Improved phase detection schemes for plasma interferometry

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Precise knowledge of the plasma density is important for the operation of a fusion device and for discharge analysis. A key diagnostic technique for density measurement is interferometry, which is applied on all modern tokamaks and stellarators. Interferometry is based on the dependence of the refractive index of the plasma on electron density. A laser beam sent through the plasma experiences a phase shift that is proportional to the line-integrated electron density along its path. By comparing the phase of the probing beam to that of a reference beam, which does not cross the plasma, or another appropriate reference signal, the line-integrated density can be measured. Depending on wavelength, machine size and maximum density, the phase shift can be larger than 2π. Therefore, multi-radian phase detectors are required in most cases. Mostly, phase detection is performed by specifically designed, hard-wired readout electronics which delivers an electric output voltage that is proportional to the plasma density. Meanwhile, the sampling rate of the available data acquisition systems is often high enough to digitize the interferometer raw signals with a sufficient oversampling factor, which allows to perform phase and density reconstruction by software.

The ASDEX Upgrade tokamak is equipped with two independent heterodyne interferometer systems, a DCN interferometer operating at a beat frequency of 10 kHz, and a two-color CO_2/helium-neon interferometer with a beat frequency of 40 MHz. On both interferometer systems, the hard-wired readout electronics is currently being replaced by more advanced phase detection schemes which rely on fast raw data acquisition and phase reconstruction by a computer algorithm. Although the involved beat frequencies differ by more than 3 orders of magnitude, similar strategies have been successfully applied to both interferometer systems. In the following, the results obtained so far are presented.

DCN interferometer

As the beat frequency of the ASDEX Upgrade DCN interferometer ($\lambda_{DCN} = 195\,\mu m$) is 10 kHz, digitization of the sinusoidal raw signals is easy to achieve with present-day data acquisition systems. Recently, an analog-to-digital converter (ADC) system with a sampling rate of 1 million samples per second (1 MSample/s) and 14 bit resolution has been installed. As the DCN interferometer has 5 probing chords and 1 common reference chord, 6 ADC channels are required. The resulting data rate of 12 Megabytes per second is well within the capabilities of the ASDEX

Upgrade standard data acquisition hardware. For phase reconstruction, the time trace of the raw signals is divided into equidistant segments, each of them containing at least one full period. The function $A \cdot sin(\omega t + \varphi) + B$ is then fitted to the data in each segment via a Levenberg-Marquardt algorithm. Since the convergence of this fit sensitively depends on realistic starting values, a crude estimate of amplitude (A), phase (φ) and offset (B) is made beforehand by determining maximum value, minimum value and zero crossings within the corresponding segment. From the phase φ delivered by the fit for a probing signal, the phase of the reference signal is subtracted, delivering the desired phase shift modulo 2π. The integer multiples of 2π are counted by assuming that phase changes from one segment to the next are always below half a period. If the fractional phase shift changes by more than half a period from segment to segment, the counter for multiples of 2π is incremented or decremented accordingly.

When the probe signals are strictly sinusoidal, which is the usual case in quiescent L-mode

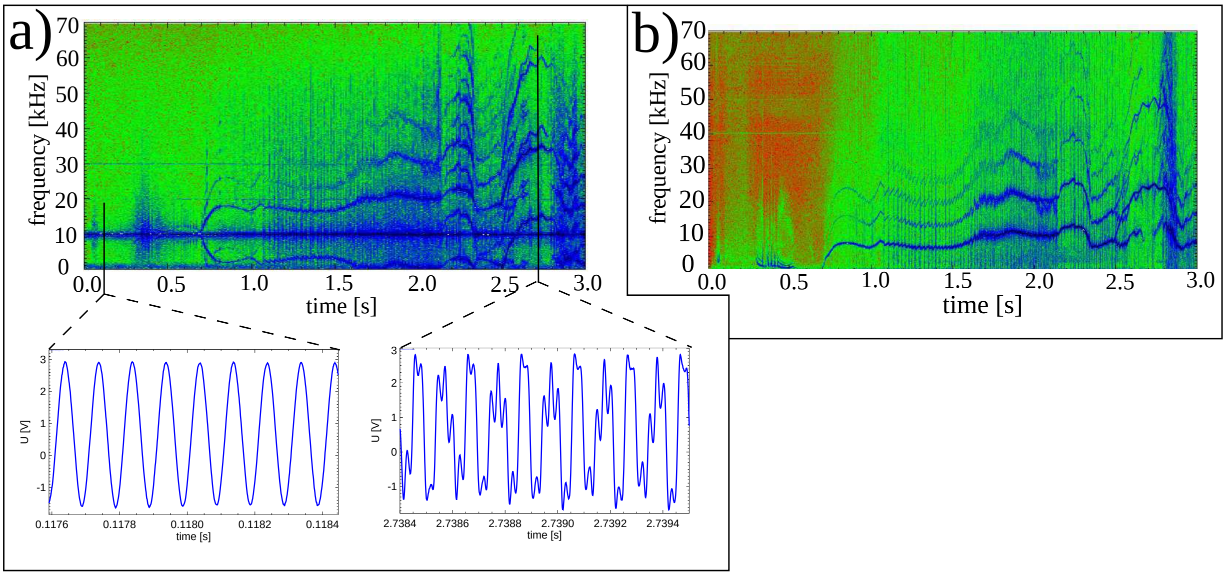

Figure 1: *a) Spectrogram of the DCN detector raw signal for ASDEX Upgrade discharge #29928 for the most central line of sight. The lower diagrams show two snapshots of the raw signal. b) Spectrogram of a Mirnov coil signal for comparison.*

discharges without magneto-hydrodynamic (MHD) activity, the residuum of the Levenberg-Marquardt-fit is low. Signal perturbation can be caused by MHD activity in the plasma, e.g. by neoclassical tearing modes, by ELMs or by pellet injection. In this case, the interferometer beam suffers from refraction, e.g. when a mode island crosses its path. The local density gradient at the island boundary deflects or de-focuses the beam, resulting in a reduced amount of power arriving at the detector. Accordingly, a rotating island causes a periodic modulation of the 10 kHz detector signal with the mode frequency f_{MHD}. This becomes apparent by sidebands at $f_1 = 10kHz + f_{MHD}$ and $f_2 = |10kHz - f_{MHD}|$ in the frequency spectrum of the detector signal. An example spectrogram is shown in figure 1. That way, as a by-product besides density measurement, the digitization of the raw signals has converted the DCN interferometer into a powerful tool for MHD detection. It provides some spatial resolution via its different lines of sight. When extracting f_{MHD} from the spectra, however, the artifacts resulting from the second frequency component at $|10kHz - f_{MHD}|$ have to be taken into account, i.e. data interpretation is not as straight-forward as for Mirnov coils.

Figure 1 also shows snapshots of the detector signal for two different points in time. It can be seen that in the presence of MHD activity, the detector signal is no longer sinusoidal. In this case, the residuum of the Levenberg-Marquardt fit performed for phase reconstruction increases. To obtain better results, digital band-pass filtering of the raw signals is applied to reject the MHD-related components in the frequency spectrum. Also the hard-wired readout electronics uses a bandpass filter. There, however, the width of the pass-band has to be adjusted in advance and holds for at least one entire plasma discharge. The setting is a compromise, as a narrow pass-band of the filter makes the phase detector less sensitive to MHD, but prevents the detection of fast density changes in the plasma, like those caused by pellet injection. A broad pass-band, on the contrary, is beneficial for pellet detection, but results in frequent phase jumps in presence of MHD. Digitizing the unfiltered raw signals and performing phase reconstruction by software gives much more flexibility, since the width of the pass-band of the digital filter can be adapted to the given situation. For example, when the characteristic pellet signature (fast drop of the signal amplitude and exponential recovery) is detected, the bandwidth can be temporarily increased to resolve the pellet well. A phase reconstruction algorithm with adaptive digital filtering is currently under development.

Two-color CO_2/HeNe interferometer

ASDEX Upgrade is in addition equipped with a two-color interferometer that uses a CO_2 laser ($\lambda_{CO2} = 10.6\ \mu m$) and a helium-neon-laser ($\lambda_{HeNe} = 633\ nm$) as light sources. The heterodyne phase detection system operates at a beat frequency of 40 MHz for both, infrared and visible branch. The method applied for the DCN interferometer, where the raw signals are digitized with a sufficient oversampling factor, also works for the CO_2/HeNe system, as described in earlier work [1] [2]. Initially, signals were digitized at 500 MSamples/s. Later, it was found that also at 250 MSamples/s, good results can be obtained. However, at those acquisition rates, the amount of data produced is large, and memory of the acquisition device is a limiting factor. Currently, this method is limited to a time window of 280 ms. Acquisition systems that are capable of recording the full 10 seconds of an ASDEX Upgrade discharge exist, but are leading-edge technology at the moment and therefore state a substantial cost factor. For this reason, it was decided to perform pre-processing of the raw signals with an electronic circuit and perform only the second step of phase reconstruction by software. That way, a sampling rate of 1 MSample/s (or even below) is sufficient.

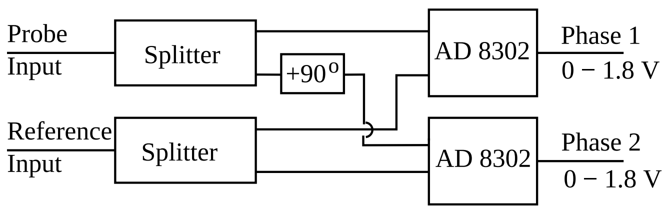

Figure 2: *Schematic of the signal pre-processing circuit for the 40 MHz signals.*

Figure 2 illustrates the electronic circuit used. The probe signal and the reference signal are both split. One part of the probe signal is phase-shifted by 90 degrees. Two integrated phase detection circuits (AD8302) then compare the phase of shifted and non-shifted probe signal to the phase of the reference signal. The output voltage of each circuit linearly increases from 0 to 1.8 V as the phase shift increases from 180 to 360 degrees. When the latter further increases, the voltage linearly returns to 0 V.

The second circuit behaves similarly, but delivers 0 V at 270 degrees and 1.8 V at 90 degrees. Both output voltages are acquired by 2 ADC channels. Having both voltages measured, the phase shift in the interval $[0;2\pi[$ can be unambiguously determined by a computer algorithm. Integer multiples of 2π are counted by software. Figure 3 illustrates the phase reconstruction from the measured voltages. With this method, the density evolution during massive gas injection (MGI) has been successfully monitored, which would not have been possible with the old readout electronics of the two-color interferometer.

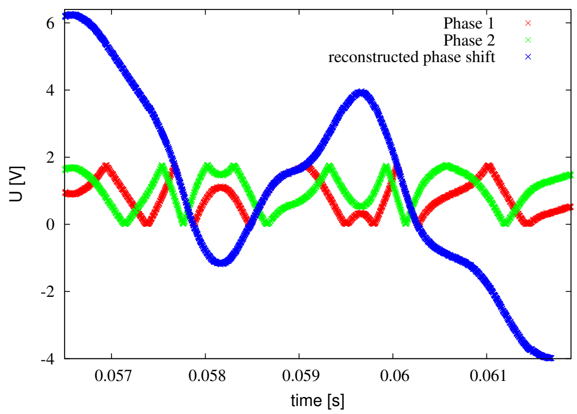

Figure 3: *Output signals of the circuit in figure 2 and phase shift reconstructed by software.*

The latter has a dynamic range ending at a line-integrated density of $5.26 \cdot 10^{20}\ m^{-2}$, which is nowadays exceeded by far in MGI experiments.

References

[1] *A. Mlynek, G. Pautasso, M. Maraschek et al.*, Fusion Science and Technology **61** 290-300 (2012)
[2] *A. Mlynek, G. Pautasso, H. Eixenberger et al.*, Europhysics Conference Abstracts **36F** (2012), P4.034