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ABSTRACT
A simple but reliable poloidal beta response model is derived from Goldston's scaling law and successfully applied to a large number of plasma configurations and pulses in the JET tokamak. It provides a good prediction of both transient phase and steady state conditions without the need of an auxiliary pulse. The model, although non linear as a function of the input power, is actually linear if the input quantity is the square root of the overall input power divided by the plasma current. The model can then be used for the design of an integrated feedback controller that simultaneously regulates plasma current, position, shape and poloidal beta.

1. INTRODUCTION
Several plasma disruptions occur whenever one or more parameters (e.g., internal inductance, poloidal beta, plasma current, magnetic energy derivative) exceed a specific operational range. Thus, a possible way to avoid abnormal pulse terminations is to keep these quantities inside the domain of the parameter space with low risk of disruption [1].

To do this, the plasma control system must simultaneously regulate a number of plasma parameters. For instance, the accurate control of the beta parameter at 95% of the stability boundary allows to avoid the occurrence of the beta-limit disruptions.

The aim of this work is to provide a simple but reliable poloidal beta response model in JET that can be used for the design of an integrated feedback controller that simultaneously regulated plasma current, position, shape and poloidal beta.

The present poloidal beta model starts from previous work [2], which assumed a linear time-invariant dynamic response of the normalized toroidal beta β_{tn} to the input power coming from the neutral beams P_{NBI}.

2. POLOIDAL BETA RESPONSE MODEL
2.1 LINEAR TIME INVARIANT MODEL
Following the approach proposed in [2] for the response of β_{tn} to P_{NBI}, a linear time-invariant model for the poloidal beta β_p to the total input power P_{IN} in the Laplace domain is:

$$\beta_p = \frac{k_1}{1+ s\tau}\, P_{IN} = k_2 \tag{1}$$

where the constants k_1, k_2 and t are obtained by best fit of the experimental data.

The main differences from [2] are that the output quantity is β_p instead of β_{tn} and that the input is this time the total input power P_{IN} (including all sources, namely ohmic and auxiliary heating). However, this linear model has the following limitations:

- it is empirical, hence different constants have to be used for different plasma conditions;
- to use this model for feedback of a given plasma configuration, an auxiliary pulse has to be planned to obtain the constants;
- it is hard to have a good fit of both transient phases and steady state conditions.

These problems can be settled using a simple nonlinear model based on physical relationships.

2.2 SIMPLE NONLINEAR MODEL

The power balance in a tokamak can be expressed as:

$$P_{IN} - P_{LOSS} = dW/dt \tag{2}$$

where t is the time, W is the plasma energy, P_{IN} is the total input power, and P_{LOSS} is the power loss. At steady state, we have:

$$P_{IN} = P_{LOSS} = W/\tau_e \tag{3}$$

where τ_e is the plasma energy confinement time.

According to Goldston's scaling for tokamaks with auxiliary heating, the confinement time is inversely proportional to the poloidal beta [3]:

$$\tau_e \propto 1/\beta_p \tag{4}$$

The plasma energy is proportional to the poloidal beta multiplied by the square of the plasma current ($W \propto I_p^2 \beta_p$), hence (3) and (4) yield:

$$P_{IN} \propto \beta_p^2 / I_p^2 \tag{5}$$

and finally:

$$\beta_p \propto \frac{\sqrt{P_{IN}}}{I_P} \tag{6}$$

at steady state.

Thus, the proposed poloidal beta response model is:

$$\beta_p = \frac{k}{1 + s\tau} \frac{\sqrt{P_{IN}}}{I_P} \tag{7}$$

The constants in (7) are obtained by best fit of the experimental data on a large variety of pulses and plasma configurations.

It is worth noticing that the model is linear time invariant when taking $P_{IN}^{1/2}/I_p$ as input quantity.

The time constant t in (7) is clearly related to the energy confinement time. Therefore, a better description of the phenomenon could be obtained by expressing t as a function of β_p, but in this case the model would become strongly non linear.

3. SIMULATIONS VERSUS EXPERIMENTAL DATA

The model described by (7) has been implemented in Matlab-Simulink and has been applied to the JET tokamak, assuming as input power:

$$P_{IN} = P_{OH} + P_{NBI} + P_{LH} + P_{ICRH} \tag{8}$$

namely the overall input power coming from ohmic heating (P_{OH}), neutral beams (P_{NBI}), lower hybrid antenna (P_{LH}), and ion cyclotron radio frequency system (P_{ICRH}).

The coefficients in (7) have been calculated so as to obtain the best fit between simulated output data and experimental values of β_p over a large number of pulses and plasma configurations. Their values in SI units are k = 414 and t = 0.300.

The agreement between the simulated results and the experimental values of β_p are fairly good, for a large variety of plasma parameters and shapes.

Figures 1 and 2 show the time response of β_p to a single rectangular pulse of P_{NBI}. The agreement of the model prediction with the experimental data is very good for Pulse No: 74299. Figure 1 also shows the role played by the plasma current when I_p ramps down from its flat top value of *2.5MA*. The predictions in all other simulations are still acceptable. The fitting error is within a 20% range of the peak value (see for instance Fig.2, where the plasma current is *1.2MA*), which makes the model well suited for feedback control.

Figures 3 and 4 show the time response of β_p to different waveforms of P_{NBI} for plasmas with a high triangularity and large excursions of the internal inductance. Also in these cases the model predictions are fairly acceptable.

CONCLUSIONS

A simple nonlinear model of the dynamic response of the poloidal beta to the overall input power has been derived from Goldston's scaling law and successfully applied to JET.

This model has the following features:

- the relationships with the nominal values of poloidal beta β_p and plasma current I_p:
- a good prediction of both transient phase and steady state conditions without the need of an auxiliary pulse;
- the applicability to a wide set of plasma conditions.

The model, although non linear as a function of the input power, is actually linear if the input quantity is the square root of the overall input power divided by the plasma current. It can then be used for the design of an integrated feedback controller that simultaneously regulates plasma current, position, shape and poloidal beta.

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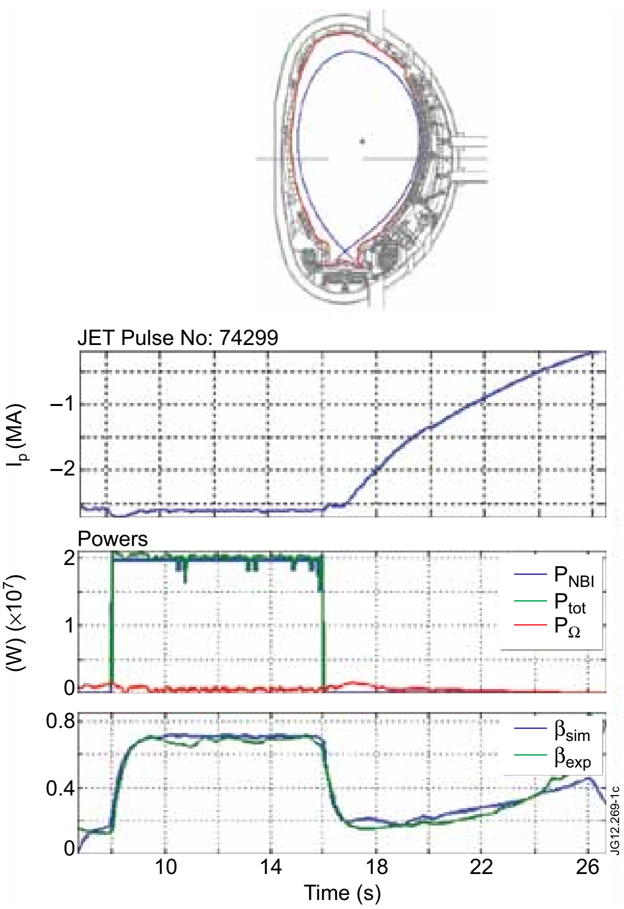

Figure 1: Poloidal beta response to the input power in JET Pulse No: 74299: simulation versus experimental data.

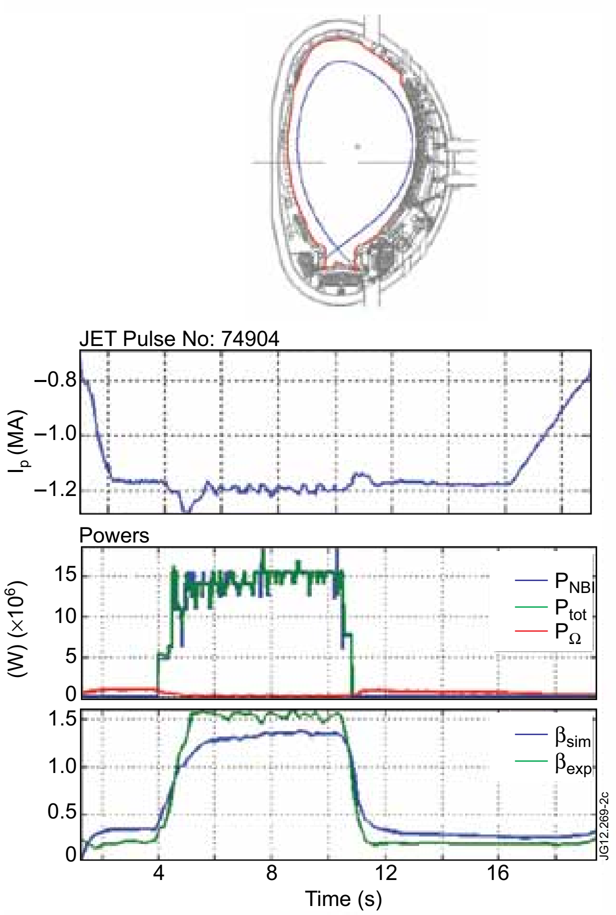

Figure 2: Poloidal beta response to the input power in JET Pulse No: 74904: simulation versus experimental data.

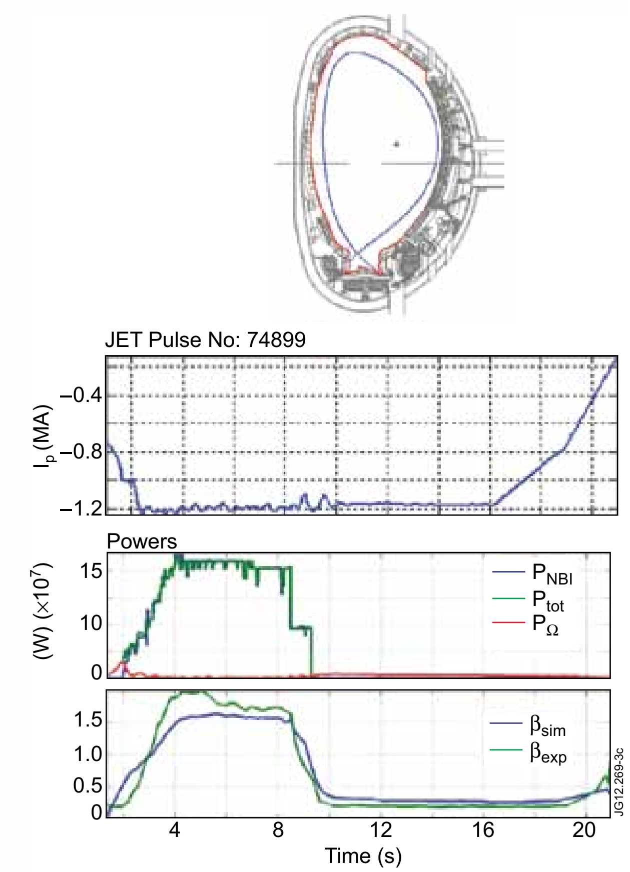

Figure 3: Poloidal beta response to the input power in JET Pulse No: 74899: simulation versus experimental data.

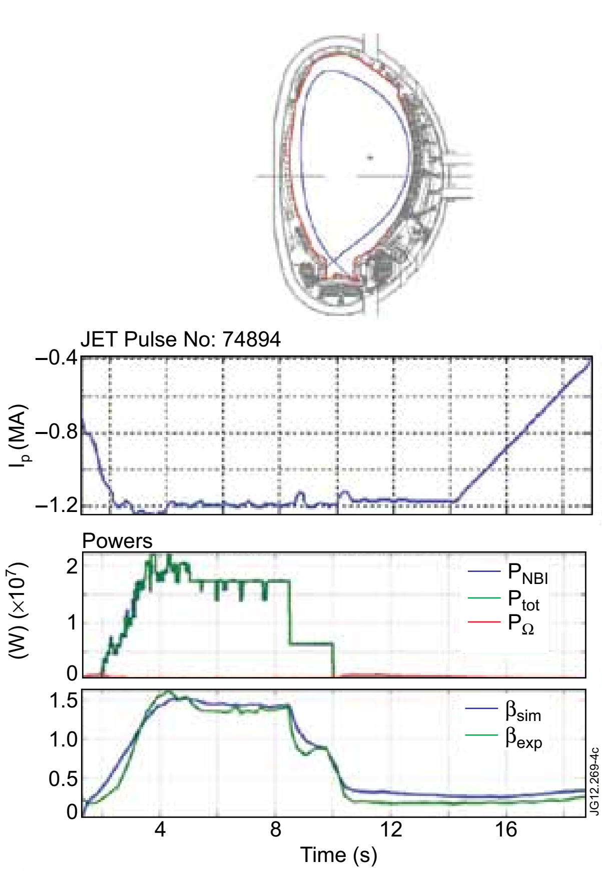

Figure 4: Poloidal beta response to the input power in JET Pulse No: 74894: simulation versus experimental data.