Advances in the FTU Collective Thomson Scattering system[a)]

W. Bin,[1,b)] A. Bruschi,[1] O. D'Arcangelo,[2] G. Grosso,[1] L. Lubiako,[3] E. Alessi,[1] C. Castaldo,[2] C. Centioli,[2] M. De Angeli,[1] L. Figini,[1] C. Galperti,[4] S. Garavaglia,[1] G. Granucci,[1] M. Lontano,[1] S. Magagnino,[2] V. Mellera,[1] D. Minelli,[1] A. Moro,[1] A. Muraro,[1] A. Nardone,[1] F. Orsitto,[5] A. Simonetto,[1] U. Tartari,[1] and the FTU team[6,c)]

[1]*Istituto di Fisica del Plasma "P. Caldirola", Consiglio Nazionale delle Ricerche, Milano, Italy*
[2]*ENEA for EUROfusion, Frascati, Italy*
[3]*Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia*
[4]*Swiss Plasma Center, Ecole Polytéchnique Fédérale de Lausanne, Lausanne, Switzerland*
[5]*Consorzio CREATE, Università degli Studi di Napoli Federico II, Napoli, Italy*
[6]*Frascati Tokamak Upgrade, CR-ENEA, Frascati, Italy*

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing above are provided by the Editorial Office)

The new Collective Thomson Scattering (CTS) diagnostic installed on the Frascati Tokamak Upgrade (FTU) device started its first operations in 2014. Purpose of the ongoing experiments is to investigate the presence of signals synchronous with rotating tearing mode islands, possibly due to parametric decay processes, and other phenomena affecting the EC beam absorption or the scattering measurements. The radiometric system, the diagnostic layout and the data acquisition system were improved accordingly. Present status and near-term developments of the diagnostic are presented.

I. INTRODUCTION

Collective Thomson Scattering (CTS) has been used for a few years to investigate peculiar experimental conditions of tokamak plasmas[1] where the power threshold for back-scattering Parametric Decay Instabilities (PDI) of Electron Cyclotron (EC) waves appears significantly reduced[2] with respect to previous theoretical calculations.[3] The interest in studying these scenarios in the Frascati Tokamak Upgrade (FTU) device led to a substantial renewal[4,5] of the CTS diagnostic, already exploited in the past experimental campaigns for CTS measurements of thermal ion temperature.[6] The first operations of the new CTS system have been performed[7,8] in 2014 and 2015. The two main goals of ongoing experiments, carried out in the framework of the EUROfusion Enabling Research project AWP15-ENR-01/ENEA-06, are the detection of low power PDI excited by EC pumping wave in presence of tearing mode islands and the investigation of their possible effects on ECRH absorption. The studies are carried out exploiting the high time and frequency resolution now reachable with a recently installed digital acquisition system and the wide range of magnetic fields and plasma parameters allowed in FTU. Experiments were performed so far injecting a 140 GHz/400 kW probe beam intersecting the CTS line of sight on or out of the equatorial plane of the torus. Plasma scenarios with different electron densities have been explored and three different toroidal magnetic fields have been applied in order to operate either with or without the 1st harmonic resonance layer in the plasma. In most cases, Neon was injected during the plasma flat-top to induce MHD activity, while the scattering volume was located at the plasma flux surface where the m:n=2:1 island is expected to form. This configuration is suitable for detection of any signal modulated in amplitude at the magnetic island frequency and originating from back-scattering PDIs.

II. RECEIVER UPGRADE

A. Dual radiometric system

In addition to the refurbishments described in Ref. 4 and 7, consisting of the addition of a new NI PXIe-5186 express digitizer (8 bit, 5 GHz analog bandwidth, sampling rate of 12.5 GS/s on two channels, 6.25 GS/s each), further upgrades have been introduced on the receiving system in 2016. A second radiometer, used in the past in the W7-AS stellarator, was reassembled, refurbished and installed for operation in FTU. The system has been integrated in the CTS diagnostic and tested off-line. This second radiometer is composed by a front-end and a back-end very similar to the first ones. The front-end is based on a quasi-homodyne down-conversion stage, with a backward wave oscillator stabilized by a phase-lock loop driven by a synthesizer. The local oscillator frequency is tunable in a range whose width is ~2 GHz around the probe beam frequency (140 GHz) and stray radiation reaching the front-end input is filtered for mixer protection. The back-end consists of 32-channels with multiplexers and band-pass filters providing 0-10 V analog outputs. Both radiometers are now installed on FTU and they are coupled to the same transmission line through a polarizing grid beam-splitter. Fig. 1-left shows the beam path (yellow arrows) at the end of the CTS line where the grid has been installed after the polarizers optics and the last shaping mirror, splitting the orthogonal polarizations of the beam towards the two identical corrugated feed horns of the radiometers. Both front-ends are

---

[a)] Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin.
[b)] Author to whom correspondence should be addressed. Electronic mail: wbin@ifp.cnr.it
[c)] See the Appendix of G. Pucella et al., Proceedings of the 25th IAEA Fusion Energy Conference, Saint Petersburg, Russia, 2014

connected in parallel either to the two channels of the fast digitizer, for Fourier transforming at high time and frequency resolution, or to a pair of acquisition modules for 2 kHz digitization of the 32 + 32 outputs of the two main analog filter banks. Both radiometers are also provided with secondary "zoom" spectrum analyzers, with a zooming capability of 100 MHz, but no use is foreseen for them at present. In addition to the optical matching of the two systems, both local oscillators can be phase-locked to the same frequency, controlled by a single remotely controlled synthesizer, in order to ensure full consistency of the spectra frequency reference.

B. Upgrade of front-end layout

The purpose of installing two synchronized radiometers is twofold: adding a second receiving line (which will be described in the next section) and detecting two linearly cross-polarized signals at the same time. The dual-polarization capability will allow measuring CTS radiation in both O- and X-modes, for the first time simultaneously during the same plasma discharge, to help distinguishing real scattering signals from other phenomena, such as back-reflections in the transmission line or detection of stray radiation, either from the vessel or from the torus hall, where the beam propagation is partially quasi-optical. A new notch filter tuned at the gyrotron frequency has been integrated in the front-end of the second radiometer to protect the mixer from stray radiation. Also the layout of the first front-end has been upgraded, inserting two notch filters, to allow collecting radiation through four different lines, selectable shot by shot. The first line connects directly the horn to the down conversion system, without filtering radiation. The second and third lines are provided with two different notch filters, tuned at the gyrotron frequency and ~25 MHz over it. The latter tuning is suitable when the protection from stray radiation is enhanced with external attenuators. In the fourth line the two notch filters are mounted in series, thus obtaining a wider stop band. In Fig. 1-right the stop bands of the two notch filters are indicated with the dashed lines while the continuous red line shows the filtering capability of the fourth line, where the filters are in series. Both front-ends have been revamped to enlarge the measurement bandwidth, so far limited to ~1.2 GHz by the Intermediate Frequency (IF) amplifiers. Since the two mixers are Schottky barrier type diodes, capable in principle to operate over a large frequency band, the IF amplifiers were replaced with new ones now providing a bandwidth of ~4.2 GHz with both the two spectrum analyzers and with the fast digitizer.

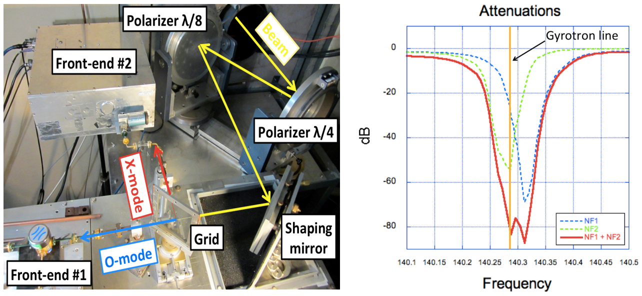

Fig. 1. Left: the polarizing grid beam-splitter coupling the two front-ends at the end of the CTS transmission line. The yellow arrows indicate the beam path while the blue and red lines are the directions of the split beams after the grid, towards the two radiometers. Right: stop-bands of the two notch filters (dashed curves) that are now installed on the first front-end. The red line shows the stop-band in the line where the two filters are mounted in series. Also the gyrotron frequency is highlighted with the vertical orange line.

IV. THE NEW REFERENCE RECEIVING LINE

The second goal for installing two radiometers is detecting radiation simultaneously from two different lines of sight in the plasma, similarly to what is implemented in the CTS system of ASDEX upgrade.[9] In particular, the goal is simultaneous detection of signals from a line of sight (see Fig. 2, top blue beam) intersecting a scattering volume with the probe beam (Fig. 2, bottom red beam), and from a reference line of sight (Fig. 2, middle grey beam) not crossing the probe beam. Such a secondary signal is suitable for cross-calibration and for reference of background radiation (i.e. not coming from the scattering volume). In order to introduce a new line in the narrow CTS front-steering launcher[10-12] which, in the proximity of the FTU vessel, is already occupied by the launching and receiving lines, a remote steering antenna (Fig. 2, box b) has been installed between the two lines, exploiting an equatorial access (with a section of 50 mm x 40 mm) which was already integrated in the original design of the launcher.[13] The antenna is an aluminum square corrugated waveguide, 1245 mm long in two pieces, with external and internal cross-sections respectively of 44 mm x 38 mm and 26 mm x 26 mm. The corrugations (depth 0.5 mm, width 0.45 mm, pitch 0.78 mm) were measured before installation in FTU. The antenna is attached to the vacuum flange holding a DN40-CF fused silica window of selected thickness for microwave transmission at 140 GHz. A transmission line with off-vessel matching optics will be installed in the torus hall to connect the second passive line to the CTS receivers, located outside the torus hall.

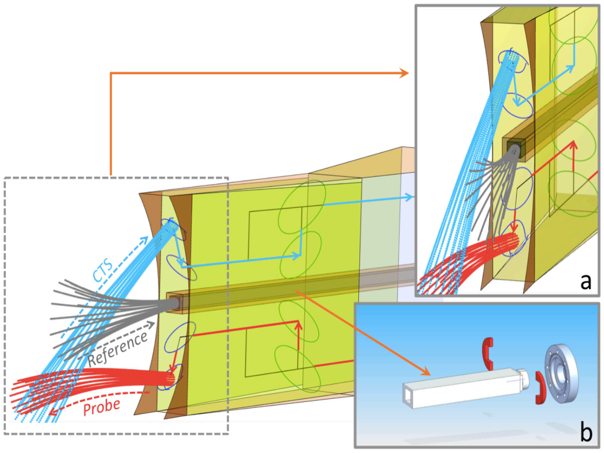

Fig. 2. 3D sketch of the FTU front-steering launcher, where the probe beam (bottom, in red), the receiving CTS beam (top, in blue) and the receiving reference line of sight (middle, grey) are shown. A different front view of the launcher and a drawing of an half section of the remote steering antenna recently installed (with the back vacuum flange) are shown respectively in the boxes (a) and (b), on the right. The beam tracings shown in this picture have been computed with the GRAY code.[14]

IV. IMPROVEMENT TO THE DATA ACQUISITION SYSTEM

Data for both the fast digitizer and the photomultiplier (used to monitor the visible light level in the launching port) reported in Ref. 7 are acquired on local memories in the experimental room.

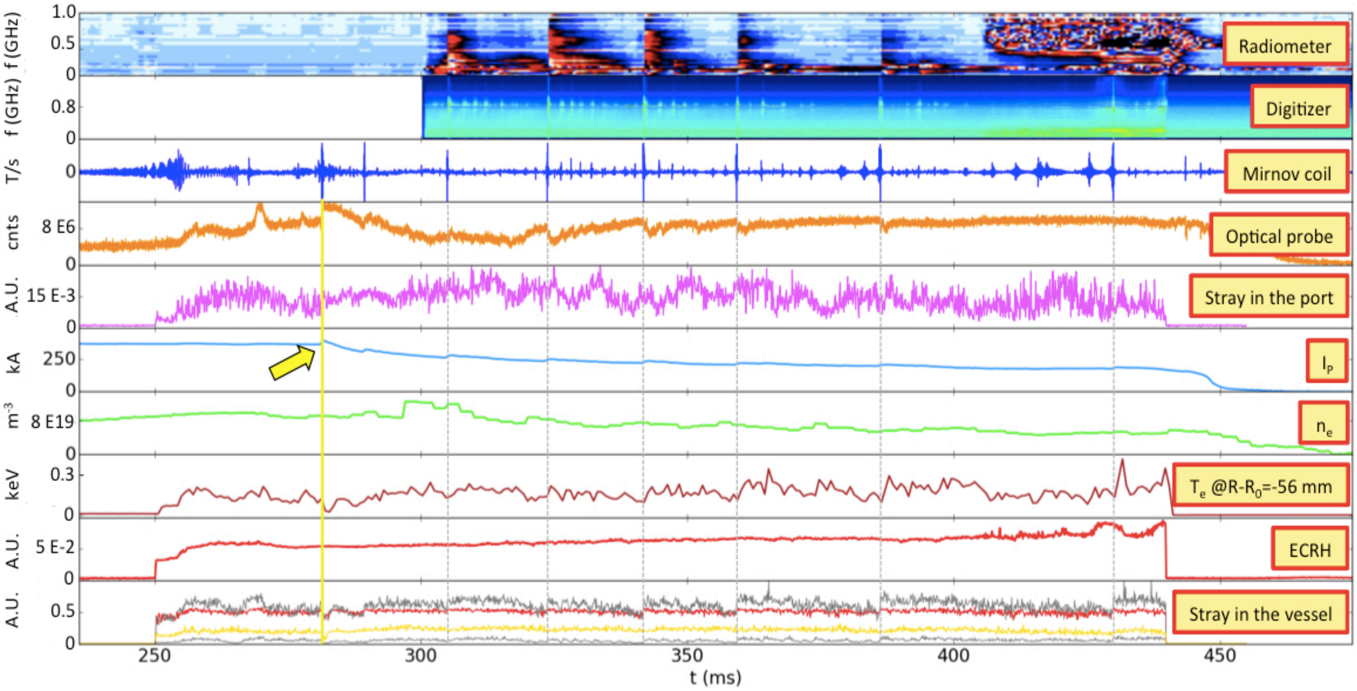

Fig. 3. The disruptive phase for density limit of shot #40284 (starting from the yellow marker) is shown as an example of output of the new software developed to show the spectrograms of the CTS systems on the same reference time of FTU. A time variation of the signals coherent with the MHD activity (Mirnov coil, 3rd line) can be seen between 300 ms and 440 ms, in particular in the (un-calibrated) spectrogram by the 32-filter bank radiometer (1st line), in that of the fast digitizer (2nd line), in the visual light level detected by the optical probe recently installed in the launching port (4th line) and in the stray radiation level measured in the FTU vessel (10th line).

A software was developed to show all CTS-relevant data (including output from the fast digitizer, the multi-channel spectrum analyzers and the optical fiber in the launcher) at the same time (with reference to the FTU shot start). An example of the output of this software is shown in Fig. 3, where correspondence of various signals provide the evidence of correlation between them. Also a new sniffer probe was installed in 2015 on a window located on the backside of the vacuum flange, as described in Ref. 7, in order to monitor the stray radiation level inside the launcher. Signal conditioning for this sensor have now been set properly and the first measurements of stray power in the CTS port have been taken. Also this signal can now be visualized (see Fig. 3, 5th line), together with all the others using the new software.

V. CONCLUSIONS

Recent upgrades were introduced in the CTS diagnostic of FTU in 2016. A second radiometric system and multi-channel spectrum analyzer have been installed in parallel to the existing ones. The two synchronized systems will allow simultaneous measurements of cross-polarized radiation (sharing the same transmission line) or additional detection of a second (reference) signal which will be acquired from a line of sight not intersecting the scattering volume, using a second transmission line to deliver the signal from the tokamak hall to the experimental room. A remote-steering antenna has been installed between the two existing CTS lines, allowing insertion of the second line of sight in the narrow launcher port. The signal of each radiometer can be acquired, at the same time, either on a pair of 32-channel filter bank spectrum analyzers (@2 kHz) and on two separate channels of the fast digitizer, at a maximum (combined) acquisition rate of 12.5 GS/s. The possibility to change the tuning frequency of both radiometers by acting on a single remotely controlled synthesizer has been implemented and the detection bandwidth has been enlarged up to ~4.2 GHz. Four microwave circuits provided with two notch filters (used either individually or in series) have been integrated on one of the two front-ends in order to take advantage of different filtering capabilities. A software was developed to allow visualization of both FTU and CTS data on the same reference time, including those of a new sniffer probe, which has been installed on the launcher to monitor the stray radiation level in the probe line.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] E. Westerhof et al., Phys. Rev. Lett. **103**, 125001 (2009).
[2] E.Z. Gusakov and A.Yu Popov, Nucl. Fusion **51**, 073028 (2011).
[3] M. Porkolab and B.I. Cohen, Nucl. Fusion **28**, 239 (1988).
[4] W. Bin et al., Fusion Eng. Des. **96-97**, 733-737 (2015).
[5] A. Bruschi et al., 9th "SMTW: Sources and Applications" (2014).
[6] U. Tartari et al., Rev. Sci. Instrum. **78**, 043506 (2007).
[7] W. Bin et al., J. Instrum. **10**, P10007 (2015).
[8] A. Bruschi et al., 42nd EPS Conference on Plasma Physics, P4.115.
[9] S.K. Nielsen et al., Plasma Phys. Control. Fusion **57**, 035009 (2015).
[10] W. Bin, E. Alessi, A. Bruschi O. D'Arcangelo, L. Figni, C. Galperti, S. Garavaglia, G. Granucci, A. Moro, J. Instrum. **9**, P05001 (2014).
[11] S. Garavaglia et al., Fusion Eng. Des. **88**, 998-1001 (2013).
[12] W. Bin, A. Bruschi, S. Cirant, G. Granucci, S. Mantovani, A. Moro, S. Nowak, Fusion Eng. Des. **84**, 451-456 (2009).
[13] A. Bruschi, W. Bin, S. Cirant, G. Granucci, S. Mantovani, A. Moro, S. Nowak, Fusion Sci. Technol. **55**, 94 (2009).
[14] D. Farina, Fusion Sci. Technol. **52**, 154 (2007).