LARGE SCALE TESTING OF SRF CAVITIES AND MODULES*

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Abstract

Series production of superconducting RF cavities, superconducting quadrupole packages and accelerator cryomodules for the European XFEL is in full swing. Mid 2014 approximately. 400 cavities will be tested, the testing of quadrupole packages will be almost finished, and regular module testing will be established. Thus this talk will emphasize the quasi industrial testing of these components, including a good overview about the used unique AMTF infrastructure.

INTRODUCTION

Currently the European X-ray Free Electron LASER (XFEL) [1] is under construction at DESY in Hamburg. The laser will produce high-intensity ultra-short X-ray flashes. Brightness of these flashes will be incomparably greater than the best conventional X-ray source. With this unique device all scientists around the world and also users from industry can explore new research opportunities [2].

Poland is one of twelve countries (Denmark, France, Germany, Greece, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden and Switzerland) participating and financing the construction of XFEL.

Figure 1: XFEL cavities installed into the insert.

A team of physicists, engineers and technicians from the Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) performs the tests of all superconducting cavities, superconducting magnets and accelerator modules as a Polish in-kind contribution for the XFEL.

IFJ PAN is responsible for preparation, conditioning and testing of 840 superconducting cavities (Fig. 1), 103 superconducting magnets (Fig. 2), 103 current leads and 103 accelerating cryomodules [2].

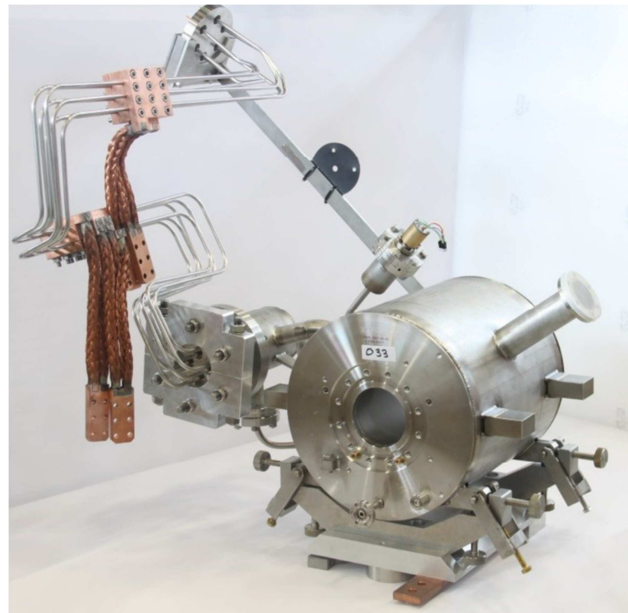

Figure 2: Superconducting magnet with current lead

INFRASTRUCTURE

The "Accelerator Module Test Facility" – AMTF hall at DESY in Hamburg is dedicated to perform the acceptance tests for superconducting cavities and accelerator cryomodules (Fig. 3).

Figure 3: Inside view of the AMTF hall – cryomodules.

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The cryomodule production rate of one eight-cavity-module per week requires in parallel an average cavity vertical acceptance testing rate of at least eight per week and cryomodule testing rate of one per week.

Therefore the AMTF hall is equipped with two vertical cryostats which are used for the vertical acceptance tests and three test-stands for the test of the accelerator cryomodules [3]. Each vertical test cryostat is equipped with its own RF test stand and accepts one of the six available "inserts" supporting up to 4 cavities each. In addition to the mentioned equipment there are also preparation areas for cavities and for cryomodules as well as storage areas for both cavities and cryomodules.

The IFJ PAN team performs cavity and cryomodule testing. The team is divided into 5 groups: Mechanical, RF, Cryo-Vacuum, Software development and Safety officer. The described work flow requires two shifts with currently 18 engineers and 24 technicians.

CRYOMODULE AND CAVITIES TESTING

In order to test the components (either a cryomodule or a cavity) several main tasks have to be performed. For both cryomodules and cavities the test workflow is similar. For a better illustration of the test program, a cryomodule test main flow diagram was created and is shown in Fig. 4.

Full test for the components means that all main tasks are done. All of these tasks are performed according to the written procedures which were created by IFJ PAN team. For each test three kinds of reports are created: incoming inspection report, outgoing inspection report and test report. These documents are stored in the Engineering Data Management System (EDMS), which is used for the technical documentation of the European XFEL. In addition to the reports the complex logistics and work flow for each cavity and cryomodule is supported by a newly developed software tool, which includes a close tracing and documentation of each work step.

The cavity and cryomodule test diagram contains only two differences. Cavities can be stored on dedicated shelves before installation to the test insert or after their vertical acceptance test. The last step for cavities is the shipment to CEA Saclay for string assembly, while the modules are transported to the XFEL accelerator tunnel or a storage area. The following chapters describe the main procedures.

Preparation and Assembling of the Cavities

The cavities are fabricated, surface treated and delivered by two vendors E. Zanon Spa. (EZ) and Research Instruments GmbH (RI) [4]. After delivery to AMTF hall each cavity must pass an incoming inspection (mechanical, vacuum and electrical check). Then the cavity is transported to preparation area, installed to the insert and connected to the vacuum line. The connection to the vacuum line has to be performed under clean room condition (class ISO 4).

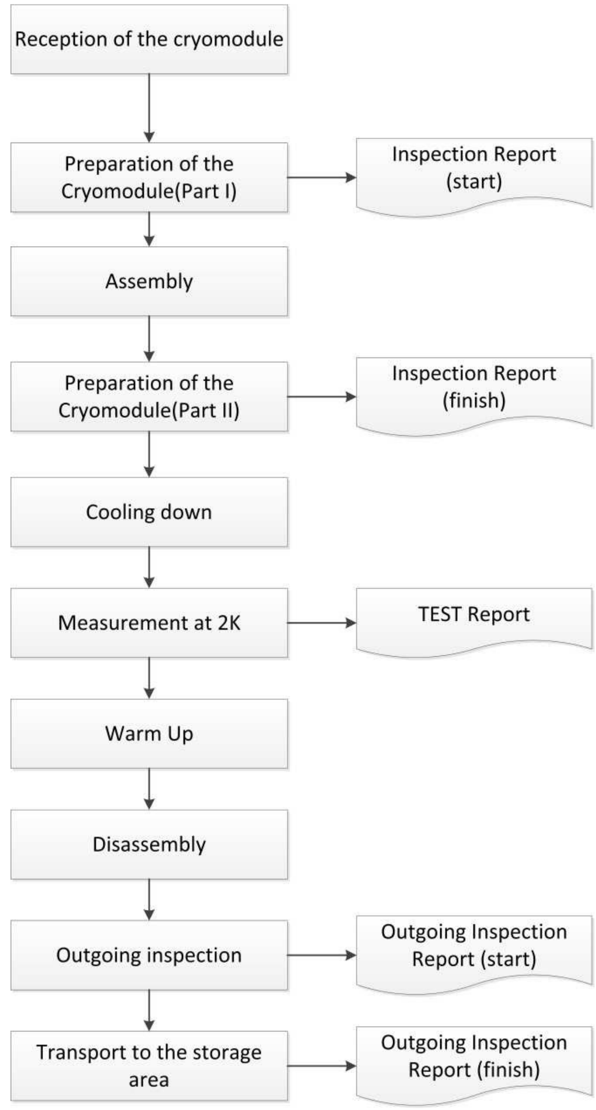

Figure 4: Cryomodule test main flow diagram.

To accomplish this task a new type of clean room was developed and is used (Fig. 5). The inserts present at AMTF hall can contain up to 4 cavities each. After connection to the vacuum line all necessary leak checks have to be performed just to make sure that cavities are connected properly (pressure < 1e-7 mbar and He background < 1 e-10 mbar*l/s). Preparation is finished with tuning of the HOM rejection filters and connections of the electrical cables [5]. The prepared insert is transported to the one of the two cryostats used at AMTF hall.

In order to perform RF measurement at 2K of the cavities the cryostat needs to be cooled down to such temperature.

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Figure 5: New type of clean room.

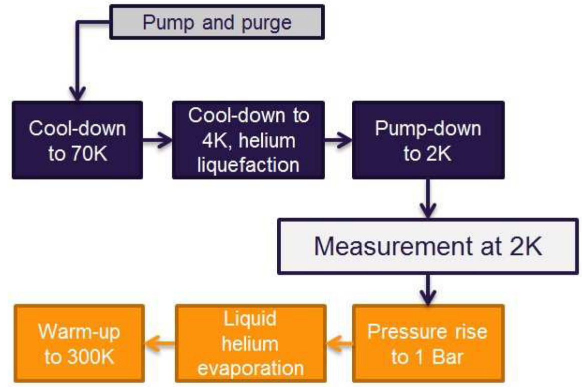

Figure 6: Cryogenics operation sequence for cryomodule test stand.

Preparation and Assembling of the Cryomodules

For the cryomodules almost the same way is realized like for the cavities. This means that after reception the cryomodule is unloaded from the truck and transported to the preparation area. In this place the incoming inspection checks have to be done before the cryomodule will be accepted for the test. This kind of checks includes mechanical check, electrical check, vacuum check and geodetic measurements. Also the data from shock loggers, which are assembled to the module during transport, are read out. If the component passes the incoming checks successfully than the additional necessary equipment for instance patch panels, cable tree, signal cables, rf cables are installed. After that, the cryomodule can be loaded on the trolley and brought into the test stand where all necessary connections to the test stand are performed. Before cold down the room temperature conditioning of the RF power coupler takes place. The purpose of this task is a “processing” of the coupler after installation to the cryomodule in order to avoid a situation in which the coupler does not work properly [6].

Cold down and Warm up

Cool down process starts with pump and purge of the cryogenics process pipes, which is done manually by the cryogenic operator. After that the final cool down process is performed using automatic software for the cavity and manually for the cryomodule. The last step of the cold down process is pump down to 2K. This means that the pressure above liquid helium is reduced to 31mbar equivalent of 2 K. The main sequence how this process runs for the cryomodule is shown on the Fig. 6. Cold down is divided for three major steps and the same is for warm up. The automatic software created for the cavities improves cryogenics operator work giving more flexibility to the operator and provides more possibility to control this process.

Vertical Acceptance Test of Cavities at 2K

The vertical acceptance test at 2K provides the most important information about the cavity performance: Maximum available gradient and dependence of quality factor and radiation on the gradient [5, 7]. These kinds of measurements are performed using a special software which has been modified to the needs of the AMTF cavity testing and in few cases a completely new software has been created. This gives the possibility to reduce the time needed to perform such tasks as well as an easier uploading of the results to the data base for the cavity test results. Two acceptance criteria have been defined: At the beginning of the production an usable gradient higher than 26 MV/m at $Q_0 \geq 10^{10}$ was required. Here 10% margin is included compared to the 23.6 MV/m average design gradient for the XFEL cavities. Since May 2014 the acceptance criterion is reduced requiring an usable gradient higher than 20 MV/m. This came up after analysis of retreatment results for optimized number of tests and energy gain. The usable gradient is defined by: gradient of quench or gradient at unloaded $Q_0 < 1\text{x}10^{10}$ or gradient at which the either X-ray level exceeds the threshold. The X-ray levels are measured inside the concrete shielding of the vertical test stands on top and below the cryostat. The thresholds are based on the experience gained with FLASH cavities.

Cavities Results/statistics

All data have the status of 31 July 2014.

This analysis includes series cavities and ILC HiGrade cavities. 404 cavities have been delivered to the AMTF and in total 382 cavities have been tested. This means that for these cavities the full test program has been performed and results were uploaded to the database.

The trend of the vertical test rate for both cavity vendors is shown in Fig. 7. Currently the test rate in average is around 9 cavities tested per week which is more than estimated rate.

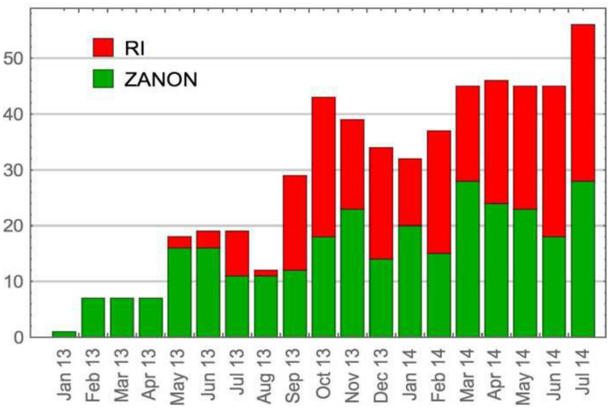

Figure 7: Trend of the vertical test rate.

The yield of usable and maximum gradient of 339 cavities “as received” is shown in the next two figures. Average usable gradient is 26.6 ± 7.6 MV/m (Fig. 8).

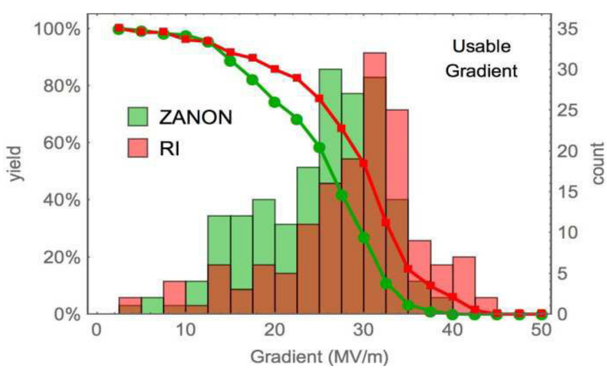

Figure 8: Average usable gradient.

For RI cavities it is 28.6 ± 7.0 MV/m but for Zanon cavities it is 24.8 ± 7.0 MV/m. There is statistical significant difference between the vendors but the achieved results both meet the acceptance criteria.

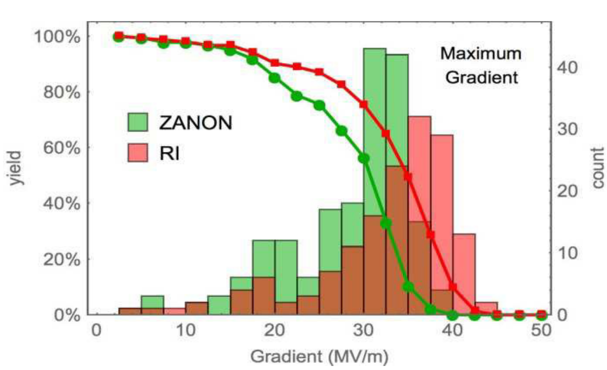

Figure 9: Average maximum gradient.

As is shown in Fig. 9 the average maximum gradient is 30.4 ± 7.6 MV/m. Results for each vendors are respectively: 28.4 ± 7.1 MV/m for Zanon cavities and 32.4 ± 7.6 MV/m for RI cavities. Given errors are standard deviations. For more details see [7].

Cryomodule Measurements at 2K

In order to check the performance of the cryomodule several measurements have to be done at 2K temperature. The main measurements are:

- cold cables calibration,
- spectra measurement,
- cavities tuning,
- HOM spectra measurement,
- couplers tuning,
- cavities calibration,
- cavities flat-top measurement,
- heat loads measurement
- and low level RF measurement.

As for the cavity measurements in several cases the applied software has been modified and for some tasks completely new software was necessary and has been created. Basically all of these measurements can be divided on two groups: mHigh RF power measurements using the klystron and low RF power measurements performed using a Vector Network Analyser (VNA) and RF amplifiers, if needed [6].

The maximum achievable gradient for each cavity in a cryomodule is in general limited to 31 MV/m by the available RF power of the klystron and the waveguide distribution. The operational gradient for the cryomodule, is lower than the maximum as it includes:

- Operational margin (0.5MV/m below quench limit)
- Effect of the XFEL “paired” power distribution, which limits to the worse cavity of each pair
- Empirical X-ray radiation limit (created by field emission.

Cryomodules Results

All data have the status of 31 July 2014. Up to this date seven cryomodules (form XM-2 to XM5) have been tested at AMTF hall. Results are presented in Table 1. The most important column in the table is fourth column where the average operational gradients for the cryomodules have been shown. All tested cryomodules meet the XFEL specification, which is 23.6 MV/m. This means that all mentioned cryomodules can be installed into the tunnel.

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Table 1: Summary of gradient performance for cryomodules with equivalent vertical test results as comparison

Module	Average max. gradient module [MV/m]	Average max. gradient Vertical [MV/m]	Average operational gradient module [MV/m]	Average usable gradient Vertical [MV/m]
XM-2	27.2	28.1	24.5	26.5
XM-1	28.2	30.8	25.1	29.4
XM1	30.3	32.5	27.6	29
XM2	27.7	32.7	25.5	28.6
XM3	30.4	32.0	28.8	29.3
XM4	28.6	33.3	23.8	30.5
XM5	27.8	28.9	24.9	26.9

Individual comparison between vertical maximum gradient and module maximum gradient shows significant performance reduction for a few cavities. This concerns about 10% of the tested cavities. An investigation of this effect is ongoing. From maximum gradient of the vertical acceptance test to the operational cryomodule gradient around 20% reduction is observed in average.

SUMMARY

In total 840 superconducting cavities and 103 accelerator cryomodules for the European XFEL have to be tested. Cavity and cryomodule testing and all work flows at AMTF hall are well established. On 31 July 2014 382 cavities and 7 cryomodules have been tested. For both – cavities and cryomodules – the acceptance test performance is in average above specification. Testing in such a large scale requires the development of many test procedures, software improvements and trainings. In addition it is a big logistic challenge. This has been succeeded with the help of DESY experts.

This success is possible only in a great collaborative effort and with a positive team spirit of all partners.

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