The 2MW gyrotron for ITER

F. Albajar (F4E) for the EU Team

Stefano Alberti, Konstantinos A. Avramides, Patrick Benin, Tullio Bonicelli, Sante Cirant, Caroline Darbos, Montse Felip, Gerd Gantenbein, Timothy P. Goodman, Mark Henderson, Stefan Illy, Zisis Ioannidis, Jean-Philippe Hogge, Jianbo Jin, Stefan Kern, George Latsas, Christophe Lievin, Ioannis Gr. Pagonakis, Bernhard Piosczyk, Anne-Kathrin Preis, Tomasz Rzesnicki, Paul Thomas, Manfred Thumm, Ioannis Tigelis, Minh Quang Tran, John Vomvoridis
Synopsis

- Why is Europe developing the 2MW gyrotron for ITER?
- What are the advantages of the coaxial gyrotron?
- Where are we in the development programme?
- What are the main risks for Europe?
- What are the main risks for ITER?

Conclusions
According to the present understanding of the ITER sharing, EU is responsible for the procurement of 8MW generated RF power at 170GHz:

- 4 power source units (tubes, SCM, auxiliaries) at 2MW or 8 units at 1MW. 

EU is procuring the power supplies feeding the 24MW gyrotrons - this is now being revised: IN DA may be supplying 1/3rd of the EC Power Supply system.

**Scope of EU contribution to 52P3 (1/2)**

In-kind procurement contributions to the ITER 52P3 package - Gyrotrons.

IO defines functional specs, interfaces, shared installation & commissioning.
The EU obligations include manufacturing and factory testing of components, pre-delivery tests, transport, installation and support for the final acceptance.

The EC Power Sources are procured on the basis of functional specifications issued by IO. The development and the detailed design compatible with IO specs is responsibility of the Parties.

The specifications for ITER go beyond capabilities of gyrotrons installed in existing facilities.

A design and R&D programme is needed for the development of the high power (≥1MW), CW operation, 170GHz gyrotron for ITER.
EU is developing the 2MW coaxial cavity gyrotron for ITER

- Coaxial concept relaxes the limits of the more conventional cylindrical waveguides due to mode competition and limiting current
Main design parameters of the 2MW, CW gyrotron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>170 GHz</td>
<td>Velocity ratio</td>
<td>1.3</td>
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<tr>
<td>RF output power</td>
<td>2 MW</td>
<td>Beam radius</td>
<td>10 mm</td>
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<tr>
<td>Magnetic field</td>
<td>6.86 T</td>
<td>Cavity peak losses</td>
<td>1.7 kW/cm²</td>
</tr>
<tr>
<td>Operating mode</td>
<td>TE34,19</td>
<td>Insert peak losses</td>
<td>0.2 kW/cm²</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>-55 kV</td>
<td>Window</td>
<td>CVD diamond</td>
</tr>
<tr>
<td>Body voltage</td>
<td>+35 kV</td>
<td>Collector loading (CW)</td>
<td>2.4 MW</td>
</tr>
<tr>
<td>Beam current</td>
<td>75 A</td>
<td>Collector loading modulation</td>
<td>3.1 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;45%</td>
<td>Single-stage depressed collector</td>
<td></td>
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<tr>
<td>Modulation frequency</td>
<td>5 kHz</td>
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</table>
R&D programme of the EU gyrotron for ITER (1/3)

Organizational structure for the design and R&D programme in EU

IO
Responsible for definition of functional specs - interfaces

F4E
Coordination EU activities – interaction with IO

synergies with the W7-X gyrotron programme

EU Associates
currently organized as ‘EGYC’ Consortium* – responsible for the design of optical & RF components, parallel theoretical & experimental investigations

EU Industry (TED)
THALES
responsible for the technical design of the gyrotron prototypes and integration

contracts & grants to carry out design & R&D

Others … (ESC, SCM, etc)

16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, 12-15 April 2010
2MW Test Facilities in Europe

**Dedicated EC CRPP test facility**
(Lausanne, Switzerland) – CW

- RF Enclosure
- CNR-SPL
- RFCU

...equipped by fully solid-state power supplies, SCM, control, services etc.

**KIT Test Facility**
(Karlsruhe, Germany)

- Short pulse pre-prototype coaxial cavity
- Essential tool for verification of re-designs
- Low power test stand or testing q.o. components

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Conclusions
R&D programme of the EU gyrotron for ITER (3/3)
Results from the industrial 1st gyrotron prototype – 2008

- The basic RF design of the tube was proved the gyrotron operated stably in the desired mode
- All new infrastructures and services of the Test Facility have proved to be operational and robust
- Good agreement between level of output power and the excitation mode sequence and mono/multi-mode wave-beam simulations
- Collector conditioning: 2MW/10s pulse and 2.4MW/2s pulse

- Highest power 1.4 MW (Goal: 2MW)
- Pulse length limited to <100ms at nom. Parameters (Goal: 1s)
Limitation of the operating parameters range to a low efficiency domain suggesting a poor quality of the electron beam at the cavity

- velocity ratio limited to $\alpha \sim 1.0$ (nominal 1.3) due to limited beam energy
- system is very sensitive to reflections
- Recent detailed numerical study with Ardiadne++ and ESRAY shows $\delta \beta_{\text{perp}} \approx 5.5\%$ (1.3\% specs)
- Poor beam quality confirmed by simulations

Limitation of the operating parameters range to a low efficiency domain suggesting a poor quality of the electron beam at the cavity
Limitation of the operating parameters range to a low efficiency domain

Voltage stand-off problems

(1) Different behaviour without magnetic field (excellent-120kV) or with $B_{\text{field}}$ (problems $>60kV$)

(2) Damages observed during opening & inspection of the tube

Suggesting *electron trapping mechanisms*: potential wells and magnetic mirror effect
Depth of the potential wells (Ariadne++)

Trajectories of the electrons trapped in a magnetic mirror
Limitation of the operating parameters range to a low efficiency domain

Voltage stand-off problems

The tube could suffer from various *parasitic oscillations*

**High frequency oscillations in the beam tunnel prior to the desired interaction zone**

- Extensive experimental investigations on the spectra and different kind of beam tunnels *(common issue W7-X 140GHz gyrotron)*
There is good agreement that the main reasons limiting the performance of the 1st gyrotron prototype have been identified.

A very important effort made in 2009 for the improvement of design, internal components, and experimental validation.

The 1st industrial gyrotron prototype presently being refurbished

- CRPP EC Test Facility equipped with a new main HV power supply – level of LF noise is expected to reduce, additional diagnostics, etc.
New electron gun
- Beam quality improved ($\delta \beta_{\text{perp}} < 3\%$)
- $E_{\text{max}}$ significantly reduced
- Free of potential wells
- without trapped electrons

New beam tunnel
- Irregular azimuthal symmetry to suppress high frequency parasitic oscillations

Improved q.o. output system
- Novel method optimizing launcher inner surface
- Gaussian content increased from $\sim 86$ to $\sim 97\%$
- Stray losses reduced

J. Jin, “Improved Design of a q.o. Mode Converter for the Coaxial-Cavity ITER Gyrotron” – Poster II
Refurbishment of the 1\textsuperscript{st} prototype (3/4)

New configuration installed in the short pulse pre-proto gyrotron at KIT

- Stable operation, \( \sim 2.2 \text{ MW at 30 \% efficiency} \) (without SDC)
- Intensity of parasitics strongly reduced
- Remarkable good agreement between experiments and simulations
  - Efficiency and power
  - Range of operation correctly predicted
  - 0 - 100\% power modulating acceleration voltage
Refurbishment of the 1<sup>st</sup> prototype

Calculation

“Hot” measurement

1148 mm after window

- mm-wave beam shows 96% of Gaussian mode content (phase reconstruction)
Why is Europe developing the 2MW gyrotron for ITER?

What are the advantages of the coaxial gyrotron?

Where are we in the development programme?

What are the main risks for Europe?

What are the main risks for ITER?

Conclusions
<table>
<thead>
<tr>
<th>ID</th>
<th>Risk</th>
<th>Level</th>
<th>Mitigation Strategy / Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2MW gyrotron for ITER: higher thermal loads</td>
<td>VERY</td>
<td>1) 3-prototypes strategy&lt;br&gt;2) Involvement of industry and structured collaboration&lt;br&gt;3) Decision points 2MW/1MW as a back-up option</td>
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<tr>
<td></td>
<td>- Resulting in: Reduced technical performances, reliability, lifetime</td>
<td>HIGH</td>
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<td>2</td>
<td>2MW gyrotron for ITER: Relatively late start of the development involving industry</td>
<td>VERY</td>
<td>1) Decision points 2WM/1MW as a back-up option&lt;br&gt;2) Working in 2 shifts during testing and increasing brazing and bake-out supplier capacity during series production&lt;br&gt;3) Anticipate procurement long lead components</td>
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<td>- Resulting in: Schedule not met or reduced technical performances</td>
<td>HIGH</td>
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<td>3</td>
<td>Single supplier of gyrotrons in Europe</td>
<td>HIGH</td>
<td>1) Partnership with industrial supplier and EU collabor.&lt;br&gt;2) Open tender outside Europe / DAs pre-agreements</td>
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<td>- Due to: Specific knowledge and technology</td>
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<td>- Resulting in: Interruption of R&amp;D phase, delays</td>
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<td>4</td>
<td>Series production and long contract duration for gyrotrons and superconducting magnets</td>
<td>HIGH</td>
<td>1) Enforce strong quality assurance and manufacturing control&lt;br&gt;2) Contracts for the industrial follow-up and inspections&lt;br&gt;3) Re-enforce measures for subcontracting management</td>
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<tr>
<td></td>
<td>- Due to: Complex quality control</td>
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<td>- Resulting in: Reduced performances, delays</td>
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<td>5</td>
<td>Demanding technical specs requested by IO</td>
<td>HIGH</td>
<td>1) Conduct urgent R&amp;D and follow several R&amp;D paths&lt;br&gt;2) Agree with IO on reduced requirements for the day-1, enhancements for the 2nd generation gyrotrons for ITER</td>
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<td>- Due to: Specs exceeding state-of-the art, e.g. reliability</td>
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<td>- Resulting in: Specs not met or Cost increase - delays</td>
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<td>6</td>
<td>Complex F4E contractual procedures</td>
<td>HIGH</td>
<td>1) Optimise F4E procedures and instruments for long-term projects&lt;br&gt;2) Organize informative sessions with potential suppliers&lt;br&gt;3) To develop tools to ease project management</td>
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<td>- Due to: Slow processes, R&amp;D based on ‘best-effort’</td>
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<td>- Resulting in: interruption of development, delays</td>
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<td>7</td>
<td>‘He-free’ superconducting magnets for ITER</td>
<td>HIGH</td>
<td>1) ‘He-free’ gyrotron magnet prototype - involvement of industry during the design phase&lt;br&gt;2) conduct independent cost and design reviews</td>
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<td></td>
<td>- Due to: Technology not well established in Europe, impact on design coaxial tube</td>
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Considerations on the decision point between the 2MW/1MW gyrotron (1/4)

The main technical risk on EU procurement is associated to the 2MW gyrotron. The main mitigation measure is the design of a more conventional (1MW) cylindrical cavity gyrotron and the decision between 2MW/1MW.

- The design of the EU 1MW cylindrical cavity gyrotron at 170GHz for ITER was initiated in 2007 and will be complete in 2010.

- Using existing expertise in Europe from the W7-X gyrotron development (1MW, CW at 140 GHz).

G. Gantenbein, “Progress in stable operation of high power gyrotrons” – Poster I

Photograph of a TED-gyrotron installed at IPP for W7-X (courtesy V. Erckmann)
Considerations on the decision point between the 2MW/1MW gyrotron (2/4)

Gyrotron development activities

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<td>2MW refurb.</td>
<td>1MW gyrotron Proto 1</td>
<td>1MW Proto 2</td>
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<td>Decision 2MW/1MW</td>
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<td>Bidding period</td>
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<td>Manufacturing, Design</td>
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<td>Proc Long Lead Components</td>
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<td>Manufacturing, FT, shipping</td>
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Considerations on the decision point between the 2MW/1MW gyrotron (3/4)
## Preliminary technical criteria for the decision between 2MW/1MW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications of the 1st prototype</th>
<th>Preliminary technical criteria for the decision</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>170 GHz</td>
<td>170 GHz ± 0.25 GHz</td>
<td>Critical</td>
</tr>
<tr>
<td>Frequency spectrum</td>
<td>-</td>
<td>99% of total RF power within the previous frequency range (a lower value would require a complete understanding)</td>
<td>Critical</td>
</tr>
<tr>
<td>Peak RF Power (in the ms range)</td>
<td>2 MW</td>
<td>≥ 2MW</td>
<td>Critical</td>
</tr>
<tr>
<td>Pulse length at high power</td>
<td>1s at 2 MW</td>
<td>&gt; 0.8 s and &gt; 1.8 MW</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A positive recommendation could be issued in case of lower values, subject to clear understanding of the reasons</td>
<td></td>
</tr>
<tr>
<td>Cavity Mode</td>
<td>TE&lt;sub&gt;34,19&lt;/sub&gt;</td>
<td>TE&lt;sub&gt;34,19&lt;/sub&gt; - single mode operation</td>
<td>Critical</td>
</tr>
<tr>
<td>RF output efficiency η</td>
<td>≥45% with depressed collector</td>
<td>A lower efficiency could be accepted if the reasons are understood and can be corrected for the 2&lt;sup&gt;nd&lt;/sup&gt; prototype</td>
<td>Critical</td>
</tr>
<tr>
<td>Mode purity in TEM&lt;sub&gt;00&lt;/sub&gt; at window</td>
<td>≥95%</td>
<td>95 %</td>
<td>Critical</td>
</tr>
<tr>
<td>Mode purity in HE&lt;sub&gt;11&lt;/sub&gt; at RFCU output</td>
<td>≥97%</td>
<td>95 % (parameter relaxed with respect to previous specs since it depends on a sub-system external to the gyrotron)</td>
<td>Not critical</td>
</tr>
<tr>
<td>Modulation capabilities</td>
<td>Modulating V&lt;sub&gt;body&lt;/sub&gt; (0.6 MW - 2 MW of P&lt;sub&gt;RF&lt;/sub&gt;) &amp; ON/OFF</td>
<td>Up to 1kHz when modulating the body voltage, and 5kHz for ON/OFF modulation</td>
<td>Not critical</td>
</tr>
</tbody>
</table>
- Why is Europe developing the 2MW gyrotron for ITER?
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Conclusions
Implications for the ITER systems

- Availability of the EU gyrotrons: a 2\textsuperscript{nd} fall back option is foreseen in EU in case of major problems during last phase of the development

- PCR-116 accepted into the ITER baseline (Oct’09): \textbf{All components of the EC system are specified to be compatible with the 2MW power level} (2MW at the entrance of the TL, 1.8MW per beam line at the launchers):
  
  i. 2MW coaxial cavity gyrotrons
  ii. JA & RF gyrotron having potential to operate at >1MW
  iii. Compatibility with \textbf{2\textsuperscript{nd} generation of gyrotrons for ITER – power upgrades of the ITER system}

  Gyrotrons have a life expectancy of \textbf{~5 yr} (cathode, collector)

- Concern on the \textbf{margin of safety between operating point} (potentially at 2MW level) and the engineering \textbf{design limit} of the EC components

  (line switches, launcher last mirrors, polarizers, etc)

  \textbf{It is strongly recommended IO addresses mitigation actions (optimization of TL & launcher components) without regards to EU 2MW/1MW decision}
Conclusions

- Development of the 2MW Coaxial Cavity Gyrotron for ITER in progress: strong collaboration among EU Associates + industrial partner + expertise from W7-X gyrotron development

- 2MW/1MW decision: discussions on the criteria have started (~2MW, ~1s, >95%GC)

- Remarkable recent results from the short-pulse KIT coaxial cavity gyrotron providing confidence on the upcoming tests with the refurbished industrial tube (2.2MW, 30% efficiency w/o SDP, >96%GC)

- All components of the ITER EC sub-systems are specified to be 2MW compatible

- The development of higher power gyrotrons is strategic for Europe, and important for ITER, DEMO, and future fusion devices

- The development of the 2MW coaxial tube should continue without regard to the decision point between the 2MW and 1MW gyrotron