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STATUS, OPERATION AND EXTENSION OF THE ECRH SYSTEM AT ASDEX UPGRADE

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Abstract

The upgraded Electron Cyclotron Resonance Heating (ECRH) system at ASDEX Upgrade (AUG) has been routinely used with 8 gyrotrons during the last experimental campaign. A further upgrade will replace the existing system of four short-pulse (140 GHz, 2s, 500 kW) gyrotrons. The final goal is to have around 6.5-7 MW at 140 GHz (or 5.5 MW at 105 GHz) from 8 units available in the plasma during the whole AUG discharge (10 s). The system operates at 140 GHz and 105 GHz with X2, O2 and X3 schemes. For B > 3T also an ITER-like O1-scenario can be run using the 105 GHz option. Four of the eight launching antennas are capable of fast poloidal movements necessary for real-time control of the location of power deposition.

Key words: Electron cyclotron resonance heating, two-frequency gyrotron, millimeter wave stray radiation.

1. Introduction

In the 2014 experimental campaign 8 gyrotrons were available for operation at ASDEX Upgrade. At 140 GHz the maximum power deposited with all gyrotrons in the plasma was 4.4 MW. Four of the gyrotrons are step-tunable. They are capable of generating significant output power at 9 different frequencies [1]. However, the development of a broadband high-power vacuum window is still ongoing. So far the only viable concept is to run the gyrotrons at two frequencies making use of the neighboring Fabry-Perot minima inherent to a single CVD diamond disc. In our case the thickness of the diamond disc corresponds to 4 x $\lambda/2$ at 140 GHz and 3 x $\lambda/2$ at 105 GHz. The transmission line consists of a quasi-optical Matching Optics Unit (MOU) and corrugated HE_{11}-mode waveguides with an inner diameter of 87 mm operating under air pressure. The polarizer mirrors in the MOU and the corrugated HE_{11}-mode waveguides both have a broadband design [2]. The total length of the waveguide lines is about 70-90 m. There are RF power monitors and calorimetric short-pulse water loads installed both in the MOU and next to the torus windows at the end of each transmission line.

2. System Status and Upgrades

Currently, a further upgrade is carried out, where the oldest part of the system which was built in 1990’s (four gyrotrons with 500 kW output power and 2 s pulse length) will be replaced with new two-frequency gyrotrons using the same launching positions with slightly modified launchers. The gyrotrons will be installed at a different location and most part of the transmission lines will be newly build. The upgrade roughly doubles the power of these four units and extends their pulse length to 10s, such that finally around 6.5 MW at 140 GHz (or 5.5 MW at 105 GHz) will be available in the plasma from 8 units during the whole AUG discharge. The system allows for power control by the Discharge Control System (DCS) of AUG. Four of the launchers (Fig.1) have a fast steering capability around one axis (mainly poloidal) and can also be controlled by the DCS.

The frequency step-tunability of the gyrotrons further increases the flexibility of the ECRH system, which is routinely used with different plasma heating schemes (X2, O2, O1, and X3) [3,4]. Due to the high toroidal magnetic field achievable in AUG (3.2 T) also an ITER-like O1-scenario can be run using 105 GHz ECRH. Compared to the X2-mode, the plasma has a much lower optical thickness and therefore lower absorption for the other heating schemes [3]. Therefore, a common problem for the new heating scenarios (O2, X3, O1) is an increased amount of stray radiation. This gives a high priority to the monitoring and minimization of millimeter-wave stray radiation [4].

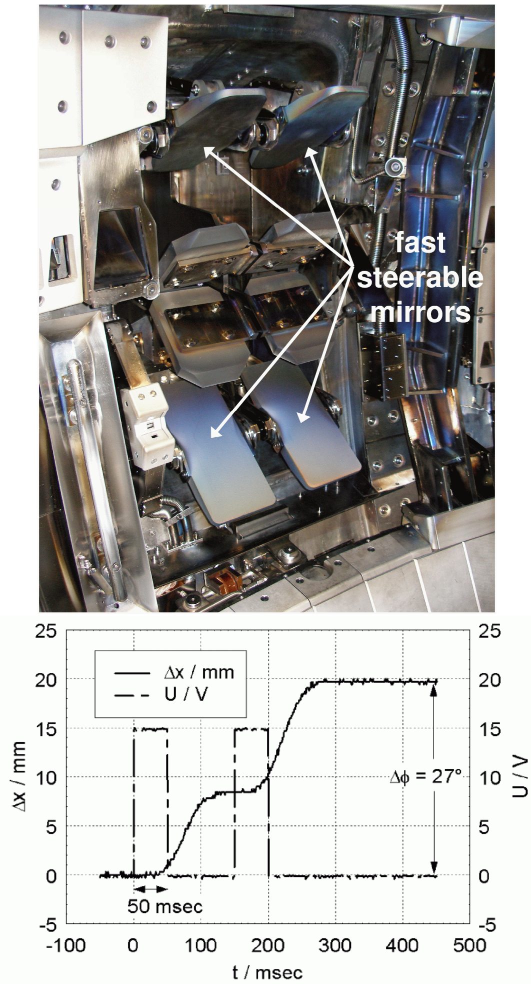

Fig.1 Mounted launcher in the ASDEX Upgrade port (top) and dynamical test of the fast steerable launcher (bottom). Dashed line: control voltage, solid line: adjustable stroke of the fast spindle drive.

3. Real-Time Control

Real-time stabilization of Neoclassical Tearing Modes (NTMs) using the fast-steerable ECRH launchers has been successfully demonstrated at ASDEX Upgrade. The correlation of data from Electron-Cyclotron-Emission (ECE) and Mirnov coil diagnostics allows the determination of the mode position in real

time. Together with a real-time reconstruction of the electron density profile from interferometer data, the Electron-Cyclotron-Current-Drive (ECCD) deposition profile can be calculated in real-time using ray-tracing [6].
New real-time capabilities are also in development for O2 heating. This enables the application of ECRH to plasmas with an electron density above the cutoff-density of the X2-mode. Special reflecting tiles with a holographic grating were mounted on the inner wall of ASDEX Upgrade (Fig.2) [3]. They reflect the non-absorbed part of the mm-wave beam again in O-mode polarization providing additional absorption in a second pass through the plasma center. With this method, the overall absorption in O2-mode can typically be increased from ~70% up to ~90%. Real-time control is required to keep the beam on the reflector in case of density profile changes or unexpected profiles. In such cases the diffraction differs from the a priori anticipated situation. To detect a variation of the beam position on the reflector fast thermocouples (< 50 ms) are implemented along the edges of the reflectors. The feedback scheme is sketched in Fig.3 [2]. Two safety levels are implemented. The absolute temperature value triggers a switch-off of the respective beam when exceeding a threshold. More refined is the interpretation of the temperature difference between the thermocouples at the upper and lower edge of the tile. If this difference exceeds a threshold the launcher is moved by a preset angle in order to move the reflection towards the center of the tile. Fig.4 shows an example where the beam was intentionally launched towards the lower edge of the tile. DCS immediately corrects the launcher angle as the temperature difference rises. In this discharge the launcher control mode was pre-programmed to switch back to feedforward slightly before the power was switched off. As a consequence the mirror moved back to its original position leading to a further rise of the temperature difference for the last 100 ms of the ECRH-on phase.

Fig.2 Holographic mirrors for O2 heating mounted on the inner wall of ASDEX Upgrade.

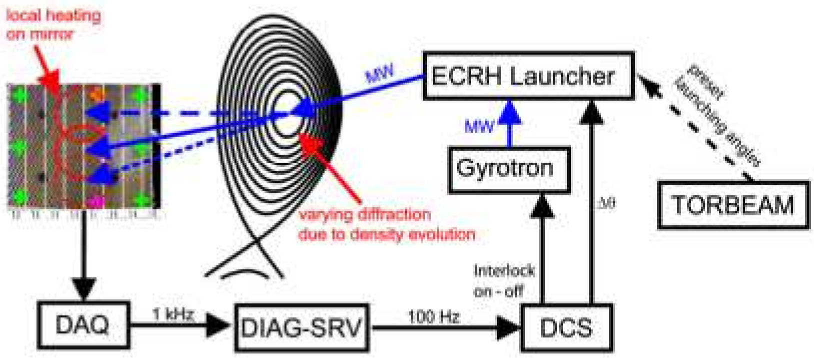

Fig.3 Sketch of the feedback scheme used during O2 heating with the first reflection on a specifically designed tile. DAQ means data acquisition and DIAG-SRV refers to the new layer for real-time diagnostics.

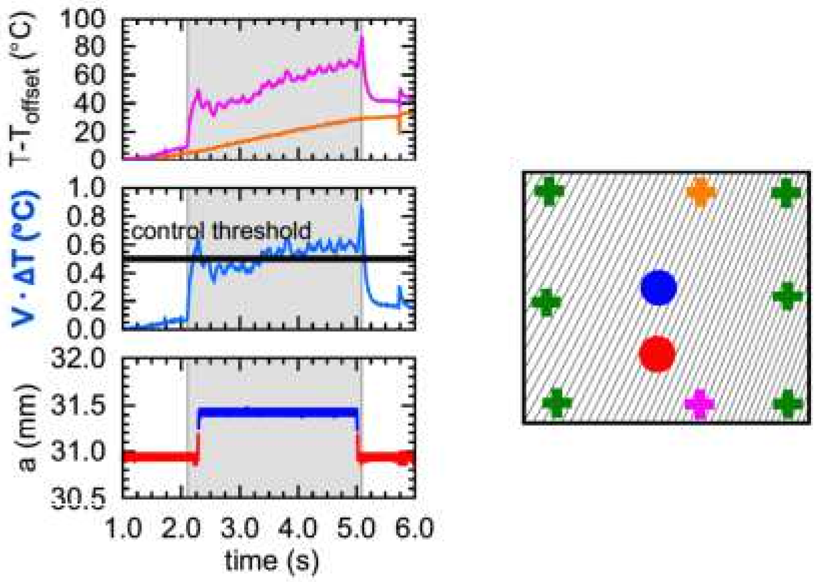

Fig.4 Right: sketch of reflector tile with positions of thermo couples (crosses) and beam positions (circles) for two launcher positions. Left: Temperatures measured at the magenta and orange cross (top). Weighted difference signal which DIAG-SRV sends to DCS, which acts when a threshold (black) is exceeded (middle). Position of the pushrod driving the poloidal launching angle (bottom). The two values marked in red and blue correspond to the respective circles on the right. This specific controller has a large hysteresis to prevent permanent flapping of the mirror.

RF-detectors are an essential tool in the gyrotron safety system at AUG. Their signals are used as an interlock for cutoffs and mode jumps in the gyrotrons, as well as for frequency measurements, e.g. during commissioning of the tubes. After calibration using calorimetric water loads they also deliver an accurate measurement of the gyrotron output power. For all this a reasonable signal to noise ratio is required. This is accomplished by incorporating a directional coupler into the second phase correcting mirror in each MOU. The power signal is delivered to the discharge control system of AUG. In case of a cutoff in the gyrotron this signal goes to zero, for a mode jump it is significantly reduced. If this status lasts more than 10 ms, the local controller pauses gyrotron operation for 100 ms and then switches the gyrotron back on. If there is no (or a significantly reduced) output power signal for another 10 ms after switching the gyrotron back on then gyrotron operation is stopped. After the second fault the DCS automatically declares the gyrotron as “not available” for the rest of the discharge and can automatically replace it with another available gyrotron which was in stand-by mode. A similar procedure is implemented for the case of arcing in the transmission line. Several optical arc detectors are installed along the transmission line. If one of the arc detectors is triggered, the pulse is stopped for 100 ms before the gyrotron is switched back on. An example for such a case is given in Fig.5.

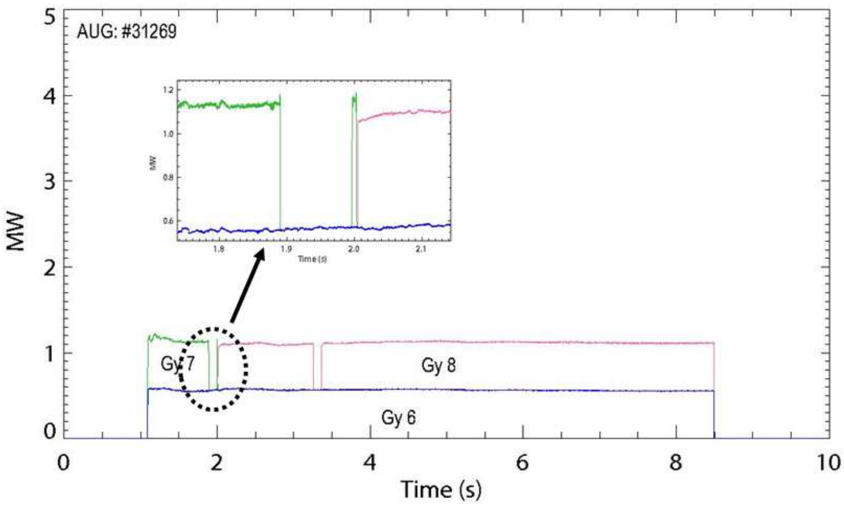

Fig.5 Time trace of the gyrotron output signals for AUG discharge #31269. An arc is detected in the transmission line of gyrotron #7 at t = 1.9 s. After switching it back on 100 ms later another arc occurs and the gyrotron is automatically replaced by the DCS with gyrotron #8. Another arc is detected in transmission line of Gyrotron #8 at t = 3.3 s, but this time the gyrotron is successfully switched back on 100ms later and the ECRH pulse is completed.

4. Stray Radiation Control

Although in general the absorption of ECRH in fusion plasmas is rather high, there is always a small fraction of non-absorbed power in the order of a few percent. This stray radiation can potentially damage in-vessel components and millimeter-wave diagnostics. If a particular heating scheme fails, the non-absorbed fraction of the ECRH beam may increase drastically (Fig.6). Additional millimeter-wave detectors, so-called sniffer probes, have been installed around the torus outer wall to monitor the stray radiation. They act as an active interlock for excessive stray radiation while their signal can also be used to check and possibly optimize the polarization of the mm-wave input beams. Polarization scans have been performed with the ITER-like fundamental O-mode (O1) [7] at a toroidal magnetic field of B_t = 3.0 T and a plasma current of I_p = 1 MA. In this heating scenario the cross-polarized fraction of the beam is directly reflected at the X-mode cutoff at the plasma boundary, therefore providing a large signal at the neighboring sniffer probes (Fig.7). In order to verify the optimum polarizer angles, the polarizer mirrors were rotated during the discharge resulting in a variation of the X- mode content (Fig.8) [5]. Fig.9 shows the theoretical X- mode content compared to the signal from an RF-detector during the polarizer scan. This RF probe acts as a protection for the ECE diagnostic at AUG. The gyrotron was operated in pulsed mode to limit the energy of the non-absorbed radiation. Due to the limited electron density and temperature of the plasma, only 92% of the power is absorbed at the first harmonic electron cyclotron resonance. The shine-through reflected from the inner wall adds to the stray radiation background. However the biggest contribution is the cross-polarized fraction of the beam reflected at the X-mode cutoff close to the outer torus wall which can cause a highly localized power density of the stray radiation while the shine-through reflected from the inner wall is a strongly divergent radiation when it arrives at the outer wall where the sniffer probes are installed. This background results in an upper limit of the measured minima of the sniffer signal given in Fig.9. Still, a correlation between calculated X-mode content and sniffer signal can be seen. At the calculated minima, the sniffer signal stays below the switch-off level for the ECRH-system by about a factor of 2. Another example for non-perfect absorption is given in Figs. 10 and 11. Here the O-mode content is varied at a second harmonic X-mode resonance. In this scenario there is no outer cutoff layer for the O-mode polarization. The O-mode content is only partially absorbed in the plasma and the stray radiation at the outer wall only results from shine-through reflected on the inner wall. Although the cross-polarized fraction is much larger during this scan compared to the previous one, the detected stray power stays in the same order of magnitude as for the polarization scan at first harmonic. At the same time the measured minima are much lower compared to the O1-X1 polarization scan.

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Fig.6 Video snapshot from AUG experiment #30230. In the upper right corner an arc can be seen on the inner heat shield. This was ignited by an ECRH beam shine through. Under normal conditions this area is dark. Most of the light comes from the divertor region at the bottom of the machine.

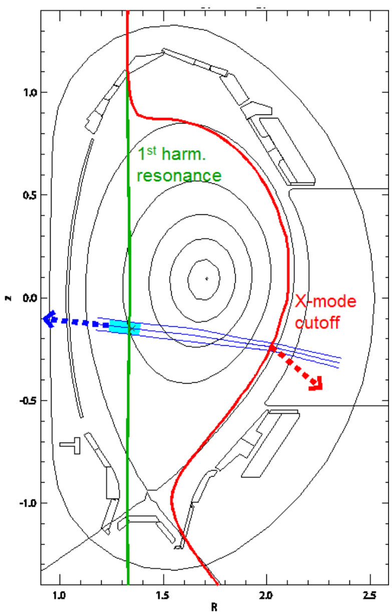

Fig.7 Results of the TORBEAM [8] ray tracing calculation for a gyrotron beam with 105 GHz in the poloidal cross section of AUG for a toroidal magnetic field of 3.0 T, a plasma current of 1 MA, poloidal and toroidal injection angles of 17° and 14°, respectively. The injected beam (blue) with mainly O-mode polarization is partially absorbed at the first harmonic resonance (green). The cross polarized beam fraction (X-mode) is reflected at the X-mode cutoff.

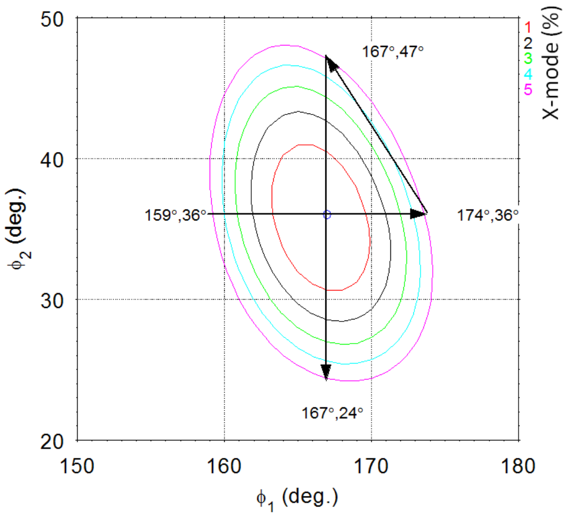

Fig.8 Calculated X-mode content as a function of polarizer mirror angles for B_t = 3.0 T, I_p = 1 MA, poloidal and toroidal injection angles of 17° and 14°, respectively. The polarizer scan is indicated by the arrows.

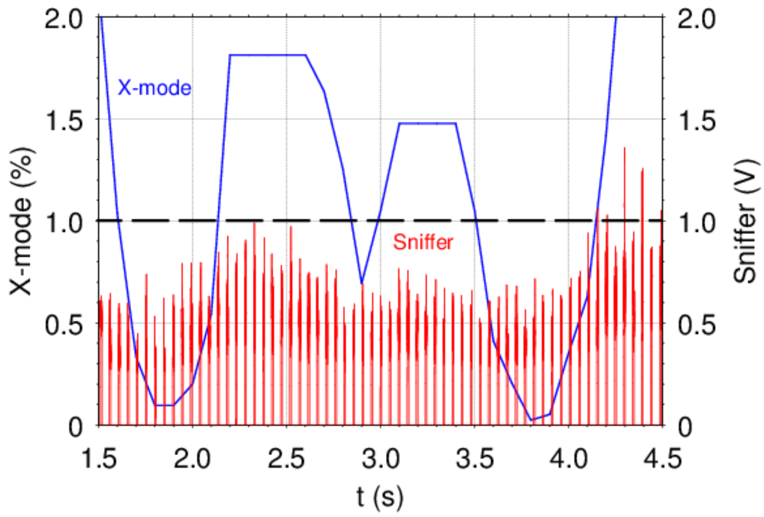

Fig.9 Measured sniffer signal (red) compared to the calculated X-mode content (blue) for the polarizer scan given in Fig.7. The typical stray radiation threshold level where the ECRH system is switched off is indicated by the dashed black line. This interlock was disabled for this modulated test pulse.

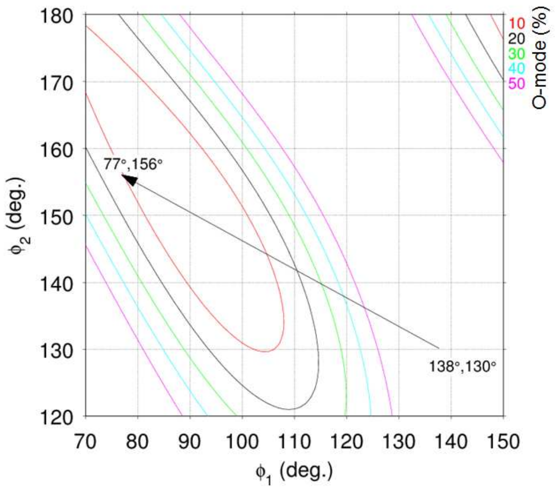

Fig.10 Calculated O-mode content as a function of polarizer mirror angles for B_t = 2.5 T, I_p = 0.8 MA, poloidal and toroidal injection angles of 32° and 10°, respectively. The polarizer scan is indicated by the arrows.

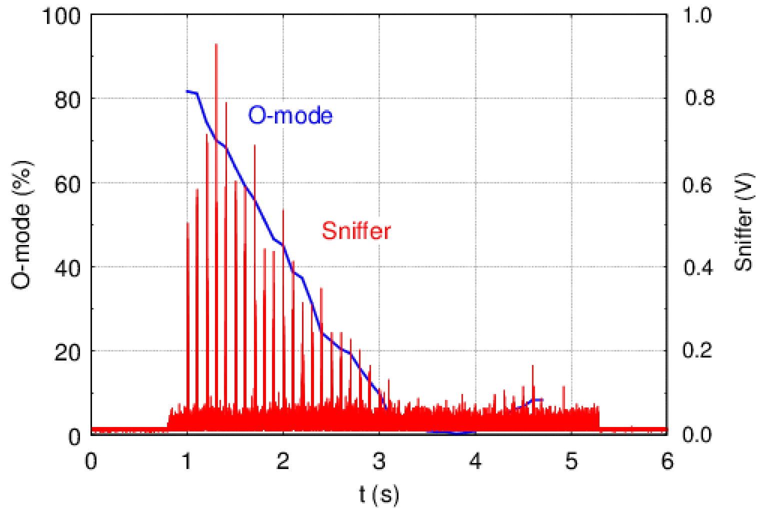

Fig.11 Measured sniffer signal (red) compared to the calculated O-mode content (blue) for the polarizer scan given in Fig.9.

4. Summary

The AUG ECRH system is operating with eight gyrotrons. In the coming years four older tubes will be replaced with two-frequency gyrotrons (105/140 GHz, 1 MW, 10 s). The operational range with respect to the magnetic field and electron density could be increased by applying other heating scenarios than the standard second harmonic X-mode scheme. In particular O1- and X3-heating scenarios are possibly applying 105 GHz. The absorption for O2-heating at 140 GHz could be increased by applying special tiles with a holographic grating on the inner column of AUG. A real-time control scheme using thermocouples incorporated in these tiles was developed to control the beam positioning on the reflectors during plasma discharges. The steerable ECRH launchers allow also for feedback controlled stabilization of NTM’s.

5. Acknowledgement

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