Real-time density feedback control on the ADITYA-U Tokamak

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Abstract

A single channel 100 GHz microwave interferometer system has been designed and installed in ADITYA-U tokamak for real time line integrated electron density measurement. It is validated for a number of plasma discharges. The real time density feedback control (RTDFC) system has been installed in the ADITYA-U Tokamak to achieve desired electron density. The RTDFC system consists of 100 GHz microwave interferometer system, FPGA based real time density estimation and feedback control system and gas fuelling control system. A proportional (P) controller is configured in voltage amplitude control mode to operate the piezo valve for gas fuel injection. Platform and profile density stability experiments have been performed during ADITYA-U plasma discharge. To overcome the decay on feedback action due to piezo stickiness, stick pulse is introduced before density feedback duration. This paper describes implementation of FPGA based RTDFC system and successfully validated during low shot duration plasma discharge in ADITYA-U. That consumes low power, cost-effective, re-programmable, easily upgraded and provides interlock with plasma parameters.

Keywords – Interferometer, Phase detection, Density feedback

1 Introduction

ADITYA-U is a medium size tokamak designed for kilo ampere plasma current and millisecond plasma duration [1]. The control of plasma parameters e.g. total plasma current, average particle density [2–5] and temperature, and position appears to be a challenging task in recent years. Real time electron density control [3, 6] plays an important role in magnetically confined fusion machines. The tokamak electron density is influenced by plasma confinement, the interaction of plasma with a wall, vessel wall condition and active gas feeding and pumping [4]. Among these, one of the most important factors is working gas fueling, which can be the most suitable actuator for density control for ADITYA-U. Various tokamak e.g. COMPASS, TEXTOR, ASDEX, JET and HT-7 have plasma density feedback control systems exploiting different techniques. The real time density control can be achieved by controlling gas injection during plasma discharge. The amount of gas injection according to the error difference between the reference and real plasma density is more popular and effective for desired density.

COMPASS tokamak has a 2 mm interferometer system for density estimation and the PI controller controls the amount of gas injection during discharge [4]. In J-TEXT tokamak, hydrogen cyanide (HCN) laser interferometer measures electron density and Proportional Integral Derivative (PID) based gas injection system controls the amount of gas during plasma discharge [6]. JET has nonlinear gas introduction module for density control [7]. Wendelstein 7-X and TEXTOR use dispersion interferometer (DI) for real time density estimation using trigonometric inversion of the diode signal followed by phase estimation of reconstructed modulation sinusoid signal based on signal envelope and feedback purpose using FPGA [8].

ADITYA-U hydrogen gas injection is normally done in pulse mode during plasma discharge [9, 10]. Gas injection pulse interval, duration and number of pulses is pre-defined before each plasma discahrge. Instead of pulse gas ingection, essential amount of gas is injected according to plasma condition.With this motivation, a new FPGA based density controlled gas injection system is developed and installed in ADITYA-U. Heterodyne interferomter [11–16] based RTDFC is used to achieve better quality discharges which are necessary for new physics studies. A stick pulse has been introduced to minimize feedback leaking delay. With this motivation, we have designed and developed heterodyne interferometer based RTDFC to achieve better quality discharge for new researchers. The developed RTDFC is able to maintain the line integrated plasma density at a desired level. In this paper, we report the initial results of the plasma electron density feedback control system in ADITYA-U tokamak.

This paper is structured as follows, Section II summarizes the experimental setup. The experimental system components are described in Section III. Section IV represents the experimental results, and finally, Section V draws the conclusion.

2 Experimental Setup

A single channel (140 GHz) real-time heterodyne interferometry (referred as ELVA-1) [17, 18] system and developed FPGA based heterodyne (100 GHz) interferometry (referred as IPR-HI) [19] are installed on ports 14 and 15 on ADITYA-U respectively. ELVA-1 system procured from Russia is used as reference for real time plasma density measurement. The complete hardware and software details are required for extraction of density feedback control signal from ELVA-1. Therefore, the developed IPR-HI is used for both electron density measurement and RTDFC using gas fuelling. The schematic layout of the RTDFC system along with components is shown in fig 1. The real time density signal generated from Virtex- II FPGA is made available on ADITYA central server using optically isolated hardware [19].

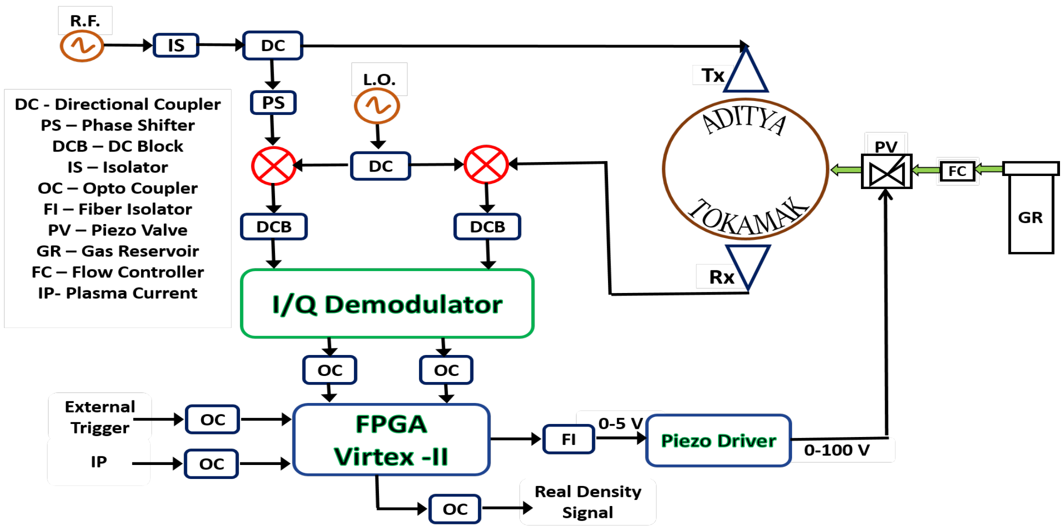
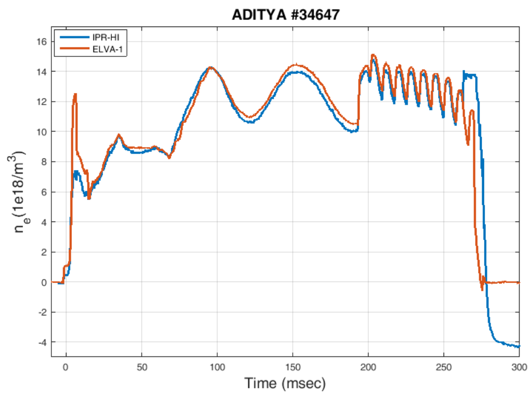


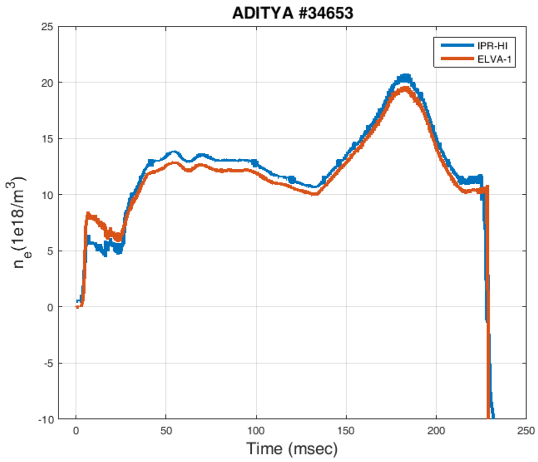
Figure 1: (Color online) Schematics of RTDFC system and system components layout. (DC - Directional coupler, IS - Isolator, DCB - DC Blocker, PS - Phase Shifter, OC - Opto Coupler, FI- Fiber Isolator, PV - Piezo Valve, GR - Gas Reservoir, FC - Flow Controller, IP - Plasma Current)

3 System components

The RTDFC system consists of three subsystems: density measurement subsystems, gas puffing subsystems and feedback control subsystems. The stability of the entire RTDFC system depends upon synchronized operation and coordination with the individual subsystems. The dynamic range of signal from millivolt to hundred volts requires signal isolation between individual systems.



(a) Platform stability plasma real time density



(b) Profile stability plasma real time density

Figure 2: (Color online) Comparison of real time density signal acquired from two interferometer system

3.1 Density measurement subsystem

Two microwave interferometers ELVA-1 and IPR-HI are used for density measurement besides IPR-HI is used for RTDFC application. A comparison of real time plasma density from these two interferometers is shown in fig 2. It can be noted that ELVA-1 system uses zero cross whereas IPR-HI uses CORDIC based phase measurement method for density estimation. The ELVA-1 system generates two 100 KHz signals from IQ detector (sin and cos) which are digitized 12 bit ADC having a sampling frequency of $\sim$ 2.5 MHz. The IPR-HI system generates two 10 KHz signals from IQ detector (sin and cos) which are digitized using 16 bit ADC having sampling frequency of $\sim$ 100 KHz. Comparison of two systems has been investigated for two different plasma shots i.e. platform and profile stability method. The average measured difference in the density for the two systems is 2-3 %. In some plasma discharge condition discrepancy observed in two systems due to phase jump estimation, Gunn oscillator phase drifts due to temperature and random noise.

3.2 Feedback control subsystem

The main function of the feedback control subsystem is to compare the pre-defined desired density with the present density signal and generate an error signal. The basic goal of the subsystem is to minimize errors by generating appropriate control voltage signals. The generated voltage signal is used to control gas fuelling inside the vacuum vessel. A proportional (P) control system was implemented on Virtex-II FPGA due to limited hardware resources available on the developed FPGA modules. The generated low voltage control signal is not sufficient to drive the gas leak valve. That needs to be magnified using a high voltage piezo driver [20]. A fibre-based optical isolator (V-F and F-V) [21] is used for isolation between FPGA and piezo driver. The piezo driver is operated with 100 Volt unipolar having slew-rate of around 1 V/μsec.

3.3 Gas puffing subsystem

Hydrogen gas is used as puffing gas for ADITYA-U Tokamak. There are two piezo electric valves installed on bottom-14 and radial-12 ports of ADITYA-U. The hydrogen gas is filled in a 20 L gas reservoir equipped with a pressure gauge to monitor the pressure of around 1200 mbar. The gas flow rate of the piezo valve is an important parameter in the gas fuelling system which works on the mechanism of the piezoelectric effect to control the amount of gas flow. It is directly related to the applied high voltage on the piezo valve. The DC and pulsed high voltage deform the piezoelectric crystal structure and generate a leak for gas passing through the tube. The relationship of gas flow rate and applied voltage is nonlinear [22, 23]. The amount of gas flow during each instant is measured using a flow controller mounted in between the reservoir and piezo valve. The flow controller total count can give the approximate amount of the gas flow during each plasma discharge.

The gas fuelling system is interlocked with the plasma current (IP) interlock. When the plasma current decreases below the pre-defined limit, IP interlock is enabled. FPGA digital input (DIO-6) acquires IP interlock signal using optical isolation and disabling control gas fuelling to the minimum piezo voltage. The minimum piezo voltage between 20-30 V is required to keep the valve an active state which can keep the piezo valve for fast feedback reaction.

3.3.1 Stickiness of piezo-electric valve

The piezo-electric valve suffers from a stickiness and temperature effect. The temperature of the piezo valve is considered almost constant during the experiment. As the duration between two consecutive shot is around twenty minutes it results in the stickiness effect on the piezo-valve. The suppression of stickiness has been achieved by using a short pulse (usually around 1-2 msec) at the initial phase of the feedback action. A pulse of voltage around 100 V is used to suppress the stickiness of the piezo valve. The stickiness effect of piezo-valve during the density feedback is shown in figure 3. The time interval of a maximum voltage applied to the piezo valve and plasma density rise is around 25-30 msec. The shot# 34653 (blue) maximum piezo voltage $\sim$

80 V reach at $\sim$ 105 msec and plasma density rise start at $\sim$ 133 msec. It can be noted that the piezo response time interval can be shortened significantly using stickiness removal pulse applied before the feedback duration. Due to initial stickiness pulse, the shot # 34774 (orange) maximum piezo voltage $\sim$ 80 V reach at $\sim$ 84 msec and plasma density rise start at $\sim$ 86 msec.

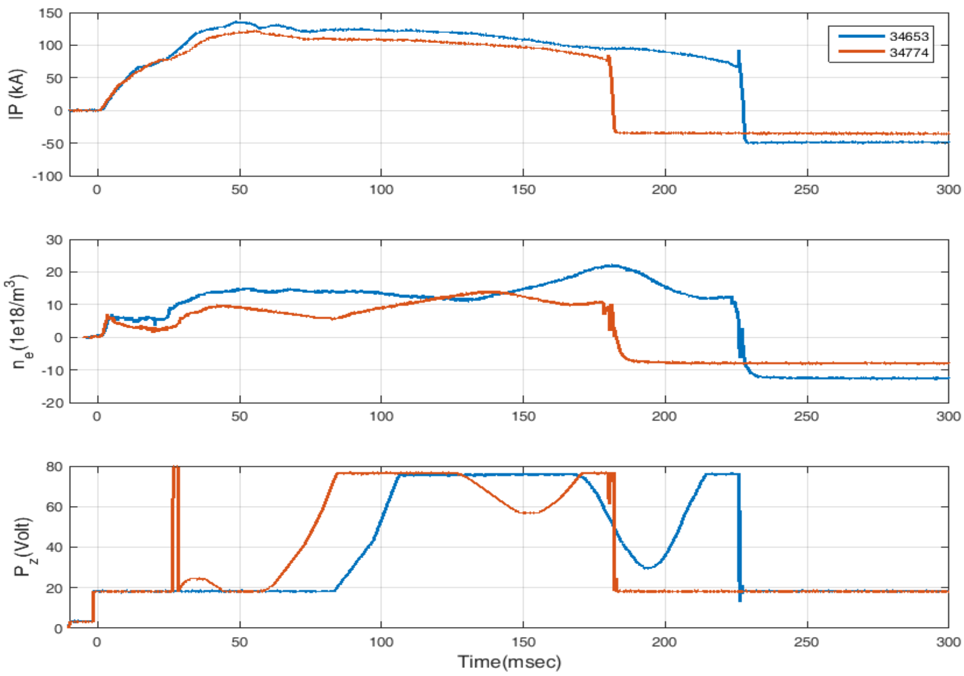


Figure 3: (Color online) Effect of stickiness removal pulse on density feedback (Shot 34653 without stick pulse and 34774 with stick pulse)

3.3.2 Valve Calibration

The gas flow rate of the piezo valve is related to the applied voltage and width of the pulse. The calibration of the piezo valve is carried out for both scenarios (voltage and pulse width). The voltage amplitude mode calibration of piezo valve used for RTDFC on ADITYA-U plasma discharge. Figure 4 shows plots between injected hydrogen gas for different piezo voltages and pulse widths corresponding to vessel pressure measured using ion gauge (IONIVAC IM210D) and ASDEX Pressure Gauge (APG). The APG [24] is installed on radial center port 7 for vessel pressure measurement and ion gauge installed on the pumping line for reference pressure measurement. The amount of the gas injected during each pulse is estimated from the totalizer count of the flow controller (Teledyne v300).

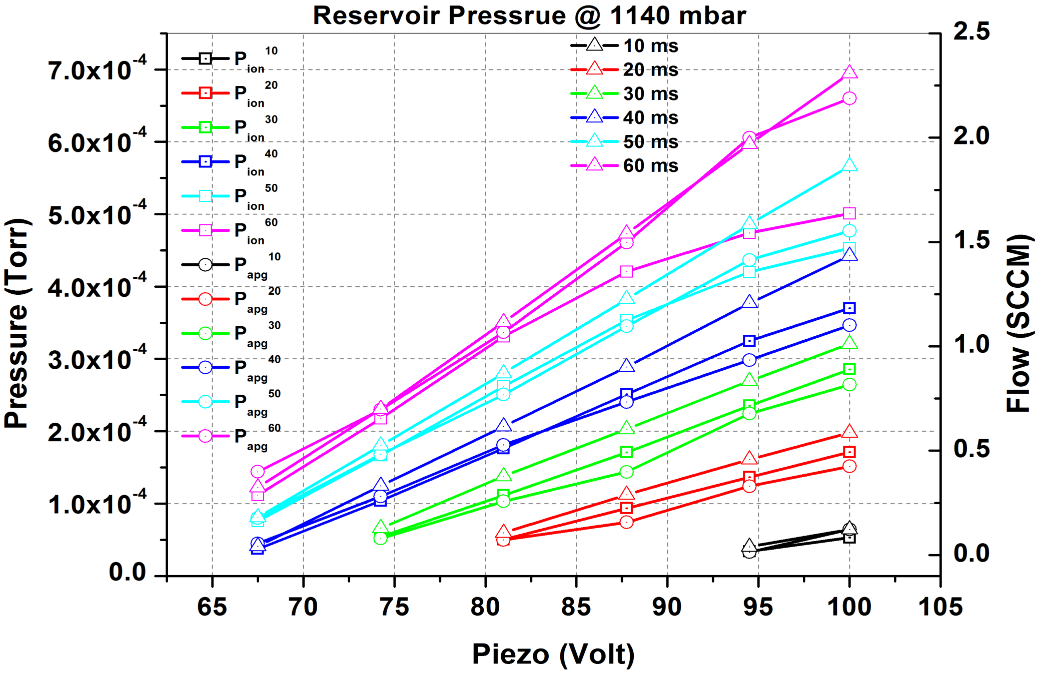


Figure 4: (Color online)Plot for vessel pressure and piezo voltage for different pulse width. (P_{ion} represent ion pressure and P_{apg} is ASDEX pressure gauge for different pulse widths.)

4 Experimental results

The RTDFC system is implemented on the LabVIEW platform. The program continuously fetches the shot number from adserver. When shot number change, the program fetches the predefined density parameter and required piezo voltage range. Figure 5 shows the LabVIEW based graphical user interface (GUI) developed for parameter configuration during the plasma discharge. The validation of the developed density feedback control system was performed on ADITYA-U tokamak with two modes viz platform stability and profile stability.

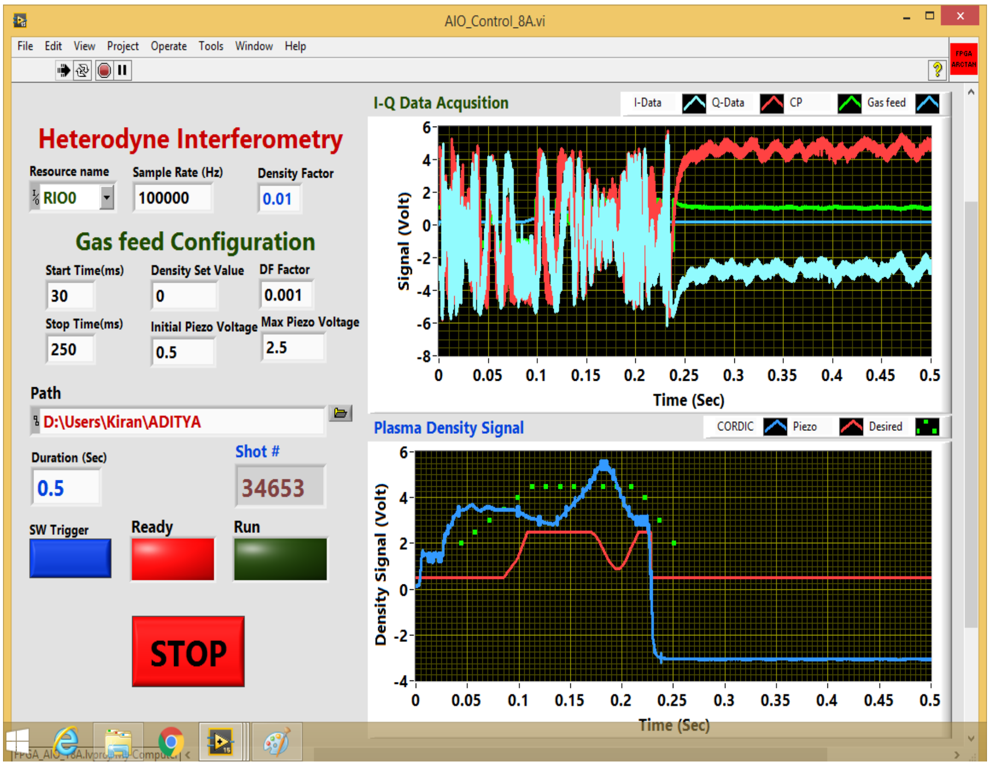


Figure 5: (Color online)

4.1 Platform Stability

In this configuration, the pre-defined density limit of the plasma is defined before the plasma discharge. The amount of gas required to achieve the predefined density is controlled from the density feedback system. The density feedback is enabled from 30 msec to 200 msec duration, which can be user-definable. In fig. 6, n_e^{real} is the actual line integral density at center location and n_e^{set} is the pre-defined density. When n_e^{real} is less than n_e^{set}, the piezo voltage signal increase up to the maximum limit set for piezo safety and avoids injection of too much gas to make plasma disruption. In other cases if n_e^{real} grater than the n_e^{set}, the piezo voltage decreases to the minimum voltage level for piezo to remain an active state. After the density feedback, the plasma density ramp occurs due to the pre-defined pulse gas injection system. The result represents the density feedback system controls the gas fuelling to minimize the error between n_e^{real} and n_e^{set}.

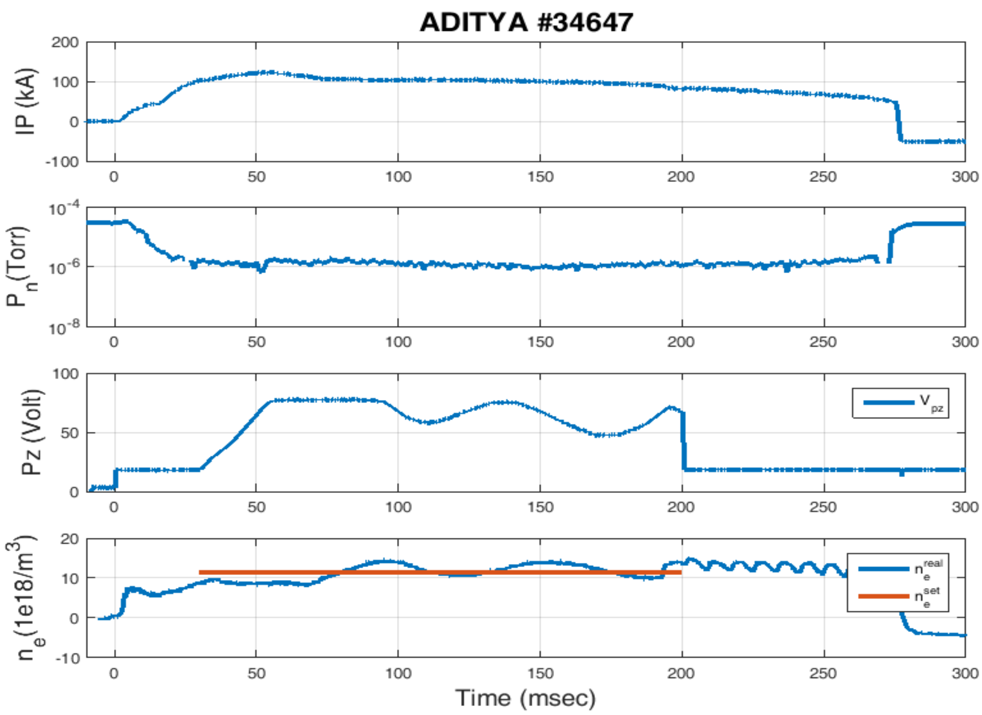


Figure 6: (Color online) Result of platform density stability.

4.2 Profile Stability

In this mode of platform density stability, the pre-defined density profile is used for the density feedback control system. The profile density data are amended before the plasma discharge. Due to limited hardware resources, entire density feedback intervals is divided into 16 equal interval and 16 density feedback profile data are fitted in feedback for each interval. Maximum and initial voltage levels for piezo are determined after many attempts. The mapping of the error between n_e^{real} and n_e^{set} to piezo voltage range is very difficult due to the limited operating range of piezo control voltage, plasma position and experimental environment. Figure 7 shows the result of the profile density feedback control system along with plasma current, piezo control voltage and neutral pressure measured using APG.

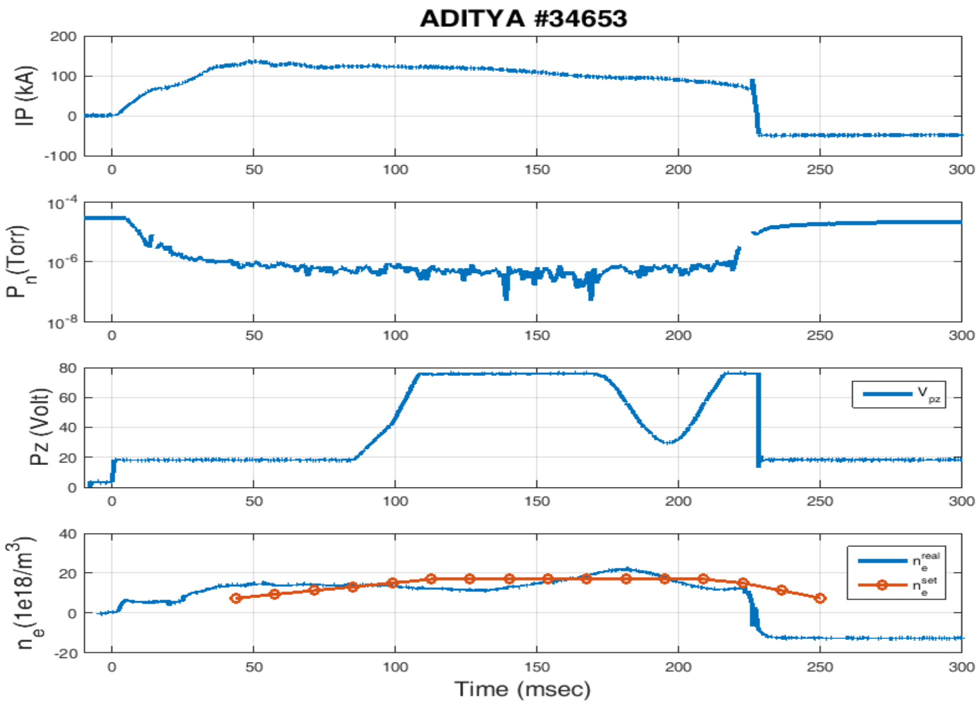


Figure 7: (Color online) Result of profile density stability.

5 Conclusion

Developed 100 GHz heterodyne interferometer successfully installed and validated for density feedback application in ADITYA-U tokamak. The average density difference 2-3% measured between ELVA-1 and IPR-HI interferometer. The pre-defined pulse gas feed system has been replaced with a new density feedback system for better plasma discharges with the required density level. Indigenous RTDFC system is commissioned and installed in ADITYA-U tokamak and successfully validated using platform and profile stability modes. To meet the physics experiment, the system needs to be optimized further using control parameters. Moreover, the developed RTDFC system is cost-effective, reliable, easy to integrate and maintain and fully automatic with plasma current interlock.

Further work in progress to improve the performance of the RTDFC system with an artificial intelligent control algorithm. As the density of the plasma is affected by other parameters like wall conditioning, plasma position and plasma start-up, in the future, the RTDFC system will be upgraded by incorporating these factors.

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