Recent Development Results in Russia of Megawatt Power Gyrotrons for Plasma Fusion Installations

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presented by G.G. Denisov

- Russian gyrotrons for plasma setups
  - ~5 / year: 2011-2012 - China, Russia, Germany, India
    (for T-10, ITER, East, HL-2A, ASDEX-Upgrade, SST-1)
- ITER gyrotron parameters and 170GHz/1MW gyrotron design
- Test facilities
- Long-pulse test of ITER gyrotrons
- 170 GHz/1.5 MW gyrotron mock-up
- Multi-frequency gyrotrons
- Conclusions
The main specifications of the gyrotrons for ITER are described below:

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal output power</td>
<td>≥ 0.96 MW at MOU output.</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>170±0.3 GHz (TBD) including initial transient phase.</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3600 sec (TBD)</td>
</tr>
<tr>
<td>RF power generation efficiency</td>
<td>≥ 50 % (with collector potential depression)</td>
</tr>
<tr>
<td>Gaussian content</td>
<td>&gt; 95 % at output waveguide (63.5 mmφ) of MOU.</td>
</tr>
</tbody>
</table>

For more details see Technical specifications ([https://user.iter.org/?uid=4GV66L](https://user.iter.org/?uid=4GV66L))
**Gyrotron. Design features.**

Experience of IAP RAS and Gycom Ltd. in development and manufacture of gyrotrons for various facilities as well as R&D of ITER gyrotron resulted in the conceptual design.

**Gyrotron cavity** is designed to operate in $\text{TE}_{25.10.1}$ mode with specific wall loading 2kW/cm$^2$ at 1MW

Diode type electron gun forms the electron beam with optimal size, up to 50A / 70-80kV

**Built-in quasi-optical converter** with improved launcher provides paraxial output radiation with Gaussian mode content over 95% at stray radiation less than 5%

**Main output window** is based on CVD diamond disk of 106-mm diameter brazed into inconel or copper cuffs with 88-mm clear aperture.

**Relief window** uses ceramics (BN or AlN) disk of 123-mm diameter to transmit 40 kW.

**Depressed-collector** with longitudinal beam sweeping is capable to withstand 1-MW electron beam. Deep recuperation enhances gyrotron efficiency over 50%.

**DC break insulator** is placed upon cryomagnet top flange. $\text{C}_8\text{F}_{20}$ fluorocarbon is used now as a coolant and as additional HV insulator.

**LHe-free cryomagnet** has a bore diameter of 160 mm

Gyrotron inner surfaces are fabricated from copper with intense water cooling for CW operation.

Gyrotron total height is 2.7m. Gyrotron weight is about 200+ kg.
Achievement of ITER relevant parameters with RF gyrotron

In the last five years four gyrotron prototypes were fabricated and tested. The following gyrotron output parameters were demonstrated so far: **1.02 MW/570 sec and 0.9 MW/1000 sec.**

It was also demonstrated a repetitive gyrotron operation (10 pulses a day) with parameters 800 kW/600 s with reliability exceeding 90%. For the 1 MW power regime the gyrotron efficiency is 53-55%.

ITER gyrotron prototypes: (a) Gyrotron V-9 tested in 2009 in GYCOM LHe cryomagnet with air cooling of DC insulator; (b) Gyrotron V-10 tested in 2010 in CRYOMAGNETICS LHe –free magnet; liquid cooling of DC insulator.

One more gyrotron prototype (V-11) was fabricated in 2010 and tested in 2011. It is important to note that two last gyrotrons (V-10 and V-11) demonstrate very similar output parameters (see Table below).
**Summary of test results attained with V-10 and V-11 gyrotrons**

<table>
<thead>
<tr>
<th>Gyrotron</th>
<th>Beam voltage (kV)</th>
<th>Beam current (A)</th>
<th>Retarding voltage (kV)</th>
<th>Output power* (kW)</th>
<th>CPD efficiency (%)</th>
<th>Pulse duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-10</td>
<td>71</td>
<td>34</td>
<td>30.5</td>
<td>~750</td>
<td>~54</td>
<td>1000</td>
</tr>
<tr>
<td>V-10</td>
<td>71</td>
<td>34</td>
<td>30</td>
<td>~750</td>
<td>~54</td>
<td>600 (serial pulses)</td>
</tr>
<tr>
<td>V-11</td>
<td>70</td>
<td>39.5</td>
<td>30</td>
<td>~850</td>
<td>~53</td>
<td>1000</td>
</tr>
<tr>
<td>V-10</td>
<td>71</td>
<td>45</td>
<td>30.5</td>
<td>~960</td>
<td>~53</td>
<td>578</td>
</tr>
<tr>
<td>V-10</td>
<td>70</td>
<td>45</td>
<td>31.5</td>
<td>~960</td>
<td>~55</td>
<td>400 (serial pulses)</td>
</tr>
<tr>
<td>V-11</td>
<td>70.5</td>
<td>45</td>
<td>31.5</td>
<td>~960</td>
<td>~55</td>
<td>400 (test continue)</td>
</tr>
</tbody>
</table>

* Power referred to MOU outlet (~ -5%)
Evacuated $\text{HE}_{11}$ transmission line with terminal load (2006)
**RF gyrotron. ITER-relevant repetitive operation.**

As for a reliability test, 0.8MW/600s shots were repeated with every 50 min. for 3 days in 12-14 of April 2011. Only 3 pulses of 30 were interrupted by some reasons. Ten pulses were made in presence of IO representatives.

Repetitive pulse operation of V-10 gyrotron

<table>
<thead>
<tr>
<th>Ub, kV</th>
<th>Urec, kV</th>
<th>lb, A</th>
<th>Im, A</th>
<th>t_req, s</th>
<th>t_g, c</th>
<th>t_pulse, s</th>
<th>Date</th>
<th>Regime</th>
<th>Pulse stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>70.9</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>70.9</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>70.9</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>71</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>510</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Cut-off</td>
</tr>
<tr>
<td>71</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>71</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>71</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>13.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>70.8</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>14.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>70.8</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>14.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
<tr>
<td>70.8</td>
<td>30</td>
<td>34</td>
<td>82.65</td>
<td>600</td>
<td>1.5</td>
<td>600</td>
<td>14.04.2011</td>
<td>Operating_800kW</td>
<td>Regular</td>
</tr>
</tbody>
</table>
0.8MW/34A/600s serial pulse of V-10 gyrotron
Power in gyrotron collector and terminal load at 800kW/1000s pulse
Power calorimetry in the V-10 gyrotron and transmission line units
Gyrotron test facilities:

1. Tokamak Physics Institute, Moscow
   Main HVPS: 60 kV/60A, 1000 sec
   (no cathode modulation, 1/6 duty, some problems with cooling water quality, limited access to test GYCOM gyrotrons)

2. GYCOM Ltd, Nizhny Novgorod
   Main HVPS: 60 kV/21A CW and 70 kV/40A, 3 sec

3. New test stand at IAP/GYCOM, Nizhny Novgorod
   Main HVPS: 60 kV/50A, 3600 sec
   (1 kHz cathode modulation, modern control and protection system
   HVPS delivery by Sept. 2012, stand operation in 2012)

HVPS bought from
INSTITUTE OF PLASMA PHYSICS CHINESE ACADEMY OF SCIENCES, P.O. Box 1126, Hefei, Anhui 230031, P. R. China
2. Studies of 1.5-2 MW gyrotron models

Ways to enhance gyrotron power:

Power enhancement in conventional gyrotrons
- 170 GHz/137 GHz gyrotron in JAEA
- Latest tests of Russian ITER gyrotron
- CPI 95 GHz 2MW gyrotron development

Development of gyrotron with a coaxial cavity
- (main efforts EU, earlier in Russia)
Hard structure and intense cooling of a gyrotron cavity provide good stability of operating frequency. Total frequency drift slightly exceeds 100MHz. After ~1.5s frequency is practically stable with very small deviations of about 10MHz.
1.2 MW/100 s operation of V-11, 170 GHz gyrotron, TE25.10 (1.2 MW at MOU output). Cavity and collector survived in long pulses.

Electron beam
(43.4 + 29.6) kV
53 A
2300 kW

Calorimeters, kW:
Main load -1150
Pre-load - 25
MOU - 35+15 (refl.)
Relief wind. - 40
Collector – 1080
Σ 2345
TE28.12 mode gyrotron model. 100-μs/5-10Hz tests.

1.5 MW CW compatible

OLD & NEW QO CONV.

Long pulse tests in 2012
3. Frequency tuning/switching in MW gyrotrons

<table>
<thead>
<tr>
<th>One mode</th>
<th>Azimuth index change</th>
<th>Series of azimuth indices at each radial index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field or voltage tuning</td>
<td>Magnetic field and voltage optimization</td>
<td>Magnetic field and voltage optimization</td>
</tr>
<tr>
<td>Typical frequency tuning ~ 0.1%</td>
<td>Typical frequency step 2-3%, 3-4 steps</td>
<td>About 10 steps in 30% frequency range</td>
</tr>
<tr>
<td>FADIS</td>
<td>Multi-purpose ECW systems</td>
<td></td>
</tr>
</tbody>
</table>
IAP/GYCOM experience in MW power level multi-frequency gyrotrons

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>Power</th>
<th>Pulse, sec</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Two- and multi-frequency gyrotrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105 / 140</td>
<td>0.7 - 0.9 MW</td>
<td>10</td>
<td>3 tubes delivered to ASDEX-Up</td>
</tr>
<tr>
<td>147 / 170</td>
<td>0.7/1.0 MW</td>
<td>0.1</td>
<td>CW design</td>
</tr>
<tr>
<td>100-150</td>
<td>1.2-1.5 MW</td>
<td>$10^{-4}$</td>
<td>Short pulse mock-up, 6 frequencies, high-eff. converter</td>
</tr>
<tr>
<td>100-150</td>
<td>0.7-0.8</td>
<td>0.1</td>
<td>Short-pulse mock-up, 11 frequencies, BN Brewster window</td>
</tr>
<tr>
<td>105 -140</td>
<td>0.7 – 0.9 MW</td>
<td>0.1 (10)</td>
<td>4 frequencies High-eff. mode converter</td>
</tr>
<tr>
<td>71.5 / 74.8 / 78.1</td>
<td>0.8 MW</td>
<td>0.1</td>
<td>3 frequencies, 56% eff. BN Brewster window</td>
</tr>
</tbody>
</table>
Example:
Design requirements for the multi-frequency gyrotron for ASDEX Upgrade

- Frequency range (at least 4 frequencies) 105 – 140 GHz
- Output power:
  - at frequency 140 GHz 1 MW
  - at frequency 105 GHz 0.8 MW
  - at intermediate frequencies 0.8 MW
- Pulse duration 10 s
- Efficiency with energy recovery 40-50%
- Output radiation Gaussian beam

7 years of common (with FZK, IPP, IPF) development
Multi-frequency gyrotron. Main problems.

- Effective gyrotron operation at different modes
- Effective conversion of all modes into Gaussian beam
- Tuneable or broadband window
One-disc CVD diamond windows for gyrotrons

- Small dielectric loss
- e-o thermal conductivity

\[ H = n \cdot \frac{\lambda}{2\sqrt{\varepsilon}} \]

\[ \frac{\Delta f}{f} = 1 - 2\% \]

Widely used for conventional single/double frequency gyrotrons; 1.8 mm thick => 4 half-wavelength at 140 GHz and 3 h-w at 105 GHz
## Options for multi-frequency gyrotron window

<table>
<thead>
<tr>
<th>Type</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-disc</td>
<td>Clear concept</td>
<td>Two discs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Narrow band of low reflection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt; probably disturb gyrotron operation</td>
</tr>
<tr>
<td>Brewster, circular</td>
<td>Wide instant band</td>
<td>High field near the disc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Require vacuum duct</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Require thicker disc</td>
</tr>
<tr>
<td>Brewster, elliptical</td>
<td>Simple scheme</td>
<td>Probably poor transmission characteristics (?)</td>
</tr>
<tr>
<td>Corrugated matched surface</td>
<td>Broad instant band</td>
<td>Expensive fabrication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worse mechanical stability</td>
</tr>
<tr>
<td><strong>Travelling wave resonator</strong></td>
<td><strong>Zero reflection</strong></td>
<td><strong>Two discs</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Easy tuning</strong></td>
<td></td>
</tr>
</tbody>
</table>
Brewster-angle single disk configuration

To direct radiation through CVD diamond disk of reasonable diameter at Brewster angle (67°) additional mirrors are to be placed in the immediate vicinity of disk.

Disk itself and its fixture must have maximal aperture and minimal axial size.

Polarization of wave beam irradiated by internal mode converter should be turned by 90° to avoid change of incidence angle due to change of cavity operating mode.
Brewster output window:
Special brazing developed
Diamond disc diameter 106 mm brazed to special copper cuffs

From atmospheric side

From vacuum side
Propagation of gyrotron radiation through Brewster-kind output window. Protection of mirror supporting structure against reflected cross-polarized radiation.
Multi-frequency gyrotron with Brewster output window:
The arc which destroyed the diamond disk

<table>
<thead>
<tr>
<th>Conditioning regime after a frequency change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, GHz</td>
</tr>
<tr>
<td>Output power, kW</td>
</tr>
<tr>
<td>Pulse duration, ms set/actual</td>
</tr>
</tbody>
</table>

Diagnostics showed that during the pulse a disruption of the operating regime to generation of the opposite rotating mode happened.

It was one of shocks due to arcing which finally destroyed the window disc with internal strengths.

Safety factor (2 in internal strength) was probably too small for a long time operation.
Multi-frequency gyrotron window after the failure
KIT concept I: double disk window
Second shot:

Cooling water leakage?
Wave reflection (R1 and R2) from window version b), and scattering into (L) to the (±1)-st diffraction beam vs frequency.

\[ \bar{H} = 14.64 \quad \text{curve R1} \quad \bar{H} = 10.1 \quad \text{curve R2} \]

\[ \bar{\ell} = 2.86 \quad \bar{d} = 3.77 \]

\[ \varepsilon = 5.67 \]

\[ \overline{H} = 2\pi \frac{H}{D} \]

\[ \bar{l} = 2\pi \frac{l}{D} \]

\[ \bar{d} = 2\pi \frac{d}{D} \]
Corrugated matched diamond window
(some conclusions from analysis of KIT and IAP)

- Expensive fabrication of grooves
- Ohmic losses in corrugations (?)
- Additional mechanical strengths (~ 2 times higher)
EFFECTIVE POWER INPUT INTO QUASI-OPTICAL CAVITY WITH TRAVELLING WAVE

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Received July 31, 1991

Abstract
The open three-mirror cavity with a travelling wave, and reflecting diffraction grating on one mirror as a coupler was excited by a wave beam at the frequency 140 GHz. The investigation showed the wave power in the cavity to be about 30 times higher than that at the cavity entrance.

Fig.1. Trajectory of the beam in the three-mirror cavity.
Mirror cavity with a traveling wave. 
M is a parabolic mirror. 
W1 and W2 are CVD diamond disks. 
T, R and A are amplitudes of transmitted, reflected and traveling wave beams.

\[ |T|^2 = \frac{t^4}{(1 - r^2)^2 + 4 r^2 \sin^2 \left( \frac{kL}{2} \right)} \]

\[ |R|^2 = \frac{4 r^2 \sin^2 \left( \frac{kL}{2} \right)}{(1 - r^2)^2 + 4 r^2 \sin^2 \left( \frac{kL}{2} \right)} \]

\[ |A|^2 = \frac{t^2}{(1 - r^2)^2 + 4 r^2 \sin^2 \left( \frac{kL}{2} \right)} \]

At the resonance frequency \( kL = 2\pi q \ (q = 1, 2, 3\ldots) \) the reflecting power from the cavity is equal zero: 
\[ |R|^2 = 0, \ |T|^2 = 1, \ |A|^2 = 1/t^2 \]
Other possible trajectories

L = 360 mm

L = 420.65 mm
Low power proof-of-principle experiment

Matching mirrors provide gyrotron-like wave beam

Broad band taper

Tunable window with quartz discs
Low power experiment

Power transmitted through the window:

a) experiment

b) calculations.

Maxima move while tuning

Power transmitted through the window:

a) experiment

b) calculations.

Resonant matching

Disc transparent
Main features of the travelling-wave window

- No reflections back, does not disturb gyrotron operation

- Easy tuning

- Not very critical to wave beam alignment (± 0.5°, ±5 mm)

- Can be based on a “standard” disc brazing (Cu cuffs)
Drawing for the gyrotron window. Standard 106 mm disc.
Quality factors of the ring resonator
\[ \sim 10000 \text{ for FADIS (} Q_{\text{FADIS}} \gg Q_{\text{gyrotron cavity}} \text{)} \]
\[ < 500 \text{ for the window} \]

If one believe that FADIS will work
then the window will work perfectly!

- 1 MW/10 sec gyrotron for ADEX-Upgrade has been fabricated
- 2-frequency tests in June, 2012
- 4-frequency tests (initial in June, 2012, final in early 2013)
Summary

Significant progress in MW (e.g. ITER) gyrotrons
- Demonstrated parameters (1 MW, > 50%, 1000 sec)
- Reliability tests of the gyrotrons

Construction of the new test facility at GYCOM

Successful tests of gyrotrons (prototypes) with enhanced power

Near-term plans for testing multi-frequency gyrotron

Missing points:
- ECRH at JET
- One more supplier of CVD diamond discs