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  o Removable Vacuum Transmission Line (RVTL) design;
  o critical RVTL technologies/know-how;
  o RF vacuum window design.

• Overall R&D strategy:
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  o planned work.

• Technical expertise and capabilities.

• Resources, tools and processes.

• Questions.
Introduction to the ICRH antenna

Ion Cyclotron Resonant Heating (ICRH) and Current Drive (H&CD)

- This system is required to provide ion cyclotron heating (20MW) and current drive into the plasma.

- The antenna will also be used for wall conditioning between pulses.

- The IC power shall be coupled to the plasma through two antennas in two equatorials ports (EU procurement).

- The IC system shall be capable of operating at any frequency in the range of 40-55 MHz.

- The pulse length will be up to 3600s with a duty cycle of 25%.
ICRH antenna – scope of work

- The antenna is in the final design phase.
- IO and F4E work together for design and procurement.
- IO is responsible for the design and F4E carries out most of the design and prototype fabrication/qualification under Task Agreement with IO.
- The antenna design includes Protection Important Components (safety-relevant).
- Scope of F4E procurement:
  - *the port plug mechanical structure and shielding elements;*
  - *the straps and four port junction;*
  - *the Removable Vacuum Transmission Lines (RVTL), each containing two RF vacuum windows (=> 16 windows per antenna;)*
  - *the Faraday Screen (FS), that is the plasma facing component of the antenna;*
  - *a grounding system and diagnostic system;*
  - *RH tooling (special tooling).*
Assessment/qualification of manufacturing techniques.

**Manufacturing prototype**: machining, welding and coating techniques, brazing of 1:1 scale curved ceramics, process reliability, testing (dimensional, vacuum pressure, mechanical).

**Functional prototype**: 1:1 real geometry and functional tests to prove the design.

**EACH STEP AIMED AT DECREASING RISK (AND COST) OF NEXT STEP/S**
• The visits to potential suppliers are part of the finalisation of the procurement strategy for the window prototypes and for the series production.

• Contract procedure for prototypes will include:
  o competition;
  o Technical negotiation.

• Within the EU procurements rules we are ideally looking for continuity of supplier from the manufacturing prototype to the series production. However, F4E reserves to make this judgement based on technical and budget considerations.

The purpose is to identify suitable companies for the manufacture of the ICRH RF vacuum windows.
ICRH antenna – overview, parts description

Antenna port plug, 43 t

3.5 m

Transition frame, 5 t

1.6 m

2 m

Straps housing & Faraday screen

4 port junction & straps

RVTL

Port plug bulkhead

05 July 2017 – ICRH antenna
• Mixed Titanium/SS construction, with Cu coating on RF surfaces.
• Active water cooling.
• 2x double-conical window assemblies, vacuum brazed alumina-to-Titanium.
• One folded service stub.
• RF contacts on both inner and outer conductors.
• Titanium manufacturing techniques:
  o various grades and thicknesses;
  o machining;
  o welding (TIG, diffusion bonding);
  o cleanliness.
• 316L(N) manufacturing techniques.
• Bi-metallic welding Ti-SS (rotary friction welding/diffusion bonding).
• Manufacture of ceramic windows of “large” dimensions and complex shapes.
• Vacuum brazing:
  o ceramic-to-metal;
  o metal-to-metal.
• Copper coating on Ti and SS substrates (e.g. cold spraying).
• Manufacture of UHV components.
• Vacuum feedthroughs.
• Procurement of often exotic materials.
• Quality Class 1 processes according to F4E QA-115 and supporting documents.
• Safety-oriented approach, in particular in the presence of Protection Important Activities and Components (PIA/PIC).
Functions of the RF vacuum window:

1. vacuum and tritium barrier – first confinement barrier, SIC1 classification;
2. RF function – transmit power, comply with requirements;
3. structural function – locate in space the inner conductor wrt the outer conductor, transmit loads to the outer conductor coming through the inner conductor from the antenna front.
RF vacuum window – design (1)
• Similar to the JET ITER-Like-Antenna (ILA).

• Alumina with low loss tangent (exact grade not definitively established).

• Titanium shell due to similarity in thermal expansion coefficient (currently Gr.5).

• Vacuum brazed (currently Ticusil).

• Double-conical alumina assembly and Titanium shell combined in a single vacuum brazing operation, pre-compressing the alumina.

• Window shape optimised to resist compressive stresses.

• Cu-coating of RF surfaces (currently low O₂ electronic copper deposited by cold spraying).
Window unit to withstand:
- axial and radial loads;
- loads due to cantilever effects of the inner conductor;
- torque about the inner conductor axis.

Window cooled passively through braze and Titanium interface via a circular water channel embedded in the Titanium structure.

Outer window (away from plasma) being exposed to negligible neutron flux.

Inner window (close to plasma) being exposed to significant neutron flux, resulting in loss tangent considerations.

Theoretical life expectancy ≥ 5 years.
Overall R&D strategy – current work

- Development of Cu-coating procedures by cold-spray technology:
  - of Titanium Gr.2 - completed;
  - of Titanium Gr.5 - ongoing.

- Rotary friction welding of Titanium Gr.5 to 316L(N) through an interlayer of pure Zirconium, Vanadium or Niobium, the first being the current candidate - ongoing.

- Uniaxial diffusion bonding of Titanium Gr.5 to 316L(N) through a pure silver or a Nb-Cu-Ni triple interlayer - recently started.

- Development of EB and TIG welding of 316L(N) plugs in butt-configuration for sealing of deep-drilled water channels - ongoing.

- Assessment on radiolysis Hydrogen uptake from the cooling water, migration within the RVTL, accumulation in the Titanium and weld interfaces, and release into the vacuum during baking - ongoing.
Overall R&D strategy – planned work

• Development of Cu-coating procedures by cold-spray technology:
  o of 316L(N);
  o of the RFW or UFB weld area, including the interlayer material.

• Window prototyping:
  o small scale technology demonstrator to prove the concept of Titanium-316L(N) welding, Cu-coating, metal-alumina brazing, etc.;
  o 1:1 scale manufacturing prototype with a level of part detail to be decided;
  o 1:1 scale functional prototype with full part detail, water cooling, RF testing, proof/destructive testing TBD.
## Technical expertise and capabilities

### Procurement
- metallic materials (316L(N), Ti and Cu alloys, Inconel, Zircadyne and other “exotic” alloys, etc.);
- components (standard pipes and bolts of certified material, cabling, sensors, etc.);
- alumina.

### Manufacturing
- precision machining of both small and large components;
- deep drilling;
- tubes bending;
- clean manufacturing conditions.

### Joining & Inspection
- TIG welding, RFW, diffusion bonding, vacuum brazing, etc.
- NDT (visual, x-ray, UT, dye pen, etc.).

### Design and reporting
- Catia 3D modelling;
- design adaptation for manufacturing;
- production of manufacturing and as-built drawings;
- manufacturing reports.

### Codes and Standards
- ASME, RCC-MR;
- ISO, ASTM, etc.;
- national and regulatory (e.g. PED).

### Manufacturing
- precision machining of both small and large components;
- deep drilling;
- tubes bending;
- clean manufacturing conditions.

### Metrology
- positioning, dimensional, alignment, etc.
- tolerance analysis for manufacture and assembly.

### Acceptance testing
- leak testing, pressure testing, flow testing, hardness, metallography, etc.
- structural integrity testing.
Resources

- team size, expertise, etc.;
- management of subcontractors;
- access to external experts;
- design office.

Plant & Tools

- production capacity;
- Machinery;
- tools, cranes, jigs & fixtures;
- clean areas, storage, etc.;
- software, etc.

QA & Processes

- traceability of documents, records, data, WPS, etc.;
- control plan;
- defined internal processes;
- internal and external audits;
- control of non-conformities and corrective/preventive actions.
Questions

1. Experience in manufacturing RF vacuum windows:
   - duration;
   - number of parts;
   - reliability of the alumina-to-metal brazing process.

2. What kind of testing was carried out? What kind of testing would the company be able to provide in future contracts?

3. Is the complete manufacturing of the RF vacuum windows carried out in-house, or are subcontractors involved?

4. Is there sufficient capacity to deal with the manufacture of 36 window units (2 antennas)?

5. Technical office 3D design and modelling capabilities.

6. Production department capacity and assets (e.g. machining, welding and inspection equipment).

7. Experience and ability in working with EU regulation, construction codes (nuclear and not) and standards for design, manufacture, inspection, assembly, testing, etc.

8. QA procedures and operator qualifications for activities such as welding and inspection.

9. Experience in requirement management and verification.

10. Procurement of the required materials accompanied by thorough EN 10204 type 3.1 certificates.

11. Experience in close collaboration with external laboratories and universities.

12. Would the company be capable/interested in manufacturing the whole RVTL?