UPGRADED ECE RADIOMETER ON THE TORE SUPRA TOKAMAK

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Abstract

An upgraded 32-channel heterodyne radiometer, 1GHz spaced, is used on the Tore-Supra tokamak to measure the electron cyclotron emission (ECE) in the frequency range 78-110 GHz for the ordinary mode (O: *E //B,k⊥B*) and 94-126.5 GHz for the extraordinary mode (X: *E⊥B, k⊥B*). From now, radial resolution is essentially limited by ECE relativistic effects related to electron temperature and density, not by the channels frequency spacing.
The principle radio frequency emitter (RF) has its frequencies down shifted into intermediary frequencies (IF) that span from 2 to 18 GHz in the single side band mode (SSB). The signal is then amplified by low noise IF amplifiers before being divided in 32 channels. A separate O/X mode RF front-end allows the use of an IF electronic mode selector. RF and IF filters reject the gyrotron frequency (118 GHz) in order to perform electron temperature measurements during electron cyclotron resonance heated plasmas. A precise absolute spectral calibration is performed outside the tokamak vacuum vessel by using a 600°C black body hot source.
Using analytical formulas, post-pulse data processing takes routinely into account the total magnetic field and the Maxwellian relativistic radial shift to improve radial location estimate. These formulates are compatible with real time processing in order to control the plasma. We are preparing temperature fluctuation measurements by using two tuning IF YIG filters, the principle and the set-up will be described in the paper. The goal is to achieve two channels having 100 MHz bandwidth and tuneable central frequencies in order to do cross-correlation measurements.

1) INTRODUCTION

The Tore-Supra heterodyne radiometer [1] has been recently upgraded. It can be used to measure the electron cyclotron emission in the RF frequency range 78-110 GHz at the first harmonic ordinary mode (O_1) or 94 –126.5 GHz at the second harmonic extraordinary mode (X_2) by using 32 channels (1 GHz spaced, 500 MHz bandwidth).

2) DIAGNOSTIC DESCRIPTION

The schematic of the new heterodyne radiometer is shown in figure 1.

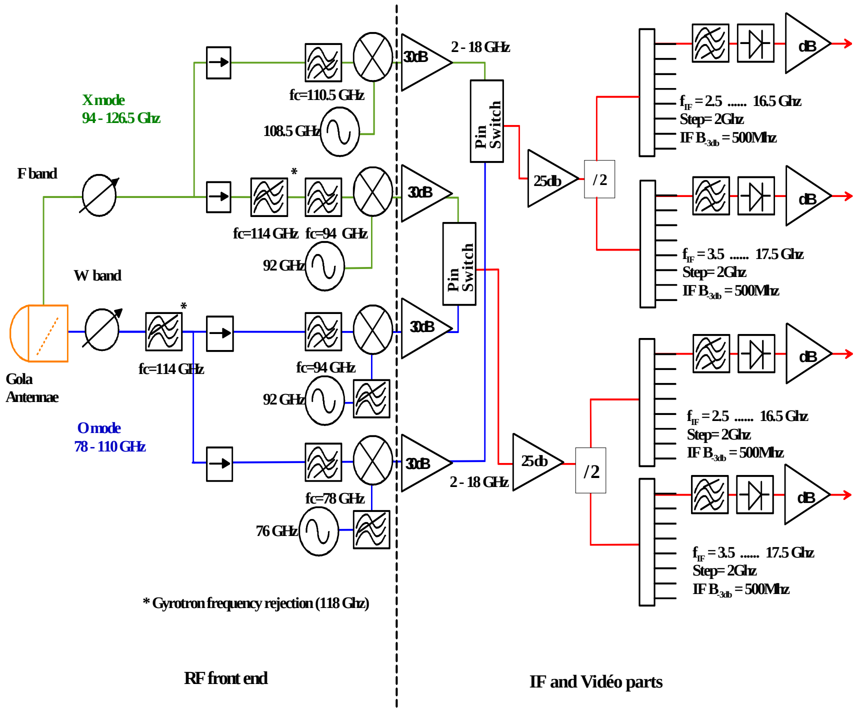


Figure 1

In the tokamak equatorial plane, a dual polarisation Gaussian optics lens antenna with a perpendicular line of sight (with respect to the magnetic field) and a low spreading beam (full width at half maximun power = 1.47 degree) gives ECE measurements with very low Doppler and refraction effects . A precise RF waveguide attenuator is used to complete the linearity range between calibration and plasmas. The principle is RF down shifted frequencies into IF intermediary frequencies (2 to 18 GHz), in the single side band mode (SSB), obtained by means of high pass millimetric RF filter (image rejection) and low noise, low loss conversion balanced mixers driven by Gunn local oscillators (LO). The IF frequencies are given by the following equation (integer p & q):

$$f_{IF} = \left| p f_{RF} \pm q f_{LO} \right|$$

We put a low pass filter to overcome IF frequencies due to higher LO harmonics with respect to the above equation (only on the O mode RF front end because ECE harmonics spectrum decrease rapidly as n increase). RF and IF selectivity components prevent any LO power or noise mixer power to disturb calibration performed by a 600°C black body (P_{BB} =-83.3 dBm where P_{BB} = kTB_{IF}, T=600°C, B_{IF} =500 MHz, k=1.6 10^{-23}). As the radiometer is near the tokamak, wide-band RF ferrite isolators have a double magnetic shielding with mumetal and iron (like Russian dolls). Lowpass RF and bandpass IF filters reject the gyrotron frequency (118 GHz) in order to perform temperature measurements during Electron Cyclotron Resonance Heating plasmas. Low noise 2-18 GHz IF amplifiers (noise figure 3 db max) allow to get enough IF power with a good signal to noise ratio. Separated O/X mode RF front-end allow the use of IF electronic mode selectors (PIN switch). IF power amplifiers (25 dBm at 1dB compression point) allow higher dynamic range. After power splitting, every channel is done by using selective IF pass-band filter (B_{IF}=500 MHz) and a video detection with a low noise and high linearity range schottky diode detector. Finally low noise video amplifiers, with low-pass filters (bandwidth B_{V0}=100 kHz) and differential drivers, give signals to isolated differential electronics data acquisition systems, located 50 meters farther, and which can act simultaneously in two modes:

-slow acquisition mode during all the plasma duration: 32 channels 1 ms sampling without aliasing (low-pass filter bandwidth B_{V1}=400 Hz)

-fast acquisition mode during time plasma windows triggered by plasma phenomenon: 32 channels 10 µs sampling without aliasing (low-pass filter bandwidth B_{V2}=40 kHz). The central toroidal magnetic field B_{tor} acts pin switch mode selectors and the frequencies channels are the following:

B_{tor}>2.16 T : O-mode, step 1GHz, $f1_{GHz}$=[78.5 to 93.5], $f2_{GHz}$=[94.5 to 109.5];
B_{tor}<2.16 T : X-mode, step 1 Ghz, $f1_{GHz}$=[111 to 126], $f2_{GHz}$=[94.5 to 109.5].

A precise absolute out-side tokamak vessel calibration is done by using:

- a hot black body (600°C) and a rotating chopper
- a radiometer set-up which can be moved without changing the instrumental function
- a local platinum temperature probe to correct sensitivity drifts (–2.7% / °C)
- a simulation of the tokamak window, which has no Fabry-Pérot effects
- efficient coherent addition techniques which use a trigger and a clock synchronous to the chopper rotation.

In this way the black body modulating signal bb(t) is decorrelated from Gaussian noise, which is limited to the 0.3-300Hz band by a video bandpass filter. Differential electronics are used to minimise electromagnetics radiations pollutions. The intercalibration precision between channels is also improved by using same ohmic plasmas having solely small changes on the magnetic field .

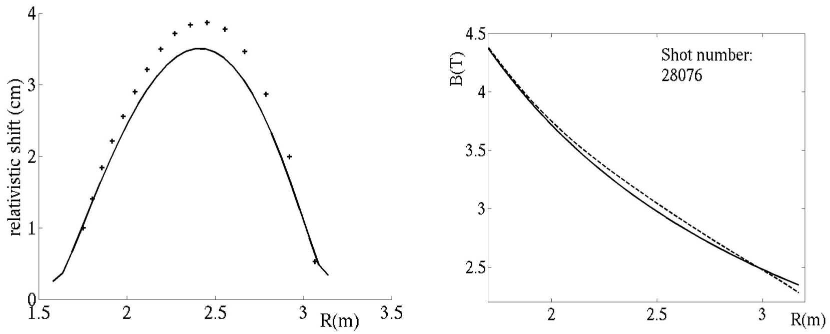
3) ROUTINE DATA PROCESSING

3.1) Maxwellian relativistic shift: The relativistic shift δR can be aproached by an analytic formulation[2,3]:

$$\delta R = R \frac{T_e}{511} \left(\frac{511}{T_e R} \frac{75\, c\, \omega_{ce}^2}{8 \sqrt{\pi}\, \omega\omega_{pe}^2 N_r} \right)^{\frac{2}{7}}$$

where $\omega = n\omega_{ce}$, n=1, N_r=$N_o$or n=2, N_r =N_x , T_e in keV

The good agreement between numerical and analytical simulations is given in the O mode , for example, by the figure 2 (full line : analytical , cross bar : numerical , with T_{e0}=10 keV, n_{e0}=2 10^{19} m^{-3}, cf [2]).



Figures 2 &3

3.2) Total magnetic field calculations (B_{tot}): These calculations are based on a magnetic equilibrium including Shafranov shift and magnetic ripple, poloidal, diamagnetic and paramagnetic fields corrections to the vacuum toroidal field (B_{vac}) [2].Plots of B_{vac} and B_{tot} versus the horizontal coordinate R for typical Tore Supra parameters are shown in Figure 3 (full line:B_{vac} , dashed line: B_{tot}).

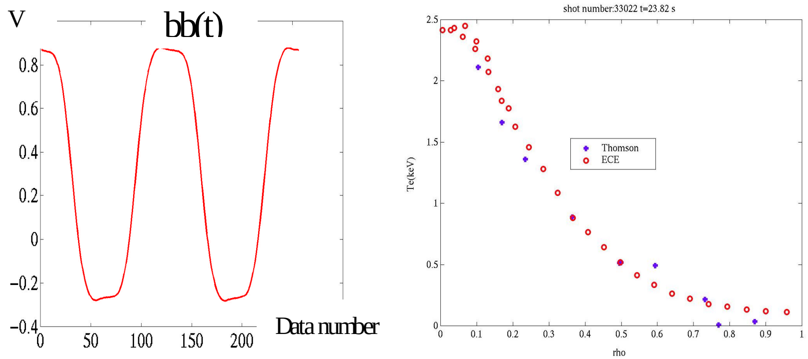
3.3) Strong refraction detection: For each channel i we detect if there is strong refraction by doing the following test : $f_i < 1.2 * f_{cut-off}(R_i)$. One has respectively:

$$n^{(x)}_{cut-off} = 1.94 \cdot 10^{19} . B^2 \quad , \quad n^{(o)}_{cut-off} = 9.72 \cdot 10^{18} . B^2$$

with $n_{cut-off}$ in m^{-3}, B in Tesla.

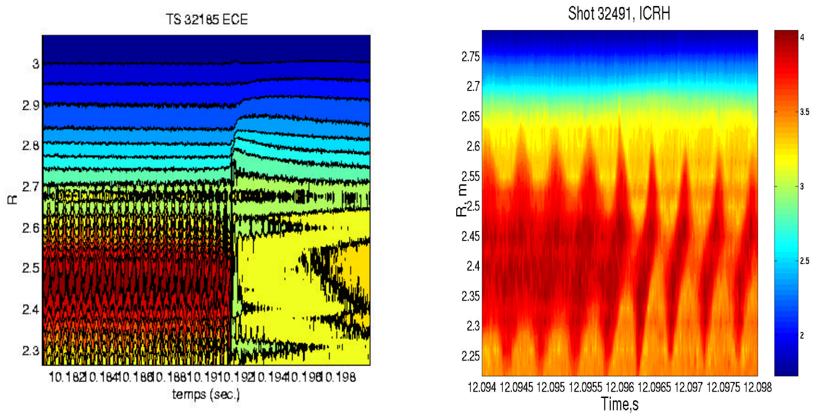
4) EXPERIMENTAL RESULTS

4.1) Calibration precision: After coherent addition, signal to noise ratio on the measured black body modulating signal is very good (>100, see figure 4 for one channel), it leeds to ECE temperature profiles which are very consistent with Thomson scattering measurements (see figure 5 : T_e versus normalized radius given by the 32 channel ECE radiometer and Thomson scattering diagnostics).



Figures 4 & 5

4.2) MHD measurements: Figures 6 and 7 show sawtheeth crashes measured in the slow (1ms) and the fast acquisition modes (10 µs) for two different shots. One can observe a strong (m=1, n=1) precursor for the first one and its manifestation as the hot core expulsion for the second one. In the latter case, no additional hot core is present on the former magnetic axis after 12.0965 s.



Figures 6 & 7

5) TEMPERATURE FLUCTUATION MEASUREMENTS

5.1) Theoretical principles : The optical thick ECE $S(t)$, as measured by each radiometer channel, consists of an average $\langle S \rangle$ and a fluctuation $s(t)$ part that are proportional to the average plasma temperature $\langle T_e \rangle$, and to its fluctuating component $t_e(t)$ plus the statistical radiation noise $n(t)$.

$$S(t) = \langle S \rangle + s(t) \propto \langle T_e \rangle + t_e(t) + n(t)$$

The limits of electron temperature fluctuations measurements due to $n(t)$ is [5,6]: $\frac{s_{RMS}}{\langle S \rangle} = \sqrt{\frac{2B_{IF}}{B_v}}$, where s_{RMS} is the root mean square amplitude of the signal fluctuation .To measure the average amplitude of temperature fluctuations in tokamak plasmas of smaller than 1-2% one needs to get rid of the thermal noise $n(t)$.

5.2) Experimental set-up: Using a single line of sight this can be achieve by cross correlation of two ECE channel signals whose temperature fluctuations are correlated while the noise fluctuations are uncorrelated. So we propose to add the following set-up (dashed line: cf figure 8) to the existing radiometer, following the [7] techniques. The goal is to achieve two channels having 100 MHz bandwidth and tuneable central frequencies to shift the plasma sample volume in the radial space.

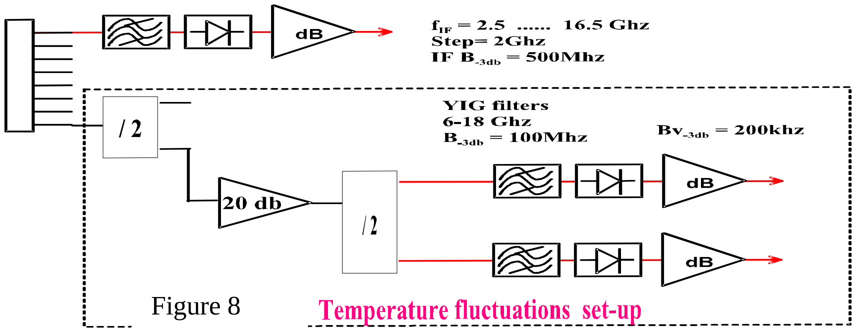


Figure 8 Temperature fluctuations set-up

The statistical noise level can be defined as follows [8,9,10]:

$$\Delta\left(\frac{t_{eRMS}}{\langle T_e \rangle}\right) = \sqrt{\frac{\Delta r_{12}}{\langle S_1 \rangle \langle S_2 \rangle}} = M^{-\frac{1}{4}} \sqrt{\frac{\sigma_1}{\langle S_1 \rangle} \frac{\sigma_2}{\langle S_2 \rangle}}$$

where r_{12} is the cross correlation fonction at zero time delay, σ_1 and σ_2 are the standard deviations of s_1 and s_2, M is the total number of samples. The video bandwidth is 200 kHz and acquisition will be done without aliasing effects. M will be of several 10^6 samples to get out efficiently the thermal noise $n(t)$.

6) CONCLUSION

The Tore-Supra ECE radiometer has reached a good degree of maturity. A good absolute calibration is performed and radial resolution is only due to relativistic effects (32 channels). Routine ECE data processing takes into account radial relativistic shift and the total magnetic field using analytic formulations which can be applied in real time processing to perform plasma control. Temperature fluctuation measurements will be done soon.

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