Non-linear digital real-time density control in the TCV tokamak

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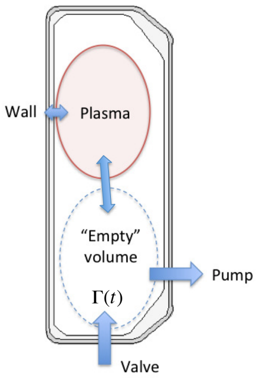
This paper describes the design, implementation and validation of a new digital real-time (RT) plasma density controller for the TCV tokamak. Accurate and responsive density control is of fundamental importance for tokamak operation, affecting operational aspects like the coupling of heating power, stability limit avoidance, fusion gain optimization (e.g. operation close to Greenwald limit), and the scientific efficacy and reproducibility. One of the challenges of this control problem is the asymmetric system response: fueling typically occurs on the ionization timescale, whereas particle loss occurs on the longer effective particle confinement time. The latter contains the effect of the wall response/recycling, which can significantly change on medium to long timescales. All relevant timescales depend strongly on the plasma and heating scenarios. Despite these challenges, the plasma density is often controlled only by proportional feedback, supplemented by a feed-forward action determined by the tokamak operator. Our goal was to develop a robust and accurate controller for the piezo-electric gas valve that relies only weakly on feed-forward programming and is robust against scenario changes. The steps taken include the development of a plant model (actuator, density response, sensor), the design and implementation of the controller, and commissioning experiments on TCV.

Plant model to aid the controller design

The full loop containing the actuator, plant, sensor and controller was modeled in Simulink to guide the controller design and to enable debugging of the controller before integrating it into TCV's digital real-time control system SCD[1]. The actuator, a General Atomics Fast Gas Injection System Model 8100A (GIS), is a piezo-electric gas valve with an internal flow controller responding to a 0-10V command voltage. With the typical GIS inlet pressure and exit orifice, however, the flow saturates at $u_{\mathrm{CMD}} \approx 7$ V instead of at the maximum command voltage. For our current purpose, the actuator could be modeled sufficiently accurately by a gain, a saturation with 0/7 V lower/upper limits and a 2 ms delay (not shown). The density response was modeled by a global particle balance between the vacuum chamber-, wall- and plasma-inventories (describing molecules for N_v, and atoms for N_p and N_w), similar to [2, 3], as shown in Fig. 1. The model contains five free parameters (characteristic times), and an unknown initial condition on the wall inventory $N_w(0)$. τ_{pump} was estimated by fitting the ex-



$$\frac{dN_p}{dt} = -N_p\left(\frac{1}{\tau_p} + \frac{1}{\tau_{retention}}\right) + \frac{N_w}{\tau_{release}} + 2\frac{N_v}{\tau_{ion}}$$

$$\frac{dN_w}{dt} = -\frac{N_w}{\tau_{release}} + \frac{N_p}{\tau_{retention}}$$

$$\frac{dN_v}{dt} = \Gamma(t) - N_v\left(\frac{1}{\tau_{pump}} + \frac{1}{\tau_{ion}}\right) + \frac{1}{2}\frac{N_p}{\tau_p}$$

$$N_p(0) = N_v(0) = 0$$

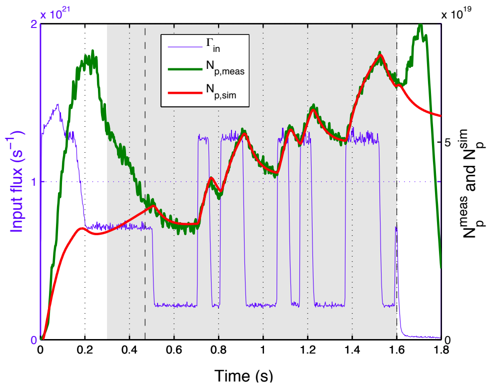


Figure 1: *Three-inventory particle balance model between plasma (p), wall (w) and vacuum vessel (v) of the density response. Graph shows measured as simulated density response during a noise injection experiment on the GIS. Shaded area indicates period in which plasma is in divertor configuration, dashed lines the times between which the parameter fit was performed.*

ponential pressure decay, measured by a fast pressure gauge after a disruption (not shown), giving $\tau_{\text{pump}} \sim 0.5$ s. This value is consistent with the theoretical maximum pumping speed of 4000 l/s (as TCV is equipped with four 1000 l/s turbo pumps) and the vacuum vessel volume of $\sim$4.5 m^3. The other four characteristic times and $N_w(0)$ were determined by fitting the model output N_p^{sim} to $N_p^{\text{meas}} = n_e^{\text{avg}}\text{Vol}_{\text{plasma}}$ (n_e^{avg} = line-averaged electron density measured by FIR, $\text{Vol}_{\text{plasma}}$=reconstructed plasma volume), measured during a pseudo-random binary noise injection experiment on the GIS using a multivariable minimum seeking algorithm. The fit parameters, shown in the table, are determined only during the flattop during the noise injection, and give a satisfactory simulated density response, as shown in Fig. 1. Outside this time window, the agreement is worse, as the parameters (e.g. τ_p) vary significantly in the ramp-up and -down phases of the scenario. This implies that we optimize the controller for best performance during the flattop, and rely on its robustness to handle the other phases. We note that, although the timescales are apparently of the right order of magnitude (compare e.g. $\tau_p = 18$ ms to $\tau_e = 22$ ms determined for this discharge), caution must be taken before administering a physics interpretation to these effective time scales. Finally, the sensor, the vertical central viewing chord of a Far-Infrared Interferometer (FIR), was modeled by multiplying the input N_p^{sim} by $A \cdot L_{\text{FIR}}/\text{Vol}_{\text{plasma}}$, where L_{FIR} is length of the intersection of the chord with the plasma and A is a conversion factor to interferometer fringes, and adding high-frequency white noise and an empirical 60 Hz oscillation to match the experimental situation.

Parameter	Fitted value
τ_p	18 ms
$\tau_{\text{retention}}$	10 ms
τ_{release}	283 ms
τ_{ion}	41 ms
τ_{pump}	0.5 s
$N_w(0)$	$2.5 \cdot 10^{18}$

Design of the non-linear controller

The design criteria for the new controller were i) reference tracking to within a few percent,

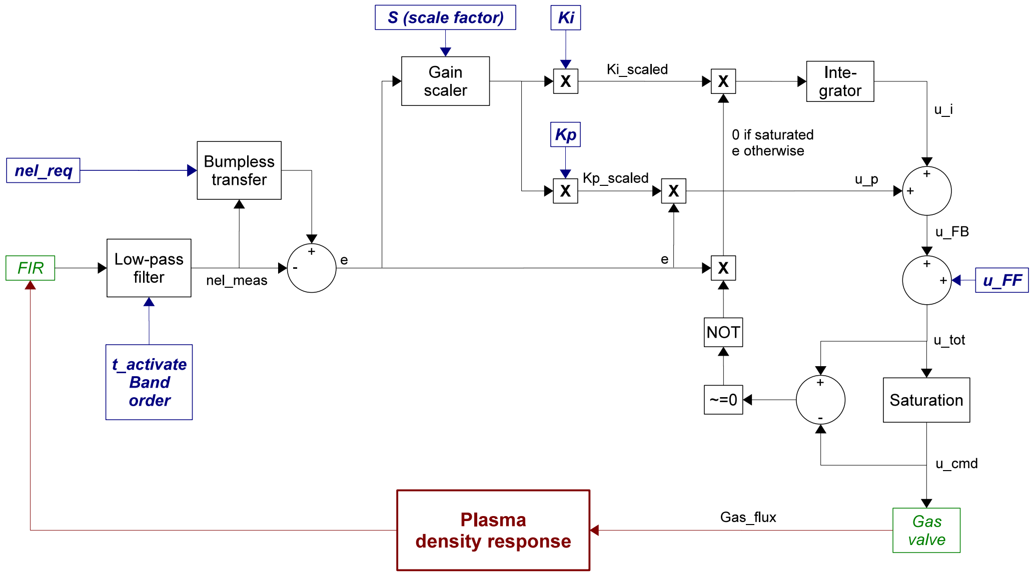


Figure 2: *Schematic of the new controller and the other elements of the control loop. Blue quantities are specified by the operator.*

ii) robustness against scenario changes, iii) minimal reliance on feed-forward programming, i.e. good disturbance rejection. The basis for the design was chosen to be a PI-controller for its proven robustness and ability to correct steady-state errors. As shown in Fig. 2, this basic controller was augmented with an anti-windup mechanism to handle actuator saturation, a low-pass filter on the input to remove sensor noise (3rd order Butterworth with 25 Hz cut-off) and a bumpless transfer mechanism to ensure a continuous command on controller activation (acting on the instantaneous error at the activation time via a modification of the request, which then decays with a time constant of 10 ms). As the fastest possible action on density overshoot is the natural decay of the density without any external fueling, the controller was improved by adding an asymmetric gain scaler, which multiplies both the proportional and integral gain by a factor $S(1-e^3)$ when $e<0$, where $e=n_{el}^{\text{req}}-n_{el}^{\text{meas}}$. This can rapidly increase the gains without introducing discontinuities in the control loop that may drive instabilities. The tokamak operator may provide the density request waveform in fringes (n_{el}^{req}), feed-forward voltage waveform (u_{FF}), the controller and filter activation times, K_p, K_i, and the gain scaling parameter S. An initial set of parameters was determined by manual intervention in the fully simulated loop. These values ($K_p=6.5$, $K_i=30$, $S=10$) were further optimized during the commissioning experiments described below.

Commissioning experiments on TCV

Owing to the flexible and user-friendly programming environment provided by the SCD[1], the controller was efficiently integrated in the TCV control system by copying its Simulink model and graphically connecting the proper in- and outputs. During commissioning, the performance of the controller was directly compared to that of the legacy P-controller during standard divertor discharges that are run at the start of every operational day with unmodified n_{el}^{req} and u_{FF} waveforms.

As Fig. 3 shows, the divertor is formed at $t = 0.275$s (dashed lines) and the shot features a cut of u_{FF} at $t = 0.75$s. Feedback is turned on at $t = 0.07$s. We observe that the new controller responds with approximately twice the feedback control signal ($u_{\mathrm{CMD}} - u_{\mathrm{FF}}$) during these events, leading to an average absolute density error in the controllable phase of the discharge that is four times smaller. We note that, in contrast to the legacy controller, it controls the density to n_{el}^{req}, even after removal of u_{FF}. The scenario change back to limiter configuration causes the final increase in density and can not be tracked due to saturation of the actuator. Both the high- and low-frequency sensor noise are effectively filtered, at the cost of a 10^{-2}s delay. Next, both n_{el}^{req} and u_{FF} were flattened for the duration of the flattop to arbitrarily chosen values, i.e. without consideration of scenario changes or an estimate of the required u_{FF} (Fig. 4). The pump-out during the divertor formation is effectively compensated and a steady-state error of <2% is achieved for 0.5 s and reaches <0.5%, even with the poorly adjusted programming (max = 6%). At the end of the flattop, the valve is closed more assertively due to the gain scaler, but Fig. 3 and 4 show that this component should be optimized for better response at small errors. The optimized gains ($K_p = 6$, $K_i = 70$) are close to those determined using the model.

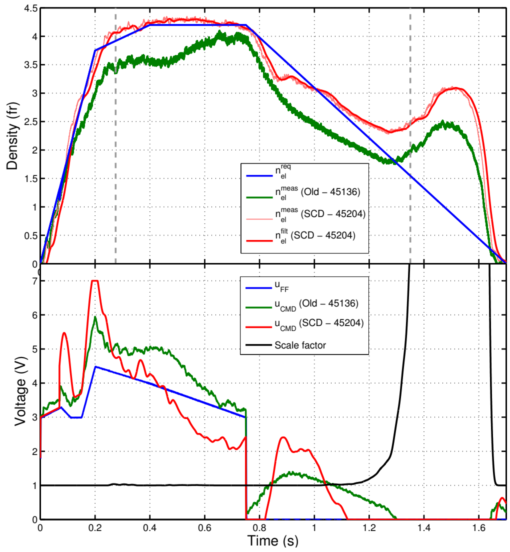


Figure 3: *Comparison of the performance of the new digital controller with the legacy analog controller on a standard divertor plasma.*

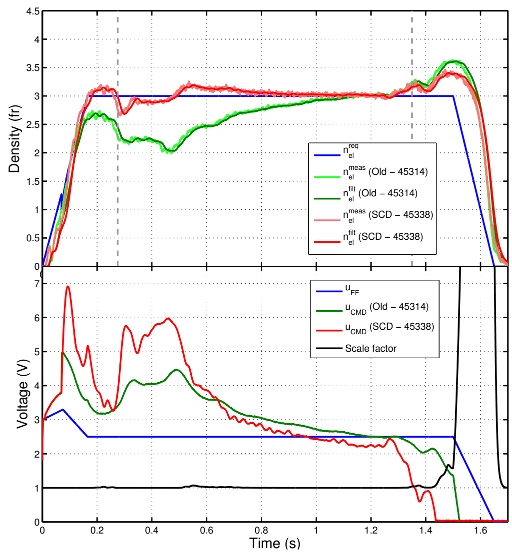


Figure 4: *Repeat of the discharge in Fig. 3 with request and feed-forward flattened. This time, the legacy controller was replicated on the SCD.*

References

[1] J.I. Paley, S. Coda, B. Duval, F. Felici, J.-M. Moret, "Architecture and commissioning of the TCV distributed feedback control system", 17th IEEE-NPSS Real Time Conference, Lisboa, Portugal (2010)

[2] H. Brelen, Fusion Technology **27**, 162-170 (1995)

[3] J. Roth, K. Krieger, G. Fussmann, Nuclear Fusion **32**, 1835 (1992)