

CONNECTION OF EU-XFEL CRYOMODULES, CAPS, AND BOXES IN THE EU-XFEL MAIN LINAC AND INJECTOR: WELDING OF CRYO-PIPES AND ASSEMBLY OF BEAM-LINE ABSORBERS UNDER THE REQUIREMENTS OF THE PED REGULATION

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Abstract

The European X-ray Free Electron Laser (EU-XFEL) [1] cold linac [2] consists of 100 assembled cryomodules, 6 feed/end boxes and 6 string connection boxes fixed to the ceiling of the accelerator tunnel; the injector consists of a radio frequency gun, one 1.3 GHz and one 3.9 GHz cryomodule, one feed and one end cap lying on ground supports. The components are connected together in the tunnel, after cold testing, transport, final positioning and alignment. The cold linac is a pressure equipment and is therefore subjected to the requirements of the Pressure Equipment Directive (PED). This paper describes the welding and subsequent Non-Destructive Testing (NDT) of the cryo-pipes (with a deeper look at the technical solutions adopted to satisfy the PED requirements), the assembly of the beam line absorbers and the final steps before closing the connection with a DN1000 bellows. A special paragraph will be dedicated to the connection of the injector components, where the lack of space makes this installation a particularly challenging task.

INTRODUCTION

The EU-XFEL cold linac cryogenic layout is shown in Figure 1. It consists of 100 1.3 GHz accelerating cryomodules divided in 3 linac sections (L1, L2 and L3); between the sections there are 2 warm bunch compressors (BC1 and BC2), where the continuity of the cryogenic distribution is made possible by 2 transfer lines.

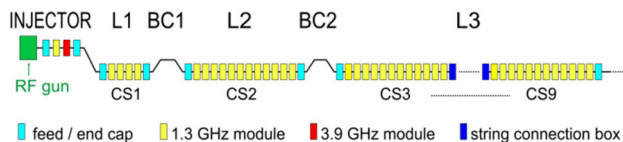


Figure 1: Layout of the EU-XFEL injector and cold linac.

The L1 section (CS1) is composed of 4 cryomodules, one feed (FC) and one end cap (EC); the L2 is section has 12 cryomodules, one feed and one end cap (CS2), while the L3 section is divided in 7 cryo-strings (CS3-9, 12 modules each), divided by string connection boxes (SCB).

A vacuum barrier is installed at the SCBs and at the FCs and ECs, to separate the insulation vacuum of each cryo-string, allowing independent pumping.

The cryogenic circuits at 2.2 K, 5-8 K and 50-80 K flow along the whole linac without interruptions, while

the 2-phase circuit and the warm up / cool down line are filled with helium at the beginning of each cryo-string through a Joule-Thompson (JT) valve and a warm up / cool down valve from the 2.2 K circuit (Figure 2).

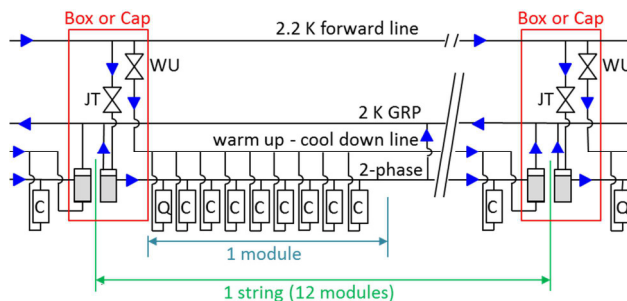


Figure 2: Flow scheme of the 2K circuit: JT = Joule-Thompson valve, WU = warm up - cool down valve, GRP = gas return pipe, C = cavity, Q = quadrupole.

The gas return pipe is connected to the 2-phase pipe at each module connection and flows through the whole linac without interruption, making also the 2 K circuit a unique cryo-circuit for the whole EU-XFEL cold linac.

The EU-XFEL injector is independent from the main linac and has one 1.3 GHz and one 3.9 GHz cryomodule, one feed and one end cap.



Figure 3: A typical module-module connection, where only the gas return pipe and 2 phase line are positioned for the first weld operations.

All the cryogenic pipes contained in the cryomodules, feed and end caps and string connection boxes are

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connected together by welding, to reduce the risk of leaks introduced by flanged connections. Each connection is made of 2 or 3 (for the gas return pipe and 2-phase pipe, shown in Figure 3) welds, since a bellows is installed between the 2 pipe ends protruding from the modules / caps / boxes.

At each connection, a beam line absorber (BLA) is mounted on the beam line with flanged connections. A portable clean room is used for this installation, to avoid contamination.

MODULE, BOX AND CAP CONNECTIONS

There are 3 slightly different types of connection in the linac: the “module-module connections”, the “module-cap/string connections” and the “module-string connections”. The only differences are: the absence of a BLA in the downstream module-string connections, and the presence of a connection between the gas return pipe (GRP) and the 2-phase pipe at the “module-module” connections.

Each connection is 850 mm wide and consists of:

- 8 cryo-pipe connections (16 or 17 welds per connection, ~ 2000 welds in the whole linac)
- one beam line connection (i.e. 2 flanged connections)
- 2 thermal shield connections (including 10 layers of Multi-Layer Insulation (MLI) at the 8K shield and 30 layers at the 80K one)
- one DN1100 interconnection bellows to guarantee continuity of the insulation vacuum along the string.

Specificity of the Injector Connections

The injector has 3 connections, one standard module-module connection and 2 special module-cap ones; the two module-cap connections have shorter bellows to reduce as much as possible the non-accelerated beam line because of beam physics requirements. Welding these connections is a really challenging task; but on the other hand, all the components at the injector are lying on ground supports, allowing more flexibility and ease of access than the cold linac components, all suspended from the ceiling.

Moreover, the DN1100 bellows at the module-cap connections are made of 2 half shelves and have to be welded on site, since the reduced space at the neighbouring components does not allow sliding the bellows.

WELDING OF CRYOGENIC PIPES

The Welding Process

A typical module-module connection is shown in Fig. 3. It consists of 6 straight pipe connections (80K, 70K, 8K, 5K, 2.2 K and WU pipes as shown in Figure 4) and 2 T-connections (Gas Return Pipe (GRP) and 2 phase pipe as shown in Figure 4 and already assembled in Figure 3). The welding sequence is determined by the space available: first the T-connections are welded and X-rayed, and only afterwards the other pipes can be welded.

The welding and beam connection is performed one cryo-string at the time, starting from the end of the string (farthest component along the beam line) and moving toward the electron source. The whole process, starting from the first weld up to the final leak test of the isolation vacuum for the whole string, should take about 3 months in ideal conditions (all modules at their place at the beginning of the operations, no interruptions, all tooling and equipment optimized, working teams trained and used to the working conditions in the tunnel...). During this period, no other activity is allowed on the whole cryo-string.

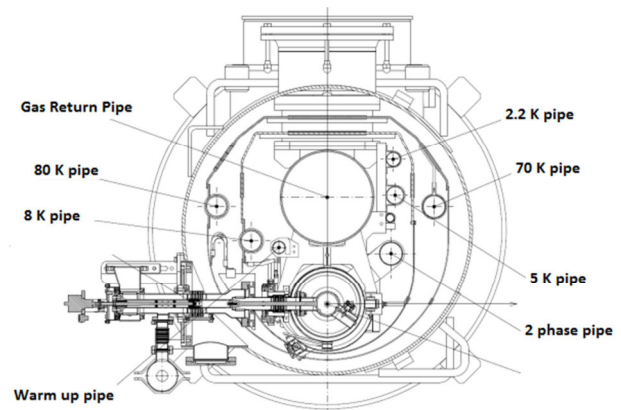


Figure 4: Cryomodule cross-section with pipe naming.

At the time of writing, the cryo-string CS1 and CS3 are completed, while the welding of CS4 has started in mid-July 2015 and is ongoing, with the hope to be completed by mid-October. The injector installation has not started yet, since the 3.9 GHz module will be available in the injector building at the beginning of September.

Material Certification

Since the cryo-piping is part of a pressure equipment, the pipes in the modules and the bellows welded in the connection area are all supplied by PED certified producers [3] and the parts are delivered with an EN10204 3.1 certificate.

Welding Technique: Orbital and Tractor Welding

The components are all automatically welded. The GRP and 8K pipe are welded with a tractor machine, while the other pipes with a commercial orbital machine (Figure 5).

The welding heads of the tractor machines had to be developed internally at DESY by the welding team since commercial parts would not fit in the tight space available around the welds. The welding nozzles are shifted laterally from the tractor rotating plane to avoid interference between the rotating components and the cryomodule. A picture of the tractor machine is shown in Figure 5.

All the Welding Procedure Specifications (WPS) and the Welding Procedure Qualification Records (WPQR) were approved by a notified body, to fulfil the PED requirements.

The welders as well needed to be certified from the notified body for each type of welding machine (tractor or orbital machine) and for the hand welds needed at the injector and for possible repair works.

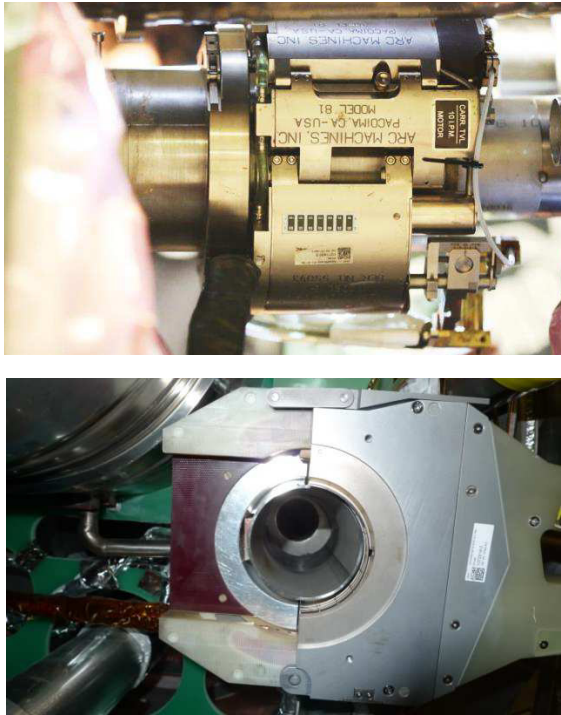


Figure 5: Tractor welding machine (up) and orbital welding machine assembled on a pipe (down).

Shielding Gas

The welding procedures require the filling the weld region of all pipes with pure argon gas with a maximum concentration of impurities below 50 ppm during the whole welding operation.

The insertion of the shielding gas is a long and delicate process. A special tool (Figure 6) is used to limit the volume where shield gas has to be inserted. The tool is slid inside the pipe from the opposite end of the cryomodule (12 m long) while the bellows is kept in position but not yet welded. The gas concentration is measured till the required value is reached. The filling with gas can take up to 15 minutes for the biggest pipe (GRP).

A special technique is being developed and certified with the notified body for the welding of the last connection, where no free end will be available and therefore the shielding gas pipe cannot be easily inserted. The technique foresees the use of a special ring at the welding position, to avoid the need of shielding gas.

Repair Welds

After the welding all the welds are visually inspected (inside with an endoscope) and subsequently X-rayed; if a weld does not pass both tests, it has to be repaired. All the repair welds are performed manually; first the area of the repair is grinded, then the weld is repeated with the use of filling material.

Special Techniques for the Injector

At the injector, the module-module connection will be performed with the standard technique described above, while about 50% of the welds at the module-cap connections will be performed by hand: due to the different geometry of the parts and the small number of connections of this type (compared to the one in the main linac), no special tooling have been developed for this installation.



Figure 6: Shielding gas purging tool for the GRP.

NON-DESTRUCTIVE TESTS AND PED APPROVAL

Qualification of the Welds

To complete the qualification of the welds as parts of a pressure equipment, the welds have to undergo a series of non-destructive tests agreed between the manufacturer (DESY) and the notified body (TÜV Nord [4]).

A standard test frequently performed to approve this type of welds is a pressure test up to 1.43 times the operational pressure (according to the PED norm); but in our case it would have implied damages to the delicate tuning mechanism of the accelerating cavities installed inside the cryomodules, with a potential consequence of being unable to operate the linac. The pressure test was then replaced with a radiography test.

The final list of NDT for each single weld agreed between DESY and the TÜV Nord is the following:

- 100% visual test
- 100% radiography test
- 100% leak test

All test procedures and evaluation methods, as well as personnel certification, are specified following the relevant DIN EN Norms.

Visual Test (VT)

The visual test is performed just after the welding and is done on both the inner and the outer surface of the weld. The inner surface is reached with an endoscope with a 18 m long arm, inserted from the opposite end of a neighbouring module. Videos of the whole inner weld surface are saved for later comparison with the results of the radiography test.

Leak Test of Single Welds and Bellows (LT)

A special tool has been developed at DESY for the XFEL design to perform the helium leak test of the single welds; it consists of two aluminium half-cylinders to be

assembled around a weld pair and the corresponding bellows (Figure 7). A gummy sleeve developed at CERN and adapted to the XFEL needs is used to test the GRP welds (no bellows in-between).

The leak test is performed after the completion of the welding operation for a whole cryo-string at a time, since the pipes to be tested are actually one long pipe. Six circuits are tested separately: the 70K, 80K, 5K, 8K and 2.2K lines and one big circuit including the GRP, the 2-phase pipe and the WU pipe.

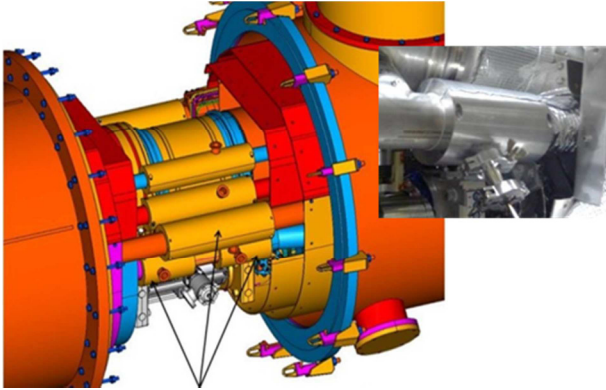


Figure 7: Tool to perform the single weld leak test.

Helium is inserted in one circuit at the time while the special tool/sleeve is assembled at the outside of the pipe, pumped and attached to the leak detector to perform the test. The 2 welds and the bellows are considered leak tight if no helium leak bigger than $1e-8$ mbar \cdot l/s is detected.

Radiography Test (RT)

The standard radiography test for pipes with thickness around 2 mm is an X-ray test; unfortunately the X-ray equipment is big and does not allow reaching the 100% requirement fixed by the notified body.

It was then agreed with the notified body to use a selenium (Se75) source of gamma rays, not optimal for this type of pipes, but allowing enough resolution to detect the non-conformities that can appear during the welding. A set of comparison tests (X-ray versus gamma-ray) was performed on typical welds, to verify that the same weld non-conformities could be detected with both methods and qualify the use of selenium.

BLA ASSEMBLY

The connection of the electron beam line is being done in most cases by the insertion of a beam line absorber (BLA) [1]. Simple copper coated steel bellows are used as few exceptions.

The beam line vacuum in the modules has a different set of requirements to what has been described in the main part of the paper. The most important requirement is to avoid contaminations of the superconducting cavities during the installation. (Over-)Pressure requirements are not an issue for this part of the installation. As both particulates and gas layers can cause deteriorations in the

cavity's accelerating gradient all installation work on the beam pipe needs to address these issues.

Avoiding Particulate Contaminations

All installation work needs to be done in a clean room environment. A custom-made dedicated clean room has been developed for the installation of the beam line absorber. As the space above the installation site is crowded with cryogenic -pipes the only solution to have a controlled airflow was to stream clean air from the bottom towards the top. This allows access with arms from both sides of the BLA.

The clean room features removable stairs due to the elevated level of the beam line and the necessity to quickly allow access for transports (Figure 8).



Figure 8: The clean room used for BLA assembly.

In addition a support lever arm system is integrated to facilitate an easy and thus reliable and reproducible mechanical installation of the BLA (Figure 9). For the pump down the mass flow is limited to avoid particle transport.



Figure 9: Assembly of a BLA.

Avoidance of Gas Layer Contaminations

Carbohydrates are typical contaminants observed in UHV systems. Their avoidance necessitates vigorous cleaning and proper handling of UHV components. Typical measures are ultrasonic cleaning, thermal treatments and backfilling with (particle-filtered) dry nitrogen directly from the liquid phase. The BLAs are conditioned in such

a way that they fulfil the DESY vacuum specifications [5].

A pump down after the installation with a short exposure to particle-filtered ambient air in the clean room, does not re-contaminate the BLA connection. As a quality control procedure the residual gas analysis and a helium leak check are being done. When this was successful, the manual gate valves on the adjacent modules are opened and the clean room is moved to the next position.

FINAL STEPS

The following components are assembled at each module connection after the completion of the welding and the installation of the BLA:

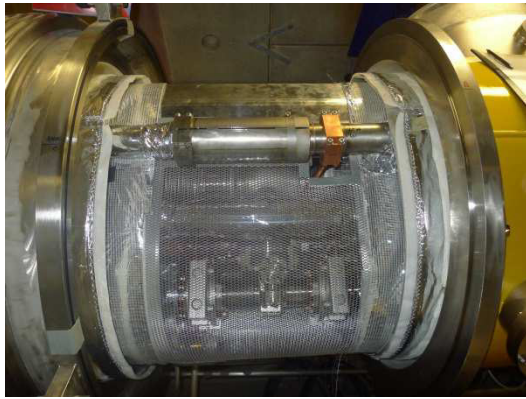


Figure 10: 4K shield and grid.

- BLA support: during the assembly the BLA is supported only from the 2 neighbouring components; a special spring support is then assembled between the BLA and the GRP to sustain part of the BLA own weight (both in warm and cold conditions) and reduce the stress on the neighbouring sensitive components.



Figure 11: MC closed.

- 80K, 70K, 8K, 5K, 2.2K and WU bellows covers: each bellows is equipped with a steel cover designed to reduce lateral stresses on the bellows, possibly caused by the misalignment of the 2 components to be connected (modules, boxes, caps) and by possible

pressure increases inside the pipe (maximum allowable pressure 20 bara). The GRP and 2-phase line bellows have no need for these transverse stiffening covers since the maximum allowable pressure is reduced to 4 bara.

- Thermal shields and Multi-Layer-Insulation (MLI): 2 thermal shield connections (one at 5-8K, Figure 10, and one at 40-80K) are assembled at the module connection; 10 layers of MLI are mounted around the 5-8K shield and 30 layers at the 40-80K one.
- DN1100 bellows (also called “Schiebemuffe”, Figure 11) to close the isolation vacuum.

LEAK TEST OF A CRYO-STRING

A leak test of the isolation vacuum is performed on the complete cryo-string after closing the DN1100 bellows. The leak rate is measured down to the level of 10^{-9} mbar l/s. The overall allowed leak rate for the isolation vacuum system is 10^{-6} mbar l/s.

CONCLUSION

The connection of the EU-XFEL cryomodules, caps, and boxes in the EU-XFEL main linac is a complex, delicate and time consuming work.

Special welding tools and processes have been developed to reach the required quality levels for the safe operation of the EU-XFEL cryogenic components for the next 20 years, while dealing with tight space requirements and a short schedule.

Special tools have also been developed to perform the non-destructive tests required for the approval of the linac as a pressure equipment.

Due to the space requirements a dedicated clean room has been developed to allow for an easily reproducible and reliable UHV connection effectively reducing the risk of particulate contaminations of the beam line vacuum.

ACKNOWLEDGMENT

We would like to acknowledge here the hard work done by all the colleagues involved in the daily activities of welding, assembling, testing of all the module connections; without them there would be no EU-XFEL cold linac. A special thanks to Dirk Noelle for documenting the work performed in the tunnel with his pictures [6], extensively used in this paper.

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