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ABSTRACT

Growth rates of the axisymmetric instability of elongated plasmas in TCV are measured, in open loop configuration, for a wide variety of plasma shapes with elongations and triangularities in the ranges, $1.3<\kappa<2.2$ and $-0.3<\delta<0.6$, respectively, and for stability margins covering the range $1.03<f<1.60$. In addition, the stability of the vertical position control system is investigated experimentally, under closed loop conditions, by varying the feedback gains and by measuring the oscillation frequencies close to the stability limit. The results of these measurements are compared with theoretical calculations, based on rigid (RPM) and deformable (DPM) plasma models. While the RPM model underestimates the open loop growth rate for large values of δ and overestimates the size of the stable domain in gain space, the DPM model gives very good agreement with the experimental results.

1. INTRODUCTION

Vertical elongation of the plasma cross section is one of the key parameters in the design of a tokamak. The history of the ITER design effort clearly demonstrates this. On the one hand, high elongation brings a number of advantages, such as higher beta limits and better confinement, but on the other hand, it leads to serious design problems, related to the appearance of axisymmetric instabilities. The fact that the elongation of the ITER reference plasma has changed considerably over the years shows that it is extremely difficult to find an optimum compromise between advantages and disadvantages. The benefits of high elongation have been investigated in great detail by numerous authors [1-7]. The disadvantages however are not so well known because they involve both physics and technology issues. A realistic assessment of the problems associated with the stabilization, or lack of stabilization, of axisymmetric modes obviously requires extensive numerical simulations, using an accurate and validated model of the complete system.

Several models have been developed in the past [8-23]. The philosophy of these models covers a wide range, going all the way from "black-box" models [23], whose parameters are usually determined by perturbation measurements on a real tokamak, to "ab initio" models [12,17], which try to represent the underlying physics of the system as accurately as possible. The models also differ widely in sophistication. In some models, the plasma is represented by a single current carrying filament [10,11,14], whereas in other models, the plasma is simulated using an ideal MHD stability code [8,15]. Some of the models have been used to predict open loop growth rates of the most unstable axisymmetric mode, i.e. the so-called vertical instability [8,9,18-24]. Other models have been applied to the problem of closed loop stability [10,11,14-17,19,21,22], and one of the models [13] has been used to simulate perturbation experiments [25,26].

In this paper, we present new measurements of vertical instability growth rates in TCV, extending previous work to very low stability margins, as well as detailed measurements of closed loop stability limits, and we compare these measurements with predictions of deformable and rigid plasma models [21,22].

2. VERTICAL INSTABILITY GROWTH RATES

2.1. Theoretical predictions

The calculation of a vertical instability growth rate is usually a two step process. The first step consists of computing an ideal MHD equilibrium and the second step involves the calculation of the axisymmetric evolution of the vertically unstable plasma in the presence of a resistive shell and other passive conductors. Since our aim is to compare theoretical and experimental growth rates, we use an equilibrium reconstruction code, LIUQE [27], to accomplish the first step. LIUQE is a free-boundary MHD equilibrium code which solves the Grad-Shafranov equation in such a way as to minimize the difference between experimental measurements and the corresponding reconstructed quantities. The equilibrium source functions are parameterized, and LIUQE can compute up to 7 independent source function parameters, depending on the type and quality of experimental data available [27]. For Ohmic plasmas, which is what we are considering in the present study, the source functions are relatively smooth and consequently, 3 to 4 independent parameters are sufficient for producing a good fit to the measurements.

For a given ideal MHD equilibrium, the linearized axisymmetric evolution of the plasma, under open loop conditions, can be described by an eigenvalue equation, the parameters of which depend on the plasma model to be used. Four models have previously been used to compute open loop growth rates in TCV, i.e., NOVA-W [24,28], DPM [22], RPM [21] and RCDM [18]. NOVA-W is a linear MHD stability code [28] that calculates the axisymmetric growth rate and eigenfunction in the presence of a resistive wall and other passive elements. DPM is a deformable plasma model, based on calculations of the perturbed poloidal flux due to perturbed currents in the vacuum vessel and active feedback coils. This model is more general than previous models of this kind in that it satisfies ideal MHD constraints and computes perturbed source functions self-consistently. The RPM and RCDM models assume the plasma to be a rigid body, with a fixed current density distribution, whose motion is constrained to purely vertical displacements. While the predictions of

NOVA-W and DPM agree very well over a wide range of growth rates, there are considerable and systematic discrepancies between the DPM and RPM results [22].

In this paper, we compute open loop growth rates of reconstructed TCV equilibria using the DPM and RPM models [22]. In these calculations, we include the stabilizing effect of the vacuum vessel, the external poloidal field coils and the internal coil. In TCV, the main contribution to the stabilizing force is due to induced currents in the vacuum vessel. Growth rate calculations with and without including induced currents in the poloidal field coils show that the stabilizing effect of the coils is small and that it depends on the value of the growth rate. For high growth rates, the effect of the coils is negligible (~3%), whereas for very low growth rates it is significant (~20%).

2.2. Measurements

Growth rates of the vertical instability have been experimentally measured in TCV for a variety of plasma shapes, using the method described in [24]. The measurement is performed by opening the vertical and radial feedback control loops, during quasi-stationary conditions, and observing the exponential growth of the vertical displacement via the magnetic diagnostics. The feedback cut is achieved in hardware by a pre-programmed switch which sets the vertical and radial PID feedback gains to zero. We limit the growth rate analysis to small displacements ($\Delta Z<4$cm) for which the plasma current and shape remain almost constant. Earlier measurements [24] were limited to plasmas with relatively low growth rates because at that time, the fast internal coil was not yet operational on TCV and it was impossible to create plasmas with growth rates exceeding $1000s^{-1}$. Recent measurements include highly unstable plasmas with growth rates up to $5000s^{-1}$ and extremely low stability margins, f=1.03. A typical example of an unstable vertical displacement following a feedback cut is shown in Fig.1.

2.3. Comparison between theory and experiment

Measured open loop growth rates are compared to RPM and DPM predictions in Fig.2. This comparison covers wide ranges of plasma elongation, $1.3<\kappa<2.2$, triangularity,

$-0.3<\delta<0.6$, and stability margin, $1.03<f<1.60$. We use the conventional definitions of elongation and triangularity, based on the shape of the plasma boundary. κ and δ are expressed in terms of the co-ordinates of the extreme boundary points, $\kappa = (Z_4-Z_3)/(R_2-R_1)$, $\delta = (R_2+R_1-R_4-R_3)/(R_2-R_1)$, where the subscripts 1 and 2 refer to the boundary points with minimum and maximum R co-ordinates, and the subscripts 3 and 4 refer to the boundary points with minimum and maximum Z co-ordinates . The stability margin is defined here as $f=1+1/(\gamma\tau_V)$, where γ is the open loop growth rate and τ_V is the decay time of the stabilizing currents in the vacuum vessel. We note that the DPM model gives excellent agreement with the measurements. The RPM model gives an average error which is more than twice that of the DPM model. If we plot the percentage errors as a function of plasma triangularity (Fig.3.), we see that the DPM errors are distributed randomly whereas the RPM errors show a clear correlation with triangularity. This is consistent with our previous results, which indicated that the differences between RPM and DPM predictions depend significantly on triangularity [22] and that the RPM model has a tendency to underestimate the growth rate both for large negative and large positive triangularities [24].

3. STABILITY OF THE VERTICAL POSITION CONTROL LOOP

3.1. Prediction of stable domain in gain space

The vertical position control system of an elongated tokamak is an exceedingly complex object [29]. It consists of a vertical position observer, using magnetic measurements at various locations inside and outside the vacuum vessel, control electronics for performing fast real-time computation, a PID controller, power supplies, active coils, the vacuum vessel which acts as a passive stabilizer, and finally, the plasma itself. In TCV, two sets of active coils are used simultaneously, slow coils outside the vacuum vessel and a fast coil inside the vessel [21]. The slow coils are driven by thyristor-controlled power supplies having a response time of about 1ms. Various combinations of slow coils can be used for active feedback. Here, we consider an up-down symmetric plasma (Fig.4), which uses four outboard slow coils (F2, F3, F6, F7) for proportional and derivative feedback, and the internal coil (G1 and G2, connected in series) for fast derivative feedback. The fast coil is driven by a power supply using insulated gate bipolar transistor (IGBT) technology [30] with a response time less than 0.1ms.

We simulate the vertical position control system of TCV by using two numerical models, RPM and DPM [22]. The only difference between the two models is that RPM assumes a rigid plasma, whereas DPM allows plasma deformations, as explained in section 2.1. Both models have been constructed with the aim of reproducing all elements of the real system as accurately as possible. Solving the model equations tells us whether the system is stable, marginally stable or unstable, for a given set of input parameters. If the system is unstable, the model also gives us the growth rate and oscillation frequency of the instability. In a previous, theoretical investigation [22], these models were used to study the effects of a number of parameters (plasma elongation, triangularity, internal inductance, and the properties of the vertical position observer) on the stability of the closed loop system. Here, we focus our attention on one particular experimental plasma which was created recently in TCV (Fig.4). The plasma is characterized by an open loop growth rate, $\gamma=2300s^{-1}$, corresponding to a very low stability margin, f=1.05. Using a reconstructed MHD equilibrium of this plasma, we compute the stability properties of the closed loop system as a function of the three feedback gains, i.e. the slow proportional gain, P, the slow derivative gain, D, and the fast derivative gain, G [22]. If we use the experimental value of G in the calculation, the result can be displayed in the P-D plane (Fig.5). For very small values of P and D, we find growing exponential solutions. For intermediate values of the feedback gains, we find a stable island where there are no growing solutions. In the remaining area of the P-D plane, we find growing oscillatory solutions whose growth rate is zero on the boundary of the stable island, i.e. on the marginal stability line, and increases as one moves away from that boundary.

3.2. Measurement of stability limits

Stability limits of the vertical position control system in TCV have been measured by systematically varying the gain settings used in the feedback loop. Starting from reference conditions (Fig.4), under which the plasma was stable, the P and D gains were increased and decreased in steps until an instability was observed. The instability usually manifests itself by an oscillation of the vertical plasma position and the currents in the active feedback coils. The oscillation can either be intermittent, or saturated with a constant amplitude, or growing, depending on whether the system is close to or beyond the boundary of the stable domain in the P-D plane. If the oscillation is growing, it rapidly leads to a disruption. The results of these measurements are shown in Fig.5. Stable discharges are shown as open squares. Discharges with intermittent or saturated, low amplitude oscillations are shown as solid squares. Experiments outside the domain defined by the solid squares produced growing oscillations and disruptions. We note that the stable domain, as determined experimentally, coincides well with the stable domain as predicted by the DPM model. The RPM model, on the other hand, predicts a stable domain which extends a considerable distance beyond the experimental stabilty limit, especially for large values of D.

3.3. Oscillation frequency in marginal stability conditions

The oscillation frequencies which are observed experimentally close to the stability limit can be compared with the frequencies predicted by the DPM model on the marginal stability line. In Fig.6, we plot experimental oscillation frequencies, as obtained from the marginal discharges shown in Fig.5. as solid squares, against theoretical frequencies, computed by the DPM model. Again, we find good agreement between theory and experiment. A similar comparison with the RPM model is not possible since its marginal line does not agree with the experimental stability limit.

3.4. Fast oscillations

The stability of the vertical position control loop not only depends on the slow gains, P and D, but also on the fast derivative gain G. Up to this point, we have always used a constant value of G and the value used in the simulations was identical with that used in the experiments. Increasing the value of G generally makes the system more stable, i.e. it increases the size of the stable domain in P-D space [21]. However, it was observed experimentally that, when G is increased above a certain limiting value, the system again becomes unstable and starts to oscillate at a high frequency, typically between 2 and 3 kHz. We have used the DPM model to calculate the threshold value of G for the onset of this fast oscillation. Fig.7A. shows the growth rate of the fast oscillation as a function of G, as calculated for our standard plasma (Fig.4). If we now consider slightly different plasmas, with elongations both larger and smaller than that of the standard plasma, we find that the maximum allowable G value is essentially a function of the open loop growth rate, γ, of the plasma under consideration. This is shown in Fig.7B. where we compare theoretical (DPM) and experimental G values, corresponding to the onset of the fast oscillation, as a function of γ. The model appears to represent the experimental trend correctly.

4. CONCLUSION

Open loop growth rates of the axisymmetric instability have been measured in TCV for a wide variety of plasma shapes, including configurations with extremely low stability margin, f=1.03. Comparing these measurements with theoretical predictions, based on the deformable (DPM) and rigid (RPM) plasma models shows that the DPM gives good agreement with the experiment over the entire range of plasma parameters. The RPM also gives fairly good agreement, but has an average error which is more than twice the DPM error. The limits of closed loop stability have been investigated exprimentally by systematic variation of the feedback gains. We find good agreement between the experimental stability limits and the marginal stability line as computed by the DPM. The stable domain of the RPM, however, is much larger than that of the DPM and goes far beyond the experimental stability limits. Measured oscillation frequencies near the stability limit have been shown to agree with theoretical frequencies on the marginal stability line, as obtained from the DPM model. Finally, the DPM appears to predict the correct threshold value of the fast gain, G, for the onset of high frequency oscillations.

In conclusion, we have shown that the open loop and closed loop behaviour of the vertical position control system in TCV can be accurately simulated by a numerical model which consists of detailed physical descriptions of all elements of the tokamak and a perturbed equilibrium representation of the plasma (DPM). This model can now be used for further optimization of the system or for design studies of new tokamaks.

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Figure Captions

Fig.1 Loss of vertical position control following a feedback cut at 0.5 s. Time is given on top of each frame. Plasma parameters: I_p=250kA, κ=2.1, δ=0.45, q_{95}=5.1.

Fig.2 Comparison of experimental open loop growth rates of the vertical instability in TCV with the predictions of rigid (RPM) and deformable (DPM) plasma models.

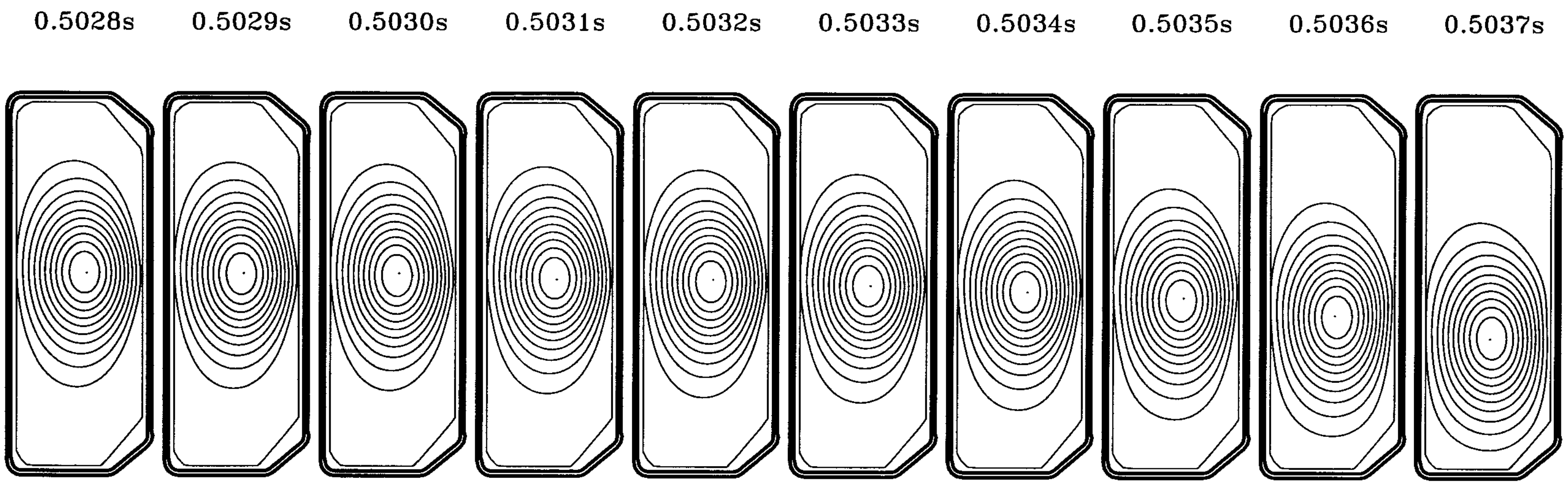
Fig.3 Difference between theoretical and experimental open loop growth rates of the vertical instability in TCV, versus plasma triangularity, for rigid (RPM) and deformable (DPM) plasma models.

Fig.4 Reconstructed equilibrium of the standard plasma used for closed loop stability studies. Active feedback applied to slow coils outside the vessel (F2,F3,F6,F7) and fast coil inside the vessel (G1-G2).

Fig.5 Comparison of closed loop stability predictions with experimental results in TCV. White and dotted areas are predicted to be stable and unstable, respectively. Stable experimental conditions are shown as open squares. Oscillations were observed on the boundary of the stable domain (solid squares).

Fig.6 Comparison of experimental and theoretical oscillation frequencies on the boundary of the stable domain in the P-D plane.

Fig.7 (A) Predicted closed loop growth rate of the fast mode versus fast derivative gain, G. (B) Comparison of experimental and theoretical (DPM) fast gain thresholds for the onset of high frequency oscillations, vs. open loop growth rate.



0.5028s
0.5029s
0.5030s
0.5031s
0.5032s
0.5033s
0.5034s
0.5035s
0.5036s
0.5037s

Fig.1.

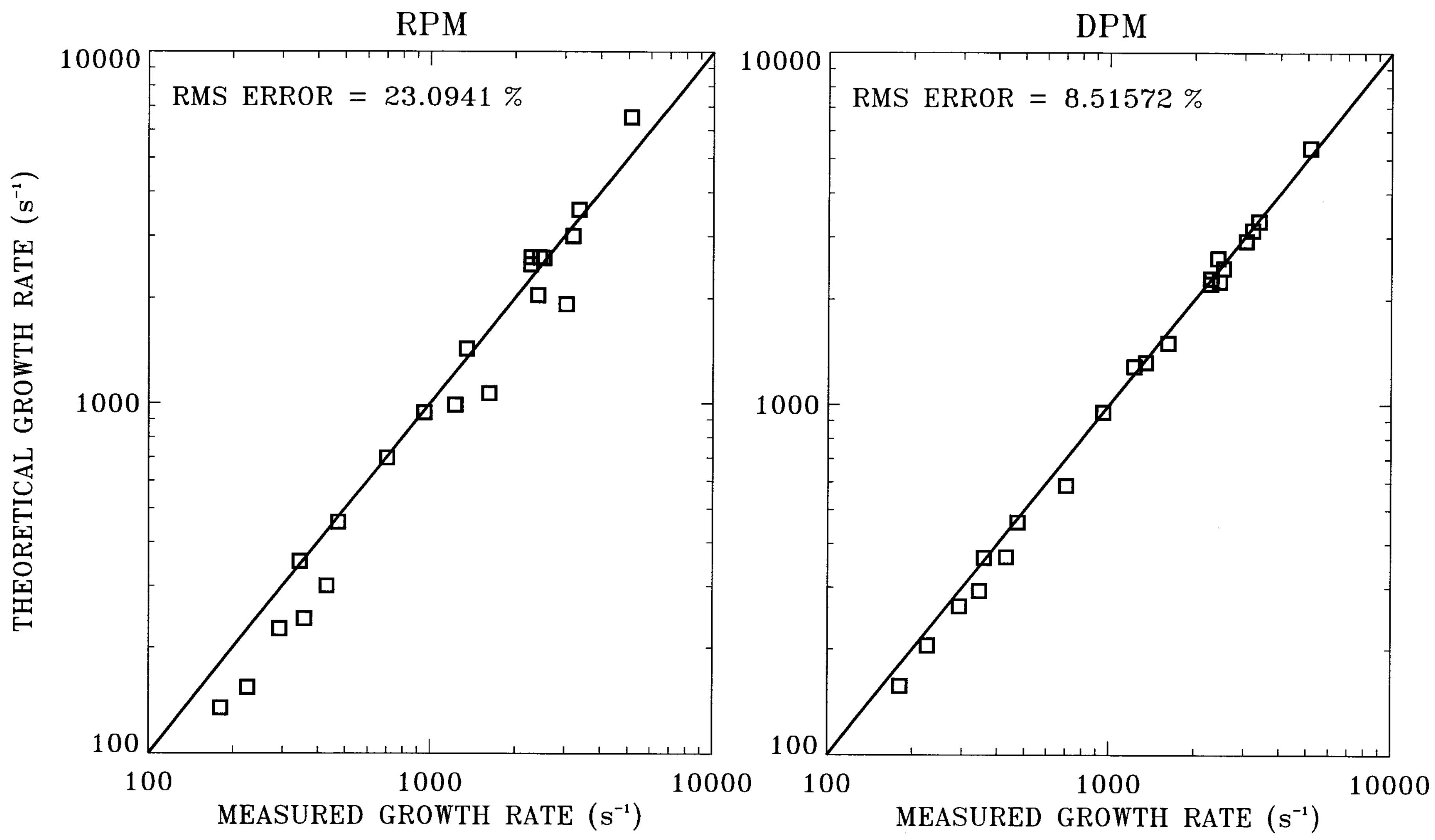

RPM
RMS ERROR = 23.0941 %
DPM
RMS ERROR = 8.51572 %
THEORETICAL GROWTH RATE (s⁻¹)
MEASURED GROWTH RATE (s⁻¹)
MEASURED GROWTH RATE (s⁻¹)
100
1000
10000

Fig.2.

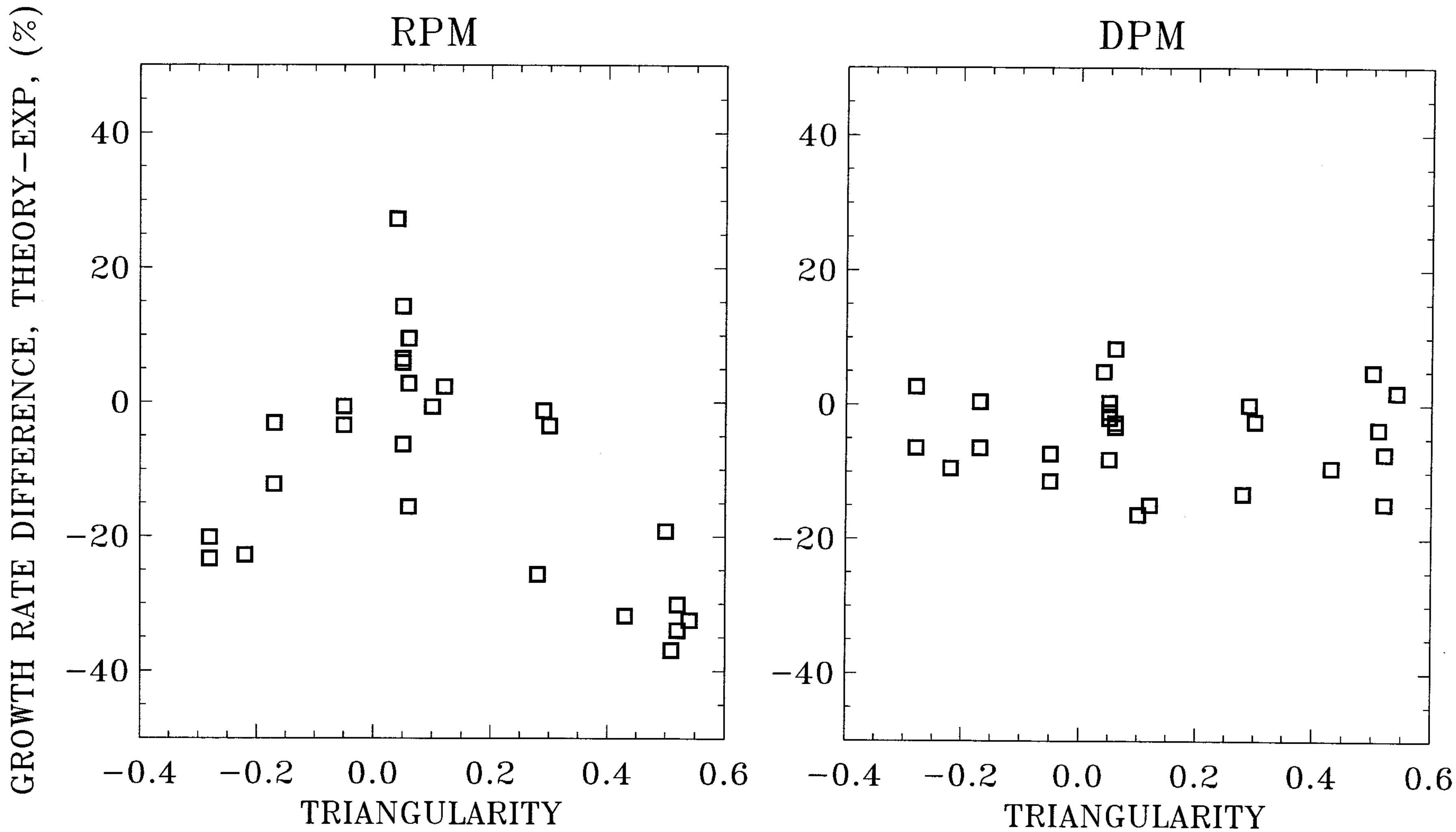
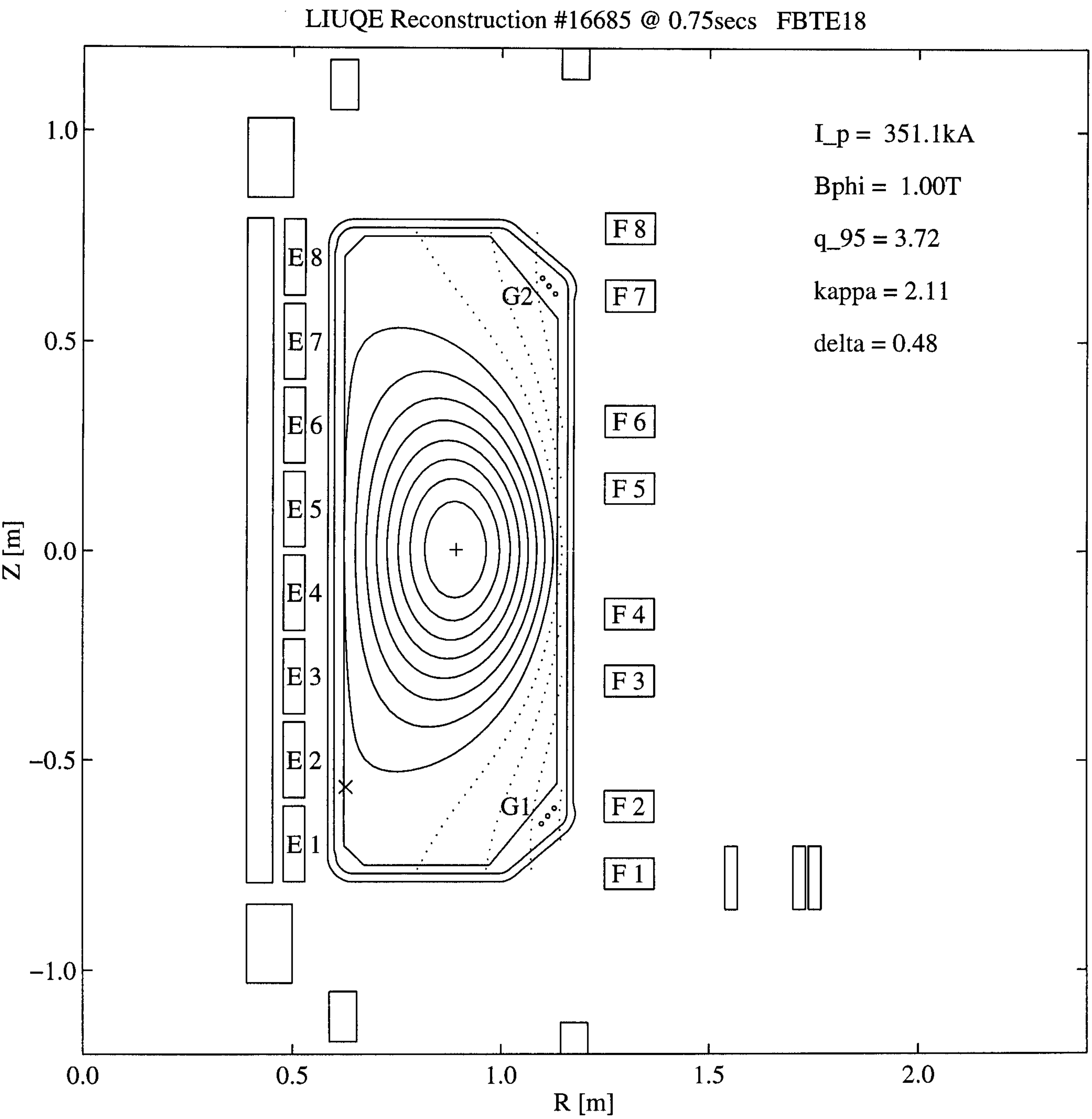

RPM
DPM
GROWTH RATE DIFFERENCE, THEORY−EXP, (%)
40
20
0
−20
−40
−0.4
−0.2
0.0
0.2
0.4
0.6
TRIANGULARITY
TRIANGULARITY

Fig.3.


LIUQE Reconstruction #16685 @ 0.75secs FBTE18
I_p = 351.1kA
Bphi = 1.00T
q_95 = 3.72
kappa = 2.11
delta = 0.48
E 1
E 2
E 3
E 4
E 5
E 6
E 7
E 8
F 1
F 2
F 3
F 4
F 5
F 6
F 7
F 8
G1
G2
Z [m]
R [m]
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0.5
0.0
−0.5
−1.0
0.0
0.5
1.0
1.5
2.0

Fig.4.

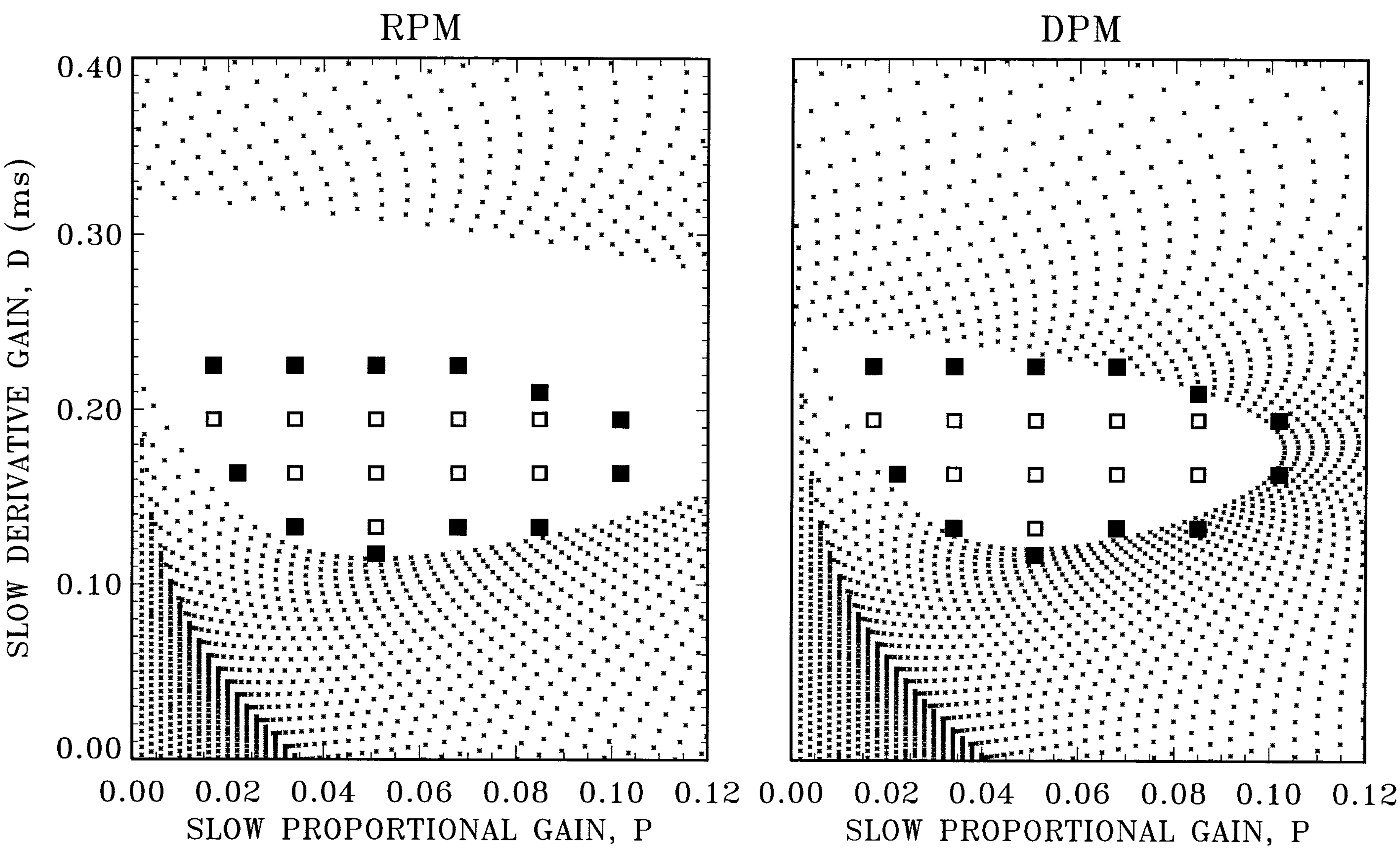
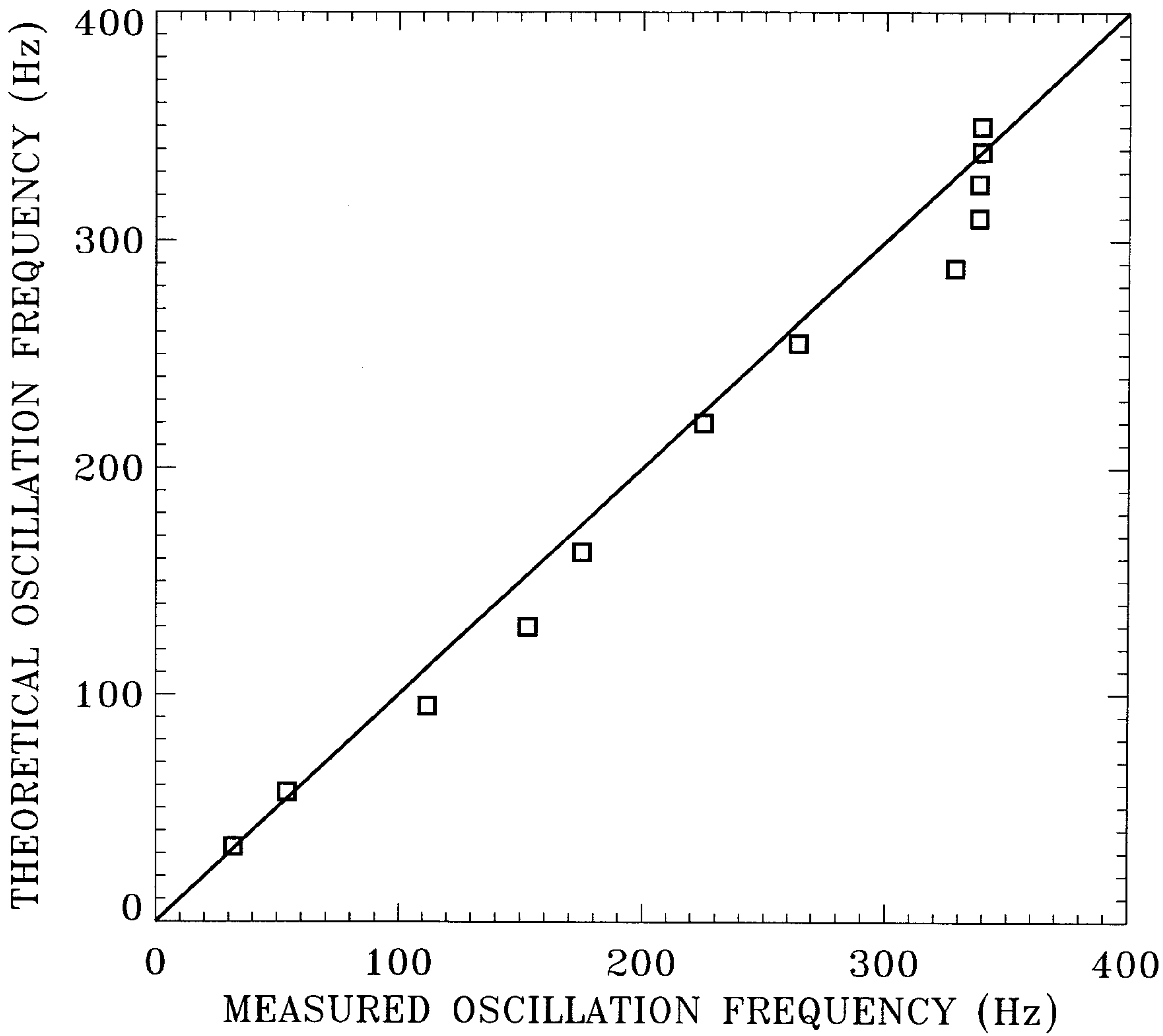

RPM
DPM
SLOW DERIVATIVE GAIN, D (ms)
0.40
0.30
0.20
0.10
0.00
0.02
0.04
0.06
0.08
0.10
0.12
SLOW PROPORTIONAL GAIN, P
SLOW PROPORTIONAL GAIN, P

Fig.5.



THEORETICAL OSCILLATION FREQUENCY (Hz)
0
100
200
300
400
MEASURED OSCILLATION FREQUENCY (Hz)

Fig.6.

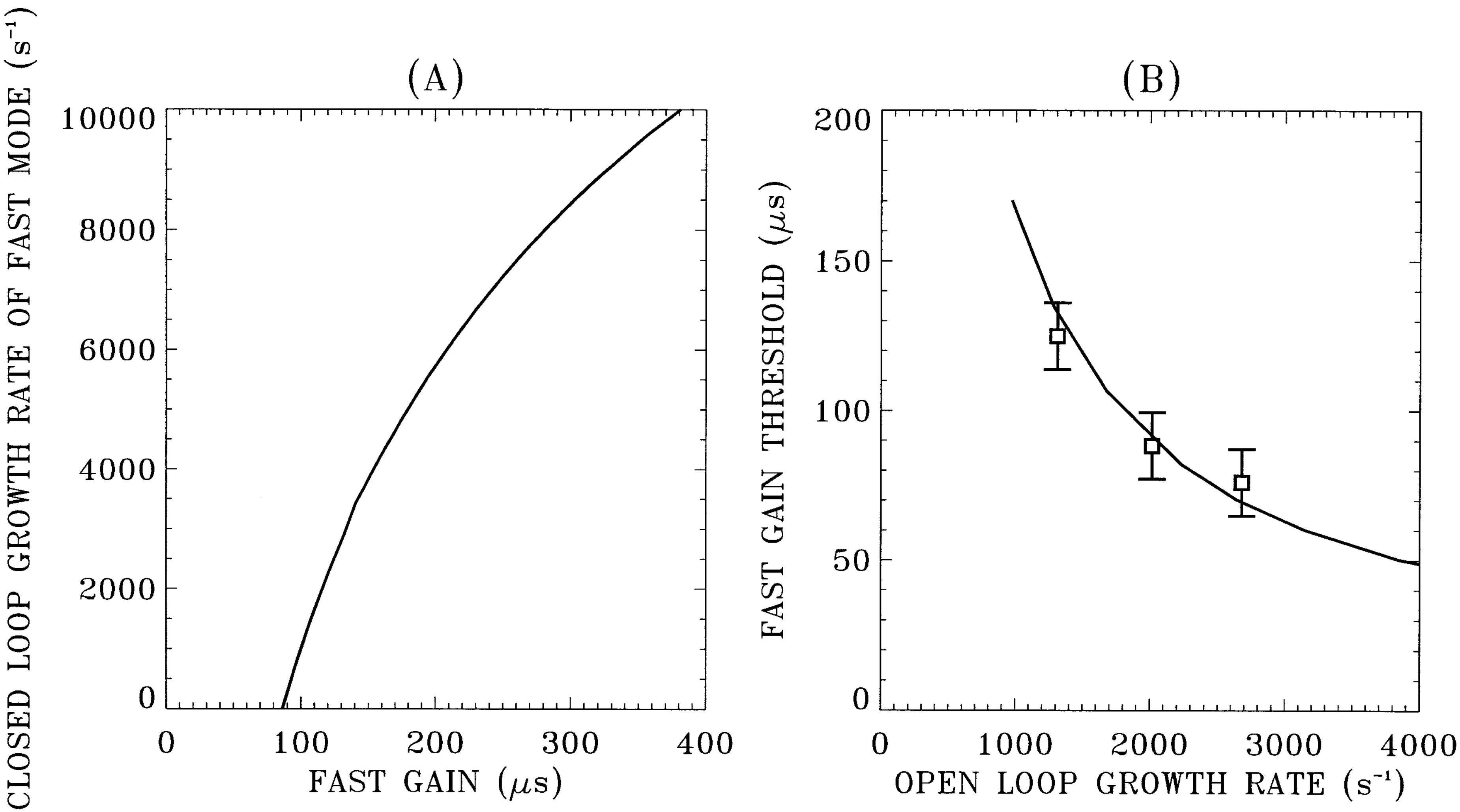

(A)
CLOSED LOOP GROWTH RATE OF FAST MODE (s⁻¹)
10000
8000
6000
4000
2000
0
0
100
200
300
400
FAST GAIN (μs)
(B)
FAST GAIN THRESHOLD (μs)
200
150
100
50
0
0
1000
2000
3000
4000
OPEN LOOP GROWTH RATE (s⁻¹)

Fig.7.