ITER bolometer-sensor prototype manufacturing

Introduction, background and context

Outline
- Introduction
- ITER diagnostics and bolometer diagnostic
- Environmental constraints
- Characteristics of bolometer sensor
- Past experience
- Context, timescale and future
- Conclusions
Aim of today’s information session:

- **Present the forthcoming call for tender** (tendering procedure and contractual conditions)
- **Present the technical scope** (Technical and Management Specifications)
  
  note that these are still evolving and some details may change
- **Explain constraints and some choices made by F4E** (details of the technical note)

Information received/published during the plenary session and face-to-face meetings:

- F4E may make use of the feedback received during plenary discussions and face-to-face meetings to adapt technical specifications in order to maximize competition and avoid overspecification of requirements
- Any new information given to participants will be published on the F4E Industry Portal to ensure equal treatment

Face-to-face meetings

- company-specific matters not suitable for plenary sessions
Diagnostics measure plasma and first-wall parameters for:

- Machine protection (e.g. first-wall temperature)
- Basic and advanced control (feedback loops) (e.g. magnetic equilibrium)
- Physics analysis and understanding

ITER will have ~50 diagnostic systems to measure a wide range of parameters.

Diagnostics typically have components located inside the vacuum vessel (e.g. some sensors, mirrors, waveguide-antennas) and components outside (transmission lines, detectors, electronics).
Bolometers measure total radiation in the wavelength range x-rays-IR main power is in VUV.

- Many line-integral measurements (>300 foreseen on ITER plus redundancy) needed to be able to make tomographic reconstructions (figure→; lines of sight still being optimized)
- 5-channel bolometer cameras (picture of early concept), for example with collimators (green block) to define the viewing cones and directions of each line of sight. Bolometer sensor is mounted in blue part, in good thermal contact with cooling.
Bolometer diagnostic (2/2)

Plasma parameters measured:
- **Total radiated power** of plasma (radiated fraction) used for machine protection. Target accuracy: 10%.
- 2D radiation profiles in bulk plasma and divertor for advanced control and physics studies. Derived from line-integral measurements by computerized tomography techniques. Target accuracy: 20%
- Required **time resolution**: 1 ms. For some phenomena 0.1 ms would be preferred if achievable.

To achieve these derived quantities within the target accuracy, **very low signal-to-noise line-integral measurements needed** → high demands on the bolometer sensors (sensitivity & signal-to-noise ratio).

The **time resolution is also a challenge** with the planned technology.

Robustness and high reliability are also essential (cannot assume that sensors can be replaced).
Environmental constraints (1/2)

Vacuum in nuclear environment

- Generally no organic materials
- Avoid highly activating materials. Most other may be accepted in small quantities
- Purity and traceability of materials is important

Loads

- Electromagnetic forces, pressure, vibrations, accelerations, steam → are thought to be under control → will be tested outside the contract of this CfT
- Electromagnetic radiation
- Nuclear radiation
  - Damage (see next slide)
  - Over ITER lifetime <0.4 dpa in typical ceramic (displacements per atom)
  - Volume heating
- Temperature transients, and high operating and baking temperatures (up to 350°C), repeated cycles
Environmental constraints (2/2)

Effects of nuclear radiation:

- Embrittlement, material strength
- Changes in electrical properties (e.g. insulators becoming conducting)
- Adhesion of layers may be affected
- Transmutation
  - Au
    - Large cross-section
    - Over ITER lifetime, 10% of Au in bolometer location will transmute to Hg
    - Au/Hg is relatively stable up to 10%. For absorber not many issues
    - For resistors, in particular temperature coefficient of Resistance (TCR) will be sensitive to even small changes in composition
  - Pt
    - Low cross-section. Transmutation largely to stable Pt isotopes.
    - Pt highly preferred from transmutation point of view.

Considerations to prefer Au and Pt over, e.g., Cu or Al:
- Higher melting temperature → more certainty about stability of thin layers
- Less environmental effects (oxidation, steam exposure)
- Pt very linear Temperature Coefficient of Resistance.
Characteristics of bolometer sensor (1/4)

Self-supporting foil

- Foil with holder
- Plasma radiation from above
  1: resistor ‘meander’
  2: absorber layer
  3: heat conduction layer
  4: substrate foil
  5: viewing aperture
  6: front plate (heat sink) (~3 mm thick)
  7: thermal contact layer
  8: metal track for electrical connection between meander and macroscopic electrical connection pads
  9: back plate (~3 mm thick)

Supported membrane

- Shown without holder
- Plasma radiation from below
  1: resistor ‘meander’
  2: metal track for electrical connection between meander and macroscopic electrical connection pads
  3: substrate membrane
  4: a support structure for membrane
  5: absorber layer

Characteristics of bolometer sensor (2/4)

4-channel **substrate lay-out** seen from the resistor side (absorbers not visible). Size ~20×30 mm².

Black rectangle: one channel. Each red area contains two resistor ‘meanders’ (see figure at left). Meanders are connected to contact pads through thicker tracks (blue). This example has support for membrane. Cut-out shows the support structure on the rear, surrounding the absorber.

**Wheatstone-bridge** schematic for one channel. Grey area indicates the two resistors corresponding to the red area in left figure.

One of the two absorbers of one channel is ‘blind,’ i.e. a **reference absorber** that does not receive plasma light. Both reference and signal absorbers receive similar amounts of nuclear radiation, the effect of which is subtracted in the Wheatstone bridge. The Wheatstone bridge is typically exited by a 20 V\_p-p 10–15 kHz AC voltage.

Rectangle ~1.5×4 mm²

Schematic of **resistor meanders**: two resistor tracks (red and blue) behind absorber (black rectangle). Pt tracks are typically 30 μm wide and with 30 μm spacing between tracks.

**Bridge imbalance** leads to drifts. Within one channel target variation of resistors is <1%. Note: laser-trimming features can reduce further. **TCR** needs to be controlled.
In the simplest case, the bolometer response is described by:

\[ P(t) = C \left( \frac{d\Delta U}{dt} + \frac{\Delta U}{\tau} \right), \]

where

- \( P(t) \): incident power;
- \( \Delta U \): measured voltage;
- \( C \): calibration factor (sensitivity);
- \( \tau \): time constant (heat transfer from absorber to heat sink).

**Ideal substrate material should have:**
- low Young’s modulus (i.e. be ductile to spread out the tension)
- high tensile strength for robustness
- moderate heat conduction (too low better: can be enhanced by thin metal layers; too high: low sensitivity at low frequencies).

**Most candidate materials for supported membranes seem similarly brittle**
\( \rightarrow \) **too little difference to solve issues** \( \rightarrow \) 1.5–5 \( \mu \)m silicon-nitride

**Self-supporting: 20-\( \mu \)m thick mica good compromise**

Heat transfer through substrate from absorber to resistor meander only affects bolometer equation at very high frequencies.
Absorber needs to absorb as much radiation as possible in the range IR to soft x-rays.

Metals with high atomic mass needed

Absorber thickness ideally >15 μm

- Au&Pt can be made by electroplating
- W has also been tried

Observations:
- Absorber thickness is key difficulty (see coming slides) → need to arrive at thickest achievable within current contract → what is deliverable?
- Vacuum-compatible blackening to achieve reasonable absorption in visible wavelengths
**Past experience (1/4)**

**First developed for ASDEX** and successfully applied on this and other fusion experiments: 7.5-μm thick Kapton® polyimide film (self-supporting) with Au absorber and resistors. Typical absorber thickness: 4 μm.


**High-temperature version (JET):** 20-μm mica film (self-supporting) and 7-μm Au absorber and Au resistors. Successfully operated at 320°C for years.


- JET bolometer irradiation tested in fission reactor up to 0.1 dpa with encouraging results (**significant transmutation of Au; 10% in ITER**)


TCR of **resistors** affected by transmutation. Au very thin. TCR of Pt linear

→ **Pt resistors preferred**

- Absorber of 7 μm too thin for ITER.
- Resistor values of 200–400 Ω too low (gold too thick to avoid failure)
- Supply chain no longer available.
- Slower than required (while maintaining sensitivity)
Silicon-nitride supported membrane with Pt absorber and resistor

- Typically 1.5–3 μm silicon nitride membrane on 0.5-mm Si support
- Potentially more radiation hard than mica-gold
- Higher sensitivity → also attractive for all fusion experiments
- Low-temperature version successfully developed and in routine use on several fusion experiments.

Manufactured by Institut für Mikrotechnik Mainz GmbH (IMM), now Fraunhofer Institute for Chemical Technology ICT, Branch ICT-IMM.

The thick Pt absorber has proved very challenging:
- Optimization for deposition with minimum stresses between absorber and substrate
- Membrane ruptures in thermal cycling to ~400°C. Problem: different thermal expansion coefficients of absorber and membrane. Measures such as shaping (e.g. rounded corners) help, but have proven not to be sufficient.
This past experience suggests the following strategy:

- **Re-establish a supply chain for mica bolometers sensors:**
  - This would be the fall-back solution that almost meets the ITER requirements.
  - Robustness (thermal cycling to ~400°C has been successful in the past).
  - **Thicker Au absorber** needed than demonstrated until now → could lead to stress problems not experienced with thinner absorber.
  - **Larger resistance values** → change from Au to Pt.
  - Supply of good quality mica → typically < Ø125 mm.

- **In parallel,** establish **silicon-nitride** as suitable bolometer-sensors
  - **Au absorber** instead of Pt (softer, less stresses).
  - Demonstrate robustness to thermal cycling.

- **Key other aspects** that are the same for both:
  - **Reliable electrical contacts** to be demonstrated: bonding of wires (spring contacts not reliable in environment and with thermal cycling).
  - **Small bridge imbalance** → processing to achieve small variation in resistance values; introduction of features for laser trimming.
  - **Blackening** by vacuum-compatible method to achieve a robust black layer; not by spray-coating with carbon.

Past experience (4/4)

Other aspects → outside of this Call for Tender
- Optimization of bolometer-sensor measuring characteristics
  - Done as much as possible for the Technical Specifications of this CfT
  - Following result of prototypes and testing, one more opportunity
- Bolometer sensor characterization:
  - Calibration ($C$, $\tau$, response curve)
- Irradiation testing
- Conventional testing foreseen:
  - Pressure test, accelerations, vibrations
  - Steam exposure
  - Destructive heat cycling

Alternative substrates → outside of this Call for Tender
- Diamond, with heat-conduction bars
- Thin glass
- ...

Development of alternatives would probably take more time than available for knowing achievability → not included in this Call for Tender

Bolometer-performance optimization (including thermal modelling) → not included in this Call for Tender
F4E has concluded a Framework Partnership Agreement (FPA) with a consortium consisting of
- Max-Planck-Institut für Plasmaphysik (IPP), Garching, Germany
- Wigner Research Centre for Physics (Wigner RCP), Budapest, Hungary
- Fraunhofer-Gesellschaft, Fraunhofer Institute for Chemical Technology ICT, Branch ICT-IMM, Mainz, Germany
- Centre for Energy Research of Hungarian Academy of Sciences (MTA-EK), Budapest, Hungary

Scope:
- **Design** the ITER bolometer diagnostic
- Carry out *conventional testing on prototype components*, including sensors
- The consortium has also offered to **manufacture prototype bolometer sensors** within the FPA \(\rightarrow\) in parallel with the current CfT

The present Call for Tender is in support of this FPA, to increase the likelihood that adequate prototype bolometer sensors are produced.

Irradiation testing in a fission reactor will be carried out under a different framework (F4E-OFC-358)
Timescale and future (1/2)

Indicative timeline:

• Call for Tender  mid-May 2015
• Tender preparation early July 2015
• Signature of contract(s) mid-Nov. 2015
• Need date for prototype sensors for irradiation testing January 2017
  • Irradiation and conventional testing completed July 2017
  • Specifications of diagnostic agreed with ITER Org. October 2017
  • Detailed design, including final specifications of bolometer sensors (opportunity to adapt following result of prototypes and testing) 2017–2020
• Manufacture of series bolometer sensors 2021–2022
• Manufacture of bolometer diagnostic 2021–2023
• Installation
• First plasma
• Bolometer diagnostic operational
Series manufacture

• Provisions in prototyping contract to avoid unfair competitive advantage that would exclude from bidding for series-manufacturing contract → e.g. foreground declarations, disclosure of all results, access to background under fair and reasonable conditions.
• Series manufacturing contract: ~105 5-channel bolometer ‘heads’ plus some spares
• Subsequently, ITER Organization may need to purchase replacements

Other applications

• Very limited further market is expected – there already is a supply chain for low-temperature versions with good performance, and the market is very small
• DEMO: the currently developed bolometers may not be adequate in terms of energy range, radiation hardness and robustness
Conclusions

- The ITER environmental conditions are very demanding
- **Need to establish a reliable supply chain for bolometer sensors**
- The bolometer types that come closest to having been demonstrated for the ITER environment are mica and silicon-nitride
- **The best likelihood of success by pursuing the bolometer types:**
  - Mica with gold absorber and platinum resistors
  - Silicon-nitride with gold absorber and platinum resistors
- **Pursue in parallel multiple bolometer types with multiple suppliers**
- Alternatives may still be explored briefly within other contract, but such a topic is not suitable as F4E commercial contract