NSTX

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Conceptual design of density feedback control system of NSTX via FIReTIP

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Nov. 8th, 2011

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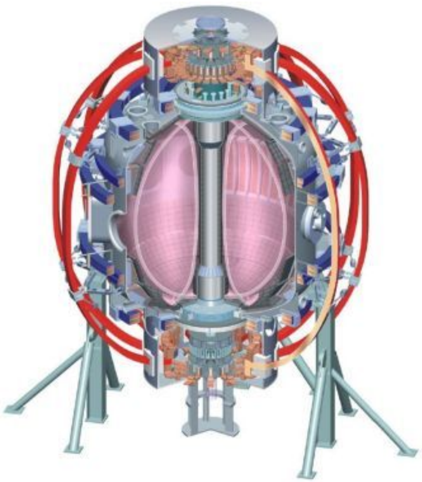

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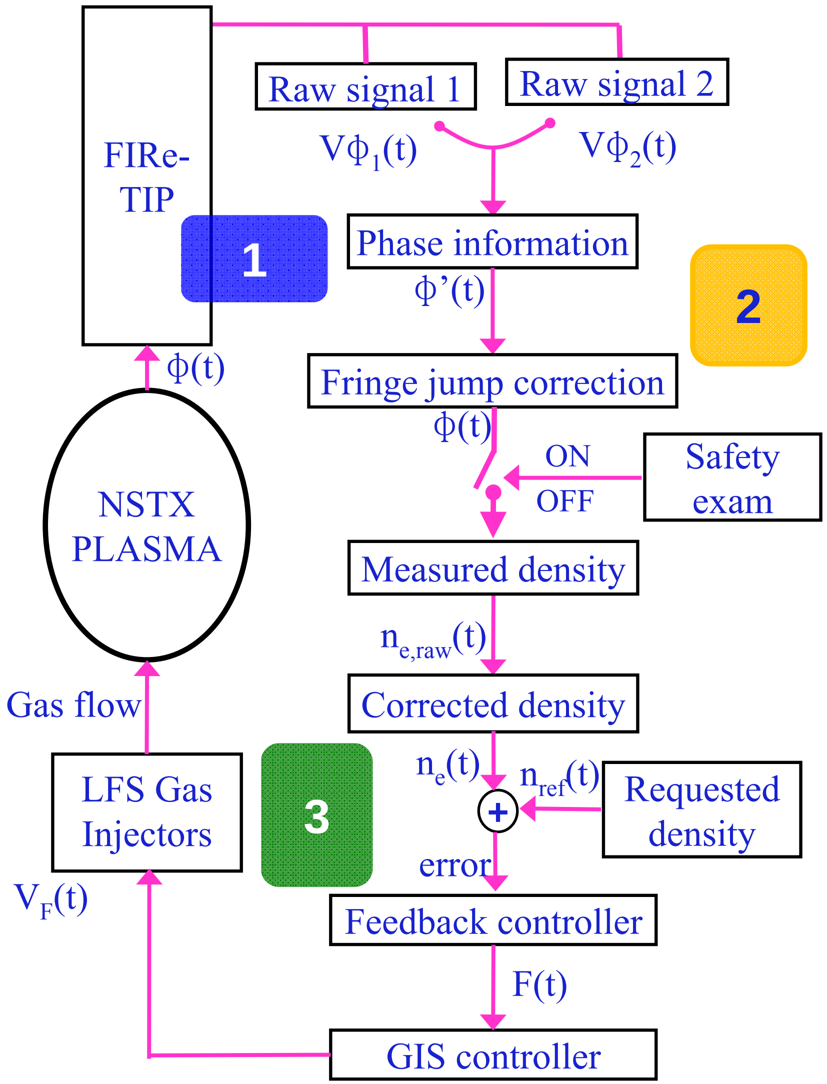
Density model is desired for reliable design and operation of feedback control

Flow diagram for density feedback control stystem



1

FIReTIP (NSTX tangential interferometer)

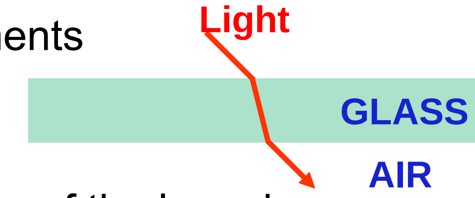
2

Fringe jump correction of the FIReTIP data

3

0-D modeling to design feedback controller

Far Infrared Tangential Interferometer/Polarimeter (FIReTIP) is a powerful diagnostic for many applications.



- Interferometer is the one of the refractive index measurements specialized to plasma density.

- A line-integrated density is obtained from phase information of the laser beam.

$$\phi = \frac{\lambda e^2}{4\pi c^2 \varepsilon_0 m_e} \int_{l_1}^{l_2} n_e \mathrm{d}l \quad = 2.82 \times 10^{-15} \lambda \int_{l_1}^{l_2} n_e \mathrm{d}l$$

- Methyl alcohol (CH_3OH) laser that emits 118.8μm far infrared (= 2.52 THz) beam which is favorite for interferometers in most mid-size tokamaks.

$$mechanical\ \ vibration\,(\propto 1/\lambda)\ <\ \ (\lambda,\ 1/\ f\,)\ <\ \ beam - path\ refraction\,(\propto \lambda, \nabla n)$$

- Simultaneous operation of interferometer and polarimeter is possible in FIReTIP.

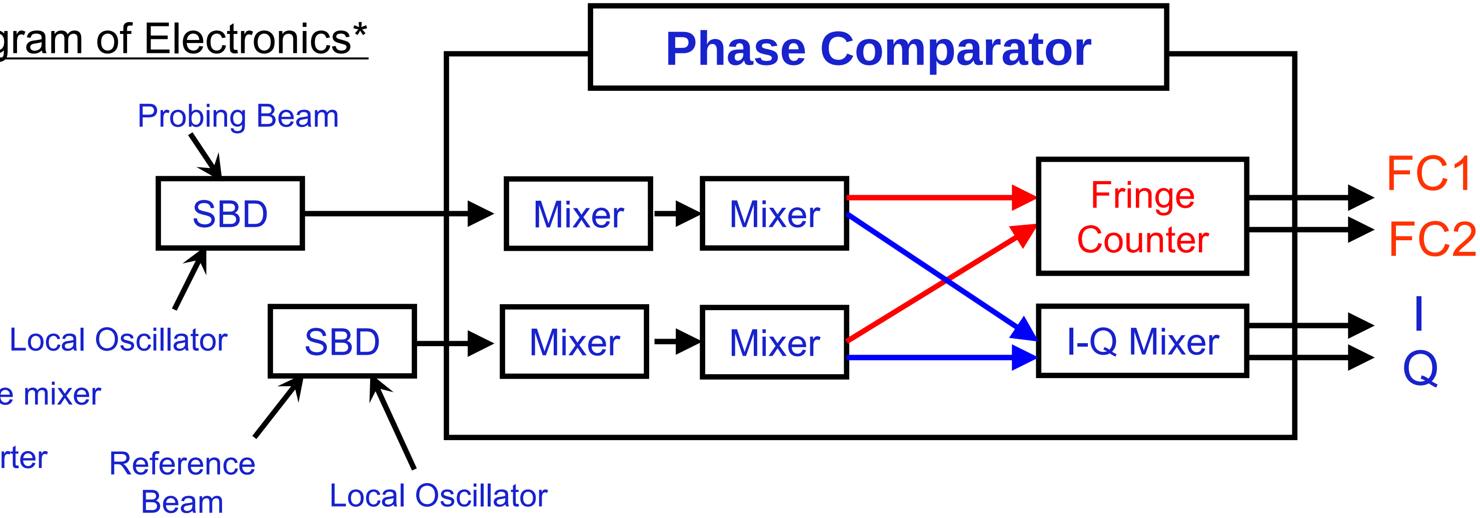
- Frequency shift from Stark-effect enables high intermediate frequency (IF) as about 5MHz which is larger than twice that of common Methyl alcohol lasers.

- High bandwidth of signal up to 4MHz is possible because of high IF and improved electronics.

Electronics in FIReTIP has been recently upgraded leading to better performance especially for fast bandwidth.

Simple block diagram of Electronics*

*W-C Tsai, UC Davis



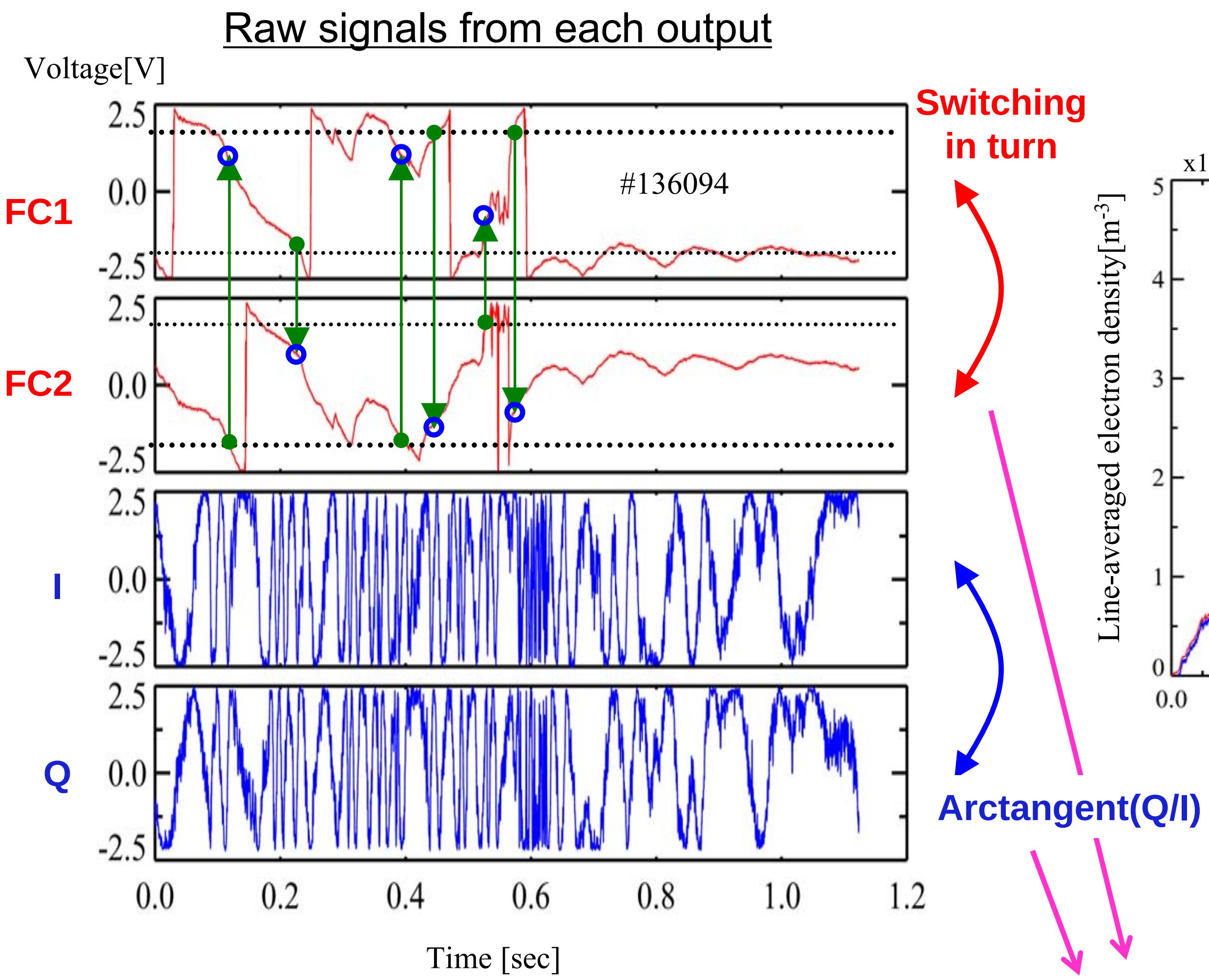
SBD : Schottky barrier diode mixer

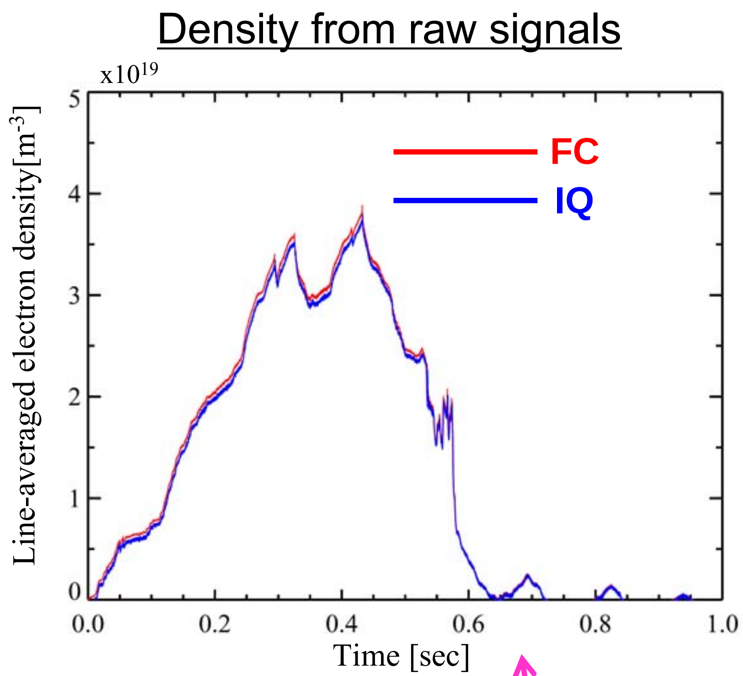
Mixer : Frequency Up-converter

Basic information about the FIReTIP output signals

Index	FC1	FC2	I	Q
Signal ~	Φ	Φ (±2.5V)	cos(Φ)	sin(Φ)
Bandwidth	1MHz		4MHz	
Sampling rate	1Ms/s		12Ms/s	
Range	-2.5 ~ 2.5V			
Fringe Information	8 x 2π		2π	
Remarks	Switching each other not to be limited in 5V		Arctangent to obtain Φ	

Both density-converted signals from the fringe counter and the I-Q mixer are in good agreement with their own features.



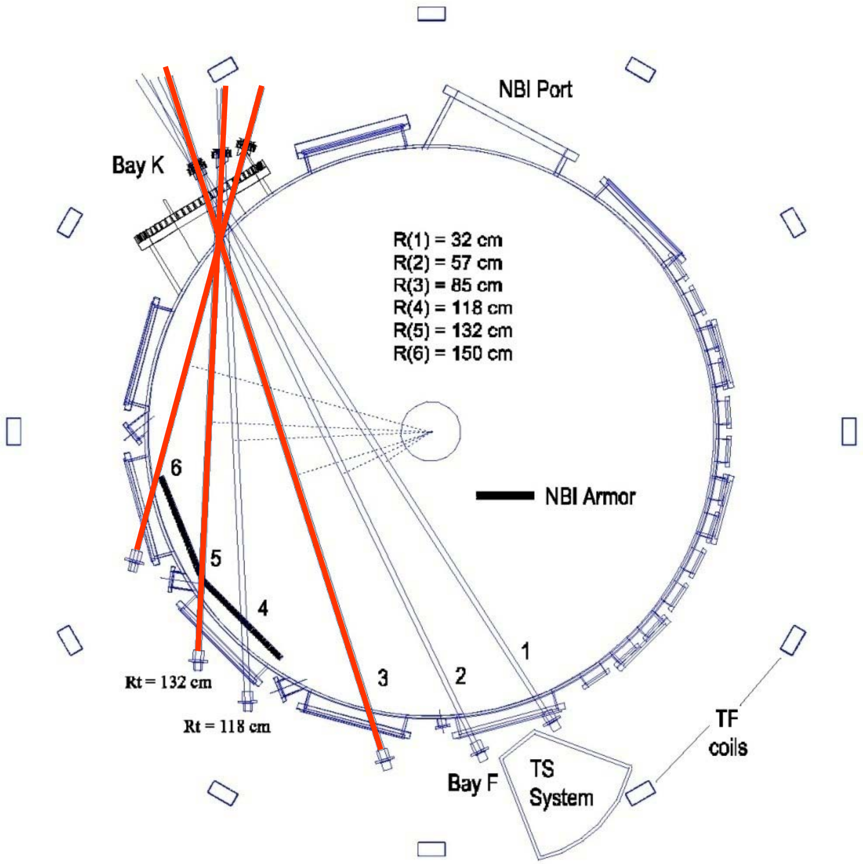


$$\phi = 2.82\times10^{-15}\lambda\int_{l_1}^{l_2} n_e \mathrm{d}l$$

Phase difference ϕ

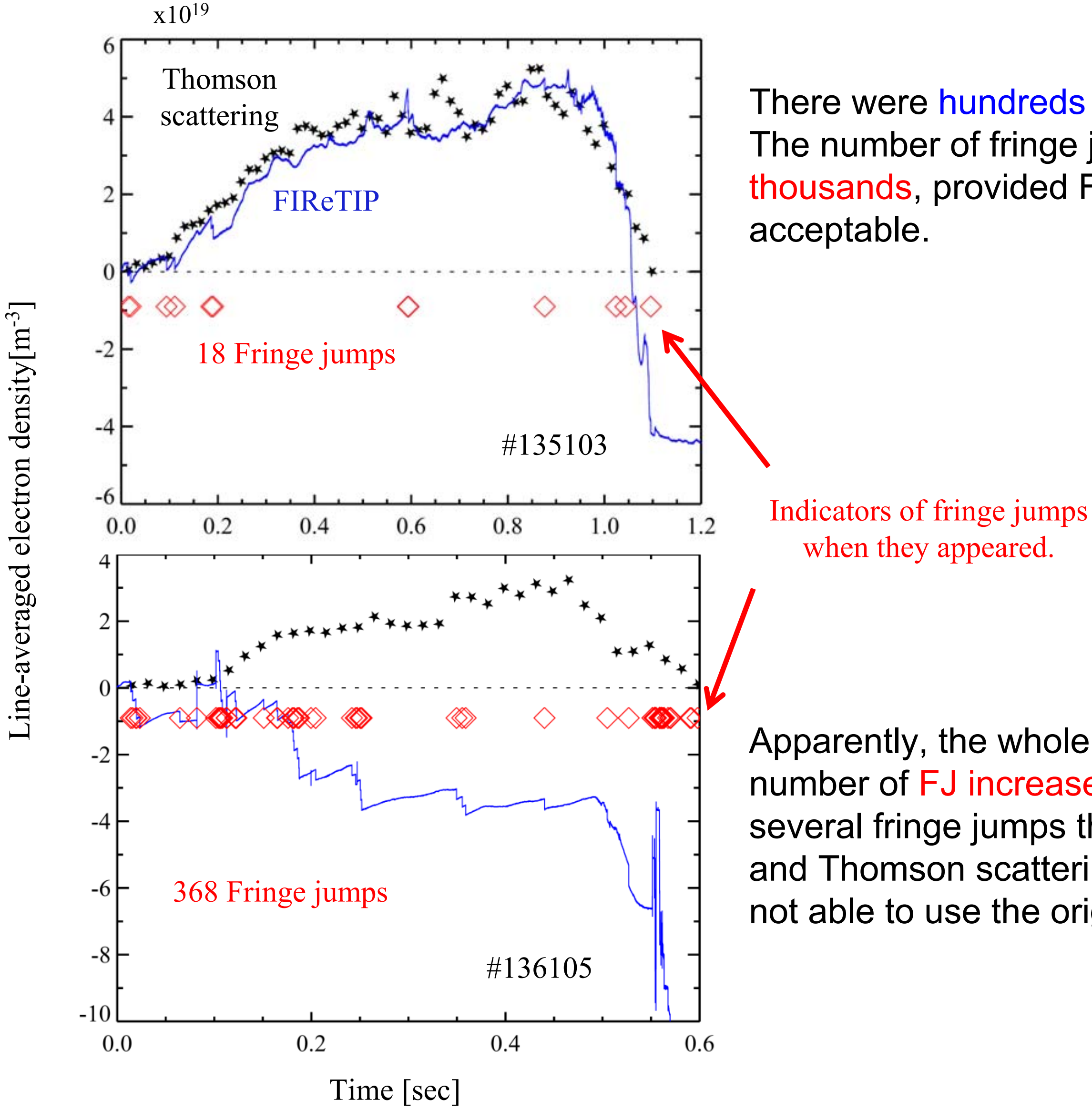
Line-integrated density up to 3 channels in mid-plane is currently being measured.

Layout of the FIReTIP beam channels.



#	Tangency Radius [cm]	One-way Path length [m]	Tag names on MDS Tree (TREE name = 'microwave')	
1	**32**	**3.07**	**FC**	**\den_firetipc1**
			IQ	**\den_fast_firetipc1**
2	57	2.93	FC	\den_firetip
			IQ	\den_fast_firetipc2
3	**85**	**2.64**	**FC**	**\den_firetipc3**
			IQ	**\den_fast_firetipc3**
4	118	2.64	FC	\den_firetipc4
			IQ	\den_fast_firetipc4
5	**132**	**1.7**	**FC**	**\den_firetipc5**
			IQ	**\den_fast_firetipc5**
6	**150**	**0.92**	**FC**	**\den_firetipc7**
			IQ	**\den_fast_firetipc7**

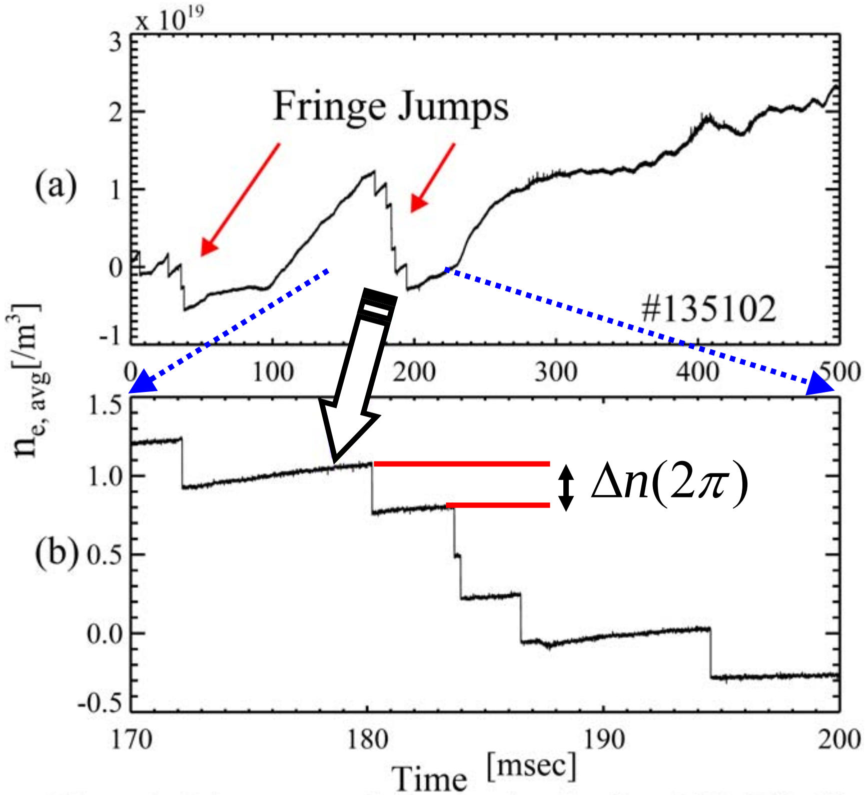
Fringe Jump (FJ) Errors has been serious problems in FIReTIP likely to most interferometers.



There were hundreds of discharges suffering from fringe jumps. The number of fringe jumps in those discharges are from zero to thousands, provided FIReTIP system including laser power is acceptable.

Apparently, the whole waveform seems to be more absurd as the number of FJ increases. Even in some discharges with only several fringe jumps the difference between data from FIReTIP and Thomson scattering diagnostics is quite distinct so we are not able to use the original data.

Fringe Jump Errors in FIReTIP has typical characteristics.



They take place in a few **microseconds** usually, and up to a couple of tens microseconds.

Most of them have typical jumps with variation of **one-fringe** equivalent voltage or density.

$$\Delta n_{e,\,avg} = \frac{4\pi c^2 \varepsilon_0 m_e}{\lambda e^2 L} \Delta\phi \leftarrow \begin{array}{l} \Delta\phi = 2\pi \\ L = 6.18\,[m] \end{array}$$

For Channel 1

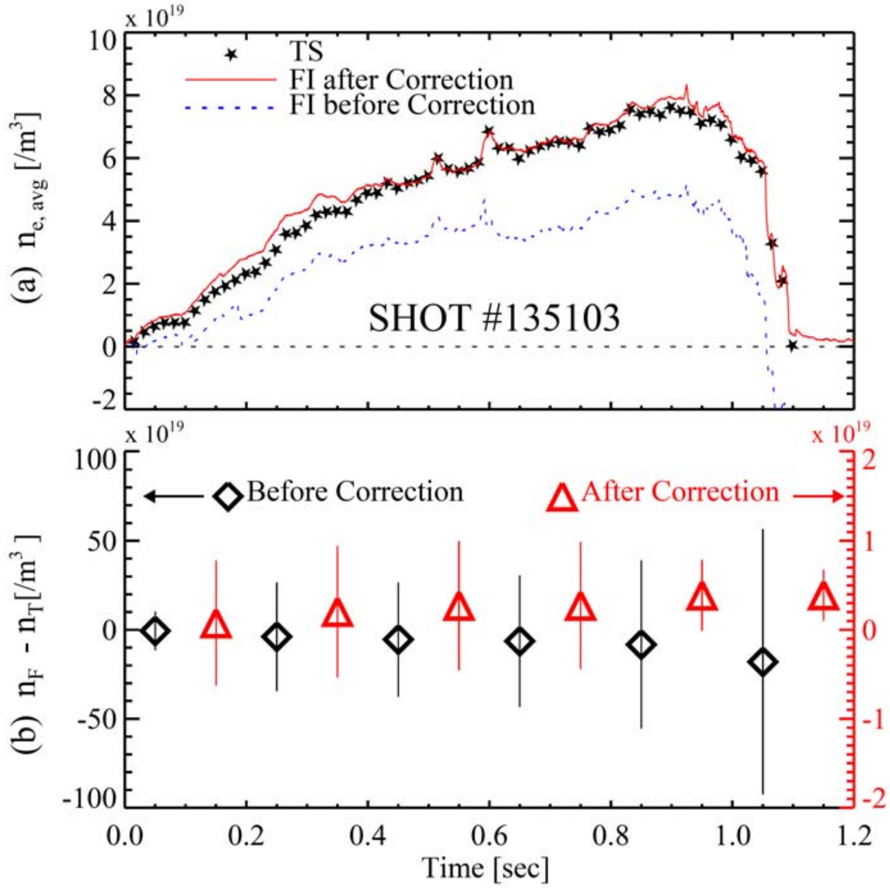
$$\approx 3.03 \times 10^{18}\ [/m^3]$$

$$\frac{\Delta n_{e,\,avg}}{\Delta t} \approx \frac{3\times 10^{18}\ [m^{-3}]}{10\ [\mu \sec]} = \frac{3\times 10^{22}\ [m^{-3}]}{100\ [m \sec]}$$

Obviously not a plasma activity

Fringe Jump Errors were suppressed by post-processing of stored data.

Fringe jump corrected data compared with those of Thomson scattering diagnostics



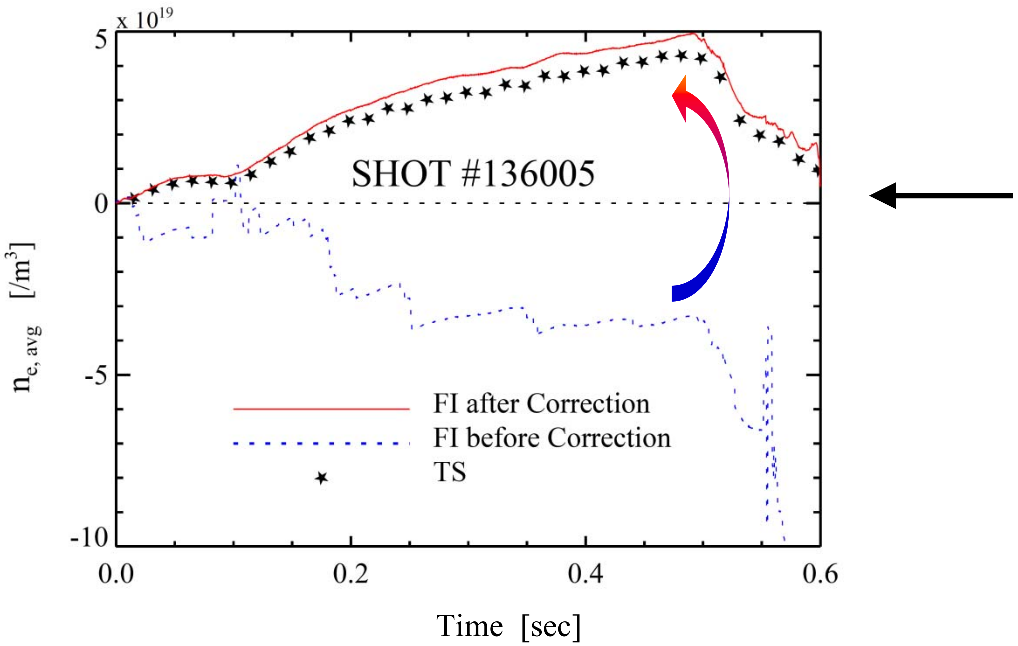
By applying the algorithm, corrected FIReTIP data is compared with Thomson Scattering data which is reproduced along the beam path of FIReTIP CH.#1.

(a) An example of full waveforms of each case: The corrected data show very good agreement with those of Thomson scattering

(b) Averages and deviations of the discrepancies from most shots after July 2009: They are distinctively reduced after correction .

This algorithm works even in cases of up to a few hundreds of fringe jumps event.

<u>Fringe jump corrected data compared with those of Thomson scattering diagnostic : FI means FIReTIP data, TS Thomson scattering diagnostic data respectively.</u>



368 Fringe jumps were reported and suppressed.

Even in this case of huge errors, corrected data has quite reasonable value compared with data without correction in dashed blue line. The correction algorithm has high opportunity to make the data reliable in most situations.

This algorithm has been routinely working since FY2010 and it is archiving the corrected FIReTIP data automatically in most cases without distinct problems.

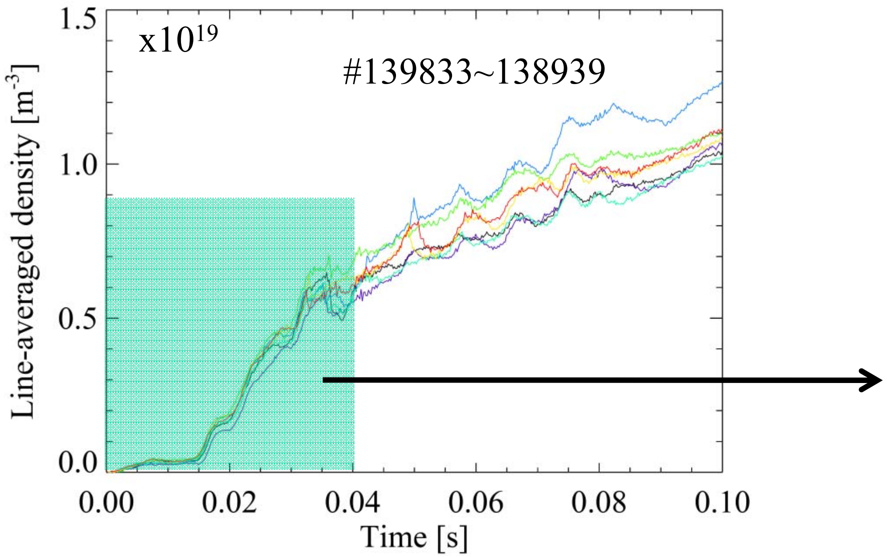
FIReTIP data is being archived though PCS digitizer for real-time density control.

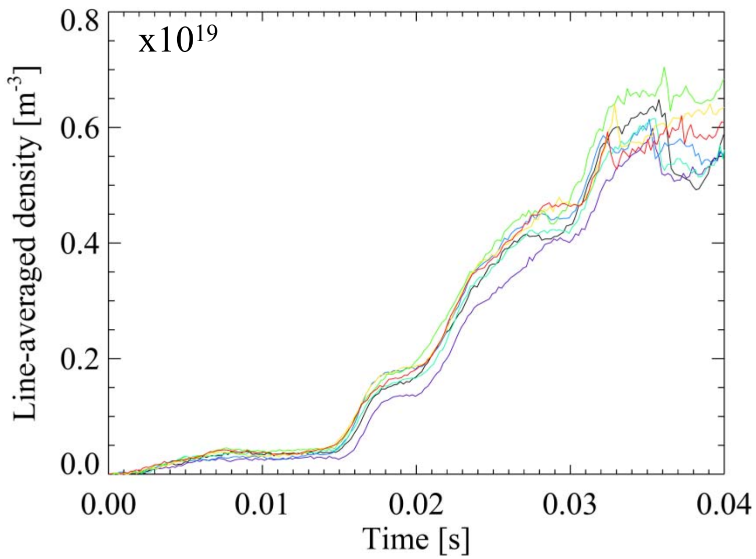
#	Tangency Radius [cm]	One-way Path length [m]	Tag name on MDS Tree (TREE name = 'microwave')	
n (~ CH3)	85	2.64	FC	\n

CH.3 Fringe counter (FC) data is being used after the fringe jump error correction and this works good as compared with the original signals.

5kHz digitizer is fast enough to control gas injection valves which operate at least in every 2ms.

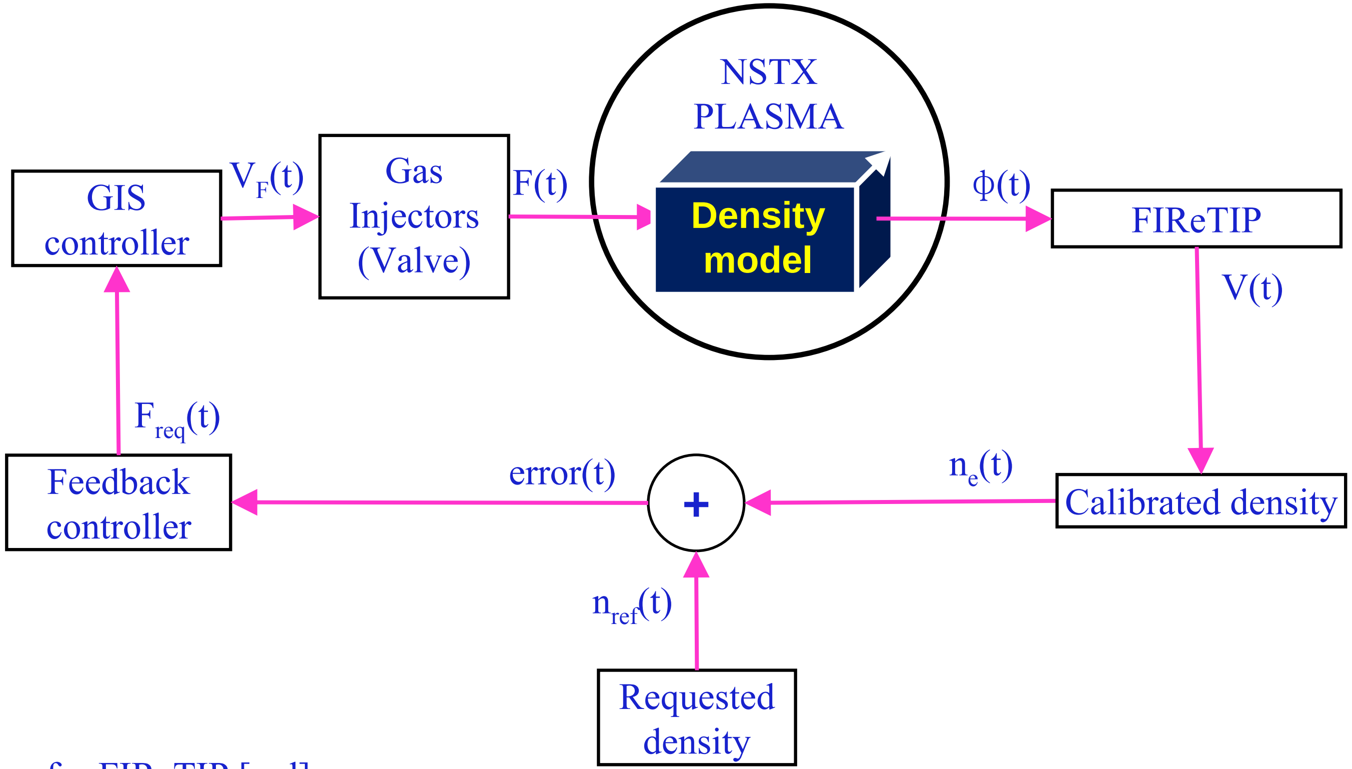
PCS algorithm for density control has to be prepared.





Density model is desired for reliable design and operation of feedback control system

3



ϕ : phase information for FIReTIP [rad]
V : phase-corresponding analog voltage output [V]
n_e : Calibrated density from FIReTIP output [m^{-3}]
n_{ref} : Requested density at certain time t [m^{-3}]
error(t) : $n_{ref}(t) - n_e(t)$ [m^{-3}]
F_{req} : requested flow rate according to the error
V_F : voltage input to gas injector valve for requested flow rate
F : Gas flow input [s^{-1}]

0-D global rate equations : Fielding's model

Fielding(1978)

Ion : N_i $$\frac{dN_i}{dt} = -\frac{N_i}{\tau_i} + \xi N_s N_i S$$

Wall Neutral : N_W $$\frac{dN_w}{dt} = -\phi \frac{N_i}{\tau_i}\frac{\sigma}{A}N_w - \frac{N_f}{\tau_f}\frac{\sigma}{A}N_w + f\phi\frac{N_i}{\tau_i}(1-\beta) + f\frac{N_f}{\tau_f}(1-\beta)$$

Fast Neutral : N_f $$\frac{dN_f}{dt} = -N_f N_i S - \frac{N_f}{\tau_f}(1-\beta) + N_s N_i X + \phi\beta\frac{N_i}{\tau_i}$$

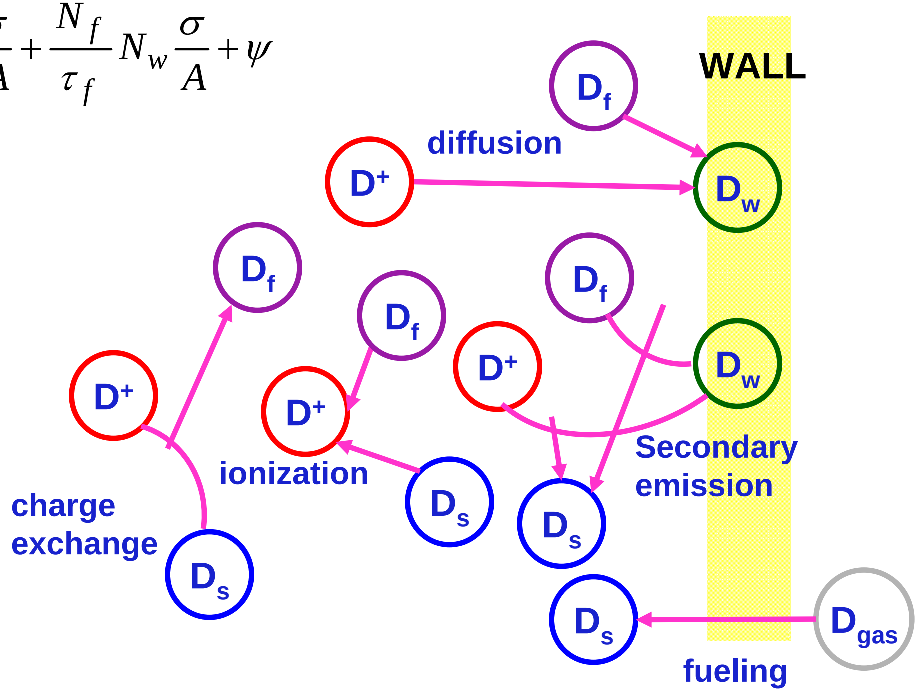
Slow Neutral : N_s $$\frac{dN_s}{dt} = -N_s N_i S - N_s N_i X + \phi\frac{N_i}{\tau_i}N_w\frac{\sigma}{A} + \frac{N_f}{\tau_f}N_w\frac{\sigma}{A} + \psi$$

A : plasma-wall interaction area
f : wall-area fraction without gettering
ξ : ionizing fraction in SOL
ϕ : escaping-ion fraction across SOL
τ_i : ion confinement time
τ_f : fast neutral confinement time

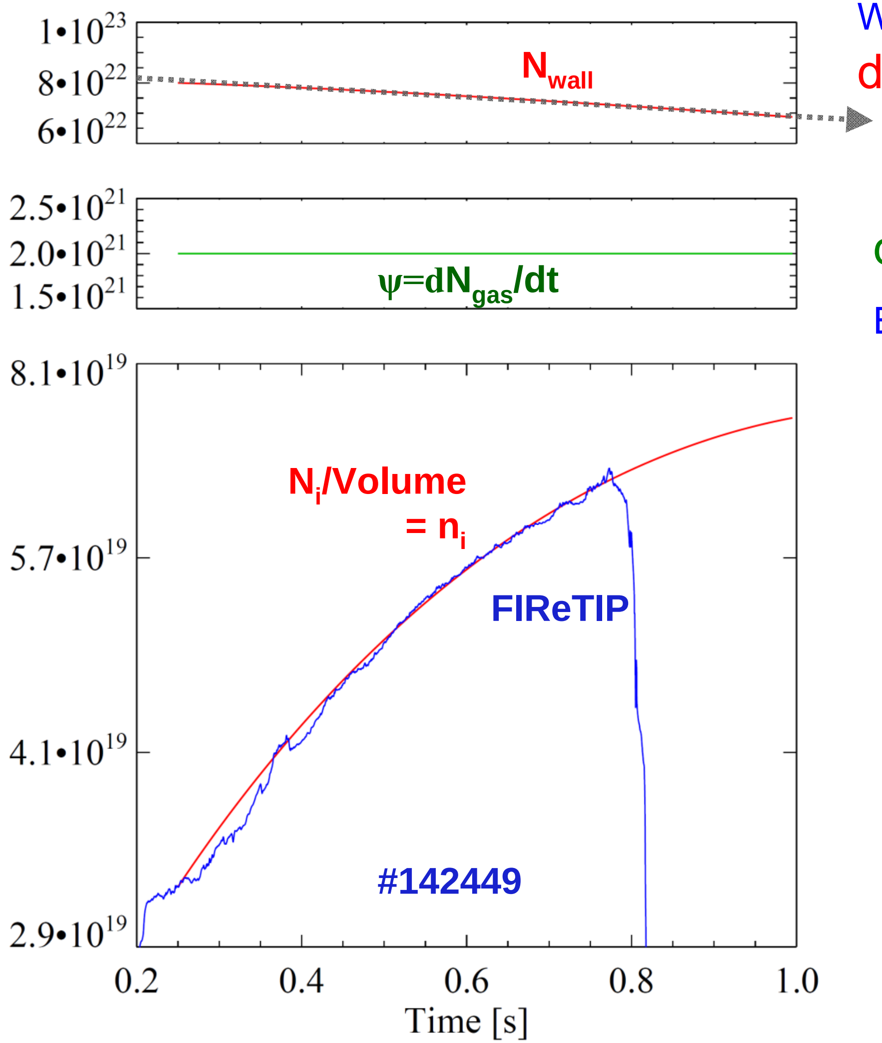
β : reflection coefficient on the wall
σ : cross-section for secondary emission on the wall
S : ionization rate coefficient
X : charge-exchange rate coefficient

Ψ : external gas input [s^{-1}]

Schematic diagram



The global density shows good agreement with FIReTIP measurement with monotonic density increase.



Wall outgassing

$dN_{wall}/dt \approx -2.3\times10^{22}$ (equiv. ~350Torr·liter/s)

x100

$dN_{gas}/dt \approx 2\times10^{21}$ (equiv. ~30Torr·liter/s)

External gas injection

Enormous WALL OUT-GASSING!!

$N_{wall,0} \approx 8\times10^{22}$: initial wall inventory

T_i = 0.8keV ion temperature

τ_f = 7.7μs : fast neutral confinement time $\tau_f \approx \frac{a}{v_f} = a\sqrt{\frac{2T_i}{m_i}}$

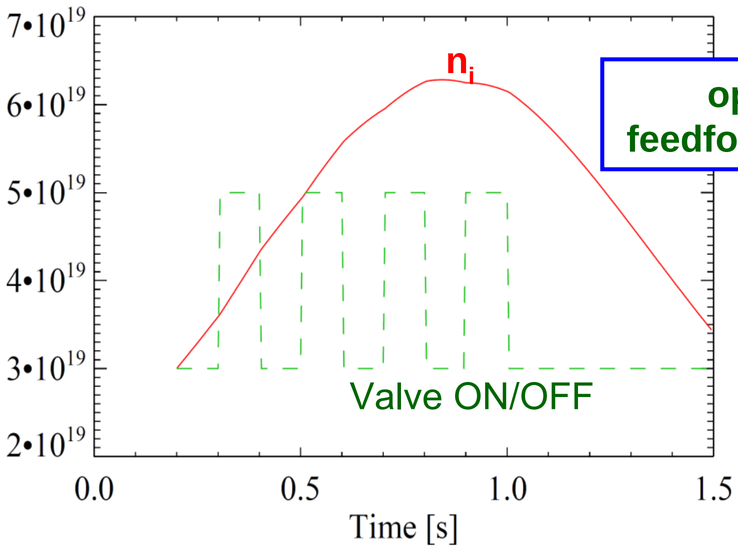
$\chi_i \approx 4$ m²/s : ion thermal diffusivity

$\tau_i \approx$ 100ms : ion confinement time $\tau_i \approx \frac{a^2}{\chi_i}$

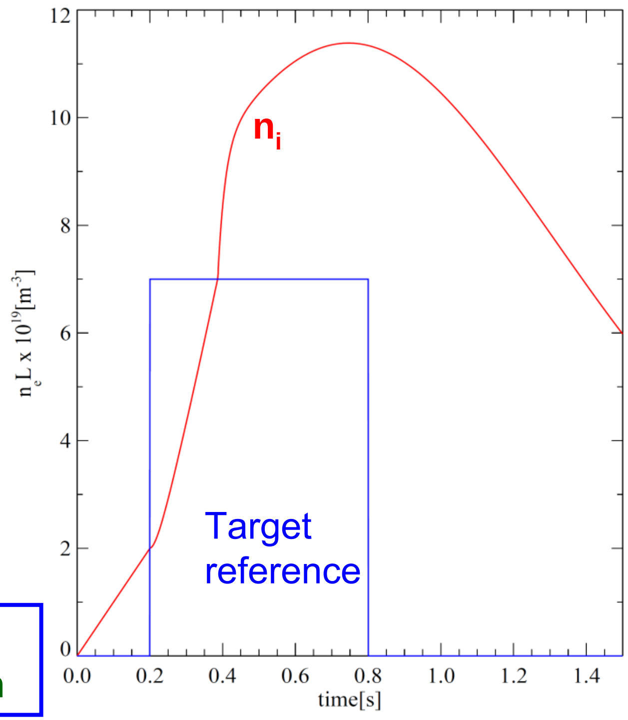
$\tau_i \approx$ 150ms : more practical

A [m²]≈ 20 : Plasma-wall interaction

The plasmas in this status are not controllable because of high wall outgassing.



open- loop feedforward system

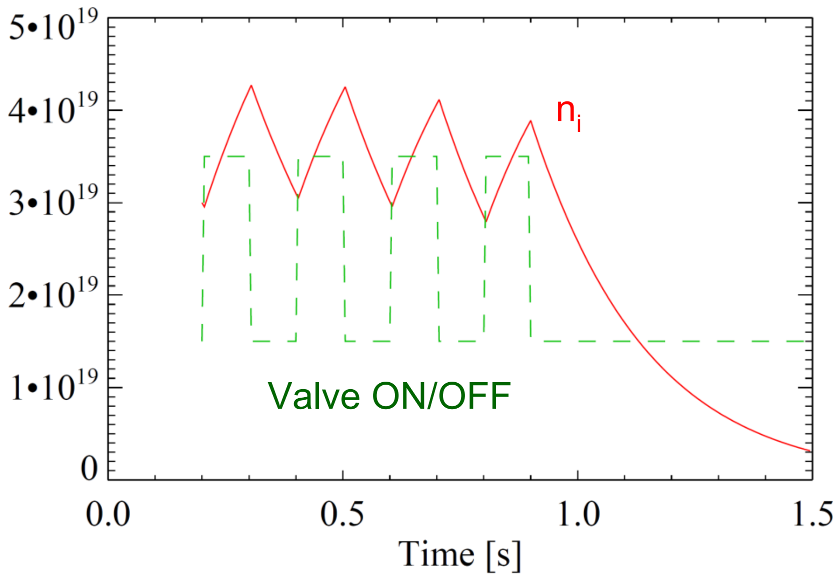


closed- loop feedback sytem

$N_{wall,0} \approx$ 8e22 : initial wall inventory

Same parameters used for measured density data are applied and do fail in feedback calculation as well as in the pre-programmed one.

Modification of wall inventory is required to control plasma by active gas injection.



$\tau_i \approx \frac{a^2}{\chi_i}$

χ_i ≈ 4 m²/s : ion thermal diffusivity

τ_i ≈ 100ms : ion confinement time

8.5e22

$N_{wall,0}$ ≈ 5.0e22 : ion confinement time

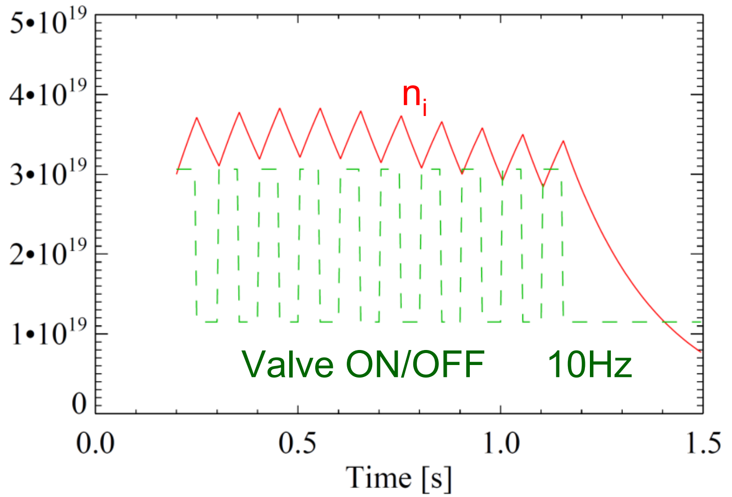
Gas flow rate ≈ 1.0e22 : ~150Torr·liter/s

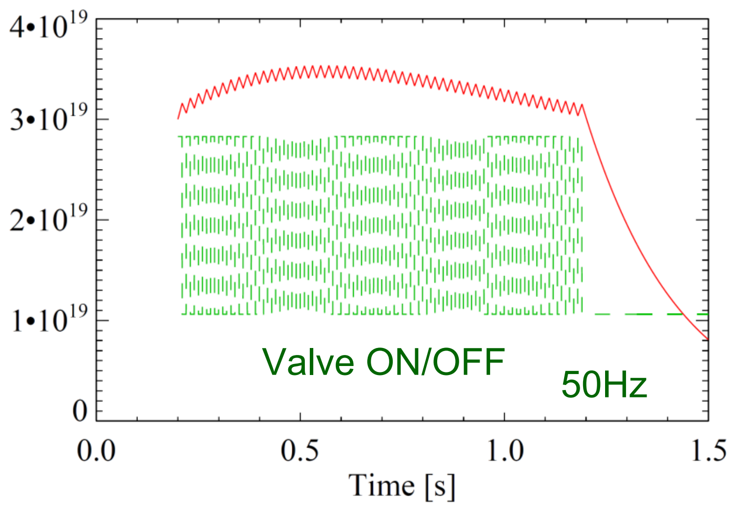
300 significant reduction

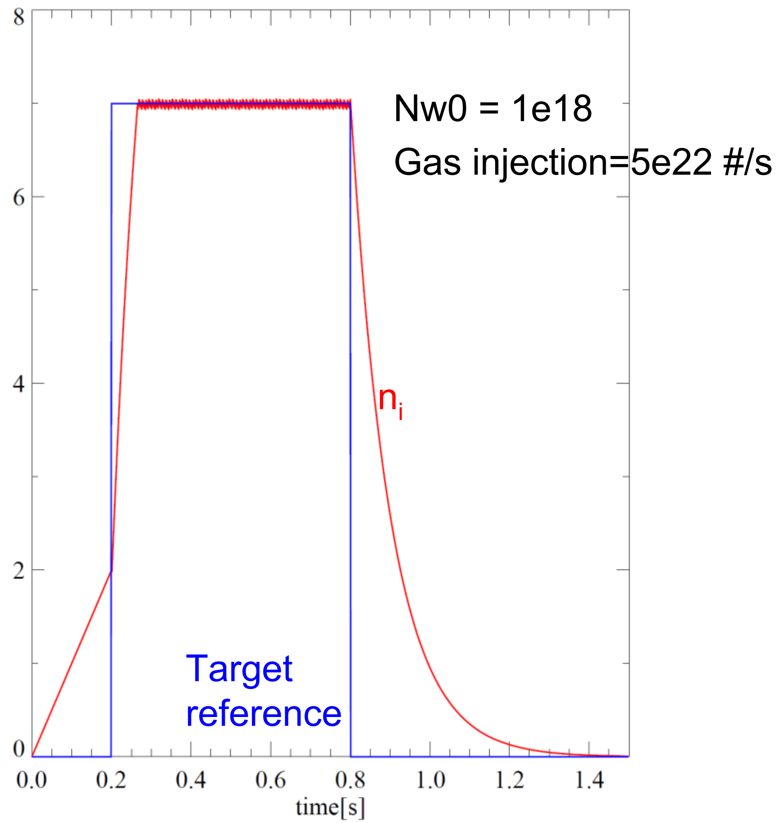
N_{wall} /dt ≈ -6.4x10^{21} (equiv. ~90Torr·liter/s)

Reduced initial wall inventory and enhancement of gas flow rate lead to success in feed-forward simulation. About 2/3 of initial wall inventory results in 1/3 outgassing from the previous calculation because of the non-linear model.

In this simple model, plasmas react rapidly upon the valve signals so that it can not be considered as realistic behaviors.



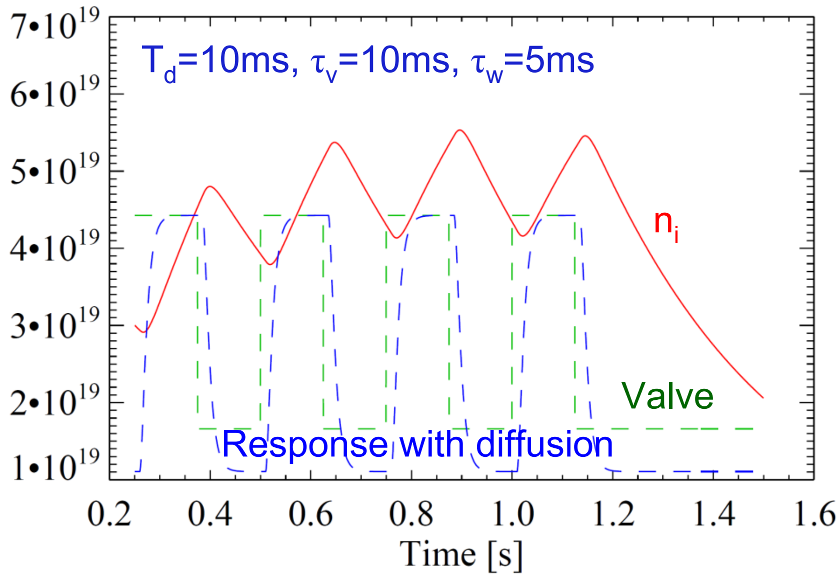




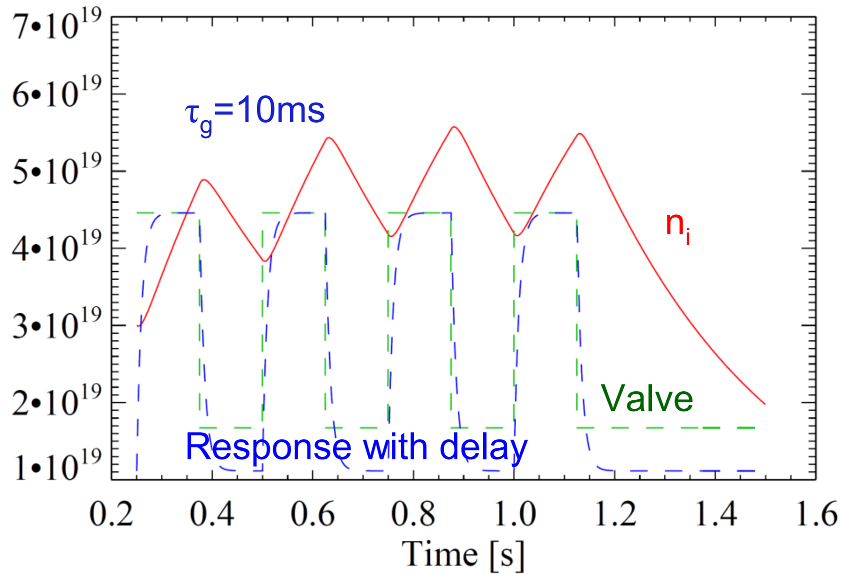
Simulations both of feed-forward up to 50Hz valve modulation and feedback give good results. These successive results, however, does not reflect the practical experiments.

2 Different approaches for diffusion or delay effects on gas fueling were tried.

Wong(1992)



Maddison(2006)



$\Psi_{diff}(t)$: Fueling rate [#/s]

$$\Psi_{diff}(t) = \Psi(t) * y(t) \quad \text{(Convolution)}$$

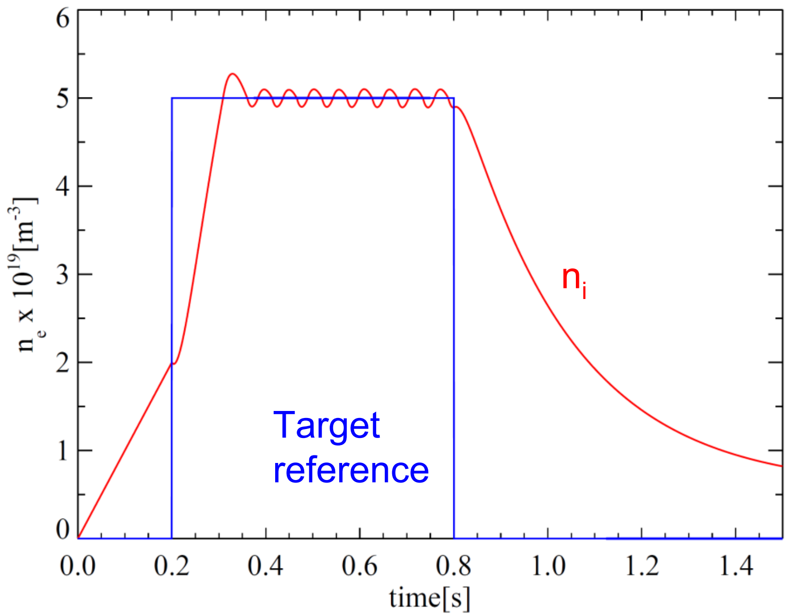
$$= \Psi(t) \times \int_{T_d}^{t} \frac{\exp(-\left|t'-T_d\right|/\tau_v) - \exp(-\left|t'-T_d\right|/\tau_w)}{\tau_v - \tau_w} dt' \quad : t > T_d$$

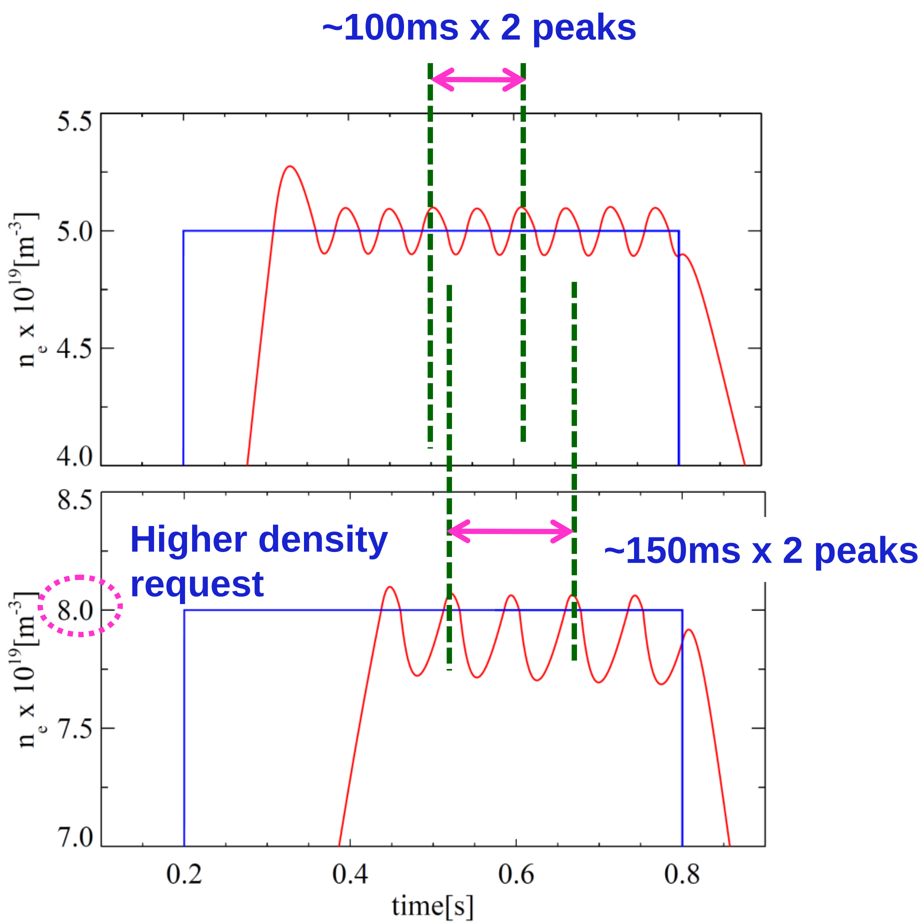
$$= \Psi(t) \times \frac{\tau_w \exp(-\left|t-T_d\right|/\tau_w) - \tau_v \exp(-\left|t-T_d\right|/\tau_v) - \tau_w \exp(-T_d/\tau_w) + \tau_v \exp(-T_d/\tau_v)}{\tau_v - \tau_w}$$

$$\Psi_{diff}(t) = e^{-t/\tau_g} \int_0^{t'} \frac{e^{t'/\tau_g}}{\tau_g} \Psi(t') dt'$$

Although each approach has different equation, both are very similar each other only with minor discrepancy of waveforms, provided with the same delay time.

Delay-introduced reaction

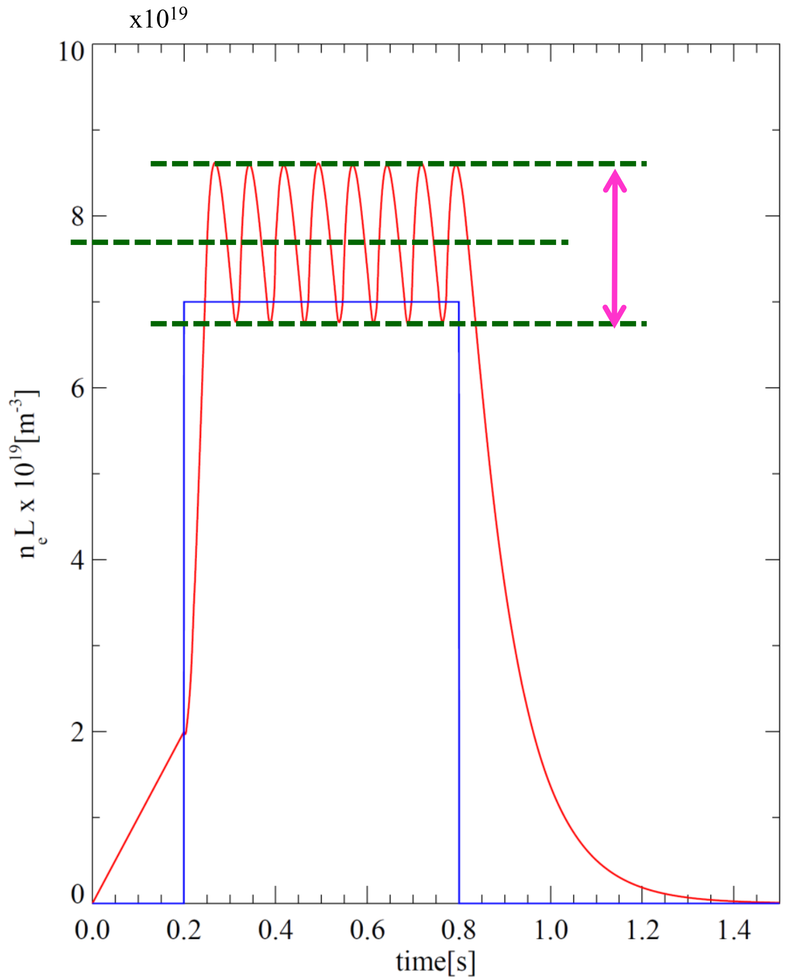




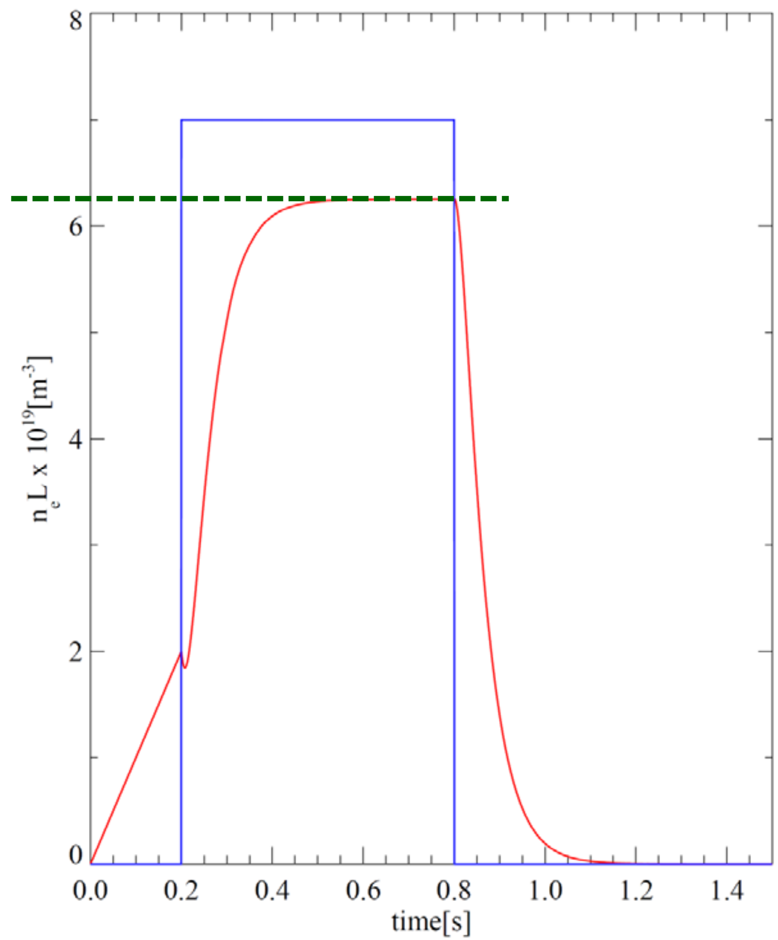
- Nw0 = 3e22
- dNw/dt ~ 2.89e21 s^{-1} ~ 20 Torr·liter/s
- Gas injection=2e22 s^{-1} ~ 300 Torr·liter/s
- Response delay time = 20ms

20ms response delay leads to 50~75 ms-oscillation period of density

Previous approach with fixed flow rate and fast response to the error is stable, but not accurate.

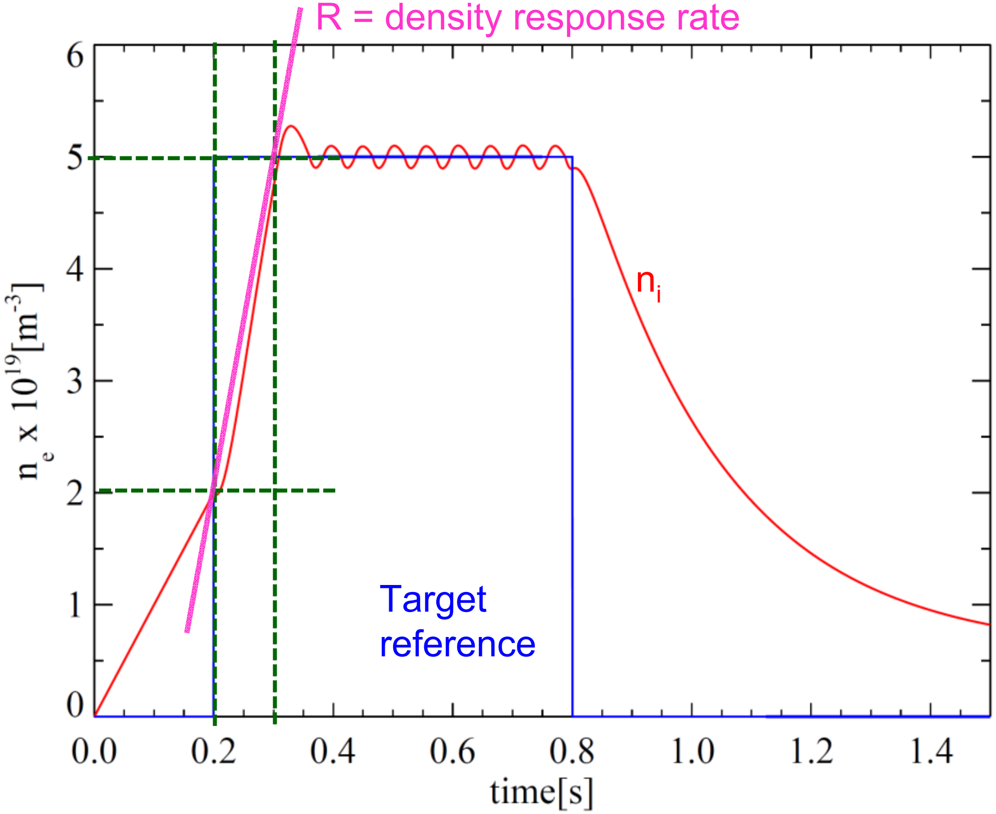


- Nw0 = 1e18
- Gas injection=10e22 <- 5e22 #/s
- Delay time = 20msec



- Nw0 = 1e18
- Gas injection=5e22 #/s
- Ion confinement time 50ms <- 100ms

Design of simple proportional feedback control algorithm



Previous approach was stable but not accurate because of fixed response.

Only ON/OFF time modulation is assumed to be applicable for gas injection control with fixed flow rate (=2x10^{22}s^{-1} ~ 300 Torr·liter/s).

$$R = \frac{(5-2)\times 10^{19}[m^{-3}]}{(0.3-0.2)[s]} = 3\times 10^{20}[m^{-3}s^{-1}]$$

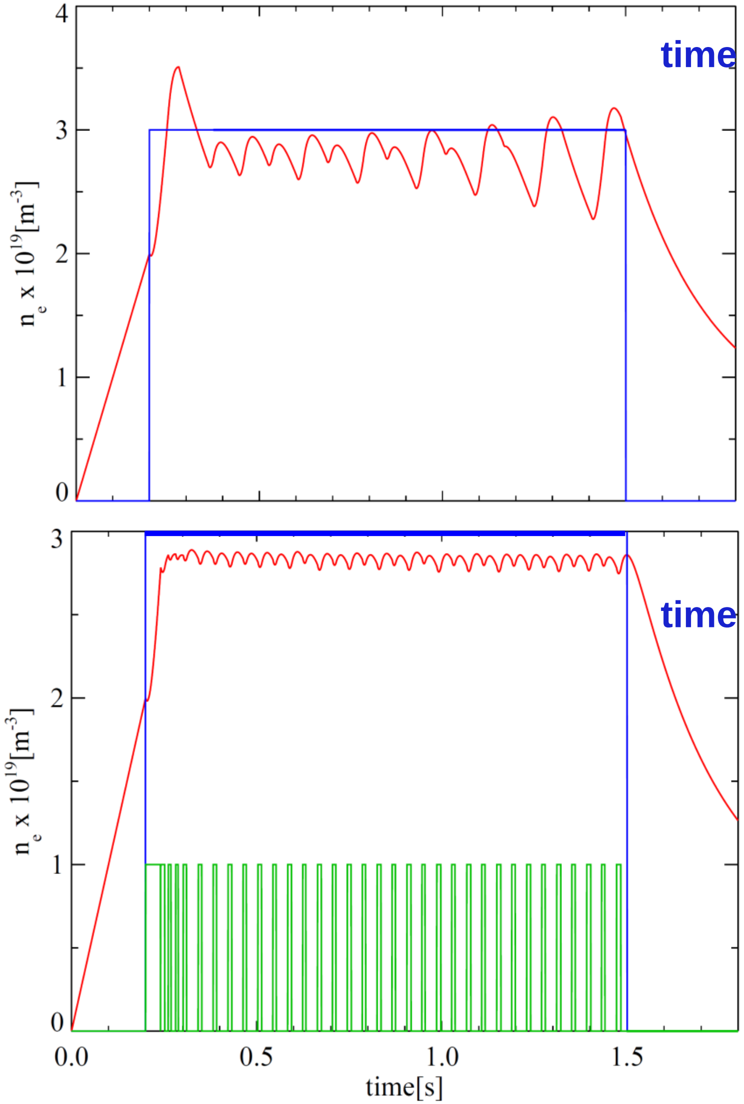
$$\Delta n = n_{ref} - n$$

$$\therefore [\Delta n / R] = m^{-3}/(m^{-3}s^{-1}) = s$$

Valve opening duration

- Nw0 = 3e22
- dNw/dt ~ 2.89e21 s^{-1} ~ 20 Torr·liter/s
- Gas injection=2e22 s^{-1} ~ 300 Torr·liter/s
- Response delay time = 20ms

Proportional controller is not the best for valve modulation



time step= 30ms

time step= 50ms

$$R = \frac{(5-2)\times 10^{19}[m^{-3}]}{(0.3-0.2)[s]} = 3\times 10^{20}[m^{-3}s^{-1}]$$

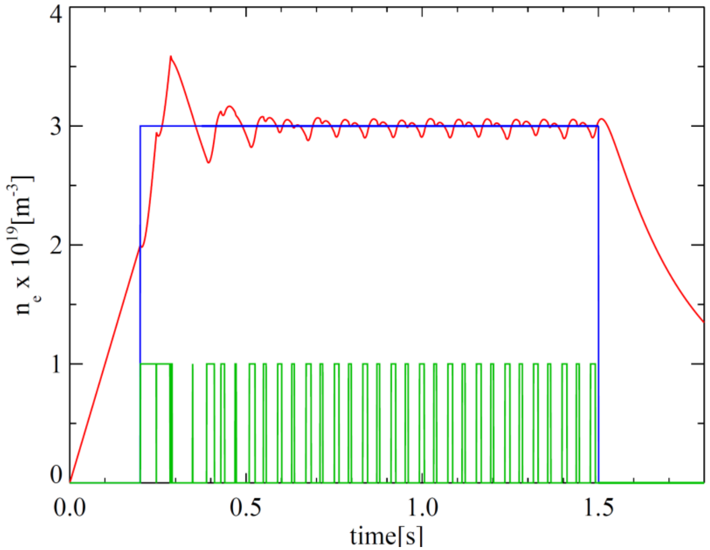
$$\Delta n = n_{ref} - n$$

$$\therefore G = 1/3\times 10^{20}\times 1.5$$

$$T_{open} = G\Delta n$$

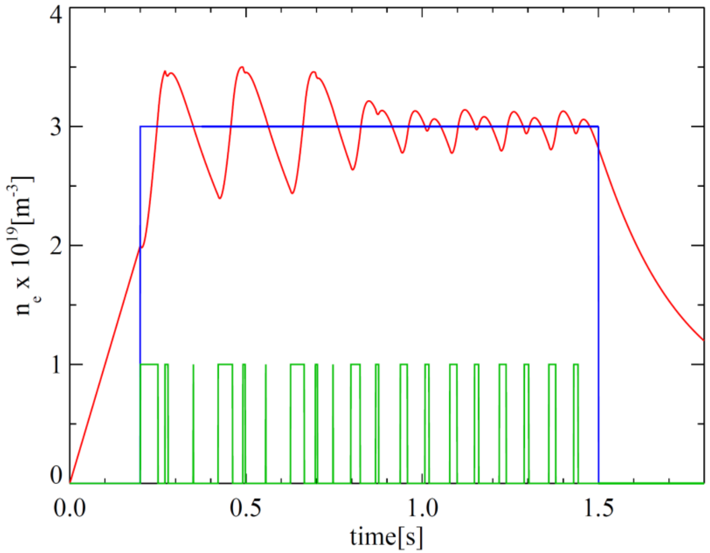
Although This controller does not guarantee the accuracy for the target value although smaller time step can provide smaller oscillation of density.

PI controller can provide density close to target but there is still oscillations.



time step= 30ms

target density= 3x10[19]



time step= 50ms

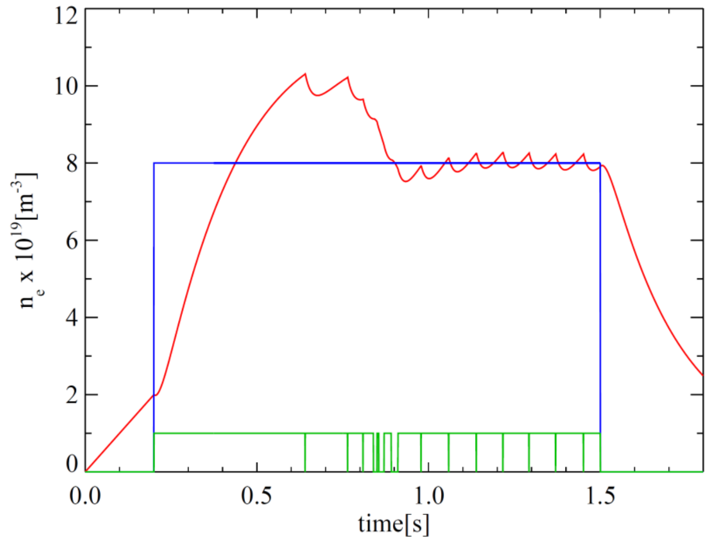
$$\Delta n = n_{ref} - n$$

$$G_P = 1/3 \times 10^{20} \times 1.5$$

$$G_I = G_p \times 0.02$$

$$T_{open} = G_P \Delta n + G_I \int \Delta n$$

target density= 8x10[19]



Valve time modulation inherently leads to oscillation even if the PI controller has been tried. Flow rate control by valve orifice variation seems to be desired for better control performance

Summary and conclusion

- Recently upgraded electronics from UC Davis enables the fast signal processing and this leads to the easy characterization and suppression of fringe jumps in FIReTIP.
- Fringe jump errors are automatically corrected after almost every shot, provided with normal status of FIReTIP.
- The algorithm is applicable to the FIReTIP signals digitized by PCS for real-time density control which are archived together.
- Preliminary density model based on that of Fielding tried and it shows good agreement provided the parameters are adjusted.
- Using feedback control, density is achieved in a desired value without huge dependence on other parameters when reduced wall degassing is guaranteed.
- Global density model has been established for NSTX plasmas and preliminary study with that model has been tried. For the simple system, the valve opening-duration modulation was tried. The proportional controller does not provide good performance. PI controller turned out to be better in terms of accuracy. Both system can not lead to full equilibrium becasue the modulation. Further experiments such as feed-forward density controls are required to obtain proper parameters. New approach is required as well if it is to be applied for NSTX start-up density control.

Acknowledgement

- Special thanks to KC Lee for a lot of advice and also for the FIReTIP!

Thanks for your moment.

If any questions and comments, please mail to :

jjuhn@pppl.gov or

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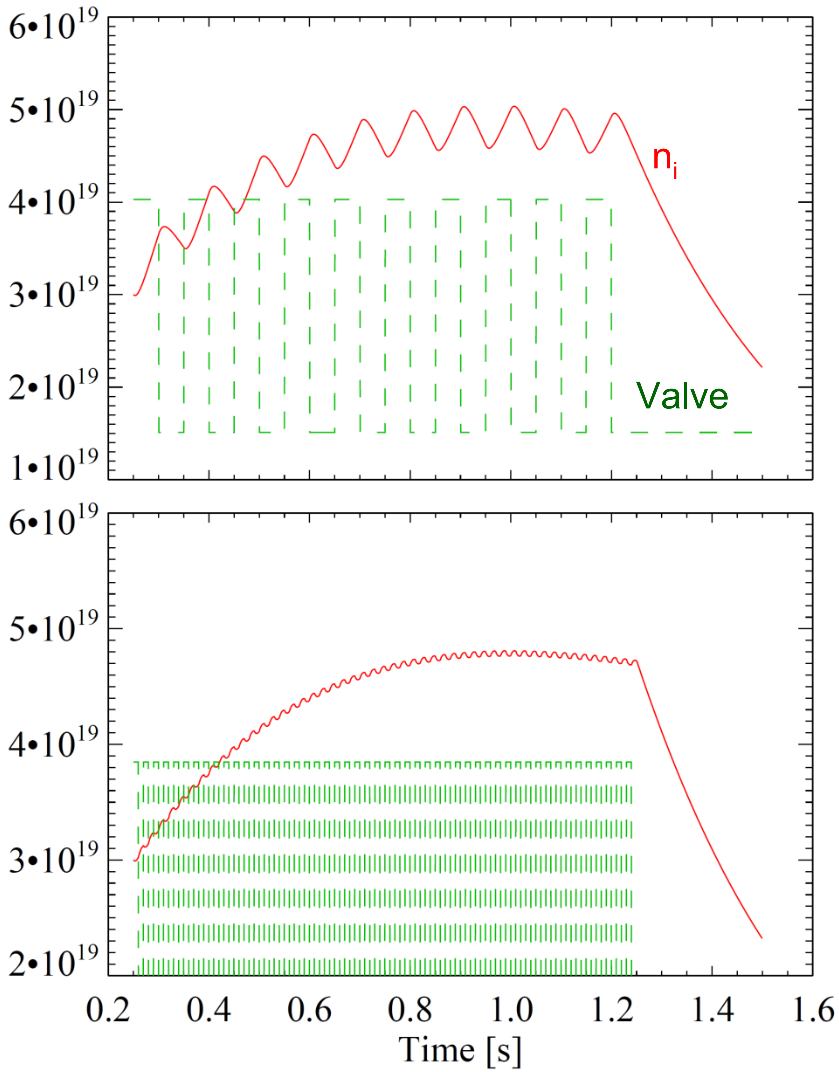
6•10^19
5•10^19
4•10^19
3•10^19
2•10^19
1•10^19
n_i
Valve
6•10^19
5•10^19
4•10^19
3•10^19
2•10^19
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Time [s]