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PROGRESS ON REAL-TIME DENSITY CONTROL CAPABILITY OF THE KSTAR TOKAMAK

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Abstract

For more than a decade, the density control capability of the KSTAR tokamak has been improved continuously to present both in diagnostics and in control knobs: from the beginning of the KSTAR tokamak, a single-channel 280 GHz radial millimeter-wave interferometer (MMWI) works with its particular phase comparator that could deliver real-time analog output signals to the plasma control system (PCS). For the H-mode target plasmas, 2.52 THz vertical single-channel far infrared interferometer (FIRI) takes its role achieving more than 50 s of long-pulse H-mode plasma density control. It has been followed by a tangential 5-chord two-color interferometer (TCI) whose wavelengths are 10.6 μm and 660 nm respectively, for the vibration noise cancellation. The latest TCI is equipped with a full digital phase comparators(DPCs) providing high bandwidth digital density signals of all five chords directly to the PCS. The density profile control also needs effective multiple actuators for realizations. In addition to the fast gas injection systems (FGI) by gas puffing, a supersonic molecular beam injector (SMBI) and pellet injection system (PIS) are ready and tested in feedback loop respectively. SMBI could increase H-mode density more effectively than gas puffs. PIS also demonstrated its working on H-mode density control for the first time in KSTAR with more than 30% of fueling efficiencies. All the diagnostic-actuator sets worked as single-input-single-output (SISO) up to date but they are ready to work as being assembled for multi-input-multi-output(MIMO) control as well as for the advanced control schemes.

■POP1. INTRODUCTION

Looking towards the energy production by fusion reactors, the robust real-time control of every essential properties are pre-requisite tasks. The number of particles either neutral or charged are of particular importance among all. The charged part is represented by the electron density because it is reliably and robustly measurable by interferometers. Far from the energy production, the electron density is still one of the most fundamental parameter to be controlled for the successful operation for the present fusion devices. It is at the same time quite difficult to be completely controllable. The reason of the toughness of the density control are many: 1) uncontrollable and unmeasurable retained particles in the wide area of surrounding plasma facing components (PFCs) and first wall (FW) whose number is frequently excessive to the active number of charged particles [1]. 2) The easiest manner for controlling the plasma density is pouring cold and uncharged neutrals inside a vacuum vessel (VV) which is called gas puffing (GP) as it is quite fast in order of sub seconds in the present devices. However, this time will be delayed critically in the future machines like ITER. Even worsening is the screening effect of the scrape-off-layer (SOL) that ionizes the majority of the gases wiping them out of building up the core charged particles. In this regard, two additional fueling techniques are proposed and installed in a number of devices: Supersonic molecular beam injector (SMBI) and pellet injector system (PIS) [2][3]. Both of them are widely used in the KSTAR experiments not only for the density feedback but many different topics such as edge-localized-modes

(ELMs) pacing and disruption mitigation (done by special shape of pellets called shattered pellet injector or SPI). While the actuator part was supplemented over decades from the day 1 of the KSTAR device, the other part was also improved significantly: real-time measurement of the charged particles or electron densities under the live link to the plasma control system (PCS). Since the day 1 of the KSTAR experiments where density control was not a inevitable tasks, the 280 GHz single-channel millimeter-wave interferometer played a crucial role to successfully start the KSTAR project providing reliable manner for the electron density information. The 2.52 THz far infrared interferometer has been taking the part of H-mode density measurement and control until it is fully covered by a two-color interferometer (TCI) with five-chord density distribution measurement. KSTAR is now with the full capability of the density profile control based on the multi-input-multi-output (MIMO) scheme.

In section 2, the different actuators of the fueling techniques are introduced. In section 3 the recent achievements of multi-chord line-density measurements in real-time are described followed by the particular experimental results with PIS-TCI combination based H-mode density feedback control in section 4. Concluding remarks will be given in section 5.

■POP2. PROGRESS ON ACTUATORS

2.1. Gas puffing

Gas puffing (GP) named FGI in KSTAR are basic fueling tools for the fusion plasmas through which the gasses are poured into the vacuum vessel. To overcome its slow responses, the FGI is operated via specially designed piezo-electric valves (PVs) and their individual controllers. A controller makes the PV open very quickly within a couple of milliseconds by applying initial high voltage, so called pop signal, which is followed by a normal feedback loop to achieve the requested level of the gas flows by in-situ flowmeters [4].
KSTAR is now equipped with 14 FGIs including impurity injectors such as N_2, Ne, Ar, and Kr for the special purposes like divertor detachments. Note that the number of the FGIs are recently increased during the upgrade period of the KSTAR divertors from the graphite tile to the current tungsten monoblock which is more resistant to the thermal heat loads. Before upgrade, it was 8 in total.
Amongst all FGIs, the main two upstream ones are dedicated to the density feedback control which is called PVMG and PVUJ (former PVLJ before W-divertor upgrade). The naming of each valve is following the KSTAR's convention: PV at port location in toroidal (A to P) and in poloidal direction as shown in Fig. 1 and Table 2.

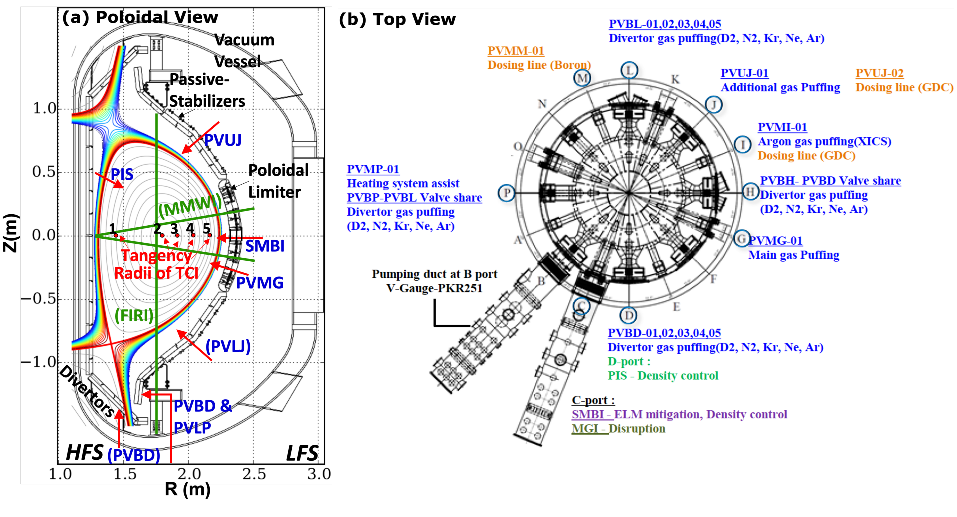

FIG. 1. (color online) (a) KSTAR's poloidal geometry with different gas puff locations with overlayed measurement lines. The red dots are tangency radii of a multi-chord two-color interferometer (see Table 3). Contour plot inside of vacuum vessel shows the real-time EFIT reconstruction results for an example of a typical shape. The name with bracket is now retired by different reasons. (b) Top view of the KSTAR with toroidal locations of each fueling system. The name of gas puffing is listed in Table 2. Note that location of vacuum pumps is next to the vacuum gauge on the structure of pumping duct connected at port B.

When it comes to the density control purposes, one of the most important features is speed of the gas puffs and the fueling efficiency. The efficiency can be obtained with the amount of the density increased by a certain amount of particle injection under the designed command. Divertor puffs are more focused on the detachment control

TABLE 1. THE FAST GAS INJECTION (FGI) SYSTEM [5] (X: IMPURITY SPECIES)

Name	Location	Purpose
PVMG	Midplane G-port	Prefill for start-up and density control
PVUJ	Upper-slanted J-port	Density control
PVMI-Ar	Midplane I-port	Ar injection for XICS diagnosing
PVMP	Midplane P-port	RF-heating coupling
PVBL(P)-X	Bottom L(P or LP)-port	Divertor fueling and detachment control
PVBD(H)-X	Bottom D(H or DH)-port	Divertor fueling and detachment control

due to its very limited spaces that imposes small size pipe lines for the gases are transmitted with relatively long time-delay, order of 100 ms. PVMG and PVUJ, on the other hand, are installed with larger guiding pipes leading to much faster injections in order of 10 ms, suitable to the feedback control usage. In addition, the efficiencies of the fueling of the upstream valves, PVMG and PVUJ are superior to the divertor puffs as shown in Fig. 2.

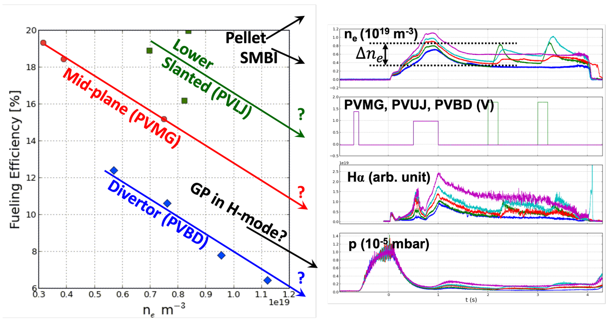

FIG. 2. (color online) (left) Fueling efficiencies on a divertor Ohmic discharges depending on the different GP locations and density levels measured by the dedicated experiment (right).

As shown in Fig. 2 gas puffs become less effective when the base density increases. The density control on H-mode plasmas is expected to be clearly pretty tougher with those gas puffs. PVUJ is a new actuator which was former PVLJ in the same distance from the mid-plane, moved its location due to the W-divertor upgrade. PVU(L)J are specially designed for the density control purpose regarding to the KSTAR's particular geometry of passive stabilizers. The large vacant spaces of the KSTAR VV (110 m^3) is occupied by the spaces behind the passive stabilizers. This space is a huge sink for the particles when it is ionized approximately 50% of the hydrogen molecules are directed back to the vacuum side [6]. To minimize this drawback of the mid-plane puff PVMG, a dedicated hole is drilled at the center of the passive stabilizers. This is thought to be the reason of the higher efficiency of the PVLJ than that of the PVMG. According to the results in Fig. 2 PVLJ has 18% higher efficiency than PVMG. And all levels are under reasonable range as other fusion devices.
Even if the specialized actuators are created, the density control of the H-mode plasmas are quite limited. To overcome the limit, some special technologies are needed such as SMBI and PIS.

2.2. Supersonic molecular beam injector (SMBI)

SMBI uses cooled gases at 105 K by cryogenic liquid N_2 (LN2). It is also utilized for particular experiments such as ELM mitigations. SMBI works only in pulsed mode due to its special valve while FGI is continuously tunable with its flow by using PCS command. In Fig 4 (a) the structures of the SMBI is presented together with the calibration results of the recent two campaigns in 2024 and 2025 [7] in Fig. 4 (b). One would have found that the SMBI can be controlled with its pulse width, meaning it can be controlled in either pulse-width-modulation (PWM) mode or frequency modulation (FM) mode depending on a control scenario.

2.3. Pellet Injector System (PIS)

KSTAR is equipped with two different types of pellets: a regular pellet for density control and two shatters pellets for disruption mitigations. The latter shoots the shatters pellets from the outboard mid-plane while the former is guided by specially manufactured 1/4 inch tubes all the way up to the inboard side for higher efficiency than outboard injection.

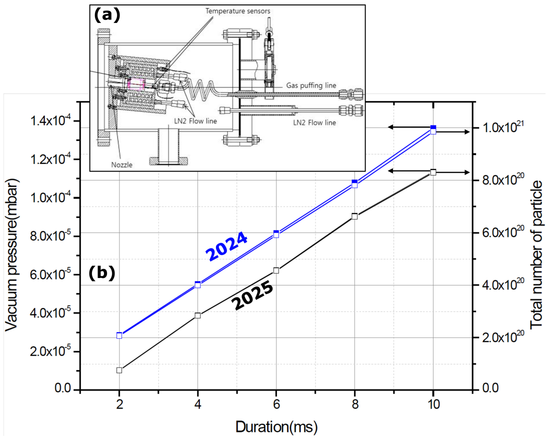

FIG. 3. (a) Drawing of the SMBI system installed on the KSTAR Port and (b) SMBI Injection amount over the opening time of the valves.

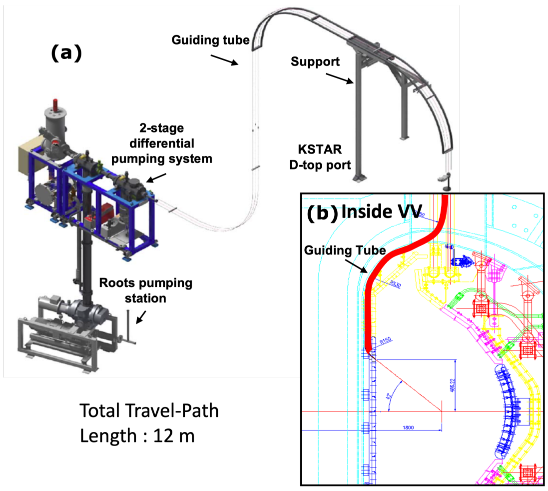

FIG. 4. (a) PIS system CAD drawing including the guiding tubes for the pellets to be injected from (b) the inboard side of the KSTAR tokamak.

TABLE 2. KEY FEATURES OF KSTAR PIS [2, 3]

Features	Typ. Setting/Conditions	Remarks
Material	D_2	Optional H_2
Extrusion Type	Screw	.
Shape	Cylinder	Fixed
Size	Dia. 2 mm, Length 2.0 mm	variable L <2.0 mm
Frequency	< 20 Hz	12 Hz confirmed
Velocity	Typ. 200 m/s	equiv. 60 ms time of flight
Reliability	>95%	100% achieved

■POP3. PROGRESS ON REAL-TIME DIAGNOSTICS

KSTAR has started with a Gunn-diode based 280 GHz millimeter-wave interferometer (MMWI) system providing reliable density waveforms during the early phase of the operation[8]. Specially designed phase comparator enabled real-time control of the KSTAR electron density as well. The robust MMWI kept running in a number of H-mode plasmas. however, due to strong density drops larger than a single fringe of MMWI equivalent to 1.1 $\times 10^{18} m^{-3}$, it suffered from a number of fringe jumps. Therefore, the MMWI utilized mainly on the L-mode and Ohmic discharges.

3.1. Far Infrared Interferometer (FIRI)

The H-mode plasmas are more easily controlled by a Far Infrared Interferometer (FIRI) whose beam wavelength was 119 μm emitted from molecules of Methanol(CH_3OH) gases. [9] Two examples of the H-mode density controls via FIRI system are presented in Fig. 5. The results of different combinations from FIRI to SMBI and PVLJ are individually drawn. SMBI was successfully regulating the density level in relatively complicated waveform even in H-mode. In the long pulse H-mode experiments, the command of gas puffing reduces as time goes due to the increase of recycling level.

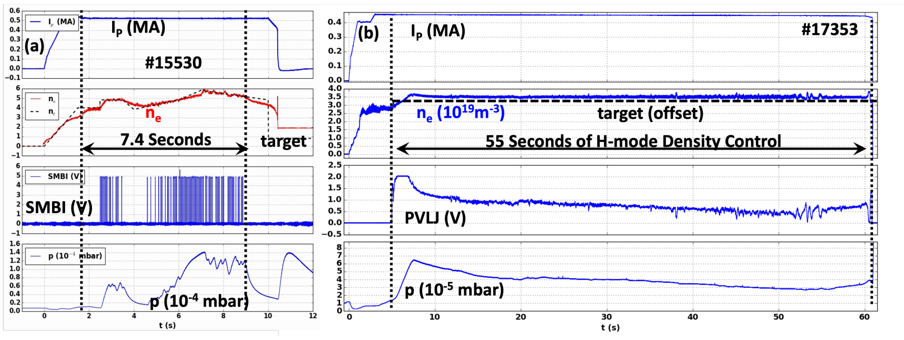

FIG. 5. (a) SMBI-FIRI based H-mode density control. Plasma current I_p in MA, electron density n_e in $10^{19}m^{-3}$ with target (black broken line), SMBI command in volts in feedback mode, and neutral pressure p in 10^{-4} mbar. (b) The long-pulse H-mode discharge with density feedback control by using PVLJ and FIRI combinations. Note that the target level in (b) is offset just for visibility.

3.2. Two-color Interferometer (TCI)

To expand the number of lines of the interferometer, a high-power CO_2 laser based two-color interferometer has been developed. All the five probing beams pass through a ZnSe window as a pivoting point, and spread with different tangency radii R_t on the mid-plane as listed in Table 3. Different R_t are also pointed in the previous Fig. 1 as five red dots. Note that KSTAR plasma's nominal magnetic axis R_0 is 1.8 m. The round-trip path lengths L_p for line-averaged density calculation of each chord are calculated with assumption of boundary location R_{out} at 2.25 m. Other details of the TCI system are completely described in [10, 11]

TABLE 3. TANGENCY RADII R_T AND PATH-LENGTHS (ROUND-TRIP)

Ch. #	1	2	3	4	5
R_t (m)	1.34	1.78	1.91	2.04	2.06
L_p (m)	7.23	5.51	4.76	3.80	2.52

All five-chord line-averaged density data are directly transferred to KSTAR PCS for real-time feedback control via reflective memory (RFM) card from the full digital phase comparator(DPC) and its host PC (HPC). The real-time data acquisition of the entire chords is demonstrated its working to be ready for the density profile control.

■POP4. REAL-TIME DENSITY FEEDBACK LOOP

The present parts that consist of the closed-loop for the density feedback control are illustrated in Fig. 6 with cartoon diagram and 3-D CAD drawing. The five different chords of the TCI beams are detected after returning back to the optical tables where two different detectors are aligned to capture 40 MHz of intermediate frequency

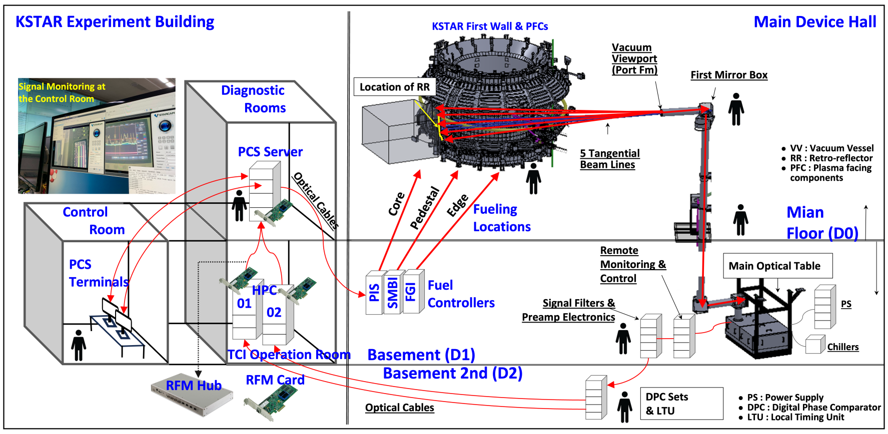

FIG. 6. A diagram of density control loop with 3-D CAD drawing and beam or signal lines connected each other in red-color line. A photo is also given on the left top corner that shows actual signal monitoring of the TCI status during experiment in the control room.

(IF) signals. These IF signals are digitized for calculation of phases that is proportional to the plasma density integrated along its beam path. This process is carried out in the DPCs which are equipped with FPGA chips and their HPCs transfer all the digital numbers to the PCS. PCS can compare the real-time signals to the reference target waveform, generating error signals for classical PID (proportional-integral-derivative) controller calculation. An example of H-mode density feedback control by multiple pellet firing is presented in Fig. 7 which was the first time achieved in the KSTAR discharges.

4.1. Pellet-based H-mode density control and its results

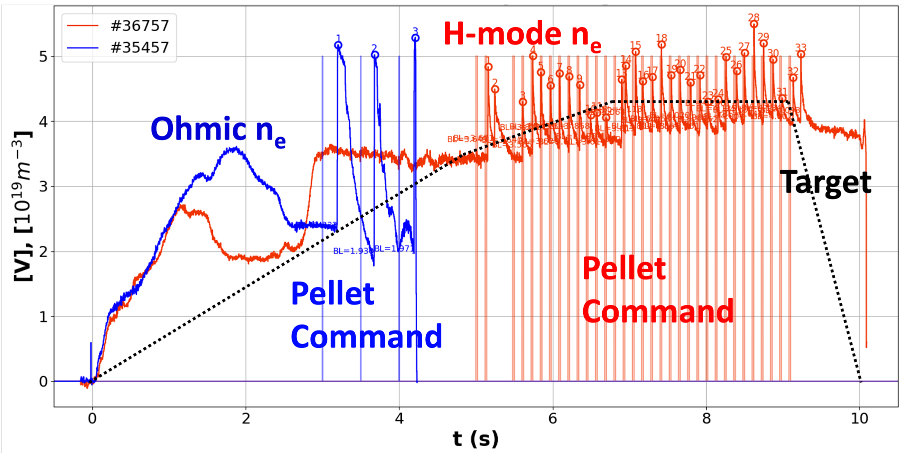

FIG. 7. (color online) The density feedback result (red) of the PIS-based control in a typical H-mode plasmas of KSTAR with a target level of broken black line. For comparison of density response on each pellet, an Ohmic discharge with several pellets is also overlayed (blue). Moreover, the each peak of density rise is counted for the further analysis.

In order to investigate the performance of the multiple pellet injections in H-mode density control, another example is together drawn of three pellets fired in Ohmic plasmas (blue-color, #35457). In each discharge, the number of density peaks induced by pellet consumption are counted by peak-detection technique. The fueling efficiencies of each pellet could be calculated one by one. The size of pellets were fixed at 2 mm of length. The total number of D of each pellet is 3.71×10^{20}. The increased number of charged particles are obtained with $\Delta n_e V_p$ where V_p is the volume of the plasmas. Therefore the fueling efficiency η is defined as follows.

$$\eta(\%) = \frac{\Delta n_e V_p}{N(D)} \times 100$$

The results of the efficiencies are given in Fig. 8 (a). The efficiency on the Ohmic discharges are almost 100% which apparently means the complete consumption of the injected pellets. On the other hand, the results of the pellet efficiency to the H-mode plasmas are just about 30%. This is dramatically lower than those of Ohmic discharge. This could be attributed by the higher density and temperature at all regions of the H-mode plasmas in the first place. However, it should be noted that there were two unusual fault status during both experiments.

- The day of the Ohmic discharge #35457 : A part of propellant system was out of running - potential risk of reduced injection speed.
- The day of the H-mode discharge #36757 : The propellant system was completely restored. This time, an automatic clustering of the PIS was not working. Manual clustering was attempted - potential risk of imperfect cluster formation.

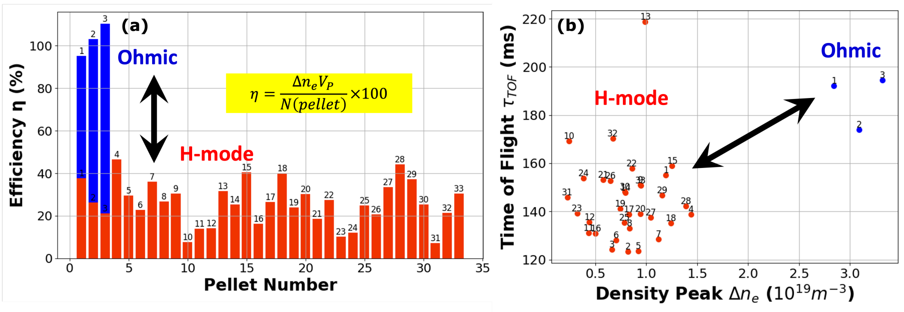

FIG. 8. (color online) (a) Pellet fueling efficiency on each discharge with blue-color bar for the Ohmic discharge and red-color bar for the H-mode discharge. (b) time of flight τ_{TOF} calculation of each peak over the density rising amount. The number on each circle corresponds to the ones on the Fig. 7 like (a).

Both of these two issues were reported before the experiment. In spite of those issues, it was found that the all 36 pellets were successfully fired without any loss. This results guarantees the robustness of the PIS even if the system is not its 100% status. Fig. 8 (b) clearly shows reduced speed of the ones in Ohmic plasmas which are about 180 ms of flying time τ_{TOF}. On the other hand, after the propellant system is fully restored, the τ_{TOF} became about 30% faster than those of the Ohmic case. Note that this is still more than twice longer than the ideal τ_{TOF} 60 ms which is calculated by the initial speed 200 m/s and the length of the guiding tube 12 m. Three candidates of causes for the low efficiencies in H-mode can be considered: i) Imperfect clusterizing - this is temporary issue. It is easy to be recovered and checked. ii) too faster than pellets in Ohmic - slowing down mimicking the ones obtained in the Ohmic discharges due to the partial fault of the propellent system, iii) nature of the hotter and denser H-mode plasma- In this case, another strategy is required such as changing the size and speed of the system.

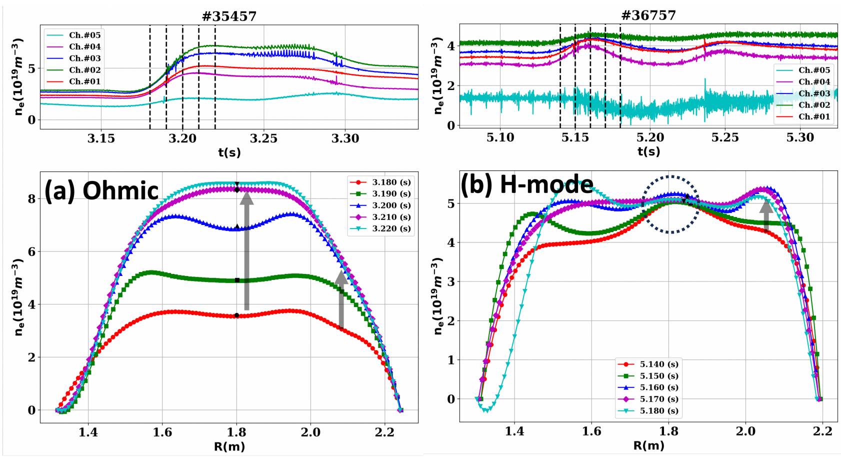

FIG. 9. Density inversion of two different cases of pellet injections: (a) #1 peak of Ohmic discharge (b) #1 peak of H-mode discharge. The vertical lines of density rising due to pellet injections are drawn in each panel in the bottom.

Actually, the five chord interferometer density can provide the fast local density responses over the pellet injections. Simple inversion from outboard to the inboard chords, shows the results of Fig. 9. The first peak of each discharge was chosen. But the other peaks showed similar pattern. In Fig. 9 (a), the density build-up in Ohmic discharge is mostly occurring near the magnetic axis. In contrast, the pellet in H-mode plasmas only contribute to the small density raise only in the pedestal top region. The central region just remains at the same level. In this case, the imperfect clustering could be the most plausible cause of such low efficiency because it could not penetrate deep into the core region at all regardless of its speed. This will be investigated again at the upcoming experiments. Note that the relatively low efficiency of pellets in H-mode, on any reason, still significantly higher than those of gas puffing whose too low fueling efficiency cannot be directly measurable.

■POP5. CONCLUSION

The density feedback control system of the KSTAR tokamak became mature for the advanced scenario research. It can provide real-time density profile with multi-chord TCI for more complicated physics study such as density peaking effect on the Greenwald density limit for instance. The advanced actuators are also established on top of the gas puffs: the SMBI and the PIS can penetrate deeper into the plasma overcoming the screening effect, which is promising for the H-mode density control. Therefore a multi-input-multi-output (MIMO) control of the KSTAR plasma density is now ready. Moreover, more advanced control scheme like model reference adaptive control can be applied. Some of those advanced approach are already begun in KSTAR by the recent progress.

ACKNOWLEDGEMENTS

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