Low-risk Beginning of the Density Feedback Control in KSTAR

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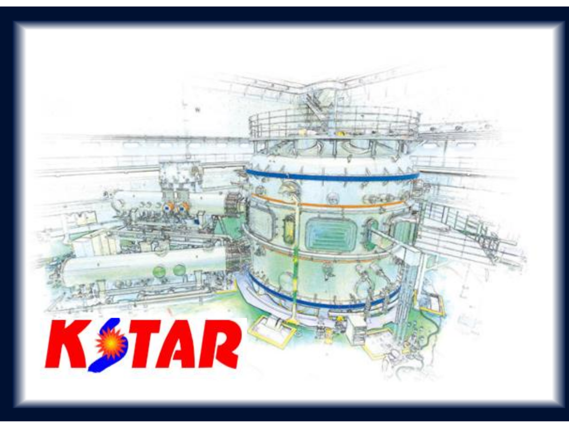
NFRI 국가핵융합연구소 National Fusion Research Institute



ABSTRACT

During the early campaigns of the KSTAR project, feedback control of plasma density has been successfully commissioned at the very first attempt by using a transfer function analysis. A stable and robust discharge was chosen for a test-bed i.e. 300 kA (I_p) 2.0 T (B_t) ohmic circular limited plasma. Before direct feedback control, pre-programmed fueling modulation was carried out by puffing the deuterium gas. Line-averaged plasma density was measured in real-time by a 280 GHz interferometer system. From the open-loop experiments, both the density decay time (τ_i^*) and the external fueling efficiency (f_{ex}) were obtained approximately: 3.0 to 5.0 s and 10 to 20 % respectively. By transfer function analysis, several transient responses such as rising time, settling time and overshoot ratio were estimated in a certain range by the measured ranges of τ_i^* and f_{ex}. It is found that τ_i^* has little effect on those response characteristics while f_{ex} plays prime role together with magnitude of the proportional gain K_p. This is due to predominance of valve response whose characteristic time τ_v was approximately 60 ms, which is much shorter than τ_i^*. Considering these values, K_p for closed-loop control were set 2.5 as minimum and followed by stepwise increment to reduce steady-state error without any integral gain K_i to avoid any uncertainty. The small initial K_p was chosen being concerned on excessive fueling. Similarly the target density waveform was also initially low and gradually increasing, eventually followed by flattop period for one second before current ramp-down. In this way the first density feedback control was successfully finished although the transient responses were far different from the experimental result while the predicted steady-state error was in good agreement with the experimental undershoot. By replacing τ_v with arbitrary characteristic time τ_α two different settling time in the two subsequent feedback experiments were both matched well with a single $\tau_\alpha \sim 120$ ms. This is due to a digital low-pass-filter included by a plasma control system (PCS) acting as 50 ms delay of response. Including the filter, transfer function becomes 3-pole system and no more simple analytic expression of response characteristics were available. Instead, they are fully numerically computed. The changed settling times including the digital filter matched well with $\tau_\alpha \sim 50$ ms which became much closer to the original τ_v. In summary, response characteristics in longer period (settling time and steady-state error) are evaluated well with the transfer functions by using the simple particle balance model with fixed τ_i^* and f_{ex} and fueling delay estimated by D_α signal including digital filter. However rising time and overshoot still does not agree with any values of τ_α, which implies the density feedback system is not simply the second or third order or even linear system. For more accurate prediction of response, therefore, nonlinear or time-varying numerical model will be necessary especially in dealing with the recycling coefficient R that underlies in $\tau_i^* \equiv \tau_i/(1-R)$ where τ_i is particle confinement time.

ACKNOWLEDGMENTS

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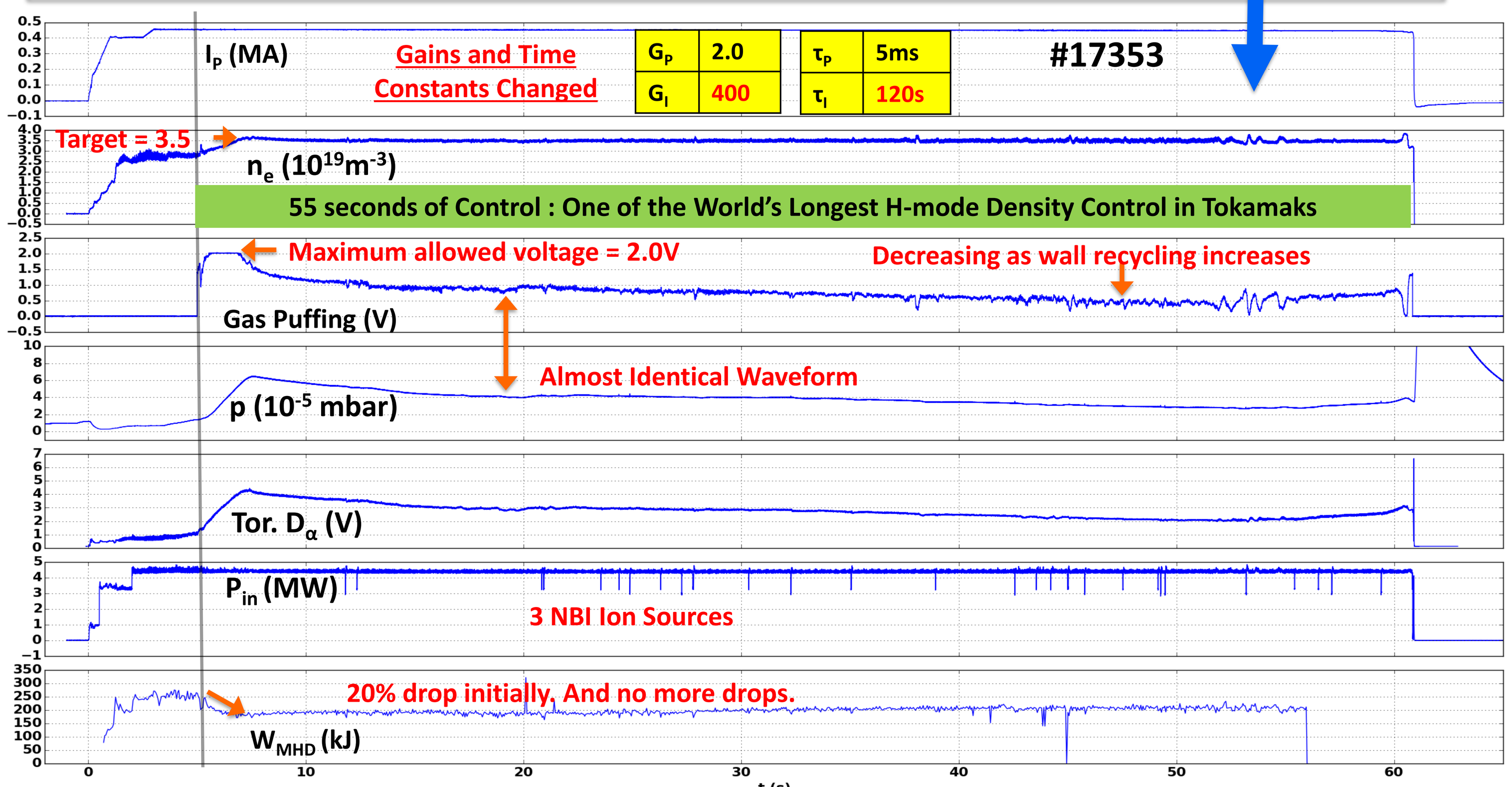
Motivation of Density Control and Recent Achievement

To control fusion reaction rate - not strongly required in KSTAR but for future reactors

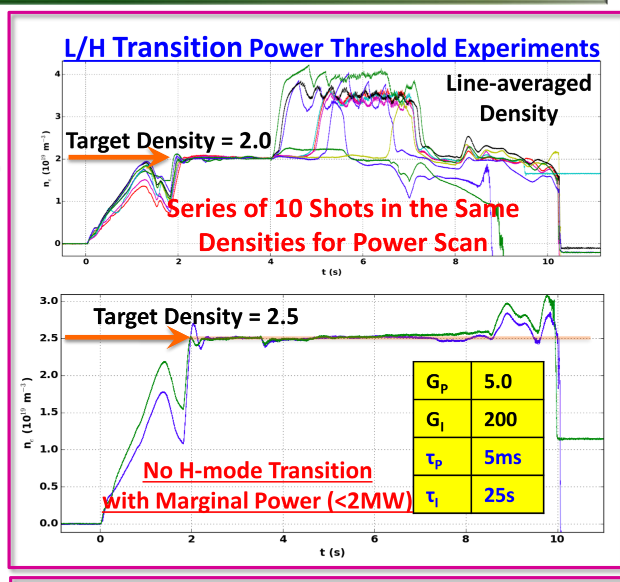
Focused In KSTAR

✓ To study plasma physics effectively and do experiment efficiently
- L/H power threshold experiments
- SOL characteristics analysis with FRPA
- Mode locking with RMP
- Rotation reversal experiments
- MGI-based disruption-mitigation experiments
- And many more …

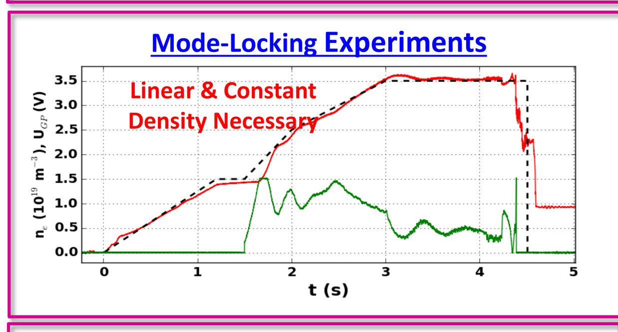
✓ To help achieve KSTAR's goal – steady-state operation with advanced scenario
- Long-pulse density sustainment against either exhaust or increase



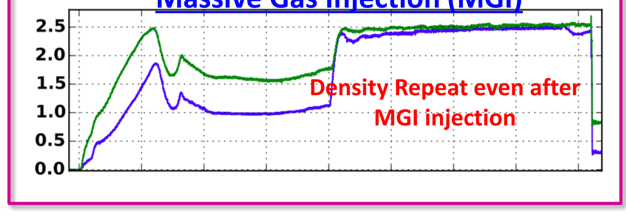
L/H Transition Power Threshold Experiments



Mode-Locking Experiments

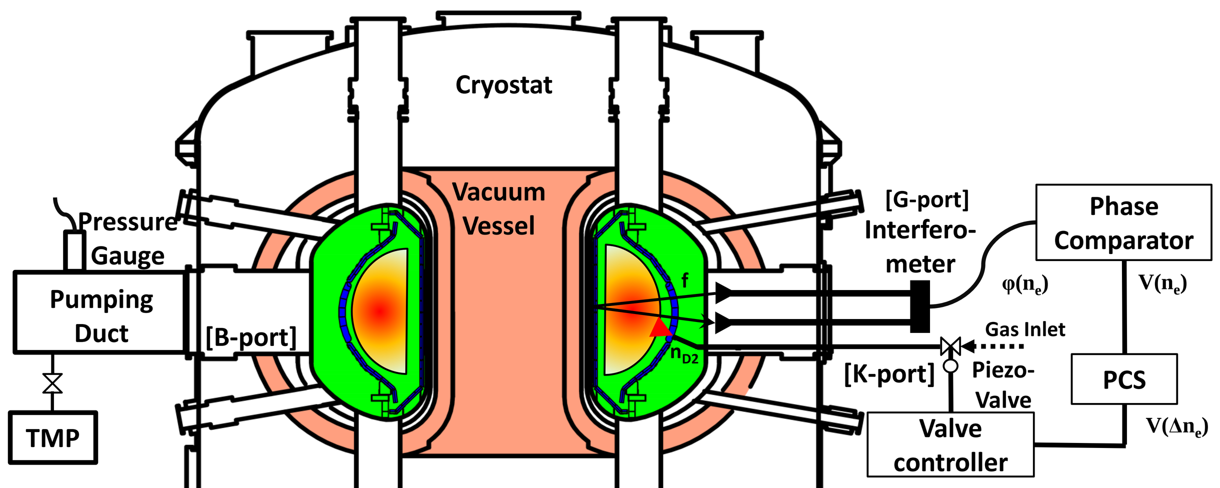


Disruption Mitigation Study with Massive Gas Injection (MGI)



2. Beginning with Gas Fueling Modulation to Use a Simplified Solitary Model of Particle Balance

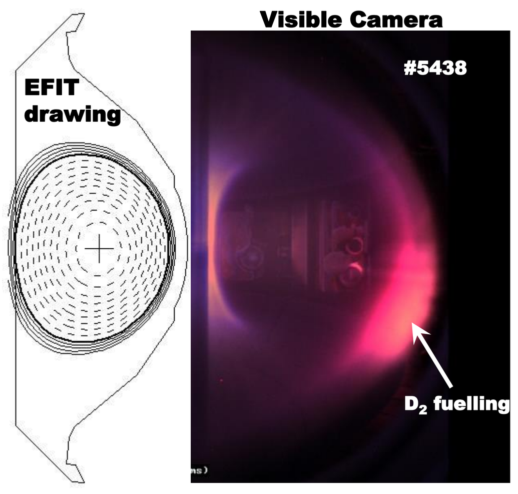
Initial Components of Density Feedback System in KSTAR

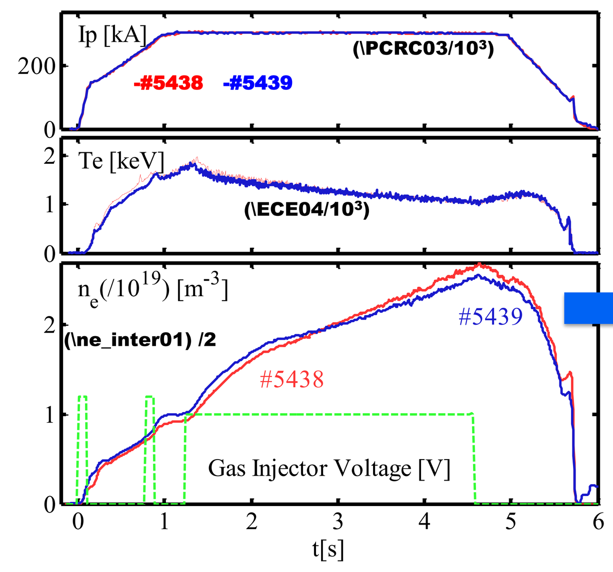


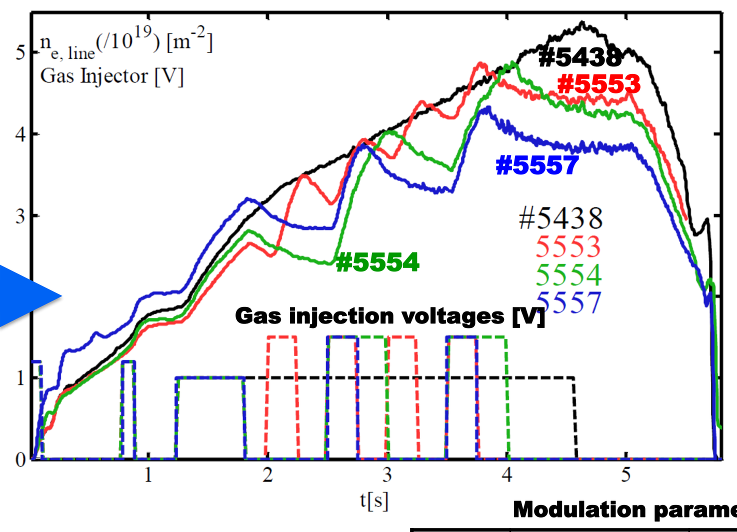
mmWave Interferometer	280GHz microwave	< ~5x10^{19} m^{-3}, 100kS/s
Piezoelectric valve (PV) & Valve control unit	General Atomics (GA) & NFRI(GA design)	463mbar l/s flow rate & ~2ms response time
Pumping duct & Turbo-molecular pump (TMP)	8.3m long, 1.38m wide & 8 x 2800 l/s OSAKA TG2810	~13.6m^3/s effective pumping speed
Pressure gauge	Cold cathode gauge Pfeiffer PKR251	10ms response time, 5x10^{-9} mbar

Basic Plasma Parameters

B_t	2.0T
I_p	300kA
R	1.5m
a	0.5m
κ	1.17
P_{aux}	0MW







Modulation parameters

#	period[s]	f [Hz]	duty
5438	.	.	.
5553	2~4	2	0.5
5554	2.5~4	1	0.5
5557	2.5~4	1	0.25

The Simplified Solitary Particle Balance Model

$$\frac{dN_i}{dt} = -\frac{N_i}{\tau_i} + R\frac{N_i}{\tau_i} + f_{ex}\Phi = -\frac{(1-R)}{\tau_i}N_i + f_{ex}\Phi$$

$$= -\frac{N_i}{\tau_i^*} + f_{ex}\Phi, \qquad \tau_i^* \equiv \frac{\tau_i}{1-R}$$

$$n_i(t') = Ce^{-t'/\tau_i^*} + \frac{\tau_i^* f_{ex}\Phi_{ex}}{V_p}$$

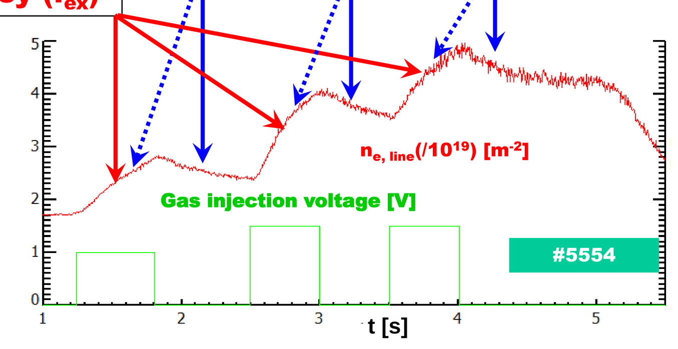
Contribution of Each Term on Density Modulations

Confinement time (τ_i)

Total recycling (R)

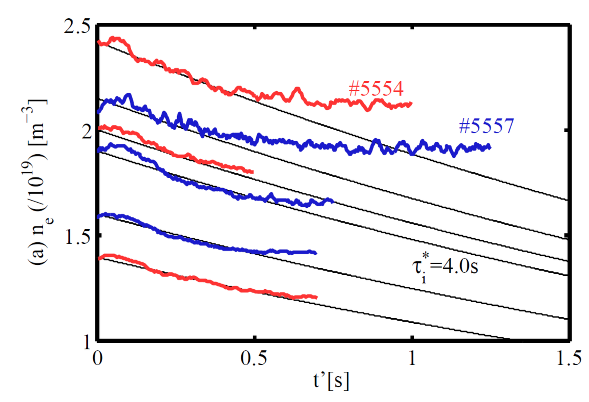
Effective confinement time (τ_i^*) = decay time or pump-out time

Fuelling efficiency (f_{ex})

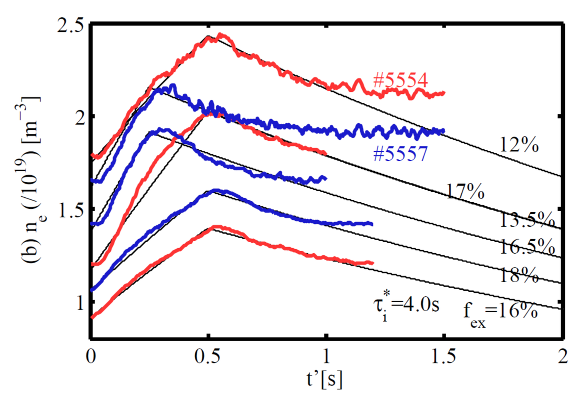


When Fuels are Turned OFF - τ_i^* is obtained

$$n_i(t') = Ce^{-t'/\tau_i^*}$$

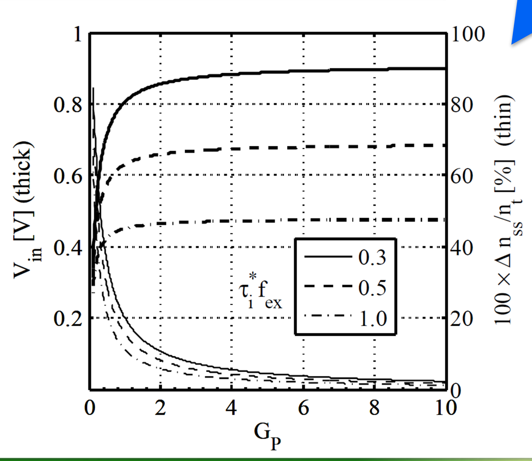


Once τ_i^* is obtained, f_{ex} obtained as below



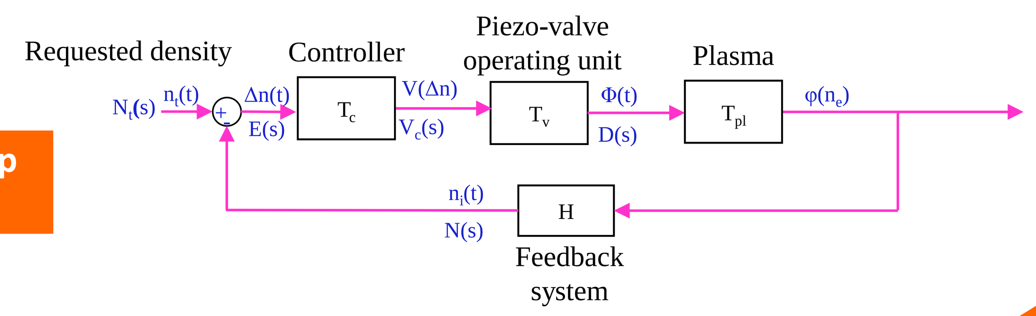
Steady-state Error Directly Calculated with the Model

$$\Delta n_{i,ss} = \frac{n_t V_p - \tau_i^* f_{ex} B}{2A/10^{19} G_P f_{ex}\tau_i^* + V_p}$$



3. Transfer Function for Density Feedback Control System

Closed-Loop Diagram



Transfer Functions

Plasma : $T_{pl} = \frac{f_{ex}}{V_p}\frac{\tau_i^*}{\tau_i^* s + 1}$

Valve operator : $T_v = A/(\tau_v s + 1)$

Controller : $T_c = 2[G_P + \frac{G_I}{s} + G_D s]/10^{19}$
$= 2G_P/10^{19}, \quad G_I = G_D = 0$

Feedback system : $H = 1$

Open-loop : $G_{FF} = T_c T_v T_{pl}$

Closed-loop :

$$G_{FB} = \frac{G_{FF}}{1 + G_{FF}H} = \frac{T_c T_v T_{pl}}{1 + T_c T_v T_{pl}} = \frac{2AG_P f_{ex}\tau_i^*/10^{19}}{V_p(\tau_v s + 1)(\tau_i^* s + 1) + 2AG_P f_{ex}\tau_i^*/10^{19}}$$

4. Analytic Approach to the Feedback System Performance

Natural Frequency

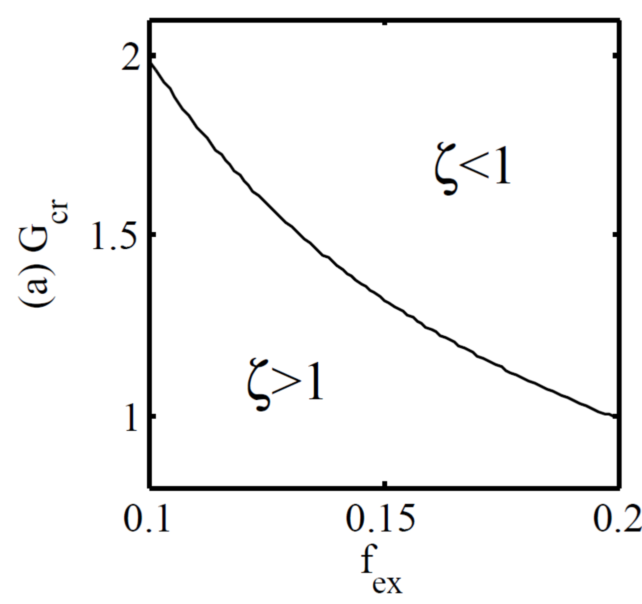
$$\omega_n = \sqrt{V_p + 2A10^{19}G_p f_{ex}\tau_i^*/(V_p\tau_v\tau_i^*)}$$

Damping Ratio

$$\zeta = \frac{(1/\tau_v + 1/\tau_i^*)}{2\omega_n}$$

Critical Gain

$$G_{cr} = \frac{\left(\frac{\tau_i^*}{\tau_v} + \frac{\tau_v}{\tau_i^*} - 2\right)V_p}{8Af_{ex}\tau_i^*/10^{19}}$$



Settlement Time (s)

$$t_s = -\frac{\log 0.05\sqrt{1-\zeta^2}}{\zeta\omega_n} = -2\tau_v \log\left\{0.05\sqrt{1 - \frac{V_p 10^{19}}{8AG_p f_{ex}\tau_v}}\right\}$$

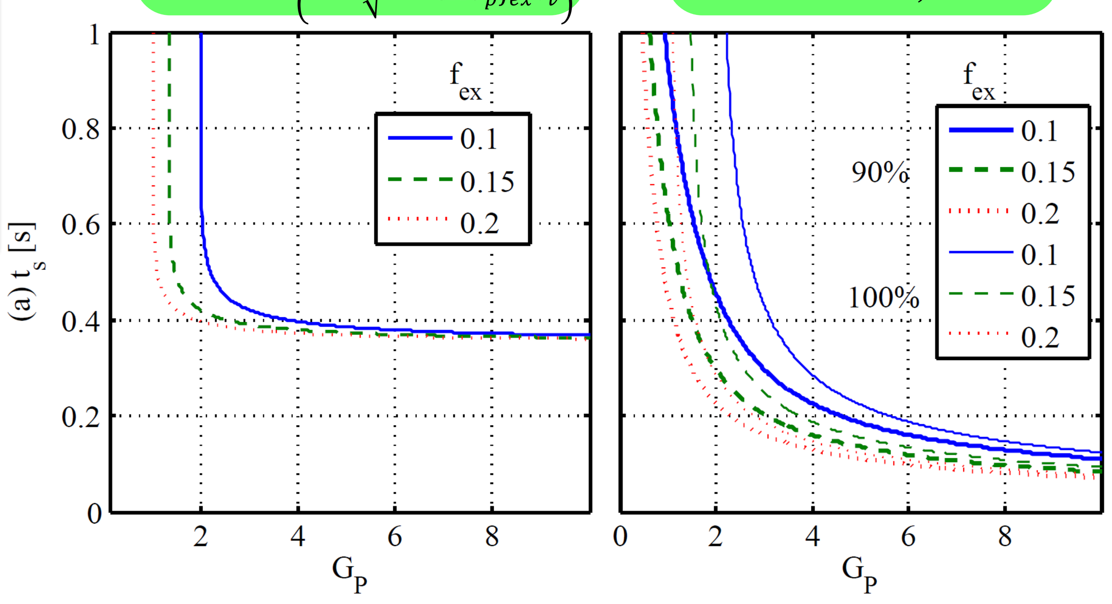
Rising Time (s)

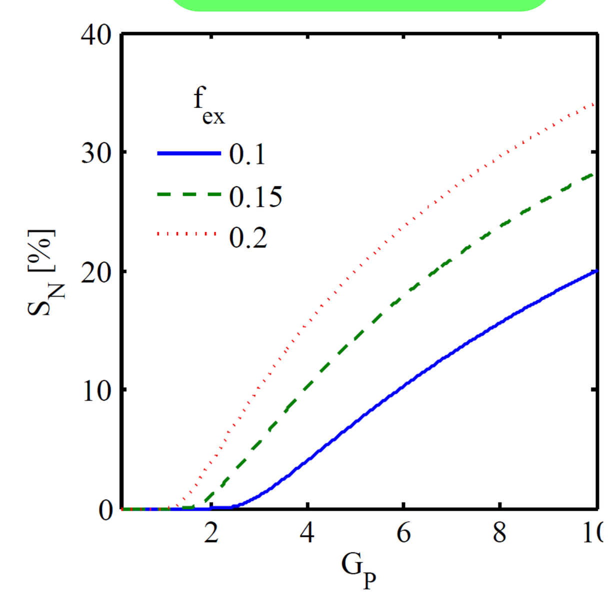
$$t_r = \pi - \alpha/(\omega_n\sqrt{1-\zeta^2})$$

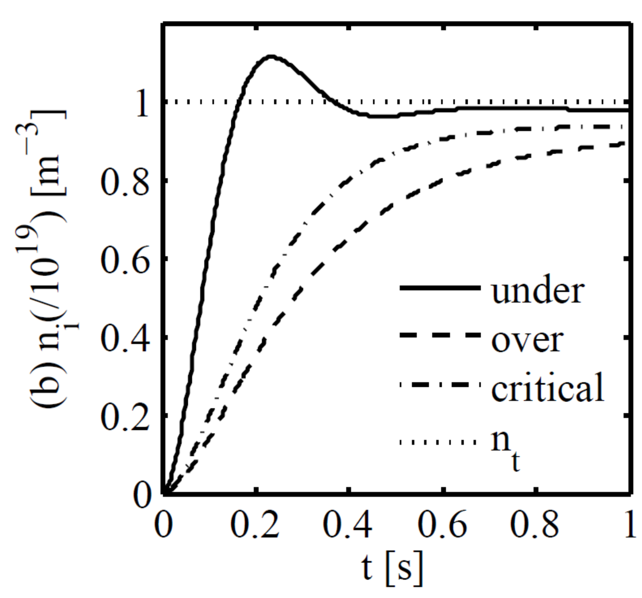
$$\alpha \equiv \tan^{-1}\left\{\frac{\sqrt{1-\zeta^2}}{\zeta}\right\}$$

Overshoot Ratio (%)

$$S_N = 100\, e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} = 100\, e^{-\pi\left(\frac{AG_p f_{ex}\tau_v}{V_p 10^{19}} - \frac{1}{8}\right)^{-1/2}}$$







5. The First Density Feedback Control Experiment

Rule of Thumb for the First Shot Attempt

✓ Use low target and gain especially in the beginning of the feedback
- Not to overshoot too much (avoiding radiative cooling and Greenwald density limit)

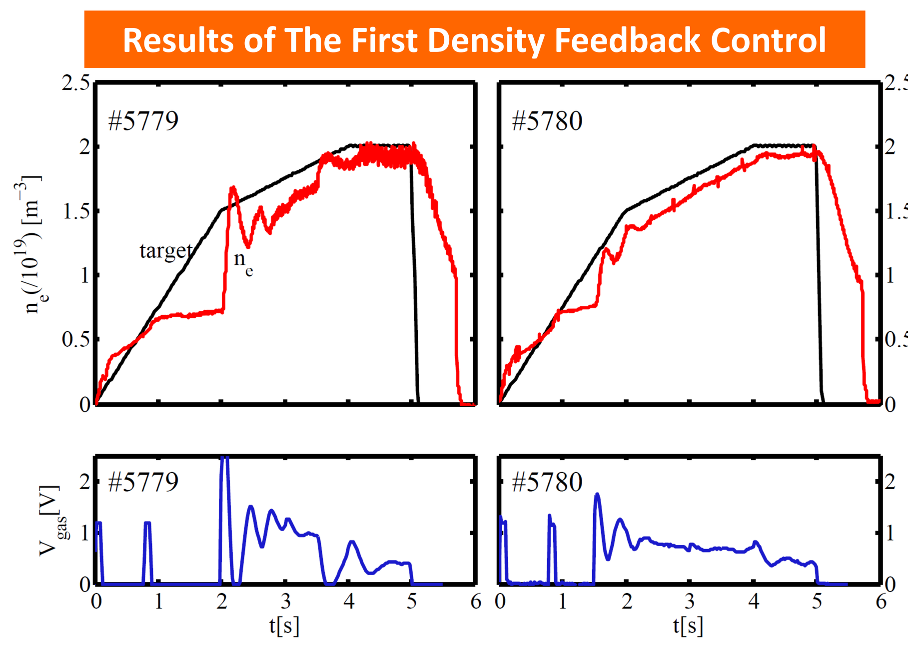
✓ Avoid to use integral gain
- For simple and intuitive design and result
- Instead, manually increase gain to reduce steady-state error

✓ No use of derivative gain
- Unexpected signal noise may amplify the signal

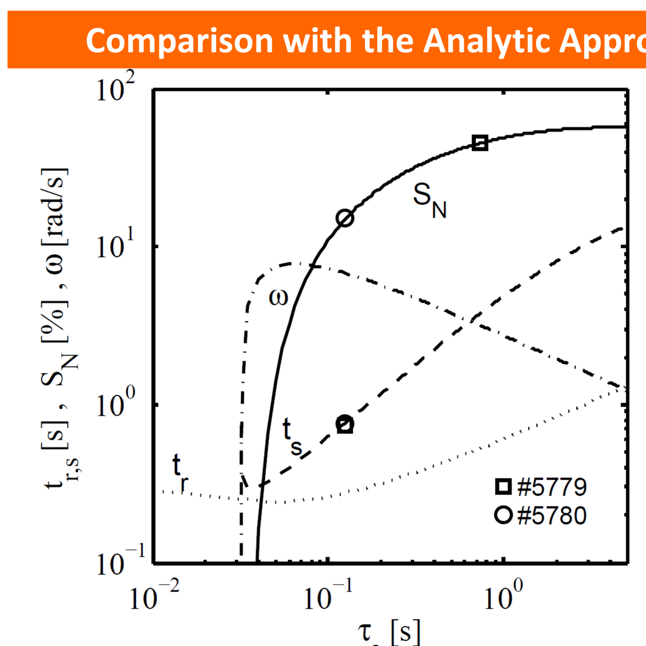
Gain and Target Setting

Gain (G_P)	Period [s]	$n_t(/10^{19})[m^{-3}]$	Period [s]
2.5	1.5-3.0	0-1.5	0.0-2.0
3.0	3.0-4.0	1.5-2.0	2.0-4.0
3.5	4.0-5.0	2.0	4.0-5.0

Results of The First Density Feedback Control



Comparison with the Analytic Approach



6. Summary and Future Work

✓ A safety-oriented density feedback experiment was fulfilled in the early phase of the KSTAR experiment
- One of the most reproducible discharge was chosen as a test-bed – circular ohmic limited plasma in 2.0 T, 0.3 MA
- Low-Ip leads to low Greenwald density limit ~4.7 x 10^{19} m^{-3}
- Because this was the first trial, no classical tuning such as Ziegler-Nichols tuning was allowed due to unstable regime approach.

✓ Before the feedback control, several preprogrammed fueling modulation experiment was carried out
- to obtain essential parameters of the simple global particle balance model

- By using the parameters, the transfer function of the feedback control system was defined.
  - from the transfer function, the expected performance of the feedback control system was calculated
  - Critical gain, overshoot ratio, settlement time and rising time

- Based on the performance indicator, only proportional gain was applied for the plasma experiment.
  - with increasing target
  - The result was successful with the expected steady-state error due to the absence of integral gain

✓ Using integral gain to suppress the steady-state error will be studied and fulfilled.

✓ Densities in higher-performance plasmas will be controlled such as diverted plasmas and H-mode plasmas