the full beam energy to the second bunch compressor even with two of the three rf stations. One rf station of the L3 may also be switched off still providing the maximum design energy of 17.5 GeV. This is even the case with the 96 modules rather than 100 modules installed in the main linac tunnel. Nevertheless, the experimental verification of the maximum linac performance is still pending.

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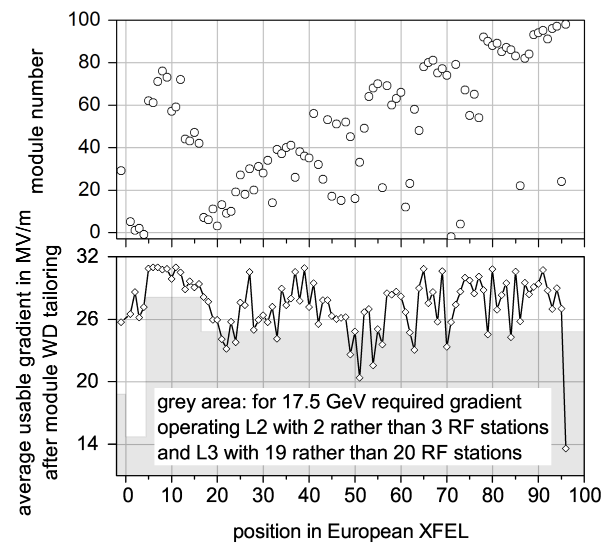

Figure 7: Module performance as measured in the AMTF and their installation position.

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