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Dual array 3D electron cyclotron emission imaging at ASDEX Upgrade\textsuperscript{a)}

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In a major upgrade, the (2D) electron cyclotron emission imaging diagnostic (ECEI) at ASDEX Upgrade has been equipped with a second detector array, observing a different toroidal position in the plasma, to enable quasi-3D measurements of the electron temperature. The new system will measure a total of 288 channels, in two 2D arrays, toroidally separated by 40 cm. The two detector arrays observe the plasma through the same vacuum window, both under a slight toroidal angle. The majority of the field lines are observed by both arrays simultaneously, thereby enabling a direct measurement of the 3D properties of plasma instabilities like edge localized mode filaments. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4891061]

I. INTRODUCTION

Since the first 2D electron cyclotron emission imaging (ECEI) system at the TEXTOR tokamak,\textsuperscript{1} ECEI systems have been installed at ASDEX Upgrade,\textsuperscript{2} DIII-D,\textsuperscript{3} KSTAR,\textsuperscript{4} (where two toroidally separated systems enable 3D measurements\textsuperscript{5}) and EAST.\textsuperscript{6} ECEI has contributed to the understanding of a wide range of plasma instabilities like edge localized modes,\textsuperscript{7–10} tearing modes,\textsuperscript{11} the sawtooth instability,\textsuperscript{12} and Alfvén eigenmodes.\textsuperscript{13, 14}

In an ECEI system, multiple lines of sight (LOSs) are simultaneously quasi-optically imaged onto a linear array of detectors. Each LOS is treated like a 1D heterodyne ECE radiometer. This results in a 2D measurement of the electron temperature, radially resolved due to the frequency resolved measurement of the ECE intensity along each line of sight, and vertically resolved due to the multiple LOSs.

In a major upgrade, the 2D ECEI at ASDEX Upgrade has been equipped with a second detector array, observing a different toroidal position in the plasma. This paper describes the properties of the upgraded dual array ECEI system and discusses the capabilities of the system to perform (quasi-)3D measurements of plasma instabilities like the edge localized mode (ELM).

II. 3D ECEI AT ASDEX UPGRADE

The updated system measures a total of 288 channels, in two toroidally separated 2D arrays with 16 (vertical) by 8 (horizontal) channels and 20 by 8 channels, respectively.

The two detector arrays observe the plasma through the same vacuum window, both under a slight toroidal angle (in opposite toroidal direction, see Figure 1), and share the optics. The typical deviations from perpendicular observation are 14° and 11°, respectively (depending on the major radius; smaller deviations at the low field side edge and larger deviations at the high field side). Before the upgrade, array 1 (the “old” array) was positioned centrally. The toroidal separation between the two poloidal observation planes is about 40 cm (at the major radius of the focal plane), which is the maximum distance allowed by the space constraints of the vacuum port, see Figure 1.

A. Front side optics

The front side optics consist of three high density polyethylene (HDPE, index of refraction 1.52) lenses, two of which are shared with a 60 channel 1D ECE radiometer (see Figure 2). A beam splitter (dielectric foil) separates these two diagnostics. The movable lens, used to shift the focal plane radially, consist of two halves that move independently, enabling independent focusing of the two arrays. The beams of each array only pass through one of the halves. The focal plane can be positioned between the low field side edge and the plasma center.

The observation areas in the plasma are centered on the plasma mid-plane, and have a vertical coverage of 40 cm for array 1 and 50 cm for array 2 (due to more LOSs). The radial coverage for both arrays is the same, around 10 cm, although array 2 has the option to measure with a higher radial resolution (narrower coverage) as discussed in Subsection II B.

To filter out the lower side band in the first down-conversion step (mixing plasma and LO beams at the detector diodes) quasi-optical dichroic plates are used as high pass filters. A single linear translation stage is used to exchange...
plates with different cut-off frequencies for both arrays simultaneously (via remote control). For each array, the filter changer can only be equipped with three plates simultaneously. Manual changing of plates is possible between plasma discharges.

Both arrays are protected against 140 GHz electron cyclotron resonance heating (ECRH) stray radiation by three quasi-optical notch filters with a combined rejection of about 60 dB. Operation during unabsorbed 105 GHz ECRH is possible for local oscillator (LO) frequencies above 105 GHz, using the dichroic plates to block any stray radiation.

B. Arrays and IF electronics

The properties of array 2 have been chosen to largely match the properties of array 1 (see Ref. 2 for a description) for compatibility. The vertical spacing between the detector diodes and the diameter of the substrate lenses is the same. Twenty diodes (compared to 16 for array 1) result in a larger vertical coverage. Distinct from array 1, array 2 has an internal beam splitter to couple the LO beam in. Half of the 20 detector diodes are in the transmission branch of the beam splitter, half of them in reflection, thereby avoiding the staggered layout as used in array 1 which caused a slight toroidal shift between the even and odd channels. The LO power is coupled from the side of the array box, and the plasma beams from the bottom. The detectors simultaneously act as mixers. The down-converted IF signal from the diodes is pre-amplified and transmitted (with low loss coaxial cables) to the IF electronics.

In the IF electronics modules, the IF signal is divided into 8 portions (giving 8 radial channels per LOS), that are subsequently mixed with 8 local oscillator signals in a second down-conversion step and finally band pass filtered (setting the IF bandwidth). The IF modules for array 1 have a 700 MHz IF bandwidth, and a channel spacing of 800 MHz. The IF bandwidth for array 2 is 390 MHz. The channel spacing for array 2 can be changed between 800 MHz and 550 MHz (see Table I for the central IF frequencies of the 8 radial channels). The reduced IF bandwidth is beneficial for the measurement of very localized structures like turbulence. The minimal measurable structure size is set by both the radial resolution of about 2 cm (determined by both plasma broadening and IF bandwidth, see Sec. II E) and the poloidal spot size of about 2.5 cm.

C. Local oscillators

Array 1 uses a synthesizer with amplifier multiplier chain (AMC) as LO. This source can deliver a minimum of 100 mW of output power over the frequency range between 105 and 115 GHz. Array 1 uses an external beamsplitter to couple the
LO beam in (see Figure 2). Two HDPE lenses (not shown) shape the LO beam to a narrow elongated parallel beam.

Array 2 uses a backward wave oscillator (BWO) as LO source. The BWO is frequency tunable between 90 and 140 GHz, and delivers typical power levels of 100 mW. A setup of two HDPE lenses and four flat aluminum mirrors is used to shape the LO beam to an elongated narrow beam and guide it from the BWO to the side of the array box (internal beam splitter). The beam paths of both LOs are completely separated by shielding to avoid illumination of the wrong array.

The power and frequency of both LOs are remotely controlled. Due to the limited number of available dichroic plates, the number of useful frequency settings is restricted. Table I shows the available frequency settings for both LOs. For 3D measurements, both LOs will be tuned to (nearly) the same frequency. By tuning the LOs to two different frequencies, 2D measurements with extended radial coverage are possible. As there is only one dichroic plate changer for the two arrays, independent tuning of the LOs is only possible by changing the selection of dichroic plates manually, which requires torus hall entry. In practice, either a plate selection optimized for 3D measurements or a selection optimized for 2D measurements will be chosen on a day to day basis.

### D. Data acquisition

A new 14 bit data acquisition system for all 288 channels (replacing the previous system with 128 channels) enables high sampling rate measurements (up to 909 kHz) for the full duration of the ASDEX Upgrade discharges (10 s). The old data acquisition system was limited to 2 s acquisition time at full sampling rate (full 10 s only up to 200 kHz). Using one data acquisition system for both arrays guarantees that all channels use an identical clock, which is especially critical for turbulence measurements (cross correlating channels from both arrays).

### E. Effects of oblique observation

The oblique observation of both arrays (typically 14° and 11° deviation from perpendicular observation, respectively) causes a slight degradation of the radial resolution due to an increased Doppler broadening. The full width at half maximum (FWHM) of the radial emission layer is around 1.4 cm for both arrays for typical ASDEX Upgrade plasma parameters (not taking into account the channel width set by the IF frequency) and is fairly independent of measurement radius. Before the upgrade (at perpendicular observation), the FWHM of the emission layer was 0.9 cm. Note that the final radial resolution of the system is determined by both the plasma broadening and the IF bandwidth $B_{IF}$. The broadening due to the finite IF bandwidth is about 7 mm for the new system ($B_{IF} = 390$ MHz), and was 13 mm before the upgrade ($B_{IF} = 700$ MHz). Hence, the overall radial resolution is about 2 cm and has not changed significantly with the upgrade. Apart from the broadening, the emission layer is also shifted radially outward by about 1.6 cm with respect to perpendicular observation.

### III. 3D CAPABILITIES

Due to the pitch of the magnetic field lines, a field line crossing one observation plane will cross the other one with typically 10 cm vertical difference (see Figure 3). For a given equilibrium, the field line pitch does not vary strongly between the different flux surfaces (hence measuring the pitch with 3D ECEI does not constitute a measurement of $q$). As the observation plane of array 2 is taller than the observation plane of array 1, almost all field lines seen by array 1 are simultaneously observed by array 2, thereby enabling a direct measurement of the 3D properties of plasma instabilities like ELM filaments. The toroidal separation of 40 cm is sufficient for the accurate measurement of both phase differences and transit times of (rotating) plasma structures, enabling a distinction between time varying 2D structures and true 3D structures (not possible with 2D diagnostics).

If a rotating toroidally localized structure passes by, the structure will be observed with a measurable time delay by the second observation plane. For structures whose life time is well above this transit time, a full 3D characterization is possible. Both the velocity and toroidal extent of such structures can be derived. The smallest measurable transit time is just over 1 μs, so parallel velocities up to 400 km/s can be resolved, which is above the toroidal plasma velocities typically observed at ASDEX Upgrade.

The two arrays are toroidally separated by about $\Delta \phi = 10^\circ$ when measuring at the low field side edge and $\Delta \phi = 17^\circ$ when measuring in the plasma center. The maximum toroidal mode number that can be resolved is hence $n = 18$ at the edge and $n = 10$ in the plasma center. In order to accurately identify the correct toroidal mode number, the phase difference of fluctuations between the two arrays has to be measured with an accuracy better than $\Delta \phi$ (the measured phase difference for an $n = 1$ fluctuation is $\Delta \phi$, for $n = 2$ $2\Delta \phi$, etc.).

The main application of the 3D ECEI diagnostic will be the characterization of the fluctuations associated with the ELM crash (precursor modes and filaments). The strong poloidal localization and complex spatiotemporal structure observed by 2D ECEI, as well as recent theoretical predictions indicate these structures are most likely to be the characterization of the fluctuations associated with the ELM crash (precursor modes and filaments). The strong poloidal localization and complex spatiotemporal structure observed by 2D ECEI, as well as recent theoretical predictions indicate these structures are most likely

**FIG. 3.** The vertical shift of magnetic field lines between the two arrays is typically around 10 cm and (for a given equilibrium) does not differ strongly between the flux surfaces. Field lines for $q = 2$ (green, at normalized poloidal flux $\rho_{pol} = 0.7$), $q = 4$ (yellow, $\rho_{pol} = 0.94$), and $q = 6$ (white, $\rho_{pol} = 0.97$) are shown (actual equilibrium of discharge 24 793).
toroidally localized. Apart from the research on ELMs, the diagnostic will contribute to Alfvén eigenmodes, turbulence, tearing modes, and the sawtooth instability.

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