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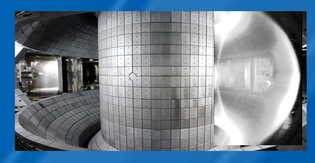
PROGRESS ON REAL-TIME DENSITY CONTROL CAPABILITY OF THE KSTAR TOKAMAK



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Abstract

- Establishment of multi-input-multi-output (MIMO) capable H-mode density control system on KSTAR
- Real-time measurement has been improved from mm-Wave Interferometer (mmWI) and far infrared interferometer (FIRI) to 5+ chords infrared two-color interferometer. (TCI)
- Gas puffing (GP), supersonic molecular beam injection (SMBI) and the inboard pellet injection system (PIS) are demonstrated their working on SISO density controls with different combinations such as basic GPs + mmWI, GPs + FIRI for long pulse H-mode, SMBI+FIRI for faster H-mode and pellet + TCI for core fueling on the higher H-mode plasma densities

References

- *Soo-Hwan Park, et al., "Development of pellet injection system for KSTAR," Fusion Eng. Des. 123 (2017) 163*
- *Soo-Hwan Park , et al., "Preparation of KSTAR pellet injection system for advanced plasma scenarios," Fusion Eng. Des. 216 (2025) 115121*
- *Y.O. Kim, et al., "Control and operation of the gas injection systems for KSTAR tokamak," Fusion Eng. Des. (2013) 1132*
- *J. I. Song, "Lecture on the KSTAR Fueling System," KFE Internal Report (2024)*
- *J. I. Song, "KSTAR Fuel System Calibration Results of 18th Campaign," Internal Report (2025)*
- *Y. U. Nam, K. D. Lee, "A 280 GHz single-channel millimeter-wave interferometer system for KSTAR," Rev. Sci. Instrum., vol. 79, (2008) 10E705*
- *J.-W. Juhn, et al., "Operation results of the KSTAR far infrared interferometer," Rev. Sci. Instrum., vol. 87 (2016) 11E131*
- *K. C. Lee, et al., "The design of two color interferometer system for the 3-dimensional analysis of plasma density evolution on KSTAR," Fusion Eng. Des., vol. 113 (2016) 85.*
- *J.-W. Juhn, et al., "Multi-chord IR-visible two-color interferometer on KSTAR," Rev. Sci. Instrum., vol. 92 (2021) 043543*

Real-time Density Measurement Sources

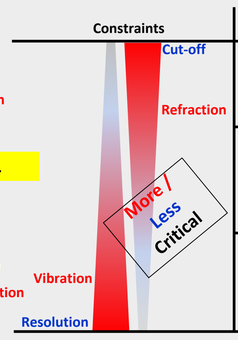
Wavelength Constraints

Upper Limit
- $\lambda \le 1.16 \times 10^{10} (Z_0 n_0^2)^{-1/3}$ m — Beam refraction
- $n_c = (1.11/\lambda^2) \times 10^{15}$ m^3 — Cut-off density

Need for proper choice of wavelength λ

+ Fast responses to avoid fringe errors from transient ELMs, Pellets, …

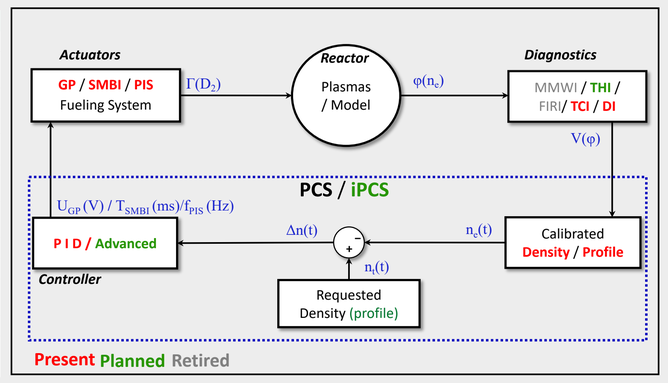
Lower Limit
- $\phi = 2.82 \times 10^{-15} \lambda \int_{Z_L}^{Z_2} n(z)\,dz$ — Phase Resolution
- $\lambda > 4.08 \times 10^{5} (r_0 n_0)^{-1/2}$ m — Mechanical Vibration



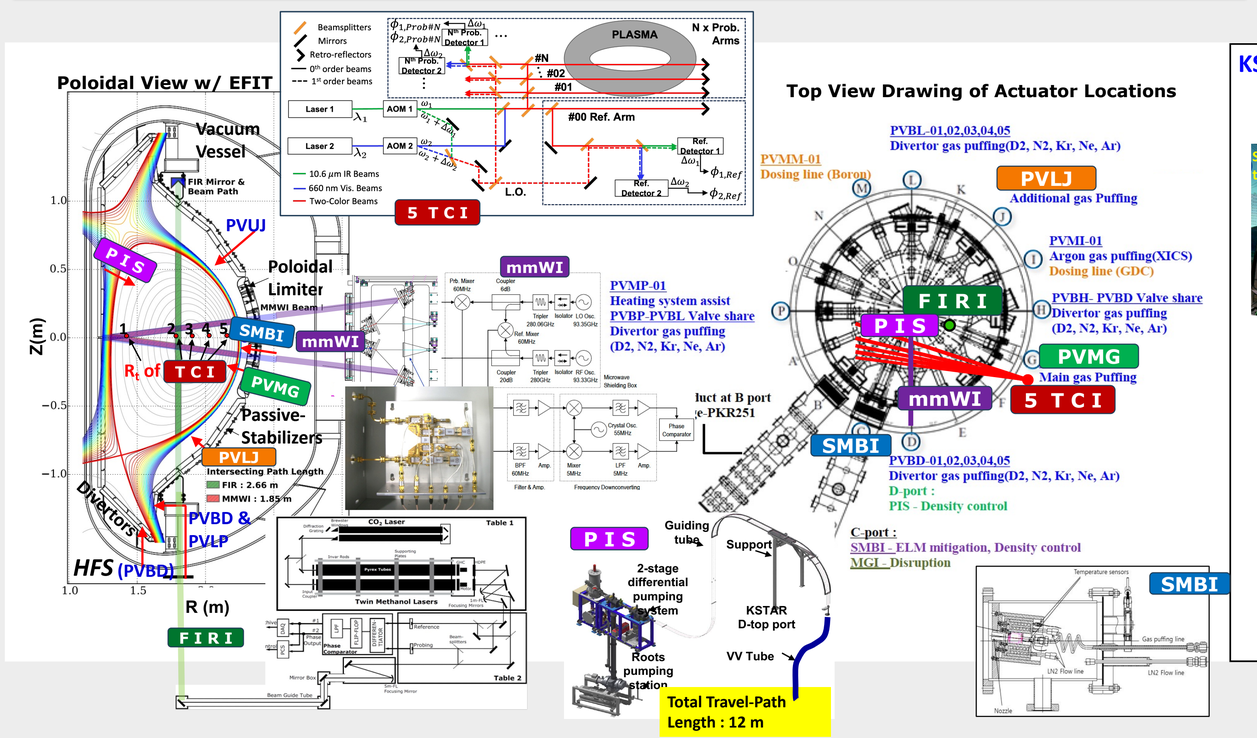
Frequency & Source	Wavelength	Type & Remarks
280GHz Gunn Diode Oscillator	1.06mm x 1/9	Millimeter-wave Interferometer — mmWI • Horizontal 1 channel • Since the first day of KSTAR plasmas • L-mode density measurement and control
2.52THz Methanol (CH_3OH) Laser	118.8μm x 1/11	Far Infrared Interferometer — FIRI • Vertical 1 channel • First measurement in 2013 and first routine operation in 2015 • H-mode density measurement and control
CO_2 Laser Vibration Compens. DPSS Laser	10.6μm 660 nm	Two-color Interferometer — TCI • Total 5 tangential chords • with real-time signal processing • Fast density profile evolution measurement • Pellet-compatible density measurement

Closed Loop Configurations on the KSTAR Tokamak

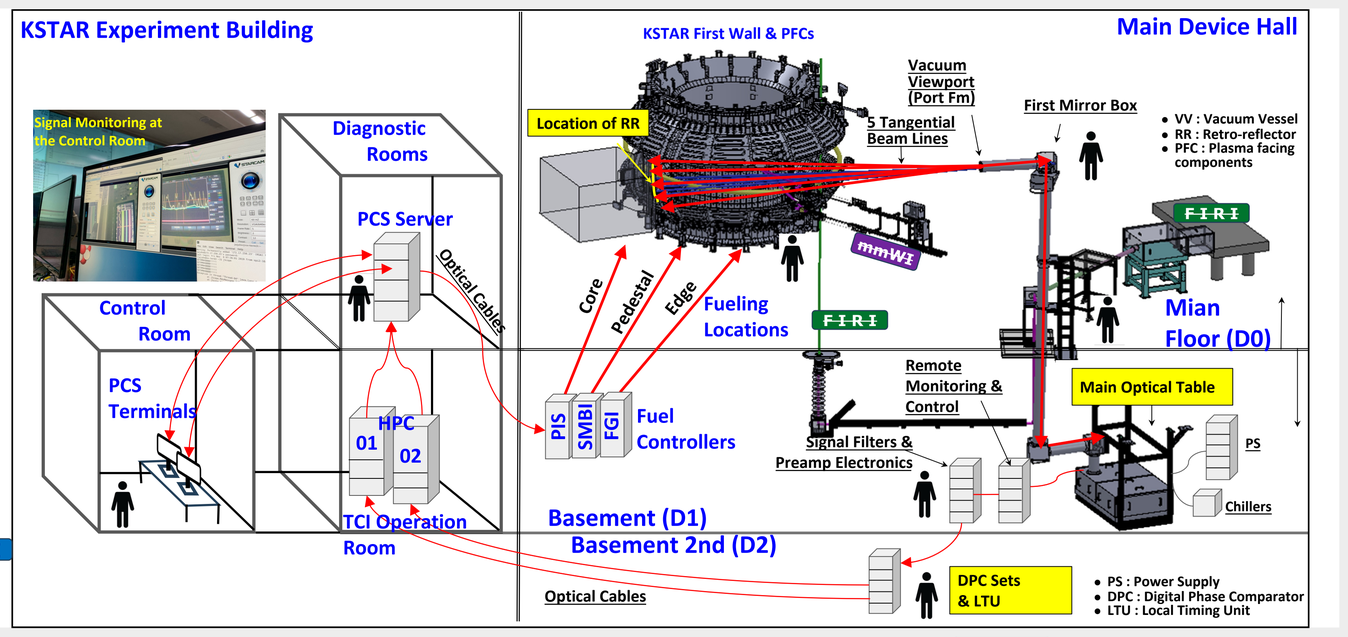
Abbr.	Full name	Role for Density Control
GP	Gas Puffing	Prefill, L- and H-mode density control in CW-mode by gas puffing
SMBI	Supersonic Molecular Beam Inj.	195K by Liquid N2. H-mode density control in pulsed-mode
PIS	Pellet Injection System	Core-density fueling for high-density operation
mmWI	mm-wave interferometer	L-mode density measurement (Retired)
THI	Tera-Hertz Interferometer	L/H mode density measurement replacing mmWI (planned)
FIRI	Far-InfraRed Interferometer	H-mode density measurement (Retired)
TCI	Two-color Interferometer	Replacing FIRI & Multi-channel up to 5 chords and more (planned)
DI	Dispersion Interferometer	High plasma density measurement in major disruption
PCS	Plasma Control System	Calculating density level and actuator command in real-time
PID	Proportional-integral-derivative	Determination of actuator response
PCS	Plasma Control System	Calculating density level and actuator command in real-time
CODAC / iPCS	Control, Data Access and Communication / ITER PCS	Replacing only related part of the PCS for the density control



Setup and Locations of the Measurements & Actuators



Present Configurations and Connections of the Closed-loop



Ch.	1	2	3	4	5
R_t (m)	1.34	1.78	1.91	2.04	2.16
L_p (m)*	7.23	5.51	4.76	3.80	2.52

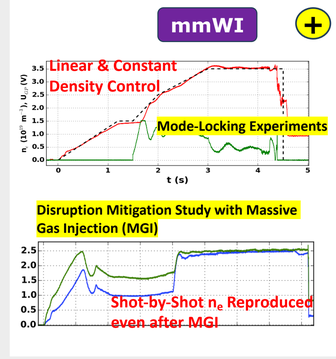
5-ch. TCI + PVLJ + PVMG + SMBI + PIS — MIMO Ready!

$* L_p \equiv n_{eL}/n_e$ from R_{out} = 2.25 m (Typical)

Present

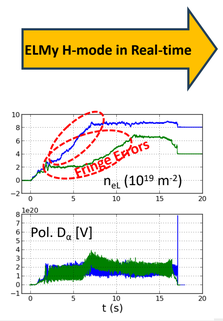
Progress towards H-mode Density Control

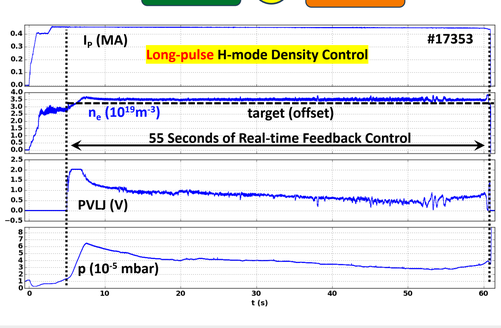
mmWI + PVLJ + PVMG



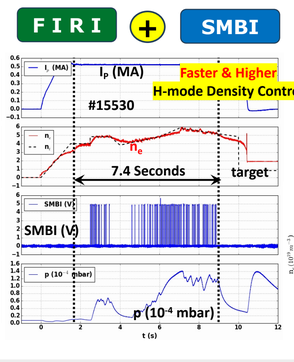
ELMy H-mode in Real-time

FIRI + PVLJ

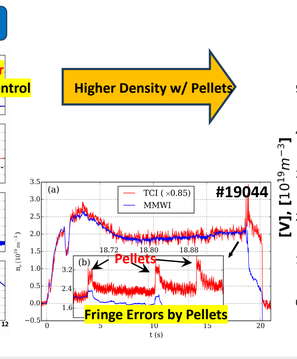




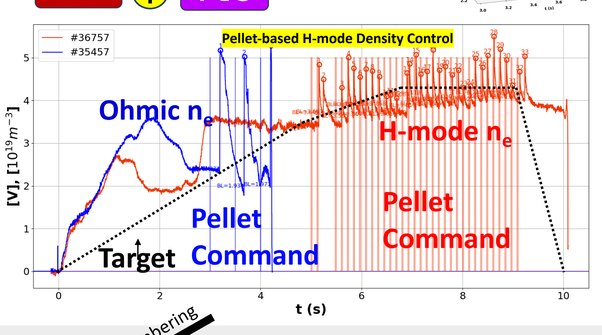
FIRI + SMBI

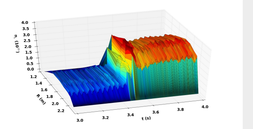


Higher Density w/ Pellets

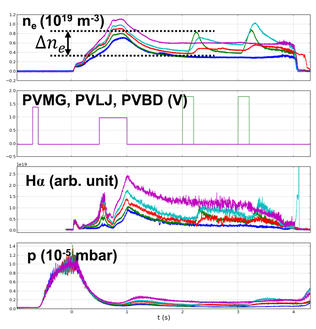


TCI + PIS

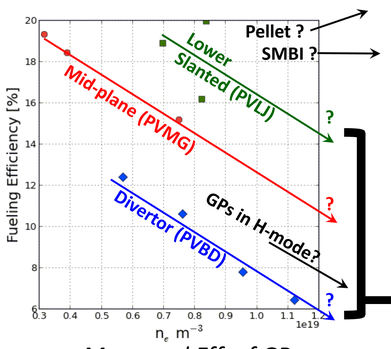




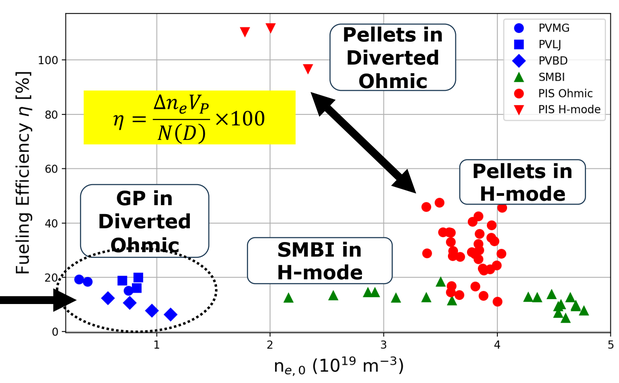
Fueling Efficiency Comparison of the Different Actuators : GPs , SMBI and Pellets

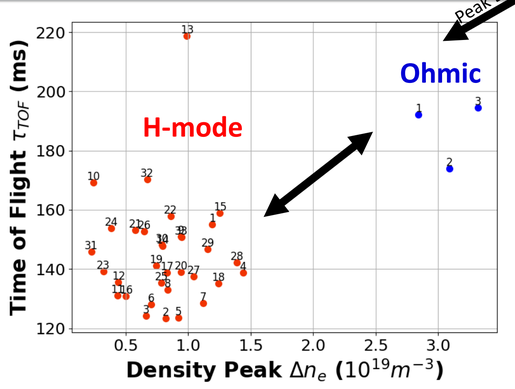


Fueling Efficiency Test



Measured Eff. of GPs





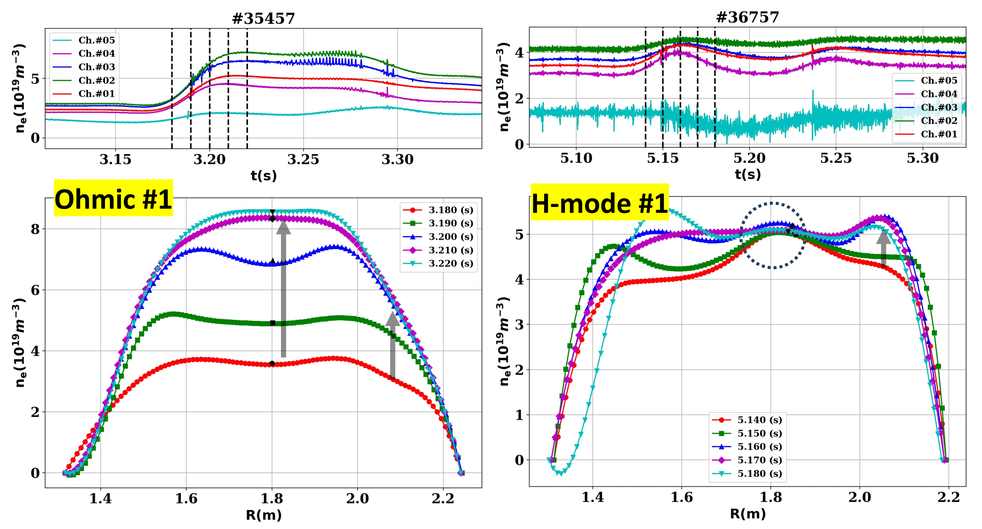
Summary and Notes on Pellet Feedback Results

Parameters	Ohmic (#35457)	H-mode (#36757)
# of Pellets	3 (pre-programmed)	33 (feedback)
Count	3	33 (100% fired!!)
Device Issues (recognized before each experiment)	Slower pellet speed with fault of propellent pumps (repaired before #36757)	Not automatically optimized pellet clustering (-> manual formation)
Efficiency	~ 100 %	~ 30 %
TOF	~ 180 ms	~ 140 ms

Conclusion & Future Plans

- Beginning from the mmWI and FIRI for basic L-mode and H-mode density measurements in real-time,
- The 5-chord TCI provides robust real-time density signals including the fast density responses on pellet injections as well as provides the density profile. The number of TCI chords will be doubled in the near future for more detail profile investigation.
- The full actuators are operating on KSTAR tokamak including GPs, SMBI, and inboard pellets.
- The fueling efficiencies from GP reduces significantly in higher density plasmas while pellet shows large amount of consumption both in Ohmic (100%) and H-mode discharges (30%). However, the dramatic degradation of efficiency in H-mode needs to be investigated further. The first inversion from 5-chord TCI showed density rise only at the pedestal top region of the H-mode while strong core peaking of the density profile was observed by firing slow pellets in Ohmic plasmas.
- SMBI is not as efficient as pellets but it is reasonably effective in H-mode for faster and higher fueling of plasmas with moderate efficiencies about 15%.
- Pellet-based density control was demonstrated in KSTAR for the first time with the real-time TCI measurements.
- MIMO control is capable for the density profile control. It already started with pedestal top height control.
- An advanced control schemes will be applied such as model-reference-adaptive controls for ITER density regulation activities.

Inversion of TCI for Density Profile Responses on the Pellet Injections



Acknowledgements

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