High resolution CO$_2$ interferometry on the TJ-II stellarator by using an ADC-based phase meter

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(Submitted 19 April 2004; published 1 October 2004)

A 10 MSample/s analog-to-digital converter has been used to analyze the signals from the double wavelength heterodyne interferometer (CO$_2$ 10.6 $\mu$m, He–Ne 0.63 $\mu$m) in the TJ-II stellarator. The phase difference between the two interferometers has been calculated using a new algorithm in Labview environment. A systematic study of the 1 MHz intermediate frequency has been done using our software and Labview tools. Different sources of noise and nonlinear effects have been analyzed. Crosstalk (from the reference path) has been detected and corrected by software. The complete system (single channel double pass) has been routinely working during the complete TJ-II autumn experimental campaign, providing the plasma line integral density in scenarios with average densities ranging from few $10^{18}$ m$^{-3}$ to more than $5 \times 10^{19}$ m$^{-3}$. The results have been compared with those from a 2 mm interferometer, obtaining an excellent agreement. Working with a final bandwidth of 4 kHz, a one pass line integral error level about $\pm 2 \times 10^{17}$ m$^{-2}$ has been achieved. © 2004 American Institute of Physics. [DOI: 10.1063/1.1786638]

I. INTRODUCTION

Two-color laser heterodyne interferometry is a proven method of measuring electron density in fusion plasmas. In this article we describe the analog-to-digital converter (ADC) system used to analyze the signals and measure the phase in the laser interferometric system for electron density measurements of the stellarator TJ-II ($R=1.5$ m, $a<0.22$ m, $B=1$ T).

The interferometer is a single channel, double-pass system that uses CO$_2$ ($\lambda=10.6$ $\mu$m) and He–Ne ($\lambda=633$ nm) laser beams traveling along the same 10 m path for vibration subtraction, with acousto-optic modulation for heterodyne detection. The aim of the diagnostic is to measure plasma densities above $10^{19}$ m$^{-3}$, and it is desirable to get an accuracy of about 1/300 of wavelength after the complete vibration subtraction effects. As a consequence, small sources of noise and nonlinearities must be eliminated or minimised. This article presents the work made in this way using an ADC system as a tool to analyze the signals. The same ADC system has been integrated in the complete system to measure the phase and calculate the line integral density.

II. INTERFEROMETER DESCRIPTION

The TJ-II stellarator heterodyne two-color interferometerr uses two different modulation frequencies for the CO$_2$ and He–Ne channels. For the CO$_2$ wavelength ($\lambda =10.6$ $\mu$m) a $f_{\text{mod}}=40$ MHz signal is used to drive the acousto-optic modulator while for the He–Ne ($\lambda=633$ nm) a frequency of $f_{\text{mod}}=80$ MHz is introduced to the driver. The 80 and 40 MHz signals coming from the detectors are down converted to an intermediate frequency (IF) of 1 MHz. The same frequency translation to IF=$1$ MHz is done for the reference signals of 40 and 80 MHz. Two different phase acquisition systems have been developed to recover the phase information from the 1 MHz (IF) signals. The first one uses a dedicated phase detector designed to operate at that intermediate frequency. The second phase measurement system is based on 10 MSample/s analog-to-digital (AD) converter sampling directly the 1 MHz reference and measurement signals. Dedicated phase measuring algorithms have been developed to recover the interferometric information from the signals.

Detection is carried out by using a HgCdTe photoconductor for the CO$_2$ laser and a Si Avalanche Photo Diode for the He–Ne laser. The HeNe laser is a 25 mW from Melles–Griot. The CO$_2$ laser is a Synrad 10 W. The laser CO$_2$ wavelength is adjusted during the measuring process.

To extract the electron density information the optical path length measured with both interferometers must be subtracted to eliminate the system vibrations. The vertical mechanical displacement of the top mirror during a current pulse is around 125 $\mu$m.

III. THE ANALOG-TO-DIGITAL DATA ACQUISITION SYSTEM

The board used has been the PCI-DAS4020/12 from Measurement Computing, with four channels, 12 bits of
resolution and 10 MSample/s per channel. It is based in the AD9225, 25 MSample/s pipelined A/D. It used a sampling and hold method of conversion being the aperture delay 1 ns, and the aperture jitter 1 ps. We will consider that the sampling is instantaneous and that the sampling frequency has no error.

After some measurements at 10 MSample/s, standard measurements have been done at 8 MSample/s. The number of samples has been 6.4 Msamples per channel. This means an 800 ms window.

Data are acquired by using previously developed software for TJ-II autonomous acquisition systems and at the end of the analysis process, elaborated data are integrated into the TJ-II central database, using the TJ-II RPC data access library.

The analysis module has been developed using LabView and it is dynamically loaded by the standard application previously mentioned. This module can be divided into three parts: (1) signals conditioning, (2) phase calculation, and (3) wavelength adjustment and integral density calculation.

After the signals have been acquired, its frequency is measured and then it is filtered with a second order bandpass Butterworth filter centered on the measured frequency. The filter width is not critical but there is a minimum limiting value to avoid big reductions of the amplitude. The filter width is larger for the HeNe signal than for CO2 one, because its wavelength is lower, and, as consequence, the dephasing is larger. Nevertheless the same filter width must be put for each reference-signal couples. The filters eliminate offset error and high undesirable frequencies. As we will explain later, the CO2 signal conditioning includes a correction for the crosstalk between the CO2 signal and its reference. To do it, simply a fraction of the reference is added, with the appropriate phase, to the CO2 signal.

The algorithm, to obtain the phase, counts the zero crosses and calculates the phase fractions. To do it, a linear interpolation is done between the two consecutive samples, $S_j$ and $S_{j+1}$, where the amplitude changes of sign. The interpolate correction time $\tau_n$, for the $n$th zero cross, will be

$$\tau_n = \frac{|S_j|}{|S_{j+1}| + |S_j|} \Delta t,$$

where $\Delta t$ is the sampling period. The linearization introduce an error lower than 1/780 of fringe for 8 MSample/s, and 1/1540 for 10 MSample/s.

Now the time corresponding to the $n$th crossing is

$$t_n = j \Delta t + \tau_n.$$

With the same procedure were obtain $t_n + 1$. The phase for a generic $i$ sample, between the $n$ and $n+1$ zero cross, will be

$$\varphi_i = 2 \pi n + \frac{2 \pi[(i - j) \Delta t - \tau_n]}{t_{n+1} - t_n}.$$

After that, the phase difference between the measuring and reference signals is obtained. Finally this difference is averaged over 1000 sampling intervals, that is 0.125 ms and 8 KSample/s. It improves very much the expected mean value.

To calculate the line integral density we must determine the CO2 laser wavelength. It is selected from a list of the possible wavelengths for CO2 laser, choosing those that have the best fit in the optical path length between the two interferometers for the previous and posterior time immediate to the discharge. Finally the one pass line integral density is calculated.

**IV. DATA ANALYSIS AND IMPROVEMENTS**

Using Labview tools, the acquired and elaborated data have been analyzed to recognize and eliminate sources of noise and errors: misalignments, VCOs power supply instability, infrared (IR) detector chilling problems and crosstalk between signal and reference in each interferometer. Other possible sources of error, as table vibration with no compensated paths, filters dephasing, and thermal effects, between others, are now being investigated.

The optimization of the first earlier-mentioned problems improved very much the results. Particularly, the crosstalk in the CO2 interferometer (mainly of electrical origin) was a very important source of noise. In addition to minimize this effect shielding the circuits, we corrected in introducing a modification in the program. Simply we add to the interfer-
ometer signal a percentage of the reference signal with an appropriate phase, as it is suggested in Ref. 5. Figure 1 shows the 10 758 pulse without and with crosstalk correction. In this pulse no plasma was generated but the current coils was as usual. The detection system was shielded and the alignment optimized to obtain the maximum possible signal to reduce the interference/signal ratio. The crosstalk effect shown could be considered a limit only correctable by software. In some initial signals the crosstalk was very much bigger. The correction parameters, amplitude and phase, are valid for all the same day pulses, and only small variations must be introduced in different sessions. Note that this correction is possible because we have the complete digitalized signals. The effect of crosstalk in HeNe signals is lower because the wavelength is 17 times smaller and no clear improvement has been achieved with correction.

V. RESULTS

During the 2003 autumn experimental campaign the system has worked routinely, almost all the pulses has been recorded and analyzed. Usually the pulses are analyzed by an operator before to save in the data base.

In Fig. 2 we can see the pulse 10 529, with neutral beam injection heating, measured with the CO₂–HeNe interferometer and with the microwave (140 GHz) one. The abscissa magnitude for microwave signal is the plasma density and the maximum value is about 3 × 10¹⁹ m⁻³ (pulses of 5 × 10¹⁹ m⁻³ has been measured). In order to compare the shapes, the CO₂–HeNe interferometer signal has been divided for a conveniently adjusted cord. Figure 3 shows the pulse 10 761, with a small density, about 5 × 10⁻¹⁸ m⁻³. The real cord for both pulses was 0.44 m, approximately 10% lower than the used to adjust the plots.

To evaluate the precision level in 10 761, we have used the time after the pulse, from 1200 to 1400 ms. The estimator used have been the deviation over the averaging time τ, the square root of

\[ \sigma = \sqrt{\frac{1}{m} \sum_{k=1}^{m} (x_k - \bar{x})^2}, \]  

where \( x_k \) is the kth average of the magnitude over duration \( \tau \) and \( \bar{x} \) is the mean over the whole data set (1200–1400 ms). Also Allan deviation⁶ has been considered.

For 10761 shot, \( \sigma \) always has been lower than 0.026 μm, and 0.02 μm for \( \tau \approx 0.8 \) ms. Allen deviation is always below 0.02 μm. The precision is in the order of 1/400 of fringe, about +/− 2 exp 17 m⁻² for the one pass line integral of the electron density and +/− 5 exp 17 m⁻³ for the average electron density. We must say that the precision has not been the same all sessions, but the worse case are typically better than 1/200 of fringe. We are working to improve the reliability of the system.

1 C. Alejaldre et al., Fusion Technol. 17, 131 (1990).
6 Dr. David Allan’s Website about Allan Variance Calculations. http://allanstime.com/AllanVariance/index.htm