Real-time plasma electron density feedback control system based on FPGA on J-TEXT

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***Abstract*–The J-TEXT newly deployed three-wave polarimeter-interferometer (POLARIS) system provides a better time and spatial resolution of the plasma electronic density than the old HCN interferometer system. The plasma electron density feedback control system is implemented on the already existing POLARIS DAQ system which is based on FlexRIO FPGA. Another FlexRIO board with an output module is added to implement the feedback control algorithm and feed the output to the piezoelectric crystal valve. The density feedback control system is able to extract the phase difference information from the intermedia frequency signal using FFT, calculate density of multiple channels and output control signal to the piezoelectric crystal valve in real-time. NI P2P technology is used to transfer processed data from a FlexRIO board to another in real-time without using the CPU. This system is also able to calculate density profile. With the density profile it can use compensated central chord line integrated or average density as control target. Also the real-time density profile data is useful for future plasma control system and disruption detection system.**

***Index Terms*—POLARIS, density feedback control, phase difference detection, FlexRIO, LabVIEW FPGA, fusion, J-TEXT tokamak**

I. Introduction

Electron density is an important plasma parameter for tokamak experiment. Control of the electron density is a mandatory function for the plasma control system [1]. The current J-TEXT density feedback control system only uses one probing chord of the old HCN laser interferometer [2, 3]. When the plasma moves side to side, it leads to incorrect control output or even plasma disruption [4]. Moreover the newly built J-TEXT 3-wave polarimeter-interferometer (POLARIS) diagnosis system [5] is more preferable for electron density measurement on J-TEXT. So there is a strong motivation to migrate the electron density feedback system to use the POLARIS signals. Also, if the density profile can be provided in real-time it will be very useful. The plasma movement is no longer affecting the average density control if the profile is provided. We can also get density peaking parameter real-time which is useful for various real-time control like disruption prediction.

Manuscript received May 30, 2016.

This work was supported by National ITER Project of China (No. 2013GB113003).

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So we have decided to develop a new density feedback system which uses the POLARIS diagnosis and can provide density profiles in real-time.

II. Real-time density calculation

A. The POLARIS Diagnosis

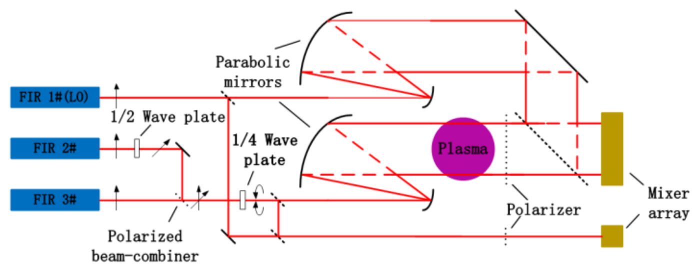

Fig. 1. Structure of POLARIS system on J-TEXT.

The structure of POLARIS system on J-TEXT is shown in Fig. 1. The POLARIS diagnosis uses 3 laser beams with slight frequency deviation to measure the chord integrated electron density and the Faraday angle.

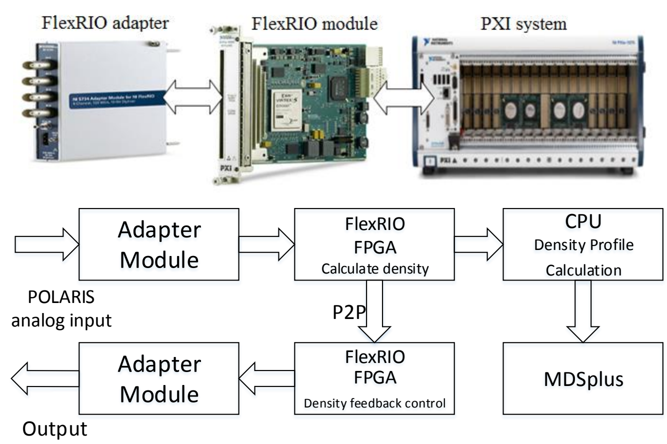

Fig. 2. The structure of POLARIS data acquisition system. The real-time density calculation and feedback control algorithm are implemented based on the FlexRIO FPGA.

The POLARIS diagnosis data acquisition system is equipped with FlexRIO FPGA boards [6]. We can implement digital phase detectors on them. The structure of POLARIS data acquisition system is shown in Fig. 2. It is able to acquire 16 channels of intermediate frequency signal from the POLARIS diagnostic at 120 MS/s rate.

B. Real-time density calculation implementation

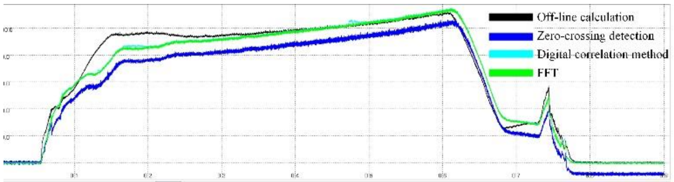

Fig. 3. The comparison of phase shift calculation algorithms. The real-time FFT is in good agreement with the off-line calculation.

On the FlexRIO FPGA, 3 different phase shift detection calculation algorithms are implemented: Zero-crossing detection, digital correlation method and FFT. The comparison of 3 algorithms and off-line calculation is shown in Fig. 3. All 3 methods yield similar result as the offline calculation, and is adequate for real-time density calculation. Consider the delay and the resources the algorithm uses, the FFT method shows the best overall performance. After we have the phase shift, it is multiply with a factor to get the line integrated density

III. Density feedback control

As soon as we have the density in real-time density feedback control is pretty straight forward. It just needs to feed the controller with a preset density waveform and the real-time chord integrated density. To control the density, we simply need to control the gas puffing valve to regulate the gas injected into the vacuum chamber. A simple PID feedback control will do the trick.

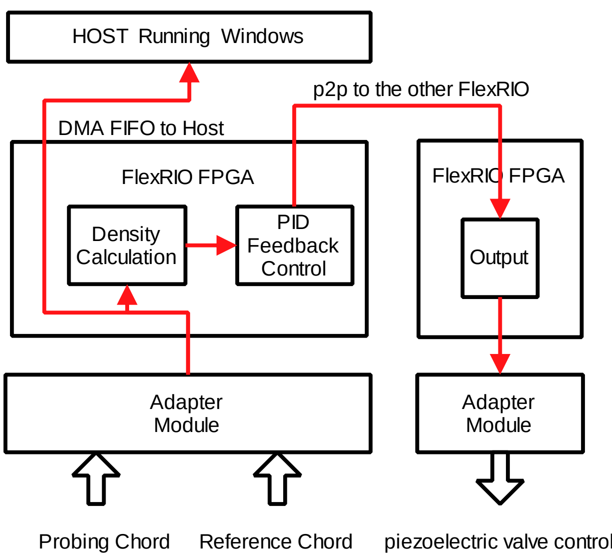

Fig. 4. The data flow of the density feedback control system

The whole real-time density calculation and feedback needs to be implemented on the POLARIS data acquisition system without breaking its existing functions. The acquisition system is a Windows based PXIe platform, without breaking the old system the only quick way is to implement all the real-time control on the FPGA board. Our solution is to install another FlexRIO board with an analog output adapter module. The high end FlexRIO board has a peer-to-peer (p2p) feature. It allows the FlexRIO boards to exchange data using only the PXIe switch without using any resources in the CPU or RAM. This means the software running on windows only need to set up the p2p function, the data transfer between two boards is completely un touched by software. The fig. 4 shows the configuration and data flow of the feedback control system.

This design is quickly implemented, but in this experiment campaign the lasers in POLARIS diagnosis is sent back to its manufacturer for maintenance so the POLARIS is absence for this experiment campaign, we are unable to test the system now.

But there is also good news, we have extra time to develop a more powerful density feedback system.

IV. System structure

Since we have enough time to develop a new density feedback control system from scratch, we decide to decide to develop a density feedback control system that can provide the electron density profile in real-time. We can then use it to calculate the correct average density or central chord interrogation density even if the plasma has moved.

A. System structure

The density feedback control system is still implemented on the original POLARIS data acquisition hardware. The software though is nearly completely re-written. The POLARIS diagnosis has 17 probing chords. The p2p feature of the FlexRIO is used again to transfer the reference chord data to others.

B. The density profile calculation algorithms

After we have multiple chord of chord integrated density, we can calculate the density profile. A common assumption when calculating the density profile of tokamak plasma is constant density on the flux surface. We take another assumption that the flus surface is circle inside the plasma and they share the same axis. And the J-TEXT is a limiter configuration tokamak, so the flux surface is considered to be circular.

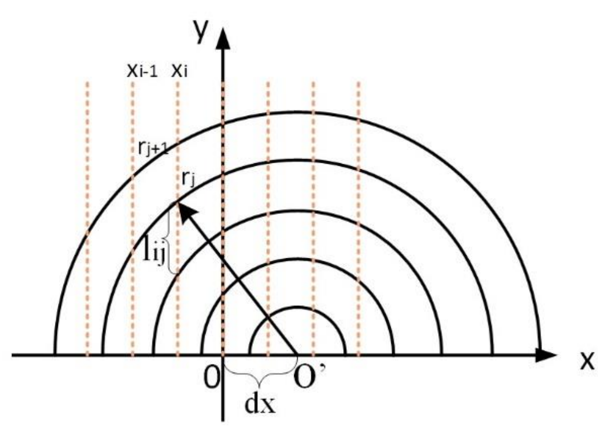

Fig. 5. Abel Inversion Modeling

Then as shown in fig. 5, the cross section of the plasma is divided into many co-axis rings with a fixed width. The ne on the same ring is constant and is denoted as *ne(rj)*. The length of the *i*th probing chord inside the *j*th ring is denoted as *lij*. Than we can easily have a linear equation as (1).

$$[l_{ij}]_{I*J} \cdot [n_e(r_j)]_{J*1} = [n_e L]_{I*1} \qquad (1).$$

$[lij\ ]_{I*J}$ is the length matrix.

We have total I probing chord and J constant density rings. Then we just need to solve the equation to get a density vector represent the ne on each ring.

We can use the calculated profile to calculate the corrected central chord line integrated and average density.

V. CONCLUSION

Unfortunately, with the POLARIS absence we cannot test the system in real experiment in this campaign. But we feed the system with the data from last campaign to see its performance.

This system is ready to serve the next experiment campaign. Beside density feedback, it will provide density profile and its peaking parameter to the disruption prediction system. By then we are planning to take into account that Shafranov shift and give asymmetric profile calculation. Also section average density will be a feedback control target option.

ACKNOWLEDGMENT

The authors wish to thank the members of laser diagnostic team and computer control team in J-TEXT laboratory for designing, developing and testing work. This work is supported by National ITER Project of China (No. 2013GB113003).

REFERENCES

[1] F. Janky, M. Hron, J. Havlicek, M. Varavin, F. Zacek, J. Seidl, et al., "Plasma density control in real-time on the COMPASS tokamak," Fusion Engineering and Design, vol. 96–97, pp. 637-640, 10, 2015.

[2] L. Gao, G. Zhuang, Z. J. Wang, W. Chen, J. Chen, Q. Li, et al., "Recent progress of the HCN interferometer on J-TEXT tokamaka)," Review of Scientific Instruments, vol. 83, p. 10E303, 2012.

[3] X. Ke, Z. Chen, W. Ba, S. Shu, L. Gao, M. Zhang, et al., "The Construction of Plasma Density Feedback Control System on J-TEXT Tokamak," Plasma Science and Technology, vol. 18, p. 211, 2016.

[4] Y. U. Nam and J. Chung, "Analysis of line integrated electron density using plasma position data on Korea Superconducting Tokamak Advanced Research," Review of Scientific Instruments, vol. 81, p. 10D510, 2010.

[5] J. Chen, G. Zhuang, Z. J. Wang, L. Gao, Q. Li, W. Chen, et al., "First results from the J-TEXT high-resolution three-wave polarimeter-interferometer," Review of Scientific Instruments, vol. 83, pp. 10E306-10E306-3, 2012.

[6] W. Zheng, R. Liu, M. Zhang, G. Zhuang, and T. Yuan, "Design of FPGA based high-speed data acquisition and real-time data processing system on J-TEXT tokamak," Fusion Engineering and Design, vol. 89, pp. 698-701, 2014.