CLEANLINESS AND VACUUM ACCEPTANCE TESTS FOR THE UHV CAVITY STRING OF THE XFEL LINAC

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Abstract

The main linac of the European XFEL will consist of 100 accelerator modules, i.e. 800 superconducting accelerator cavities operated at a design gradient of 23.6 MV/m.

In this context CEA-Saclay built an assembly facility designed to produce one module per week, ready to be tested at DESY. The facility overcame the foreseen production rate to one cryomodule each 4 days.

We would like to highlight and discuss the critical fields: cleanliness and vacuum.

A new assembly method to protect final assembly against particulates contamination has been implemented on the production line. Modules RF tests results are compared.

Particle transport measurements on components used for the European XFEL accelerator module are presented. The results indicate that the nominal operation of the automated pumping and venting units will not lead to particle transport.

Vacuum acceptance tests are of major interest: leak tests and residual gas analysis (RGA) is used to control the absence of contamination and air leak. The RGA specifications have been slightly relaxed.

INTRODUCTION

The assembly of the beam vacuum string of the XFEL accelerator modules needs to be made under clean room conditions [1]. Particle contaminations of the superconductor surface of the cavities for beam acceleration must be avoided to prevent deterioration of the cavity gradient. Apart from particle cleaning of components and avoiding the generation of particulates it is mandatory not to transport particles with the gas stream. It has been shown that turbulent flow supports transport of particles [2]. As Ultra High Vacuum with associated pump down and venting cycles for assembly of components is a requirement for the successful operation of the superconducting accelerating structures, a setup for venting and pump-down attached to a turbomolecular pump station has been developed [3]. The system (SVPS) is able of slow venting and pumping. Their operation is briefly described in [3]. Six of these pump stations are in operation at CEA.

NEW ASSEMBLY METHOD IN ISO4 CLEANROOM

Environment and Nominal Work Flow

The first week of work consist of cold coupler parts assembly to the 8 cavities on the so called “cold coupler” workstation (CC). The next week the cavities with coupler (CCC) and quadrupole package are assembled in a string on so called “string assembly” workstation (SA). Both workstations are in a ISO4 clean room with laminar flow of air.

For the last connection of the cavity string to the pumping system before the final leak check while in the vacuum vessel (CO workstation), special care has to be taken to maintain the same cleanliness level even if in mobile clean room.

Control of the Parts

Control of all the parts in contact with the cavity RF surfaces is required. This process is strongly operator dependent and well trained operators are required [4]. The control of the inside of the angle valve closing the device under test (DUT) is crucial. This last point is one of the many points raised in the audit of the module XM26*.

Control of the Vacuum Pumping Lines

After each change in the piping configuration or cleanroom maintenance (twice per year), the vacuum pumping lines including nitrogen flushing are systematically qualified by a leak check, a RGA [5], and a particle counting. The criteria threshold is “not more than 10 particles per minute of size bigger than 0.2 µm compare to reference measurement for detail see [6].

New Assembly Method: Solution n°3

The conservative assembly method n°3 proposed in [1] to has been qualified by steps: test part, cavity alone then a complete module. The goal is to maintain cavity performance from vertical test to module test.

The key improvement is the reduction of the risk of contamination by avoiding close and open steps of the angle valve which isolate the cavity. The main difference between nominal and solution n°3 is summarized in the fact that cavities with cold part of the coupler are vented on CC workstation instead of being vented in SA. First

* XM*i* refers to XFEL module n°*i*,

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tested on one module, nominal assembly method has been used waiting for the RF test result, qualifying solution n°3. In November 2014, during the qualification of pipes and filter on the way back to nominal assembly scheme, the use of the SVPS in wrong initial conditions leads to misleading interpretations.

The solution n°3 has been implemented definitely since XM54. The table 1 shows the very good results of the solution n°3 in terms of reducing the performance degradations.

Table 1: Degradations of Module Performance Solution n°3 Applied for Lot 4

Modules (XM n°)	Module degradation [MV]	Modules units	Mean gradient degradation [MV/m]
1st lot (1-17)	-17.6	16.0	-2.1
2nd lot (18-35)*	-18.4	16.0	-2.2
3rd lot (26,36-53)	-7.5	16.0	-0.9
4th lot (55-57)	-0.2	3.0	-0.02

* XM26 Audit occurs after XM35

BASIC PRINCIPLE OF THE SVPS

The SVPS (or “Fluter” elsewhere) relies on proper initial conditions. Either the system is under vacuum and thus all particles stick to the surface or the DUT (e.g. a cavity) is vented and has been assembled under clean atmosphere and again there are no particles in the gas volume.

Figure 1: DESY Pumping group including SVPS unit at CEA, outside ISO4 cleanroom.

A slow pumping aims to avoid the particle transport using the clean atmosphere in the DUT with a sufficiently low flow rate (< 3 l/min in the case of SVPS). Even though the gas volume might be very clean – most air particle filters for clean rooms give excellent results – assembly procedures with screws and metallic tools inevitably generate particles which should not be moved uncontrolled. A slow venting relies on a supply of filtered gas (here N_2) that is transported with a sufficiently slow flow. Under-vacuum particle counter measurements have been used to qualify the above processes [2, 3]. All results demonstrate that particle transport is avoided indeed.

An important limitation of the SVPS is the fact that particles that enter the gas stream cannot be intercepted. External effects e.g. vibrations on the pump lines can lead to the release of particles from the surface. The initial setup does not foresee a point-of-use filter.

OBSERVATION OF PARTICLE TRANSPORT IN NOVEMBER 2014

In November 2014 measurements at venting ports on the SVPS have shown that a lot of particles (the particle counting (> 0.2 µm) is larger than 10 000 / min) were transported. The initial source was not immediately clear. The venting lines in the clean room are combining two gas transport systems with a T-piece (Figure 2). The first is the SVPS as described before.

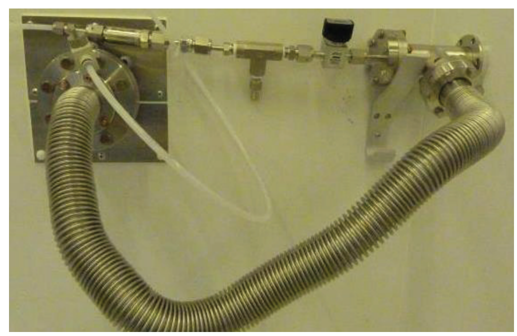

Figure 2: Connection of SVPS (behind the wall) and flushing unit inside cleanroom on the T part to be connected to the cavity (plastic cap on the flange).

The second system is used to generate a continuous inside flow (or ‘Flush’) of nitrogen during the assembly of components in the clean room.

Using this continuous gas flow particles should be transported away from the inner surface. A reduction of surface contamination is aimed for.

The flushing line uses a point-of-use particle filter right before the T-piece. Regular quality control using a particle counter is always being done and did not show deterioration.

SVPS –FLUSHING OPERATION

The suspicion was that the SVPS is generating particles. It was found that indeed particles are transported when the system is used in a non-standard configuration. This happened in an exceptional case.

It should be stressed that the activation of this mode was never used during the standard procedures but rather an accident during particle tests of the venting/flushing line.

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QUALIFICATION MEASUREMENTS ON THE SVPS

The results triggered a series of measurements at CEA and DESY to demonstrate that nominal operation of the SVPS does not cause a problem. A device critical to the qualification towards particle free gas transport is a vacuum particle-counter. Before the final tests with this device were done several measurements were done to prepare the measurement campaign.

Tests at CEA

Further tests on the venting lines were done on pre-cleaned test volumes with standard air particle counters: particle counting of the opened test volume after its venting, showed no significant contamination.

Tests at DESY

SVPS Tests in the Staging Area

An SVPS was tested in a dirty environment were no care of particle cleaning was done. Thus the surface was loaded with particles. It is important to note that also the gas atmosphere loaded with particles. This is due to the problem that particles in gas atmosphere will need significant time to settle down and stick to the surface. This can take several hours. The figure 3 shows this in the first quarter of an hour.

As soon as the slow pump down, most particles will transported together with the gas stream towards the pump. The strong reduction of the particle count can be seen clearly. The subsequent venting cycle with particle filtered nitrogen gas is starting at half an hour. It demonstrates that no particles are being transported even though the surface is full of particles. The nominal operation of the fluter does not move particles.

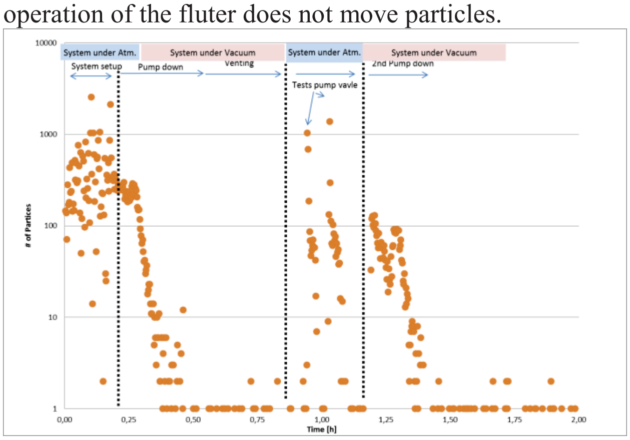

Figure 3: Test measurements at DESY.

When the system was under atmosphere valve operations on the pump station valve have been forced. As can be seen this leads to the release of significant amounts of particles.

The second pump down shows again that the particles in the system (from the operation of the pump station valve) have still not settled. Thus particles are transported again.

SVPS Tests at the DESY Cavity Clean Room

A SVPS system is set up at the DESY cavity cleanroom. It has been used since more than a year for the assembly of several components. In total probably more than 50 assemblies have been done.

A venting test with a small test volume and a demountable flange has been made. After the venting cycle the test flange was immediately removed. Particle count was done on the flange and yielded less than 60 particles. The volume was then flushed with a system similar to the one described above. No particles were detected again. These measurements indicate that nominal operation does not transport particles.

TESTS WITH THE VACUUM PARTICLE COUNTER AT CEA

Comparison with an Air Particle Counter

In order to validate the vacuum particle counter (VPC) measurements initially a comparative measurement with a standard air particle counter (APC) has been made.

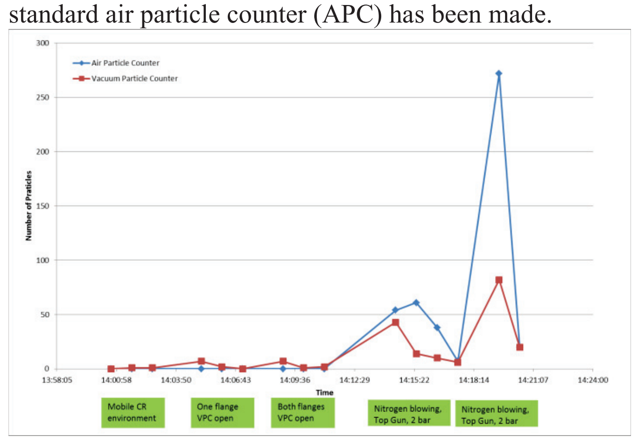

Figure 4: Comparison of air and vacuum particle counters

After setup of the systems in the local clean room, the flanges of the VPC were opened one after the other. Then the system was blown with dry nitrogen. During all steps particles were counted. Between the two systems roughly a factor 3-4 is observed (Figure 4). The general behavior is very similar and comparable.

The difference can be explained partially by the fact that the active areas of APC and VPC are not the same. It can also not be excluded that a few particles from external surfaces are counted as well.

Standard Pumping and Venting Cycles

In the next step, the VPC was taken into the clean room for module string assembly. Initially, pump down and venting tests were done on a small test volume. A series of full cycles of pumping and venting were done. Only very few particles are being transported (Figure 5).

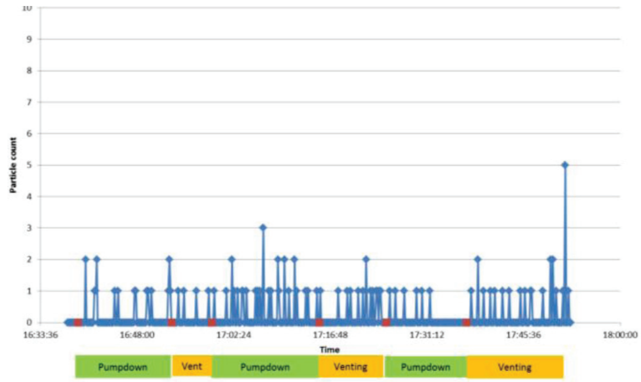

Figure 5: Pumping and venting on test volume.

The same behavior was observed when a cavity was pumped and vented. As expected particle transport could not be observed (Figure 6).

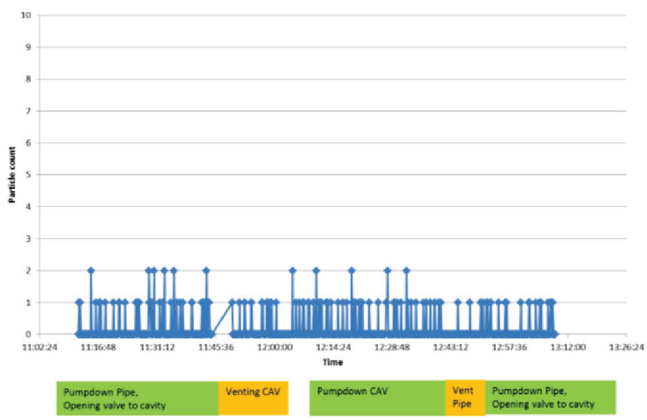

Figure 6: Venting and pumping on a cavity.

RGA SPECIFICATIONS

RGA Specification and their Modification

As a reminder the vacuum acceptance test consist of Leak tightness with integral leak rate (sum of all leaks) has to be $\leq 1\cdot10^{-10}$ mbarl/sec. Components are considered free of hydrocarbons if in a leak-free system with a total pressure below 10^{-7} mbar the sum of the partial pressures of masses above mass/q 45 is less than 10^{-3} of the total pressure [5].

On the production line of cryomodule, the time laps between the beginning of the pumping and the validation of the RGA of the DUT (cavity with coupler or string or string in module) is not always the same and difficult to fix. Thus the pressure can vary from the maximal pressure requested to accept a spectrum $9.99\text{x}10^{-8}$ mbar to $9.9\text{x}10^{-10}$ mbar (minimum recorded on CCC assembly[†]).

As a consequence of different pumping efficiency of the different masses, a DUT can toggle between conformity and non-conformity; or as the example of cavity CAV293 become not conform, see table 2.

[†] CCC*i*: assembly cold coupler plus cavity n°*i*

Table 2: Example of Cavity n°293; RGA Conformity of the Assembly Cold Coupler Plus Cavity (CCC) over Time

DUT	Ptot [mbar]	SUM m/q >45	Conform Y/N	Date yymmdd
CAV	9,69E-08	8,6E-11	CONFORM	150722
CCC	9,01E-08	8,32E-11	CONFORM	150722
CCC	1,11E-08	2,95E-11	NOTconform	150723

RGA specifications have been relaxed:

- If the pressure of the device-under-test is below 10^{-8} mbar, it is required that all peaks including and above 45 are less than a per mille of the total pressure.
- If the pressure is between 10^{-7} and 10^{-8} mbar the DESY spec is applied as is, meaning the summation is required.

Observation of Small Contaminations

Small contamination (about 10^{-4} less than the partial pressure of water at m/q=18, have been observed in RGA. When several peaks of mass/q> 45 show up, it becomes hard the DUT to be conform to the specification. On the other hand there is no restriction in the specification for mass/q less than 45.

Table 3: Main Observed Contaminants and their Characteristic Peaks.

CONTAMINANT	CHARACTERISTIC m/q
Acetone	43;58;
Ethanol	31;45
Isopropanol	45;
Benzene	50;51;52;77;78
Sulphur Dioxide	64;48;32
Fluorine-based polymer	69;31;others

Masses 69 and 20 could indicate wear on the seal of the scroll pump.

Examples of Cavity Contamination

Cavity	Contaminant m/q	Date	Status
CCC710	SO_2	13.11.14	Rejected
CCC231	Benzene	11.5.15	Accepted
CCC826	m/q=69	06.5.15	Rejected

A clear contamination during the measurement of CCC231 with benzene can be identified on 11.5.2015 (Figure 7a). Subsequently, mass 50 is still being observed in RGAs. But the signal reduces while pumping is going cf. Figure 7b on 13.5.2015. So far the source of benzene is not understood. Deviation requests to the specifications has been accepted

Many spectrum data's have been recorded. A deeper analysis is ongoing. The potential relation between RGA slightly contaminated and cavity degradation has to be investigated.

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Interest of RGA after Coupler Assembly?

In case the connections are done in a hydrocarbon-free environment and as the components assembled already get a RGA conform, the real importance of these measurements in contrast with their large disruptive impact on the schedule of the module assembly is questionable.

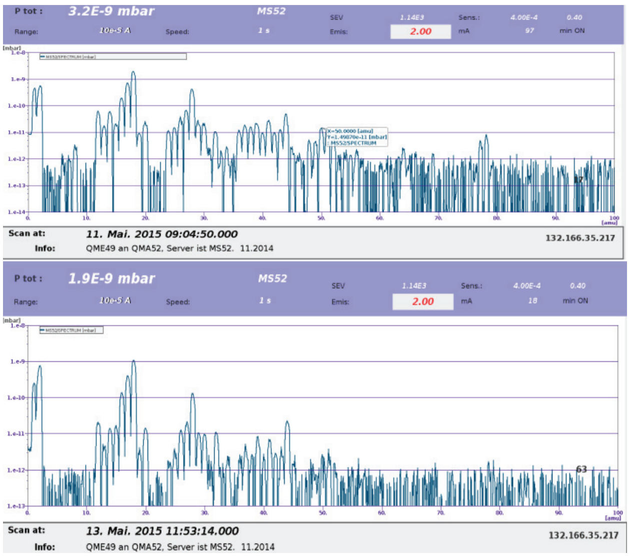

Figure 7: (a) top: RGA of CCC231 on 11.5.2015 (b) bottom: RGA of the same empty pumping line on 13.5.2015. Deviation accepted.

In particularly the measurements done after the cold coupler assembly since we connect two components which have been qualified under high RF fields. On this works station at XM62, half of the cavities should have gone through RGA: 114 files haves been saved on server in order to discussed conformity of estimated 248 RGA. 66 deviation requests went through mail exchange to decide whether or not the part (CCC) can be kept. Only two cavities have been sent back for rinsing due to non-conform RGA (CAV710 and CAV826). With the coming precise RGA analysis will be published a recommended specification an optimum set of criteria for residual gas analysis.

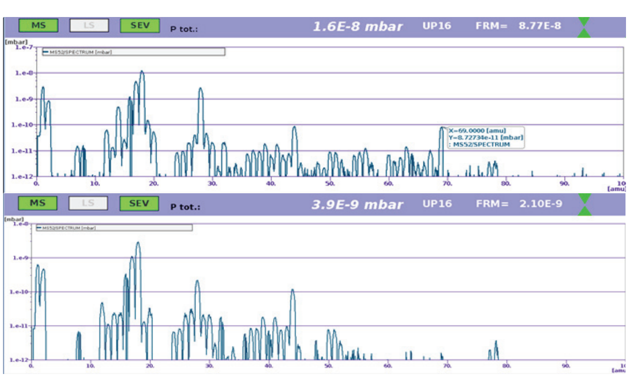

Figure 8: (a) top: RGA of CCC826 (b) bottom: RGA of the pumping unit on 06.5.2015. Rejected due to fluorine-based polymer contamination (m/q=69).

CONCLUSION

The results of tests with particles counters show that standard operations on the slow venting and pumping system and the CEA pumping system do not cause particle transport. There is no indication that a hardware component has failed. Additionally, all qualification procedures implemented by the personnel that were needed to set up the systems on the pump stations have shown their efficiency.

RGA spectrums are complex and predefined specifications are difficult to establish. Nevertheless, a deep analysis of the large amount of data will probably help to choose adequate criteria to soften the decision process.

Solution n°3 and the solid plastic shells for the leak check of the string in cleanroom are both contributing to decrease the takt time from 5 days to 4. Three cryomodules assembled with this method have been tested successfully by DESY XM55-56-57. The solution n°3 is reducing considerably the cavity degradation see [7]. To avoid degradation of the cavity string performance, the solution minimizing both the number of venting of the cavity and the particles displaced by vibrations: Solution 4a has been proposed in [1] it should minimize both contamination from valve actuating and contamination from vibration during transport in cleanroom.

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