Microwave experiments on the tokamak CASTOR: fundamental ECE radiometry

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Theoretical models of EBW conversion mechanism are verified on Castor with simulated overdense plasma. Direct EBW–X conversion has been detected by a recently constructed ECE radiometer 17÷40 GHz with a perpendicularly positioned antenna. The crucial role of plasma edge density gradient has been confirmed.

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1 Introduction

The CASTOR tokamak is a small tokamak operating in Prague ($R = 40$ cm, $r = 10$ cm, $a = 8.5$ cm, $B_t = 1.35$ T, $n_0 \leq 2 \times 10^{19}$ m^{-3}). A microwave 32 channel frequency scanning radiometer 17÷40 GHz was constructed. The object of investigation is the Electron Cyclotron Emission (ECE) at the fundamental harmonics by means of Electron Bernstein Wave (EBW) conversion. It follows from calculations that edge plasma properties strongly influence the conversion efficiency. Controlled plasma density and magnetic fields are used to meet predicted conditions. Recent results of ECE radiometry are presented in this paper. Other effects observed during the experiments, as MHD instability and influence of plasma edge biasing, are also shown.

2 Radiometer design and operation

The frequency range of the radiometer was chosen to cover ECE at the fundamental harmonics when the toroidal magnetic field of the Castor is lower than the standard one. The combination of the low magnetic field and achievable plasma density approaches conditions in overdense plasma: $f_{\mathrm{pe}}/f_{\mathrm{ce}} \gg 1$ (f_{pe} and f_{ce} are plasma and electron cyclotron frequency, respectively). Technical specifications: Radiometer is sweeping superheterodyne type. Two inputs have bands 17÷27 GHz and 27÷40 GHz. Each band has 16 frequency channels sweeped in 160 μs sweep rate. Arbitrary frequency can be chosen in single frequency mode.

A circular horn antenna is placed inside the tokamak's vacuum port. A movable array of 16 Langmuir probes monitores the edge plasma properties near to the antenna's mouth. The waveguide part consists of the oversized waveguide, the polarizer for the linear polarization mode selection and the waveguide transitions. The received signals are mechanically switched to the one of radiometer inputs. Only one frequency band can operate during a single tokamak shot. The frequency of the voltage controlled oscillator (VCO) in the microwave mixing part defines the received frequency channel. The sweeping ramp generator produces 16 voltage steps for the VCO tuning. During quick channel switching strong disturbing pulses are produced. The disturbances take not more than first 7 μs of the 10 μs channel steps. Useful signals between 7^{th} and 10^{th} μs are separated from the glitches by consequent data processing. The overall sweep rate 160 μs determines time resolution of the system. Fast measurement is possible in the non–sweeping mode for a chosen single frequency.

The intermediate frequency part of the radiometer heterodyne scheme consists of IF filters, IF amplifiers and power detectors. Both logarithmic (70 dB dynamic range) and linear detectors (30 dB dynamic range) are in parallel operation. The output voltage is sampled by 1 μs data acquisition system (DAS).

A suitable "black body" radiator for the calibration has not been available yet so the radiometer is not absolutely calibrated. It means that we cannot estimate the radiating temperature of the plasma. All results in this paper show radiated power in relative logarithmic or linear units.

3 ECE and EBW conversion on the Castor

Microwaves are commonly used for fusion plasma heating and current drive. In the electron cyclotron (EC) frequency range the plasma core is accessible for the frequency of launched wave well above the density cutoffs. Very high EC frequency, the second or higher harmonics, have to be used, which is a major drawback of this method. The problem is particularly acute for spherical tokamaks and stellarators. A possible and theoretically described mechanism to by–pass these problems is to convert the launched electromagnetic mode to EBW. Of course, a reversible process makes it possible for ECE to get through cutoffs out of the plasma. A recent review is in [1].

EBW are electrostatic waves driven and absorbed in the vicinity of EC frequency. EBW propagate inside the plasma with no density limits. Near the Upper Hybrid Resonance (UHR) EBW have a confluence with the electromagnetic X–mode (polarization perpendicular to the magnetic field). Unfortunately, behind the UHR and towards the Low Field Side (LFS) of the tokamak, existing R–cutoff reflects X–mode back to the plasma. Two scenarios of passing a barrier are suggested:

1. In the direct EBW–X conversion the tunnelling of the X–mode wave through an evanescent region between the UHR and the R-cutoff is possible, but only in case that the thickness of this region is less or comparable to 0.1 of the vacuum wavelength. Therefore, the density gradient in this region at the plasma edge strongly influences the direct EBW–X conversion efficiency. The outgoing X–mode wave is linearly polarized and leaves the plasma perpendicularly.

2. More complex EBW–X–O conversion consists of two conversion steps. In the first step EBW is converted to the X–mode wave which is furthermore, in the second step, converted to the O–mode wave (polarization parallel to the magnetic field). The outgoing O–mode wave is circularly polarized and leaves the plasma obliquely.

A numerical study of ECE resulting from EBW conversion has been performed by a full wave finite element code [2], [3]. Suitable conditions, i.e. frequency, polarization, angle of incidence, plasma density and magnetic field of both conversion scenarios on the Castor have been found. The real plasma edge density fluctuation and density gradient obtained by Langmuir probes have been included in the calculations. This typical course of density fluctuation is shown in upper graph in Fig. 1. Below is the direct EBW–X conversion efficiency evaluated numerically, both graphs in detailed 1 ms view. The characteristic strong amplitude modulation of the EBW–X conversion has been utilized for it's identification. Efficiency of EBW–X conversion is low, about 25 %, with regard the Castor conditions.

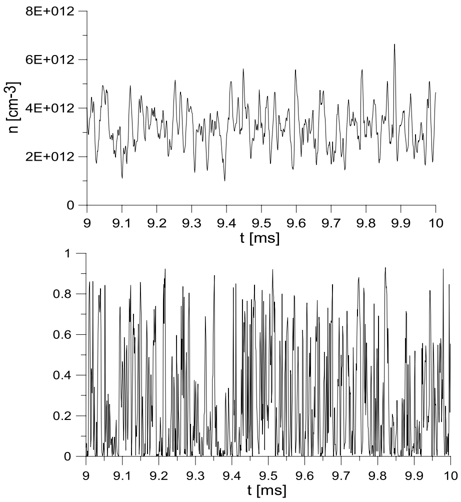

Fig. 1. Detail of edge density fluctuations and efficiency of direct EBW–X conversion.

On the other hand, the EBW–X–O conversion is practically not influenced by the fluctuating density gradient. Theoretically, 100 % efficiency can be achieved.

4 Experimental observation of EBW conversion

The radiometer horn antenna beam is oriented perpendicularly to the plasma column. Direct EBW–X conversion at about 17÷22 GHz had been numerically predicted providing central plasma density is $\sim 1.5\times10^{19}\mathrm{m}^{-3}$ and central toroidal magnetic field is 0.65 T. The plasma density was affected during the experiments by impulse gas puffing. The radiometer was in the single frequency mode to enable us detailed time resolution.

The examples of EBW–X conversion are demonstrated in Fig. 2 at 18 GHz and in Fig. 3 at 40 GHz (second harmonic ECE), respectively.

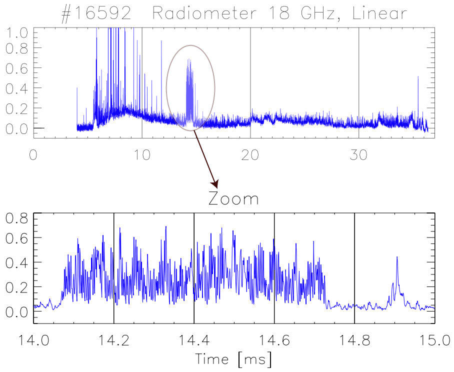

Fig. 2. EBW–X in 14÷15 ms, 18 GHz.

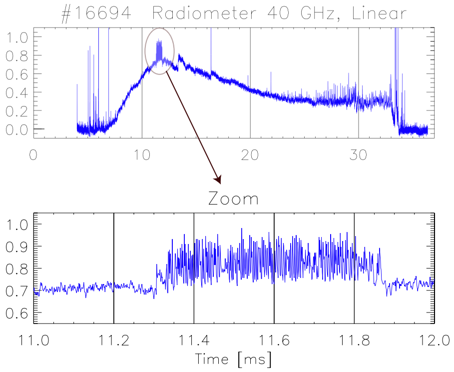

Fig. 3. EBW–X in 11÷12 ms, 40 GHz.

Bursts usually appear during the plasma start and decay. A short, strongly modulated signals in the zoomed parts indicate a direct EBW–X conversion influenced by edge density fluctuation (c.f. the same character in Fig. 1). These cases seem to be rare and short in comparison to the numerical models. One reason could be that the edge process is more complex than the modelled one and experimental conditions have not satisfied the direct EBW–X conversion well. The other obvious reason results from the general disadvantage of small tokamaks like the Castor. The plasma produces a mixture of thermal ECE, suprathermal ECE and plasma frequency emission [4]. The optical depth at this frequency and plasma densities $< 2 \times 10^{19}\mathrm{m}^{-3}$ is too small to absorb multiple reflections of microwaves from the tokamak chamber and plasma cutoffs. The resulting background radiation is wideband, has fuzzy polarization properties and is relatively strong enough to overlap ECE. Only exceptional conditions give ECE a chance to exceed the background level. The signals in our measurements have got these properties. A similar properties of the ECE radiation has been reported in [5] recently.

Formation of a plasma edge potential gradient by the “edge biasing” is a subject of long–term investigation on the Castor [6]. Biasing electrode voltage creates in the plasma edge the particle transport barrier and increases the plasma density in this region. During some experimental works, sweeping voltage from power supply has been fed in the rake of Langmuire probes placed in the plasma edge near the radiometer antenna. An interesting influence on the radiometer signal has been observed. Fig. 4 demonstrates visible effect on the received signal at 21 GHz. For a period 10 ms the voltage of biasing electrode was +200 V and probes were swept by ±30 V. It looks like that EBW conversion efficiency followed the probe voltage swing as the voltage probably affected the edge plasma density gradient.

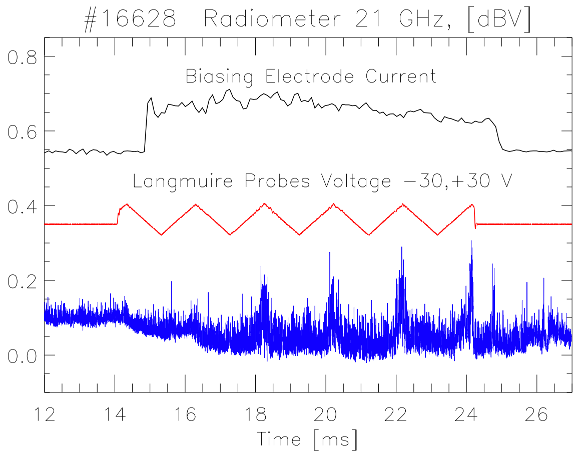

Fig. 4. EBW–X conversion influenced by biasing and probe voltage.

5 MHD instabilities observed in the range of plasma frequency

The unspecified background radiation mentioned above is affected by processes inside the plasma so it can indicate the state when a plasma instability appears. Intensive bursts of emission can occur under some circumstances, e.g. the typical saw–teeth oscillations occasionally accompanied ECE measurements. The time course of 8 channels (17÷23 GHz) is in lower part of Fig. 5. Central plasma frequency shown in the upper part of Fig. 5 is derived from measured line-averaged plasma density, provided that the density has a parabolic course. The course of EC frequency in the same picture follows the course of toroidal magnetic fields at High Field Side (HFS), center and LFS of the Castor. Saw–teeth oscillations have got a wideband character, but they are well visible by the radiometer only below EC frequency because the background radiation is partly absorbed in EC resonance layers between HFS and LFS.

6 Conclusions

Radiometry at fundamental ECE harmonics has confirmed direct EBW–X conversion in simulated overdense plasma in a small Castor tokamak. Excellent time resolution allowed to watch the strong influence of edge plasma properties on the conversion process predicted by computation. Moreover saw–teeth oscillations were demonstrated for the first time on the Castor.

We are preparing some improvements for further experiments. The radiometer apparatus will be equipped with low–noise band preamplifiers and filters. A new movable antenna should enable us to place the antenna mouth inside the plasma edge close to the UHR region. As the EBW–X–O conversion is more promising than the EBW–X one, the design of another antenna for oblique radiation detection is under development. To suppress the

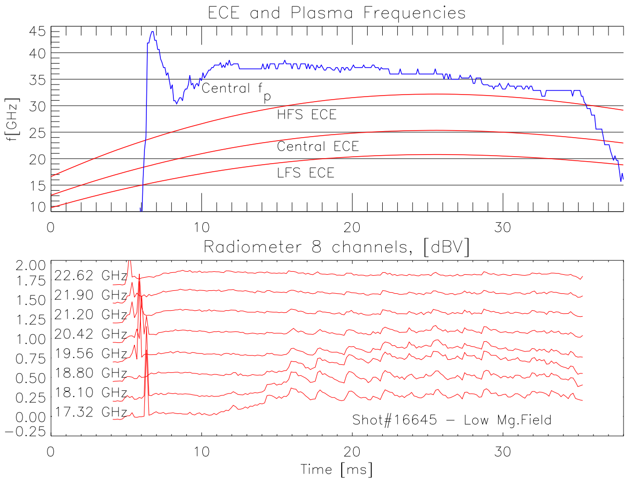

Fig. 5. Saw–teeth oscillations visible below EC frequency.

background radiation at admissible level a new calculations and experiments at higher plasma density will be done.

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