Turbulence measurements and improved confinement regimes on FTU

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Introduction. We present in this paper an overview of recent turbulence measurements carried out on the FTU tokamak. We deal in particular with the relation between improved confinement regimes and the change in turbulence properties as measured by reflectomety.

The FTU machine. FTU is a high field, high current density, high density, circular cross section tokamak based in Frascati. It features three RF additional heating systems: LH, ECRH and IBW and has two separate pellet injectors launching horizontally and vertically. Its main parameters are: Bt≤8T, Ip≤1.6 MA, P_{LH}≤2MW,P_{ECRH}≤1.5MW, P_{IBW}≤600kW.

The FTU reflectometer. FTU, among its diagnostics, is equipped with a two channel heterodyne poloidal correlation reflectometer[1,2]. The launching system consists of two BWO that can be tuned in the range 50-80 Ghz and which are connected to two horns: one launching the ordinary polarization (O-mode) and the second one launching the extraordinary polarization (XL-mode). The receiving horns are two pairs (one below and one above the midplane) all pointing towards the center of the vacuum chamber. In each pair the 2 horns are separated by an angle $\alpha=5^o$. The frequency range of the BWOs allows for the probing of densities in the range 3-8x10^{19}m^{-3} in the O-mode and in the range 1.4-2.5x10^{20} m^{-3} in the XL-mode. The heterodyne is obtained by keeping the 2 oscillators locked in phase with a frequency gap of $\Delta\nu$=20MHz. The sine and cosine component of the beating wave are separately digitized with a sampling frequency of up to 2 MS/s.

It is possible to measure with a good accuracy the radius of the reflection layer using the density profiles given by the new multi-channel (up to 40 chords) CO_2 interferometer[3].

Since only a single frequency may be chosen for each pulse, and since during the interesting regimes both the average density and its peaking factor can vary by a large factor we have that turbulence evolution during a discharge must always be compared with a similar discharge with a similar reflection radius (rather by comparing spectra during the same pulse). The system is aslo very simple and does not allow for radial correlation measurements nor for toroidal or larger angle poloidal correlations. Another important limitation is that the plasma center is almost always unaccessible by our system. We usually can only probe the region r/a>0.35. This is a strong limitation for instance with e-ITB where the barrier foot is located at r/a between 0.3 and 0.4.

Improved confinement regimes on FTU. On FTU the additional RF power systems heat preferentially the electrons and it is therefore common to obtain regimes where electrons and ions are not in thermal equilibrium. This is what we expect to obtain (albeit in somewhat different conditions) in burning plasmas where the alpha particle heating is dominant. On the other hand, high densities ohmic discharges may show both improved confinement features and strong thermal coupling between ion and electrons.

In ohmic plasmas the confinement time scales linearly with the electron density up to a critical saturation density which is about 9x10^{19}m^{-3}. The linear density scaling may be recovered for much higher densities when the fuelling is done by pellet injection. This improved ohmic confinement regime (PEP mode[4]) has given so far the best results both in confinement time (up to 120 ms) and D-D neutron yield (up to 10^{13} s^{-1}).

Internal transport barriers (ITB)[5] may be obtained on FTU with dominant electron heating in discharges with combined LH and ECRH RF power. The barrier is characterized by a steep Te gradient in a central region, almost full current drive and moderately inverted q profiles. Record central Te have been achieved of up to 15 keV.

Light gaseous impurity injection (usually Ar) are used to obtain the RI mode[6]. The injection is made on a target plasma of Bt=6T, Ip=800kA and $n_e=10^{20}$ m^{-3}. Over a period of several confinement times the density progressively peaks and the neutron yield grows by a factor up to 4. Unfortunately most discharges with RI modes terminate with a loss of the improved confinement regime closely followed by a disruption.

Finally, interesting confinement properties have been obtained by launching only moderate RF power under the form of ion-Bernstein waves (IBW)[7]. Experiments in both H and D have been carried out with the RF power resonant with a high harmonic of the ion-cyclotron frequency. In such conditions, a region of good confinement is observed inside the absorption layer of the RF power.

The experimental turbulence spectra. Like on many other devices the spectrum consists mainly of 3 components: a sharp peak at low frequencies (LF) which extends up to about 20-30 kHz, a bump (or maybe even two or more bumps) in an intermediate frequency region between -say- 30 and 300 kHz which has varying width and central frequency. This band is usually referred to as quasi-coherent (QC) component. Finally a broad band (BB) component that can extend up to 700-800 kHZ for FTU discharges.

Turbulence during pellet fuelled discharges. We present here the results obtained during pellet fuelled discharges. The target plasma (Bt=6T, Ip=500kA, before pellet $n_e=6x10^{19}$ m^{-3}) is not the one that yields the best performances in terms of neutron rate or confinement time but, on the other hand, allows for the probing of a region very close to the magnetic axis (r/a≈0.35). The pellets may be launched both by the horizontal injector or by the vertical one. The first one has a higher speed whereas the second one can exploit better the drift of the plasmoid and achieve therefore comparable penetration. Depending on the target plasma, we observe that the particle confinement can be either good or bad. The good confinement phase is also distinguished by peaked T_e and n_e profiles and by a growth of the density profile peaking factor. On the other hand the bad particle confinement phase has inverted central n_e and T_e profiles with also a tendency of constant or decreasing n_e peaking factor. This double behavior is closely reflected by the turbulence properties. In figure 1 we observe that the first pellet creates a high particle confinement, the spectrum is dominated by the LF component. On the other hand, the QC component is dominant for the bad confinement phase (2[nd] and 3[rd] pellet). We also observe that the QC componet for the 1[st] pellet, albeit smaller, extends up to very high frequencies ν_{QC}≈300 kHZ but does not exceed 150 kHz for the 2[nd] pellet and 200 kHz for the 3[rd] one. The 300 kHz activity corresponds to poloidal mode numbers m of the order of 150 and to $k_\theta \rho_i$≈0.7 whereas the 200 kHz activity corresponds to m≈80 and $k_\theta \rho_i$≈0.7 These values, which would point to ITG-TEM instabilities responsible for the bad confinement and to the onset of DTEM during the good confinement phase, should be taken

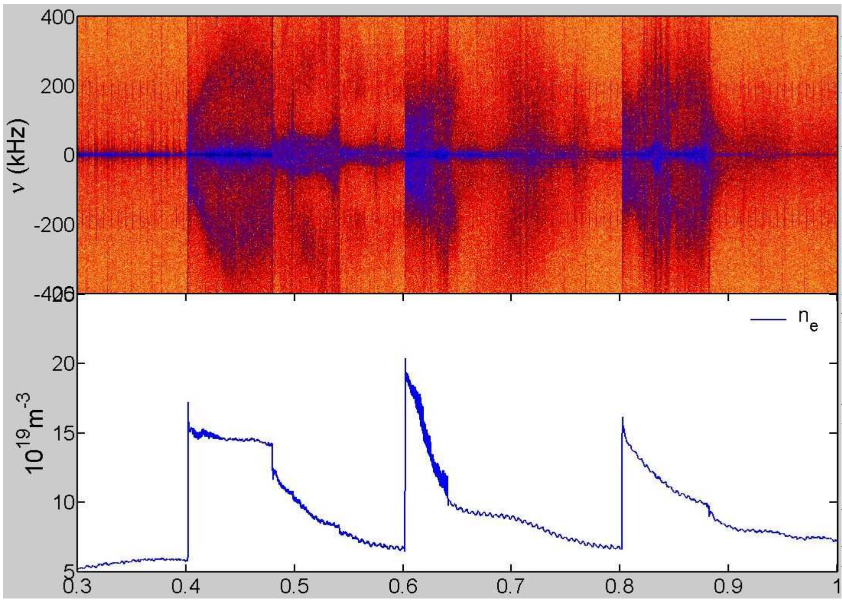

Figure 1: FTU pulse 27943. Reflectometry spectrogram during multiple pellet injection. The turbulence properties differ during good and bad particle confinement

with care as mode number of the order of 150 are outside the resolution limit of the instrument. Also the width of the self correlation function in the case of the 1st pellet is much wider (100 μs for the width at half height) compared to about 40 μs for the 2nd and 3rd pellet.

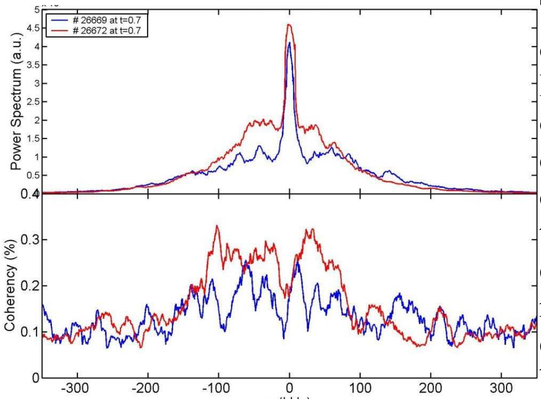

Figure 2: Comparison of spectra and coherency for two discharges (26669-Blue, with ITB and 26672-Red without ITB)

Turbulence during e-ITB. ITBs were obtained with a target plasma with Bt=5.3T, Ip=350kA and $n_e=5x10^{19}$ m^{-3} (before the onset of the ITB). As we have mentioned before, the density evolution during the discharge makes it difficult to distinguish between the changes in turbulence behavior due to the improved confinement and those due to the shifting reflection radius. We can however make a good comparison between spectra and coherency between two similar pulses: one with and one without the ITB. In both pulses (see figure 2) the reflection layer was located roughly at the same radius (r/a≈0.4) which corresponds also to where the barrier foot is located . We can observe that the QC component is suppressed by the barrier. Here the modes in the QC frequency range (ν_{QC}≈80kHZ) have a poloidal mode number m≈50 and $k_\theta\rho_i$≈50. In figure 3 we can observe a complete spectrogram of the reflectometer signal for discharge 27749. We can distinguish two phases: in the first one the LH power suppresses the QC component, in the second one (during which the real barrier is observed) the ECRH suppresses also the LF component of the spectrum. Actually the QC component is not really suppressed but rather spread over a larger range of frequencies. By careful comparison of the evolution of turbulence properties during discharges with and without the ITB we can conclude that during the ITB there is a suppression of the LF component, a moderate suppression of the self correlation function and a speed up of the poloidal rotation. No appreciable reduction of the QC activity is observed if the whole 20-300 kHz band is considered. We must however point out that these results are usually taken for reflection radii away from the barrier foot.

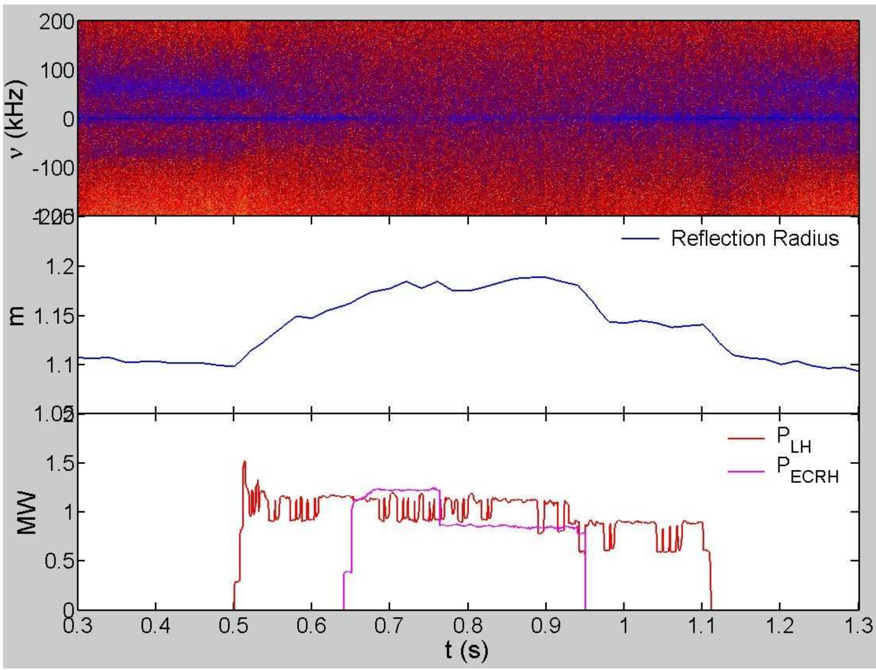

Figure 3: FTU shot 27749. a) Reflectometry signal spectrogram. b) Reflection radius. c) Additional heating

Turbulence during RI modes. The RI mode is obtained on a discharge with Bt=6T, Ip=800kA and $n_e=10^{20}m^{-3}$. The density is chosen so that the plasma is already in the saturated ohmic confinement regime and any improvement in the confinement time can not be attributed to the density raise. The target density is most unsuitable for reflectometry measurements as it falls right in a gap between O-mode and X-mode accessibility limits. In the first campaign we chose to use the O-mode polarization and chose to probe a peripheral region (r/a≈0.8) away from the region where the improved confinement is supposed to take place. We can however observe (see figure 4) that during the RI mode phase (after Ar injection, red trace), the cross correlation function grows, the poloidal rotation speeds up and the coherency, both in the LF and QC components, grows. At similar reflection radii no coherency growth is observed without Ar injection. The discharge terminates with a disruption after having lost its improved confinement properties.

Turbulence during IBW induced barriers. The interpretation of these experiments is the most controversial. There is a set of discharges where a clear indication of improved confinement inside the deposition layer of the IBW is observed. However reflectometry measurements are available only for a second set of discharges where no evidence of improved confinement was observed. We have, on the other hand, a very good set of measurements in which we can compare behaviors inside and outside the deposition layer and in discharges with and without IBW heating. The effect of the IBW is clear on the turbulence properties: we have that inside the absorption layer the LF component is reduced but not the QC component; at the barrier foot the effect is inverted: the LF component is unchanged and the QC component is reduced. It may be argued that we are starting to observe a turbulence reduction but that such reduction is not sufficient to trigger a sizable reduction of the heat fluxes.

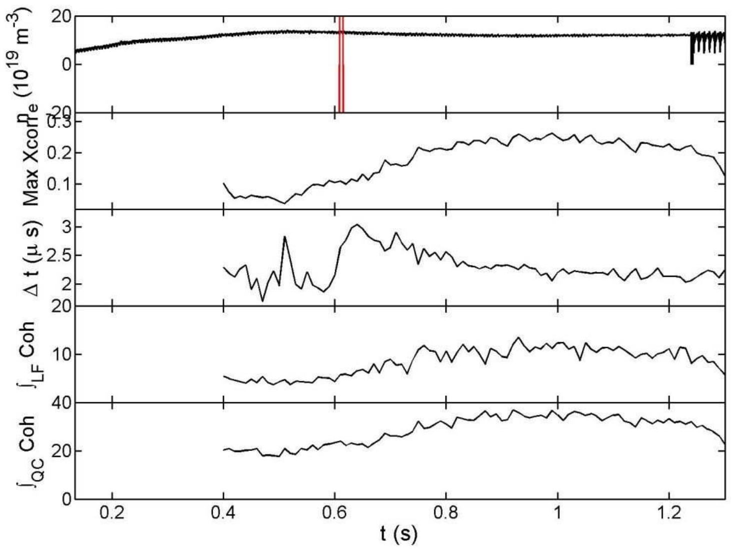

Figure 4: FTU shot 25500. Evolution of turbulence properties during RI mode phase. a) electron density. b) Max of cross correlation function. c) Delay between 2 channels. d,e) Coherency of LF and QC components

Conclusions. The FTU reflectometer, with all its limits, is a suitable instrument to observe turbulence behavior in very different regimes. Good particle confinement after pellet injection, electron-ITBs, RI modes triggered by Ar injection and IBW induced transport barriers have all been investigated with success. Further experiments are however desirable to have a complete set of comparable conditions between normal and improved confinement regimes.

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