Amplitude Correlation Analysis of W7-AS Mirnov-coil Array Data and Other Transport Relevant Diagnostics

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Abstract. This work is based on the amplitude correlation analysis of the signals from a poloidal Mirnov-coil array on the Wendelstein 7 - Advanced Stellarator (W7-AS). The motivation behind this work is an earlier finding, that changes in the RMS amplitude of Mirnov-coil signals are correlated with the amplitude of small scale density turbulence measured by CO2 Laser Scattering. Based on this and other measurements, the hypothesis was set, that some of the magnetic fluctuations are caused by transient MHD modes excited by large turbulent structures. The statistical dependencies between the power modulations of different eigenmodes can provide information about the statistics of these structures. Our amplitude correlation method is based on linear continuous time-frequency representations of the signal, we use Short-Time Fourier Transformation (STFT) with Gabor-atoms to map the signal onto the time-frequency plane, as two dimensional power density distributions. From these transforms we can recover the power modulation of different frequency bands. Provided the selection of the resolution of the transforms and the limits of the frequency bands were correct, the time series calculated this way resembles the original power fluctuation of the selected eigenmode. The only distortion introduced is a convolution smoothing by the time-window used in the transformation. Detailed correlation analysis between different bandpowers of the Mirnov-coil array signals were carried out and presented in bad and good confinement states. In order to reveal the true structure and cause of magnetic fluctuations Mirnov-coil diagnostic signals were also compared with Lithium beam and CO2 Laser Scattering measurements. In our analysis we have found, that there was a strong and systematic difference in the cross-correlations of power bands between different confinement states.

1. Introduction

The confinement transition in the W7-AS stellarator around the 1/3 edge rotational transform [1] is the manifestation of the rotation transform sensitivity of the anomalous transport phenomena. There is a twofold change in energy confinement time in a response to a small change of the rotational transform at the plasma edge (ι_a). At ι_a=0.344 we have good confinement, while at ι_a=0.362 we have bad confinement. In this paper we are analyzing this transition by processing magnetic fluctuation signals of the poloidal Mirnov-coil array of W7-AS and comparing these signals to other transport relevant diagnostics.

Mirnov-coil signals exhibit quite frequently bursts, which have been linked to transient MHD modes in the Wendelstein 7-AS stellarator. In an earlier analysis [2] it was found that transient MHD modes are localized radially and might have a poloidal structure [3].

We analyze transient perturbations in Mirnov-coil signals and their relation to other transients and profile changes retrieved from Li-beam Beam Emission Spectroscopy (Li-BES)[2] and LOTUS[4] collective laser scattering signals. In previous observations the following, presumably transport-related, transients were observed in diagnostic signals:

- Burst of magnetic field fluctuations in the 10-100 kHz frequency range with about 100 microsecond characteristic duration.[3,5]

- Modulation in mm-scale density fluctuation amplitude measured by collective laser scattering[6]. The characteristic autocorrelation time of these modulations is around 100 microsecond.
- Centimeter-scale flattenings in the temperature profile measured with Electron-Cyclotron Emission[7]. The autocorrelation time of the associated temperature modulation is also on the 100 microsecond scale.
- Transients in the edge density profile measured by Li-beam emission spectroscopy[2]. The characteristic timescale is also in the couple of hundred microsecond range.

Although the characteristic timescale of all of these perturbations is around 100 microseconds it is yet unclear whether they are different manifestations of the same phenomena or independent of each other. Some previous analyses gave a hint that these are related, e.g. a clear correlation between mm-scale density fluctuation amplitude and Mirnov-coil signal RMS fluctuation amplitude was observed[6]. Based on these hints a working hypothesis has been set up to explain the observed phenomena. According to this, some transient event transports particles and energy across magnetic surfaces, which results in a sudden profile change. The resulting profile is a deviation from the MHD equilibrium, therefore the plasma responds with some kind of MHD waves. These are observed in the Mirnov-coil signals as different frequency magnetic field modulations with an associated density perturbation as detected by the Li-beam at the plasma edge. ECE measurements revealed that the sudden profile changes occur at random locations, exciting different MHD modes. (Due to their frequency GAE modes[8] are a good candidate for these modes.) In the above model the MHD burst do not cause transport, they are merely a consequence of transport events.

To support this hypothesis it would be necessary to characterize the temporal correlation between different measurements. Although it seems to be quite straightforward to perform correlation analysis between the various diagnostic signals, a more detailed analysis reveals that in its usual form this is not appropriate due to various reasons. First, the Mirnov-coil bursts are periodic, while the profile changes are not. A little jitter in the phase of the Mirnov signal results in a complete destruction of the correlation. Such a phase jitter can be caused by different poloidal location of the triggering transport phenomenon. Another difficulty arises if the transient profile changes occur at random radial positions. As a result the presence of an MHD burst in the Mirnov signal might be either positively or negatively correlated with the local density and temperature change. This will again destroy correlation.

Due to the above considerations it is clear that new numerical methods need to be developed and applied to the situation. This paper presents the first attempt on the way of a complete correlation analysis of the above described phenomena. First a new technique is described for the correlation analysis of magnetic field fluctuation bursts at different frequencies. As a second step we present first correlation results with density profile changes at the plasma edge.

2. Correlation between the bandpowers of Mirnov-coil signals

A traditional way of the analysis of stochastic signals used to be the estimation of its spectrum components, i.e. the estimation of the auto power spectral density (APSD) in most of the case using FFT technique. While traditional Fourier decomposition can divide the signal into infinite long Fourier components, linear continuous time-frequency transforms like Short-Time Fourier Transformation (STFT) or Continuous Wavelet Transform (CWT) are capable of decomposing it into localized time-frequency atoms, wavelets or bursts as well [9]. This technique is not easy since a suitable selection of the time-frequency atoms can decide the fate of such decomposition. Linear continuous time-frequency transforms promise a way to resolve the time variation of the spectral components. The uniform frequency resolution of the STFT suited our signals, so we decided to use this transform instead of CWT.

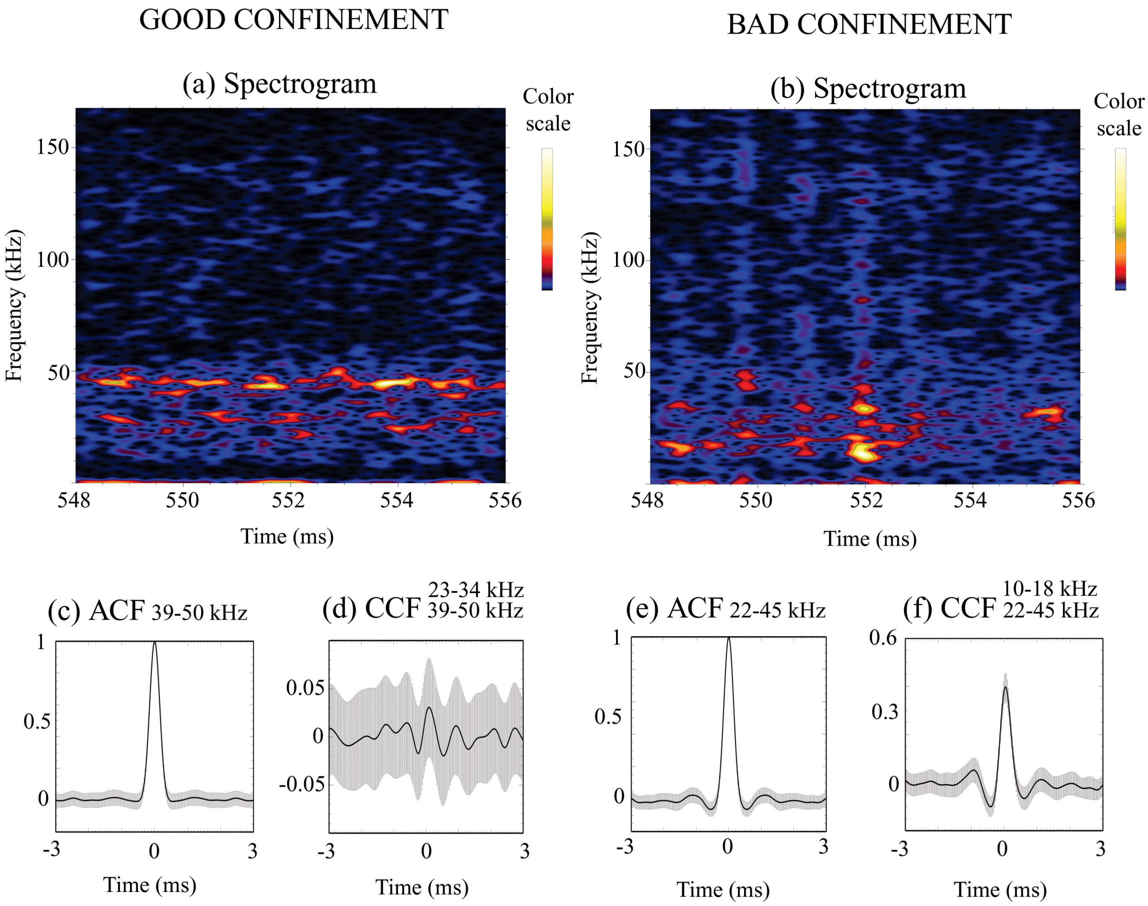

FIG. 1. a) and b) Spectrograms in good and bad confinement states, respectively. c) and e) the ACF of bandpower variation of selected frequency bands (Note, that frequency bands are different in the two cases). d) and f) show the CCF between frequency bands in case of good and bad confinements respectively.

First, using Gabor-atoms, which resemble Morlet-wavelets, we calculate the spectrogram (the time-frequency power density distribution calculated using STFT) of the Mirnov-coil signals. Such technique lead us to two dimensional time-frequency resolution of power variation as it can be seen on Fig. 1a) and Fig. 1b) which are a clear representation of time variation of APSD of Mirnov signals in two cases: Fig. 1a) when we have good confinement (shot 52123) in the plasma, Fig. 1b) when confinement was bad (shot 52153). Notice that there are at least two major distinct frequency bands, where most of the power is concentrated, but neither of them is continuous, but typically we have spikes, flitters or bursts in those frequency bands. Fig. 1a) and Fig. 1b) represent only short segments of long spectrograms. For further analysis frequency bands were selected from longer averages. Bandpowers were calculated by integrating the spectrograms in frequency within the range of the frequency bands selected.

The fact that the power of Mirnov signals is concentrated in frequency bands is not a new finding, since it was claimed earlier, that due to the non-uniform poloidal plasma rotation and different mode numbers, modes at different radial locations appear at different frequencies in the diagnostic signals [10]. A study [5] on temporal variations in the amplitude of small-scale density turbulence also found roughly 100 μs long bursts which were linked via correlation with changes in the RMS amplitude of poloidal magnetic field perturbations.

Therefore it was natural to think that these variations of band limited frequency power are linked together when transport events extend across a considerable part of the minor radius or events are localized but have a common drive. As transport is higher and the wavenumber spectrum of turbulence shifts toward long wavelengths[10] in bad confinement we expect higher correlation between the amplitude of different frequency MHD modes in bad plasma confinement than in good.

The prediction above and the method of decomposition have been checked using simulation (see in more details in [5]). We simulated two or more frequency bands, which were modulated with burst like events having three randomly chosen parameters: the start time, the length and the rise time of the burst. These simulated signals were mixed, a background white detection noise was added. Using the STFT technique mentioned above the signal was successfully decomposed into components [5]. Bandpower signals were also correlated, and it was demonstrated that the original crosscorrelation function (CCF) of the simulated modulating envelopes can be extracted correctly in spite of the decomposition and a relatively strong added background noise.

The correlation functions of bandpowers were analysed in depth in the 52123-52175 experiment series consisting of shots of good and bad confinement discharges with four plasma densities. We have found differences in the autocorrelation functions (ACF) of bandpowers from good and bad confinement (see Fig. 1c) and Fig. 1e)), but the real difference between good and bad confinement bandpower statistics was found in the CCF between the different frequency bandpowers of the same signal. For good confinement states we have got zero or very little correlation as seen in Fig. 1d), while in bad confinement states we have clearly significant correlation like in Fig. 1f). Results of the analysis reproduced well in identical shots and we got similar results for all plasma densities.

Such a significant correlation in CCF in case of bad confinement can be explained by energy transport between frequency bands, or at least by having common origin of those bandpower fluctuations.

3. Common origin of fluctuation, correlation between different signals

Recently changes in density fluctuations associated with confinement transitions close to a rational edge rotational transform were found in the W7-AS stellarator [10]. It was shown that mode-like fluctuations measured by the Mirnov-coils and the Li-beam are the same. The covariance between a Li-beam light signal and all the Mirnov signals showed that a correlation indeed exists and it changes its character when a transition takes pace from good confinement to bad confinement. On Fig. 2a) and Fig. 2b) the cross correlation between channel 13 of Li-BES (looking into the edge plasma close to the LCFS) and all of the Mirnov-coils are presented in two intervals of shot of 47940. This is a slow current ramp shot in which both Li-BES and LOTUS data are available. The slow current ramp changes the confinement quality gradually from good to bad. In the first half of the shot we had good confinement, while in the end the state of the plasma was changed gradually to bad confinement. [10].

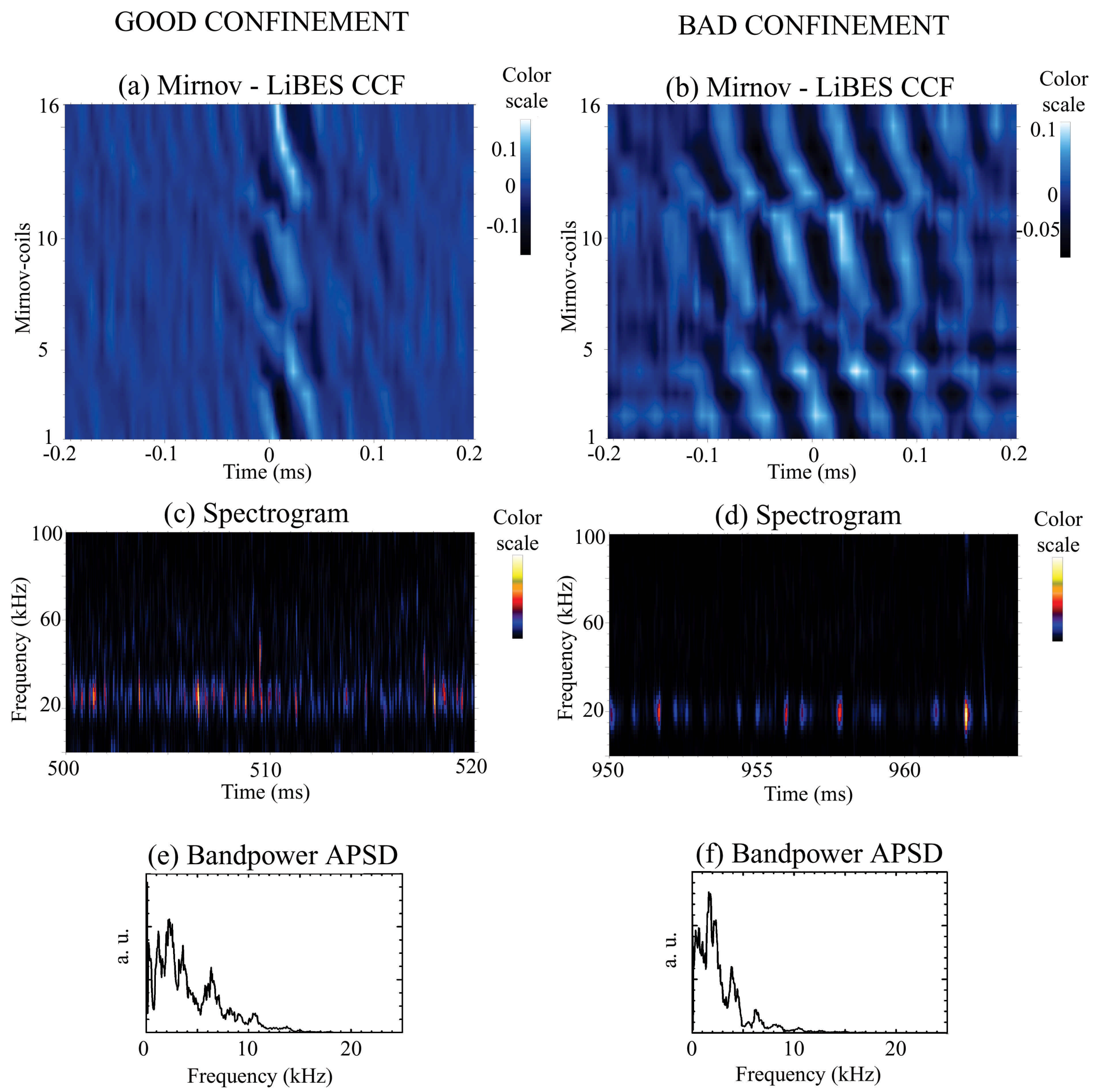

FIG. 2. a) and b) Cross correlation between Li-beam signal and the total Mirnov signals show characteristic undulation with 0.05 time constant, tilted due to delay for different Mirnov-coils and having different relaxation lengths for good and bad confinement. The characteristic undulation is due to main frequency band 20 kHz. c) and d) Spectrograms of Mirnov-coil signals in the processed intervals of shot 47940. e) and f) autospectra of the 15-30 kHz bandpower variations.

There are two structures mixed in these CCFs. The first is the basic undulation of CCF with time period roughly 0.05 ms. This corresponds to the 20 kHz basic frequency, which is the lowest frequency and most powerful band in this shot. The tilted character of these undulations can be explained by time delays due to poloidal rotation of the B_q component of the MHD mode. Since this rotation has time delay for different Mirnov-coils this time delay can be seen in CCF. These are practically the same for both states. However an important difference can be seen for bad and good confinements: the difference in relaxation time lag, where that structure can be seen. In case of bad confinement the relaxation length of the structure is about ±0.15 ms around the middle (zero time), while in case of good confinement it is much narrower about ±0.04. This structure can be understood if we take a closer look at Fig. 2c) and Fig. 2d). First of all it is clearly seen from the spectrograms that the dominating frequency component in both cases is about 20 kHz (more precisely between 15 and 30 kHz). If we estimate the APSD of the bandpower variation of this frequency band then we get

Fig. 2e) and Fig. 2f) for good and bad confinement respectively. They have interesting structure. It is clear that the spectrum is much wider in case of good confinement. That means that the rate of the flashes in good confinement is relatively higher in case of good confinement than in case of bad confinement, as it can also be clearly seen on Fig. 2c) and Fig 2d) as well. The wider spectral band is manifested in shorter relaxation length of CCF in the case of good confinement as seen in Fig. 2a).

In the Fig. 2) correlation figure a time delay can also be observed. In this and in all the later correlation plots in this article the convention is that the time axis shows the time delay of the Mirnov-coil signals with respect to Li-BES or LOTUS signals. Here we have a positive time lag, that would mean that the Mirnov-coil signal is slightly delayed with respect to the Li-BES signal. However, the two data were collected by different ADCs, this way time lags this small have to be treated with precaution.

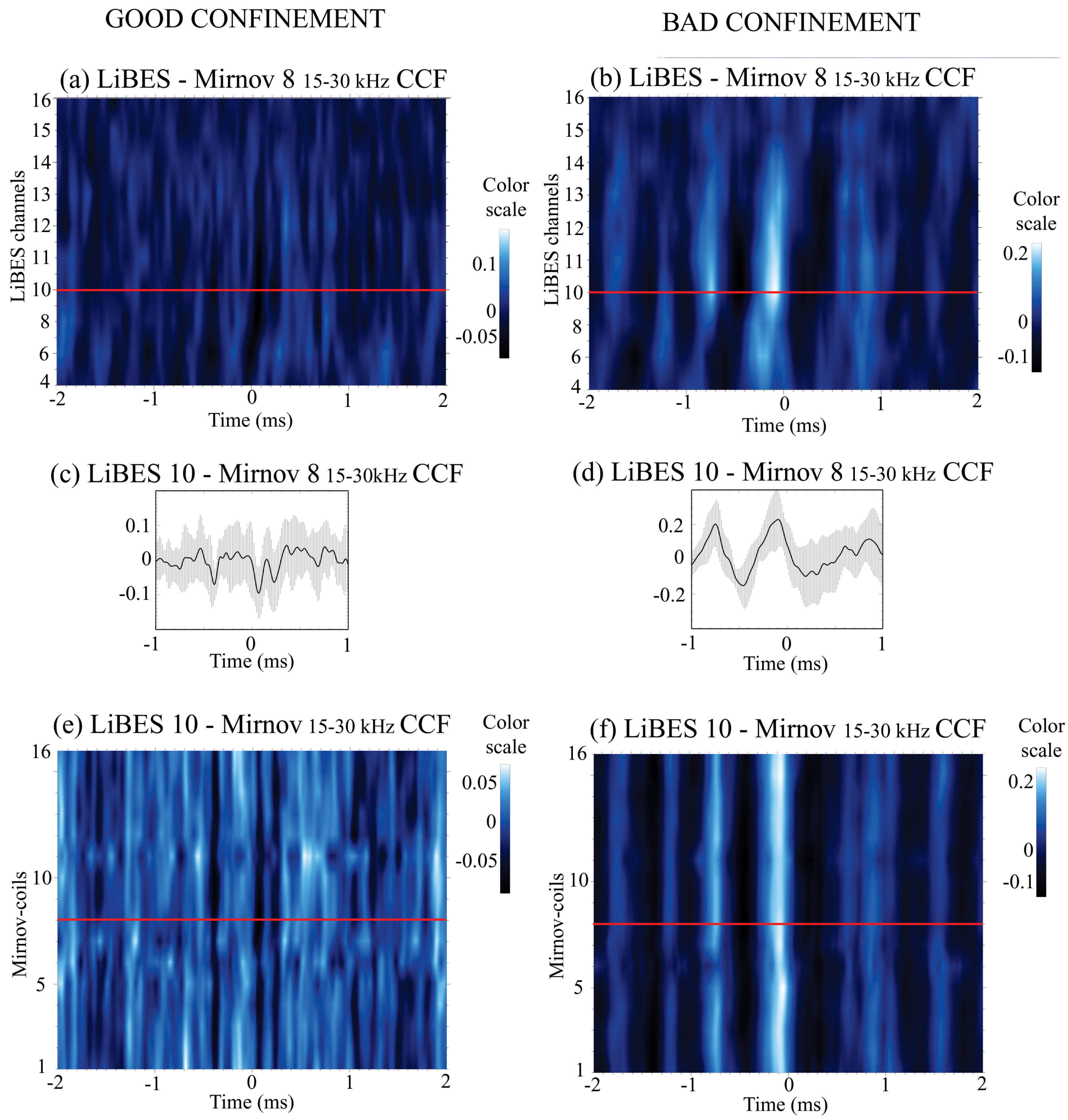

FIG. 3. Cross correlation between the Li-beam signals and the bandpower variation of the frequency band 15-30 kHz of the Mirnov-coil signal Li-BES channel4 is in the outer SOL,channel 16 is in the edge plasma.

It is worth to examine the cross correlations between the Mirnov-coil bandpower (15-30 kHz) variation and the Li-beam signals (Fig. 3). On the upper two figures (Fig. 3a) and Fig. 3b)) the CCFs of a selected (coil 8) Mirnov-coil with the Li-beam light signals can be seen, while on the bottom two (Fig. 3e) and Fig. 3f)) figures the CCFs between a selected (channel 10) Li-beam and all Mirnov-coil signals have been plotted. In the middle, two selected CCFs between Mirnov coil 8 and Li-beam channel 10 are presented for good and bad confinement sates respectively. From Fig. 3c) and Fig. 3d) it is easy to conclude that CCF for good confinement (0.50-052 s part of shot of 47940) shows no correlation (it is smaller then the estimated statistical error) and the undulation on that picture comes solely from the smoothing window of the STFT (Fig. 3c)). In the case of bad confinement (0.950-0.963 s part of shot 47940) significant correlation was found (Fig. 3d)). The bottom picture (Fig.3f)) proves that this is true for the combination of the given Li-beam with all Mirnov-coil signals, that one strong middle peak and a satellite can be observed with period about 0.6 ms.

It is important to understand the meaning of the correlation functions of Figure 3. Here we correlate the power of the Mirnov signal activity at a certain frequency band with a Li-beam signal, therefore we are not looking at the density change (Li-beam light change) associated with the MHD mode seen by the Mirnov coil but we try to detect whether there is a density profile change correlated with the MHD activity. Indeed we see some change in bad confinement, the edge density profile changes when the MHD burst occur.

It is worth to pay attention to the time delay of the central and side line on Fig. 3b) and Fig. 3f). Those are not due to poloidal time delay between the Mirnov-coils, which was the case in Fig. 2b). Here the time delay is a magnitude larger than the period time of the Mirnov-coil signal component. Bursts in the Mirnov-coil signals appear slightly before the low frequency change in the Li-BES signal.

We believe it is worth to call the attention to the Fig. 3b), where significant CCF was found between a Mirnov-coil signal and all of the Li-beam signals. The form of that light spot in the picture is interesting. It is also tilted a little bit and it is slightly shifted in comparison with the zero time lags. The inclination might indicate a radial propagation in the profile change.

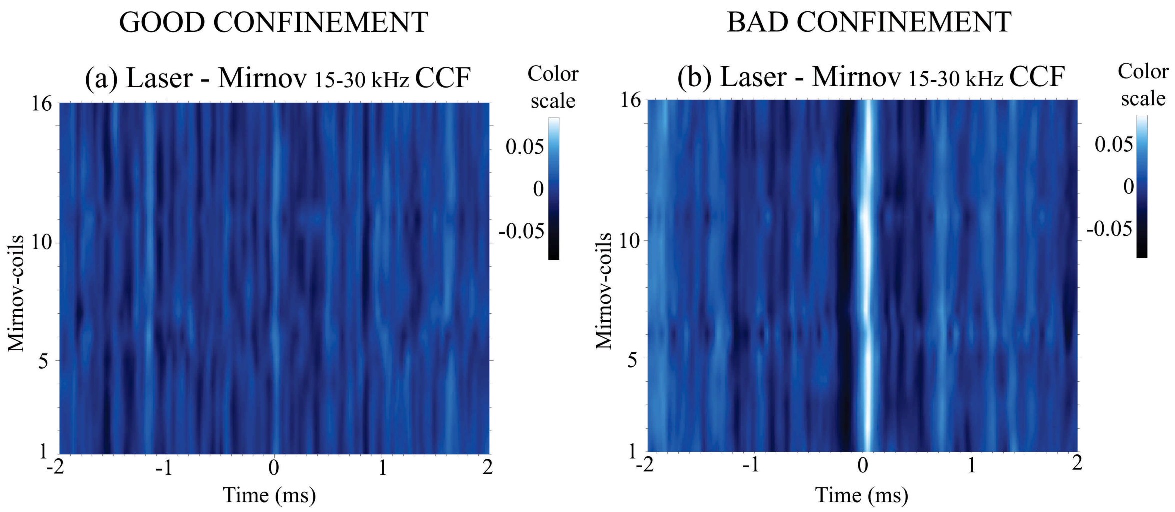

FIG. 4. CCF between the 750 kHz CO_2 laser scattering bandpowers and the bandpower variation of the frequency band 15-30 kHz of the Mirnov-coil signals.

Finally the first results on correlation between the power of small-scale density turbulence (measured by collective laser scattering) with the bandpower variation of the frequency band 15-30 kHz of all the Mirnov-coils in shot 47940 can be seen on Fig. 4 for the time intervals 0.42-0.56 s and 0.9-096 s, which are good and bad confinement states, respectively. It is similar to that of with Li-beam. In the case of bad confinement we have significant CCF (Fig. 4b)), while in the case of good confinement there is no significant correlation between the selected frequency bandpower variations. In case of bad confinement the turbulence at 750 kHz measured by the LOTUS laser scattering appears to strengthen just before the burst in the Mirnov-coil signal and weaken after it.

4. Conclusion

STFT technique was used to build spectrograms, which were able to follow the time variation of the bandpower in the Mirnov signals from shots of the W7-AS stellarator. It was shown, that bandpower fluctuations have special spectra with several peaks. Its character changes, when the plasma state changes from good confinement to bad confinement. The most important change was the reduced flashing rate of the bandpower variation, which was manifested in the fact that only the lower frequency components remained in the spectra. The structure of the spectra of bandpower variation is an ultimate goal in the near future.

Selected bandpower variations of the signals from Mirnov-coils were correlated with other frequency bands and other diagnostic signals. Significant CCF was found for bad confinement and no correlation was found for good confinement. This proves that in case of bad confinement there are large scale complex events seen by all the diagnostics included in this paper. These events are probably the ELM-like structures observed frequently in W7-AS[7].

We found time delays in CCF between the bandpower fluctuation of the Mirnov signals and the signals from Li-beam or laser scattering. This might shed light on the propagation and causality of events, but more work is related to separate instrumental and physical effects.

6. References

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