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Relevant improvements in the two color interferometer diagnostic in TJ-II Stellarator.

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Introduction

The double color heterodyne interferometer system described in [1], wiich uses a phase measurement based on the Analogical to Digital Converter (ADC) presented in [2], has allowed us to obtain the line integral electron densities in TJ-II stellarator [3] since late 2003. From the beginning several improvements have been introduced. The most significative has been the detection and correction of a thermo-optical effect in the ZnSe windows [4]. Also recently an undersampling technique has been employed inan attempt to reduce computer time for phase measurements.

Phase measurement procedure

Initially the ADC sampling rate was 8 MHz, well above the 1 MHz intermediate frequency(IF). Using Labview, the four signals (two for each interferometer) are processed. The signals were conditioned using a second-order Butterworth band-pass filter centered on the measured frequency. The algorithm used to obtain the phase accumulates the counts of the zero crossing when two consecutive samples, S_j and S_{j+1}, change sign (usually from positive to negative). The apparent resolution is a 1/8 of fringe, but a linear interpolation is done between two consecutive samples. The interpolation correction time over the n-th zero cross, will be $\tau_n = \frac{|S_j|}{|S_{j+1}|+|S_j|}\Delta t$, were Δt is the sampling interval. Next the time corresponding to the n-th crossing is $t_n = j\Delta t + \tau_n$. Using the same procedure we obtain t_{n+1} as $t_{n+1} = k\Delta t + \tau_{n+1}$. The period will be $T_n = (k-j)\Delta t + \tau_{n+1} - \tau_n$. The phase for a generic i sample, between the n and n+1 zero cross, will be $\varphi_i = 2\pi\left(n + ((i-j)\Delta t - \tau_n)/T_n\right)$.

After that, the phase difference between the measurement and reference signals is obtained . Finally this difference is averaged over 1000 sampling intervals, wich improves significantly the expected mean value. The procedure to obtain the phase introduces an error that is less than 1/780 of a fringe for 8 MSamples/s and 10 bits of resolution. The average reduces very

much the expected mean value (about 1/32), That means about 6exp(-5) of phase resolution for final 8 KHz sampling rate .

Now, in order to calculate the line integral density the optical paths must be obtained. For a CO_2 laser we the selected wavelength is determined from a list of possible emission lines i.e., choosing that which has the best fit from a time before the discharge (about 200 ms). Finally the single pass line integral density is calculated. The phase measurement procedure is not the precision limiting factor as there are other different sources, e.g., low frequency thermal running, laser stability, non compensated paths, non linearities (cross-talk, beam shape and possible diffraction effects, electronic phase filter effects…), and other possible intrusive sources such as the detected thermo optical effect in ZnSe windows.

Thermo-optical effect in ZnSe windows

The thermo-optical effect in the ZnSe windows arises from of the difference between the refractive index variation with temperature in ZnSe for the different laser wavelengths [5]: $\left(\frac{dn}{dT}\right)_{0,6328} = 1.06\times10^{-4}K^{-1}$ for He-Ne and $\left(\frac{dn}{dT}\right)_{10,6} = 6.1\times10^{-5}K^{-1}$ for CO_2 laser and because the windows are heated by microwaves (53,2 GHz) that are not absorbed by the plasma during the ECRH heating. In an experiment performed to verify this hypothesis, was introduced into the TJ-II vacuum chamber a series of microwaves pulses without magnetic fields and gas injection. The signal traces of the two interferometers obtained are shown in the Fig. 1 (a). It can be seen that the ratio between the mean values for the two laser is 1.746, which is almost identical to that obtained when dividing the thermo-optical coefficients for the two wavelengths, i.e. 1.754. The Fig.1 (b) shows the interferometer optical path length difference signal between the two signals.

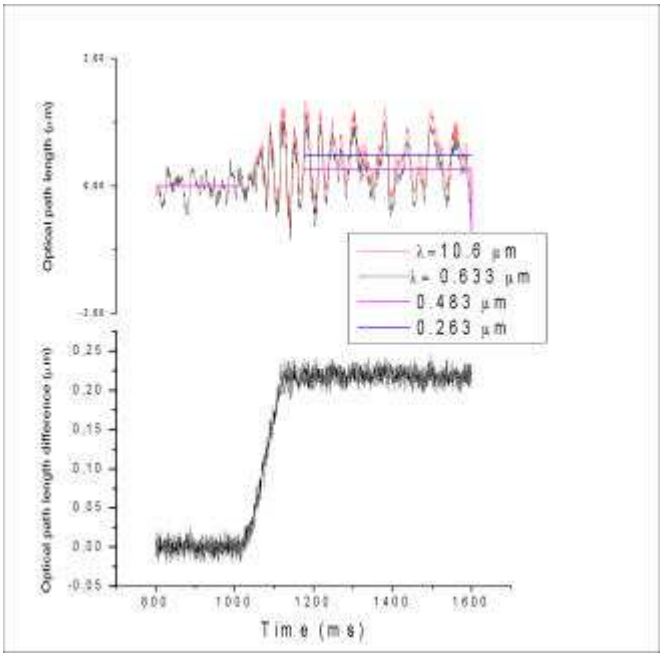


Fig 1. Signals without discharges

In practice the thermo optical effect produces a pedestal in the baseline. The magnitude of the pedestal depends of the unabsorbed microwaves. We use a correction subprogram that integrates the signal from a bolometer (BOL4), which is sensitised to microwaves, and subtracts it from the line density to make the mean value zero after the pulse. Fig. 2 shows shot number 11861 pulse signal before and after this correction.

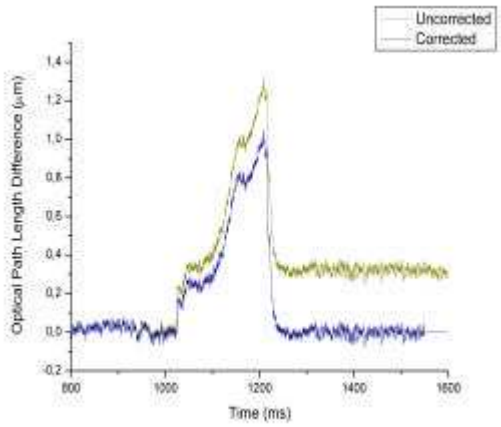


Fig.2 Shot 11861

Undersampling trials.

The high sampling rate emplyed, together with the long recording time, 800 ms, results in the collection of 25,6 Msamples as well as lengty computer time, 4 minutes. To improve this circumstances, the undersampling technique was applied. That t is widely used in digital radio and other technologies. This technique uses the alliasing phenomena in a advantageous way. Which does not contradict the Nyquist criterion because when all frequencies are into a bandwidth B around a frequency f_n, the Shannon criteria is applicable. A sampling frequency greater than two times B is enough to reconstruct the signal. It is easy to see that the phase difference between signals is conserved in the alliased signals. If the signals have the form $S(t) = A\sin(2\pi f_m t + \varphi(t))$ then a sample j corresponding to the time $t = j\Delta t$ were $\Delta t = 1/f_s$ and f_s is the sampling frequency, is $S_j = A\sin(2\pi (f_m/f_s) j + \varphi_j)$ When $f_m = nf_s \pm f_{us}$, where n is an integer, then $S_j = \pm A\sin(2\pi f_{us} j\Delta t \mp \varphi_j)$, being f_{us} the undersampled frequency.

Next the bandwidth is related with the Doppler frequency shift corresponding to the maximum mirror velocity $B = 2f_d = 4\frac{V}{\lambda} = \frac{1}{\pi}\frac{\partial\varphi}{\partial t}$

Now for on the intermediate frequency of about 1MHz and a maximum mirror velocity of 30 mm/s, the bandwidth for ?=0.6328 μm, will be about 200 KHz. Taking into account the Shannon criterion, the sampling frequency must be greater than 400 KHz. In a first steep we used 800 KHz as the sampling frequency. The Fig.3 shows the line-averaged electron density for the 12421 TJ-II shot superposed on the obtained with the microwave interferometer.

The number of samples per period is about four. We used the same procedure for the phase measurement, but averaged over 100 samples. The interpolation error is about 1/85 of a fringe, while an error of about 1/850 of a fringe is expected for the averaged sampling (Below other sources of error).

The IF of the two interferometers are not stable and not exactly 1 MHz. The frequency was about 1.04MHz for CO_2 and 0.98 MHz for He-Ne. For this reason a sampling rate of 1.25 MHz was tried. It is more convenient than 800 KHz because it increases the number of samples per period for the CO_2 laser which is more sensitive to phase error. With this sampling rate we have more than 5 samples per period and the estimate error reduces about half, i.e. 1/1800 of a fringe. In Fig. 4 the signal for the 13682 shot, sampled at 1.25 MHz is plotted.

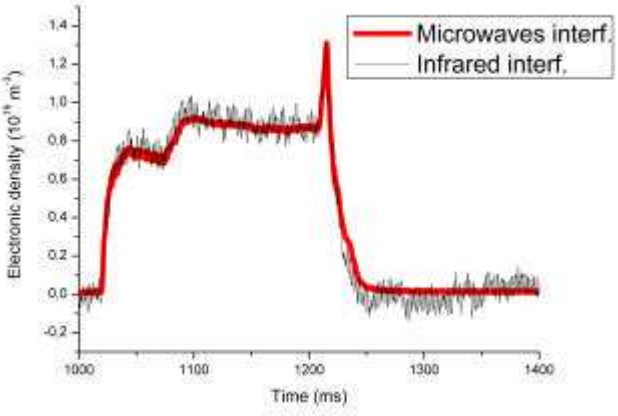
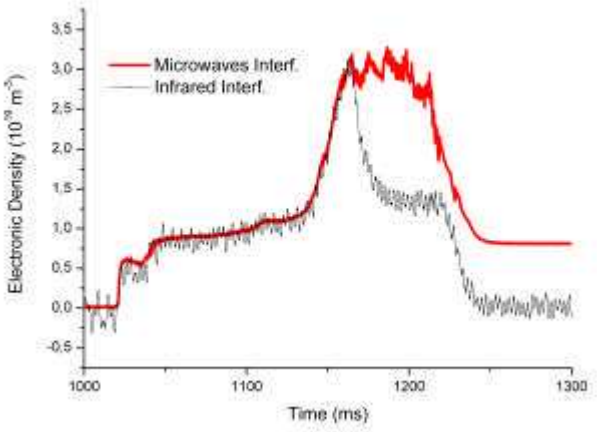


Fig.3. Shot 12421, f_s =0.8 MHz

The computing time with the undersampling technique is about 20 seconds, which is 10 times lower than with the 8 MHz sampling rate. Also the volume of data is reduced by the same proportion. The limiting error is not the sampling procedure but other factors such non-compensated path lengths, diffraction, etc.

Finally the four raw undersampled signals can be transmitted to the TJ-II general data base so the process becomes closer to being done in real time.



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