# DIRECT MEASUREMENT OF THE PLASMA EQUILIBRIUM RESPONSE TO POLOIDAL FIELD CHANGES AND $H_\infty$ CONTROLLER TESTS IN TCV

J.B. LISTER[1], R. ALBANESE[2], G. AMBROSINO[3], M. ARIOLA[3], I. BANDYOPADHYAY[4], A. COUTLIS[5], D.J.N. LIMEBEER[5], A. PIRONTI[3], F. VILLONE[6], P. VYAS[1], J.P. WAINWRIGHT[5]

1) Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
2) Associazione Euratom/ENEA/CREATE, Dipartimento di Ingegneria, Università degli Studi di Napoli Federico II, Via Claudio 21, I-80125 Napoli, Italy
3) Associazione Euratom/ENEA/CREATE, Dipartimento di Informatica e Sistemistica, Università degli Studi di Napoli Federico II, Via Claudio 21, I-80125 Napoli, Italy
4) Institute for Plasma Research, Bhat, Gandhinagar 382428, India
5) Centre for Process Engineering, Imperial College of Science, Technology and Medicine, Roderic Hill Building, London SW7 2BZ, United Kingdom
6) Associazione Euratom/ENEA/CREATE, Dipartimento di Ingegneria Industriale, Università di Cassino, I-03043, Cassino (Fr), Italy

## Abstract

The control of ITER provides several challenges which can be met using existing techniques for the design of modern controllers. The specific case of the control of the Poloidal Field (PF) system has sollicited considerable interest. One feature of the design of such controllers is their dependence on a sufficiently accurate model of the full system under control. To this end, experiments have been performed on the TCV tokamak to validate one plasma equilibrium response model, the CREATE-L model. Using a new technique, the open loop response of TCV has been directly measured in the frequency domain. These experimental results compare well with the CREATE-L model. This model was subsequently used to design a PF system controller, using methods proposed during the ITER EDA and the first test on TCV has been successful.

## 1. INTRODUCTION

Present tokamaks typically use low order PID controllers. Recently, considerable attention has been focused on the design of plasma position, current and shape controllers for the ITER Poloidal Field (PF) system. The controller is restricted to demand as little power as possible, to limit surges in the total power required for the PF system and to maintain the specified shape in the presence of disturbances. Simulations using modern controllers have provoked a great deal of interest due to their ability to deliver this performance. These design techniques require an accurate model of the tokamak, which is used in a mathematical optimisation to find an optimal controller. There has been some concern that the rather unpredictable nature of a tokamak, together with plasma noise and internal disturbances, might pose problems for these controllers. A long term program was therefore undertaken to validate the full ITER EDA design procedure of such an advanced controller from both modelling and controller design aspects. The TCV tokamak possesses a large number of PF coils, all separately powered, and represents a suitable device for such studies; technical details of TCV control are in [1].

Firstly, we required an accurate model of the TCV tokamak and there are two standard approaches to do this. The most prevalent method for modelling the plasma response has been phenomenological. A mathematical model is constructed from the relevant physical laws with appropriate, but often debated, simplifying assumptions. Benchmarking a linearised deformable plasma equilibrium model, CREATE-L [2] was started with closed loop performance comparisons between the modelled tokamak and experiments on limited discharges [3] and diverted discharges [4] in the presence of external PF coil voltage perturbations. These experiments showed no discrepancies between the model and the experiment. A new circuit equation model of TCV also showed good agreement (RZIP [5]).

The second approach to modelling the plasma response is based on system identification. No *a priori* physics knowledge is assumed. Instead, a fit to experimental data is used to determine a suitable mathematical model. The main features of TCV, that it is unstable with a large number of inputs and a large number of outputs, make identifying TCV a challenge for such techniques. The open loop response cannot be measured by simply opening the feedback loops, since the vertical position of the plasma is unstable once the plasma cross-section is elongated. However the open loop response can be recovered from sufficient closed loop data. These experiments lead directly to an open loop model of the current, shape and position responses at a set of driving frequencies.

These frequency response estimates can be compared directly with open loop plasma response models. This open loop comparison corrects a recognised deficiency in previous model-experiment comparisons of the closed loop behaviour in TCV [3,4]. A feedback system generally tends to reduce the sensitivity of the closed loop system to variations in the open loop plasma response model, whereas the success of a high-performance controller design depends on the accuracy of the open loop model. The effect of the feedback controller is no longer present in our new open loop data and a direct comparison is possible.

Finally, we designed a modern controller and tested its functionality on the TCV tokamak using a fast digital plasma control system [6]. The complete life-cycle of *a priori* modelling, closed loop comparisons, open loop measurements and controller design illustrates that such new techniques can be considered for a future large tokamak.

## 2. MEASUREMENT OF THE OPEN LOOP RESPONSE

A weakly shaped plasma was chosen since no experience of this type of multivariable identification was available. A low vertical instability growth rate (~200s$^{-1}$) implied a low open loop bandwidth which was considered to be more suitable for this first attempt. The main parameters were: $R$=0.87m, $a$=0.24m, $B_\phi$=1.4T, $I_p$=200kA, $k_{95}$=1.4, $\delta_{95}$=0.23, $q_a$=4.6, $n_e$=2.2×10$^{19}$m$^{-3}$.

Point frequency estimates were obtained by exciting the system with a multi-sinusoidal signal with 29 sine waves spanning the angular frequency range 20rad/s to 3000rad/s. The smoothness of the underlying response as a function of frequency is assumed. The period of the slowest sine wave in the excitation signal was designed to be 0.3s, resolvable during the experiments. The highest excitation frequency was designed to be below half the sampling frequency and also above the assumed TCV bandwidth. The excitation signal is injected at point *s* in Fig. 1. The phases of the different frequency components were chosen to minimise the maximum amplitude of the total stimulation waveform. During each identification experiment, the input voltages and the output signals were acquired at 5kHz, over a time interval of 0.5s. The transients following the start of the stimulation were allowed to decay. Any offsets and linear drifts were removed from the signals before analysis.

The test signal was scaled to ensure that it was within the linear range of the power supplies but also large enough to provided sufficient signal-to-noise ratio in the resulting data. The final voltages applied to the PF coils lay within 80% of the power supply limits. If the response is noise-free, linear and time-invariant, the frequencies of the spectral components in the measured signal will match those in the test-signal exactly. The frequency spectrum of the measured signals at these frequencies was obtained by a least squares fit. The amplitudes of the residuals, which cannot be decomposed into the measurement frequencies, are a measure of data corruption due to external disturbances, measurement noise and non-linearities of the system. The smaller the residuals, the greater the confidence in the results of the identification procedure. The residuals in these experiments were small compared with the signals.

The frequency spectra of all of the input and output data collected during the identification experiments was then used to obtain the open loop frequency response. For the $j^{th}$ experiment we define the input frequency spectrum as $U_l^j(\omega_i)$ and the output frequency spectrum as $Y^j(\omega_i)$, where $l$ indexes the inputs. Our estimate of the system frequency response at each measurement frequency is then given by,

$$\hat{G}(\omega_i) = \begin{bmatrix} Y^1(\omega_i) \\ \vdots \\ Y^q(\omega_i) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} U_1^1(\omega_i) & \cdots & U_q^1(\omega_i) \\ \vdots & \ddots & \vdots \\ U_q^1(\omega_i) & \cdots & U_q^q(\omega_i) \end{bmatrix}^{-1} \tag{1}$$

The invertibility of the matrix ($\mathbf{U}_i$) at each frequency is a mild assumption that is satisfied if the corresponding matrix for the designed test-signals is invertible. If that is the case, then the experiments performed are said to be independent. Since TCV has 18 separate PF coil voltage inputs, 18 experiments were required. The condition number of the $\mathbf{U}_i$ matrices varied from 3 to 30, with lower values at higher frequencies, and so were easily invertible.

The agreement between the *a priori* models (CREATE-L and RZIP) is excellent for almost all parameters. Three representative results of input-output frequency responses are shown in Fig. 2.

Many responses show a relatively weak dependence on the model and even agree with the plasmaless model (centre row) and these are always accurate. Some cases show a difference between the plasmaless model and the plasma models (upper row) and the plasma models all agree. Only a few cases are sensitive to the plasma model details (lower row). We also developed a "Grey-Box" model allowing only 6 plasma parameters in the RZIP model to be fitted, fixing all the electromagnetic properties of the tokamak with no plasma, The Best Grey Box Model (BGBM) gave a better result than the *a priori* models in only a few cases. The BGBM approach also indicates which parameters of the plasma response model are most accurately determined by the experimental data and are therefore most important for generating an adequately accurate model. Fig. 3 shows the variation of the Grey Box Model agreement as the 6 plasma coefficients are varied, showing that apart from the plasma inductance and the radial force balance (M33 in Fig. 3) the *a priori* model is barely different from the fitted model. This method has therefore allowed us to measure specific elements of the RZIP circuit equation model.

## 3. CONTROLLER DESIGN AND TEST

We chose the tracking of separate square pulse reference excursions as a suitable test [1], positioning the plasma above the mid-plane. In this case the natural decoupling between the vertical movement and the other 4 control parameters is lost. Since this was the first attempt, a set of relatively conservative design goals were chosen. The controller should:

- stabilise the reference plasma and similar weakly shaped, symmetric, plasmas positioned at the midplane;
- tolerate uncertainties in the PF coil currents with respect to the nominal model;
- be robust to unpredictable behaviour of the PF coil supplies;
- be insensitive to real experimental noise in the estimators;
- have a low closed loop bandwidth for lower power and minimising voltage saturation.

The main design challenge was therefore to demonstrate that the $H_\infty$ controller could function given real conditions in the tokamak operation, not included explicitly in the linearised model. A simple algorithm was used to avoid large transients when switching between the digital implementation of the PID controller and the $H_\infty$ controller. Details of the $H_\infty$ controller design and implementation are found in [7].

The new controller was implemented in the DPCS and shadowed the analogue control system during the operation of a single tokamak discharge, including the switching between PID and $H_\infty$ controllers during the flat top. This open loop verification of the controller and switching algorithms was adequate to believe that the closed loop control would be acceptable. Following this single test discharge, the DPCS was given control of all the PF coils and the first successful closed loop operation of this controller was achieved. Closed loop stability was obtained. The switching produced no visible transient effects on the overall closed loop control. Fig. 4 shows the behaviour of the 5 controlled parameters during this experiment. The decoupling performance is superior to the PID for all responses and all parasitic cross-couplings. The tracking and decoupling benefits of the $H_\infty$ controller have been clearly demonstrated and no unforseen difficulties were encountered. Work will now concentrate on Power Management strategies, saturation strategies and the explicit control of separatrix gaps during the flat-top.

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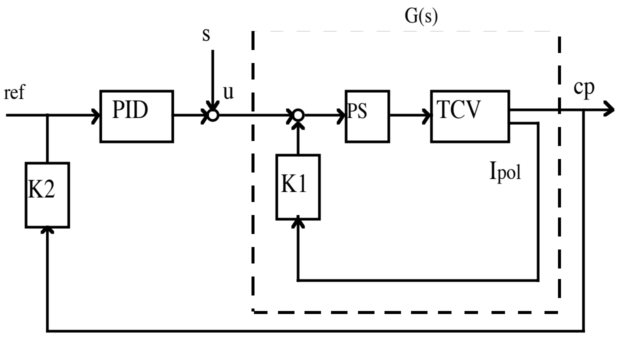

Fig.1 - Schematic of the TCV control loop, showing the power supplies (PS), the tokamak (TCV) and the PF current control loop (K1) as the open loop system G(s), and the controller, comprised by the blocks K2 and PID.

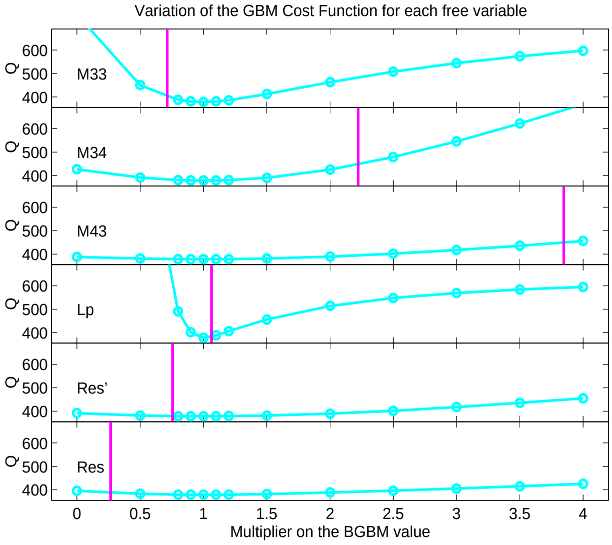

Fig.3 - Open loop results:model cost function sensitivity to the plasma related elements of the RZIP circuit equation model. The most critical elements are the plasma inductance Lp and the Shafranov shift (M33). The nominal model values are shown as vertical bars. When the parameter is critical, the *a priori* estimate is close to the optimum.

Fig.4 - Results of the first experimental test of the $H_\infty$ controller on TCV, indicating good decoupling between the 5 controlled variables. P_VERT controls the radial position, TRI_IN and TRI_OUT control the shape and zIp and Ip control the plasma height and current respectively. The previous PID controller, based on a plasmaless model, showed poor decoupling of some parameters.

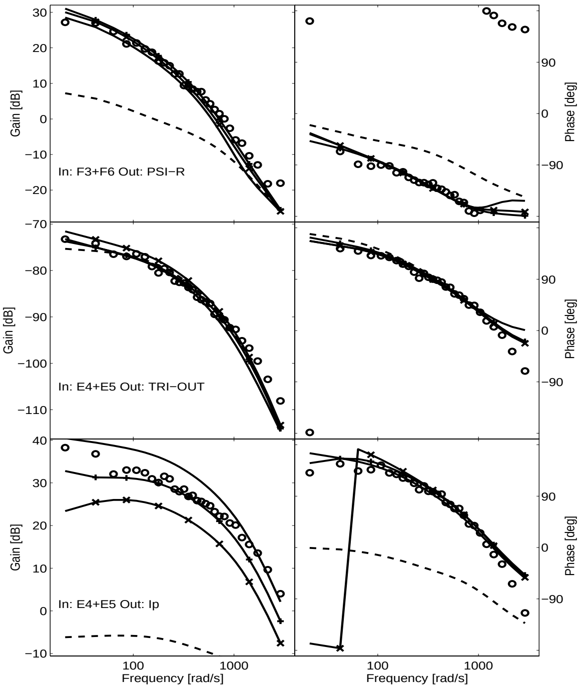

Fig.2 - Frequency responses representing:
a) good agreement between the measured and RZIP and CREATE-L predictions,
b) agreement between the measurements and plasma-less predictions, and
c) BGBM improvement. Measured frequency responses (o), plasma-less model (--), RZIP model (×), CREATE-L (-), and BGBM model (+)