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Fast Fourier Transform based Diagnostics for Spectral Characterization of Millimeter Waves in Tokamaks

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Abstract— A Fast Fourier Transform (FFT) based wide range millimeter wave diagnostics for spectral characterization of scattered millimeter waves in plasmas has been successfully brought into operation. The scattered millimeter waves are heterodyne down-converted and directly digitized using a fast analog-digital converter (ADC) and a compact Peripheral Component Interconnect (cPCI) computer. Frequency spectra are obtained by FFT in the time domain of the intermediate frequency signal. The scattered millimeter waves are generated during high power Electron Cyclotron Resonance Heating (ECRH) experiments on the TEXTOR Tokamak and demonstrate the performance of the diagnostics and, in particular, the usability of direct digitizing and Fourier transformation of millimeter wave signals. Major benefit of the new diagnostics is a tunable time and frequency resolution due to post-detection, near-Real-Time processing of the acquired data. This diagnostics has a wider application in astrophysics, earth observation, plasma physics and molecular spectroscopy for the detection and analysis of millimeter wave radiation, providing high-resolution spectra at high temporal resolution and large dynamic range. Such a diagnostics also has the potential to detect Electron Cyclotron Emission (ECE) and to be used in Real-Time ECE feedback control systems.

I. INTRODUCTION AND BACKGROUND

In a Tokamak, which is the main route to fusion power plants, high temperature plasma is confined by magnetic fields, which form closed toroidal magnetic surfaces [1]. Fusion performance limiting instabilities can occur in these plasmas with for example the Neoclassical Tearing Mode (NTM). NTMs lead to a local loss of current in the islands.

The suppression of NTMs by high power Electron Cyclotron Waves (ECW) has been demonstrated on a number of Tokamaks. Absorption of these waves as well as Electron Cyclotron Emission (ECE) occurs in the region where the wave frequency is resonant with the electron cyclotron frequency or one of its harmonics. In Tokamaks, the relevant frequencies are of the order of 100 GHz. Suppression of NTMs is achieved by replacing the missing current inside the island by currents driven by the ECW power. Effective and efficient control of NTMs therefore requires accurate localization.

The TEXTOR Electron Cyclotron Resonance Heating (ECRH) installation [2] consists of a 140 GHz, 800 kW, 10 s gyrotron with steerable launcher. The installation features a pilot scheme of a line-of- sight feedback system [3] (In-Line), designed to detect the radial location of the island and the phase between O-point and X-point. In this scheme the ECW launcher is used as antenna to feed an ECE spectrum centered on the gyrotron frequency through the ECW transmission line into a radiometer.

During In-Line ECE measurements an unexpectedly strong millimeter wave signal was observed, limiting operation of the In-Line receiver. The nature of this spurious signal is yet unknown and is new physics [4]. By its frequency content it is shown to be no direct reflection of the ECH&CD waves from the plasma. Investigation of the origin of the spurious signals requires measurements at high frequency resolution, high temporal resolution and high dynamic range. Therefore a new dedicated diagnostics has been developed [5], using direct digitizing and post data acquisition, near-Real-Time (RT) processing based on Fast Fourier Transform (FFT).

II. SET-UP

The basic set-up of the diagnostics is a heterodyne frontend down converting the Radio Frequency (RF) band of interest (136-140 GHz) to the lower Intermediate Frequency (IF) band (DC-4 GHz). The signal is amplified by an amplifier (Noise Figure (NF) = 4.6 dB, Gain 34 dB) and filtered with an anti-aliasing filter on-board the analog to digital converter (ADC). The broadband IF signal is directly digitized with the high speed ADC and near-RT processed with Fast Fourier Transform (FFT) algorithms for frequency spectra. To retrieve a spectrogram with a range of 4 GHz, Nyquist states that a sampling rate of at least 8 GHz is required. Extensive research on the optimal component selection has been carried out,

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dominated by digitizer performance. The ADC of choice is an Agilent Technologies/Acqiris DC222 ADC, in combination with a compact Peripheral Component Interconnect (cPCI) dual core computer for near-RT signal processing. The ADC is operated and the signals are processed by LabVIEW®. Measurements are initiated by a predefined number of external hardware triggers, corresponding to the waveforms to be converted to frequency spectra.

III. Theory

In a FFT the frequency resolution Δf is determined by: $\Delta f = f_s / N$, with f_s the sampling frequency of the ADC and N the time domain number of samples in the waveform (series of acquired samples). For a fixed sample rate, the frequency resolution, dynamic range and waveform rate are dependent on the time domain sample size [5], resulting in a tunable frequency resolution and allowing for optimization of the time and frequency resolution. The least detectable power of an FFT based radiometer can be calculated with $P_{\min} = k_B f_s T_{total} \sqrt{1/N}$, where k_B is Boltzmann's constant and T_{total} the total equivalent noise temperature in Kelvin. The calculated equivalent noise temperature of this FFT radiometer is 3.5×10^4 K, giving a $T_{total} = 18 \times 10^6$ K.

IV. Results

Low power system tests showed compliance with the requirements [5]. The diagnostics is able to acquire 4 GHz wide spectra of signals in the range 136-140 GHz. The rate of spectra is tunable and has been tested between 200k spectra/s for a frequency resolution of 100 MHz, via 10k spectra/s (1.0 MHz frequency resolution) and 120 spectra/s with a frequency resolution of 25 kHz. The respective dynamic ranges are 63, 86 and 103 dB. This allows for ~ 1s record length, limited by the 2 GB RAM memory of the computer.

Validation and measurements on TEXTOR during high power ECRH pulses show the diagnostic is capable of detecting scattered signals [4]. In figure 1 time resolved frequency spectra of mm-wave radiation are shown. The dynamic ergodic divertor (DED) on TEXTOR is used to excite m/n = 2/1 tearing modes in the plasma. The island is rotating at a frequency of 2 Hz, and moved with the DED through the observation region of the In-Line ECE system. The scattering is in phase with the island rotation [4]. The dark blue spacing from 50 ms to 280 ms is showing the calibrated noise floor as well as reflected gyrotron signals. The yellow line in this time interval is the gyrotron frequency, being suppressed over 120 dB. The green line is a harmonic of the gyrotron.

V. Discussion and Future Work

An FFT millimeter wave diagnostics for high frequency resolution and high temporal resolution research has been developed. A heterodyne front-end is combined with an 8 GHz high speed ADC from Acqiris/Agilent Technologies. Validation tests show that the performance of the diagnostic matches or exceeds the requirements that were defined.

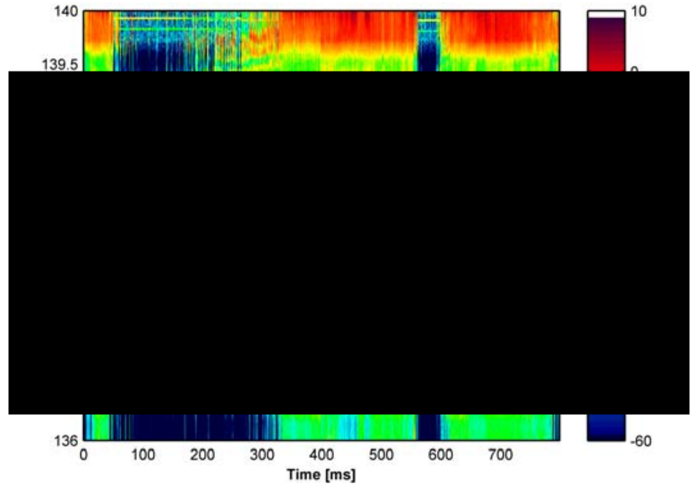

Figure 1 Plot of time-resolved frequency spectra of mm-wave radiation in the TEXTOR Tokamak, shot number 108086. The DED is used to move the magnetic island slightly back-and-fourth through the observation region with a frequency of about 2 Hz. The thin yellow/green lines in the 139.8 GHz range are the reflections on the plasma of the gyrotron and one of its harmonics. The gyrotron signals are being suppressed more than 120 dB. The frequency resolution is 0.2 MHz with a time resolution of 1 ms. The dynamic range of signal power exceeds 60 dB.

Future work on improved FFT millimeter wave diagnostics includes:

- Use of a 140 GHz phase locked oscillator to decrease local oscillator noise in the IF components;
- Optimizing the SNR by replacing the current mixer (Conversion loss ~15 dB) and amplifier for low noise, broadband components (NF_{mixer} ~ 5 dB, NF_{amp} ~ 1 dB) in order to be able to detect ECE;
- Optimizing software, memory and (multi core) processor settings for both increasing the amount of data stored and to explore the possibility of RT (10kHz) data processing;
- Combination with the In-Line ECE system on ASDEX-U [6] could result in an ECE feedback system with tunable spatial resolution.

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