Fusion Engineering and Design 112 (2016) 952–956

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

The implementation of real-time plasma electron density calculations on EAST

Z.C. Zhang*, B.J. Xiao, F. Wang, H.Q. Liu, Q.P. Yuan, Y. Wang, Y. Yang

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui, PR China

HIGHLIGHTS

- The real-time density calculation system (DCS) has been applied to the EAST 3-wave polarimeter-interferometer (POINT) system.
- The new system based on Flex RIO acquires data at high speed and processes them in a short time.
- Roll-over module is developed for density calculation.

ARTICLE INFO

Article history:
Received 19 June 2015
Received in revised form 18 February 2016
Accepted 2 April 2016
Available online 8 April 2016

Keywords:
Real-time
Plasma electron density
Polarimeter-interferometer
FPGA

ABSTRACT

The plasma electron density is one of the most fundamental parameters in tokamak experiment. It is widely used in the plasma control system (PCS) real-time control, as well as plasma physics analysis. The 3-wave polarimeter-interferometer (POINT) system had been used to measure the plasma electron density on the EAST since last campaign. This paper will give the way to realize the real-time measurement of plasma electron density.

All intermediate frequency (IF) signals after POINT system, in the 0.5–3 MHz range, stream to the real-time density calculation system (DCS) to extract the phase shift information. All the prototype hardware is based on NI Flex RIO device which contains a high speed Field Programmable Gate Array (FPGA). The original signals are sampled at 10 M Samples/s, and the data after roll-over module are transmitted to PCS by reflective memory (RFM). With this method, real-time plasma electron density data with high accuracy and low noise had been obtained in the latest EAST tokamak experiment.

1. Introduction

In tokamak experiments, one of the most important quantities to measure is the plasma current density, which is not only closely relevant to plasma confinement and Magneto-Hydro-Dynamic (MHD) activity, but also plays an important role in advanced tokamak operation [1]. To measure the current density, polarimetry based on the Faraday-effect is widely recognized as one of the most reliable diagnostics [2]. There are many research achievements have been demonstrated on plasma electron density calculation by mean of polarimeter-interferometer system [3–5]. Recently, a Far-Infrared (FIR) laser polarimeter-interferometer has been established on EAST [6], and the phase shift information can be extracted from the signals after POINT system mixer. Since the electron density is proportional to the phase shift, electron density can be obtained for the plasma control system in real-time. The paper is organized as follows: the principle of this method is described in Section 2; the structure and the realization of the real-time density calculation system (DCS) are presented in Section 3; the application, including the bench test and experimental results are shown in Section 4; finally, the summary and future work are given in Section 5.

2. Principle

In the three-wave technique, two collinear laser beams with counter-rotating circular polarization are injected into the plasma to measure the Faraday angle, while an additional laser beam, employed as the local-oscillator (LO) beam, is mixed with the two probing beams to obtain the line-integrated density [7]. The three beams are slightly frequency offset (∼1 MHz) for high temporal resolution measurement; therefore, the detected signal consists of three intermediate frequency (IF) carriers: one of them con-

* Corresponding author.
E-mail address: zzc@ipp.ac.cn (Z.C. Zhang).

http://dx.doi.org/10.1016/j.fusengdes.2016.04.005

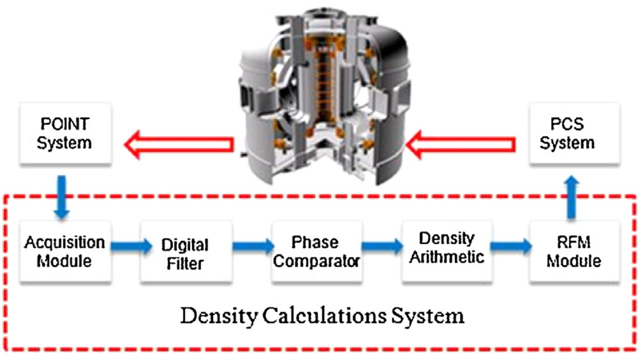

Fig. 1. Module design for density calculations system.

tains information of Faraday angle, while the other two contain information on the line-integrated density [8].

$$\phi = 2.82 \times 10^{-15}\lambda \int n_e dl \qquad (1)$$

Eq. (1) expresses the relationship between density n_e and phase shift ϕ, λ is the wavelength of the beam, the unit is μm. So the DCS, aims at calculating the density, is designed to connect the POINT system with PCS for feedback control (Fig. 1).

The functions of DCS are shown above. It acquires the IF signals from the POINT system, separates the density information by digital filter, gets the phase shift after phase comparator, calculates the density, and transfers the results to PCS though RFM network.

3. Realization

3.1. Architecture

The DCS system should increase capability as well as improved extensibility by using Commercial Off-The-Shelf (COTS) components. NI PXIe standard devices are chosen, and the system platform is comprised by: (i) a 18-slot PXIe chassis features a high-bandwidth backplane; (ii) a controller equipped with an Intel Core i7 processors and 4 G DDR3RAM; (iii) PXIe-7966R Flex RIO device with a Virtex-5 SX95T FPGA on board. (iv) NI 5734 digitizer adapter modules are adopted with 16 bits analog-to-digital converter (ADC) resolution. (v) Reflective memory (RFM) card with 450–500 ns of latency between nodes. The software architecture of DCS is shown below (Fig. 2).

Since there are three Flex RIO modules in the system, one of these modules is selected as the master module to receive a trigger from central timing system [9]. The digitizer adapter converts the analog signal to digital data. After Flex RIO module, phase shift will be transferred to the host memory via Direct Memory Access (DMA) [10].

In the RT controller program, there is no user interface, when the power on, the system starts to work automatically. During the initialization, the FPGA and module parameters are configured; on

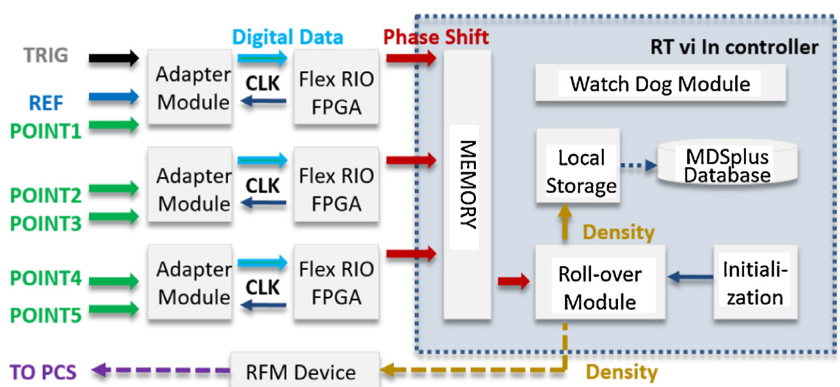

Fig. 2. Software architecture of density calculations system.

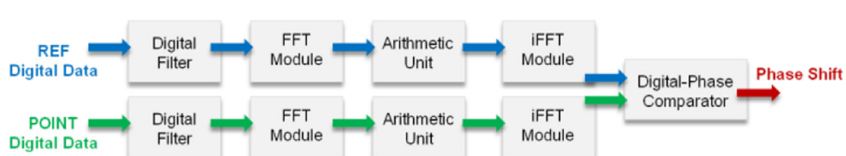

Fig. 3. Block diagram of Flex RIO FPGA.

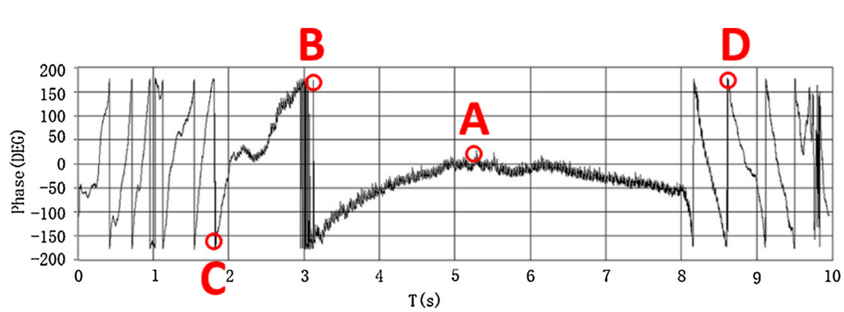

Fig. 4. Phase shift @ Shot NO.50650 on EAST.

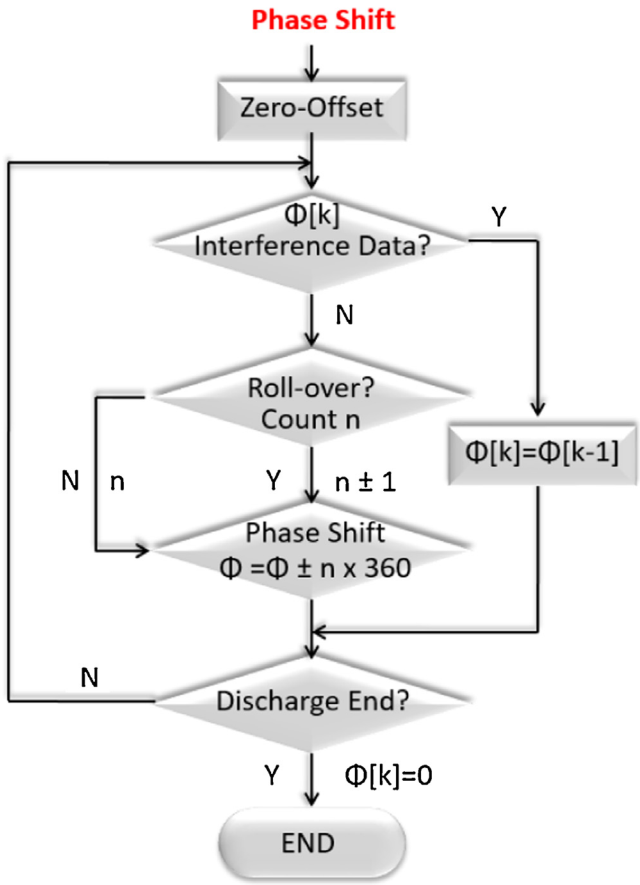

Fig. 5. Software workflow of roll-over module.

receiving phase shift data from FPGA, the roll-over module starts to calculate the density. The final results are sent to PCS for control, at the same time, the calculation results are stored in local hard disk and then uploaded to MDSplus database after each shot. A watch dog module is used to monitor the whole proceed.

3.2. FPGA implementation

The FPGA is an important part in this new system, and it can be compiled for custom device. The block diagram of Flex RIO FPGA is shown in Fig. 3.

The reference and plasma signal each containing the three frequency bands of information, currently centered at 0.850, 1.275, and 2.125 MHz with about a 100 kHz tolerance [6]. 1.275 MHz signal corresponds to the plasma density [11]. Digital band-pass filter is used to separate the 1.275 MHz signal from the different frequency waves. FFT module completes the analysis of the raw signal spectrum, after the arithmetic unit, time-domain signal is retrieved by the inverse FFT transform. Phase shift is determined by the digital-phase comparator. The number of points in FFT module is 512, the phase shift chooses the average value of 512 points after each transfer, so the 10 M Samples/s raw data is compressed into 20 K Samples/s. Right now, the digital filter is implemented by the LabVIEW FPGA module, the next step IP (intellectual property) core will be used to replace the former filter for reducing the cost of the FPGA source.

3.3. Roll-over module

In this module, 2 Pi roll-over algorithm is used to distinguish the points in phase shift. Fig. 4 displays the points categories in the phase shift results, (1) normal data points, area marked A, the differences value among adjacent points are very closed; (2) points in B area are interfered data, which introduced by pulse noise inter-

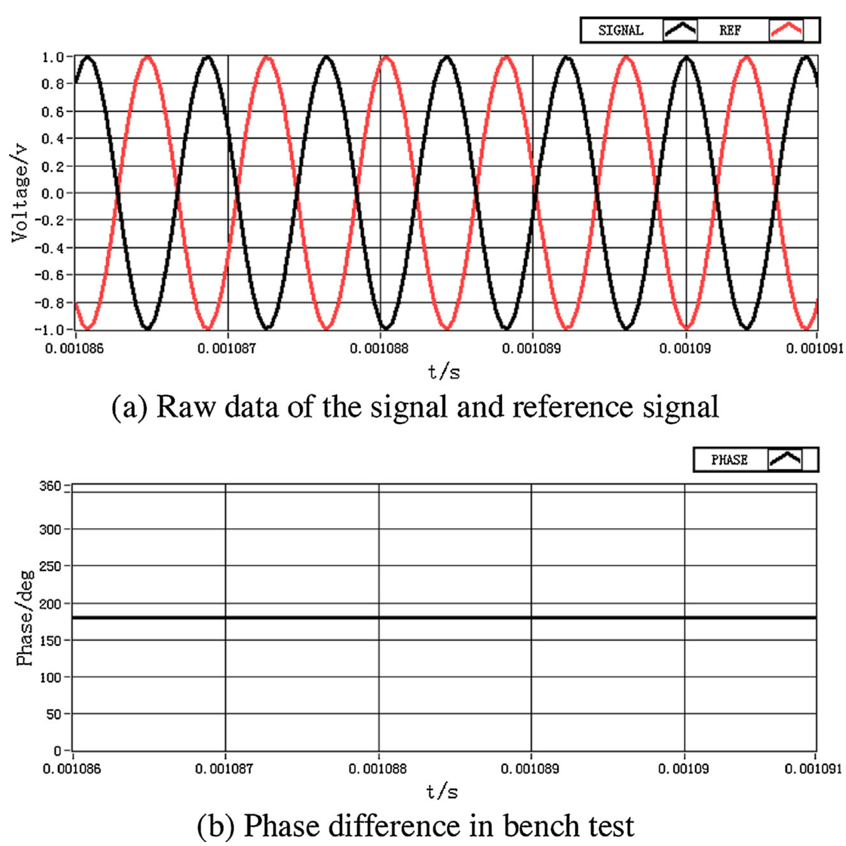

Fig. 6. Results of bench test.

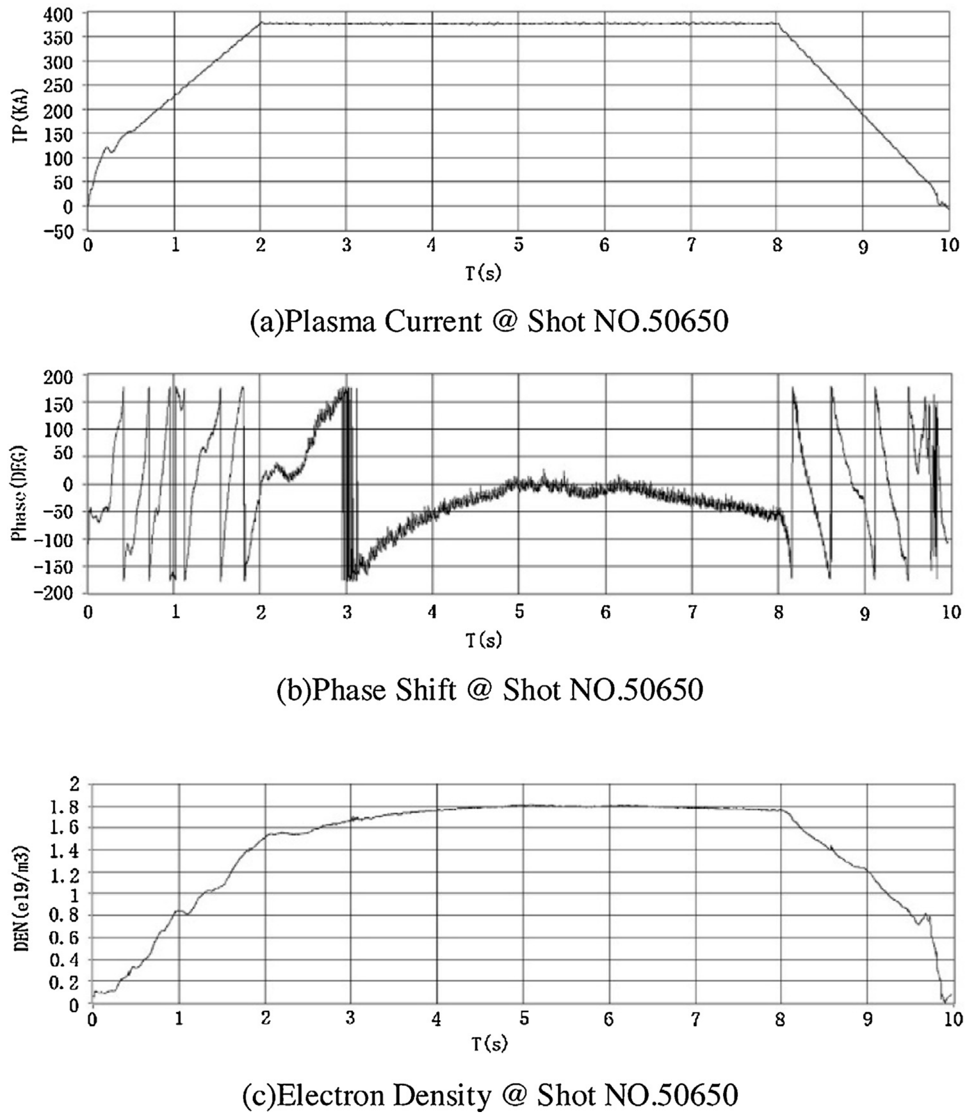

Fig. 7. Processing results of density calculations system during discharge.

ference or vibrations, should be replaced by the former point; (3) up roll-over point, like C, has large difference value from the former point, smaller than former value; (4) down roll-over point, the value of the point D much bigger than former one [12].

The software workflow of roll-over module is shown in Fig. 5.

In the discharge experiment, tokamak device has its plasma electron density only when plasma current exists. Before the discharge time reaches 0, the signal acquisition starts and average calculation is processed as zero-offset value. $\Phi[k]$ is adopted as the point value. If the point belongs to the interference noise, the value is replaced by the former point, otherwise, the point is considered whether it a roll-over point. At the up roll-over point, counter n which represents the time of roll-over plus one, and the phase result adds 360°; at the down roll-over point, n minus one and the phase result subtracts 360°. If the adjacent points have similar values, the phase shift keeps the original value. $\Phi[k]$ is set 0 when discharge end.

4. Measurement results

Before applied to the machine hall, the new system had been tested in the laboratory. Signals from dual-channel signal generator are used to simulate the POINT data. Fig. 6(a) shows the raw data of the signal and reference signal. The two signals have the same frequency centered at 1.275 MHz, and the phase difference is 180°. The standard sinusoidal signals stream to the digitizer adapter and measured in FPGA module, phase difference between the test signals is obtained in Fig. 6(b). The constant line remains around 180°, consistent with the real signal.

According to the processing method described in Section 3, the real-time density calculation system had been applied to EAST since 2014 physical campaign. Some of the experiment results are shown below. Fig. 7 (a) is plasma current signal, Fig. 7 (b) is phase shift result from FPGA, and Fig. 7(c) is finally electron density.

The curve in Fig. 7(a) demonstrates the changes of plasma current. The current starts to increase from 0 s and gets the flat-top at about 2 s, after 6 s duration, then tips into ramp-down phase, the value of plasma current returns to 0 at around 10 s. The tendency of electron density in Fig. 7 (c) is agreed with the curve of I_P signal in Fig. 7(a). The values of the electron density are also confirmed by FIR(far-infrared) team who ran the POINT interferometer.

5. Conclusion and future work

At present, a five-chord layout of POINT had been installed on EAST, and the DCS has been developed to provide a powerful data acquisition and real-time data processing ability for it. By using Flex RIO devices, the DCS can access 5 channels data at the rate of 10 M Samples/s, and transfer the density results to PCS at the rate of 20 K Samples/s. The results in 2014 experiment meet the requirements of design.

The DCS will upgrade to 11 channels to satisfy the POINT expansion 11 chords anticipated to fully diagnose the core region of EAST plasmas [6]. More precise plasma electron density distribution will be obtained.

Acknowledgments

The author would like to thank the EAST CODAC Team and FIR Team for their works and help. This work is supported by the National Natural Science Foundation of China under Grant No.11505239, Science Foundation of Institute of Plasma Physics CAS under Grant No. DSJJ14GC02, and National Magnetic Confinement Fusion Science Program of China under Grant No. 2014GB103000.

References

[1] C.Y. Xiong, J. Chen, Q. Li, Y. Liu, L. Gao, A real-time laser feedback control method for the three-wave laser source used in the polarimeter-interferometer diagnostic on Joint-tEXT tokamak, Rev. Sci. Instrum. 85 (2014) 123502.

[2] A.J.H. Donné, Diagnostics for current density and radial electric field measurements: overview and recent trends, Plasma Phys. Controlled Fusion 4 (2002) B137.

[3] P. Gaudio, M. Gelfusa, A. Murari, F. Conetta, Analysis of JET polarimeter with a propagation code based on the stokes formalism, IEEE Trans. Plasma Sci. 41 (2013) 5.

[4] A. Boboc, B. Bieg, R. Felton, S. Dalley, Y. Kravtsov, A novel calibration method for the JET real-time far-infrared polarimeter and integration of polarimetry-based line-integrated density measurements for machine protection of a fusion plant, Rev. Sci. Instrum. 86 (2015) 091301.

[5] T. Kondoh, A. Costley, T. Sugie, et al., Toroidal interferometer polarimeter density measurement system on ITER, Rev. Sci. Instrum. 75 (2004) 3420.

[6] H.Q. Liu, Y.X. Jie, W.X. Ding, et al., Faraday-effect polarimeter-interferometer system for current density measurement on EAST, Rev. Sci. Instrum. 85 (2014) 11D405.

[7] Z.Y. Zou, H.Q. Liu, Y.X. Jie, et al., Optical layout and mechanical structure of polarimeter-interferometer system for Experimental Advanced Superconducting Tokamak EAST, Rev. Sci. Instrum. 85 (2014) 11D409.

[8] Q. Xu, X. Gao, Y.X. Jie, et al., HCN laser interferometer on the EAST superconducting tokamak, Plasma Sci. Technol 10 (2008) 4.

[9] Z.C. Zhang, Z.S. Ji, B.J. Xiao, et al., The upgrade of EAST central control system in PXI platforms, Fusion Eng. Des. 89 (2014) 582.

[10] W. Zheng, R. Liu, M. Zhang, G. Zhuang, T. Yuan, Design of FPGA based high-speed data acquisition and real-time data processing system on J-TEXT tokamak, Fusion Eng. Des. 89 (2014) 698.

[11] Y. Zhou, Z.C. Deng, Y.G. Li, J. Yi, Multi-channel far-infrared HL-2A interferometer-polarimeter, Rev. Sci. Instrum. 83 (2012) 10E336.

[12] S.B. Shu, J.R. Luo, E.B. Xue, J. Sheng, Plasma electron density measuring and processing on the J-TEXT Tokamak, J. Donghua Univ. 28 (2011) 576.