Fringe-jump corrected far infrared tangential interferometer/polarimeter for a real-time density feedback control system of NSTX plasmas[a)]

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The far infrared tangential interferometer/polarimeter (FIReTIP) of the National Spherical Torus Experiment (NSTX) has been set up to provide reliable electron density signals for a real-time density feedback control system. This work consists of two main parts: suppression of the fringe jumps that have been prohibiting the plasma density from use in the direct feedback to actuators and the conceptual design of a density feedback control system including the FIReTIP, control hardware, and software that takes advantage of the NSTX plasma control system (PCS). By investigating numerous shot data after July 2009 when the new electronics were installed, fringe jumps in the FIReTIP are well characterized, and consequently the suppressing algorithms are working properly as shown in comparisons with the Thomson scattering diagnostic. This approach is also applicable to signals taken at a 5 kHz sampling rate, which is a fundamental constraint imposed by the digitizers providing inputs to the PCS. The fringe jump correction algorithm, as well as safety and feedback modules, will be included as submodules either in the gas injection system category or a new category of density in the PCS.
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I. INTRODUCTION

Real-time control of high-temperature plasmas is essential to achieve a long-term and eventually steady-state operation of magnetic fusion devices. There are tens of parameters to be controlled, such as position and shape of plasmas and profiles of plasma temperature and pressure. Electron density is one of those primary parameters. There have been many experiments to control the electron density in real-time especially via interferometers, but this has not been done in NSTX.

An interferometer, as the favorite diagnostic for electron density measurement and, at the same time, for feedback control, is a powerful source since it produces reliable data with very fast temporal resolution. The interferometer/polarimeter in NSTX or the far infrared tangential interferometer/polarimeter (FIReTIP) is briefly introduced in Sec. II with its recently upgraded electronics. Despite the advantages of interferometers, one crucial problem for real-time application is fringe jump errors. These fringe jumps in the FIReTIP will be discussed in Sec. III. Based on the results shown in Sec. III, a conceptual design for the density control system including the FIReTIP, control hardware, and software is presented in Sec. IV.

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II. THE FIRETIP AND ELECTRONICS

The FIReTIP is one of the most successful interferometers for high-temperature plasma diagnostics. It utilizes methyl alcohol (CH_3OH) lasers to generate a far infrared beam of wavelength $\lambda = 118.8$ μm. This is not only the favorite for many magnetic fusion plasma interferometers but is also carefully chosen for the NSTX plasma.[1] What makes the FIReTIP unique is the frequency shift from the Stark effect implemented on the one laser that works as a local oscillator.[2] An approximately 5 MHz intermediate frequency (IF) has been obtained from the line shift of the Stark effect, which is larger than twice that in common methyl alcohol interferometers.

Together with the IF from the Stark effect, an improved electronic system[3] has made it possible to achieve much faster temporal resolution since July 2009. It provides four analog outputs: two narrow band and another two wide band. The former ones for the fringe counter (FC) have eight-fringe phase information with 1 MHz bandwidth. One FC signal lags 180° behind the other FC signal so that we can accumulate the density data whenever they exceed $8\times 2\pi$ without imposing any fundamental limitation on fringe number counting. The other pair of outputs has only one-fringe information from peak-to-peak but with 4 MHz bandwidth: one labeled "I" in our device is proportional to $\sin(\varphi)$ and the other (Q) to $\cos(\varphi)$. These signals are extracted from a quadrature IF mixer, or IQ mixer (IQ). The new electronics of high bandwidth enables not only the study

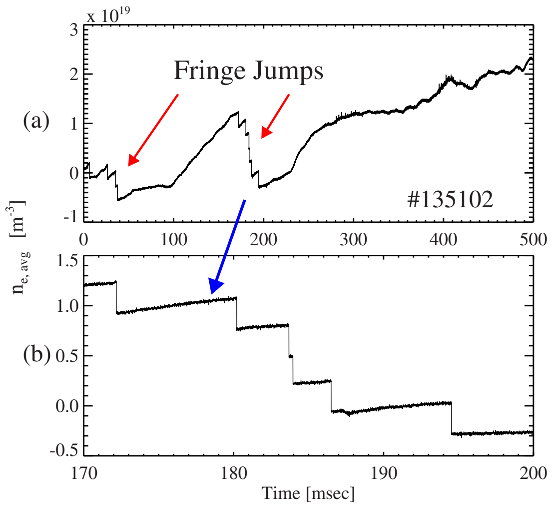

FIG. 1. (Color online) Line-averaged electron density from the FIReTIP: (b) is a magnified view of (a) with series of fringe jumps.

of fast density fluctuations such as Alfvèn eigenmodes but also a clear characterization of fringe jump errors.

III. FRINGE JUMP ERRORS

As the overall performance of fusion plasmas progressed, fringe jump errors came to be recognized as a serious problem. Some transient events, such as edge-localized modes, pellet injection, and major disruptions tend to cause dramatic changes in electron density on very short temporal or spatial scales. Under these circumstances of highly localized plasma density gradients, the probing laser beam suffers from refraction so that the signal-to-noise ratio diminishes severely. This relation[4] between the refraction angle (α) and plasma density is approximated in Eq. (1),

$$\alpha[\mathrm{rad}] = \frac{1}{2n_e}\frac{\partial}{\partial r}\int n_e(r,z)dz, \qquad (1)$$

where n_e is the electron density. The direction of r is transverse to z, i.e., the beam propagation.

These losses of laser beam bring about sudden leaps or falls in the output signals, which do not reflect sensible variations for plasma density. Researchers have tried extensively to solve this problem with various correcting methods in many fusion devices such as JET, Tore Supra, and LHD. Electronics rather than other hardware were applied recently and demonstrated their effectiveness.[5,6] Before finding any solutions to suppress them, fringe jumps in the FIReTIP need to be investigated.

A. Fringe jump errors in the FIReTIP

From the data obtained with new electronics, it is found that most density jumps occur in microseconds. They seem to have a similar amount of variation in each case. Even some larger jumps turned out to have the shape of a cascade of 2π as shown in Fig. 1. Those variations of each jump became clear as being equivalent to one fringe, i.e., 2π from the basic interferometer formula

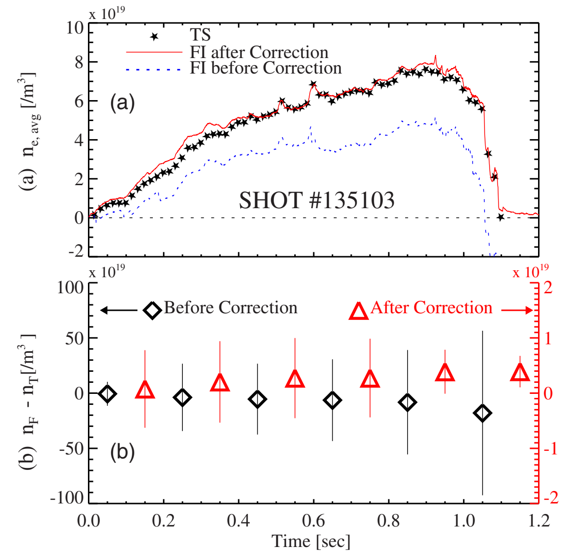

FIG. 2. (Color online) The FIReTIP (Fl) data compared with those of TS diagnostics: (a) the waveforms of each case and (b) the averages and deviations of discrepancies between Fl (n_F) and TS (n_T) since July 2010. Note the different axes for each set.

$$n_{e,\ \mathrm{avg}}[\mathrm{m}^{-3}] = \frac{4\pi c^2\varepsilon_0 m_e}{\lambda e^2 L}\phi. \qquad (2)$$

In our experiment, λ is 118.8 μm and L, the path length, is 6.18 m. Hence, the one-fringe, 2π equivalent line-averaged density is about 3.03×10^{18} [m^{-3}], which is in the range of a typical variation. These values vary when it comes to other FIReTIP channels, but they are still one-fringe equivalent because the relevant path lengths change together. Some variations in the actual density are even much larger than the single (2π) jumps with the periods up to a couple of tens of microseconds so that neglecting those whole jumps can perform quite well.

B. Corrected FIReTIP data

Most corrected data are in good agreement with those from the Thomson scattering (TS) diagnostic,[7] as TS measurements are reconstructed along the direction of the FIReTIP path. An example is depicted in Fig. 2(a). By subtracting each datum point from the TS, it is easily seen in Fig. 2(b) that the disagreements are reduced significantly after correction. Although this postprocessing algorithm has been routinely being used to store data since 2010, we still need to develop another method to generate real-time feedback signals free from fringe jumps. Instead of following other solutions such as adding electronic equipment, we decided to make direct use of a powerful real-time control system in NSTX in parallel with existing data storage channels. This method has the merit of no negative effect on the bandwidth of the original FIReTIP signals to be archived.

IV. REAL-TIME CONTROL SYSTEM WITH THE FIRETIP

NSTX has been successfully operating in real-time using its well-established control system. For better performance, it is continuously being improved in both hardware and software.[8] Control of the electron density, however, has not

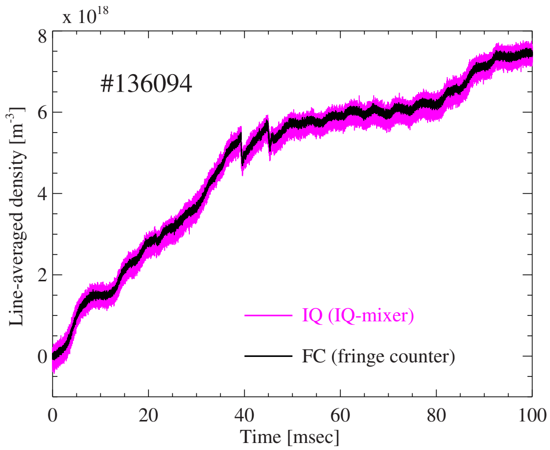

FIG. 3. (Color online) Comparison between both signals.

been introduced yet into the real-time control system. Since the low-field-side (LFS) gas injectors are the only actuators capable of density control at this moment, a new modular system has to be developed particularly in the early phase of discharge, that is, the regime of break-down and start-up, which is typically from 0 to 20 ms in NSTX.

A. The FIReTIP configuration

The FIReTIP is responsible for providing reliable data for the real-time control. Two basic aspects need to be chosen first: one is the signal output from the electronics, and the other is the channel of the laser beam line.

As introduced in Sec. III, the FIReTIP has four parallel outputs labeled 1, 2 for fringe counter signals and I, Q for I-Q mixer signals, respectively, with their own features. Since both pairs of signals provide basically the same information, it is required to choose the better one with respect to the feedback control system.

The signal bandwidths are generally most important in order to detect fast density variations. As the bandwidth of the order of megahertz from both outputs, however, are much higher than the sampling rate of the plasma control system (PCS) digitizer that is 5 kHz, it is not a serious constraint in terms of control. While the bandwidth is not a concern for the real-time system in our case, electronic noise levels of each signal are the most important factors since it might result in significant errors even after the fringe jump errors are corrected.

Electronic noise levels mainly depend on the laser power as the rf source to the mixers. If the laser power is too low, the signal-to-noise ratio decreases in both types of outputs, even leading to serious fringe jump errors as if the laser beam is refracted by the plasma as discussed in Sec. III. Under normal circumstances, the noise level remains in a specific range, so the noise values for both outputs were compared with some typical discharges. An example is shown in Fig. 3. Noise in the FC signals is roughly $\pm 0.5 \times 10^{17}$ m^{-3}, while that of the IQ is about $\pm 2 \times 10^{17}$ m^{-3}. Since the line-averaged density in the early phase is of the order of 10^{18} m^{-3}, uncertainty in the IQ signals reaches tens of percent of the bulk data. It is clear that the FC signals are more suitable for the density control system.

In addition to the signal type, a selection among various geometrical beam lines of the FIReTIP is also essential, especially in our case of control within early phases of discharges where the density is too low to neglect geometrical factors. The layout of the FIReTIP channels and the typical results of several discharges are depicted in Fig. 4. It is obvious that the signals from channel 5 are unlikely to be usable during the early discharge. Even between the other two channels, where 1 and 3 pass through the magnetic axis, it is quite easy to choose the former due to its higher signal level at each time. This is as expected from the previous start-up experiments and their explanation:[9] the early density growth is concentrated on the inner-most side of the NSTX vacuum vessel because both the toroidal electric fields (E_t) and toroidal magnetic fields (B_t) at the smaller radii are stronger, with a sufficiently high ratio of $E_t B_t / B_p$. Together with this aspect and the considerable noise values previously dis-

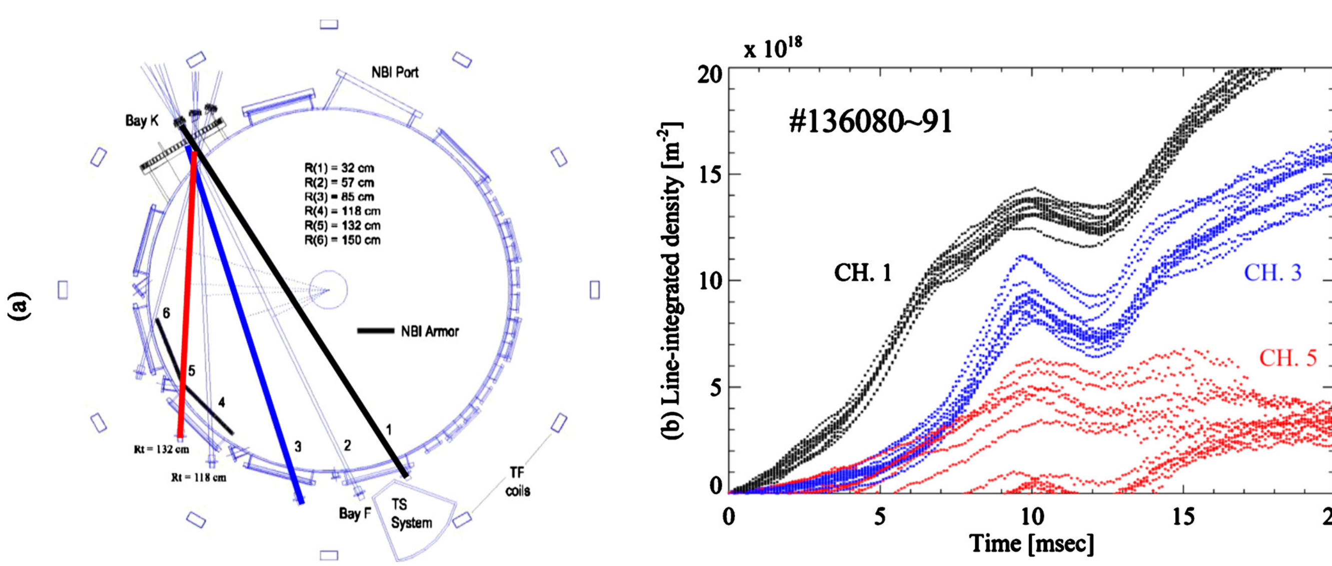

FIG. 4. (Color online) Density obtained from three different channels of the FIReTIP: (a) top-view of the NSTX vessel and the layout of the FIReTIP beam lines on its mid-plane. (b) Line-integrated densities from three different channels during the start-up phase in each discharge.

cussed, it is inevitable to choose channel 1 to stably control the plasma density during early discharges. Nevertheless, further investigation for the FIReTIP configuration is still required if we need to measure some specific density variations such as caused by MHD instabilities.

B. Hardware

Even though future work will focus on the development of control software, the control hardware still limits the overall speed of the process. The following characteristics could anticipate constraints for this work.

(i) The FIReTIP provides two real-time density signals with band widths of 1 and 4 MHz, respectively, and the former one is expected to be used as discussed previously. These signals are sent to the front panel data port (FPDP) digitizers.
(ii) FPDP digitizers with 5 kHz sampling rate convert analog density data. These data are transferred to the PCS system.
(iii) Computers with new 2.4 GHz CPUs calculate the digitized density data in the PCS system, both with fringe correction and density feedback algorithms. This work will be included in a new category (density), or an existing one, "gas injection system (GIS)" of PCS. The feedback data are sent to the GIS controller.
(iv) From the GIS controller, the feedback signals are converted into voltages to operate gas injectors, i.e., the piezoelectric valves of the LFS gas injectors.
(v) The valves of the gas injectors require about 2 ms for the full opening or closing function, and it is operated from the gas-prefill phase to the early plasma phase typically until 100 ms.

Consequently, we have at least a 2 ms interval to transfer signals and handle with the data. The bandwidth of the FIReTIP signals and the speed of the CPU are fast enough. Instead, the 5 kHz sampling rate of digitizers fundamentally restricts our processing speed. The application of the fringe jump correction algorithm to the 5 kHz-sampled data, which are extracted from the existing 500 kHz-sampled data or 1 MHz sampled data, has been carried out, and the results are as shown in Fig. 5. It should be noted that data from the two diagnostics (TS and the FIReTIP) are compared only before 80% of the completion of each discharge. This constraint excludes the biggest discrepancies during the density termination, which is not our concern for feedback control. Obviously, the 5 KHz sampling rate is too slow to follow such fast variations during termination but is still fast enough to distinguish the fringe jumps ($\geq 15\times 10^{18}\ \mathrm{m}^{-3}/\mathrm{ms}$) from the normal density variations on the order of $1\times 10^{17}\ \mathrm{m}^{-3}/\mathrm{ms}$. Even if we concentrate on the start-up phase, the highest variation is roughly about $1\times 10^{18}\ \mathrm{m}^{-3}/\mathrm{ms}$. This is still one-order smaller than that of fringe jumps. In addition, one may be concerned about aliasing because the sampling rate is lower than the signal bandwidth. However, this is also not critical since the electronic noise level is only about $\pm 0.5 \times 10^{17}\ \mathrm{m}^{-3}$ as mentioned in Sec. IV A. The more important issue about aliasing may be the MHD instabilities in frequencies higher than 5 KHz. However, they have just a few percent of the amplitude of the global plasma density and thus do not affect density control. Hence, even with a 5 kHz sampling rate, the data after fringe jump correction are in good agreement with the Thomson scattering data as shown in Fig. 5. This correction method for 5 KHz signals will be implemented directly into the PCS as a new submodule or a new category.

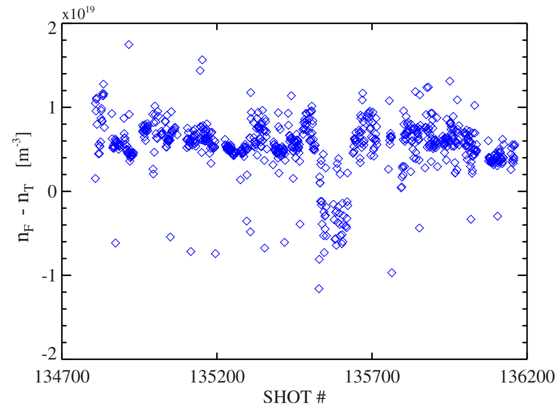

FIG. 5. (Color online) Max. discrepancies during each shot between the TS and the 5 KHz sampled FIReTIP data ($n_F - n_T$) since July 2009.

C. Software

The PCS consists of several categories for real-time control. It is integrated with others such as the power supply real-time controller that is responsible for most categories except the GIS category. This category is directly related to the density control system and is followed by a GIS controller that generates the actual output signals for density control. To utilize those systems, first of all, the density conversion submodule will be inserted. This module includes the fringe jump correction algorithm as well as several elementary ones such as a switching algorithm between the two raw FC signals. They are stacked in turn when they approach to the floor or the ceiling of their range, specifically from -2.5 to 2.5 V. These integrated voltage signals will be also converted into the actual electron density data in this module.

These corrected density data need to be examined by the safety submodule. Either extremely low or high density, in spite of the correction process, will halt the density feedback. At the same time, the raw signals that reach their bottom or top levels too many times are a similar indicator of the fault modes for the FIReTIP. Hence, we can use the FIReTIP signals directly or implement another new signal to indicate the status of the FIReTIP. The former one is attractive because the existing signals of the FIReTIP already impose information about fault modes such as laser power loss, vacuum window degradation, and Schottky barrier diode failure, as any of them leads to an unreasonable density. A separate status signal, however, is expected to provide a more direct indication of the FIReTIP conditions.

If the data succeed in passing the safety module, the feedback algorithm works with the basic formula of the simple proportional controller as follows:

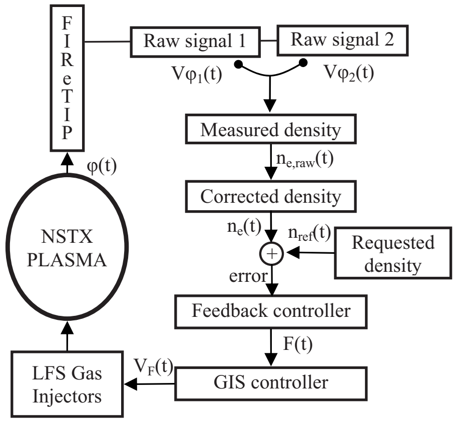

FIG. 6. Block diagram of feedback control system of plasma density via the FIReTIP.

$$F = G(n_{e,\mathrm{ref}} - n_e), \tag{3}$$

where F is the flow rate from the LFS gas injectors, G is the gain constant to be adjusted by experiment or theoretically, and $n_{e,\mathrm{ref}}$ and n_e are the requested and measured electron densities, respectively, at each control time. The flow rate as the final signal will be applied either independently to open or close the valves on the LFS gas injector or added to the existing modulation pulses. The controller schemes, such as a conventional PID, also need to be investigated for better performance. The resultant electron density will be sent back to the PCS via the FIReTIP. This entire process is summarized in Fig. 6.

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