Development of plasma shape control using real-time equilibrium reconstruction on TCV

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Introduction: A tokamak discharge requires accurate feedback control of many of the discharge parameters, including plasma shape. The plasma shape plays a particularly important role in the stability of global magnetohydrodynamic (MHD) modes and in heat and particle transport [1-3]. The required plasma boundary shape can generally be obtained with reasonable accuracy by preprogramming the appropriate currents in the poloidal field coils. However, departures of the plasma parameters from the model values used in the pre-calculation, most notably in the plasma current profile, can result in unwanted shape changes. Real-time control thus becomes necessary when better accuracy is required. The most complete evaluation of plasma shape comes from solving the Grad-Shafranov equation, which describes the force balance of the tokamak equilibrium, constrained by diagnostic data. This full reconstruction of the equilibrium is normally performed offline using a computation intensive fitting algorithm. However, practical methods for performing an equilibrium reconstruction in real time [4] for arbitrary time varying discharge shapes and current profiles are now possible.

Real-time equilibrium reconstruction (RTLIUQE) on Tokamak à Configuration Variable (TCV): The task of the equilibrium reconstruction algorithm LIUQE [5] is to compute the distributions in the (R, Z) plane of the poloidal flux, ψ, and of the toroidal current density, J_t, that provide a least squares best fit to the diagnostic data and that simultaneously satisfy the Grad-Shafranov equation

$$\Delta^*\psi = -\mu R J_t(R, \psi)$$

Here the total poloidal flux is $\psi = \psi_p + \psi_c$, where ψ_p is the poloidal flux generated by the plasma current and ψ_c is the poloidal flux generated by current sources external to the plasma. The full reconstruction algorithm iterates the solutions for ψ and J_t until the changes in ψ between two successive iterations are sufficiently small. In the real time version of the equilibrium reconstruction algorithm (RTLIUQE), the time consuming process of iterating to a well-converged solution eliminated. Instead, for each new reconstruction, the most recent equilibrium solution is used as the starting point and one iteration is performed. The reference of the vertical position is updated at each step leading to the stabilization of the algorithm.

Figure 1 left shows the histogram of the vertical position of the magnetic axis, relative to the offline solution, for different time steps. The highly peaked histogram corresponding to a time step of 0.5 ms clearly illustrates the accuracy of the real time algorithm as benchmarked to the offline version. The real time resolution scheme for TCV indeed operates on a timescale < 1 ms, with equilibrium reconstruction, post processing and analogue/digital IO accounting for time scales of the order of 250 μs, 100 μs and 10 μs. The equilibrium reconstruction is performed on a real-time node of the TCV digital control system (SCD) [6-7].

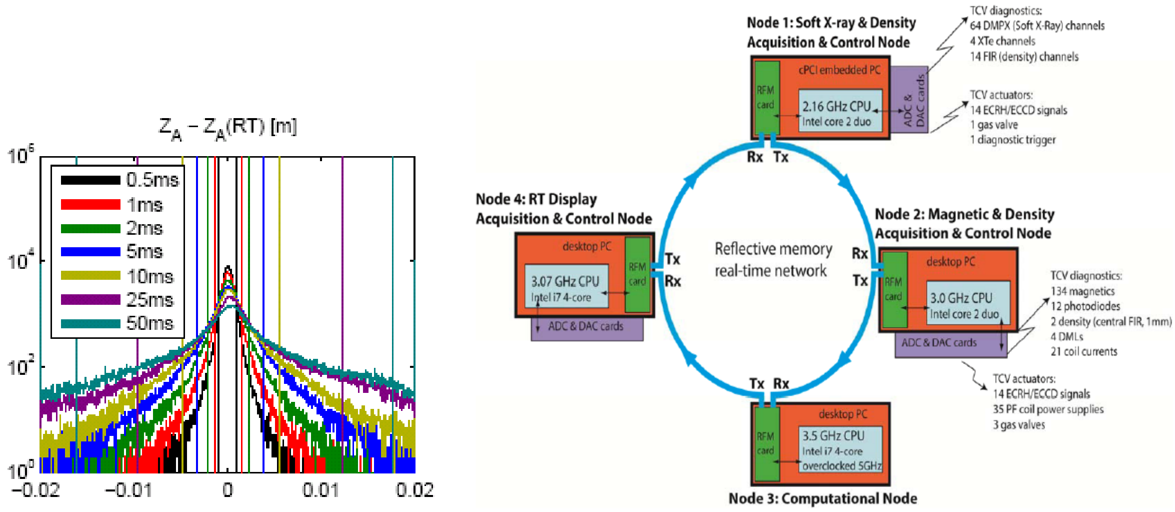

Figure 1

Figure 1 right shows an overview of the SCD system consisting of 4 nodes. Node 1 comprises 96 ADCs and 16 DACs and runs at 100 μs when used for sawtooth (ST) or neoclassical tearing mode (NTM) control or at 900 μs for running the real-time transport code RAPTOR. Node 2 comprises 192 ADCs and 96 DACs and runs at 100 μs when used to emulate the TCV analogue control system or at 20 μs for ST and NTM control. Node 3 does not have independent input-output capabilities but shares data via the reflective memory (receiving from and sending to other nodes) and is dedicated to heavily computational algorithms. It runs at 500 μs when used for RTLIUQE. Node 4 is considered as a backup, and used for real-time display of diagnostic or processed signals during the discharge. The SCD code is split into two main parts. The control algorithm, written in Simulink block language, uses a standard identical Simulink template for each node and performs signal processing and computational actions to provide output signals. Using the Embedded Coder, the Simulink model is automatically converted into C code, then compiled into a dynamically linked shared object library (".so" file), and copied to each RT node (new ".so" every shot). The second component is hardware specific code: written in C language by the system developer, this handles the data input-output for each time step and dynamically loads the ".so" file. Once compiled, the executable is uploaded to RT nodes, where it is considered fixed and unchanging between plasma shots.

Development of prototype plasma shape controller algorithm for Tokamak à Configuration Variable (TCV): A prototype plasma shape controller was developed that addresses the question of shape in isolation without consideration of vertical stabilization (handled separately by the existing analogue control system, possibly to be integrated later). Eddy currents in the vessel have also been neglected for now under the assumption that the shape control would be performed over sufficiently slow time scales. The poloidal flux change produced by the change in the plasma current distribution caused by the shape variation itself is neglected (approximation verified *a posteriori* to be amply justified). The controller is based on the premise that the real time equilibrium reconstruction code RTLIUQE provides the spatial distribution of the poloidal flux and current density, allowing accurate evaluation of the boundary shape. The last closed flux surface is an isoflux surface, with the flux conventionally set to zero in the LIUQE environment. The flux values at a discrete set of boundary points are compared with reference flux values, and these flux errors are used to drive the poloidal field coils on TCV. The shape control algorithm calculates the perturbation in the coil currents needed to correct the plasma boundary, thus the coil current perturbations produce poloidal flux that exactly cancels the flux error at each boundary point. Due to high degree of under-determination, the perturbed coil currents obtained by solving in a least squares sense can be very high, leading in particular to large currents of similar magnitude and opposite signs in adjacent coils. Cost functions are thus included to minimise these dipole terms as well as the power dissipation in the coils with appropriate weighting coefficients, which can be adjusted to reach an optimal solution. Alternatively a cost function can be employed to minimise the change in coil currents relative to the preprogramed value. The final result is a simple linearized proportional controller whose time dependent coefficients can be precalculated provided the boundary error is small. For offline checks, the new poloidal flux distribution is then derived from the perturbations in the coil currents and compared with the desired distribution. From this the new boundary is determined and verified. Figure 2 shows the comparison of the solutions obtained without and with a cost function. The perturbed coil currents in the latter case lead, as expected, to a smaller value of the dipole function ($\sum(\delta I_i - \delta I_{i+1})^2$ = 1.47e+9 A^2 vs. $\sum(\delta I_i - \delta I_{i+1})^2$= 1.53e+9 A^2). The first experimental tests of this prototype controller are imminent.

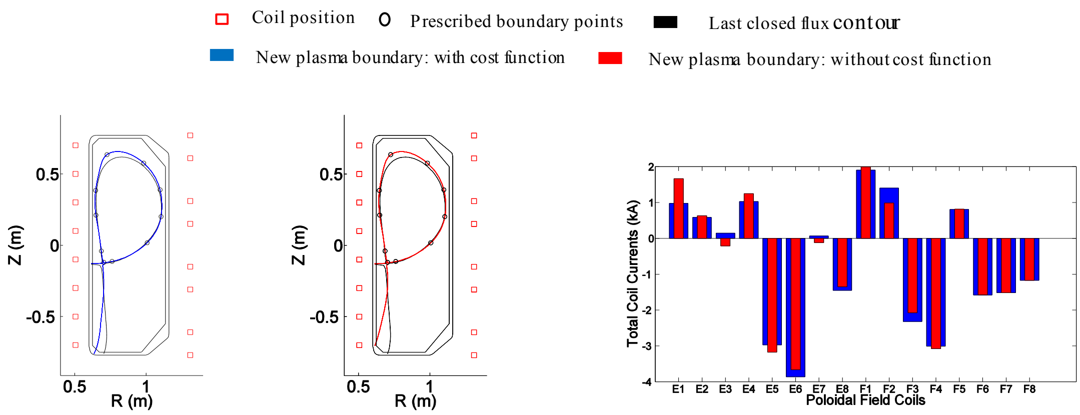

Figure 2

Once it is tested and operational, progressive upgrades are planned, in particular, non-linear optimisation to avoid saturation in the coil currents, a full feedback scheme without a feedforward component, and the inclusion of image currents in the vessel.

Conclusions: A real-time equilibrium reconstruction code, RTLIUQE, has been fully implemented and is now operating on the TCV digital control system with a time step of < 1 ms. An execution time of 250 µs for one iteration of equilibrium reconstruction was achieved on a 4 core Intel i7 overclocked at 5 GHz. Shape control tests with a prototype plasma shape controller algorithm are imminent. Progressive refinements and improvements are planned for the remainder of the 2013 campaign. Once commissioned, the controller is planned to be applied in particular to the following avenues of research: H-mode at negative triangularity [3-4] and parametric studies of snowflakes [8].

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