Industrialization Process for XFEL Power Couplers and Volume Manufacturing

SRF 2007 at Beijing, October 2007
Serge Prat / LAL – Orsay

presented by W.-D. Moeller / DESY - Hamburg
Scope of delivery

Manufacturing parts and sub-assemblies

In ISO 6 and ISO 4 clean room:
- Cleaning
- Pre-assembly
- Vacuum oven outgassing
- Final assembly on test stand

Final assembly
- Vacuum pumping
- In situ baking
- Connect to RF power

800 couplers are needed for XFEL

Deliver 2 by 2

RF conditioning
- Dismount
- Pack
- Transport

800 couplers are needed for XFEL
Expertise required from industry

- EB welding
- TiN coating th. ~ 10nm
- Vacuum brazing
- Surface finish and cleanliness

Precise geometrical tolerances

- Motorized tuning
- TIG welding
- Cu plating: $10 < \text{RRR} < 100$
- Special austenitic stainless steel

Motorized tuning

- EN 1.4435
- EN 1.4429

Surface finish and cleanliness

- He leak rate $< 10^{-10}$ Pa.m$^3$/s
- Careful Handling with gloves
- Assembly in clean room
- RF Conditioning
Industrialization studies: Why?

Start with: Prototypes (40 Couplers)

End objective: Large series
- XFEL: 800 Couplers
- ILC: 16 000 Couplers

Quality: - uneven
- NC, several anomalies

Manufacturing: - long and difficult
- lack of procedure
- only a few people have the competence

High cost

Quality: - equal for all items
- reliable

Manufacturing: - regular process
- written procedures
- standard competence

Lower cost: - 60% cost decrease

Industrialization process
Functional specifications

- Functional analysis
- Design for manufacturability
- Risks analysis & mitigation
- Lean manufacturing methods
- Validation models & tests
- Industry know-how + ISO 9001:2000

Industrialization studies: Working process

Engineering Design, Reliable processes, Production Plan, Precise costs estimate

Manufacture 2 prototypes
Stainless steels quality is essential

**Delong model:**
Equivalent Chrome: \( (Cr)_{eq} = (\%Cr) + 1.5(\%Si) + (\%Mo) + 0.5(\%Nb) \)
Equivalent Nickel: \( (Ni)_{eq} = (\%Ni) + 0.5(\%Mn) + 30(\%C) + 30(\%N) \)

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Chemical Composition</th>
<th>Characteristics</th>
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</thead>
<tbody>
<tr>
<td>EN 1.4404</td>
<td>X2 Cr Ni Mo 17-12-2</td>
<td>Ferrite number ~ 2, Easy to procure</td>
</tr>
<tr>
<td>EN 1.4435</td>
<td>X2 Cr Ni Mo 18-14-3</td>
<td>Ferrite number ~ 0, ( \mu_r &lt; 1.01 ), Less easy to procure</td>
</tr>
<tr>
<td>EN 1.4429</td>
<td>X2 Cr Ni Mo 17-13-3</td>
<td>CF flanges, Cavity flange</td>
</tr>
</tbody>
</table>

Standards have a wide range:
- CF Flanges
- Cavity Flanges
- EN 10088
- Hardness 150 / 190 HB
- Refined by electroslag process
- Forged in bars
- Stands baking 2h at 950° C
- Difficult to procure

Verify the real chemical composition!
Copper for couplers

Cu-OFE: UNS C10100
« Electrolytic copper with high conductivity and 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 \geq 100
• chemical composition:
  • Cu > 99.99%
  • O2 < 5 ppm
  • S < 18 ppm
  • Se < 10 ppm
  • Te < 10 ppm
  • Pb < 10 ppm
  • Bi < 10 ppm
  • P < 3 ppm
  • others < 40 ppm

Ceramic for windows

Cylindrical windows made of Al₂O₃ (97.6%):

2 qualified vendors:
- SCT (F - Tarbes)
- WESGO (D - Erlangen)

Highly controlled process:
- high purity powder
- isostatic pressing
- "green" machining
- high temperature sintering
- fine grinding
- grinding of grooves
- metallisation Mo-Mn

Measurements done at LAL:

13 GHz resonator
# Materials resistant to ionising radiations

Dose specification for XFEL lifetime (15 years): \( 1 \text{ MGy} \) (Absorbed energy = \( 10^6 \text{ J/kg} \))

Effects of radiations on matter:
- ionisation of atoms
- break of atomic bonds
- creation of free radicals
- organic materials are the most sensitive

Degradation of properties

Selection of organic material which are reasonably resistant

<table>
<thead>
<tr>
<th>Material Details</th>
<th>Uses</th>
</tr>
</thead>
</table>
| PPS (Poly Phenilene Sulfide) | → Isolating body in electrical connectors  
→ microswitch case |
| Polyester reinforced with glass fibre | → actuator parts |
| Composites glass fibre - 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  
→ insulating film for capacitor  
→ cables insulation |
| PI (Poly-Imide) ex. Kapton | → actuator  
→ cables insulation  
→ thread locker |
| 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 industrial studies

- **Functional analysis**
  - Small thermal emissivity coefficient → Polish the antenna (gain in radiative thermal power)
  - 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 radiation resistant materials
  - Floating big flanges must be supported

- **Design for manufacturability**
  - Choose deformation techniques instead of machining: *deep drawing, spinning, pull-out*
  - Optimize the process for vacuum brazing by use of special tooling: *adapt tolerances & thermal expansion*

- **Lean manufacturing**
  - Industrial design for the capacitor
  - Use chain clamp instead of screws for assembly:
    - Decrease number of parts and junctions:
      - 6 Parts → 4 parts
      - 5 Junctions → 2 junctions
Proposal 1
• Joining done as for TTF3 couplers baseline:
  ➢ Stainless steel parts: TIG welds
  ➢ Cu to stainless, Cu to ceramics: vacuum brazing
  ➢ Final joints by EB-weld

Proposal 2
• Final assembly by TIG welding:
  ➢ Stainless steel parts: TIG welds
  ➢ Cu to stainless, Cu to ceramics: vacuum brazing
  ➢ Final joints by TIG weld

Proposal 3
• All metallic joints are brazed under vacuum:
  ➢ Brazing to bellows → annealing: fatigue test on bellows to validate
  ➢ Cu to ceramics: vacuum brazing
  ➢ Final joints by brazing → problem of Ti diffusion into ceramic
Cu coating

- Different processes are proposed for electroplating:
  - DC current
  - variable pulsed current
  - pulsed current with reverse polarity

- Different bath types are investigated:
  - alcaline cyanide bath: 0.2M CuCN + 0.5M KCN
  - acid sulfate bath: 0.1M CuSO$_4$ + 1M H$_2$SO$_4$
  - pyrophosphate bath: Cu$_2$P$_2$O$_7$ + K$_4$P$_2$O$_7$

- samples received by LAL to measure RRR
  Before baking: RRR = 22
  After baking 2h at 400°C: RRR = 63
2 different processes are proposed:

- **vacuum evaporation techniques**
  - direct deposit of TiN: evaporation of Ti in N2 atmosphere
  - 1st tests show a fast TiN buildup on Ti wires → deposited layer limited to 15 Å,
  - effect on multipactor under investigation

- or deposit of Ti, then transformation into TiN by introduction of NH3 gas
  - NH3 is more reactive than N2, but requires careful safety process and equipment

- **sputtering process** under N2+Ar pressure
  - 1st tests results are promising
Manufacturing techniques:
- tube pull out for e- pickup and pumping ports
- deep drawing for conical part

TIG welding: Validate TIG welds from outside:
- stainless - stainless
- Cu - Cu
- stainless - Cu

Vacuum brazing:
- He leak test < 10^-10 Pa m³/s
- pull tests on window assembly

Cu coating:
- adhesion test (thermal shock)
- thickness uniformity measurements on bellows: T, S, V
- RRR measurements

TiN coating:
- layer thickness and stoichiometry: (RBS): 5 \times 10^{16} \text{ at/cm}^2 \sim 10 \text{ nm}
- \varepsilon_R and tan\delta measurements on ceramic

Validation samples and tests

OK if \[ \sigma_m > 100 \text{ MPa} \]
Some work results

Warm window sample

Sliding support
Keypoints & Project Reviews for industrial studies

Award of 3 contracts in March 06: ACCEL, e2v, TOSHIBA

Kickoff meetings

System Design Review:
- functional analysis
- make sure requirements are well understood
- set the right amount of resources

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

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

2 full days for each review at each contractor
Objective:

SMART COUPLER FACTORY

- Plan, Anticipate, Organize
- Process control & Monitoring
- Fabrication, Assembly, tests
- 800 Couplers

- Certified materials
- Industrial processes
- Written procedures
- Standard competences
- but Qualified operators
- Adequate means size
- Optimized costs

- Traceability
- Constant Quality
- Reliability
- Replaceability
Example of test station at LAL, sized for 50 couplers /year:

- clean room with 2 zones:
  - class 1000: wash and rinse
  - classe 10: dry, bake, assemble
- Klystron 5 MW and modulator

Baking each element 150°C (20h) before assembly → long process
+ in-situ baking just before conditioning
Assembly, test & conditioning station for 400 couplers / year:

- wash, rinse, store: 2 technicians
- assembly on test stand: 2 technicians
- in-situ baking after assembly while pumping (4 or 5 pairs together): \[ \rightarrow \text{gain of time} \]
- RF conditioning by pairs: 2 or 3 pairs / week for each RF line
RF conditioning

Total duration for conditioning + tests → 40h / pair if OK
Main phases of couplers production

Manufacturing

Ind 1

Clean rooms operations

Ind 1

 Conditioning station

Ind 2

Single location with 2 RF lines

- Acceptance tests
- Dismount
- Return packing + supports
- Store coupler parts in N2
- Assemble on modules

Cryomodules assembly

To reduce transports: single location is better

Assuming 2 industrial contracts

- 1.3 GHz tuning
- RF conditioning

Ind 2
Phase 2: Manufacturing of parts and sub-assemblies

- Check project organization at industry
- Verify manufacturing drawings
- Control procurements: raw material, subcontractors
- Check manufacturing plan
- Check joining processes (welding, brazing)

At Industry

- Control manufacturing process:
  - Witness points, Hold points
- Collect data
- Project reviews
- Quality parameters control
- Schedule control
- Documents control
- Collect data and watch drift
- Invoices control
- Report to XFEL project group

Phase 3: Cu + TiN coating and final joining

- RRR measurements on samples
- Test final joining on samples

At LAL

- Control Cu coating process parameters
- Control final joining process: H points
- Collect data
Evaluation of tenders will include:

- Technical content and justifications
- Production schedule
- Price table
- Risks analysis: technical & financial
- Technical audit of candidates:
  - Expertise in the domain
  - Previous experience with couplers
  - Manpower and equipment
  - Logistics
  - QA audit wrt ISO 9001:2000

Call for tenders for production of XFEL couplers will be initiated mid 2008, based on functional specifications.

Negociation procedure: both on technical content and on price.
Schedule of « Production of Power couplers for XFEL »

<table>
<thead>
<tr>
<th>Nom de la tâche</th>
<th>Début</th>
<th>Fin</th>
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<tr>
<td>Aware of manufacturing contracts</td>
<td>10/1/2007</td>
<td>10/12/2008</td>
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<td>XFEL couplers manufacturing phase</td>
<td>05/01/09</td>
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<td>06/02/09</td>
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<td>Material procurement and part production</td>
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<td>10/12/09</td>
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<td>Manufacturing of sub-assemblies</td>
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<td>Joining control by LAL Inspector</td>
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<td>Cu coating and final weld</td>
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<td>17/12/10</td>
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<tr>
<td>2 series of 20 couplers</td>
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<td>Cleaning, Assembly &amp; Baking</td>
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<td>Assembly control by LAL</td>
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<td>Conditioning, shipping and delivery</td>
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<td>Acceptance tests + Storage</td>
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<td>30/09/11</td>
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