INDUSTRIALIZATION PROCESS FOR XFEL POWER COUPLERS AND VOLUME MANUFACTURING

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Abstract

The XFEL (**E**uropean **X**-Ray **F**ree-**E**lectron **L**aser) is a new international large-scale research infrastructure to be built in the north west of Hamburg, Germany [1], [2].

The power coupler TTF3, developed at DESY for TESLA was chosen to be the first choice for the XFEL. For further development, testing and conditioning of the power coupler a collaboration is working between LAL, Orsay and DESY, Hamburg since 2004. Up to 60 power couplers of the TTF3 type are fabricated, conditioned and under operation at the TESLA Test Facility.

For the industrialization of the power coupler three contracts where placed at the Industry. The follow up of these contracts is under the supervision of LAL.

We will report about the approach of the contract and some results.

INTRODUCTION

The XFEL construction is a great engineering challenge: 800 input couplers are needed for XFEL. The chosen design of RF input high power coupler (see Fig.1) is based on the type known as TTF3 [3], already thoroughly tested on the test stands at DESY and LAL, as well as at the Cryo Module Test Stand and **F**ree-electron **LAS**er in **H**amburg (FLASH) facilities at DESY [4]. Reducing the unit cost for mass production is a challenging objective which requires tremendous efforts. Preliminary studies on manufacturing processes and on how to reduce the XFEL coupler cost have started in March 2006. Three industries were awarded study contracts and are applying different technical recipes to reduce the production cost.

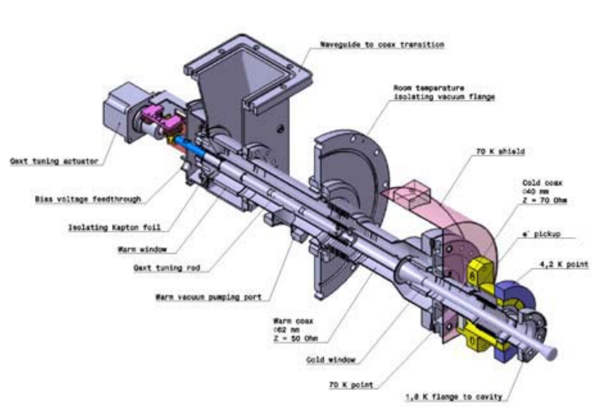

Figure 1: XFEL-type input RF power coupler.

SCOPE OF DELIVERY

The production of the 800 input couplers includes several specific tasks requiring expertise and careful execution. Main phases are:

1. Manufacturing parts.
2. Joining parts into sub-assemblies (Fig.2).
3. Preparation in ISO 6 clean room:
   - Washing in warm ultrasonic detergent bath
   - Rinsing with ultra pure water (18 MΩ×cm)
4. Operations in ISO 4 clean room:
   - Drying with warm filtered air
   - Assembly of 2 cold parts on test cavity
   - Vacuum pumping and He leak test
   - Assembly of 2 warm parts
   - Final assembly on test stand
   - Vacuum pumping and He leak test
5. Preparation for conditioning:
   - In situ baking under vacuum
   - Assembly of waveguide interface box, capacitor and tuning mechanism
   - Tuning to 1.3 GHz
   - Start the ion pumps
   - Connect to waveguide and diagnostics (Fig.3)
6. RF conditioning (Fig.4)
7. Dismount, pack and transport.
8. Deliver by pairs assembled on the test stand to the cryomodule assembly location

Figure 2: Coupler parts and sub-assemblies: cold coax, warm coax, tuning pushrod and waveguide box (from left to right).

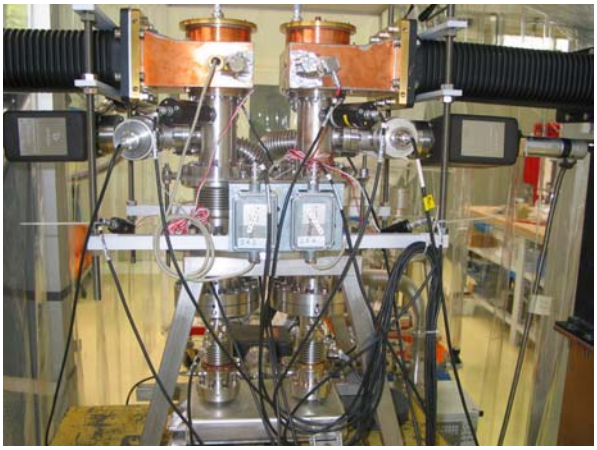

Figure 3: Two couplers on the test stand.

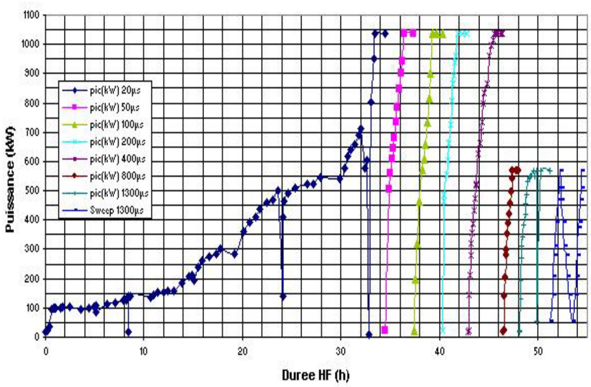

Figure 4: Coupler RF conditioning: input RF power versus time for increasing RF pulse lengths.

Expertise required from industry:

- Procurement of special austenitic stainless steel
- TIG welding
- Vacuum brazing
- EB welding
- Cu plating: 10 < RRR < 100
- TiN coating, thickness ~ 10nm
- Precise geometrical tolerances
- Surface finish and cleanliness
- Motorized tuning
- He leak rate < 10^{-10} Pa×m^3/s
- Careful and clean handling
- Assembly and cleaning in the clean room
- RF Conditioning

INDUSTRIALIZATION STUDIES

The Purpose

Starting with a series of 40 prototype couplers having uneven quality and several anomalies, long and difficult manufacturing process lacking precise procedures and calling for expert technicians, and obtained at a high cost, the industrialization process has the end objective of mass production of 800 XFEL couplers (16000 for the ILC) having all equal and reliable quality, manufactured using regular processes with written procedures and standard competences, and at a significant cost reduction.

Working process

Starting from functional specifications and using the industry know-how in an ISO 9001:2000 environment, the industrialization process includes several steps:

- functional analysis which aims to parts simplification,
- design for manufacturability to simplify manufacturing process,
- validation models and tests,
- lean manufacturing methods to optimize the functions,
- risks analysis and mitigation [6], [7].

Results of the process are the full engineering design, reliable manufacturing processes, detailed production plan and a precise costs estimate. Besides, each of the 3 industries will finally deliver in March 2008 two prototypes which will be tested at the LAL high power RF station. This method has already led to a significant reduction of the number of parts and hence of junctions.

The coupler technical designs for both XFEL and ILC involve high quality materials and sophisticated joining techniques.

Specific materials

The following points are critical and should be respected:

- Stainless steels quality [8]: real chemical composition must be verified and batches selected according to the specific needs (Table 1). The actual material must be delivered with its certificate type 3.1. The equivalent Cr and Ni contents must be calculated and can be plotted in the Delong diagram:
  (Cr)eq= (%Cr) + 1,5(%Si) + (%Mo) + 0,5(%Nb)
  (Ni)eq= (%Ni) + 0,5(%Mn) + 30(%C) + 30(%N)
  Finally the relative magnetic permeability must be measured on the delivered material.
- Copper for couplers [9]: quality of oxygen free copper is essential and its specifications (Table 2) must be respected to guaranty leak tightness and high thermal and electrical conductivity.
- Ceramic for coupler windows (Table 3).
- Materials resistant to ionizing radiations [10]: specification dose for XFEL lifetime (15 years) is 1 MGy (Absorbed energy = 10^6 J/kg). The main destructive effects of radiations on matter include ionization of atoms, break of atomic bonds and creation of free radicals. Organic materials are the most sensitive and the result is a degradation of their mechanical and electrical properties. A selection of organic materials resistant to the 1 MGy dose is given (Table 4) for the uses in input couplers.

Table 1. Stainless steels in couplers production process.

EN 1.4404, X2 CrNiMo 17-12-2 (316L) • ferrite number ~ 2 • easy to procure	tubes, bellows, fittings
EN 1.4435, X2 CrNiMo 18-14-3 (316L) • ferrite number ~ 0 • μr < 1.01 • less easy to procure	tubes in cold part
EN 1.4429, X2 CrNiMo 17-13-3 (316LN) • μr < 1.005 • N_2 enriched: Hardness 150 / 190HB • refined by electroslag process • forged in bars • stands H_2 outgassing 2h, 950°C • difficult to procure in small quantities	CF flanges, doorknob, cavity flange

Table 2. Copper in couplers production process.

Cu-OFE: UNS C10100

- Electrolytic copper with high thermal and electrical conductivity
- oxygen free
- state: half-hard
- 3D forged & work-hardened
- grain size < 90 μm
- US test at 4MHz: attenuation should be < 20%
- inclusions: class 1 & 2 (ASTM F 68-99)
- RRR ≥ 100
- chemical composition:

Cu > 99.99%	Se < 10 ppm	Bi < 10 ppm
O_2 < 5 ppm	Te < 10 ppm	P < 3 ppm
S < 18 ppm	Pb < 10 ppm	others < 40 ppm

Table 3. Ceramics in couplers production process.

Cylindrical windows made of Al_2O_3 (97.6%):
2 qualified vendors for similar material properties:

- SCT (F – Tarbes)
- WESGO (D – Erlangen)

Highly controlled process:

- high purity powder
- isostatic pressing
- « green » machining
- high temperature sintering
- fine grinding
- grinding of grooves
- metallization Mo-Mn

Measured dielectric properties of samples:

- $\varepsilon_R = 9.0 \pm 0.1$
- $\tan\delta = (2.2 \pm 0.2) \times 10^{-4}$

Table 4. Radiation resistant materials.

PPS (Poly Phenilene Sulfide)	Isolating body in electrical connectors, micro switch case
Polyester reinforced with glass fiber	actuator parts
Composites glass fiber – epoxy resin	mechanical supports for thermal insulation
PAI (Poly-Amide-Imide) ex. Torlon 4203	mechanical parts for electrical insulation
PEEK (Poly-Ether-Ether-Ketone)	insulated covers for capacitor
PI (Poly-Imide) ex. Kapton	insulating film for capacitor, cables insulation
grease: APIEZON	actuator
epoxy glue ARALDITE 2011	mechanical assemblies
epoxy glue STYCAST 2850F	assemblies with good thermal conduction
glue LOCTITE 638	thread locker

Some Results of industrialization studies

Functional analysis

- The antenna should be polished to obtain a small thermal emissivity coefficient (reduction of thermal radiation to 2 K).
- Thermal model: Cu rings at 4K point can be attached on thicker tube instead of bellows, brazed or glued.
- Big flange on vacuum vessel: 12 holes are enough instead of 24.
- Choose gamma radiation resistant materials.
- Floating big flanges must be supported to prevent lateral bellows deformations and risk of antenna contact with cavity wall, see Fig.5 and Fig.6.

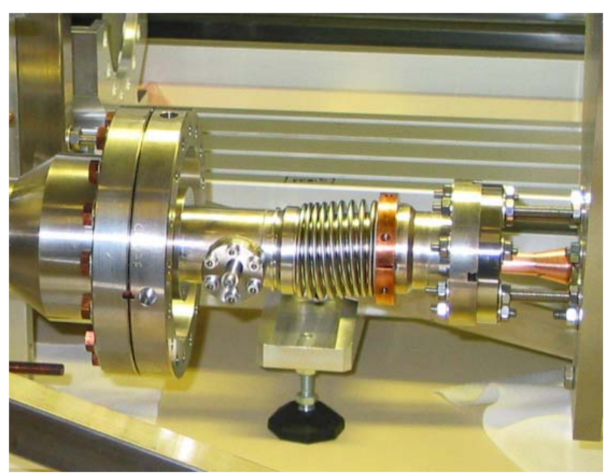

Figure 5: Coupler cold bellows lateral deformation.

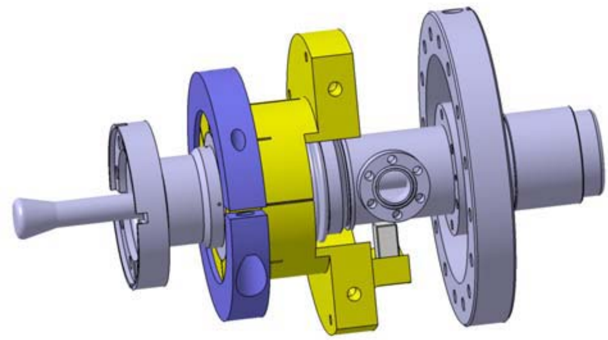

Figure 6: Coupler cold bellow support design proposal, the support is the part of the 4 K thermal shield.

Design optimization and lean manufacturing

- Choose deformation techniques (deep drawing, forming, spinning, pull-out) and casting (lost wax process) instead of machining by material removal
- Decrease number of parts and junctions
- Optimize the process for vacuum brazing by use of special tooling jigs: adapt tolerances & thermal expansion.
- Design of the capacitor for industrial manufacturability.
- Use chain clamp instead of screws for assembly.
- Decrease number of parts and junctions.

Joining techniques

The joining techniques used in the couplers assembly require precise procedures and very clean environment. Adequate jigs must be designed and built to guarantee precise alignment of the different parts. The three industries have already demonstrated their ability to perform such joining on a regular basis.

Joining for TTF3 couplers baseline is as follows:

- TIG welding of stainless steel parts
- Vacuum brazing of Cu to stainless, Cu to ceramics
- Final joints by EB-weld

Alternate proposal 1: Final assembly by TIG welding.

Alternate proposal 2: All metallic joints are brazed under vacuum, which raises the following concerns:

- Brazing of bellows is similar to annealing, which causes the loss of elastic behavior. Fatigue tests on bellows after thermal cycle was done on the small inner bellows and the larger cold bellows with repeated movements of ± 10 mm: rupture occurred after respectively 11000 cycles and 23000 cycles. These results tend to validate the choice of joining by brazing.
- Final joints by brazing: the question of how much Ti diffusion into the ceramic is still open when the TiN coating is done before brazing. This effect will reduce the active layer of TiN on the surface. The remaining efficiency to decrease multipactor phenomenon is not yet proven, on the other hand, a coating on the finished brazed assembly seems to be difficult.

Copper plating

Different processes are proposed for electroplating, depending on each industrial know-how (Fig. 7):

- DC current
- variable pulsed current
- pulsed current with reverse polarity

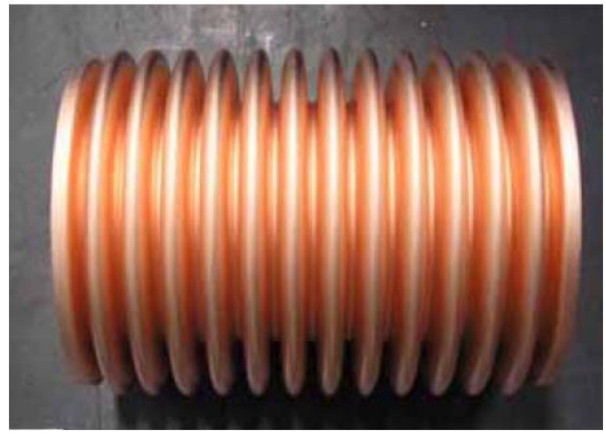

Figure 7: Copper coated bellow for the inner coax conductor.

Different bath types are investigated:

- alkaline cyanide bath: 0.2M CuCN + 0.5M KCN
- acid sulphate bath: 0.1M $CuSO_4$ + 1M H_2SO_4
- pyrophosphate bath: $Cu_2P_2O_7 + K_4P_2O_7$

Samples of different geometries were Cu coated and several tests made for process qualification:

- adhesion test by thermal shock
- fine cuts for micrographic analysis to control coating thickness of bellows (top, flank, valley)
- Electrical resistivity measurements and RRR calculation
- Outgassing spectrum for coated parts

TiN coating

Two different processes are proposed:

a. Vacuum evaporation techniques:
   - Deposit of Ti, then transformation into TiN by introduction of NH_3 gas which is more reactive than N_2 [5], but requires careful safety process and equipment. This method was used for the production of the last 60 couplers.
   - Direct deposit of TiN by evaporation of Ti in N_2 atmosphere: first tests show a fast TiN build-up on Ti wires which stops the coating process. The deposited layer is limited to 15 Å, its efficiency on multipactor reduction is under investigation.

b. Sputtering process under N_2+Ar pressure: first tests results are promising.

Validation samples and tests:

Manufacturing techniques:

- tube pull out for e- pickup and pumping ports
- deep drawing for conical part

TIG welding: Validate TIG welds from outside:

- stainless to stainless
- Cu to Cu
- stainless to Cu

Vacuum brazing:

- He leak test < 10^{-10} Pa.m^3/s
- pull tests on brazed window: OK if σ_m > 100 MPa

Copper coating:

- thickness uniformity measurements on bellows
- RRR measurements
- adhesion test (thermal shock, ultrasonic bath)

Ceramic:

- ε_R and tanδ measurements on ceramic material
- TiN coating:
  layer thickness and stoichiometry by RBS:
  5.10^{16} at/cm^2 is equivalent to 10 nm

Key points & Project Reviews

In March 2006 three contracts were awarded to the following manufacturers: ACCEL, e2v and TOSHIBA. Since then, an extensive follow-up has been going on through regular progress meetings and several exhaustive project reviews at the industrial sites.

The main project key points are:

Kick-off meetings just after contract award

System Design Review (2006):

- functional analysis
- make sure requirements are well understood
- assign the right amount of resources

Preliminary Design Review (1^{st} half of 2007):

- demonstrate that the proposed design is adequate
- feasibility of the manufacturing processes
- explain how the mass production will be organized
- deliver joining samples, machining samples

Critical Design Review (2^{nd} half of 2007):

- freeze the final design, deliver detailed drawings
- define assembly in clean room: means, organization
- risks analysis table
- validation samples of Cu plating and TiN coating

Final Review (1^{st} half of 2008):

- deliver 2 prototypes with control data
- volume manufacturing plan
- costs estimate for XFEL couplers

PRODUCTION OF XFEL COUPLERS

Public procurement procedure

For reasons of safety of procurement, 2 contracts of 400 couplers will be awarded to industry at the end of 2008:

- A call for tenders for production of XFEL couplers will be initiated by CNRS (LAL-IN2P3) in the middle of 2008, based on functional specifications.
- A negotiation procedure will be used, allowing discussing both the technical contents and the prices [11].
- At the end, tenders will be evaluated by a set of criteria including:
  a. Technical content and justifications
  b. Production schedule
  c. Price table
  d. Risks analysis: technical & financial
  e. Technical audit of candidates:
     - Expertise in the domain,
     - Previous experience with couplers,
     - Manpower and equipment,
     - Logistics
     - QA audit versus ISO 9001:2000.

The following main phases in the couplers production are defined:

- On the two industrial locations:
  1. Manufacturing
  2. Clean room operations
- On a single conditioning station location:
  3. 1.3 GHz tuning
  4. RF conditioning
- On the cryomodules assembly location:
  5. Acceptance tests
  6. Dismount cold & warm parts
  7. Return test stand, test cavity + attachments
  8. Store coupler parts in N2
  9. Assemble on module

Assembly

Assembly, baking and test station planned for 200 couplers per year at each industry location is presented in Fig.8. Main tasks are:

- wash, rinse, and store for drying: 2 technicians,
- assembly on test stand and leak test: 2 technicians,
- in-situ baking after assembly while pumping (2 or 3 pairs together).

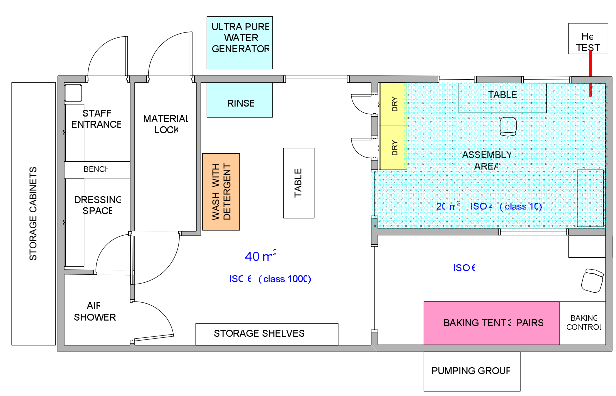

Figure 8: Clean room for assembly and baking for 200 couplers / year.

RF conditioning

To optimize the costs of infrastructure, a single location for conditioning is envisaged, where 2 RF power lines will be installed, each being dedicated to one industry and operated under his own responsibility. There the tasks will be:

- Final assembly of waveguide interface
- 1.3 GHz tuning
- RF conditioning by pairs: 2 or 3 pairs / week for each RF line using the standard procedure defined by LAL [12]

By respecting precise and mandatory procedures for cleaning and assembly, the total duration for conditioning and tests is about 40 h per coupler pair when everything is normal. For the mass production, it is necessary to set a duration limit, a conditioning time between 2 and 3 days for which, if the coupler pair cannot be conditioned satisfactorily during this time, this pair should be set aside for subsequent dismounting and analysis. The production rate should go on without interruption.

Acceptance tests

The industry will be responsible up to the delivery of the couplers to the cryomodule assembly station. There, some acceptance tests will be performed:

- Visual inspection
- Analysis of the shock data recorded during transport
- Leak test
- Analysis of the data recorded during conditioning:
  - Vacuum levels and variations
  - Electronic activity records from e^- pickups
  - Interlock events
  - RGA records (see Fig. 9)

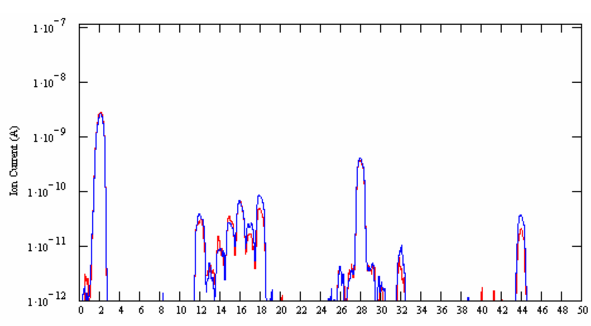

Fig. 9: Typical spectrum recorded by RGA on a pair of couplers after conditioning

CONCLUSION

The method of industrialization studies is a necessary and useful step towards the mass production of input couplers. Action plans, anticipation and organization will ensure fabrication, assembly and tests with minimum risks and at an optimized cost.

LAL will perform extensive process control and close monitoring of the mass production through recorded data and indicators, in view to guarantee that the 800 input couplers for XFEL show a constant quality with full traceability, reliable components and replaceable assemblies.

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