MEASUREMENT OF MICROWAVE FREQUENCIES EMITTED BY INSTABILITIES OF ECRIS PLASMA WITH WAVEGUIDE FILTERS AND MICROWAVE SENSITIVE DIODES*

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Abstract

Periodic emission of strong microwave bursts at certain frequencies is a characteristic feature of kinetic instabilities in ECRIS plasmas. Precise measurement of the temporally evolving microwave frequency spectra requires a high bandwidth oscilloscope, which can make the experiments prohibitively expensive to conduct. An alternative low-cost method to study the microwave emission in narrow frequency bands is to apply band-pass waveguide filters and microwave sensitive diodes. The microwave emission from the plasma of the JYFL 14 GHz ECRIS has been studied with both methods. The results of the experiments are compared and their interpretation is discussed. It is demonstrated that the method based on filters and diodes can provide useful information about the microwave emission spectra induced by electron cyclotron instabilities.

INTRODUCTION

The electron velocity distribution in electron cyclotron resonance ion source (ECRIS) plasmas is non-Maxwellian and strongly anisotropic i.e. $v_{e,\perp} \gg v_{e,\parallel}$ [1,2]. Magnetized non-equlibrium plasmas are prone to cyclotron instabilities emitting microwaves due to resonant amplification of plasma waves by hot electrons [3]. The Doppler shifted emission frequency (see e.g. Ref. [4]) can be expressed as

$$\omega = \frac{\omega_{ce}}{\gamma} \pm |k_{\parallel} v_{e,\parallel}|, \quad (1)$$

where $\omega_{ce} = eB/m_e$ is the cold electron gyrofrequency, $\gamma = 1 + E_k/E_0$ the relativistic Lorentz factor expressed here with the electron kinetic (E_k) and rest ($E_0 = 511$ keV) energies, $k_{\parallel}$ the longitudinal wave number of the plasma wave and $v_{e,\parallel}$ the longitudinal (hot) electron velocity. The measurement of the emission frequency serves as an indirect plasma diagnostics method, which can be used e.g. to determine the excited wave mode [5]. Since ω is a function of magnetic field strength B and electron kinetic energy E_k, measuring the emitted microwave frequencies together with the energies of the electrons escaping the magnetic confinement as a result of the interaction with the plasma wave, would also allow determining the range of magnetic field values where the instability is triggered.

The purpose of this paper is to demonstrate the feasibility of low-cost bandpass filters and Schottky diodes for the measurement of the microwave emission frequencies related to kinetic instabilites of ECRIS plasmas.

EXPERIMENTAL SETUP

In earlier experiments two techniques have been used for the detection and diagnostics of the instability-related microwave emission of the A-ECR-U type JYFL 14 GHz ECRIS [6]:

- a Schottky diode, sensitive to frequencies of 0.01–50 GHz [7] and
- a high-bandwidth (25 GHz / 100 Gs/s) oscilloscope [5].

In both experiments the microwave emission was detected by connecting the diagnostics system to the ECRIS through an off-axis WR-75 waveguide port (cut-off frequency of 7.9 GHz) normally used for injection of microwave power at secondary frequency. Appropriate adapters and attenuators were used to transport the signal and protect the equipment. The Schottky diode alone is sufficient for measuring the duration of the microwave bursts while the oscilloscope can be used for measuring the dynamic spectrum of the microwave emission i.e. the frequencies emitted by the instabilities as illustrated in Fig. 1.

The dynamic spectrum yields all the necessary information on the microwave emission, i.e. temporal evolution of the emission frequencies and their intensities. However, the measurement technique requires purchasing or renting a high-bandwidth oscilloscope, preferably having a sampling rate ≥ 100 Gs/s to allow collecting sufficient number of data points per microwave cycle for a Fourier transform. Unfortunately, such devices are prohibitively expensive in most cases. Thus, development of an alternative method for detecting the emission frequencies on daily basis is desirable. This work benefits from the fact that the microwave emission has been shown [5] to exhibit certain characteristic features that are also visible in Fig. 1. The emission

* Work supported by the EU 7th framework programme 'Integrating Activities — Transnational Access', project number: 262010 (ENSAR), the Academy of Finland under the Finnish Centre of Excellence Programme 2012–2017 (Nuclear and Accelerator Based Physics Research at JYFL).
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ISBN 978-3-95450-186-1

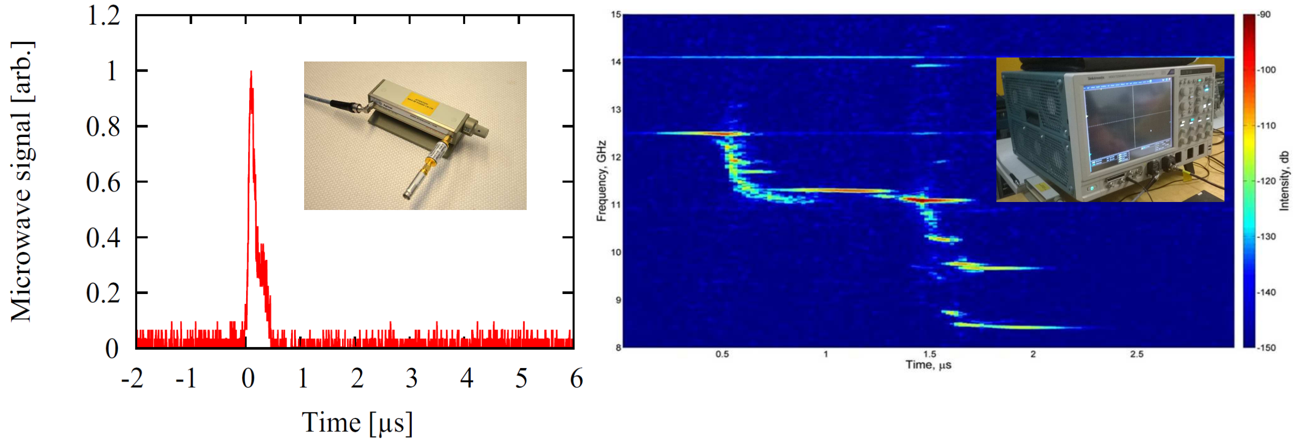

Figure 1: The voltage signal of the microwave sensitive Schottky diode (left) and dynamic spectrum obtained with the high-bandwidth oscilloscope (right).

related to an onset of the instability occurs in bursts, each of them lasting for some hundreds of nanoseconds. Moreover, the frequencies of the microwave emission within each of these intense bursts are limited to a narrow range of about 0.1 GHz and have a descending tone from 'packet-to-packet' as explained thoroughly in Ref. [5]. In the case of the JYFL 14 GHz ECRIS the dominant emission frequencies in temporal sequence are 12.5–12.6, 11.1–11.2 and 9.4–9.6 GHz. The separation of these emission bands makes it possible to study the microwave emission by applying a combination of waveguide filters.

The diagnostics setup used in this feasibility study is shown in Fig. 2. Similar to the experiments described in Refs. [5, 7] the microwave emission was studied by connecting the diagnostics setup to the WR-75 waveguide port of the JYFL 14 GHz ECRIS. A low pass filter (later referred as filter A) with a cut-off frequency of 13.2 GHz was used in order to suppress the signal of the 14 GHz primary frequency. Thus, the frequency range that can be detected, namely 7.9–13.2 GHz, is defined by the waveguide and low pass filter cut-off frequencies. Following the signal path, the subsequent component is a hybrid coupler known as a 'magic tee', which splits the microwave signal of the H-arm (port 3) equally between the two E-arms (ports 1 and 2) ideally attenuating both signals by -3 dB. The remaining H-arm (port 4) of the 'magic tee' is connected to a matched load. The signal from port 1 is adapted to a coaxial line and attenuated by a combination of attenuators by -40 dB before it is detected by a Schottky diode. The signal from port 2 first passes through a high-pass filter (B,C or D), is then adapted to a coaxial line of equal length and attenuated before being detected by another identical Schottky diode. The signals from the Schottky diodes are compared with an oscilloscope which is also connected to an X-ray detector sensitive to burst of bremsstrahlung generated by the electrons expelled from the magnetic trap by the plasma wave [7].

The described setup allows identifying the range of microwave emission frequencies through a comparison of the signals measured from ports 1 (unfiltered) and 2 (filtered). The 'resolution' of the method depends on the number of available high-pass filters. Three different high-pass filters with cut-off frequencies of 9.4 GHz (B), 10.2 GHz (C) and 11.8 GHz (D) were designed and constructed in-house for this feasibility study. Combined with the low-pass filter (A) they form a set of interchangeable band-pass filters limiting the detectable frequency ranges to 9.4–13.2 GHz (A+B), 10.2–13.2 GHz (A+C) and 11.8–13.2 GHz (A+D). The transmission curves of these filter combinations, measured with a 15 GHz network analyzer, are shown in Fig. 3. The frequency ranges were chosen to cover/exclude the afore-mentioned emission bands of the JYFL 14 GHz ECRIS plasma.

RESULTS AND DISCUSSION

An example of the diagnostics signals, measured with an oxygen plasma (400 W / $2.8\cdot10^{-7}$ mbar / $B_{\mathrm{min}}/B_{\mathrm{ECR}}$=0.77) through different filter combinations is shown in Fig. 4 together with a typical dynamic spectrum recorded earlier [5].

The following interpretations can be made:

- It can be seen from the upper right subfigure that only the first microwave 'packet' is detected by both diodes of the diagnostics setup with the filter D attached to the output of port 2. The subsequent emission signals can be seen only in port 1. This implies that the first emission burst (f_1) emits microwaves in the frequency range of 11.8 GHz < f_1 < 13.2 GHz while the following bursts (f_2 and f_3) emit at frequencies f_2, f_3 < 11.8 GHz.
- The lower left subfigure shows that the first two microwave 'packets' are detected by both diodes with the filter C attached to the output of port 2. This implies that 10.2 GHz < f_2 < 11.8 GHz and restricts f_3 further down to f_3 <10.2 GHz.
- Finally, the lower right subfigure shows that all microwave 'packets' are detected by both diodes with the filter B attached to the output of port 2. Hence, 9.4 GHz < f_3 < 10.2 GHz.

ISBN 978-3-95450-186-1

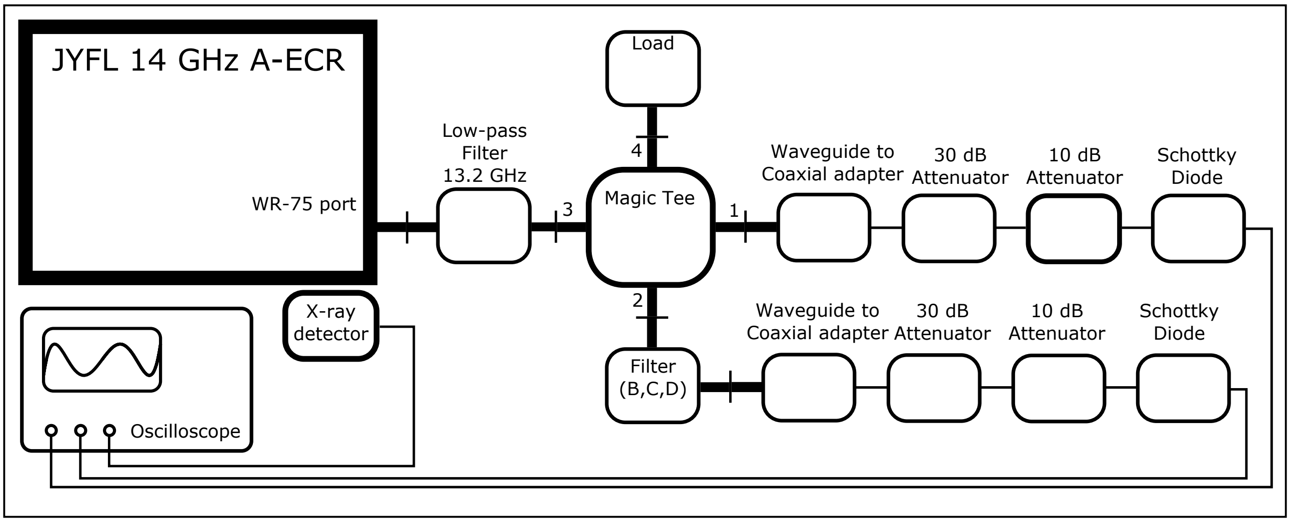

Figure 2: Schematic presentation of the diagnostics setup.

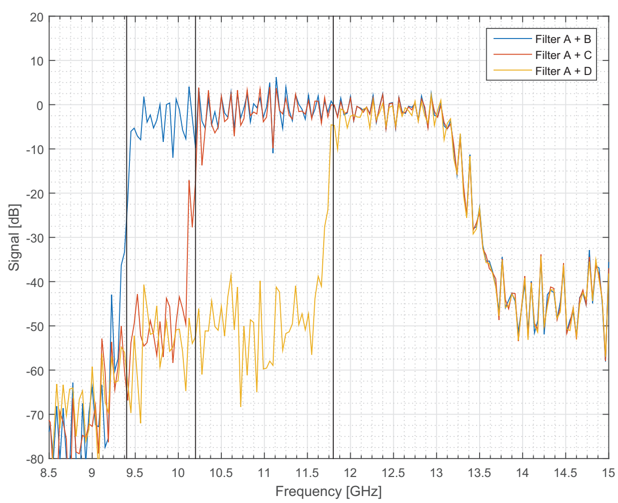

Figure 3: The transmission curves of the filter combinations.

The diagnostics signals presented in Fig. 4 are snapshots of the vast amount of data collected during the experiments. However, they are representative examples that match the microsecond-level temporal sequence and intensity of the dynamic spectrum (recorded earlier) remarkably well. It must be emphasized that the diagnostics signals are highly repeatable from pulse-to-pulse.

The summary of the results is presented in Table 1 comparing the two diagnostics methods in terms of cost and obtained microwave emission frequency information.

The content of this work can be summarized as follows: it has been demonstrated that low-cost bandpass filters and Schottky diodes can be applied for the measurement of the microwave emission frequencies related to kinetic instabilites of ECRIS plasmas. The 'frequency resolution' of the method depends on the mechanical design and number of available high-pass filters. In principle with the demonstrated design, featuring a cut-off edge of approximately -20dB/100 MHz, the resolution could be as good as ±0.1 GHz.

Table 1: Comparison of the ECRIS Plasma Microwave Emission Frequency Detection Methods

Method	100 Gs/s oscilloscope	Filters & diodes
f_1 [GHz]	12.5–12.6	11.8–13.2
f_2 [GHz]	11.1–11.2	10.2–11.8
f_2 [GHz]	9.4–9.6	9.4–10.2
Cost	Buy ~ 250 k€ Rent ~10 k€	2–3 k€

Thus, the presented method can be considered as an attractive alternative for the high-bandwidth oscilloscope especially if the research budget is scarce, which is often the case. The selection of filters should be designed individually for each ECRIS as their instability-related emission frequencies cannot be expected to be identical to the JYFL 14 GHz ECRIS.

REFERENCES

[1] C. Barue, M. Lamoreux, P. Briand, A. Girard, and G. Melin, *J. Appl. Phys.* **76**, 5, (1994).

[2] G. Douysset, H. Khodja, A. Girard, and J.P. Briand, *Phys. Rev.* E **61**, 3, (2000).

[3] S.V. Golubev and A.G. Shalashov, *Phys. Rev. Lett.* **99**, 205002, (2007).

[4] D. Mansfeld, I. Izotov, V. Skalyga, O. Tarvainen, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, and J. Laulainen, *Plasma Phys. Contr.* F. **58**, 045019, (2016).

[5] I. Izotov, O. Tarvainen, D. Mansfeld, V. Skalyga, H. Koivisto, T. Kalvas, J. Komppula, R. Kronholm, and J. Laulainen, *Plasma Sources Sci. Technol.* **24** 045017, (2015).

[6] H. Koivisto, P. Heikkinen, V. Hänninen, A. Lassila, H. Leinonen, V. Nieminen, J. Pakarinen, K. Ranttila, J. Ärje, and E. Liukkonen, *Nucl. Instrum. Methods* B 174, (2001), p. 379.

[7] O. Tarvainen *et al.*, *Plasma Sources Sci. Technol.* **23**, (2014), 025020.

ISBN 978-3-95450-186-1

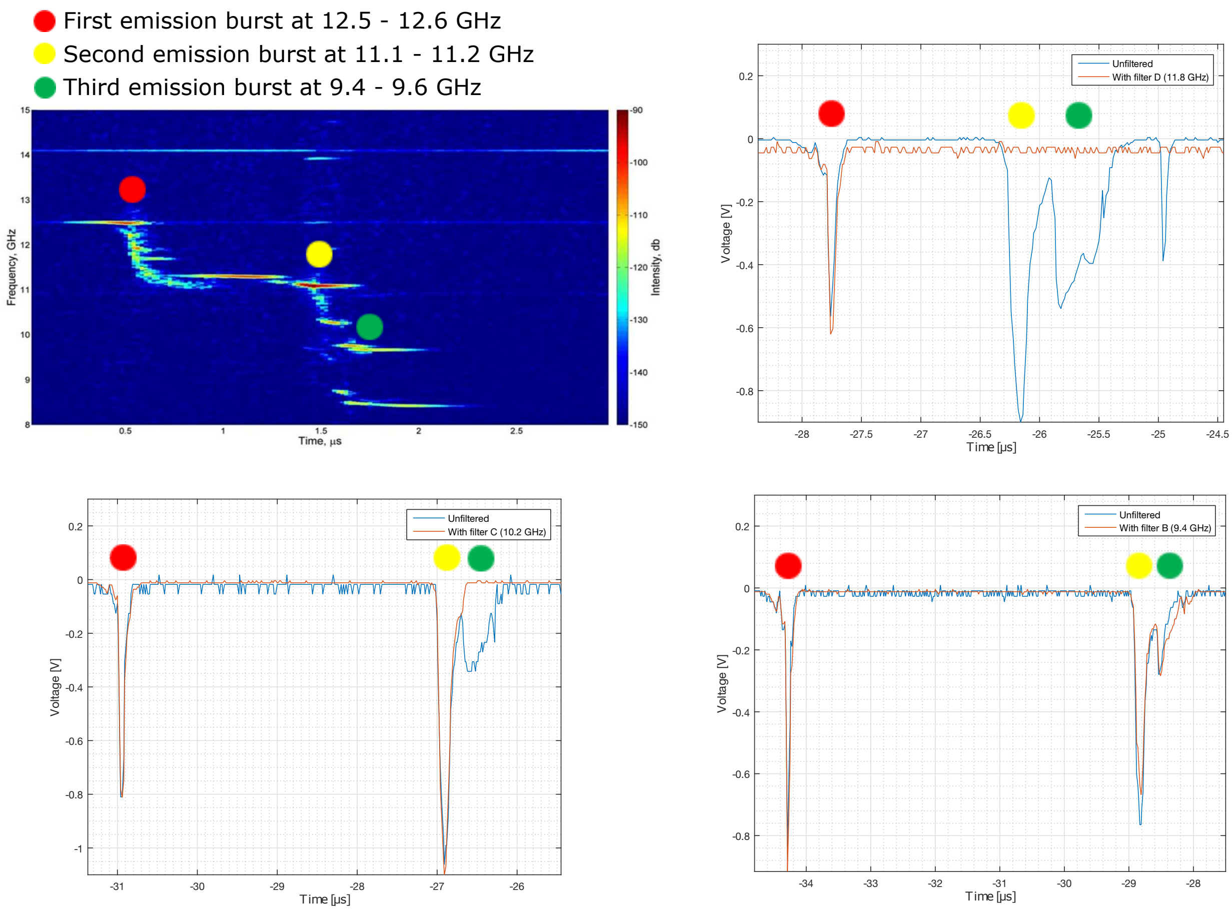

Figure 4: Typical dynamic spectrum of the microwave emission (upper left) and examples of diode signals in frequency ranges of 7.9–13.2 GHz (unfiltered) and 11.8–13.2 GHz (upper right), 7.9–13.2 GHz and 10.2–13.2 GHz (lower left) and 7.9–13.2 GHz and 9.4–13.2 GHz (lower right). Different emission ‘packets’ are identified in each figure with corresponding color symbols.

ISBN 978-3-95450-186-1