

# EUROPEAN XFEL LINAC RF SYSTEM CONDITIONING AND OPERATING TEST

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## Abstract

96 accelerating modules with 768 TESLA / European XFEL type superconducting cavities were installed in the European XFEL ([1] – [3]) LINAC tunnel (XTL) in fall 2016. Warm conditioning of the RF system - High/Low Level RF System and main input couplers - begun even before finishing the accelerator installation works. All modules were conditioned and tested prior to the installation in the tunnel in the AMTF test stand at DESY. Nevertheless, due to some repair activities on warm input coupler parts, warm conditioning was needed on a few modules/couplers. Cooling down to 2K begun in December 2016 and was finished in January 2017. Since then cold conditioning and tests are running. A few input couplers did have problems with conditioning and were disconnected, limiting otherwise the system performance. Some cavities in the modules showed multipacting (MP) effects, mostly because the cavity vacuum was vented with dry nitrogen gas because of mentioned repairs on couplers in some modules. Such MP effects did appear in AMTF as well. All MP effects were successfully conditioned until now.

## INTRODUCTION

The European XFEL layout is described in ([1] – [3]). Prior to Linac accelerating modules installation in the tunnel SRF cavities and modules were tested, their performance and limits evaluated and documented ([3] – [7]). Tunnel installation is almost finished now. High power RF system (HPRF, klystrons) are commissioned, low lever RF (LLRF) system is being commissioned [8]. Parallel to LLRF commissioning fundamental power couplers (FPC) conditioning is done, followed by SRF accelerating cavities conditioning and operating test.

## FUNDAMENTAL POWER COUPLERS

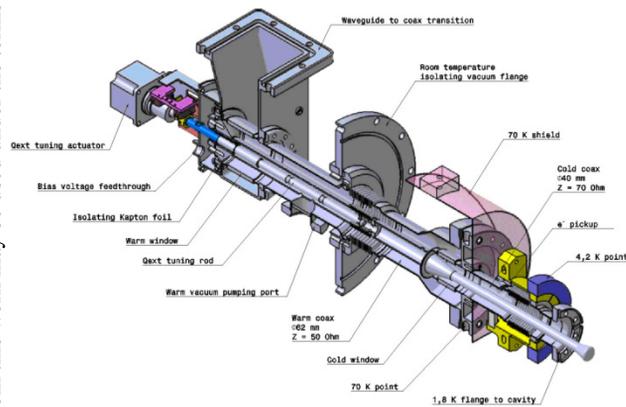


Figure 1: European-XFEL FPC layout.

Last developments for the European XFEL FPC are described for example in [9].

## Solving Push-Rod Vacuum Leak Problem

During the module tests in AMTF 35 warm parts (WP) were replaced because of inner screw contact problems and problems with the conditioning, cold 70K window overheating and not conditionable discharges. Another recurrent problem were the tuning push-rod bellow (inside the FPC warm window, Fig. 1) vacuum leaks – 30 push-rods were replaced until the problem was understood and solved finally in the tunnel.

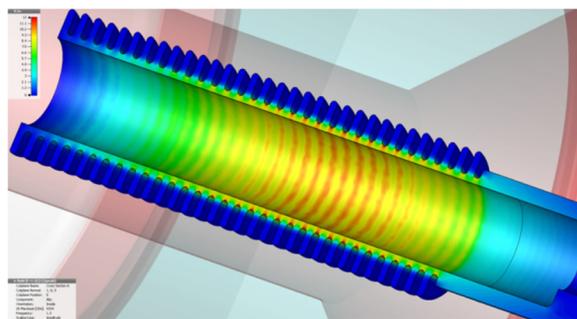


Figure 2: CST MWS FPC simulation: push-rod bellow.



Figure 3: FPC push-rod bellow vacuum leak spot cut-out.

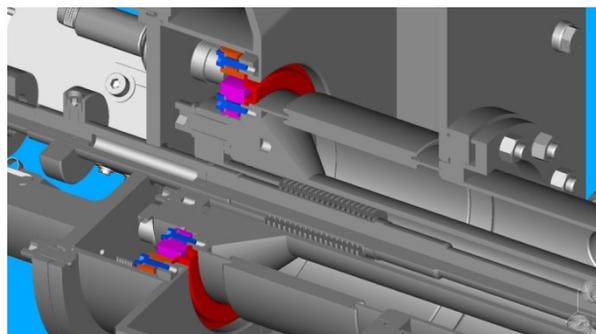


Figure 4: FPC copper coax-gasket (red).

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Simulation of the FPC done with the CST Microwave Studio showed the EM-field penetration inside the push-rod bellow with a local electrical field maximum where the bellow deformation caused contact is possible (Fig. 2), hence the RF discharge and thin (0.15 mm) bellow wall deterioration (Fig. 3) causing the vacuum leaks with RF power on. The applied solution was a replacement of the HV-bias capacitors with a copper coax-gaskets (Fig. 4), preventing the EM-field coupling to the push-rod bellows. In case of need for the HV-bias (which was not the case since long time) another solution was developed as well. All the capacitors were replaced with coax-gaskets in the tunnel (no HV bias is possible) – where the last push-rod vacuum leak did occur – there was no leaks since then.

### FPC Conditioning

The warm off-resonance FPC conditioning in the tunnel was done to a possible extent: not all RF-stations were ready for RF at the start of the cool-down, so it was not done for all installed modules. The RF stations are A1 .. A25, A1 is injector one with 1 module, A2 .. A25 are in the main (XTL) tunnel with 4 modules in each station (A26 not yet installed, see Fig. 5). The warm conditioning is done up to A17, A18..A25 were not ready for RF. After cool-down was finished the cold off-resonance (cavities not tuned) couplers conditioning for stations A18..A23 was performed. Stations A24 and A25 are still not ready for RF. After this a short cold conditioning and test of the modules - mostly cavities multipacting conditioning did follow. The coupler conditioning in the tunnel is done up to lower RF power compared to AMTF cryo-module test and the RF power for individual couplers is also affected by the adapted waveguide RF power distribution. So the coupler conditioning was done up to 100..300 kW and full RF pulse length (750+650µs).



Figure 5: European-XFEL layout.

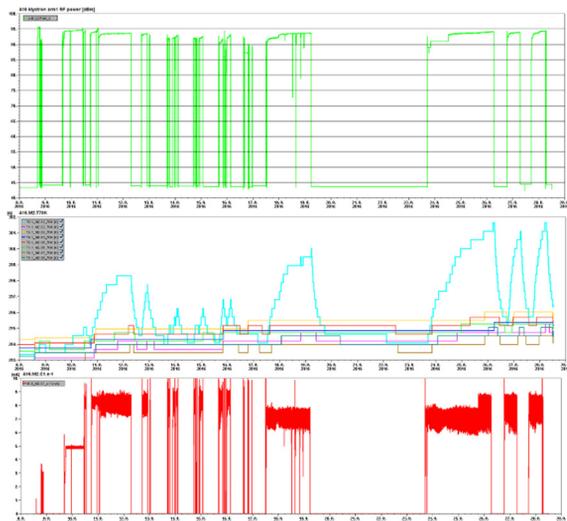


Figure 6: FPC warm conditioning – cold part problem.

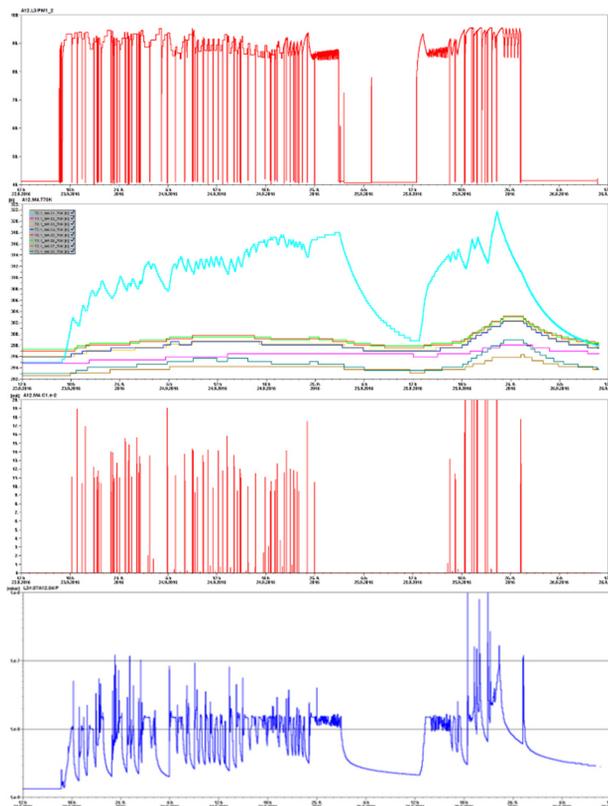


Figure 7: FPC warm conditioning – warm part problem.



Figure 8: FPC cold conditioning – T70K overheating.

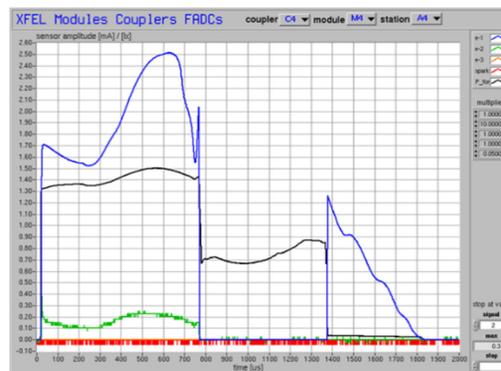


Figure 9: FPC cold conditioning – discharge indication.

In a few cases FPC conditioning was not successful – the problem did persist. Using the FPC technical interlock sensors, such as e- probes, temperature sensors and spark detectors augmented with coupler vacuum pressure gauges one can distinguish the coupler parts (cold/warm) having a problem (Fig. 1) and judge its severity. In Fig. 6 a typical unsuccessful warm conditioning example is

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shown – RF power[dB], cold 70K window temperature T70K[K] and e-1 (cold part) e- probe signal [mA] vs time for a certain period – showing almost no progress for 2 weeks. This indicates a cold FPC part problem. Figure 7 shows RF power[dB], cold 70K window temperature T70K[K], e-2 (warm part) e- probe signal [mA] and FPC warm part vacuum pressure vs conditioning time – an example of a problem connected with a warm FPC part. In both cases an RF discharge did increase cold window temperature – very obvious compared to other couplers in a module. Such a hard cases were nevertheless tested at cold conditions (cavities at 2K) and, in case cold window temperature went over 150K, as shown in Fig. 8, coupled with persistent RF discharge indication (Fig. 9) – such an FPC was judged to be not conditionable and was disconnected (shorted). Using the FPC with T70K over-temperature and permanent RF discharge is not advisable because of possible further system deterioration and vacuum problems, even more severe ones in case of a cold FPC part, being a part of a beam vacuum system. Table 1 summarizes FPC conditioning problems. Until now 4 FPC are disconnected from RF power source because of not conditionable RF discharge and cold window overheating, 2 others are under evaluation.

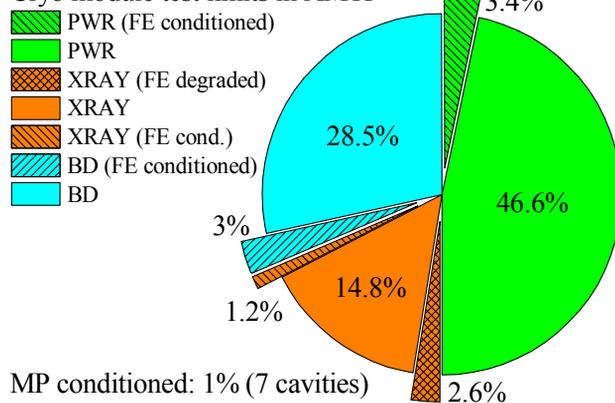
Table 1: FPC Conditioning Problems Summary.

N	position	module	status	summary
1	A4.M4.C4	XM72	shorted	T70K → 200K, high e-1 signal - discharge, cold part problem.
2	A12.M4.C1	XM53	shorted	T70K → 150K, discharge, warm part problem.
3	A13.M2.C8	XM51	OK	high e-2 signal - conditioned.
4	A16.M1.C1	XM69	OK	high e-1 signal - conditioned.
5	A16.M2.C1	XM60	shorted	T70K → 150K high e-1/2 signals, cold part problem.
6	A16.M2.C2	XM60	OK	high e-2/3 signals - conditioned.
7	A16.M4.C7	XM66	OK	high e-2/3 signals - conditioned.
8	A19.M3.C4	XM-2	testing	T70K overheating - no discharge.
9	A19.M3.C6	XM-2	OK	conditioned - 5 hr.
10	A20.M4.C1	XM65	shorted	high T70K, cpl.vac. increased, high e-2 signal bursts, warm part problem.
11	A21.M2.C5	XM92	testing	T70K overheating - no discharge. WP already replaced.

## ACCELERATING SRF CAVITIES

After cooldown to 2K each RF station (4 modules – 32 cavities) was tested separately to achieve maximum performance. Three main limiting factors for the European XFEL cryo-modules cavities are breakdown (31%), field emission/X-rays (19%) and available RF power – as known from AMTF tests, see Fig. 10. RF conditioning was applied to cure the breakdown and field emission cavity performance limits. RF conditioning of a cavity breakdown (quench) without field emission was mostly unsuccessful (no improvement). An RF station is limited by one cavity of 32 – usually by a breakdown – given by the waveguide RF power distribution.

Cryo module test limits in AMTF



MP conditioned: 1% (7 cavities)

Figure 10: Cavities operating gradients limits in AMTF.

### Multipacting

Another limiting effect is a multipacting (MP) – this phenomenon is a resonant RF discharge in the cavity, it depends on the cavity surface properties – mostly on secondary electron emission yield (SEY), occurs at 19 .. 25 MV/m for the TESLA type cavity and is conditionable in the most cases. SEY is decreased during the conditioning, which takes from 15 minutes up to several hours and is done by keeping the cavity breakdowns with a short RF pulse (750 + 100 μs) until no further progress is seen. Apparently more MP conditioning (~ 16 times) was done in the European XFEL linac tunnel compared to the AMTF. All MP cases were conditioned successfully until now. In Figs. 11 – 13 MP statistics is presented.

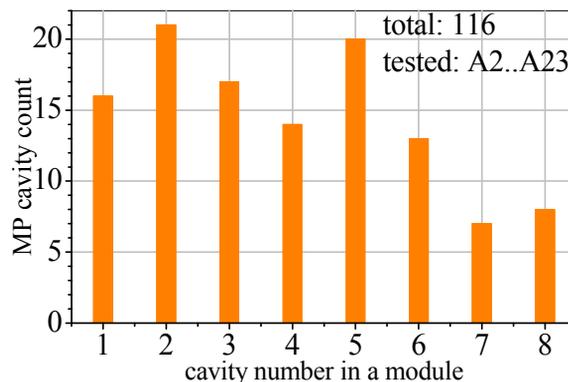


Figure 11: MP with a cavity number in a module.

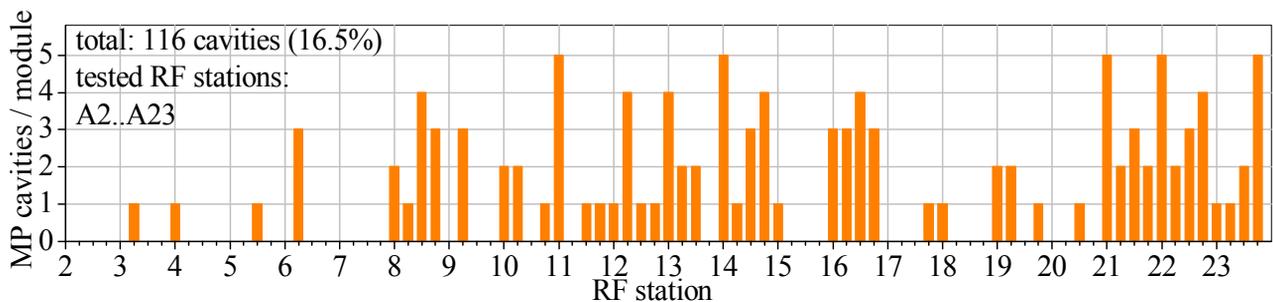


Figure 12: MP distribution over RF stations modules.

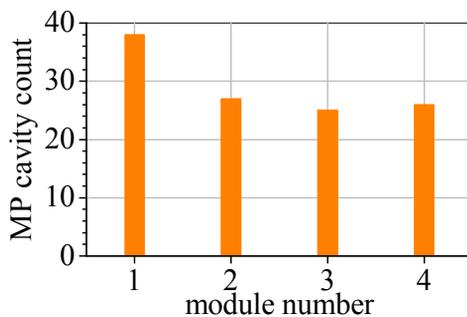


Figure 13: MP with a module number in the RF station.

### Commissioning Summary

88 cryo-modules – 704 cavities are commissioned and accelerating the beam up to 14 GeV already. 116 cavities (16.5%) needed the multipacting conditioning. Last cryosting (CS9) having currently 8 modules (4 to be installed) is not yet ready for RF power and is being completed.

9 cavities from 704 – 1.3% – are not used: 4 cavities are disconnected because of FPC problems and 5 did show a bad performance (low breakdown gradient and/or high field emission) in AMTF.

### OUTLOOK

Currently the RF stations performance is under optimization. Linac is being characterized and tested in order to get planned accelerated electron beam energy of 17.5 GeV. LLRF system is under commissioning and still needs some optimization and study, which will lead to a full use of possible operating cavities gradients.

### SUMMARY

- 96 European XFEL accelerating modules installed in the main linac tunnel (XTL), 4 modules are postponed.
- Technical Interlock (TIL) system is installed, completed and commissioned.
- All fundamental power couplers (FPC) capacitors were replaced by the coax gaskets – no push-rod vacuum leaks were detected anymore with RF power on, problem is well understood and solved.
- Warm FPC conditioning is done with 64 modules (stations A2..A17). Cold FPC conditioning is done up to station A23 – 88 modules. Stations A24 and A25 (8 modules) are yet to be taken into operation.

- 4 FPCs are shorted (not used) because of the coupler problems – cold 70K window overheating caused by the cold/warm parts coupled with not conditionable RF discharge, two more couplers show T70K overheating effects – to be tested and decided.
- 88 cryo-modules are commissioned and accelerating the beam up to 14 GeV already. Some cavities did show multipacting effects during the commissioning, conditioning was successful.

### ACKNOWLEDGMENTS

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