New position control tools for runaway experiments at JET

L. Calacci[1], M. Ariola[2], G. Artaserse[4], M. Baruzzo[5], D. Carnevale[1], G. De Tommasi[4], E. Joffrin[6], K. Damien[5], M. Lennholm[5],M. Passeri[1], C. Possieri[1], C. Reux[6], F. Rimini[5], Niko Sciatore[1], D. Valcarcel[5], the JET Contributors[7]

[1] Dip. di Ing. Civile ed Informatica, Università di Roma Tor Vergata, Italy.
[2] CREATE-Università degli Studi di Napoli Parthenope, Centro Direzionale di Napoli, Isola C4, 80143 Napoli, Italy
[3] CREATE-Universit degli Studi di Napoli Federico II, via Claudio 21, 80125, Napoli, Italy
[4] ENEA, Fusion and Nuclear Safety Department, Via E. Fermi 45, 00044 Frascati, Italy
[5] Euratom-CCFE, Culham Science Centre, OX14 3DB, Abingdon, UK
[6] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[7] See the author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001

Abstract. Runaway beam confinement and dissipation remain one of the main concern for ITER operation and a clear solution has not been found yet. ITER will be provided with a Shattered Pellet Injection (SPI) system as the primary disruption mitigation technique given the promising results provided by DIII-D [3]. To further study such technique an SPI system has been recently installed at JET and to provide reliable results an improved runaway beam position control system [2, 1] is proposed. We propose to use a dynamic observer to estimate in realtime the slow vertical drift of the runaway beam. This dynamic observer should replace the static one once the runaway beam is detected. The observer parameters have been optimized in order to fit the vertical position z_p reconstructed using EFIT. The new observer has the same high frequency behavior of the standard one plus the capability of detecting the RE beam slow vertical drift. An innovative tool to improve the beam position control is also described. This method uses a graph data structure to store an adaptive probabilistic route-map that links different states of the plasma and that can be obtained either using experimental data or via simulators. Such structure is then used to provide an optimal control feedforward IP4 current references via reinforcement learning techniques.

1. Runaway plateau control strategy

The actual JET vertical stabilization system (VS5) is unable to prevent slow plasma vertical drift of the post disruption runaway beam since the standard velocity observer acts as an high-pass filter. This fact, can be clearly seen from Figure 1 where the output of OBS5, the VSEL signal, is almost zero while the runaway beam vertically drift.

In first instance we needed a tool able to trigger our new observer during the RE beam plateau phase. For such purpose we implemented an RTCC network able to

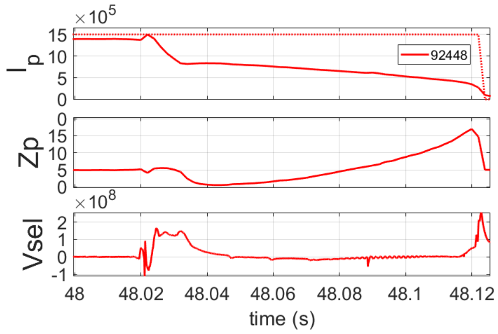

Figure 1. Shot 92448 - A visible drift of plasma vertical position (Z_p) not seen from OBS4 (Vsel).

discriminates among three main event: current quench, plateau and final loss. This tool processes the plasma current signal (I_p) and its derivatives, obtained by using FIR filters to retrieve the different runaway beam phases.

The new position control has been conceived in a modular way to be plugged on the standard control system during the current plateau of RE beam - it can be considered as a patch to the standard control scheme. Whenever the plateau signal is detected the standard plasma velocity observer is substituted by the new one and and simultaneously different references for the P4 coils and plasma references are used in order to obtain a controlled current ramp-down.

2. Vertical velocity observer

The new estimator is composed of two sub-systems: a static gain (like the standard observer) and a low pass filter. The matrix gain D_{high} is used to generate high frequency contributes and the low pass filter to estimate low frequencies velocity changes. The two are then summed up to provide a more reliable estimation of the vertical plasma/RE beam velocity.
The inputs of this new observer are still the magnetic coils used in the old one, so no code changes are necessary.

The design of the new observer hinges upon optimization techniques as follows:

- for the high frequency part we minimized the mean square error (MSE) from the VSEL signal and the output of $y = D_{High}\, u_{mag}$, where D_{High} was the matrix of the parameters to be optimized and u the magnetic coils signal.
- for the low frequency part we used MSE from dz_p, obtained by differentiating the z_p signal and the output of $y = D_{Low}\, u_{mag}$ where D_{Low} was the matrix of the parameters to be optimized. We obtained a system able to approximate the signal dz_p and is described by:

$$\dot{x} = -100x + D_{Low}\, u_{mag} \tag{1}$$

$$y = 100\, k_{low}\, x, \tag{2}$$

where $x \in \mathbb{R}, k_{low} \in \mathbb{R}_{+}$ and $u_{mag} \in \mathbb{R}^{32}$. In Figure 2 it is possible to see the output of of the term $D_{Low} u_{mag}$ and its filtered version y as in (2).

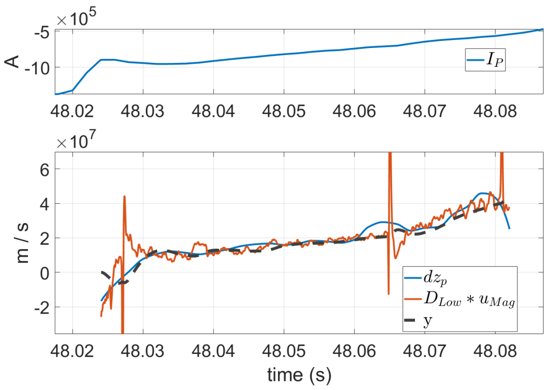

Figure 2. Shot 92457 - Real time plasma velocity signal.

During the 2019 restart campaign the new observer has been tested on normal plasma but oscillation were induced. The analysis of experimental data revealed that there was a phase lag of about 8 milliseconds in the reconstructed plasma position signal z_p (the one used by the shape controller) that we used during the optimization process. Such a delay was then reproduced by the estimated model introducing oscillations of the closed loop plant. In order to prevent it we shifted backward the dz_p signal of 8 millisecond and re-estimated the matrix D_{Low}. As can be seen from Figure 3 the phase lag has been cancelled and the responsiveness of the new observer is the same of the old one.

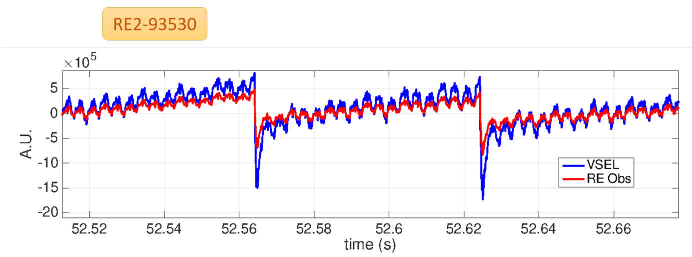

Figure 3. Shot #93530 - Performances of the new observer (red, RE obs) and the standard one (OBS5, VSEL).

With respect to figure 4 the benefits of the new observer becomes clear. In fact, there can be seen different versions of the new observer with different gains k_{low} (that can be easily changed using the MARTe configuration file) in which during the plasma position slow drift the output is no more zero. These simulation shows that the slow vertical drift can be seen from the position controller and, consequently, it should counteract it.

3. Stability analysis

Using CREATE models we performed a closed loop stability analysis. As can be seen from Figure 4 the diagram circles the minus one point exactly once anti-clockwise, in the model there is just one unstable pole, we can assert that the closed loop system is asymptotically stable.

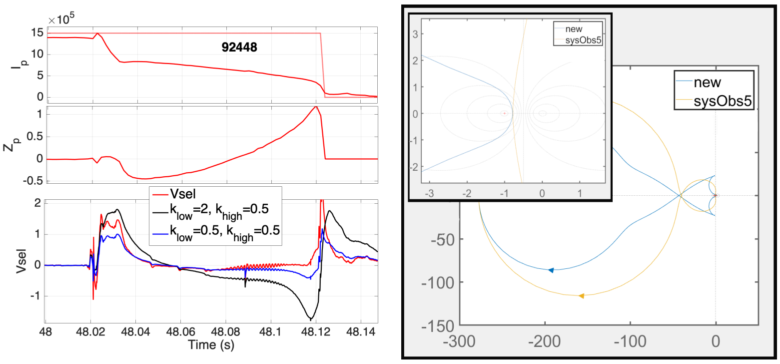

Figure 4. At left Shot 92448 - Output comparison from OBS5 and the new one. At left Nyquist diagram of the new observer in cascade to the CREATE model of the plasma (blue) compared to old observer.

4. Graph controller

In order to improve plasma position control another strategy has been proposed: a new tool able to improve P4 coils preprogrammed reference for specified plasma configuration. This tool uses a probabilistic graph model by using a graph structure in which the plant state-space is subdivided into macro-states and each edge models the transition distribution to reach another node by applying a specified control. Using data of different experiments it is possible to estimate/improve the transition distribution and to discover new route (it converges to a Markov Decision Process of the plant). Using graph theory it is possible to generate references from one plasma configuration to another. Shot by shot this new algorithm could provide better feedforward current signals for IP4 coils.

5. Conclusions

In conclusion a new RTCC network for plasma current event triggering has been implemented and tested. Such network is used to switch control policy during the RE beam plasma current plateau. We proposed a new control strategy: a new vertical velocity observer and a tool to improve P4 coils references and current ramp-down. The new observer has been validated either via a stability analysis and restart experiments.

[1] L. Boncagni et al., A first approach to runaway electron control in FTU, FED 88 (6-8), 1109-1112
[2] D. Carnevale et al., Runaway electron beam control, PPCF 61 (1), 014036 (2018)
[3] N. Commaux et al., First demonstration of rapid shutdown using neon shattered pellet injection for thermal quench mitigation on DIII-D, Nucl. Fusion 56 046007 (2016)
[4] C. Reux et al, Runaway electron beam generation and mitigation during disruptions at JET-ILW, Nucl. Fusion 55 129501 (2015)
[5] B. Esposito et al., Runaway electron generation and control, PPCF 59 (1), (2017)