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Utilization of collinear ECE detection/ECRH heating for active stabilization of plasma instabilities

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Abstract—**Experiments on TEXTOR have successfully demonstrated the proof of principle [1] of using Electron Cyclotron Emission (ECE) measured along the Electron Cyclotron Resonance Heating (ECRH) line-of-sight [2] for the control of magnetohydrodynamic (MHD) modes. This work, which was done with a quasi-optical system, motivates the further development and implementation of a similar, but in-waveguide system for detection and control of Neoclassical Tearing Mode (NTM) in larger fusion machines. Progress on the implementation of such a system on ASDEX-Upgrade [3], based on waveguides equipped with a Fast Directional Switch (FADIS), is presented. Since FADIS, will be installed at ASDEX, to switch the gyrotron power between different launchers [4], FADIS can also be employed as a frequency filter serving the purpose of separating a low-power ECE signal from the high power ECRH radiation as required in the co-aligned ECE-ECRH setup [5]. Because additional absorptive filtering is required after the FADIS ECE output in [5] and [6] a non resonant two-beam Mach-Zehnder–type interferometer was chosen. This system has been built and partially tested.**

I. INTRODUCTION AND BACKGROUND

Active stabilization of neo-classical tearing modes in fusion plasmas is needed for safe plasma operation close to the performance limits. Electron Cyclotron Resonance Heating and Current Drive (ECRH/CD) is proposed as the actuator in such a stabilization system. ECE Spectroscopy at frequencies around the gyrotron frequency can then be used as a sensor, to provide the feedback signals required to control the ECCD power deposition within the island's O-point with an accuracy of 1 to 2 cm. It has been demonstrated that a collinear ECE/ECRH system, in which the sensor is combined into the transmission line of the ECRH system [2], has the advantage that the sensed data can be readily interpreted without any assumptions on the plasma equilibrium [1], see Figure 1. Moreover, drifts in the system calibration and alignment are self-compensating. First successful tests of such a system were done on the TEXTOR tokamak in a quasi-optical transmission line. The measured ECE signal was used to actively feedback on the injection angle of the ECRH launcher and on the gyrotron and power. The challenge of a collinear system is that the typical signal level seen by the detector is on the nano-watt level, whereas the

ECRH systems work at the mega-watt level and strong filtering is needed to separate the gyrotron frequency from the ECE radiation in neighboring frequency channels.
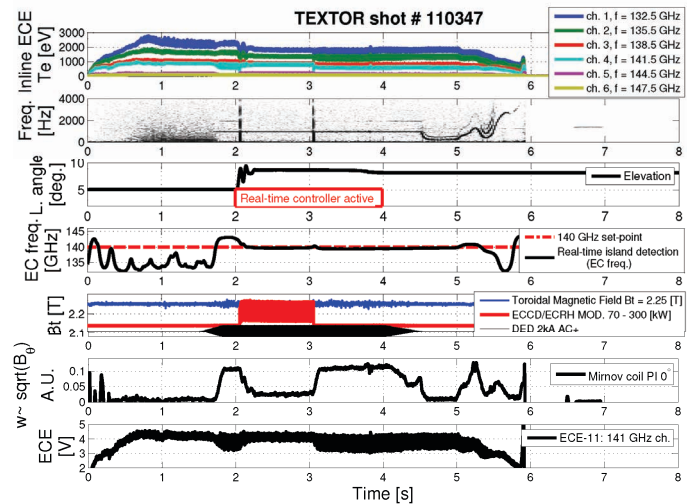

Figure 1 On TEXTOR the ECE is separated from ECRH/ECCD using a frequency selective dielectric quartz plate in the quasi optical transmission line. ECE is measured using a 6-channel radiometer (132.5-147.5 GHz) with 3 GHz spacing and a 0.5 GHz bandwidth [2]. The panels show subsequently: 6 electron temperature traces [1], the spectrum of ECE channel 2, the launcher elevation angle θ, alignment between 140 GHz ECRH frequency and the radial island location visualized in the EC frequency spectrum, B_t, the DED current, modulated ECRH/ECCD, an estimate of the tearing mode width as derived from a Mirnov coil signal and one ECE channel enlarged. Operation sequence of the real-time control system [1]: Tearing Modes (TM) observed as oscillation on ECE channels, island position determined from the counter phase between adjacent ECE channels, steering trajectory for the launcher derived and applied in real-time feedback loop. Automatic TM tracking and gyrotron triggering based on the alignment accuracy. Phase locked loop locks on TM rotation frequencies and modulates gyrotron (ECRH/ECCD) in phase with TM rotation. The applied ECRH/ECCD suppresses the tearing mode's size significantly.

Further development and the implementation of such a collinear ECE system for NTM control in larger fusion machines are required. As a first step a practical implementation of such a system is prepared for ASDEX-Upgrade, based on 87 mm corrugated waveguides equipped with a combination of FADIS and Mach-Zehnder separation/filter system.

II. REQUIREMENTS

In order to set the requirements for a collinear ECCD/ECE diagnostic for NTM feedback purposes on AUG, typical specifications in terms of the desired positional accuracy, resolution, and radial observation range for sensing of the magnetic islands must be translated into the ECE frequency domain. The minor radius of AUG is ~0.45 m; the major radius is 1.65 m. The maximum magnetic field strength is 3.1 T. For AUG experiments on NTM control, the 140-GHz ECCD resonance condition is typically met on the high field side at a normalized flux coordinate of ~0.7. The full-width ECCD power deposition profile is ~0.7 cm. This is very similar in size to the minimum island size that will have to be stabilized. The requirement on accuracy and resolution is therefore set to 0.7 cm, which corresponds to ~0.015 in normalized radial coordinate (or flux coordinate). A series of beam-tracing calculations for typical conditions of AUG show that the spatial requirement is met with an electron cyclotron frequency resolution of 1 GHz. To cover a ~20 cm range in plasma minor radius, a frequency range of the order of 20 GHz should be adequate. Thus, the requirements on the ECCD-aligned ECE diagnostic includes a total of 20 data channels with 1-GHz separation, centered around the ECCD frequency of 140 GHz.

Additional requirements, to be fulfilled, are that the separation system of the ECE from the high power transmission line has to accommodate possible frequency changes of the gyrotron (~300 MHz, see Figure 2), whilst providing sufficient attenuation ~50 dB in the oversized part of the diplexers to prevent breakdown of the standard waveguide notch filter protecting the ECE detection system (breakdown in the notch filter could result in unsuppressed transmission of gyrotron stray radiation and damage to the notch filter and or mixers of the radiometer).
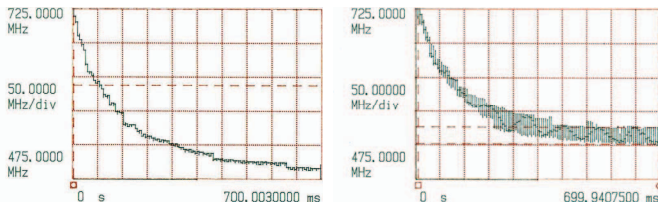

Figure 2 Frequency drop of the gyrotron during the start up without- and with power modulation. The ECE receivers must be protected by the system by synchronous tuning or a sufficient large notch range of the separation system.

III. PROPOSED CONFIGURATION

Since a Fast Directional Switch (FADIS) [4] based on the quasi-optical interferometer principle will be installed at ASDEX for switching the power of a step tunable gyrotron between different launchers, FADIS can be employed also as a frequency filter in a co-aligned ECE-ECCD setup serving the purpose of separating the low-power ECE signal from the high power ECRH radiation [5] and [7], see Figure 3.

Because the FADIS notch width is only a few MHz wide for at least 20 dB suppression, FADIS must be synchronously tuned to follow the center frequency of the gyrotron during the frequency droop of the gyrotron within the first seconds of its pulse (~0.3 GHz) to measure ECE during this period.
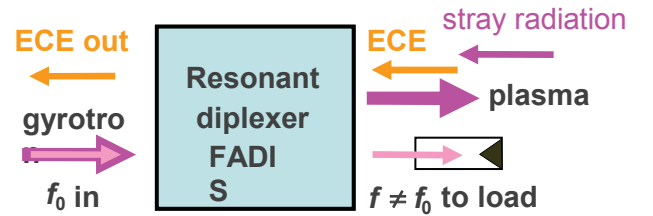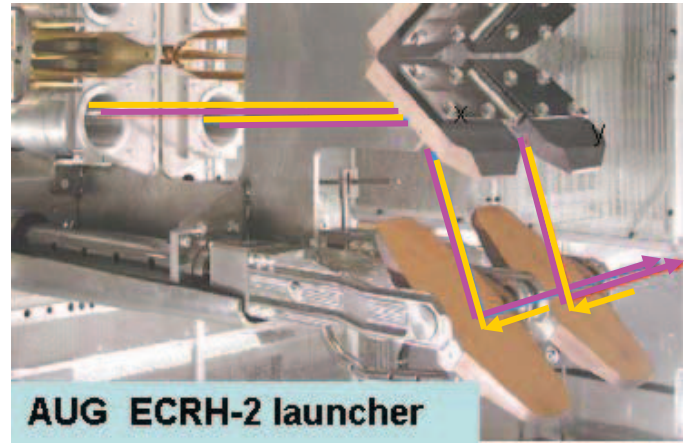

Figure 3 Upper: Launcher of ECRH-2 system at ASDEX Upgrade. Bottom: diplexer set-up for in-line ECE. The ECE receiver is connected, by a cascade of an additional oversized interference filter and a standard waveguide notch filter, to the port which is isolated with respect to the gyrotron input.

From [7] we conclude that the worst case situation for inline-ECE occurs if the error of the FADIS tuning is such that power is divided in equal parts at the outputs. In this case combined with mono-mode HE_{11} reflection at the plasma or at an arc in the transmission line, FADIS will suppress the reflected power fed back to the non resonant ECE output port by 6 dB. Multi-mode (scattered) reflection of plasma is no problem and results in 40 dB. During good synchronous tuning, FADIS will isolate the forward power on the ECE output with at least by 20 dB. In any case FADIS produces power levels in excess of ECE receiver loads. By employing a second oversized interference filter in tandem with the FADIS this problem can be overcome. However, in order to prevent interference and isolation decrease caused by back reflections of these filters, absorptive filters are the preferred solution. A good compact filter is a non resonant two-beam Mach-Zehnder-type interferometer [5] shown in Figure 4, coupled at the non-resonant output of FADIS.

This system is very flexible in customizing frequency filter characteristics. In the regime of the gyrotron frequency, the suppression notch width is only determined by the window thickness inside the beam splitters and independent of the phase lag path. The reason for this is that a maximum transmission is obtained at resonant frequencies while the phase lag path is switched off. Outside this frequency regime the beam splitters are operational and beating occurs between the frequency response of the interferometer and the window.

ECE out to radiometer by notch filter (3)

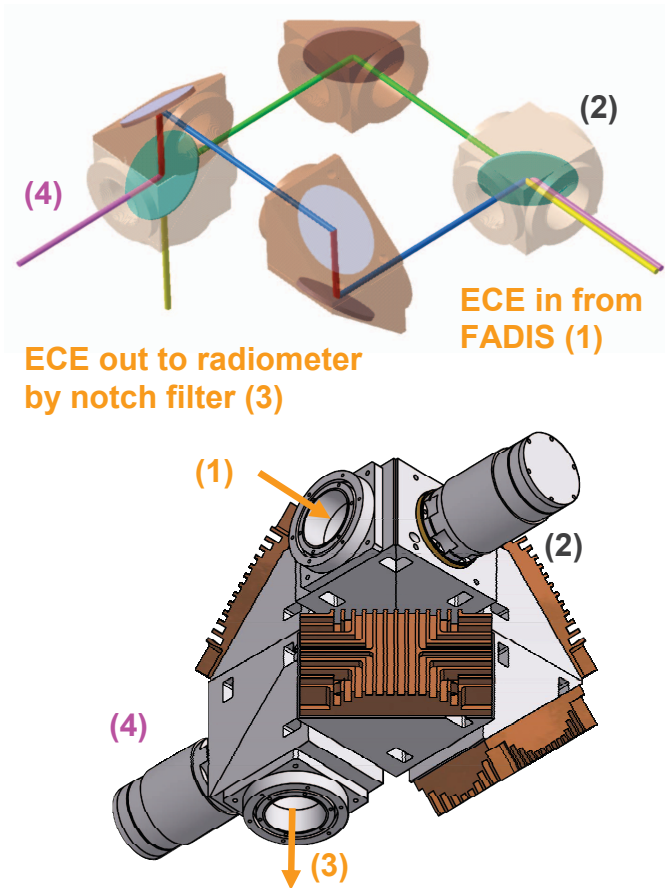ECE in from FADIS (1)

(2)

(4)

(1)

(2)

(4)

(3)

Figure 4 Exploded (top) and composed (bottom) view of the design of a polarization insensitive 4-port Mach-Zehnder-type two-beam interferometer. It is used as an absorptive separation filter, to separate the ECE diagnostic signal (yellow, route port 1-3) from the stray gyrotron radiation signal (purple, route port 1-4, signal goes from right to left). The interferometer consists of 2 beam splitters with windows (green) in opposite beam planes and 4 mitre-bends. As such,, a polarization insensitive configuration is made where the additional phase path (red) could be minimized to fit the required channel width of the ECE diagnostic in combination with FADIS. In this application, port 2 and 4 are terminated by Macor cone loads (bottom).

The Mach-Zehnder design has two equal beam splitters with the following properties of the windows: refractive index n=1.9506 and tanδ=2.9*10^{-4} (Quartz, Infrasil 301). The thickness of the windows, d=4.714 mm ± 1 μm, is chosen such that during the entire pulse (including startup) of the Elisey-1 gyrotron installed at ASDEX a Mach-Zehnder an attenuation of 30 dB on the actual gyrotron frequency is guaranteed.

IV.   SIMULATION AND MEASUREMENTS

To verify the properties of the beamsplitter, it was tested at IPF in Stuttgart, for transmission and reflection, see Figure 5.

The phase lag length is chosen such that the frequency periodicity of the Mach-Zehnder equals an integer number of the frequency periodicity of the chosen FADIS configuration and is optimized such that the average power integrated over the ECE channels of the radiometer is maximized. For a conventional ECE system around 140 GHz with 6 channels spaced by 3 GHz an optimal design in combination with FADIS (with 141.34 MHz periodicity) would result in Δf=424.03 MHz (3x141.34 MHz).
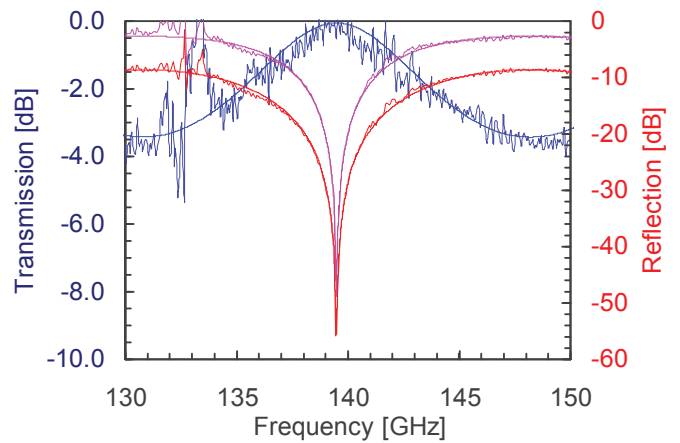

Figure 5 Calculation (smooth) and measurement (dithered) of the frequency response of the beamsplitter of the Mach-Zehnder interferometer. The transmission is given for the perpendicular polarization to the beamplane (blue) and the reflection for both the perpendicular- (purple) and parallel (red) polarizations. The calculations fitted to the measurements confirm the properties of the quartz and reveal an initial to large thickness of 4.729 mm average. This was confirmed by several precise thickness measurements over the surface and averaging them over the beam area.
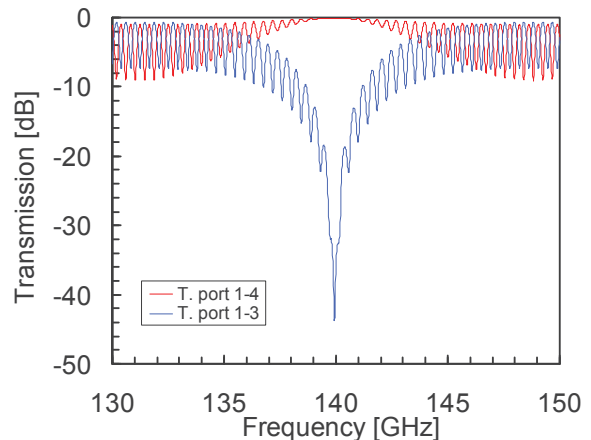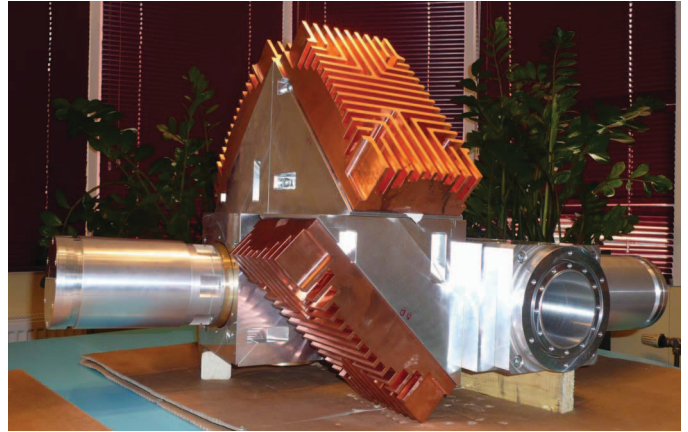

Figure 6 On top a picture of the polarization independent Mach-Zehnder-type two-beam interferometer build from a 87 mm corrugated oversized waveguide is shown. The input flange, the terminators and the cooled mitre bends are visible. Below the simulation results are given of route 1–3 (see also Figure 4) which offers a minimum of 30-dB suppression of the gyrotron stray radiation over a 0.3 GHz band caused by start-up frequency droop of the gyrotron (< 1 s time). Combination with a synchronously tuned FADIS gives at least 50 dB suppression on 140 GHz.

The quasi optical diplexer, used in the line-of-sight system at TEXTOR [2], had for each ECE channel a constant insertion loss of about 8 dB. In the proposed waveguide system, where FADIS is combined with the Mach-Zehnder interferometer, the attenuation, integrated over the frequency bands of the separate ECE Channels, at frequencies 132.5, 135.5, 138.5, 141.5, 144.5 and 147.5 GHz are respectively 2.5, 3.7, 10.8, 10.1, 4.0 and 3.1 dB, which is on average somewhat better.

The accompanying phase lag length is 0.7071 m which results in filler HE_{11} waveguides of 153.6 mm placed just before the 2 mitre bends (of 0.2 m path length each, see Figure 4 (top) in red trajectory).

The simulation result of the total Mach-Zehnder interferometer configuration is presented in Figure 6. The route 1–3 (Figure 4) offers a minimum of 30-dB suppression of the gyrotron stray radiation, coming from the tokamak, over at least 0.3 GHz band.

Although the combination with a synchronous tuned FADIS gives at least 50 dB suppression to the gyrotron power, the gyrotron should be interrupted if a reflected power of more than 5% is measured. This is necessary to prevent breakdown in the standard waveguide notch filter, which is placed after the oversized Mach-Zehnder, where, in worst case, the adjustment of FADIS by tuning is such that the power is equally divided at the FADIS outputs.

In [8] promising results are shown in high power experiments with a feedback/feedforward controlled FADIS equipped with output power sensors and a frequency sensor. FADIS was tuned on the slope to demonstrate fast and slow switching and tuned on the resonance dip for power combination and the line-of-sight application. In the latter, the aim was to stay tuned during the entire gyrotron pulse including start up.

V. Conclusions

At TEXTOR successful tearing mode control has been demonstrated using the line-of-sight ECE/ECRH concept. Novel elements for implementation of this in-line ECCD feed-back control system in a corrugated oversized waveguide transmissionline, were designed and tested. The proposed scheme combines a polarization independent two-beam interferometer absorptive filter in tandem with FADIS for separation of low-power ECE signals from high power ECRH radiation. Experimental results proof the attainability of this setup. Next development steps include demonstration of the system on AUG and a possible implementation for ITER.

VI. Acknowledgements

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