HOW TO PRODUCE 100 SUPERCONDUCTING MODULES FOR THE EUROPEAN XFEL IN COLLABORATION AND WITH INDUSTRY

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Abstract

European XFEL accelerator module production is in almost full swing by the time of IPAC 2014. This is the first project of this size that includes many partner laboratories and transfer of technology for mass superconducting RF cavity and accelerator module production to industry. This talk will illustrate the organization of the production and the lessons learned, illuminating what one should or would do differently for future projects.

INTRODUCTION

The accelerator complex of the European XFEL [1] is being constructed by an international consortium under the leadership of DESY. Seventeen European research institutes contribute to the accelerator complex and to the comprehensive infrastructure. DESY coordinates the European XFEL Accelerator Consortium but also contributes with many accelerator components, and the technical equipment of buildings, with its associated general infrastructure. With the finishing of the accelerator tunnel infrastructure, the installation phase was started in 2013.

ACCELERATOR MODULES

The accelerator of the European XFEL is assembled out of a large number of 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 overall design of a standard XFEL module was developed in the frame of TESLA linear collider R&D. Final modifications were done for the required large scale industrial production.

Main Specification and Basic Structure

The main constituents of the standard accelerator module are eight superconducting cavities supplied by one RF power coupler each, a superconducting quadrupole package which includes correction coils (steerer) and a beam position monitor, cold vacuum components like bellows and valves, and frequency tuners. The string of cavities with the quadrupole magnet attached to the upstream end is suspended from the upper part of the cryomodule's cold mass. The outer vacuum vessel houses the complete unit. Table 1 summarizes the major contributions.

Table 1: Contributions to the XFEL Accelerator Module

Institute	**Component / Task**
BINP Novosibirsk, Russia	Cold vacuum bellows, coupler vacuum line
CEA Saclay / Irfu, France	cavity string and module assembly; cold beam position monitors; magnetic shields, superinsulation blankets
CIEMAT, Spain	Superconducting magnets
CNRS / LAL Orsay, France	RF main input coupler incl. RF conditioning
DESY, Germany	Cavities & cryostats; contributions to string & module assembly; coupler interlock; frequency tuner; cold vacuum system; integration of superconducting magnets / current leads; cold beam position monitors
INFN Milano, Italy	Cavities & cryostats
Soltan Institute, Poland	Higher Order Mode coupler & absorber

Experience with accelerator modules built for DESY's FLASH facility [2] was used for the detailed definition of sub-components and the cavity string and module assembly. All built modules are to be tested prior to installation in the European XFEL accelerator tunnel. Thus the so-called Accelerator Module Test Facility [3] is operated at DESY to perform the cavity and module testing. Execution of the tests is done by a larger team of IFJ Cracow, Poland [4-7]. The project schedule calls for an overall delivery rate of one module per week, requiring a corresponding delivery rate of sub-components like cavities, couplers, tuners etc.

Before going into detailed description of sub-component production, testing, delivery, and of module assembly, it is worth comparing this effort with the achieved rates during the extensive TESLA R&D and XFEL preparation phase. First superconducting TESLA shape cavities were produced in the early 1990ies. The yearly rate of new cavities brought into testing at DESY slowly went up and finally reached approx. 15 per year at the time when the TESLA Technical Design [8] was presented (see also Figure 1). It is remarkable that in average over the more than 15 years of R&D only one new cavity per month was produced, delivered, and studied.

The number of accelerator modules installed in DESY's FLASH facility is based on successful TESLA R&D. Altogether seven modules housing 8 cavities each were installed. Less than one module per year was assembled. Thus the increase in production rate for the European XFEL with now 8 cavities / coupler and 1 module per week is at least a factor 30.

Superconducting Cavities

The contracts for the delivery of 800 cavities were placed in 2010, and first of the series cavities were delivered beginning of 2013. Both, production and surface preparation are done in industry [9, 10]. Contracts were allocated by DESY to the Italian company E. Zanon and the German vendor Research Instruments, the supervision being a shared responsibility of DESY and INFN Milano. Details of the cavity specifications were made available to the SRF community half a year after contract placement. Both companies were contracted to produce each 4+4 pre-series cavities followed by 320 XFEL type series cavities and 12 so-called HiGrade cavities, to be used for quality assurance [11] and later made available for further investigation & treatment. After the evaluation of the successful start of the series production additional 80 cavities were ordered based on a fix price.

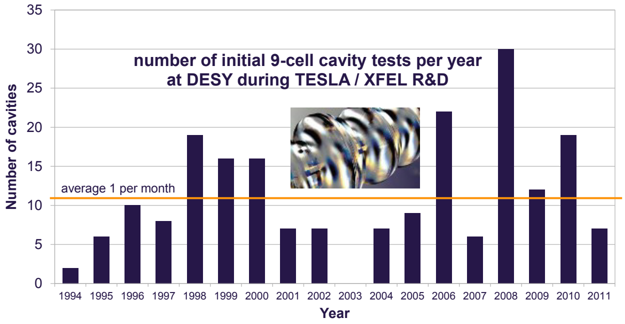

Figure 1: During the almost 20 years of TESLA / XFEL R&D in average one new TESLA shape 9-cell cavity per month was introduced in the work effort. The European XFEL requires a rate strongly increased by a factor 30.

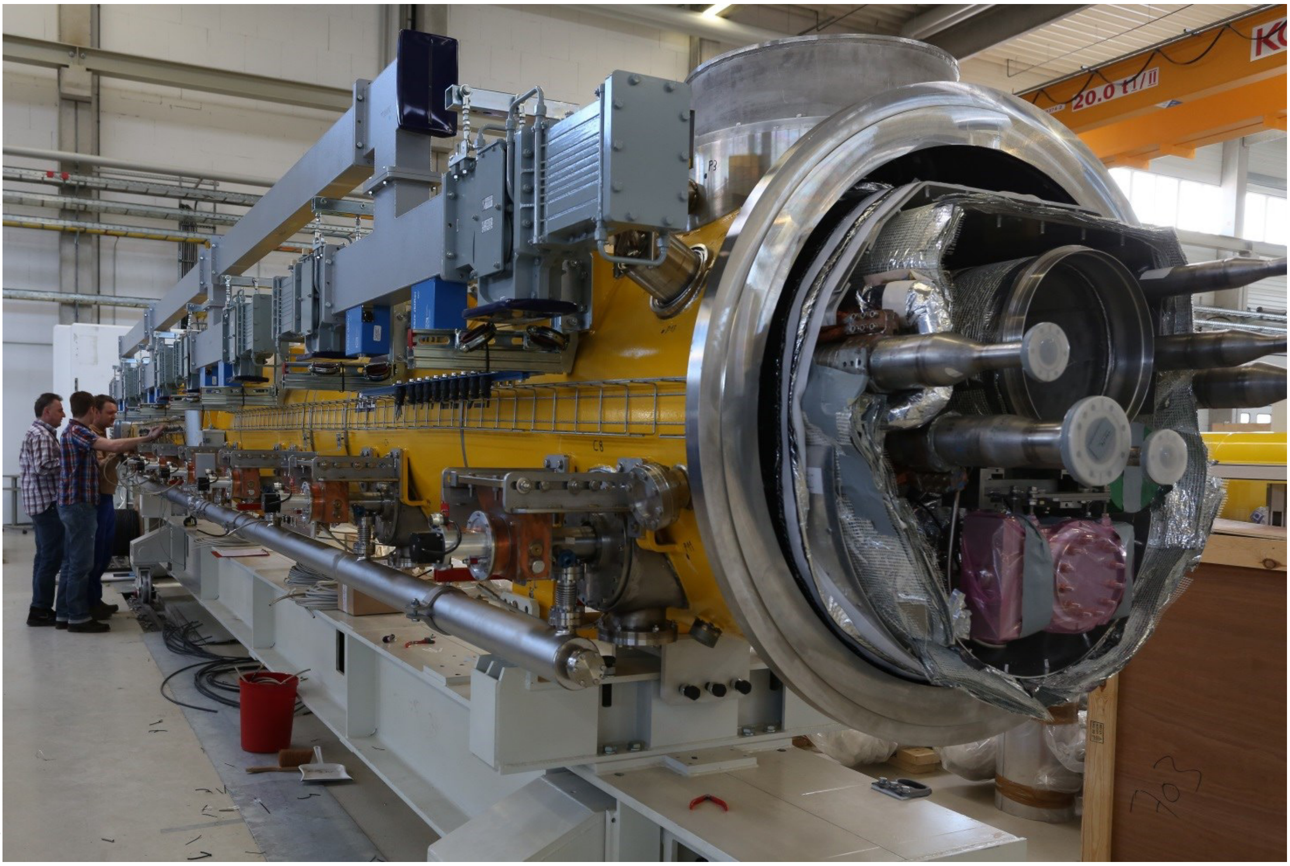

Figure 2: One of the first accelerator modules built for the European XFEL. The picture is taken in the Accelerator Module Test Facility at DESY which is used to carry out a full performance test of all superconducting cavities and finished modules. The cryostat cross section shows most prominently the large diameter Helium gas return pipe with the cavity string below. Temperature shields and the cryogenic process lines are visible. Along the module eight RF power couplers with its vacuum line are visible. The waveguide distribution – here not yet connected to the coupler windows – is tailored to the accelerating gradients measured during module test.

First delivery of series cavities was originally scheduled for beginning of 2012; and all cavities to be delivered within two years. The set-up of infrastructure including its commissioning took considerably longer. Now, after the production ramp-up early 2013 the last cavities are scheduled for middle of 2015.

Nb / NbTi were supplied by DESY [13] and the cavity production follows precisely the specifications developed by DESY which also includes the exact definition of infrastructure to be used. The final treatment after bulk electro-polishing (EP) is different for the two selected vendors: EP for Research Industry / so-called flash BCP for E. Zanon [14, 15].

No performance guaranty was given by the vendors, i.e. the risk of an unexpected low gradient or field emission is with the contractor DESY. The responsibility for re-treatment is only at the vendor if the surface treatment followed by clean room assembly did not follow the specifications given. The gradient goal is an average usable XFEL gradient of 23.6 MV/m at an unloaded quality factor of 1E10. During the vertical acceptance test at DESY the 'usable gradient' is determined, defined as the lowest gradient given by either quench, or E_{acc} at Q_0=10E10, or E_{acc} with radiation above 10E-2 mGy/min.

As of writing (June 2014) approx. 350 cavities are delivered and almost all vertically tested. Details are published elsewhere [16, 17]. In summary 2/3 of the cavities are accepted for accelerator module assembly immediately after the initial test; the gradient reached for those cavities is almost 30 MV/m. The remaining cavities undergo a retreatment at DESY, almost all of them a high pressure rinse only. By this the number of cavities clearly above XFEL specifications is increased and a forecast until the end of production gives a potential additional energy of 1.3 GeV in excess of the XFEL design energy of 17.5 GeV. Without any retreatment the average gradient of 23.6 MV/m for the complete linac can be reached accepting some accelerator modules with batches of lower gradient cavities.

RF Power Couplers

The responsibility for the XFEL RF power coupler production was taken over by LAL Orsay, France. An industrial contract was placed at the company Thales, France, producing most of the couplers (670) in a consortium with Research Instruments. A smaller number (150) was ordered directly by the European XFEL company at CPI, U.S. In order to carry out the RF conditioning of the power couplers a new dedicated 5 MW RF station was set up by LAL Orsay. Parallel conditioning of four coupler pairs is done on a regular basis which fulfils the required conditioning rate of in average eight couplers per week.

The ramp-up of the coupler production needed reasonably more time than originally assumed [18]. The copper plating at Thales was the biggest challenge. Even if copper thickness and RRR were finally acceptable, some small surface defects still remain. While the used XFEL specifications require defect free plating, a sufficiently large magnification shows repeatedly small circular spots with typically 0.1 mm diameter, especially in the bellows convolution (valleys). In view of the required long operation time of the couplers only a very small number of such spots can be accepted. Other non-conformities like peeling-off even in RF-uncritical areas lead to a rejection of parts. Particle-free installation procedures cannot handle such cases.

Critical quality control accompanies the complete coupler production which finally ends with cleanroom assembly of coupler pairs ready for RF conditioning at LAL Orsay. Due to the stringent quality assurance of the copper plating basically all delivered couplers are successfully conditioned within the scheduled time of approximately 35 hours. Details are given elsewhere [19].

Cavity Bellows and Cold Vacuum

The assembly of eight superconducting cavities complemented by the quadrupole package to a string requires copper-plated bellows. Since particle contamination in the cavities can cause field emission and thus lower usable gradients, particle cleaning has to be done similar to what is being done with the accelerating structures. Besides cleaning the specifications require 1E-10 mbar pressure in all sections next to the cavities, which requires a sufficient leak-tightness of the bellows but also of valves and of the mentioned quadrupole package. No carbohydrates should be visible in the mass spectra. All 800 cavity bellows are produced by BINP Novosibirsk, Russia. Commercially available gate valves (manual at the cavity string end, and automated at the string connection boxes after each twelve modules) are used but careful quality control points to the need of additional particle cleaning at DESY. The RF power coupler vacuum line is produced by BINP Novosibirsk, Russia, and attached to the accelerator module as one of the last assembly steps.

Quadrupole with Beam Position Monitor

Each XFEL accelerator module has one superferric quadrupole magnet including dipole correction coils for both planes; and a beam position monitor is attached. The magnet design and prototype development was done by CIEMAT, Spain, in 2006, and then repeated in collaboration with industry in 2010; some improvements, both technical and cost wise, were necessary to prepare for mass production [20]. The contracts for series production (103 magnets) were awarded to Trinos Vacuum Projects and ANTEC, S.A. (coil fabrication), both being Spanish companies. A thorough quality assurance system was implemented since amongst others the European Pressure Equipment Directives have to be observed. All individual magnets undergo a complete measurement (quadrupole and dipole fields) at the new

DESY XFEL Cold Magnet Test Stand. While a stretched wire system determines the absolute field strength as well as the magnetic axis and field angles, a rotating coil system measures the integrated field quality expressed by the harmonic content. All cold measurements are done at four different current profiles. Warm and cold tests of all parts are done at DESY together with IFJ-PAN as part of the Polish and German in-kind contributions.

So far only one magnet out of the already tested 65 was rejected due to one flange position being out of tolerance. Cold leaks and high voltage tests (250 & 500 V) perform very well. All magnets successfully passed the tests and no quench occurred in a 12 hour stability test at maximum design current (50 A). Measurements show that all magnets behave identically. The magnetic field properties compare very well to the model predictions, larger non-linearities are mainly due to the persistent current in the superconducting wires and iron effects.

The quadrupole package includes a beam position monitor. Two different types are used, a button BPM [21] estimated to be rather simple and robust and a re-entrant cavity BPM [22], providing the potential for better resolution. CEA Saclay / Irfu contributes a total of 31 re-entrant cavity BPMs. The remaining 72 button BPMs are provided by DESY. Even if the production of the re-entrant cavity BPMs is still ongoing, sufficient BPMs can be supplied for the module assembly process. On request from the assembly work package the BPMs are prepared according to the cleanliness requirements defined by the module assembly process. The quadrupole package is assembled and tested in the clean room at DESY and is then shipped to CEA Saclay / Irfu for further installation [23].

Frequency Tuner & Magnetic Shielding

Each XFEL accelerating cavity is supplied with a motor driven frequency tuner with piezos being integrated for fine-tuning. A detailed description is given in [24]. The design is based on the so-called Saclay tuner developed in the frame of TESLA R&D. The tuning system consists of a stepping motor with a gear box and a double lever arm. The moving parts operate at 2 K in vacuum. The frequency tuning range is about 400 kHz with a resolution of 1 Hz, and length adjustment is possible with sub-micron accuracy. In contrary to previously used systems the cavity is stretched by the tuner which has the advantage that the piezo elements are compressed under all circumstances. Tuner mechanics is built by the German company Astro- und Fernwerktechnik with the drive unit coming from Harmonic Drive using motors from Sanyo Denki, piezos from PI Ceramic. The delivery of components is accepted only after detailed dimensional as well as functional checks including a successful pre-assembly, a cold test of the drive unit, and a burn-in of the piezos; conformity is certified. During assembly at CEA Saclay / Irfu in France, a special test device developed by INFN Milano is used for further electrical control.

A precondition for reaching high cavity quality factors even after string assembly is the use of proper magnetic shielding. While Cryoperm® was used for the TESLA Test Facility, the European XFEL project uses a material from a different supplier (Cryophy® / Aperam) but with similar magnetic properties. After a pre-qualification the final contract for series production was awarded to the French company MecaMagnetic. The production rate follows the needs for one module output per week.

The cryogenic insulation requires qualified super-insulation blankets be wrapped around the cryostat shields. CEA Saclay / Irfu designed special blankets for the 2K and 80K shields which were tested at the XFEL pre-series modules. Series production is done by the French company Jehier.

Fastening hardware (screws, nuts, gaskets, seals etc.) were planned to be ordered particle-clean packed. Nevertheless, high costs caused to reconsider this. All parts are now prepared at CEA Saclay / Irfu.

Cryostats

Similar to the superconducting cavities the production of a large number of series cryostats required pre-qualification. Out of the few companies two were selected based on extensively tested prototypes. IHEP Beijing, China, is acting as a vendor with Chinese subcontractors, and produces 58 cryostats. E. Zanon, Italy, well known from the previous TESLA and XFEL R&D, fabricates 45 vessels and cold masses. Both contracts were placed beginning of 2011, and delivery of first units was in summer 2012. Both vendors started the production with only minor non-conformities which could be handled after delivery either to DESY or directly to the assembly site at CEA Saclay / Irfu. Extensive feedback to the companies reduced the number of non-conformities and thus the additional work load for the receiving laboratories [25, 26]. The first deliveries from China unfortunately suffered from mishandling after successful production. In total seven cold masses in the beginning were send back for repair. The overall schedule is uncritical since the last cryostats are expected for end of 2014.

ACCELERATOR MODULE ASSEMBLY

Cavity string and module assembly is one of the major in-kind contributions to the European XFEL. It happens at CEA Saclay / Irfu and uses a complete new and dedicated infrastructure [27, 28]. Construction of the so-called 'XFEL village' has started already in 2009, and major parts of the new infrastructure were commissioned in 2010. First experience was gained with the assembly of two of the XFEL prototype modules. Since 2012 the three pre-series modules XM-3 to XM-1 were used to train the company ALSYOM, France [29], contracted by CEA Saclay / Irfu. At the same time procedures were further optimized such that the assembly of the first series module was finally started in Q4/2013.

The string and module assembly is directly impacted by the availability of all accelerator module subcomponents. Thus buffers are defined to be filled equivalent to the number of parts needed for four modules. Logistics is required to arrange for timely delivery of e.g. tested cavities or preassembled quadrupole packages coming from DESY. Any possible break in the supply chain has to be seen as a risk for the module assembly schedule and thus for the delivery back to DESY. The somewhat late availability of cavities and especially couplers (see above) together with additional time needed for the assembly training and optimization of procedures brought the module production on the critical path of the European XFEL project. All collaboration members try to minimize the delay and the discussion of an Accelerated Module Assembly scheme started, most likely based on additional resources.

COLLABORATIVE EFFORT

Building the worldwide largest superconducting linac is only possible in collaboration with sufficiently developed SRF expertise. Major key-player already working together in the TESLA linear collider R&D phase joined the European XFEL in an early phase. DESY has the role as coordinator of the accelerator complex including the superconducting linac. At the same time large in-kind contributions in the field of SRF technology are coming from DESY. Work packages contributing to the cold linac are in all cases co-led by a DESY expert and a team leader from the institutes contributing. Integration into the linac installation and infrastructure is a DESY task.

Large series production in industry requires pre-qualification. While in some cases vendors were qualified already during the TESLA R&D phase, in some other areas a careful multistep qualification was done. There was a strong effort to always have at least two qualified vendors, and where possible the overall production was split accordingly.

After contract award a continuous close cooperation with vendors is needed. Many of the used components remain challenging, and non-conformities can be reduced only in fruitful discussions. SRF technology does not allow real compromises, i.e. problems have to be smoothened out in a common effort.

The European XFEL is built based on in-kind contributions. The project includes technology transfer between the different institutes and also industry. In such a model the coordination effort should not be underestimated. The original budget estimate needs to take care of this. Difficult to handle are also the duties defined by dependencies, e.g. in the supply chain. In a technically ambitious project the responsibilities in terms of work sharing may be clear but in case of sudden and unexpected technical problems the collaborative spirit is needed and of utmost importance. Discussion of legal constraints is often of no avail, even if necessary.

The European XFEL clearly profits from the long-time experience of DESY in SRF technology, and from the history in building and operating large scale accelerator facilities. Coordination and integration of in-kind contributions requires not only additional resources but also relies on the possibilities of a strong laboratory. Expecting turn-key systems is an incorrect approach. Both partner, the receiving party but also the in-kind contributor need expertise and excellent communication skills. A well-developed team spirit is of large benefit.

Documentation plays an important role. Large series production almost automatically generates the need for a well-developed quality management plan [30, 31]. The single component systems bear the risk of remaining badly documented since they are too often treated as prototypes. Receiving in-kind contributions and taking over the responsibility for operation requires documentation and excellent knowledge transfer.

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