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

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Abstract

Currently, a new multi-frequency ECRH system is 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 first two gyrotrons, working at 105 and 140 GHz, were installed and tested. 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 non-evacuated corrugated HE_{11} waveguides with an inner diameter (I.D.) of 87 mm and has a total length of about 70 m. Transmission losses were deducted from calorimetric measurements both at the beginning and at the end of the transmission line at both frequencies and are in reasonable agreement with theory. Two transmission lines are completed so far and first plasma experiments with the new system have started. The first gyrotron Odissey-1 is currently being equipped with a broadband chemical vapour deposition (CVD) diamond Brewster output window and will become a step-tunable gyrotron with the additional frequencies 117 and 127 GHz. A tunable double-disc CVD diamond window will be mounted at the torus. The system includes fast steerable launchers at the front end that will allow very localized feedback controlled power deposition in the plasma.

1. Introduction

The power deposition of ECRH in the plasma is primarily determined by the magnetic field B(r). For given plasma parameters and fixed ECRH frequency this requires a specific magnetic field in the center. The magnetic field is thus no longer a free parameter. This can be overcome if the gyrotron frequency can be varied [1]. 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. Again, this can be satisfied if the gyrotron frequency is variable [1].

Figure 1 shows the extension of the ECRH operation space with respect to the plasma radius (rho_p) and the toroidal magnetic field for an ECRH system with four frequencies. 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 electron temperatures $T_e > 10$ keV, is several seconds, we need a pulse duration of 10 sec compatible with the limit of ASDEX Upgrade flat top discharges. 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 paper describes the main components of the new system (gyrotrons, MOU, transmission line, vacuum windows and launcher) with its particularities that are mainly connected to the application of multiple frequencies.

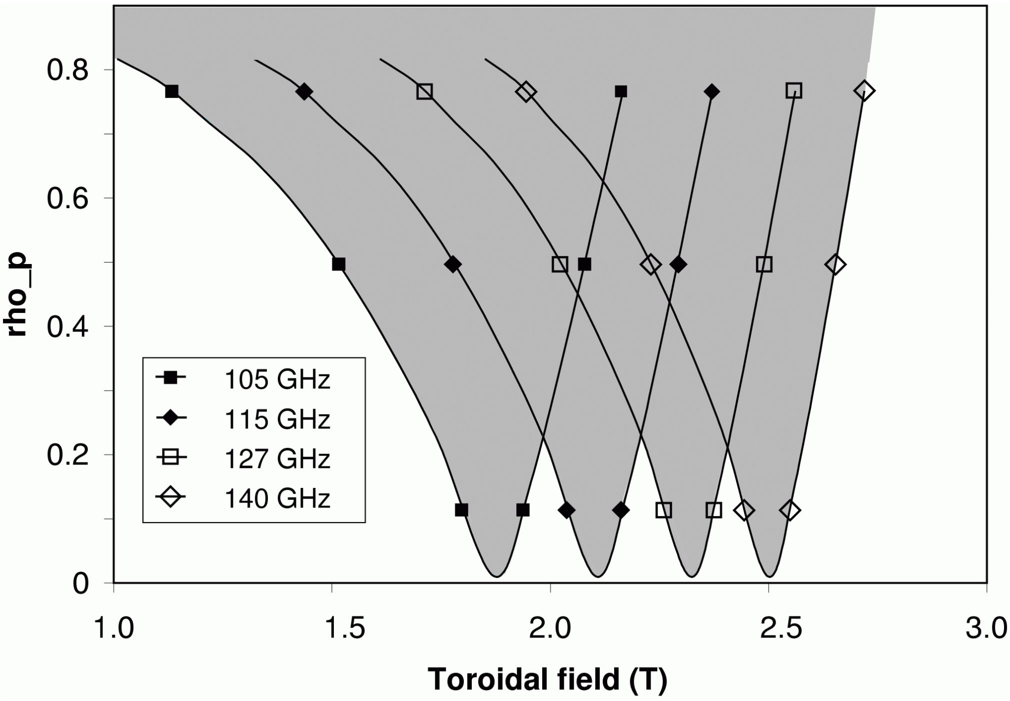

Figure1 Extension of the operating space for multi-frequency ECRH at ASDEX Upgrade.

2. Gyrotrons

The first two-frequency gyrotron Odissey-1 was successfully commissioned in 2005. The second two-frequency GYCOM gyrotron Odissey-2 has recently been installed and put into operation. They 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 (λ is the wavelength) of the single-disc synthetic diamond vacuum window at these frequencies. The refractive index of CVD diamond is quasi-constant over the whole frequency range of the system [6]. The gyrotrons have 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 sec (Table 1).

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 [7]. Two modulation schemes have been tested with the gyrotrons. 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 % at 140 GHz were achieved by a reduction of only the cathode voltage to a value where the gyrotron still oscillates while keeping the body voltage constant. While the long-pulse testing of the first two-frequency gyrotron 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 pulse lengths of several seconds. If the gyrotron is equipped with a broadband output window it can oscillate at additional frequencies. Figure 2 shows the possible modes and frequencies. The first gyrotron Odissey-1 was damaged due to a vacuum leak in its superconducting magnet. It was sent back to GYCOM for repair and is currently being equipped with a broadband Brewster CVD-diamond output window and will therefore become step-tunable.

The total measured frequency variation during a gyrotron pulse was 140 MHz [8]. Out of this, a drift of ~100 MHz happens in the first 100 msec of the pulse and repeatedly during on/off modulation (figure 3), very likely due to frequency pulling (voltage rise time), space charge effects and plasma formation in the cavity [9]. The remaining shift of 40 MHz to steady state results from the thermal expansion of the cavity and takes several seconds. In the case of the modulation only by a reduction of the cathode voltage (figure 4), the large frequency drift due to neutralization in the cavity only occurs at the start of the pulse. During the pulse, only frequency pulling (variation of the cathode voltage U_{cath}) and a slow frequency drift due to thermal expansion of the cavity wall are observed. This mode of operation allows beam switching via a frequency diplexer (FADIS project [11]) or is also suitable for CTS experiments [8].

Frequency	**Gyrotron**	U_{cath}	U_{body}	I_{beam}	**output power**
105 GHz	**Odissey-1**	-44.6 kV	+24.5 kV	37.8 A	**640 kW (± 10 %)**
	Odissey-2	-50.0 kV	+28 kV	35.0 A	**638 kW (± 10%)**
140 GHz	**Odissey-1**	-49 kV	+24 kV	40.2 A	**820 kW (± 10 %)**
	Odissey-2	-56 kV	+29 kV	41.0-37.5 A	**890 kW (± 10 %)**

Table 1 Performance of the two-frequency gyrotrons Odissey-1 and Odissey-2 at ASDEX Upgrade.

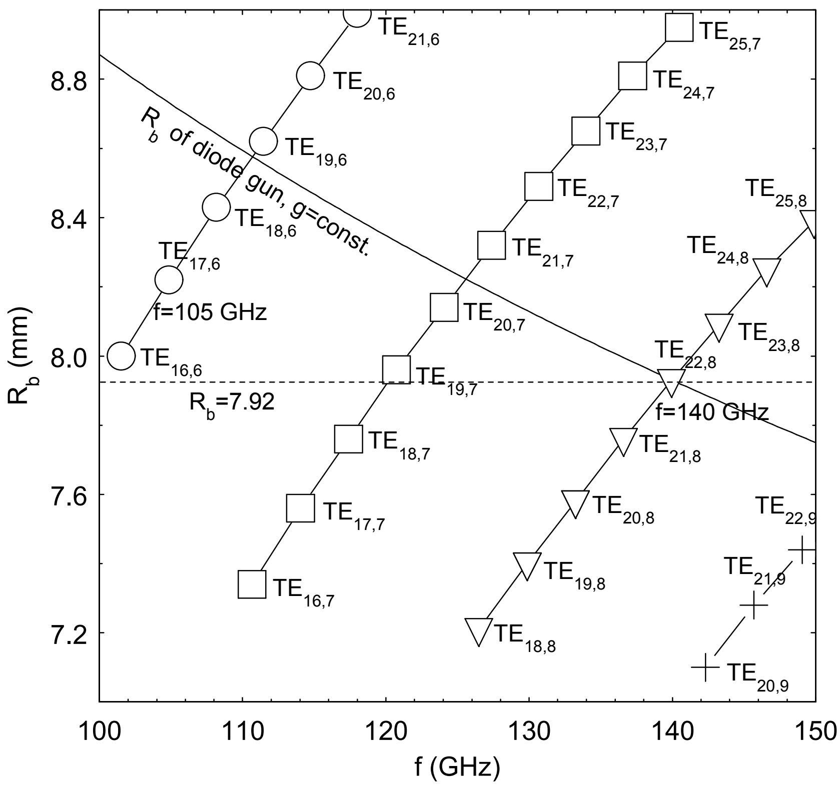

Figure 2 Electron beam radii and frequencies for operating $TE_{m,n}$ modes of the step-tunable gyrotron [5]. Also shown are curves for constant beam radius (R_b = 7.92mm) and R_b as a function of frequency for constant pitch factor (g = const.).

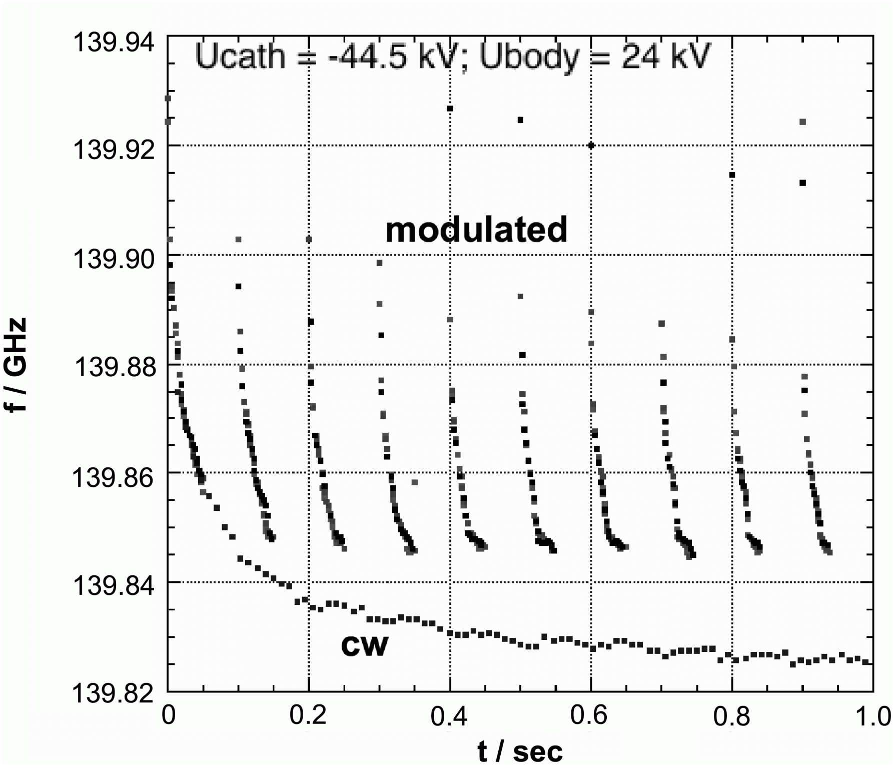

Figure 3 Measured frequency drift of gyrotron Odissey-1 during a cw 140 GHz pulse and a corresponding pulse modulated with complete switch on/off of both cathode and body voltage (50msec/50msec).

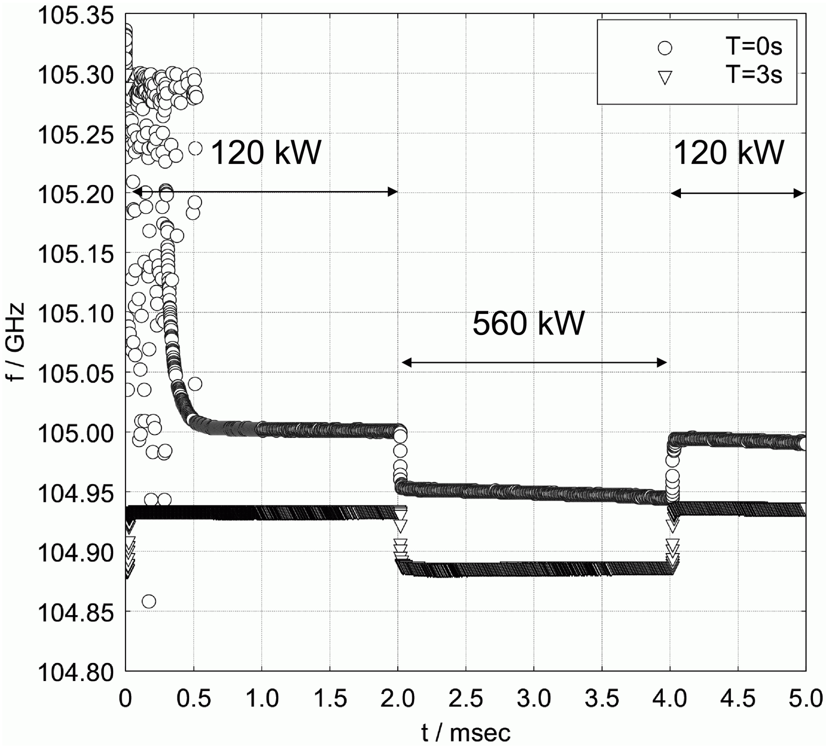

Figure 4 Measured frequency drift of Gyrotron Odissey-2 at the beginning (circles) and after 3s (triangles) during a 105 GHz pulse with modulation by reducing only the cathode voltage (rather than complete switch on/off).

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 (figure 5) 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 [12] 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 2). The estimated error bar in the calorimetric measurements is about 10 %. 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. This might be responsible for the difference in the two measurements.

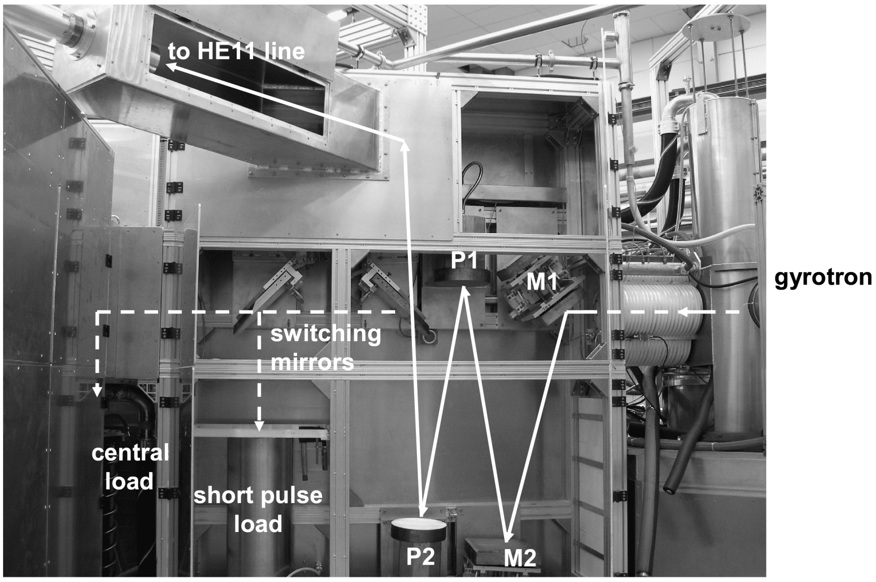

Figure 5 Matching optics unit with phase correcting mirrors and polarizers.

Estimated losses		
Frequency	**105 GHz**	**140 GHz**
Ohmic losses (70 m HE_{11} waveguide)	0.12 %	0.05 %
Ohmic losses (8 miter bends)	0.76 %	1.03 %
Diffraction losses (8 miter bends)	5.28 %	3.43 %
Atmospheric absorption (L = 70 m)	1.2 %	3.17 %
Total losses	**7.36 %**	**7.68 %**
Measured total losses		
Transmission line 1 with Odissey-1	(12.0 ± 2.4)%	(10 .0± 2.0) %
Transmission line 1 with Odissey-2	(5.0 ± 1.0) %	(8.0 ± 1.6) %

Table 2 Estimated and measured transmission losses.

4. Broadband Vacuum Windows

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. The gyrotron with its linearly polarized output beam allows the application of a Brewster window. The gyrotron Odissey-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 (figure 6a). 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 (figure 6b). 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 any intermediate frequency the double-disc window can be tuned to reflection minima by changing the distance between the two discs (Fabry-Perot resonance). A critical value is the width of the resonance at intermediate frequencies (see example in figure 7). 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 %. Figure 8 shows the double disc window together with a comparison of the calculated reflection with the cold test measurements. The volume between the two discs will be evacuated in order to increase the power handling capability.

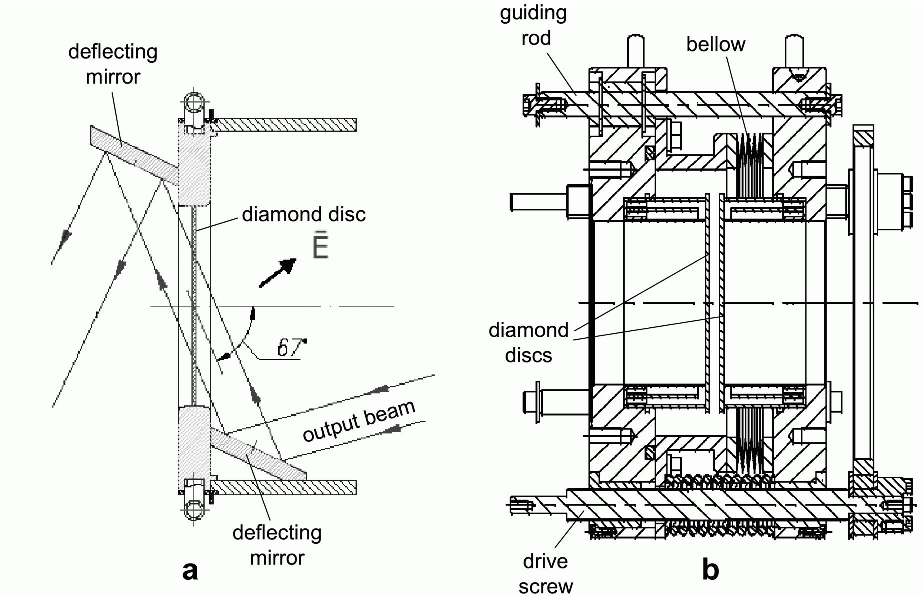

Figure 6 Schematic of both broadband windows: (a) Brewster and (b) double-disc.

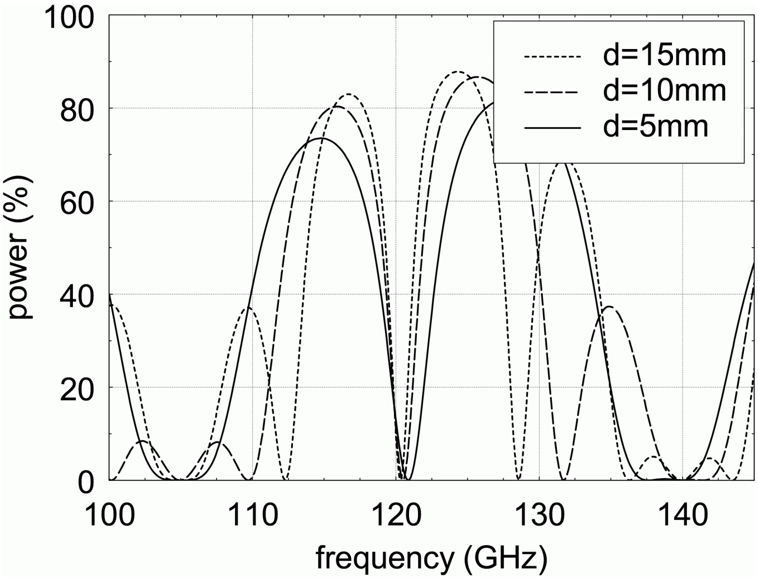

Figure 7 Calculated reflection of a double disc window for different distances d between the discs.

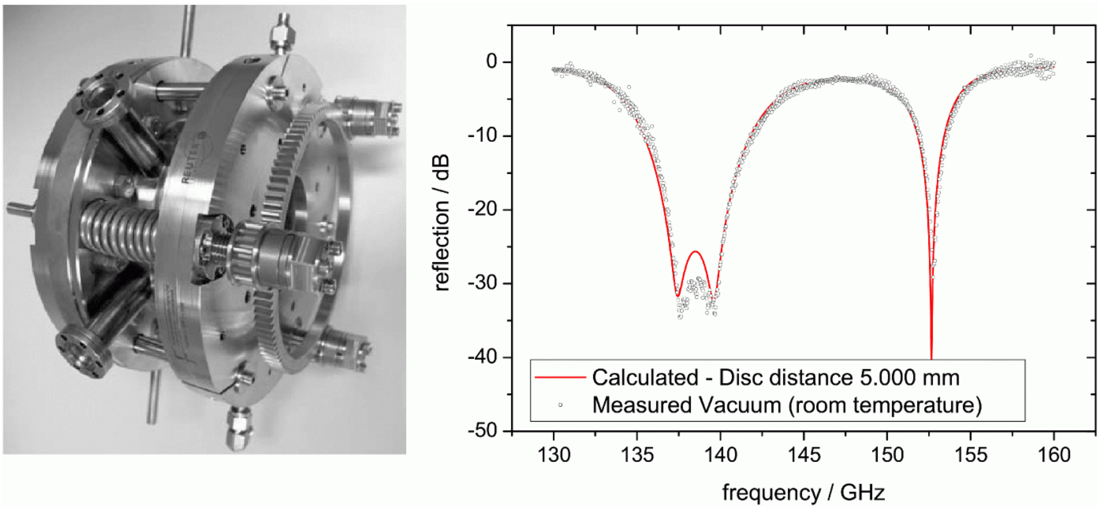

Figure 8 Double disc torus window with cold test results.

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 numerical 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 (figure 9). Figure 10 shows the mounted launchers in the ASDEX Upgrade port and 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.

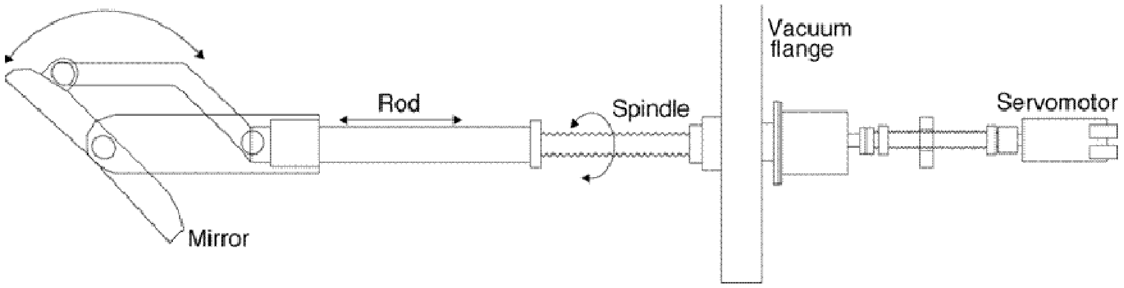

Figure 9 Push-rod drive for the fast steerable launcher.

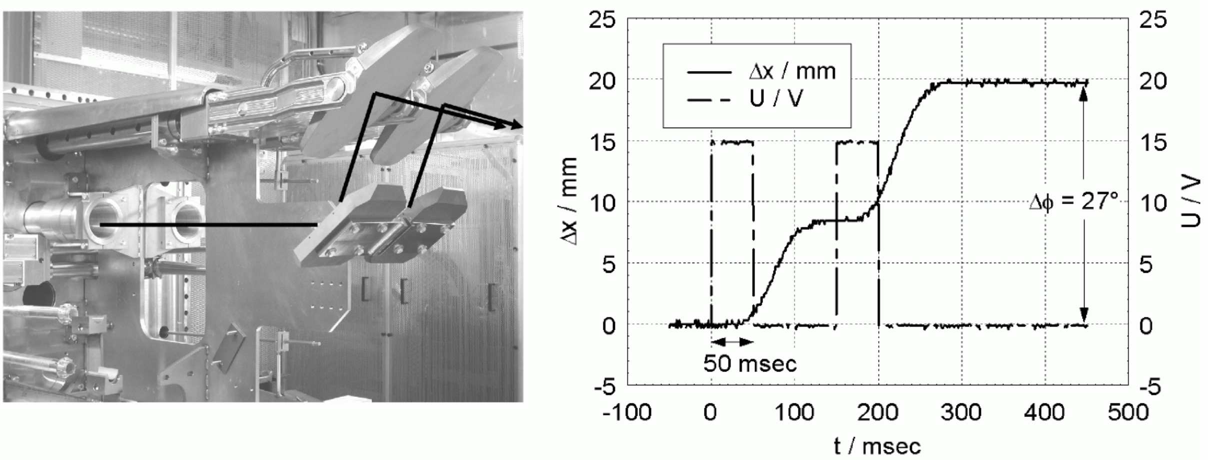

Figure 10 Mounted launcher in the ASDEX Upgrade port (left) and dynamical test of the fast steerable launcher during an ASDEX Upgrade shot (right).
Dashed line: control voltage, solid line: adjustable stroke of the fast spindle drive.

6. Conclusions

A new multi-frequency ECRH system (4 MW, 10 sec pulse length, frequency range 105-140 GHz) is currently under construction at the ASDEX Upgrade tokamak. This system poses new challenges not only to gyrotron development, but also to the matching optics and transmission elements, which have to be broadband. Two transmission lines are completed so far. The two-frequency gyrotrons Odissey-1 and Odissey-2 have successfully been tested together with the first transmission line. Gyrotron Odissey-1 is being equipped with a broadband Brewster CVD-diamond output window. Together with the installation of the first broadband CVD-diamond double disc window this will allow for the operation at additional intermediate frequencies. Further extension to four gyrotrons and transmission lines is underway. A fast steerable launcher, which will be used for feedback controlled deposition, was tested under experimental conditions during plasma discharges in ASDEX Upgrade. With this system, the first large scale multi-frequency ECRH system on a fusion device will be realized, leading to unprecedented flexibility in ECRH operation on ASDEX Upgrade.

7. References

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