INDUSTRIALIZATION OF SUPERCONDUCTING ACCELERATOR MODULE PRODUCTION

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Abstract

As part of the EUROFEL Design Study, two industrial partners recently took part in the assembly of superconducting TESLA modules for FLASH. The aim was to transfer the module assembly knowledge to industry and to analyse the assembly sequence to prepare for industrial production for future projects such as the XFEL. This paper will discuss the background and the conclusions of this study and identify issues that must be considered when transferring SRF technology to industry.

INTRODUCTION

The construction of the European XFEL project [1] has started at DESY. A 1.5-km long superconducting linear accelerator will deliver a pulsed electron beam of 17 GeV to operate a free electron laser in the x-ray region at 0.1 nm. The design of the XFEL-linac is based on the technology, which was developed in the framework of the TESLA Technology Collaboration in the past 15 years. The XFEL linear accelerator will consist of about 800 superconducting niobium 1.3-GHz 9-cell cavities, which will be cooled in a liquid-helium bath at a temperature of 2 K, to achieve a cavity quality factor $Q_0=10^{10}$ at the accelerating gradient of 23.6 MV/m. Eight cavities and one superconducting magnet package will be assembled in cryomodules of about 12-m length. The 2-K cryostat will be protected against heat radiation by means of two thermal shields cooled to temperatures from 5 K to 8 K and from 40 K to 80 K, respectively.

The industrial production of the about 100 XFEL cryomodules has been prepared in different phases during the preparation of the project. Based on the TESLA proposal, the industrialization consists of a suited design concept, extensive testing, re-designs for optimization and the early review by industry. For the XFEL-project industry was involved be means of an industrial study. This study was supported by the EUROFEL design program also in view of FEL projects beyond the XFEL.

DESIGN & PROTOTYPING

The XFEL cryomodules inherit the basic design concepts from the TESLA 500 GeV linear collider layout [2]. The superconducting TESLA technology was competitive because the costs per unit length of linac could be reduced by the design of long cryomodule units, which were suited for an easy and cheap assembly in industry. The aspect of the industrialization of the cryomodule production was incorporated in the first TESLA Test Facility (TTF) design (TTF-type-I cryomodule) from the very start of the project. The type-I design was introduced by the INFN Milano institute in co-operation with the ZANON company in Italy as a contribution to the TESLA collaboration. The successful operation of the concept could be demonstrated at the TTF. In the next step, the connections of the helium process tubes to the thermal shields were completely re-designed and simplified, to save costs (TTF-type II.)

EXTENSIVE TESTING

The TTF cryomodules have been tested in the TTF-linac since more than 10 years. During different modifications and extensions, the facility was finally converted to the Free Electron-LASer in Hamburg (FLASH) and serves now as a FEL user facility. Several aspects of cryomodule operation can be investigated in FLASH and the design could be validated for the XFEL-project. In addition, dedicated beam time is allocated for investigations for the International Linear Collider project (ILC) and the development of other FEL light sources.

The experience with several cryomodule assemblies at DESY and the preparation of the TESLA technical design report led to a complete re-design of the TTF cryomodule [3] (TTF-type-III.) The positions of the cavities were fixed by means of a support, which uses an Invar rod inside the module, to avoid thermal shrinking of the structure. As a consequence, the positions of the main RF couplers were fixed also. The support of the cavities is fixed to the gas return tube (GRT) at the center of the modules and at both ends the cavity support can slide relative to the GRT. In addition, the diameter of the vacuum vessel was reduced to 38'' to match standard industrial tube size. Again the new design was validated in FLASH. Presently 3 type-II and 3 type-III modules are installed in the FLASH-linac.

In addition to the TTF and the FLASH-linac a cryomodule test bench (CMTB) was erected at DESY for specific investigations of the cryomodule design and construction. Here specific cryogenic and RF tests can be conducted independently from the operation of the FLASH- linac. The CMTB can be adapted to different cryomodule types. Up to now cryomodules with the production numbers 3* and 7 (type-II) and 5 and 6 (type-III) were extensively tested at the CMTB. At present, module 8 will be tested. Important results were achieved regarding cavity performance, coupler conditioning and response of alignment to thermal cycling. The temperature dependence of the RF heat losses of the cavities was monitored down to 1.6 K. The coupler positions for modules type-III were validated by X-ray investigations during thermal cycling. By intention, module 3* was crudely handled by venting both the insulation vacuum and the beam vacuum with ambient air. The FLASH operation as well as the CMTB tests demonstrated the suited and robust design of the TTF-cryomodules.

INDUSTRIAL STUDIES

The TTF-type-III cryomodule serves now as a generic design approach for several superconducting RF linear accelerator projects beyond the TESLA poposal: such as e.g. the ILC as well as for different FEL-light sources, which use superconducting linacs as drivers for the laser. There are pulsed machines like the European XFEL-project but also cw-machines like the BESSY-FEL or Energy-Recovery-Linacs (ERL) like the Cornell University ERL x-ray facility.

For the realization of the European XFEL-project the module production has to be transferred to industry. In the next step towards the XFEL, industry should be involved as early as possible for the project preparations by means of industrial studies. At the same time, DESY cannot act legally for the future XFEL company, which is still to be established. As a result, the call for tenders for the industrial studies had to be separated clearly from the final cryomodule call for tenders. Also the technical results of the studies had to be published, to ensure equal treatment for the final call for tenders.

These attempts fitted perfectly in the EUROFEL design study (DS6, contract No. 011935): to prepare for the construction of the European XFEL and other superconducting linac based light sources like the BESSY-FEL, the existing cryomodule design and assembly procedures had to be reviewed. The aim was to prepare series production, as well as to reduce the effort and cost and to increase the performance and the reliability. The objective of EUROFEL design study task DS6 was to establish design and assembly procedures for superconducting accelerator modules, which are adapted and qualified for industrial series production, including the verification of these procedures by testing complete cryomodules on a test stand (CMTB). Both, the preparations for the cryomodule technology transfer to industry as well as the erection of the CMTB were part of DS6. The framework of the cryomodule design and assembly industrial studies was defined and specified in detail by the DS6 task partners BESSY and DESY. As a result of a European negotiated procurement procedure, two European companies were qualified to take part in the studies.

Within the framework of the cryomodule design and assembly industrial studies the DS6 partners BESSY and DESY concentrated on different technical details: BESSY took care of the cw-operation of cryomodules while DESY specified the general requirements and the requirements for pulsed operation of the cavities. All these aspects were covered in one joined technical specification and the related joined procurement procedure. The request for quotation was launched on February 21, 2005.

Finally, two bidders could be awarded with the order for the industrial studies. The contractors were ACCEL Instruments GmbH and Babcock Noell Nuclear GmbH (BNN). The ACCEL company has experience in many fields of applied superconductivity and in particular in the production and preparation of superconducting RF cavities. Moreover, ACCEL has already designed and built complete cryomodules for particle accelerators. BNN has managed the large scale production of superconducting accelerator equipment in many projects already (HERA quadrupoles, Wendelstein 7-X, ITER etc.) For the LHC-project at CERN, BNN has supplied about 400 coils and cold masses for the superconducting LHC dipoles.

The industrial study was linked to the assembly and test of two cryomodules (production numbers 6 and 8) at DESY. Following each assembly, the contractors had to deliver a report as part of the study. In addition, a separate report had to be supplied, which should cover the special aspects of the design and assembly of cryomodules suited for the cw-operation of the cavities (DS 6 part of BESSY).

In contrast to former industrial studies for the TESLA design report, which were based on fixed laboratory recipes, here an active role of industry during the assembly work of two cryomodules was an essential part of the study. The cryomodule assembly consists of the assembly inside a clean room and the assembly outside the clean room. All steps of the assembly procedures, in particular the assembly of the cavity string inside the clean room, can strongly affect the final performance of the cryomodule. The final accelerating gradients and the onset of field emission are extremely sensitive to any contamination with particles caused during the assembly. Also the mounting of other equipment, like the tuners and main couplers, requires extreme care. During the assembly of module 6 industry experts watched the assembly. For the assembly of module 8 main assembly work was actively done be the industry experts.

As a general result of the study reports, the existing design and assembly procedures are suited for the industrial production of about 100 cryomodules. A production rate of one cryomodule per week can be achieved, if a redundant production line in the clean room is built and the quality inspection is improved. In the reports many detailed recommendations to improve the assembly procedures can be found: there may be simpler tools for faster alignment of the cavity string in the clean room. The cleaning of several small components should be sourced out. Outside the clean room the alignment procedures for the cavity string and the cold mass can also be improved.

As a special issue of the industrial study, the transportation of XFEL cryomodules and the related safe guard design should be investigated. Both contractors delivered valuable recommendations from different approaches. The ACCEL company suggested two different designs for suspension frames, with regard to existing transport experience.

The BNN identified the most critical module parts by finite element calculations and presented safe guard designs for the inner parts of the cryomodule. Based on the industrial study, prototype safe guards for transportation are now ordered from both companies.

Issues that must be considered when transferring SRF technology to industry

Both industrial partners fulfilled the requirements of the 'Cryomodule Design and Assembly Study' completely and delivered most valuable input for the preparation of the XFEL cryomodule production. From the start, the studies were conceived as a chance for mutual transfer of information and skills between the experts from industry and laboratory. As a result, several TESLA technology skills could be transferred to industry during the study. Beside the excellent documentation gained from the study, it became very clear that the personal communication and the direct demonstration of clean room assembly details are imperative for an effective transfer of knowledge and skills. Even very complete protocols can not replace the direct communication between the experts. The active role of industry during the assembly of module 8 showed how the transfer was received and gave already some feed-back to the specifications.

PROTOTYPE CALL FOR TENDERS

In parallel to the industrial cryomodule design and assembly study the TÜV Nord GmbH was put in charge, to deliver the particular specifications for the XFEL cryomodules to fulfil requirements of the European pressure vessel directives and the European harmonized design rules.

Up to module 9 all 'cold-masses' (= vacuum tank, thermal shields, helium process tubes and all supports) of the cryomodules were ordered from the ZANON company in Italy, who was involved in the module development from the start. For two XFEL prototype cold-masses beyond module 9, a European call for tender was launched and orders were given to the FELGUERA Construcciones Mecanicas (Spain) and THALES (France) companies. As an In-Kind contribution of China to the XFEL-project a third cold-mass will be supplied by IHEP Bejing. A draft of the final XFEL cryomodule specification served for this orders.

It should be noticed that modules 8 and 9 differ from the TTF-type-III design. Here also the support of the superconducting superferric magnet package is integrated in the support of the cavities and the magnet will be cooled in the 2 K helium bath ('type-III-plus'.) In addition to these design changes, the final XFEL cryomodules will differ only slightly in length, to match the N x $\lambda/2$ - distance between cavities in order not to exclude potential ERL options for the XFEL.

FINAL PRODUCTION SITE

As part of an In-Kind contribution of France to the XFEL-project it is proposed that CEA Saclay will take over the XFEL-cryomodule assembly. Clean room facilities, which were already planned for the 'Spiral-2-project' will be modified and used for the assembly. The assembly will be supported by personal from industry. CEA Saclay placed an order for a preliminary study for the industrialization of the cryomodule assembly on the Saclay site to the THALES company. As a result of this study, the infrastructure and tooling shall be defined, a fabrication folder shall be established and the risks shall be analyzed.

In addition, it is proposed that France will take over the production of 50% of the cryomodule cold-masses. The remaining cold-masses will be supplied by In-Kind contributions from Italy and Germany.

CONCLUSIONS

The industrialization of cryomodule production consists of several phases, starting with the basic design, extensive testing and design improvements. As soon as the basic concepts of design and assembly have been validated on the laboratory scale, the review by experienced industrial companies is needed, to prepare the industrial series production. For the preparation of the European XFEL-project an 'Industrial Cryomodule Design and Assembly Study' was carried out and delivered valuable input for the preparation of the series production. The active role of industry was mandatory for the mutual exchange of knowledge and skills between the laboratory and industry.

ACKNOWLEDGEMENTS

The author wants to thank the involved experts from ACCEL and Babcock NOELL companies for the excellent and valuable work for the industrial studies. Many colleagues from BESSY and DESY supported the studies from the laboratory side. Colleagues from INFN Milano and CEA Saclay supplied additional information.

The Industrial Cryomodule Design and Assembly Study was supported by EUROFEL Design study contract No 011935.

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