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ECRH on ASDEX Upgrade
- System Status, Feed-Back Control, Plasma Physics Results -

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Abstract. The ASDEX Upgrade (AUG) ECRH system now delivers a total of 3.9 MW to the plasma at 140 GHz. Three new units are capable of 2-frequency operation and may heat the plasma alternatively with 2.1 MW at 105 GHz. The system is routinely used with X2, O2, and X3 schemes. For B_t = 3.2 T also an ITER-like O1-scheme can be run using 105 GHz. The new launchers are capable of fast poloidal movements necessary for real-time control of the location of power deposition. Here real-time control of NTMs is summarized, which requires a fast analysis of massive data streams (ECE and Mirnov correlation) and extensive calculations (equilibria, ray-tracing). These were implemented at AUG using a modular concept of standardized real-time diagnostics. The new real-time capabilities have also been used during O2 heating to keep the first reflection of the non-absorbed beam fraction on the holographic reflector tile which ensures a well defined second pass of the beam through the central plasma. Sensors for the beam position are fast thermocouples at the edge of the reflector tile. The enhanced ECRH power was used for several physics studies related to the unique feature of pure electron heating without fueling and without momentum input. As an example the effect of the variation of the heating mix in moderately heated H-modes is demonstrated using the three available heating systems, i.e. ECRH, ICRH and NBI. Keeping the total input power constant, strong effects are seen on the rotation, but none on the pedestal parameters. Also global quantities as the stored energy are hardly modified. Still it is found that the central ion temperature drops as the ECRH fraction exceeds a certain threshold.

1 Introduction

This paper summarizes progress on the ECRH system of ASDEX Upgrade and its applications since the last workshop of this series [1]. The limited space does not allow a discussion of all aspects, so we restrict ourselves to some examples and many references otherwise. Since the three following sections are quite disjunct in content an outlook will be given at the end of each section and a conclusive common section is skipped.

The ECRH system of AUG consists of two parts: four units each delivering 0.5 MW at 140 GHz for 2 s, in the following called old system or ECRH-1 [2] and four new units (out of which three

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are operational) each delivering 1 MW at 140 GHz or 0.8 MW at 105 GHz, both for 10 s, in the following called new system or ECRH-2 [3,4]. Both systems operate with air-filled 87mm corrugated waveguides.

2 System Status

The old system is still routinely operated especially when high power levels are requested. Major developments in the last years concentrated on the new system. Since the last workshop units 2 and 3 were taken into operation and were used in the 2011 campaign. The maximum power deposited with both systems together was 3.9 MW.

Initially it was intended to develop a multi-frequency system. The gyrotrons are capable to generate significant output power at 9 different frequencies [5], but the problems related to the gyrotron and torus windows were initially underestimated. So far the only viable concept is a dual-frequency gyrotron making use of the neighboring Fabry-Perot minima inherent to a single diamond disk. In our case the thickness of the diamond disc corresponds to $4 \times \lambda/2$ for 140 GHz and $3 \times \lambda/2$ for 105 GHz. Several concepts to reduce reflectivity for intermediate frequencies were considered. At the last meeting the failure of a Brewster-type gyrotron-window was reported and grooved diamond surfaces were envisaged in order to generate anti-reflective coatings at intermediate frequencies [6]. Stress analysis revealed meanwhile that such groves reduce the mechanical strength of the disk by a factor of three [7] such that a pressure difference of 1 bar is too close to the mechanical limits. Therefore this concept has been aborted. As a final option for this project, the window of the forth gyrotron will be mounted with its surface normal inclined by 15 degrees with respect to the output beam. This allows to mount a feedback-controlled ring resonator on the other side of the window, which shall minimize the effective reflection of the window for any intermediate frequency [8]. This resonator is equipped with a second similar disk in the microwave beam and a mirror system which allows a controlled interference of the reflection from the second and the first window. The gyrotron shall be installed at IPP before the summer break 2012. It will first be used as 2-f unit without resonator during the ongoing AUG campaign and the resonator shall be attached and tested in early 2013.

Meanwhile the multi frequency double-disk torus-window [9] has been tested in beam-line number two, although only for one of the two frequencies for which each single disk should be resonant (i.e. 140 GHz). It is noted that the single-disk resonance and the gyrotron frequency were detuned by approximately 0.3 GHz, for which the reflection should still be below 1%, a value considered as critical level. The air-pressure exposed disk cracked after pulses of approximately 600 kW and 4 s. This window was mounted with a tilt of two degrees in order to prevent any reflections to re-enter the gyrotron. Post-mortem analysis showed that such a tilt increased the stray radiation leaving the space between the two disks radially by a factor of 8. These disks were each cooled from one side only, using concentric cylinders brazed on the one side of the disk. Any stray radiation between the disks can enter these cooling channels directly through the diamond disk. A speculation goes that the additional stray radiation related to the frequency mismatch and the two degrees inclined window was sufficient to create a water vapour bubble, which was stabilized in the stream of cooling water by its buoyancy in the upper region inside the horizontally mounted cylinders. The temperature difference between the water vapour and the cooling water finally cracked the diamond disk due to thermal stress. Without having done the numerical analysis of thermal stresses and stray radiation, this speculation still lacks any definite proof. As an intermediate solution it was decided to equip all new ECRH-2 launchers with 2-f single-disk windows. The upcoming multifrequency gyrotron would, in a first step, be used to test any modification of the second (and only remaining) double-disk window in a test stand using the long-pulse load rather than the AUG plasma. Only after successful long-pulse tests this window would be mounted on AUG. We note here that above indicated ring-resonator design of a multi-frequency window is polarisation independent and therefore also suited for torus windows. Space limitations at the torus do prevent in the AUG-specific launcher design the mounting of such a ring resonator instead of a double disk window.

In addition to the expected power upgrade related to the last gyrotron for the ECRH-2 system, it has been decided to replace the ECRH-1 system with a third ECRH system similar to the ECRH-2

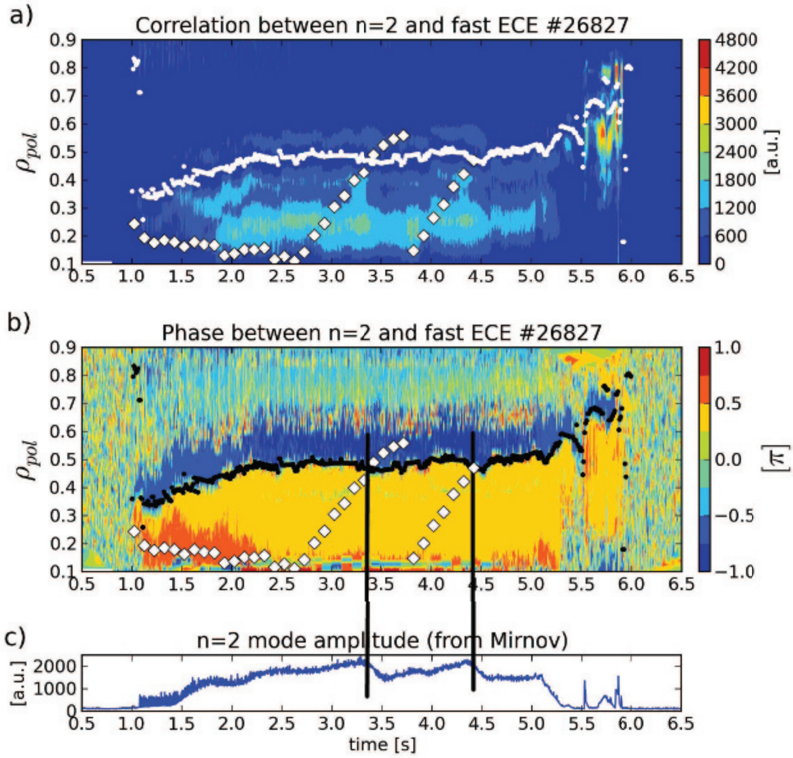

Fig. 1. (from [15]) a)+b) n=2 and ECE-temperature correlation, ECCD location from RT-Torbeam (white diamonds). a) Amplitude between ECE and Mirnov and calculated NTM location (white dots). b) Phase between ECE and Mirnov and calculated NTM location (black dots). c) Island-size estimate from envelope of n=2 signal (Mirnov).

(4x1MW, 10s, 105 and 140 GHz). First calls for tender just have started. The new system which is built in a new location will reuse upgraded ECRH-1 launchers. It is planned to be fully operational by end 2016.

For completeness, it is mentioned here that first plasma experiments have started using a fast directional switch (FADIS) on AUG [10], which, in a second step, shall also be used for in-line ECE [11]. Crucial for this application is a feedback-control of the FADIS resonator to compensate thermal drifts [12].

3 Feed-Back Control

Both systems allow power control by the discharge control system (DCS). For the new launchers the movement around one axis (mainly poloidal) is fast ($\approx 1^\circ/10$ ms) and can also be controlled via DCS. The movement around the other axis (as well as both movements of the old launchers) are slow and are presently not included in DCS. The goal defining the feedback requirements was the stabilization of NTMs [13, 14].

3.1 NTMs

The physics and the stabilization of neoclassical tearing modes (NTMs) have been widely discussed in literature. These helical islands short-cut radial transport and are precursors to disruptions. Especially for the latter reason their stabilization is highly desirable in ITER and future reactors. The stabilization

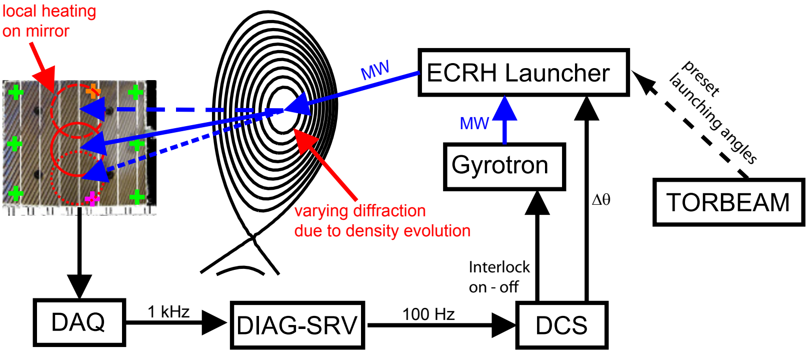

Fig. 2. Sketch of the feedback scheme used during O2 heating with the first reflection on a specifically designed tile. For details see text. DAQ means data acquisition and DIAG-SRV refers to the new layer for real-time diagnostics. DCS means discharge control system. TORBEAM refers to a beam-tracing code [19].

has been demonstrated on several devices using ECCD in proof-of-principle experiments as well in feedforward as in feedback set-ups. A robust universal feedback system using several launchers with different launching geometries has not been reported yet. Any feedback system consists basically of two parts, i.e. the identification of the resonant surface and the localisation of the ECCD. In principle the system has to locate the ECCD on the resonant surface with sufficient accuracy. If the accuracy is not high enough additional feedback loops may be necessary. It is possible to feedback on the mode amplitude but this becomes difficult if more than one parameter has to be controlled, for example two launching angles for beam lines with non-equivalent geometries as in AUG or ITER. Alternatively, separate in-line ECE systems may be used [16] for non-equivalent launchers.

On AUG a new concept of a real-time diagnostic layer supporting DCS has been triggered by the NTM-stabilization project. These diagnostics operate from separate systems on a common shared memory from which and in which they read and place their data. Major components are an equilibrium solver [17], density profile from interferometry [18], ray-tracing for all ECRH-beams and a correlation analysis of the 60 new fast ECE channels with the n=2 component (for (3,2)-NTMs) or the n=1, m=2 component of the Mirnov-signals [15]. Figure 1 summarizes the level reached so far: the ECE-Mirnov correlation allows reliably to localize a (3,2)-NTM. The launcher slowly crosses the resonant surface two times in its feedforward movement. These crossings correlate with a reduction of the NTM amplitude. During this reduction the flux surface for which the real-time ray-tracing predicts the maximum of ECCD coincides with the flux surface on which the ECE-Mironv correlation predicts the resonant surface. As soon as all systems are available in the 2012 AUG campaign the feedback circuit will be closed.

3.2 O2-Heating

During the last workshop a concept to use O2-heating in AUG with specific reflectors on the inner heat shield was presented [20]. The reflector allows to reach a central absorption of more than 90% although the single pass absorption only reaches 70%. This concept was realized as planned. In the context of real-time control we address here the issue of keeping the beam on the reflector in case that the density profile changes or has an unexpected profile, such that diffraction differs from the a priori anticipated situation. One option would be to use above mentioned real-time ray-tracing. For safety reasons a more direct appoach was favoured in this context making use of very fast thermocouples (< 10 ms) implemented along the edge of the reflectors. The feedback scheme [21] is visualised in figure 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 elements 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. Figure 3 shows an example for which the beam was launched intentionally towards the lower

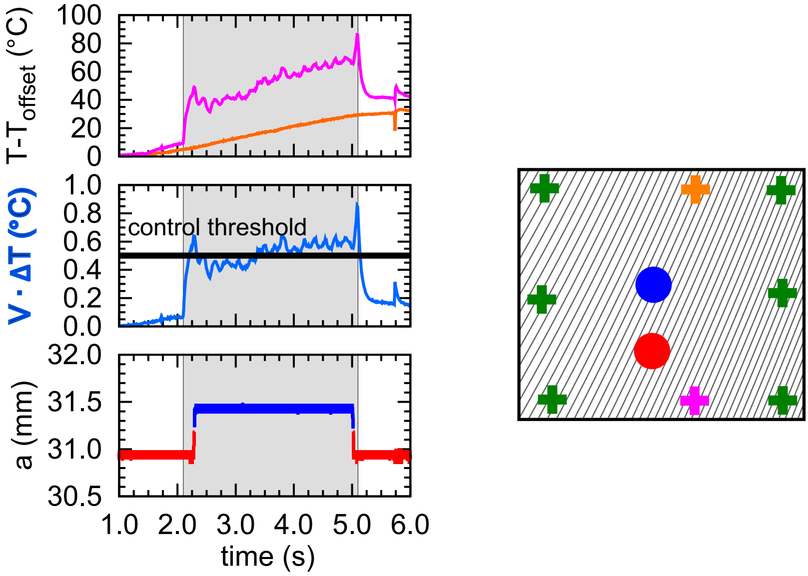

Fig. 3. Right: sketch of reflector tile with positions of thermo couples (crosses) and beam positions (circles) for two launcher positions. Left: Temperatures measured at the magenta and orange cross (top). Weighted difference signal which DIAG-SRV sends to DCS, which acts when a threshold (red) is exceeded (middle). Position of push-rod driving the poloidal launching angle. 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.

edge of the tile. DCS immediately corrects the mirror position as the temperature difference rises. 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 phase. In the context of O2 heating we note here that new diagnostics for the monitoring of stray radiation were developed on ASDEX Upgrade since the last workshop. They are presented in [22].

4 Plasma Physics Results

A large fraction of the AUG plasma physics programme uses ECRH and we have to refer here to the major conferences. The upgrade of the ECRH power on AUG has triggered additional plasma physics studies, for example on intrinsic rotation and momentum transport in L-mode and H-mode [23] and on L/H-mode transitions at low density [24]. In the following a comparison of the effects of different heating mixes on transport in H-mode is discussed.

In contrast to ITER and future fusion reactors, plasmas used today for preparational or fundamental studies are often heated dominantly via the ion channel and with strong concurrent momentum input. This is due to the dominance of NBI heating systems, which are widely used because of their reliability and universal applicability. The potential danger of this approach is an over-estimation of the scaled fusion performance, which depends on T_i and not T_e, but the ratio of these temperatures may depend on the heating mix. Even worse, an increasing value of T_e/T_i is expected to increase the ITG dominated turbulent transport in the ion channel reducing T_i further [26]. Additionally, the significantly reduced torque of future NBI-systems may increase transport due to a reduction of rotational shear. To clarify above mentioned uncertainties it is important to study the effect of dominant electron heating with a minimum of momentum input. At ASDEX Upgrade such studies have been started using the upgraded ECRH system, the available power exceeding the minimum H-mode power threshold for typical high I_p, B_t conditions by a factor of two. Additionally, 6 MW of ICRH and 20 MW of NBI are installed at AUG. H-mode plasmas have been studied in which the heating mix between the three available

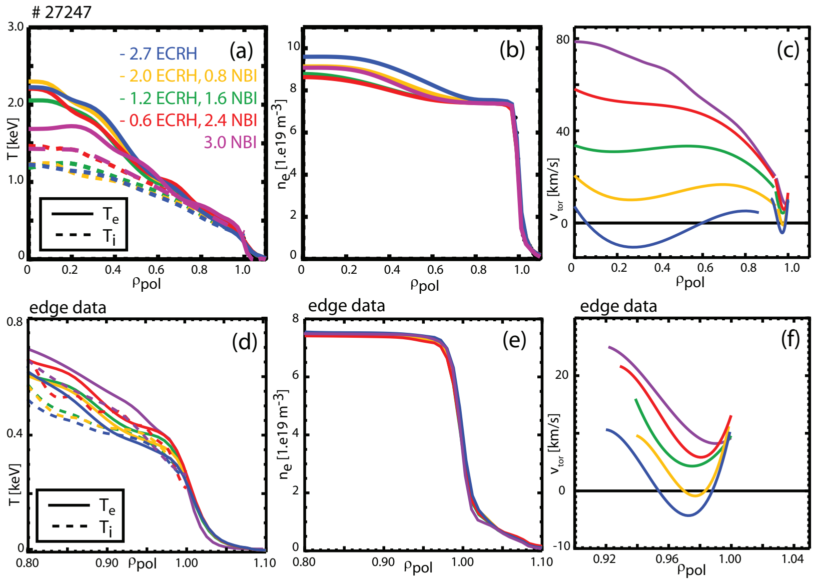

Fig. 4. (from [25]): Averaged kinetic profiles of discharge #27247 during different heating phases: (a) electron (solid) and ion (dashed) temperature; (b) electron density; (c) toroidal rotation; NBI-only profiles (purple) taken from discharge #26457; (d), (e), (f) edge data, note different ρ_{pol} scale for (f).

systems is varied while keeping the total heating power constant. This was done for several different levels of total heating powers. Typical results for the comparison of ECRH and NBI are shown in fig. 4. The collisionality is close to unity, i.e. much higher than in ITER, which is due to moderate heating power and high density ($0.7 \times n_{GW}$). Significant plasma current (1 MA) was used in order to keep some relevance in q_{95}. The value of q_{95} was ≈ 4.4 for most experiments using X2-heating at 140 GHz, while some were also performed with X3-heating at 140 GHz, which allowed q_{95} to be reduced to 3.0 as will be the case in ITER. The core and edge profiles corresponding to the different phases shown in fig. 1 illustrate the major findings: no effect of the heating mix on pedestal pressure although plasma rotation varies significantly, no direct correlation of the rotational shear with the shape of density or temperature profiles, and a significant increase of T_e/T_i as the fraction of electron heating exceeds a certain threshold. Kinetic profiles (n, T, v, E) are measured using the recently upgraded suite of diagnostics in the core and, with high spatial resolution, in the pedestal region, allowing small variations to be resolved with significant resolution. In the context of this workshop we explicitly refer to a refined analysis of the ECE-channels in the steep gradient zone at the plasma edge [27]. Although the collisionality and therefore the heat exchange between ions and electrons is rather high, variations in T_e and T_i can be sufficiently well resolved such that the heat fluxes in the ion and electron channel can be significantly separated, at least for the inner half of the plasma radius. Experiments have started to extend the study towards significantly higher total heating powers in order to reduce collisionality. For such total heating powers, ECRH-only heating will not be possible with the current ECRH power. Since our results so far indicate that changes in the ratio of T_e/T_i occur at moderate ECRH-fractions and seem to saturate at higher fractions (fig. 1), we expect that the limitation in ECRH power is not a significant constraint for this extension of the study.

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