MECHANICAL DESIGN OF CRYOGENIC VACUUM FEEDTHROUGHS FOR XFEL BUTTON BPMS

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Abstract

The European XFEL is a 4th generation synchrotron radiation source, currently under construction in Hamburg. Based on different Free-Electron Laser and spontaneous sources and driven by a superconducting accelerator, it will be able to provide several user stations with photons simultaneously.

Due to the superconducting technology in the accelerators modules many components have to operate at liquid helium temperature.

This poster will concentrate on high frequency ultra-high vacuum feedthroughs used for the beam position monitors of the cryogenic accelerator modules. Main emphasis will be put on the design of these feedthroughs, their material composition and the production process. The capability to be used under these very special conditions was investigated with FEM simulations, as well as with a test procedure. The results of these simulations will be presented; the tests and their results will be explained in detail.

INTRODUCTION

In particle accelerators like European XFEL (E-XFEL) many feedthroughs are used to monitor the electromagnetic field to determine and verify the actual beam position. At the European XFEL the Beam Position Monitors (BPM's) operate under two different ambient conditions, one under normal room temperature and the other one in a cryogenic environment, at ~4K. The cold button BPMs are installed close to the superconducting accelerator structures. Therefore they have to fulfil strict ultra-high vacuum and particle cleanliness requirements.

Many companies offer vacuum feedthroughs. Here the focus is on feedthroughs suitable for RF applications.

Such feedthroughs are coaxial structures, on one side with a pin, open conductor or button; on the other side a connector. In between there is a coaxial vacuum barrier, composed of inner and out conductor with dielectric material in between, providing the required leak tightness. Properties and geometry of the system has to be chosen such that they match to the required impedance of the coaxial system. The choice of isolation material is open to a wide field of materials. The usual technical ceramic materials are classified in three big groups, the oxide-ceramic (ZnO, LiO, SiO, Al_2O_3,), silicate ceramics (Stealit or porcelain) and non-oxide ceramics (Si_3N_4, BN or SiC).

The goal is to develop custom designed feedthroughs with well defined RF properties for accelerator applications at low temperatures and minimum particle emission. Therefore it is essential to understand the design principles and the mechanical characteristics of feedthroughs and BPM systems. Feedthrough prototypes installed on a test BPM at PSI, Fig. 1. The design of custom made feedthroughs requires, besides deep understanding of the RF requirements, other skills like knowledge in mechanical design and fabrication as well as some material science. Nowadays the extensive use of simulation tools help to speed up the design for the mechanical layout of a complete BPM [1], [2].

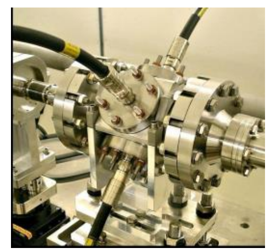

Figure 1: Cold button BPM mounted at SwissFEL test injector*.

R&D DESIGN PROPERTIES

The European XFEL is a 17.5 GeV superconducting linear accelerator with 71 button BPM's installed in superconducting cryostats next to the cold quadruple at temperatures about 4K. The beam pipe apertures of these BPMs is 78 mm, the length is 170 mm.

The BPM bodies, feedthroughs, cables have to deposit only negligible heat load into the cryogenic environment. High losses will increase the cryogenic cooling power and will raise the operation costs [3]. BPM body and button have to have high surface conductivity in order to minimize ohmic losses of high frequency HOM fields in the superconducting cavities. Therefore, all parts are copper plated or made from copper.

The nominal bunch charges of E-XFEL are between 0.1 and 1 nC. The BPMs must be able to measure position of single bunches with 220 ns spacing, in trains of up to 2700 bunches, and a repetition rate of 10 Hz. Train-by-train rms position resolution averaged over the bunch train was specified to be better than 10 µm, single bunch resolution should be better than 50 µm [4].

Mechanical robustness was the leading criterion. Vacuum tightness at 330 K and liquid helium temperature, as well as during cool down and warming up cycles and thermal-shock resistance are main design issues. Further requirements were implied due to the particle cleanliness requirements and the conformity to assembly procedures in the clean rooms. Therefore, the flange was designed for the so called diamond shaped aluminium gaskets, used for E-XFEL cavity string assembly. Due to the vicinity of the superconducting quadruple of the model as well as the cavities strict requirements on nonmagnetic materials had

*This photography is provided by Daniel Treyer, PSI, Swiss.

to be fulfilled. As required nonmagnetic material, thermal-shock resistance, robust design and full metal sealing were following by the cleanroom requirements of cleaning and assembling.

According to the vacuum and particle cleanliness requirements for the E-XFEL cryogenic environment the “diamond shaped” aluminium gasket also were required for the module string assembly for flanges.

A market analysis has shown no suitable commercial feedthroughs, therefore new development was started. First steps were simulations using CST [5].

Step by step approach:

1. Simulate loss factor
2. Simulate temperature gradients with different materials to decide for the best material combination. This is an iterative process, due to temperature dependency of the thermal conductivity of the materials. (here some steps have to be done because thermal conductivity is a function of temperature and CST provides only one conductivity per material)
3. Tolerance studies of feedthrough in order to meet the requirement: S11< -10dB up to 2.5 GHz also with fabrication tolerances
4. Simulate BPM property: determine the monitor constant
5. Tolerance studies: change position of button and monitor the button signal and data processing to obtain offset. The deepness of the buttons tolerance can be directly converted into a position offset which affects the BPM accuracy: requirement 0.1 mm
6. Based on the design from different companies the design is reviewed with the simulation (frequency domain solver for reflection including mechanical tolerance influence on reflection, thermal simulation for temperature)

The RF simulation results were used as the input for mechanical design and the material composition for prototyping feedthroughs.

PROTOTYPING

The prototyping phase covered the main project management work. In this phase the scope properties have to be distinguished and completed for procurement process to start a call for tender.

The RF designer has to work close with the mechanical design engineer and the material experts, to choose suitable materials, proper matching glass/ceramics to metal, appropriate fabrication processes with feasible mechanical tolerances. In this phase the RF simulation work grows up to an extensive calculation volume.

After the prototype design was finished all relevant mechanical properties have been defined, the design was finally evaluated by an FEM simulation, to check the mechanical conditions for the combination of feedthrough flanged to the BPM body in the relevant temperature range, especially at cryogenic conditions. The cryogenic requirements were checked by FEM simulations done by the company Novicos [6], Hamburg, Germany. Figure 2 shows simulations of thermo cycles between 330 k and 4 K. One critical aspect is to select the proper coefficients of thermal expansion (CTE) for the material composition; which combination of titanium, copper, stainless steel to oxide ceramic or non-oxide ceramic has the best reliability under the specified conditions?

The relative big difference of the CTE for stainless steel and aluminium-oxide-ceramic of about a factor of two was the issue to have this FEM simulation for stainless steel and Al_2O_3. The CTE of titanium is just in the range of aluminium-oxide ceramic. For the FEM analysis it was a critical point to use the correct CTE for the cryogenic temperature**. Due to high costs the FEM analysis was done for stainless steel, only.

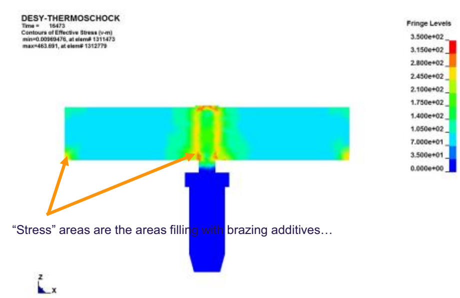

Figure 2: Thermo shock-analysis during cold/warm phases, stress of pin/ceramic/shell material (Novicos, Hamburg).

Based on the experience with cryogenic feedthroughs in the HERA proton ring brazing technology was chosen for the production process in order to have a “soft” buffer material to compensate the different CTE during cool down or warm up phases of XFEL modules. The allowed materials for the fabrication have been titanium or high quality stainless steel (316L/LN) for outer shell and flange. Titanium was preferred, because its CTE is closer to aluminium oxide ceramics.

For hermetic sealed ultra-high vacuum applications using brazing technology aluminium-oxide ceramic (Al_2O_3) was chosen to be the dielectric or isolation material. It allows brazing to copper, stainless steel and also titanium can braze too.

Finally molybdenum was defined to be the material of the inner pin. The material for the button, on the vacuum-side, was not defined at the time of the prototypes, due to unfinished wake loss simulations. A threaded end was a good compromise to test suitable materials.

The design of the feedthrough has to be robust with respect of all following handling steps like cleaning, drying, leak check, assembling and connection to cables.

**Properties of material at low temperature (Phase I), Victor J. Johnson.

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Therefore an N-connector for the cryogenic connecting cabling was selected.

Thermal-shock resistance and permittivity of the isolation barrier were the two important issues.

From those the resistance to thermal shock for operation under cryogenic conditions is the main topic. Therefore a cryogenic test process was defined. A controlled shock test in liquid nitrogen was required for quality check process before delivery to DESY.

The open call for tender resulted in a few quotations. Two companies fulfilled the required parameters. One company quoted a design in high alloy stainless steel and the other in titanium. An amount of 20 pre-series feedthroughs was ordered from both suppliers. The detailed test procedure will be described in the following.

TEST PROCEDURES

This passage describes all test procedures done for the prototypes and the series productions. Visual check of pin and connector centre alignment, purity of the feedthroughs and functionality of the gasket surface were the first steps. The alignment of button, pin and air-side connector were checked and the flatness and roughness of the sealing area. The packaging and UHV cleanliness were inspected followed by first leak checks. To ensure traceability, every feedthrough was individually labelled with part number, production date and company label. The critical mechanical tolerances were inspected by means of 3D measurements of random chosen parts.

For the cryogenic test the prototype items were assembled to a test vacuum vessel, inserted into a cryostat to be flooded with liquid helium. The mechanical test adapter is shown in Fig. 3. Ten cryogenic cycles were driven from 330 K up to 4 K in 20-30 min per cycle. Approximately 30 min at low temperature followed by a quick warm up in few minutes. The vacuum inside the test adapter was monitored during the tests, in order to detect temporary leakage at certain temperatures.

For the series production the test procedure was simplified. The feedthroughs were placed on horizontal multilevel table, shown in Fig. 4. The cryostat was flooded with liquid helium and the setup stayed under liquid helium for more than two hours, sometimes overnight.

Figure 3: Vacuum test adapter for cryogenic tests under vacuum with continuous leak check in a vertical cryostat.

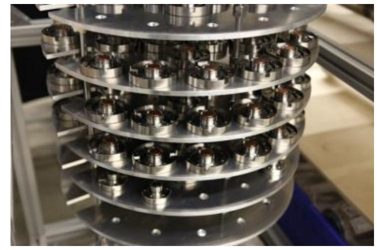

Figure 4: Multilayer table to "cryogenic-check" the serial production of feedthroughs.

The cryogenic tests ended with an individual leak check of each feedthrough. The next step was the check of RF properties. The reflection and transmission coefficients at the desired frequency were measured in a special mechanical setup with an automated procedure using a network analyzer. After this procedure the feedthroughs with similar transmission within the working frequency range of 0.3 to 2.5 GHz were paired.

The final step is the cleaning in a cleanroom, according to the particle cleanliness requirements for the E-XFEL cavity environment. The items are cleaned, starting with ultra-sonic bath cleaning with Tickopur R33, rinsing with clean alcohol and purging in ultra-pure water, until the resistance of the bath exceeds 12 MΩ. The parts are dried under pure air in a full metal oven up to 100 °C for several hours. The final step is particle counting and documentation of the results. Then the parts are packed in pairs and ready for assembly to the BPM bodies in a cleanroom class 4. Documentation of each BPM is available in the E-XFEL documentation using EDMS [7].

The electrical center of BPM depends on the position of the two pairs of feedthroughs with respect to the beam axis. The relevant mechanical tolerances were calculated during the design process. A FEM simulation and practical test were done with the prototype parts to optimize the assembly. The feedthrough flange has to be precisely mounted to fulfill the required tolerances.

Figure 5: Assembling of feedthroughs with torque wrench in classroom class 4.

A further aspect for the assembly is to guaranty the leak tightness under cryogenic conditions for a long time. Based on FEM analysis results from Paolo Michelato [8], the aluminum gaskets have by squeezed approximately 0.3 mm to ensure safe tightening.

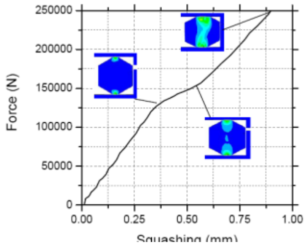

Figure 6: The deformation of the gasket cross section is shown. First step is the elastic to plastic zone. The distribution of equivalent plastic strains is shown at three different levels for alloy Al 5754.

SERIAL PRODUCTION

This passage describes the process steps of the series production. After all parts of pre-production were tested from both vendors, some changes and revaluations have been made.

The material of the button was defined to be copper and to be welded to the inner pin. The number of screws of the flange connection was increased from six to eight. Some changes for vacuum aspects were made and some tolerance changes were corrected due to the results of RF measurements.

The visual inspection in the last step before delivery was defined more precisely and the packaging was changed asking more robust boxes. After all drawings and specifications were updated, a restricted call for tender for the series production of 320 parts was send to both suppliers of the pre-production. The serial production was placed at the company providing the feedthrough shell in titanium, decided on the price. At beginning of the production a start-up meeting was held at the company, to fix all the production processes, quality assurance measurements and the delivery schedule. A jour-fix was agreed for monthly communication. The first lot arrived at DESY after 4 months. After 14 month the series production was complete.

PROJECT MANAGEMENT EFFORTS AND COMPETENCES

This task covered the complete project work for a R&D project including the fabrication a large scale of costumer designed feedthroughs in industry.

The phase plan with milestones has to elaborate and a work breakdown structure (PSP) has to be developed. Furthermore the evaluation of total cost and resources has to be done. The PSP integrates all working steps with a detailed description, effort and process activities. After them a net plan is derived of the PSP. These process steps will become time units of each work packet. The net plan showed the critical path of the project. The first version of the plan showed that the delivery will be months later than the requested milestone of pre-installation. Therefore other options had to be investigated. The leading documents are very often the technical documents and specifications, but they are not sufficient for project success. Important is a total quality management, a complete documentation, claim and change management.

RESULTS

The results are divided in technical and organizational aspects. After four months ramp-up time of the serial production, the production went very equally.

The RF simulation results defined all mechanical tolerances and in several iteration steps all critical aspects were fixed in the drawings and technical specifications. The wake losses simulations showed that copper is the proper material for the button of serial productions. The results of the RF measurements and simulation for the feedthroughs agree well. The mechanical changes were very small.

The FEM simulation of the cryogenic conditions and the excellent results of the cryogenic tests for the prototype items of both suppliers prove that the design is sufficiently robust. All forty prototypes feedthroughs passed the tests. The FEM simulation showed also a button position movement due to thermo cycles below 0.05 mm. Furthermore the deformation of the aluminum gaskets are in the correct tolerance range for a vacuum connection and don´t exceed the yield strength limit. The sealing area of the feedthrough flange was well defined and very painstakingly and carefully inspected.

The feedthrough assembly under cleanroom conditions had a good correlation to the mechanical FEM calculation. This tightening torques guaranty also the squeezing of the gasket within 0.3 mm. Due to these tests a special titanium stud-bolt was designed and ordered to reduce the friction during assembly under particle clean conditions, implying very clean surfaces with minimum abrasion. General frictional forces are not included in the values to be found in publications or specification for bolts, nuts and screwed connections. Therefore the practical test in cleanroom environment with different material compositions gave a very good matching between stainless steel BPM body and high-tensile titanium stud-bolts of Ti6 Al 4V. The grade 5 titanium with more than 1200 N/mm^2 tensile strength is excellent for applications in a cleanroom because of the minimum abrasion. This material is made for aerospace applications and can be hardening and has a very adherent oxide layer. The second important result was to increase the amount of bolts in the feedthrough flange from six to eight, to guaranty the accuracy of 0.1 mm feedthrough assembling.

The brazing technology of titanium or high-alloy stainless steel to metallized aluminum-oxide-ceramic provided sufficient stability for the cryogenic application. The ten successfully cycles for the pre-series items promise robustness for the long reliable operation of the cold linac modules. The feedthroughs of the series delivery were only cycled three times to avoid aging.

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The design of the feedthrough is robust with respect of all following handling steps like cleaning, drying, leak check, assembling and connection to cables. Therefore an N-connector for the cryogenic connecting cabling was selected. A part of project success was due to practiced project management competences. Due to the item identification numbers the traceability for each part is given, and used in the E-XFEL documentation processes.

Only few parts had not the necessary cleanness. Some leavings of glass blasting process were inspected or the brazing process. Furthermore few parts had a misaligned copper button or damaged outer connector. The covering boxes from one vendor of prototypes were not sufficient for this product.

CONCLUSIONS

Make in house or buy from industry is very often a serious question. Though it seems to be easy to buy good feedthroughs commercially in the market, lot colleagues think about this question. It is true that many vendors or suppliers can produce feedthroughs and you have only to answer which provider is the best for you.

The R&D of a costumer designed feedthrough can extend to a very complex project taking more time and efforts you will expect. If no real experts on RF simulations, matching feedthrough and front end electronics and mechanical skills in feedthrough and vacuum design, fabrication and project management are available, it will be smarter to buy and not to make in – house developments. Only with a good idea, a team of post docs or temporary staff will run in trouble.

It took 4 years to develop the cryogenic Feedthroughs for E-XFEL from the idea to the last shipment, and the final quality checks. Special attention has to be given to the feedthroughs which need to be produced with high precision and high quality in parallel or even before the mechanical design and electronic readout concept. A detailed specification with all requirements including beam parameters, environmental performance is fundamental.

The leading technology for this project was brazing of metallized ceramic to titanium. The colleagues from CERN used the same technology for the cold feedthroughs of LHC [9].

Under implementation of project management competences the project targets like budget, specifications, time schedule, procurement processes, change management and quality management are better controlled and get more reliable.

Based on the pre-production experience the series production went unobstructed. Therefore, pre-production for a R&D project like this is essential.

OUTLOOK

Based on the experience with the feedthrough for the cryogenic environment, a second project was started to develop and produce also a custom made feedthrough, especially suited to the requirements of linac driven facilities like E-XFEL. The design takes advantage of the relaxed restrictions from low average current machines and low synchrotron radiation or wake field power impacts. This allowed for a design with much better signal properties.

Although the cold feedthroughs were based on brazing technology the decision of fabrication of the warm feedthroughs went to glass to metal sealing technology in microprocessor-controlled furnaces. With this technology non oxide-ceramic-compositions with metals like high-alloy stainless steel or titanium can melt together. These glasses can have very low porosity, low or negative thermal expansion coefficients, low dielectric loss, a better permittivity than oxide-ceramics, high mechanical strength, very high thermal-shock resistance and high abrasion resistance to chemical substrates.

The diameter and the thickness which have big effects to the RF performance could be designed smaller. The normal voltage standing-wave ration losses are typical in the range from 1.1 to 1.3 for higher frequency for commercially feedthroughs. Furthermore this field of non-oxide ceramic is much larger as expected.

Meanwhile, also this project was finished successfully and 1400 feedthroughs of this type have been produced in collaboration with company VACOM in Jena, Germany.

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