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Vertical Instability in TCV: Comparison of Experimental and Theoretical Growth Rates

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Abstract

Growth rates of the axisymmetric mode in vertically elongated plasmas in the TCV tokamak are measured and compared with numerically calculated growth rates for the reconstructed equilibria. This comparison is made over a range of discharge parameters including elongation, triangularity, and vertical position within the vacuum vessel. Growth rates increase with respect to increasing elongation, decreasing triangularity and increasing vertical distance from the top of the vacuum vessel, as expected. The agreement between the measured growth rates in the experiment and the numerically determined growth rates is excellent, in particular for the full linear MHD model which accounts for the non-rigid motion of strongly shaped plasma cross-sections.

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1. Introduction

Passive and active stabilization of the vertical instability in elongated tokamaks has become standard practice in many laboratories throughout the world [1-7]. Theoretical understanding and experimental implementation of this technique are sufficiently advanced that, in most cases, no serious problems are encountered. However, there are cases where an acceptable solution to the problem of vertical stability is not at all trivial. One example is a tokamak with superconducting poloidal field coils. Here, the voltages that can be applied to the PF coils must not be excessive to avoid coil quenches due to AC eddy currents. This imposes severe constraints on the vertical position control system [8]. Another example is a highly elongated tokamak ($\kappa > 2$) where the growth rate of the vertical instability can become much larger than the inverse decay time of the m=1 shell currents, and hence, the stability margin can shrink to dangerously low values.

The TCV tokamak [7,9] is a typical case of the latter category since it is designed to create plasmas over a wide range of cross-sectional shapes, up to an elongation of 3. Theoretical calculations [10] have shown that a D-shaped plasma in TCV with a plasma current of 1MA and an elongation of κ=3 has a vertical growth rate of the order of 2500 sec^{-1}, corresponding to a stability margin of approximately 1.05. Such configurations are very close to the absolute stability limit given by the fast motion on the Alfvén time scale. Under these circumstances, theoretical estimates of the vertical growth rate are extremely important in the design phase of new discharge scenarios, since they can tell us whether a particular scenario is feasible or not.

In order to test the accuracy of our theoretical models, we compare, in this paper, measured and calculated vertical growth rates for a variety of TCV plasmas, covering a wide range of parameters such as elongation, triangularity and vertical position within the vacuum vessel. Experimental growth rates are derived from magnetic measurements and soft X-ray tomography. Theoretical growth rates are determined from the full linear MHD calculation of the NOVA-W code [11] and from a Rigid Current Displacement Model [12].

Similar comparisons of measured and calculated vertical growth rates have also been made on other tokamaks. On PDX [13] and DIII-D [4], measured growth rates were compared with the results of a filamentary current model. On Compass-D, open loop growth rates were determined from perturbation measurements using system identification techniques [14], and compared with theoretical results obtained from an axisymmetric current filament simulation programme [15]. However, none of these previous studies have included scans of vertical position within the vacuum vessel or triangularity scans extending to negative values.

2. TCV Tokamak

The main aim of TCV is to investigate the effects of plasma shape on tokamak physics. Consequently, the machine has been designed such that it can produce a large variety of plasma shapes without requiring hardware modifications. At high elongation, this versatility is obviously in conflict with the necessary requirement of a close fitting passive shell. As a result, the design of TCV is a compromise between maximum shape variability and good passive stabilization.

The vacuum vessel is a continuously welded structure with very low toroidal resistance (49 μ Ohms) and a nearly rectangular cross section. The decay times of toroidal vessel currents are 13 and 8.5 ms for the m=0 and m=1 modes, respectively. The poloidal field system (Fig. 1) consists of an Ohmic transformer and 16 independently driven shaping coils located between the vacuum vessel and the toroidal field coils. The shaping coils are driven by thyristor-controlled power supplies with a response time of the order of 1 ms. Two additional poloidal field coils are mounted inside the vacuum vessel, near the outer corners. These coils are driven by a fast power supply [16] and will be used to stabilize plasmas with very high vertical growth rate. TCV has an advanced plasma control system based on analog-digital hybrid technology [17].

3. Experimental Growth Rates

Growth rates of the vertical instability have been experimentally measured in TCV in a variety of low-current (250kA) discharges. Low current was used in order to minimize the harmful effects of repetitive disruptions. The measurement was 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 and soft X-ray diagnostics [18]. The feedback cut is achieved in hardware by a pre-programmed switch to a new set of control matrices, in which the vertical and radial PID feedback gains are set to zero.

Earlier experiments [19] showed that, for a particular configuration, the unstable plasma motion was always in the same direction, either up or down and that the initial vertical displacement could not be fitted with a single exponential function. This behaviour was caused by a small radial magnetic field which was applied inadvertently at the time of the feedback cut. The radial field was subsequently eliminated by a fine adjustment of the vertical position reference signal, such that the direction of the initial vertical displacement became virtually unpredictable. Under these conditions, the plasma trajectory agrees very well with a single exponential function, and an accurate value of the growth rate can be extracted. Fig. 2 shows an example of a vertical feedback cut during the flattop (t=0.47 s) and the subsequent vertical displacement of the plasma.

Vertical displacement can be measured in TCV in three different ways: (1) the real-time Ip*z observer used for feedback control of the vertical position [20], (2) a full equilibrium reconstruction [21] based on a complete set of magnetic measurements, and (3) the centroid motion of the tomographically reconstructed soft X-ray emissivity [18]. The soft X-ray diagnostic consists of a poloidal array of 10 cameras with a total of 200 viewing chords. Experimental growth rates obtained from the three methods are compared in Fig. 3, where we show the vertical displacement as a function of time together with the exponential functions that give the best fit. We limit the growth rate analysis to small displacements ($\Delta z \leq 4$cm), for which the plasma current and shape remain almost constant.

Growth rates were measured for different values of elongation ($1.43 \leq \kappa \leq 1.75$), triangularity ($-0.27 \leq \delta \leq 0.27$) and initial vertical position within the vacuum vessel ($0 \leq z \leq 0.29$m). Equilibrium reconstructions corresponding to the extreme values of these parameters are shown in Fig.4. In Figs. 5 and 6, we compare experimental and theoretical growth rates for the different values of the global plasma parameters, κ, δ and z. The error bars shown in these figures represent the average statistical error obtained from repeated measurements on identical plasmas, using the three different experimental methods.

4. Modelled Growth Rates

4.1. NOVA-W Calculations

NOVA-W is a linear MHD stability code [11] which calculates the vertical growth rate and eigenfunction in the presence of a realistic resistive wall, conductors, and active feedback. To calculate the growth rate of an equilibrium from an experimental discharge, the data for the profiles and plasma boundary definition at the desired time point is retrieved from reconstructed equilibria of that discharge. These profiles are then used as input to the CHEASE equilibrium code [22] which recalculates the equilibrium with the high resolution needed for stability calculations.

NOVA-W treats the plasma itself as ideal. Plasma resistivity does not affect vertical stability since the driving terms of the instability are ideal and resonant surfaces do not come into the n=0 calculation. Indeed, the resistive plasma time scale is much slower than the L/R time scale of the surrounding passive conducting structure, which defines the time scale of the vertical motion. No assumptions are made about the plasma motion, and therefore the resulting eigenfunction reflects the true non-rigid, deformable motion of the vertically unstable plasma in the linear regime.

All resistive elements of the tokamak, such as the vacuum vessel and poloidal field coils, are treated realistically in the calculation. The vacuum vessel enters into the calculation through a Green's function integral along the wall in the poloidal direction [11], taking into account the resistance with respect to poloidal position. The wall resistance is represented by values at 256 grid points. While the wall is treated as axisymmetric, the resistance at each point has been adjusted to be consistent with measurements of effective toroidal resistance at 38 poloidal locations on the vacuum vessel. This accounts for the effect of the numerous ports in the actual TCV vessel. All 16 external poloidal field coils and 2 coils internal to the vessel are included in the calculation.

4.2. Rigid Current Displacement Model

Vertical stability growth rates have also been calculated using a Rigid Current Displacement Model (RCDM) [12]. This model differs from the NOVA-W model in two respects. Firstly, the plasma current distribution, obtained from reconstructed equilibria, is assumed to be fixed and the unstable plasma motion is constrained to be a purely vertical displacement. Secondly, the induced currents in the vacuum vessel are expressed as a sum of eigenmodes in which the slowest 32 modes are taken into consideration. An RCDM calculation uses almost no computer time compared with a typical NOVA-W calculation.

5. Discussion

Open-loop vertical growth rates have been measured in TCV. Single-parameter scans of plasma elongation and triangularity show that the vertical growth rate increases strongly with elongation, highlighting the importance of active vertical position control, while positive triangularity has a stabilizing effect in these discharges. A series of similar discharges in which the plasma is progressively shifted towards the top of the vacuum vessel (Figs. 5c and 6c) clearly demonstrates the stabilizing influence of the conducting vessel wall. Growth rates up to 1000 s^{-1} have been stabilized in TCV using only the shaping coils outside the vacuum vessel.

A comparison of experimental growth rates with NOVA-W results (Fig. 5) shows excellent agreement over the entire parameter ranges investigated. The RCDM model also gives good agreement with the measurements (Fig. 6) except for the case of large negative triangularity, $\delta = -0.27$. Here, the RCDM underestimates the growth rate by 40%, Fig. 6b, whereas the deformable plasma model NOVA-W continues to predict the growth rate accurately. We believe that this large discrepancy must be due to the inherent limitations of the RCDM model, which ignores plasma deformation. It should be noted that the RCDM errors appear to be generally larger in the δ-scan (Fig.6b) than in the κ-scan (Fig.6a). However, if we compare similar parameter combinations in the two scans ($\kappa \approx 1.4$, $\delta \approx 0.27$), we find that the relative errors are comparable.

An overall comparison of experimental and theoretical growth rates, as obtained from the NOVA-W code, is presented in Fig. 7 for all discharges included in this study. We conclude that a linear MHD stability code can give accurate estimates of vertical growth rates of highly elongated tokamak plasmas. This allows us to predict growth rates of theoretical equilibria which have never been created in a real tokamak. Before implementing a new discharge scenario we can thus obtain valuable information on whether the plasma can or cannot be stabilized with a given feedback control system.

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Figure Captions

Fig.1.: Cross section of the TCV tokamak, showing the vacuum vessel, the fast stabilization coil inside the vessel (3 turns in top and bottom outer corners), 16 shaping coils (inboard and outboard stacks of 8 coils each), and the OH transformer (remaining 7 coils)

Fig.2.: Loss of vertical position control following feedback cut at 0.470 sec.

Fig.3.: Vertical displacement as a function of time obtained from three different measurements in the same discharge: (1) off-line equilibrium reconstruction (crosses), (2) real-time Ip*Z observer (open circles), and (3) soft X-ray tomography (asterisks). Growth rates are listed in units of sec^{-1}. The time bases for measurements (2) and (3) have been displaced for clarity.

Fig.4: Plasma configurations: extremes of elongation, triangularity and initial vertical position.

Fig.5.: Comparison of experimental (crosses, average of three methods) and theoretical (NOVA-W, open circles) vertical growth rates as a fuction of a) elongation, b) triangularity and c) initial vertical position. The error bars (± 6%) indicate the overall accuracy of the experimental measurements.

Fig.6.: Comparison of experimental (crosses, average of three methods) and theoretical (RCDM, open circles) vertical growth rates as a fuction of a) elongation, b) triangularity and c) initial vertical position.

Fig.7.: Overall comparison between theory (NOVA-W) and experiment (average of three methods).

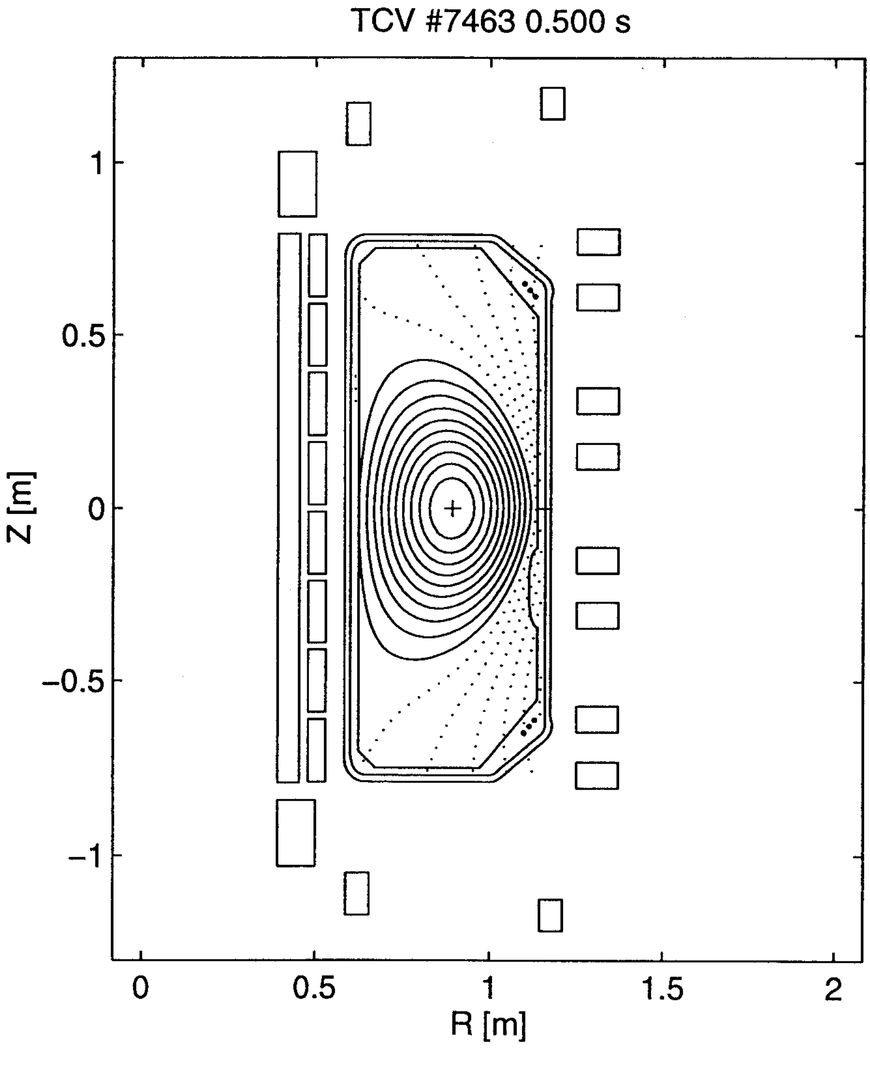


Fig. 1.

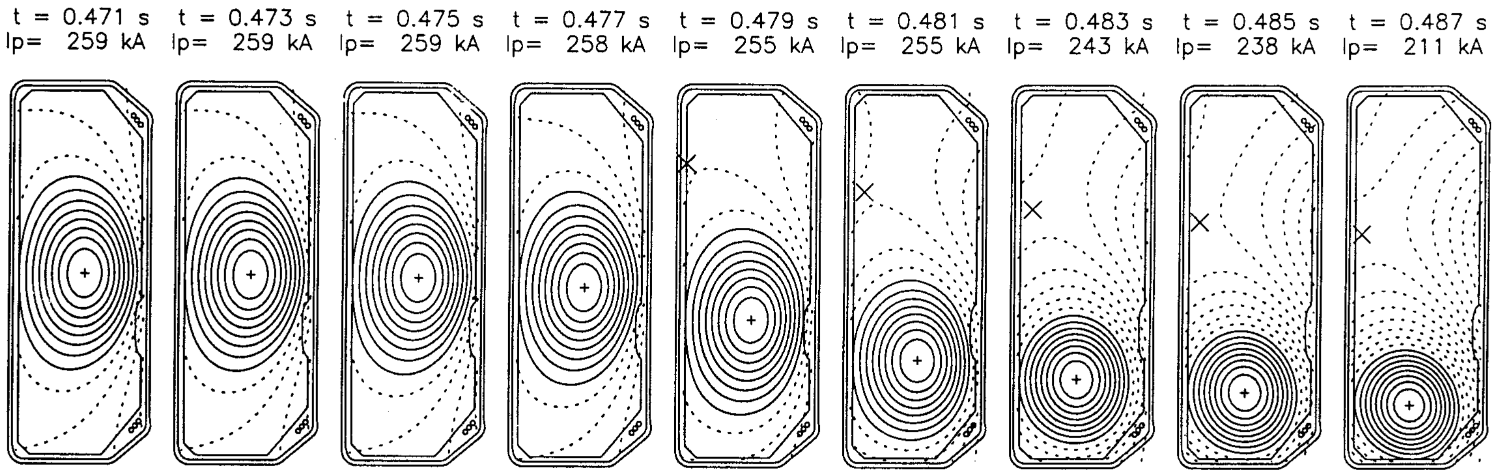
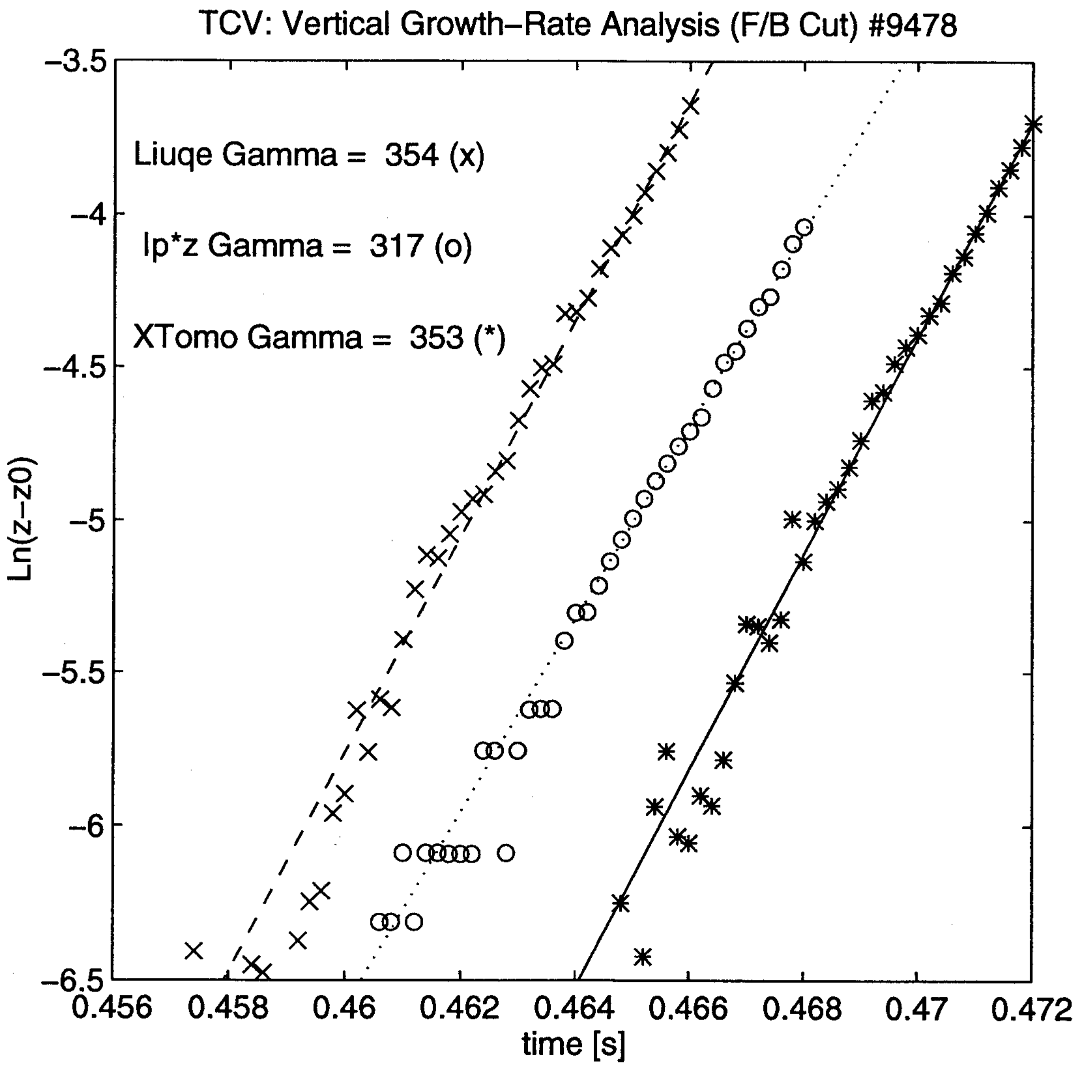

t = 0.471 s Ip= 259 kA
t = 0.473 s Ip= 259 kA
t = 0.475 s Ip= 259 kA
t = 0.477 s Ip= 258 kA
t = 0.479 s Ip= 255 kA
t = 0.481 s Ip= 255 kA
t = 0.483 s Ip= 243 kA
t = 0.485 s Ip= 238 kA
t = 0.487 s Ip= 211 kA

Fig. 2.



TCV: Vertical Growth–Rate Analysis (F/B Cut) #9478
Liuqe Gamma = 354 (x)
Ip*z Gamma = 317 (o)
XTomo Gamma = 353 (*)
Ln(z–z0)
time [s]
−3.5
−4
−4.5
−5
−5.5
−6
−6.5
0.456
0.458
0.46
0.462
0.464
0.466
0.468
0.47
0.472

Fig. 3.

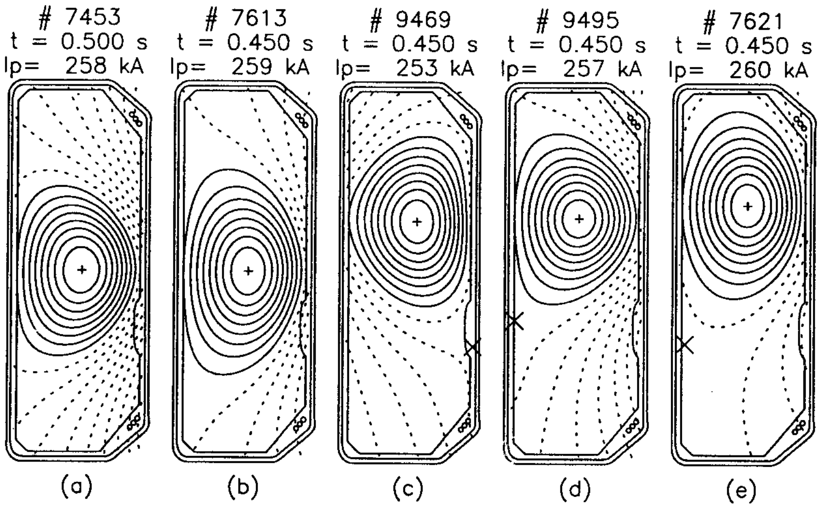
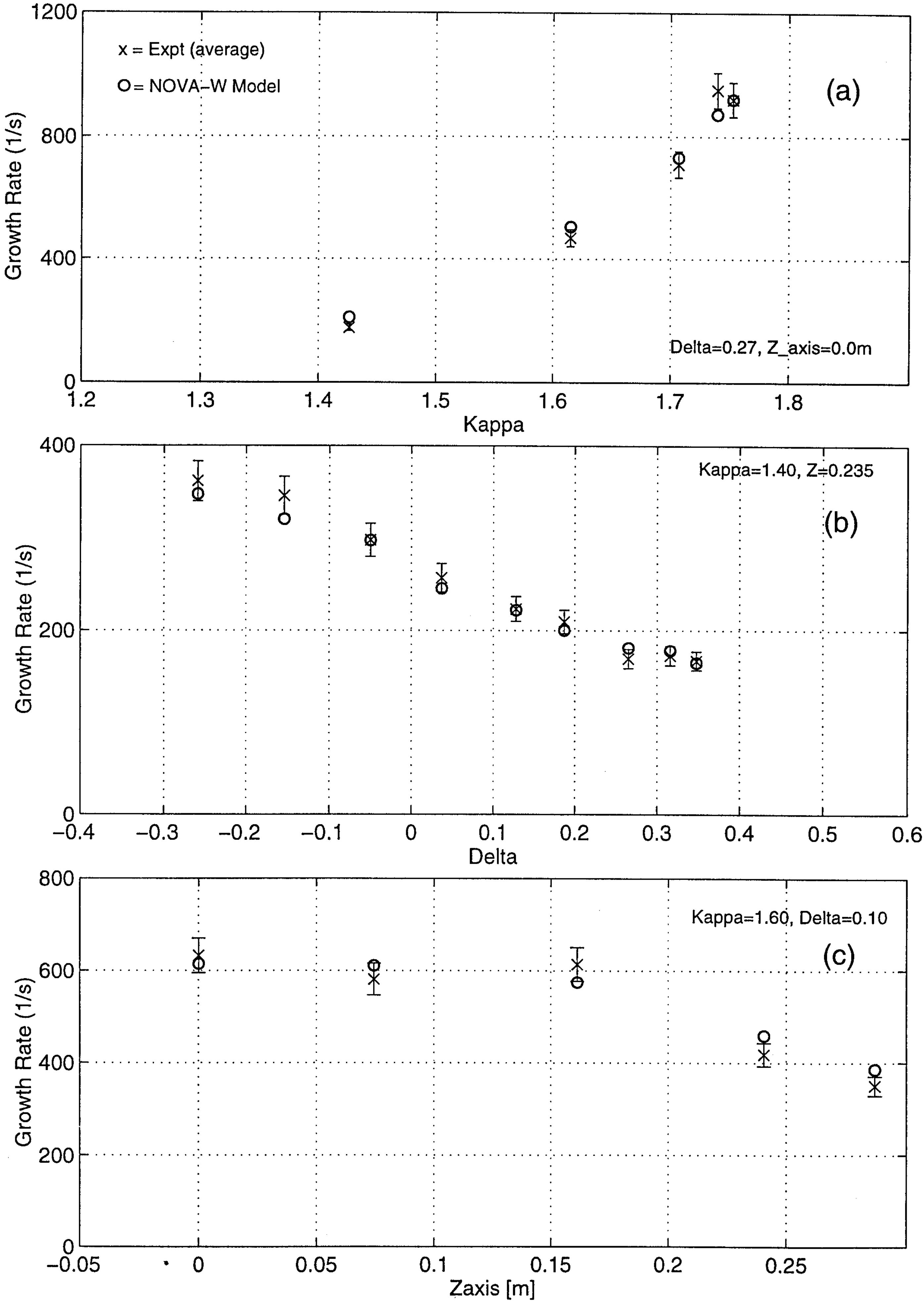
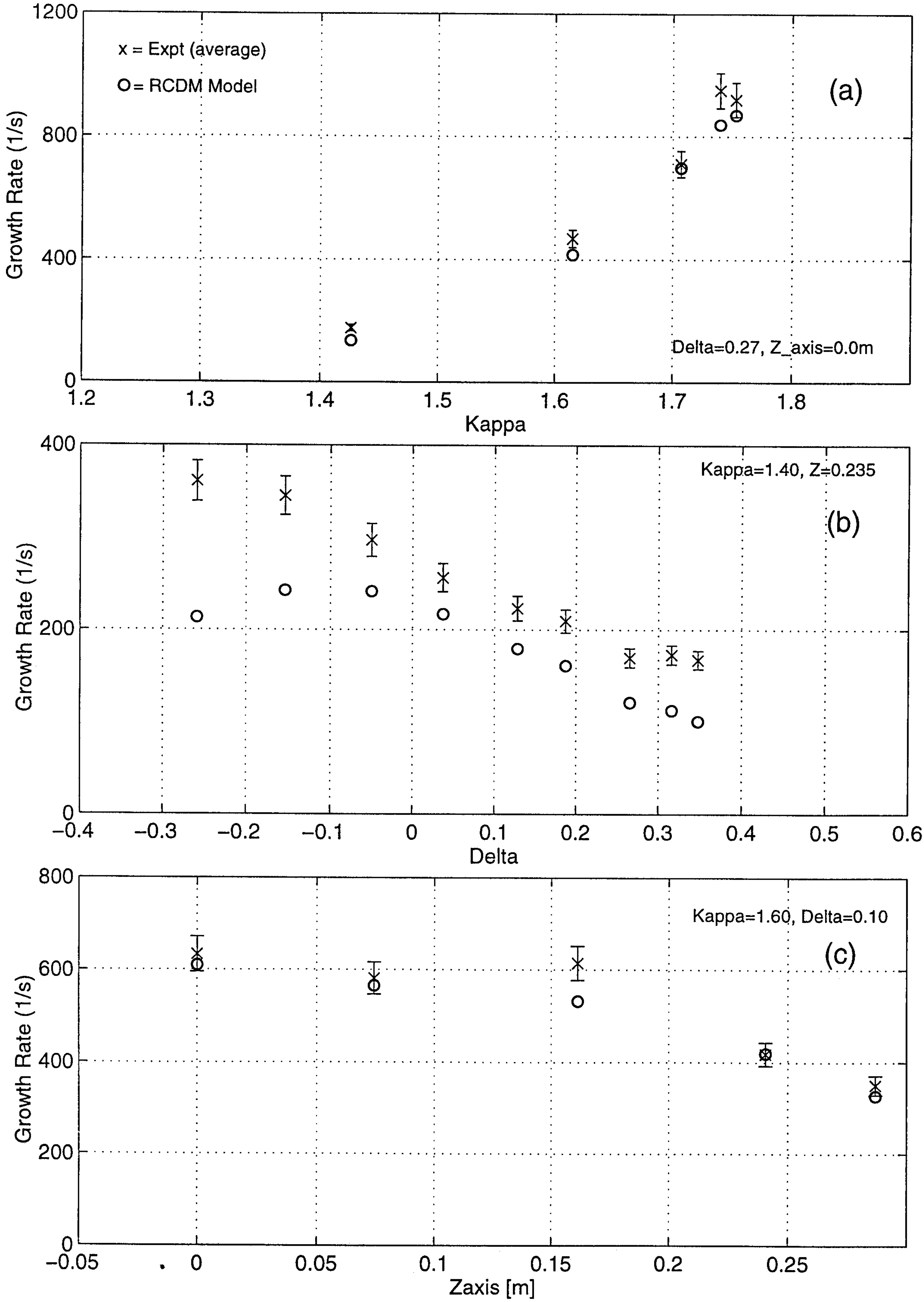

# 7453
t = 0.500 s
Ip= 258 kA
# 7613
t = 0.450 s
Ip= 259 kA
# 9469
t = 0.450 s
Ip= 253 kA
# 9495
t = 0.450 s
Ip= 257 kA
# 7621
t = 0.450 s
Ip= 260 kA
(a)
(b)
(c)
(d)
(e)

Fig. 4.



x = Expt (average)
O = NOVA-W Model
(a)
Delta=0.27, Z_axis=0.0m
Growth Rate (1/s)
Kappa
Kappa=1.40, Z=0.235
(b)
Delta
Kappa=1.60, Delta=0.10
(c)
Zaxis [m]

Fig. 5.



x = Expt (average)
O = RCDM Model
(a)
Delta=0.27, Z_axis=0.0m
Growth Rate (1/s)
Kappa
Kappa=1.40, Z=0.235
(b)
Growth Rate (1/s)
Delta
Kappa=1.60, Delta=0.10
(c)
Growth Rate (1/s)
Zaxis [m]

Fig. 6.

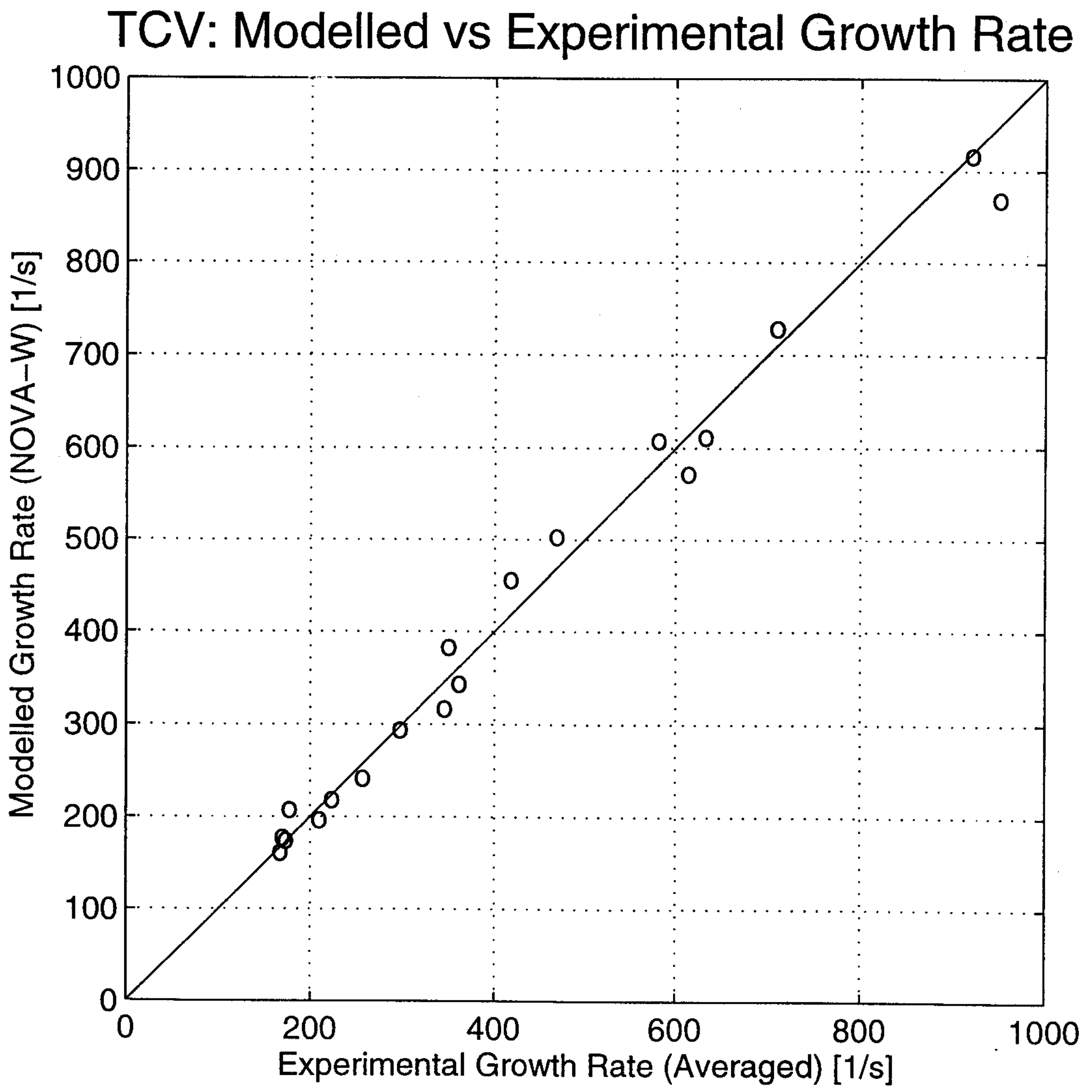

TCV: Modelled vs Experimental Growth Rate
Modelled Growth Rate (NOVA–W) [1/s]
Experimental Growth Rate (Averaged) [1/s]
0
100
200
300
400
500
600
700
800
900
1000
0
200
400
600
800
1000

Fig. 7.