

# DIRECT MEASUREMENT OF THE PLASMA EQUILIBRIUM RESPONSE IN TCV

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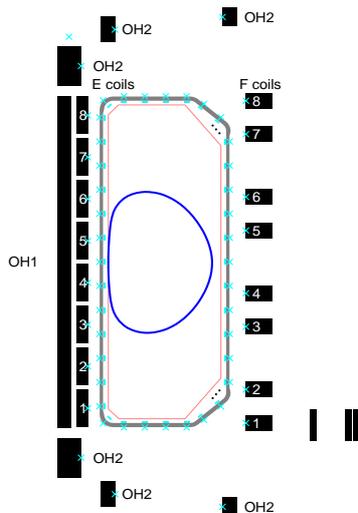
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**ABSTRACT** This paper presents a new technique and results for the estimation of the open loop frequency response of the plasma equilibrium, avoiding disadvantages of previous closed loop comparisons. The results are compared with the CREATE-L model [1]. A circuit equation model has been developed and compared with the experiments. An alternative “Grey Box” modelling method combines features of both theoretical and experimental techniques and provides further insight into the plasma response.

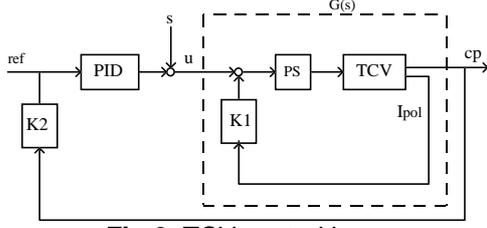
**1. INTRODUCTION** On most tokamaks, controllers are low order (proportional integral derivative), based on simple plasma response models or tuned empirically. Modern control strategies all rely on the availability of an adequately accurate linear model. The ITER reliance on modern high-order controller design methods, lead us to test the methodology in TCV. This validation involves generating an appropriate linear model, validating it against experiment and designing a controller to qualify the method experimentally. The most prevalent method for modelling the plasma response is based on establishing relevant physical laws with appropriate simplifying assumptions. A second approach is system identification. A fit to experimental data determines a suitable mathematical model with no *a priori* assumptions. The main features of TCV for equilibrium response modelling are that it is

unstable with a large number of inputs (18 independently powered PF coils) and a large number of outputs (6 control parameters used in these particular experiments), Fig.1. Complete details of this work and references are available [2].



**Fig.1.** TCV vessel, poloidal field coils, poloidal field probes and separatrix

**2. METHOD** The open loop response cannot be measured by simply opening the feedback loops, since the vertical position of the plasma is unstable with an elongated plasma cross-section. However the open loop response can be recovered from closed loop data. In the block diagram of the TCV control loop, Fig.2, we identify a model for  $G(s)$ , using measurements of the voltage commands ( $u$ ) and the control parameters ( $cp$ ), taken at 5kHz over 0.5 s. Six electromagnetic parameters are considered: P\_VERT (the radial flux imbalance measuring the radial position), TRI\_OUT (the outboard field curvature) and TRI\_IN



**Fig.2.** TCV control loop

(the inboard field curvature) define elongation and triangularity,  $I_p$  (the plasma current),  $zI_p$  (the product of the plasma current and the vertical plasma position).  $\Psi_R$ , the difference between the  $R^2 I_p$  and  $R_0^2 I_p$  current moments, is the only parameter not under feedback control. All are estimated by linear combinations of fluxes,

poloidal fields, and poloidal field coil currents. The E and F coils were excited symmetrically with respect to the horizontal mid-plane to form pairs driven in two modes, symmetric and anti-symmetric. This decouples the allowable motion for up-down symmetric and centred plasmas. A weakly shaped plasma with a low vertical instability growth rate ( $\sim 200s^{-1}$ ) was chosen. The main parameters were:  $R=0.87m$ ,  $a=0.22m$ ,  $B_\phi=1.4T$ ,  $I_p=200kA$ ,  $\kappa_{95}=1.4$ ,  $\delta_{95}=0.23$ ,  $q_a=4.6$ ,  $n_e=2.2 \times 10^{19} m^{-3}$ .

The excitation signal,  $s$  in Fig.2, contained 29 sine waves spanning the range 20 rad/s to 3000 rad/s, lying within 80% of the power supply limits. The response of all the measured signals at the driven frequencies was obtained by a least squares fit.

The frequency spectra of all of the input and output data were used to obtain the open loop frequency response. To identify a 1-output,  $q$ -input system we need to have performed  $q$  experiments. For the  $j^{th}$  experiment we define the input frequency spectrum as  $U_i^j(\omega_i)$  and the output frequency spectrum as  $Y^j(\omega_i)$ , where  $l$  indexes the inputs. An estimate of the open loop frequency response at each measurement frequency is given by

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

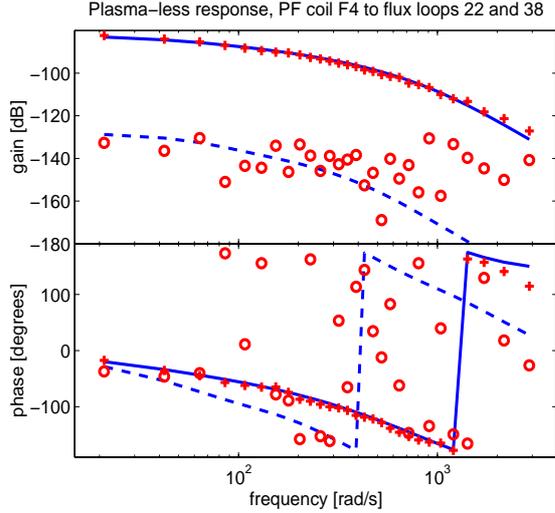
**3. MODELS** We compare these measured open loop responses with those predictions of different plasma models.

A ‘plasma-less’ model, represents only the interactions between the applied voltages and the active currents, passive currents and diagnostic measurements.

The CREATE-L model [1] is a locally linearised representation of the response of a fully deformable equilibrium, derived from the PROTEUS non-linear model.

RZIP [2] is a circuit equation model of TCV based on the supposition that the plasma current distribution remains constant during any control action, but that its position can move vertically and radially and the total plasma current can change. Quantities dependent on the plasma current distribution are obtained by averaging over the reconstructed plasma current distribution. The Shafranov radial force balance and the conservation of poloidal flux weighted by the plasma current distribution are assumed.

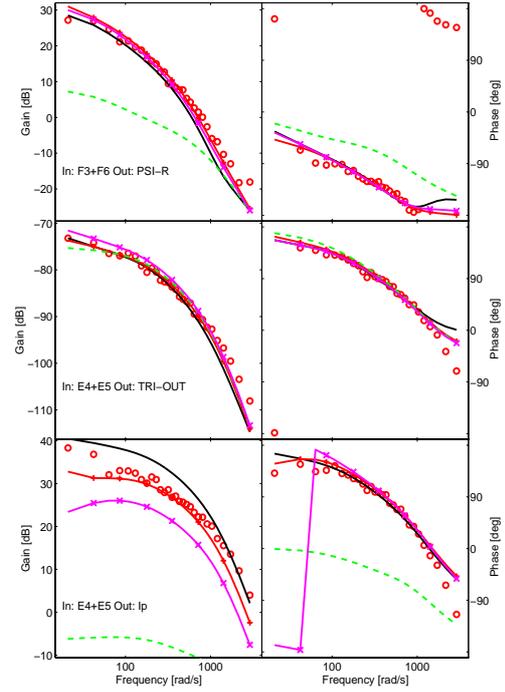
**4. RESULTS** The plasma-less model was validated with a series of tests with no plasma. Where the variance of the estimates is low the model-estimate fit is extremely accurate. Typical errors lie within 1dB and 5 degrees for frequencies below 1000 rad/s, Fig.3. For small output responses, the estimate variance is poorer but the data never invalidate the model.



**Fig.3.** Modelled (curves) and measured (crosses and circles) responses of the plasma-less system

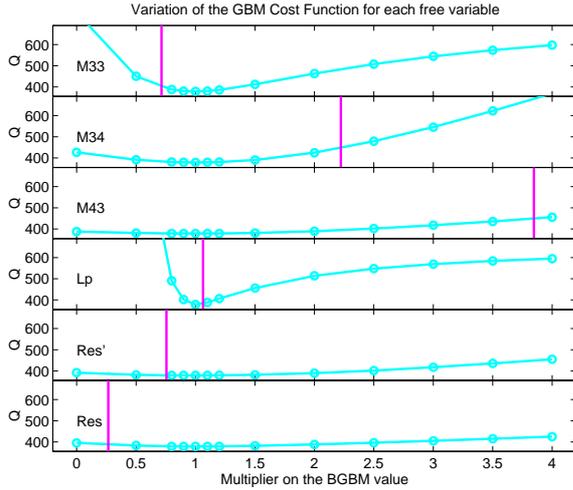
The experimental data from the anti-symmetric coil-pair experiments generated the  $zI_p$  frequency responses and a fitted model with a single unstable pole and 3 stable poles. The predictions of the growth rate are very close ( $213 \text{ s}^{-1}$  measured compared with  $209 \text{ s}^{-1}$  for RZIP).

The agreement for the symmetric responses is generally good, typified by Fig.4. The input-output pair F3+F6 to  $\Psi_R$  illustrates the most typical result - both plasma models agree with the experimental data, but the plasma-less model is incorrect. In a few cases, even the plasma-less model agrees, such as E4+E5 to TRI-OUT. For only some plasma moments the models can differ by more than the experimental variance, illustrated by E4+E5 to  $I_p$ . There is no significant difference between the reliability of the CREATE-L model or the RZIP model.

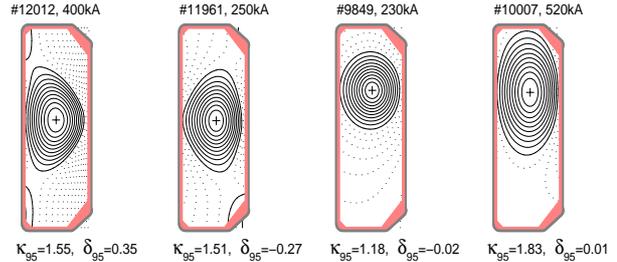


**Fig.4.** Symmetric frequency responses

**5. GREY BOX MODEL** We have developed a hybrid approach to modelling which incorporates well defined *a priori* knowledge for part of the model and experimental data to identify the intrinsic plasma response. “Grey Box” modelling is particularly suited to our present problem due to the large number of known coefficients compared with the small number of uncertain coefficients. The RZIP circuit equations contain a large number of coefficients, most of which are independent of the presence of the plasma and can, in principle, be modelled or measured with unlimited precision. The plasma response part of the RZIP model is dominated by only six coefficients  $M_{33}$ ,  $M_{34}$ ,  $M_{43}$ ,  $L_{p0}$ ,  $\Omega_p$  and  $\Omega'_p$  [2]. Varying these defines our set of possible GBMs. We evaluated the  $10 \times 5$  input-output transfer functions for up-down symmetric excitation at all frequencies. A simplex search on the six GBM parameters minimised a suitably chosen cost function and produced the ‘Best GBM’ (BGBM). A single parameter scan was performed on each element around the BGBM, Fig. 5. The parameter causing the most rapid variation of the cost function is  $L_{p0}$ , the plasma inductance. The next sensitive parameter is  $M_{33}$ , which defines the Shafranov equilibrium constraint. The parameters  $M_{34}$  and  $M_{43}$  have much shallower minima and predominantly define the interactions between the loop voltage and the position and between the vertical field and the plasma current. Finally, the resistive terms,  $\Omega_p$  and  $\Omega'_p$ , are the most shallow.



**Fig.5.** Cost function variation with the unknown elements of the circuit equations



**Fig.6.** The extreme plasma shapes for which the RZIP model was calculated

The vertical lines indicate the values of the *a priori* model parameters. Fig.4 superimposes the BGBM model on the *a priori* transfer functions. Most are unchanged to the eye. The worst case of the plasma current response has been significantly rectified.

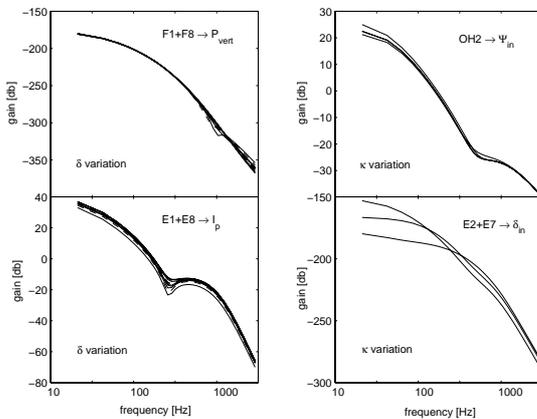
Having located the BGBM, we floated the power supply time-constant, finding a minimum at 0.6 ms, and we floated the number of vessel eigenmodes required, finding that 15 eigenmodes should be included.

**6. DISCUSSION** We investigated whether the good agreement is limited to modest elongation. Fig.6 shows some extreme cases of elongation and triangularity. The dominant parameters vary little, whereas the parameters which vary the most are those with the least effect on the response. Fig.7 confirms this for selected input-output pairs. We tested two even simpler models, assuming a circular parabolic plasma current distribution and one with the ellipticity of the outer magnetic surface. Fig. 8 confirms the insensitivity to the current profile, although the model remains dependent on the plasma position.

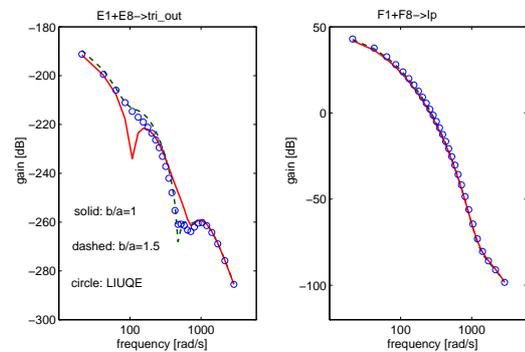
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## References

- [1] R. Albanese and F. Villone: Nucl. Fusion **38** (1998) 723.
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**Fig.7.** The variation of the RZIP model for the equilibria in Fig.6



**Fig.8.** Transfer functions for the nominal RZIP model (circles), the model with circular current distribution (solid curves) and the model with elliptical profile (dashed curves)