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Pulsed radar reflectometry of broadband fluctuations

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The possibility to use pulsed radar reflectometry for turbulence studies is investigated. Good qualitative agreement is found between the power spectrum of variations in time-of-flight and the quadrature spectrum of a continuous-wave fluctuation reflectometer. Standard Fourier analysis is hampered considerably by missing samples in part of the experimental data. Using the Lomb-Scargle normalised periodogram for power spectrum estimation, reliable spectra are obtained even for signals in which as much as 60% of the samples is missing.

Introduction

TEXTOR-94 is equipped with a ten-channel pulsed radar reflectometer, measuring the time-of-flight in reflection of short (approx. 1 ns) microwave pulses. The system currently installed is a ten-frequency O-mode system running at a 20 MHz total pulse repetition rate [1,2]. This translates to ten-channel measurements at 2 MHz, or four or two channels at a maximum rate of 5 or 10 MHz, respectively. The accuracy in the time-of-flight determination for a single pulse equals 74 ps. Several subsequent pulses can be averaged to further lower this figure. The goal of the diagnostic is three-fold: to study density profile developments, coherent macroscopic fluctuations, and broadband microscopic fluctuations.

The system differs from previous pulsed radar reflectometers mainly in two ways: in the higher number of channels (ten versus four) and in the very high pulse repetition rate (2–10 MHz versus 500 kHz). The number of channels will allow for reconstruction of the full (LFS) density profile, while the high pulse repetition rate makes the study of broadband density fluctuations possible.

Pulsed radar techniques have, to our knowledge, not yet been employed for the study of broadband density fluctuations in tokamaks. The time-of-flight of pulses can be expected to be sensitive not only to the precise location of the reflecting layer, but also to fluctuations in the local gradient just before reflection. Some degree of robustness against 2D interference effects might be expected, since each pulse contains a range of frequencies.

Earlier work has shown the presence of non-coherent fluctuations on time-of-flight signals: on RTP, a spread in the plasma reflection time-of-flight of about 300 ps was observed, compared to a spread of only 30 ps without plasma [3]. Also on T11-M an increased time delay scatter during plasma was reported and attributed to plasma inhomogeneities [4]. Investigations on the RTP system ruled out instrumental effects as cause of the increased scatter. Two possible causes remained, each of which could fully account for the observed scatter: a possibly decreased signal-to-noise ratio due to strong background emission from the plasma combined with a low power level of the reflected pulses, or, alternatively, density fluctuations in the plasma. The distribution of the scattered time-of-flight signal remained near-gaussian. Data taken from the present TEXTOR-94 system is expected to contain more information because of the much higher sampling rates that can be reached.

The rest of this contribution will focus on a method for the analysis of high sampling rate pulsed radar data. In order to distinguish between plasma fluctuations and noise as cause for signal broadening, the statistical properties of the signal should be studied. Here we will concentrate on the power spectrum, also of high interest for studying the plasma fluctuations themselves.

Power spectrum estimation

Conventional FFT analysis for power spectrum estimation does not work well for part of the pulsed radar data. The analysis is hampered by the fact that sometimes many samples in the time series are missing: launched pulses for which the detected reflection was not high enough to trigger the time-of-flight measurement.

These 'lost pulses' occur because the reflected pulses generally show a large variation in amplitudes. Constant Fraction Discriminator modules ensure that this variation in itself does not lead to a significant walk in the measurement of the pulse flight times. To prevent false triggering on noise, however, these discriminators only trigger on pulses higher than an adjustable threshold amplitude. If the average pulse amplitude is low, then part of the pulses will not exceed this threshold amplitude. The cause for the large amplitude scatter in the reflected pulses is probably related to plasma density fluctuations. Note, however, that the important factor for losing pulses is the average reflected amplitude, which depends mainly on probing oscillator strength and on the distance from the antennae to the reflecting layer. Depending on these factors and on the setting of the threshold amplitude, the fraction of lost pulses can be anything between 100% (very low oscillator power, reflecting layer in the very centre) to 0% (oscillator power at or above design value, reflecting layer in gradient region).

For profile measurements one can use an average value for the time-of-flight, which is well defined even for the case of a large fraction of lost pulses. For power spectrum estimation, however, one needs to find a way to treat the resulting missing samples in the time series. Three cases are distinguished:

Case I: No pulses are lost. In this case the power spectrum can be easily calculated by conventional Fourier transformation, applied in a sliding Hamming or other

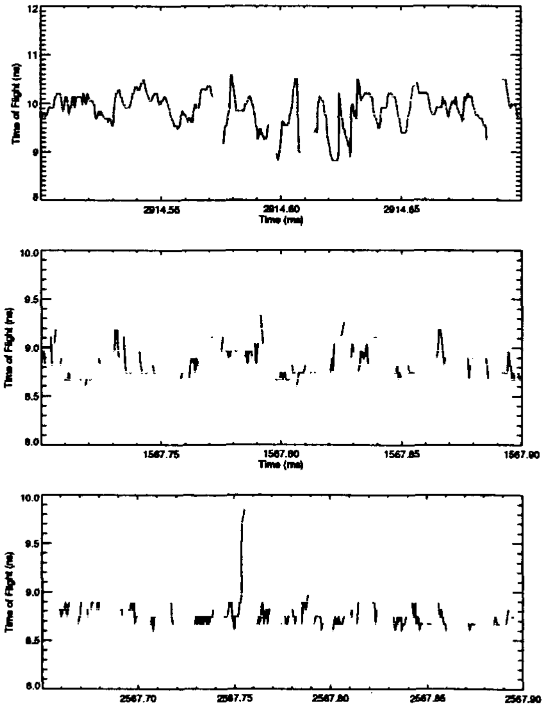

Fig. 1: Details of some time-of-flight time traces. The top trace corresponds to case II; the two lower traces stem from discharge #91082 and are case III.

suitable data window to obtain a spectrogram.

Case II: A small fraction (<10%) of pulses is lost, distributed more or less evenly over time. See for an example the top trace of figure 1. In this case we might expect the spectrum to be reasonably unaffected by the missing samples, provided we assign some reasonable values to them. Several options are possible: we choose to substitute the missing samples by linear interpolation from neighbouring points. After this we proceed as in case I with Fourier analysis.

Case III: A large fraction (>10%) of pulses is lost, or the missing pulses adjoin in time to form large gaps in the data. In this case we cannot expect valid data from standard Fourier analysis anymore. The assumption we make to fill in the missing points, whatever it is, is going to have a significant impact on the resulting spectrum. For this case therefore, we use a different analysis method: the Lomb-Scargle normalised periodogram. This method was designed to detect periodic signals in irregularly sampled data sets, in a way that is mathematically equivalent to the least-squares fitting of sines of different frequencies to the data [5,6, our implementation: 7,8]. We have applied the method in a short, sliding Hamming window and, like in the Fourier analysis, averaged over several windows.

Even though a large portion of the data falls into cases I and II it has been important to develop a standard analysis algorithm for case III, since this then covers all data. We want to successfully recover spectrograms from all discharges and channels, even from those with extremely bad signal quality, to have a fluctuation measurement in each and every discharge.

Results

The capabilities of the different methods for spectrum estimation will be demonstrated on an extremely 'low-quality' signal of only 40% detected pulses. Some zoomed-in portions of the signal are shown in the two lower traces of fig. 1. An overview of the different phases of the discharge is depicted in fig. 2. The top two graphs in this figure show the evolution of line integrated electron density and the total diamagnetic energy content of the plasma. In this particular discharge the effect of strong D_2 puffing on confinement in the Radiative Improved (RI) mode was investigated. The increase in energy confinement following the neon injection at t = 1.1 s is completely undone by a strong D_2 puff, starting around t = 1.7 s. The spectrogram of density fluctuations as obtained from one of the channels of a (continuous-wave, not pulsed) quadrature-detection correlation reflectometer is shown in the bottom panel of fig. 2. This reflectometer is measuring near the plasma edge, but still a few cm inside the last closed flux surface. As the D_2 puff is injected and global confinement deteriorates, a clear enhancement of low-frequency turbulence is observed.

Spectrograms of pulsed radar reflectometry signals, calculated using the different methods, are shown in the third and fourth panel. For comparison with the quadrature channel at 37 GHz, the 39 GHz pulsed channel was chosen. The upper spectrogram was calculated using a sliding window FFT after linear interpolation of the missing data points. Although it shows the reduction in high frequency fluctuations starting around t = 1.7 s, the behaviour of the low frequencies is opposite to that measured by the correlation reflectometer: the low frequencies appear at a high level during RI mode, and at a much lower level afterwards in the

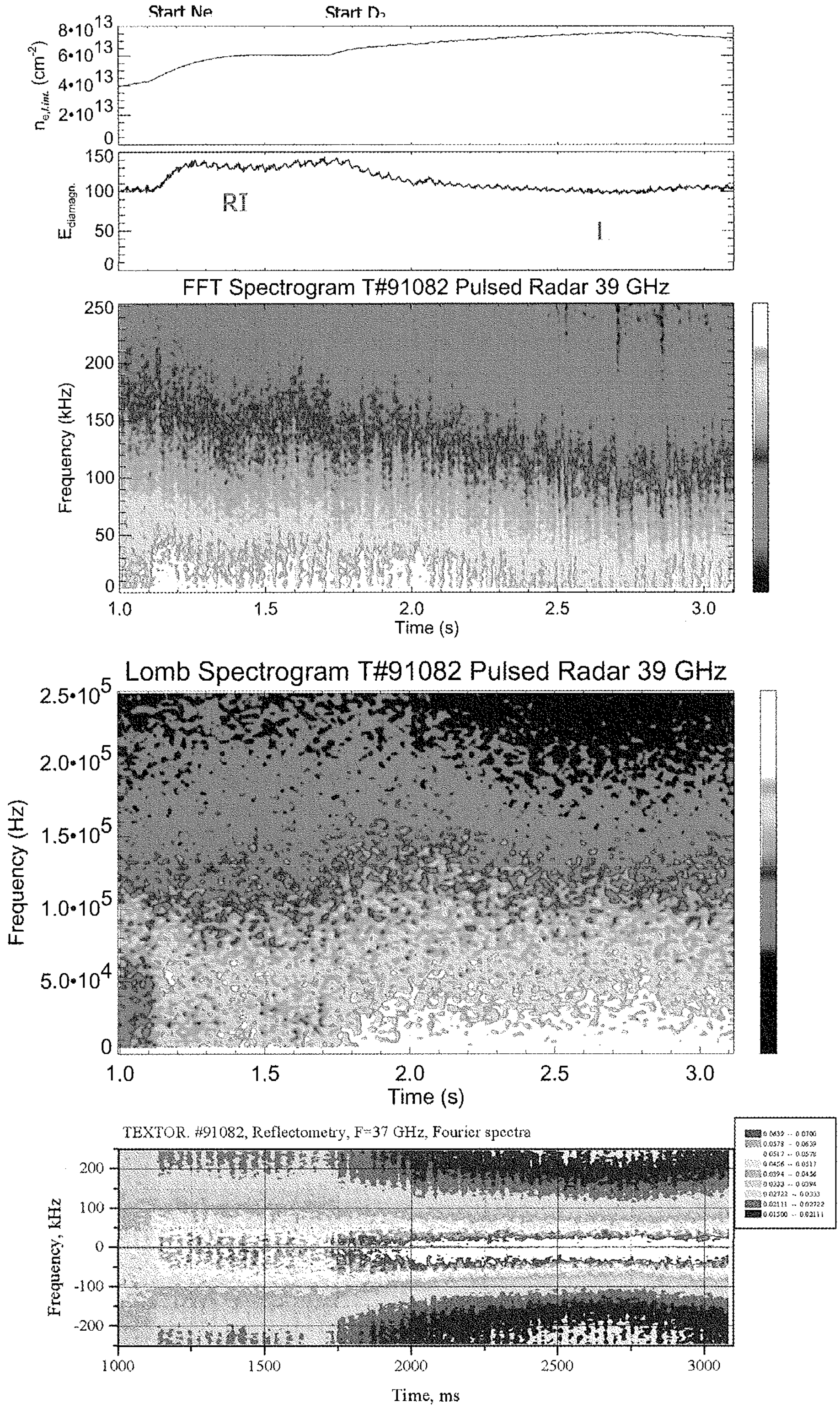

Fig. 2: Overview of Textor discharge 91082, showing (top to bottom) line integrated electron density, diamagnetic energy content, spectrogram of pulsed radar time-of-flight fluctuations calculated with FFTs after linear interpolation of missing points, the same spectrogram calculated via the Lomb-Scargle method (no interpolation needed), and, for comparison, a double-sided spectrogram from a continuous-wave, quadrature-detection reflectometer channel (courtesy of S. Soldatov).

L mode phase. The disagreement in particularly the lower frequencies is not unexpected, since the applied interpolation distorts the power spectrum mainly at frequencies with periods comparable to the gaps in the time series.

The spectrogram as calculated via the Lomb-Scargle periodogram shows good qualitative agreement with the correlation reflectometer. This agreement extends from the high frequency reduction after t = 1.7 s to the behaviour of the low frequencies: a low level in the RI mode phase, with higher levels in the following D_2 puffing phase. Note also the spread-out spectrum from 1.0 s to 1.1 s: this coincides with an asymmetric, Doppler-shifted spectrum on the quadrature channel. This spectral broadening is attributed to plasma rotation, which has been corroborated by the correlation measurement with another, poloidally separated quadrature channel.

Conclusion

Good qualitative agreement has been found between the power spectrum of fluctuations in time-of-flight (pulse group delay) as measured by pulsed radar reflectometry, and the double-sided spectrum of a continuous-wave fluctuation reflectometer. This provides a sound basis for the application of the TEXTOR-94 pulsed radar reflectometer as a standard fluctuation diagnostic.

Another important step towards the routine evaluation of pulsed radar fluctuation data from all plasma discharges has been taken with the implementation of the Lomb-Scargle normalised periodogram for power spectrum estimation. It has been shown that, using this method, spectrograms can be obtained successfully for signals with as little as 40% detected pulses.

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