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

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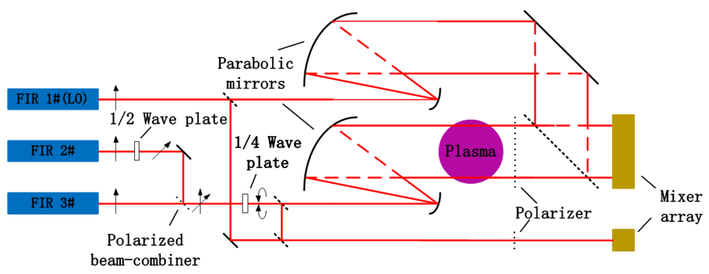
1. Introduction

- J-TEXT has a density feedback control system based on the single chord measurement of the HCN interferometer.
- The original system is not sufficient for future experiment due to unreliable density measurement and limited function.
- J-TEXT newly deployed three-wave polarimeter-interferometer (POLARIS) system provide better measurement of the density over the interferometer.
- POLARIS has 17 probing chords, time resolution 1~10 μs, spatial resolution 15mm, phase resolution 0.1°
- The real-time electron density feedback control system is implemented on the already existing POLARIS DAQ system which is based on FlexRIO FPGA.
- NI P2P technology is used to transfer processed data from a FlexRIO board to another in real-time without using the CPU.



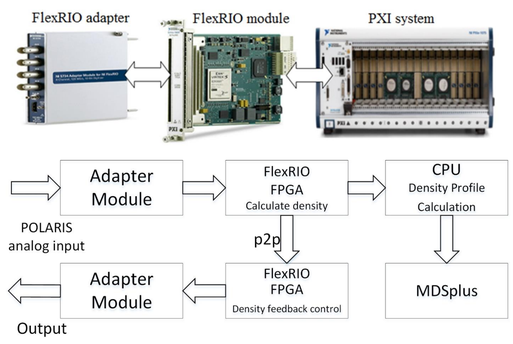
Structure of POLARIS system on J-TEXT.

The Line integrated electron density can be written as

$$n_e L = \int_{-a}^{a} n_e(r)\,dr = \frac{\Delta\varphi_r + \Delta\varphi_l}{2C_i}$$

- This system is able to calculate density profile in real-time.
- With the density profile it can use compensated central chord integrated or average density as control target.
- Profile can also be used in the future PCS and disruption prediction system
- The density profile calculation cycle rate is within 1KHz.

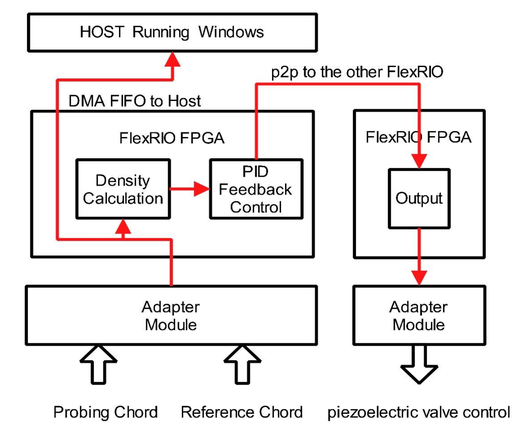
2. Real-time density calculation and feedback control system



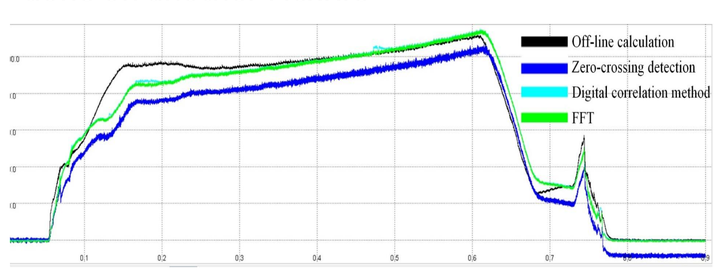
The structure of POLARIS data acquisition system.

- Implemented on POLARIS DAQ system
- Minimum changes are made to the existing DAQ system
- Acquire 16 IF signal channels at 120 MS/s rate
- Density calculation and feedback control algorithm implemented on FlexRIO FPGA
- The host upload data to MDSplus database by Ethernet

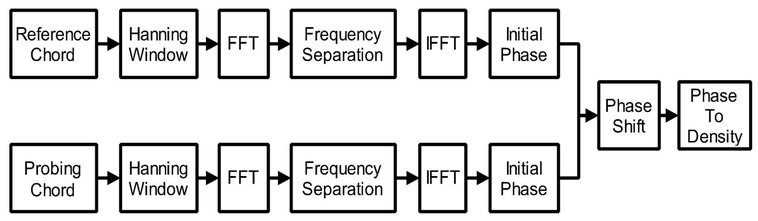
- Using p2p feature to exchange data among FlexRIOs
  - ✓ data transfer delay < 20μs
  - ✓ band width 1.5GB/s
- Chord integrated density calculated on one FlexRIO and streamed to another FlexRIO using p2p
- Host running Windows is only archive the data, not involved in any real-time control
- PID feedback control the gas puffing valve done on another FlexRIO



Data flow of the density feedback control system



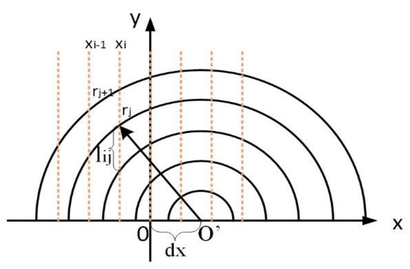
The real-time FFT is in good agreement with the off-line calculation.



The block diagram of the FFT phase shift and density algorithm on FlexRIO FPGA.

- Chord integrated density calculation delay 80 μs, feedback control cycle 1 kHz
- 3 phase shift detection methods are implemented on the FPGA and evaluated
- The FFT method has the best overall performance on speed, resource and accuracy

3. Real-time density profile calculation



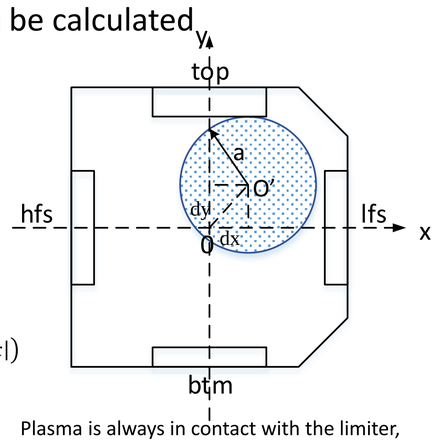
Abel Inversion Modeling

- 13 chords, 9 constant density zone are chosen to calculate the profile
- In J-TEXT limiter plasma, flux surface is considered to be circular
- plasma displacement is considered
- Shafranov shift is ignored, symmetric profile can be calculated

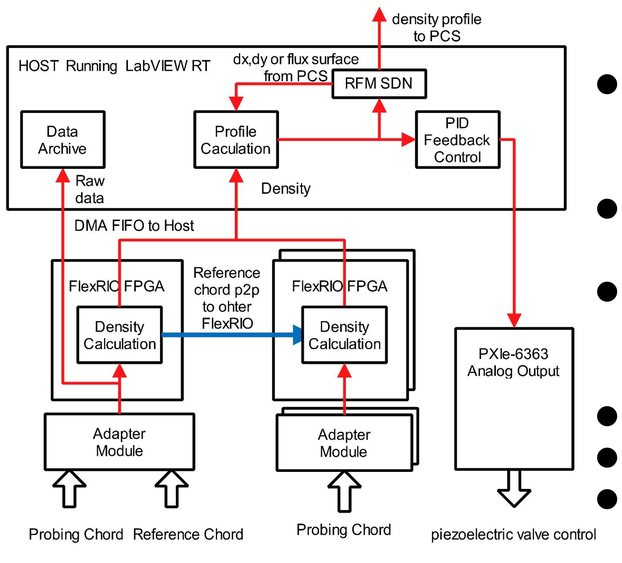
$$a = \min\{r_{lfs} - dx, dx - r_{hfs}, r_{top} - dy, dy - r_{btm}\}$$

$$l_{ij} = \begin{cases} 0 & (r_j < |x_i - dx|) \\ 2\sqrt{r_j^2 - |x_i - dx|^2} & (r_{j-1} < |x_i - dx| < r_j) \\ 2\left(\sqrt{r_j^2 - |x_i - dx|^2} - \sqrt{r_{j-1}^2 - |x_i - dx|^2}\right) & (r_{j-1} > |x_i - dx|) \end{cases}$$

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



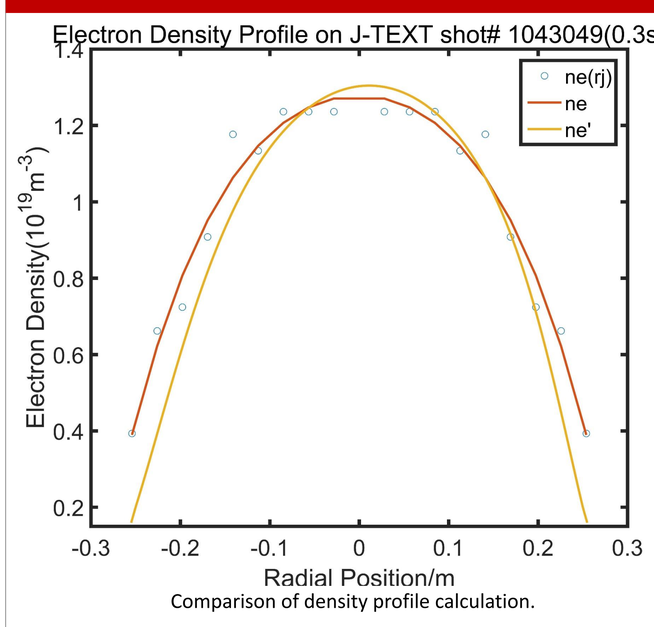
Plasma is always in contact with the limiter, flux surface is circular



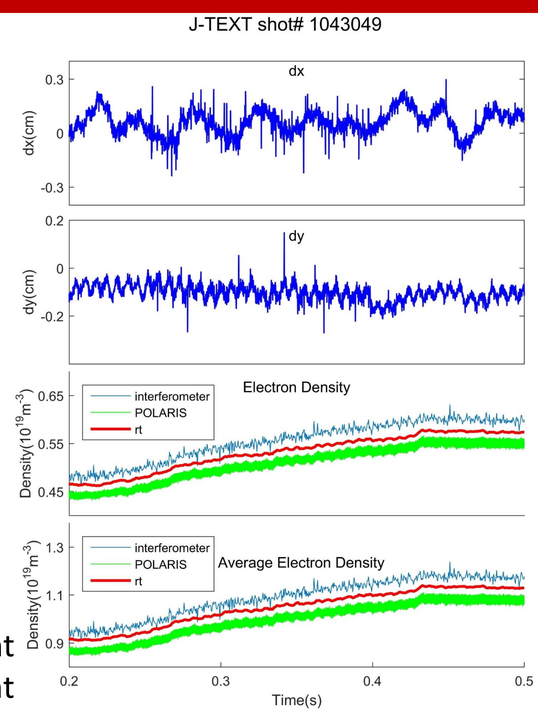
The configuration and data flow of the density profile calculation

- Plasma vertical and horizontal displacement from PCS via reflective memory
- 16 IF signal is acquired and chord integrated density is calculated density on the FlexRIO FPGA
- Reference probe signal is transferred using p2p
- Profile calculation and feedback control is on the host running LabVIEW-RT
- Density profile calculation ≈ 400μs
- Whole control cycle < 1ms
- Future, the real-time reconstructed flex surface from PCS will be used

4.Result



Comparison of density profile calculation.



Comparison of central chord integrated density.

- Real-time density profile is in good agreement with offline result (which takes into account the Shafranov shift and takes minutes to run)
- Real-time compensated central chord integrated density result calculated using the real-time profile is slightly bigger then the direct central chord measurement which is affected by the plasma displacement
- The real-time calculated profile can be used in density feedback control, future PCS and disruption prediction system.