ASSEMBLY OF XFEL CRYOMODULES: LESSONS AND RESULTS

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Abstract

The industrialized string and module assembly of 103 European XFEL cryomodules has been performed at CEA-Saclay between September 2012 and the July 2016. The general features and achievements of this construction project will be reviewed, including lessons learned regarding organization, industrial transfer, quality control and assembly procedures. An overview of the cryomodule performance and RF test results will be presented.

INTRODUCTION

The accelerator of the European XFEL is assembled out of 101 superconducting accelerator modules being contributed by DESY (Germany), CEA Saclay, LAL Orsay (France), INFN Milano (Italy), IPJ Swierk, Soltan Institute (Poland), CIEMAT (Spain) and BINP, Russia. The 17.5 GeV Linac is made of 808 9-cells cavities at 1.3 GHz and 25 RF stations of 5.2 MW each.

The CEA was in charge of assembly of 103 accelerator modules on the Saclay site and with CEA infrastructure while the workforce is given by an industrial contractor Alsyom. The very challenging delivery rate was to produce one module per week. The performance goal is an accelerating gradient $E_{acc} > 23.6$ MV/m and a quality factor $Q_0 > 1^{10}$ at 2 K.

In this paper, the preparation phase of this construction project will be briefly reminded, then the achievements including lessons learned regarding organization, industrial transfer, quality control are presented, finally the cryomodules performance are analysed regarding the assembly procedures. Some cryomodules repair activities will also be presented.

Due to their good performances 96 modules are enough to meet the energy goal with some margins. These 96 modules have been installed in the tunnel. More details on the status of XFEL are presented in [1].

PREPARATION PHASE

A set of three building have been refurbished and assembly halls were organised in 7 workstations (WS). The so-called XFEL Village consists of 200 m^2 clean room complex with 112 m^2 under ISO4 allows assembling the couplers to the cavity and two cavity strings in parallel; the cryostating will be held on the 1325 m^2 of assembly platforms and 400 m^2 are dedicated to storage [2]. During the preparation phase, many automated or demi-automated test benches have been developed. DESY lent CEA nine pumping systems (with mass-spectrometers) and one laser-tracker. INFN developed for the Saclay site two piezo tuner control racks, CEA bought a washing machine to enter parts into ISO4 clean room, and three pumping units (slow-venting) with leak detector in the cleanroom dedicated to non-vacuum experts. CEA developed four RF crates for automatized RF measurements namely RF spectra, transmission and field flatness measurements and Time Domain Reflexion. This crates have been used at different workstations to: control the HOM coupler rejection filter, monitor the cavity tuner installation, tune the HOM and check RF cable integrity.

The breakdown of the total assembly work over 7 workstations aims at:

- balancing almost equally the occupancy of each WS,
- bringing the longest WS occupancy below 5 days, it impacts directly the throughput

Preparation phase was also used to qualify the providers of the parts CEA had in charge: beam vacuum gaskets and fastening, multi-layer insulation and magnetic shielding. For one module, there are 9 422 individual components integrated and over 12 400 individual parts manipulated per cycle time. The use of reliable Enterprise Resource Planning ERP is highly recommended.

PRODUCTION PHASE

Cryomodule Production

A detailed presentation of the cryomodule mass production is given in [3]. The modules delivery to DESY ends on 2016 July the 28th. In total 103 modules were delivered to DESY (including the so-called pre-series cryomodules XM-3, XM-2, XM-1).

Figure 1 shows the number of cryomodule produced as a function of the delivery dates. As indicated in Figure 1, in 2015, one cryomodule was delivered every 4 working days, 52 in total. The Cold Linac will also include two pre-series cryomodules: XM-2 and XM-1.

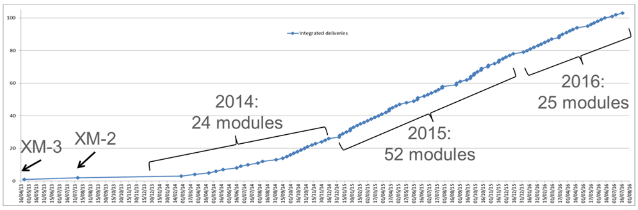

Figure 1: Number of cryomodules delivered vs. the delivery dates, from XM-3, XM-2, XM-1 and XM1-XM100.

Figure 2 shows the production throughput over time. The throughput of one module every 5 days have been reached mid-October 2014 with XM15 confirming that the design of the Assembly Infrastructure was correct.

Thanks to organisational efforts, the 4-day throughput was reached in January 2015 with XM25 and maintained till the completion.

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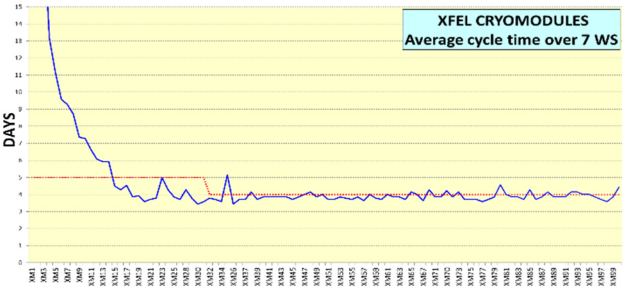

Figure 2: Production throughput from 2014 January with XM1 to 2016 July ends with XM100.

The production phase is a continuous improvement process. The acceleration from 5 days to 4 days throughput and the quality of production benefited mostly from:

- New clean room assembly procedure: moving individual cavity venting after the leak check of the cold coupler assembly, rather than later, before the string assembly. This eliminates one connection to pumping stations for cavity venting, and one valve closing-opening cycle,
- New equipment, e.g. string leak test plexi-box to leak test the intercavity connections (bellows, pick-ups, fundamental power coupler, HOMs) as shown in Fig. 3,

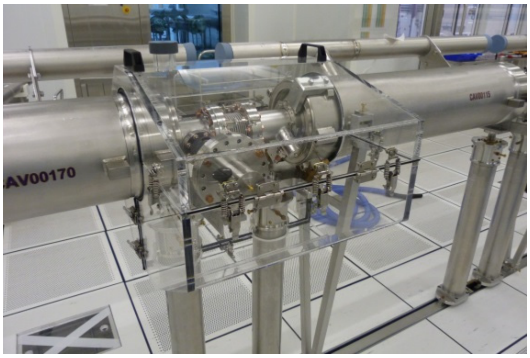

Figure 3: Test plexi-box to leak test the intercavity connections.

- Pure Argon gas for Titanium welding, instead of He-Ar (50%-50%), to avoid the long and unpredictable time to pump and purge the Helium tank to reach the He background for the leak test by external accumulation,
- Reducing the impact of non-conformities, particularly imported non conformity. More human resources have been put on incoming inspection and quality control.

In the XFEL scheme for quality control, the Manufacturer qualification is performed by our lab partners, thus all parts coming at CEA are supposed to be conform.

Non Conformities (NC) recorded by Alsyom fall mainly into 3 categories:

1. Tooling and equipment (TOOLING), responsibility by CEA/DESY
2. Accelerator components (PRODUCT), responsibility by suppliers
3. Assembly operations (PROCESS), responsibility Alsyom

As shown on Figure , the number of PRODUCT Non-Conformities has not gone down. But, with better and more efficient detection at incoming inspection, the impact of PRODUCT non-conformities on the module assembly has considerably decreased, compared to when many non-conformities were discovered online.

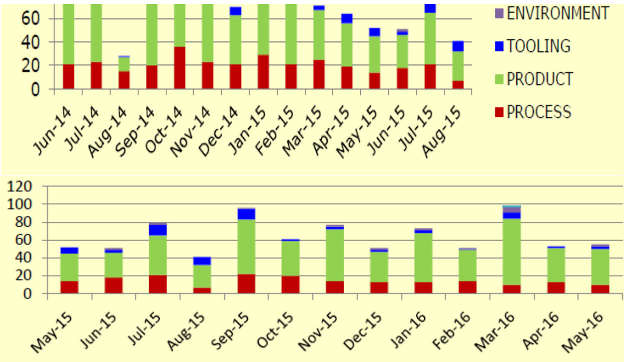

Figure 4: Number of non-conformities sorted by categories, over June 2014 to August 2015 (top) and May 2015 to May 2016 (bottom).

Even if the parts are inspected at CEA (when possible at arrival) not everything can be inspected so some inspection occurs during assembly e. g. clean inter-cavity bellows.

As some stock was available, the part was parked with its NC report and repaired later) and replaced by next part. The non-conform parts are either reworked, sent back or trashed.

Until end of 2014, the quality control group of Alsyom was too small (3 people) so they performed incoming inspection and documenting in priority. CEA took over the assembly work controlling ('Hold Points'). The 'every day' or 'random' controls were too few and this led to many mal-fabrication, most of them recorded at DESY before or during cryomodule cold test

In November 2014, an increase of the quality control group of Alsyom to 5 people and a better organisation, cover the need of QC. In August 2015, increase of CEA quality control group. CEA also took over the NCR editing on EDMS and improvement proposal

CEA performed global audits (XM26) or local ones (XM84 in clean room) are good feedback from the auditors (CEA experts) to the operators. Audit findings during XM26 in cleanroom (Cold Coupler and String Assembly WS):

- Operators walk too fast in the clean room.
- Record the cleanliness level (< 10 particles / min) reached on the angle valve before the pump connections to the cavity (CC and SA).
- Two operators are requested to connect cavity to the pumping system (CC and SA).
- Two operators are requested to position inter-cavity bellows and screw first 4 studs (SA).
- Pre-alignment of parts (coupler and cavity flanges at CC, inter-cavity bellow/cavity-coupler-side flange at SA) need more care for easy and clean assembly.

- Improvement of operator positions versus critical RF surfaces (avoid assembly from the top, request seated).
- Gate valve connection to pumping system procedure has been reviewed recently to ensure better cleanliness (CC).

All production documents (specifications, test report, traveller, PED certification data, etc.) recorded electronically in data management system (EDMS) [4].

The non-conformance mitigation is first proceed in a quick close loop with DESY co-Work Package Leader. Then it's recorded in the CEA-Alsyom documentation and in EDMS data management system.

Module Performance

The cryomodule performances are measured in AMTF (DESY); the individual cavity gradient measurements during the cryomodule test are limited to 31 MV/m by the RF power system. Other measurements are of interest: the leak rate, the alignment, the cryogenic heat loads, the HOM coupler rejection filter, the compliance to the PED regulation.

The module accelerating gradients measured in AMTF give an average gradient 18% above specifications: $\langle E_{acc} \rangle = 27.8$ MV/m.

All but 7 of 103 tested modules are on XFEL specifications (23.6 MV/m):

- XM33, XM58, XM68, XM98 and XM99 are limited by individual cavity performance in vertical test,
- XM45 was correlated with an accidental loss of power in clean room power,
- XM46 was impacted by several beam vacuum leaks. Both leaks have been repaired at Saclay but they generated 2 extra connections of the beam vacuum to pumping groups, and 2 additional venting-pumping cycles.

The cryomodule XM20 is on specification thanks to the individual powering of the cavities, it wouldn't have be the case with the initial powering by cavity pair foreseen for XFEL.

Module Performance vs. Cavity Vertical Test

The comparison between Average operating gradient per cryomodule, and the usable gradient (usable gradient is defined in [5]) from the vertical tests with the aim of string assembly evaluation is delicate. The usable gradient measured in VT need to be clipped to 31 MV/m for this comparison purpose.

A direct comparison between the vertical test usable gradient which takes Q_0 as well as field-emission performance into account and the operational gradient in the cryomodule test is difficult. Only cavities observed quench limits in both tests can be strictly compared (see [3] for details).

The cavities performance tests are carefully described in [6] and tests of all cavities before and after module assembly are summarized in [7].

Significant gradient degradation from XM6 to XM23, while CEA and Alsyom put all their effort in achieving production goal of 1 CM/week throughput: an audit of string and module assembly was conducted by CEA on XM26

A simplification of the clean room procedures was introduced at XM54. This cleanroom procedure change has been proposed in fall 2012 to WP09 internally and on 20/09/2013 to Alsyom [8].

Module Performance vs. Clean Room Procedures

The procedure changes are needed to keep the cavity performance and in the same time get some margins on the assembly time. These margins are needed to fit to the four days throughput but also to have time to solve RGA non-conformity after the cold coupler to cavity assembly. Table 1 summarizes for different procedures the number of vacuum operations taken in consideration.

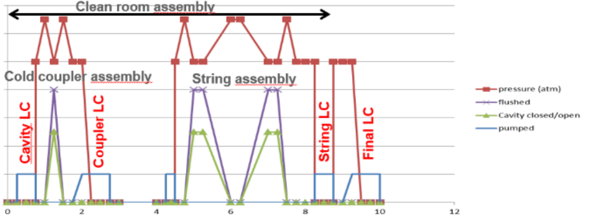

Figure 5 and 6 show respectively the procedures 1-2 and 3-4.

Table 1: Number of Vacuum Operations for a Complete Cryomodule Assembly for Different Procedures

Procedure n°	1	2	3	4
# Gate valve to pipe connections	34	22	14	14
# Gate valve open/close cycles	33	21	13	13
# N2 blowing after an opening	17	17	9	9
# Leak checks	52	40	32	23

Table 2 shows a comparison of the following procedures for cryomodules of the tunnel.

Procedure n°1: XM-3 to XM3 This procedure had the Reception workstation in addition to the Procedure n°2. The Reception consist of cavity and coupler leak checks under ISO5 laminar flow without venting. It create additional work and additional risk but avoid the entrance in clean room of non-conform parts.

Procedure n°2: XM4 to XM53 (except XM27) The coupler assembly to cavity occurs in CC workstation then string in SA one. The Reception workstation is skipped: it avoids one leak check (LC), including one angle valve connection to pump unit, and one open/close cycle.

Procedure n°3: XM27, then XM54 and followings excepted if procedure n°4 The solution also named 3 in reference [8] consists in exchanging filter and valve closing nitrogen on the flushing line. It saves one closure – opening cycle of the main cavity valve and one connection to a pumping pipe. First experienced with success on the cavity 085, then on the complete string XM27 this simplification was definitely implemented at XM54.

Procedure n°4: XM75-79, XM93-94, and XM99-100 Cavity string assembly is followed by connection of the 8 cold couplers w/o pumping. This solution was implemented during coupler shortage periods: it saves labour and vacuum operations. It correspond to the solution 5 in reference [8] it's a compromise to take advantage of distributed work on two workstations. The only drawback is the handling of the cavity not under vacuum which is believed to be critical about particulate displacement inside cavity.

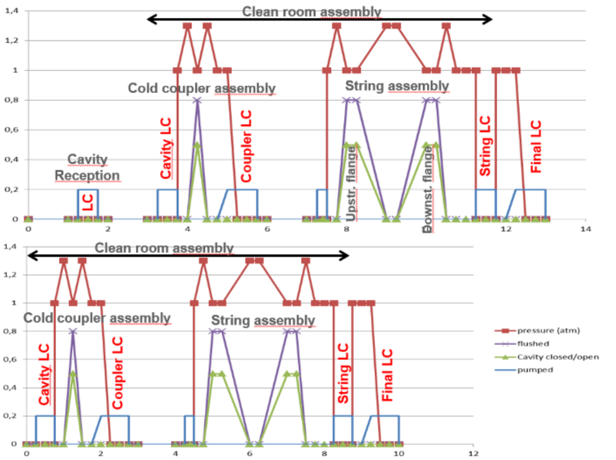

Figure 5: Cavity history for procedures n°1 and 2 showing Pressure in atm., and if the cavity is flushed with nitrogen or not, closed or open (Arbitrary units except for pressure level). LC means Leak Check.

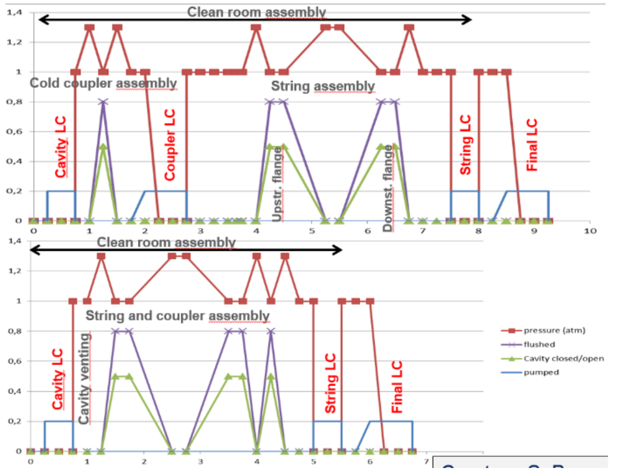

Figure 6: Cavity history for procedures n°3 and 4 showing Pressure in atm., and if the cavity is flushed with nitrogen or not, closed or open (Arbitrary units except for pressure level). LC means Leak Check.

Table 2: Comparison of Different Procedures for Cryomodules of the Tunnel. Average gradient in AMTF $\langle E_{acc} \rangle_{AMTF}$ and difference with operational E_{acc} ΔE_{op}

Procedure	# modules	$\langle E_{acc} \rangle_{AMTF}$ [MV/m]	ΔE_{op} [MV/m]
n°1	5	28.3	-0.5
n°2	46	27	-1.8
n°3	39	28.3	0.4
n°4	7	29.6	0.4

Module Performance vs. Heat Load

The cryogenic head load is measured for a cryomodule with the cryogenic losses on each helium circuit.

The dynamic part of the losses measured at the operational gradient (20-23.6MV/m). The average Q_0 value are equal to $1.4 \cdot 10^{10}$ for cryomodules, same as for vertical tests, despite the large scatter in both. All but two cryomodules (XM48, XM70) are in the 14W budget at 2K (see Figure top panel). Looking at the dynamic component alone all but two cryomodules (XM34, XM70) are in the Q_0 goal $\geq 1\ 10^{10}$ (see figure 8 in [6]).

The static load on the on 5/8K (40/80K) shield are in the 16W (125W) budget (see Figure middle panel and bottom respectively).

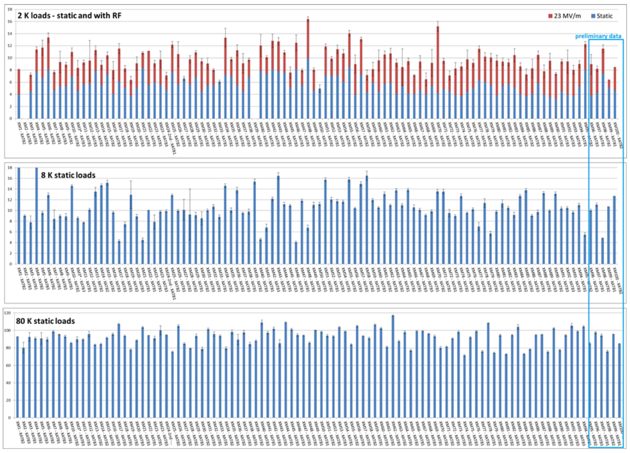

Figure 7: Cryogenic Heat Loads. The dynamic heat loads, measured at operational gradient (20-23.6 MV/m). Top panel: The dynamic (in red) plus static (in blue) loads are in 14W budget at 2K except for XM48 and XM70. Middle and bottom panel resp.: Cryomodules heat loads are in the budget 16W on 5/8K shield and 125W on 40/80K shield.

Module Certification vs. PED

PED Certification of He-Tank Titanium Welds

DESY and CEA teams succeeded in implementing and complying to the PED certification, in particular the RT norms 'NF EN ISO 17636-1 (2013) class B ' for the execution and 'NF EN ISO 10675-1 (2013) level 1' for the interpretation: this was a major effort over the year 2013. Alsyom has successfully taken over welding coordination within the 'EN ISO 3834-2' norm.

Figure shows the number of welds per level versus module number. Level 2 pores have been repaired or subjected to exemption. No pore beyond 0.5 mm diameter has been accepted.

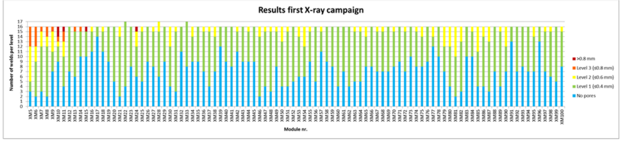

Figure 8: X-ray campaign results before any repair. The plot shows the number of welds per level versus module number. Level 2 pores have been repaired or subjected to exemption.

The porosity problem in the Titanium orbital welds was overcome by a combination of process cleanliness, US cleaning of Ti-bellows and welder 'humility'.

Module Repair Activities

Cryomodules XM46, XM50 and XM54 have been repaired in CEA, other cryomodules hereafter in DESY.

Cryomodule XM-2 missed a PED stamp from the TÜV. This module had to be disassembled until the 2-phase pipe was accessible in order to get X-ray. The module got the TÜV approval, had been tested and is installed in the tunnel.

The cryomodule XM8 had a leak in the 2K circuit. It had been disassembled till 2-phase pipe is accessible. The leak found and repaired. It passed leak test but got a smaller leak at room temperature. The module passed RF tested, leak reappeared after warm-up. XM8 is not accepted for tunnel installation.

XM22 had a beam vacuum leak which occurred after cool-down, it had unstable cryogenics conditions and got warmed-up. The leak has been found on HOM feedthrough then exchange under local clean room. The second AMTF RF test was successful and module is installed.

XM24 had a beam vacuum leak which occurred after RF test and warm-up. It was due to a leaky RF pick-up feedthrough it had be exchanged under local clean room. The second AMTF test is conform. The module is in the tunnel.

XM46 had a beam vacuum leak discovered (1 10^{-7} mbar l/s) at the end of the cryomodule assembly in Saclay. The module was disassembled till string hanging under cold mass. The leak check implied tightening of the leaky cold coupler connection on Cavity 4. The module has been measured in CMTB with strong dark current on cavity 6; it's not accepted for tunnel installation.

XM50 had a beam vacuum leak (1 10^{-10} mbarl/s) discovered at the end of the cryomodule assembly in Saclay. The module was disassembled till string hanging under cold mass. The careful leak check was not able to find the leak. The module was tested with strong field emission and leaky again. It's not accepted for tunnel installation.

XM54 module upstream gate valve was found defective (in-line leak) once closed and tests at DESY. The module was disassembled till string hanging under cold mass in front of the clean room. The exchange procedure was controlled by a particle counter in local cleanroom hutch with horizontal laminar flow. Cavity 1 is degraded by field emission nevertheless the module is in the tunnel.

XM91 had a leak at beam vacuum, it occurred during coupler repair after the cool-down; the module had been RF tested and warm-up. DESY found a leaky HOM feedthrough then exchanged under local clean room, the module is the tunnel.

CONCLUSIONS

The success of E-XFEL Cryomodule Assembly at Saclay implied to master 4 main overlapping phases:

- assembly procedures [T1/2008 –T1/2013], achieved with XM-3
- infrastructure and tooling [T3/2010–T1/2013], achieved at XM-1
- non-conformities handling, both imported-PRODUCT and PROCESS-generated non-conformities [T3/2012–T3/2014], achieved at XM15
- industrial operator contract follow-up :
  - Productivity [T1/2014–T4/2014], achieved at XM25
  - Quality Assurance [T4/2014–T3/2016]

This process depends on the early availability of the cryomodule components. The difficulties and the risks of coupler assembly had been under-estimated by CEA, especially for the coupler warm part.

The better module RF performance is correlated to clean room practice and clean room procedures. Clean room assembly can be further improved, qualitatively and quantitatively, e.g. by unifying cold coupler and string assembly in a unique workstation (2 shifts required to achieve 3-day throughput).

ACKNOWLEDGEMENT

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