Present Status of the New Multi-Frequency 
ECRH System for ASDEX Upgrade

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Abstract
A new multi-frequency ECRH system is currently under construction at the ASDEX Upgrade 
Tokamak experiment. This system employs, for the first time in a fusion device, multi-
frequency gyrotrons, step-tunable in the range 105-140 GHz. The power deposition in the 
plasma is primarily determined by the magnetic field \( B(r) \). For a single frequency ECRH 
system this has the consequence that for central heating the magnetic field is no longer a free 
parameter. However, for plasmas with different plasma currents or different equilibria, the 
magnetic field should be a free parameter in order to operate at a reasonable edge safety factor 
\( q(a) \). Furthermore, in a plasma with given parameters, some experimental features, like 
suppression of neoclassical tearing modes (NTM), require to drive current on the high field 
side without changing the magnetic field. These requests can be satisfied if the gyrotron 
frequency is variable \(^1\). In the experiments performed up to now in ASDEX Upgrade the 
installed power was only 2 MW, of which 1.6 MW was coupled to the plasma. This imposes a 
limit for current drive, NTM stabilization or generation of internal transport barriers \(^2\). The 
requirement for the new system is therefore an installed power of 4 MW. Since the current 
diffusion time in hot plasmas, like those with an internal transport barrier and \( T_e > 10 \) keV, is 
several seconds, pulse duration of 10 s compatible with the limit of ASDEX Upgrade flat top 
discharges is necessary. A further requirement is the capability for very localized power 
deposition such that its center can be feedback controlled, for instance to keep it on a resonant 
q-surface. For this purpose fast movable mirrors have been installed. 
The Matching Optics Unit (MOU) includes a set of phase correcting mirrors for each 
frequency as well as a pair of broadband polarizer mirrors. The transmission line consists of 
onevacuated corrugated HE11 waveguides with I.D. = 87 mm and has a total length of about 
70 m. The two-frequency gyrotron Odissey-2 has been installed recently. It is equipped with a 
single-disc diamond window. The gyrotron Odissey-1, which was originally installed but 
needed a repair, is currently being equipped with a broadband Brewster output window and 
will become step-tunable with two additional frequencies between 105 and 140 GHz. It will 
also require a broadband torus vacuum window which will be a double-disc window.

2. Gyrotrons
The two-frequency GYCOM gyrotron Odissey-2 has recently been installed and put into 
operation. It can work at 105 GHz and at 140 GHz. The corresponding operating modes are
TE_{17,6} and TE_{22,8}. Here we make use of the 3\lambda/2 and 4\lambda/2 resonances (\lambda is the wavelength) of the single-disc synthetic diamond vacuum window at these frequencies. The gyrotron has a single-stage depressed collector. Therefore the cathode voltage can be limited to a maximum value of 60 kV. The maximum beam current is 40 A. There is a separate set of series tetrode and body modulator for each gyrotron, which will allow maximum flexibility for the experimental program. The frequency can be changed between two ASDEX Upgrade pulses and requires an adjustment of the cryomagnetic field, the gun and collector magnetic fields and operating voltages. The measured output power at 105 GHz and 140 GHz was 640 kW and 890 kW, respectively for a pulse length of 10 s.

For NTM stabilization experiments a fast modulation capability of the gyrotrons is required. This is especially important for future experiments like ITER where the width of the driven EC current will be larger than the marginal island size of the NTM leading to a loss of current drive efficiency in the non-modulated case \textsuperscript{6}. Two modulation schemes have been tested with this gyrotron. A 100\% power modulation up to 0.5 kHz was achieved by switching both, cathode and body voltage on and off. This scheme will be mainly used for heat wave analysis. Higher modulation frequencies up to 25 kHz with modulation depths up to 90 \% were achieved by a reduction of only the cathode voltage from 42 kV to 25 kV while keeping the body voltage constant. While the long-pulse testing of Odissey-1 was limited by the available high-power long-pulse load, a new larger GYCOM stainless-steel load allowed for repetitive 10s pulses with full power at both frequencies. The load contains no additional absorptive coating. First plasma test shots were performed with maximum power at 140 GHz and a pulse lengths of several seconds. The total measured frequency variation during a gyrotron pulse was 140 MHz \textsuperscript{3}. Out of this, a drift of \textasciitilde100 MHz happens in the first 100 ms of the pulse and repeatedly during on/off modulation (Fig. 1), very likely due to space charge effects and plasma formation in the cavity \textsuperscript{8}. The remaining shift of 40 MHz to steady state results from the thermal expansion of the cavity.

![Fig. 1](image)

**Fig. 1** Measured frequency drift of gyrotron Odissey-1 during a modulated (50ms/50ms on/off) and a cw 140 GHz pulse.

### 3. Transmission Line

One of the complicating features with step-tunable gyrotrons is that the output beam leaves the gyrotron window at slightly different azimuthal angles and positions due to the varying caustic radii for different modes. Therefore the MOU (Fig. 1) contains different sets of phase correcting mirrors (M1, M2) to match the gyrotron output beam at different frequencies to the transmission line input. In order to limit the number of required phase correcting mirror sets we chose four frequencies as our main operating modes for the step-tunable gyrotrons. The phase correcting mirrors are mounted on rotating discs and can be set according to the operating frequency. The second mirror M2 contains a coupling-hole array for pulse
monitoring and power measurement. Only one set of polarizers (P1, P2) with groove depths of $\lambda/4$ and $\lambda/8$ scaled to the center frequency of 122.5 GHz proved to be sufficiently broadband to provide the required range of ellipticity and orientation of the polarization ellipse for all necessary injection angles over the whole frequency band of the system (105-140 GHz). The MOU contains also two switching mirrors that can direct the beam to a 1 s calorimetric load which is part of each MOU, or to a central long pulse load. Using the 1 s loads, all four gyrotrons can be started up simultaneously every day. The transmission to the torus is in normal air, through corrugated aluminum HE$_{11}$ waveguides with I.D.= 87 mm over a total length of about 70 m. Since most part of the waveguide path is straight, the number of miter bends could be limited to eight. Another calorimetric load (0.1 s) is installed at the end of the transmission line at the torus. This load is used to test the transmission line prior to plasma shots as well as for calorimetric measurements of the transmission efficiency. Table 2 gives the measured transmission loss for the two-frequency gyrotrons Odissey-1 and Odissey-2, which are in reasonable agreement with the theoretical predictions (Table 1). The estimated error bar in the calorimetric measurements is about 5%. The overall losses are also sensitive to the alignment of the gyrotron output beam to the transmission line which directly affects the mode purity in the waveguide.

![Matching optics unit with phase correcting mirrors and polarizers.](image)

<table>
<thead>
<tr>
<th>Estimated losses</th>
<th>105 GHz</th>
<th>140 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohmic loss (70 m HE$_{11}$ waveguide)</td>
<td>0.12%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Ohmic loss (8 miter bends)</td>
<td>0.76%</td>
<td>1.03%</td>
</tr>
<tr>
<td>Diffraction loss (8 miter bends)</td>
<td>5.28%</td>
<td>3.43%</td>
</tr>
<tr>
<td>Atmospheric absorption (L=70m)</td>
<td>1.2%</td>
<td>3.17%</td>
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<tr>
<td>total loss</td>
<td>7.36%</td>
<td>7.68%</td>
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</table>

<table>
<thead>
<tr>
<th>Measured total loss</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>TL1 with Odissey-1</td>
<td>12%</td>
<td>10%</td>
</tr>
<tr>
<td>TL1 with Odissey-2</td>
<td>5%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 1 Estimated and measured transmission losses.
4. Broadband Vacuum Window

Except for the two-frequency gyrotron, where a single-disc diamond window is transparent at both frequencies, the vacuum windows required for the step-tunable gyrotron and at the torus must be broadband. For the gyrotron with its linearly polarized output beam allows the application of a Brewster window. The Gyrotron Odyssey-1 is currently being equipped with such a window. A gyrotron with Brewster window requires additional mirrors providing the passing of the beam through the window at the correct angle (Fig. 3a). To avoid constraints with respect to polarization which is set by the two polarizers in the MOU, a tunable double-disc window with a remote controlled adjustment of the distance between the discs will be used at the torus (Fig. 3b). Two diamond discs with a thickness of 1.8 mm will be utilized for this window, where the discs themselves are resonant at 105 and 140 GHz ($3\lambda/2$ and $4\lambda/2$ respectively). For intermediate frequencies the double-disc window can be tuned to a reflection minimum by changing the distance between the two discs. A critical value is the width of the Fabry-Perot resonances at intermediate frequencies between the single-disc resonances. Only a maximum distance of 10 mm between the discs can be allowed for a possible frequency drift of 140 MHz during the gyrotron pulse to keep the reflection below the critical value of 1 %. The volume between the two discs will be evacuated in order to increase the power handling capability.

![Fig. 3 Schematic of both broadband windows: (a) Brewster and (b) double-disc.](image)

5. Fast Steerable Launcher

A steerable launcher will enable the steering of the beam over the whole plasma cross-section. In order to cope with thermal load, disruption forces and mechanical dynamics of the fast poloidal steering, the mirror is made out of high heat conductivity fine grain graphite. In order to reduce its ohmic losses it has a copper coating on the reflecting surface. High power tests at IPP Greifswald using a 750 kW beam at 140 GHz with repetitive pulses of 20 s proved the thermal stability of the metallic layer. The measurements are in good agreement with numeric analysis predicting maximum surface temperatures of 350 °C during the pulse and a rise in bulk temperature of 40 °C after the pulse. Two different types of drives are used for the launcher. A slow drive rotates the launcher around its axis on a shot to shot basis, mainly to set the toroidal launching angle. A fast spindle drive controls the poloidal launching angle during a discharge. Fig. 4 shows the result of a dynamical test of the launcher during a typical ASDEX Upgrade plasma discharge. The launcher movement (solid line) contains both acceleration and deceleration of the mirror as well as a phase with constant velocity. There is also a delay in the response to the start and stop signal of the remote control (dashed line). The design value of 10° / 100 msec for the fast poloidal steering was achieved during the tests. Currently two more launchers are being built into the port. This capability will allow
feedback control of the deposition on the time scale of NTM growth, providing the possibility to validate this scheme for ITER in ASDEX Upgrade.

![Graph](image.png)

**Fig. 13** Dynamical test of the fast steerable launcher during an ASDEX Upgrade shot. Dashed line: control voltage, solid line: adjustable stroke of the fast spindle drive.