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1. Introduction

The limits of operation of an elongated tokamak are generally defined by axisymmetric (n=0), free-boundary n=1, and ballooning modes. While it has become common practice to stabilize n=0 modes by a combination of passive and active systems, very few experiments [1] have been done so far to investigate active stabilization of n=1 modes. It is expected that, if the plasma is surrounded by a closely fitting shell, active stabilization of n=1 modes will considerably increase the current limit of an elongated tokamak. If the current can be increased, for a given plasma shape, the n=0 growth rate is reduced, and the beta limit may be raised.

In this paper, we discuss the possibilities for active stabilization of n=0 and n=1 modes in the TCV tokamak [2]. A cross section of TCV is shown in Fig.1.

2. Axisymmetric Modes

2.1. Growth Rates

Growth rates of axisymmetric modes, including the effects of a resistive vacuum vessel, have been computed [3] for a variety of TCV plasmas. Typical results are shown in Fig.2, where τ_p is the time constant of the unstable plasma motion in the resistive shell, and τ_s is the decay time of the induced currents in the shell. In TCV, τ_s=6.7ms. The growth rate is plotted against elongation, for symmetric and asymmetric scenarios and for two different current profiles. The maximum growth rate in each of these scenarios is listed in Table1.

Table 1
Time Constants of Axisymmetric Instabilities in TCV

Scenario	Minimum value of τ_p (ms)
standard profile, symmetric	0.17
standard profile, asymmetric	0.33
bell-shaped profile, symmetric	0.51
bell-shaped profile, asymmetric	0.87

2.2. Detection system

TCV is equipped with 38 flux loops, 24 saddle loops and 152 magnetic field probes. The probes are mounted inside the vacuum vessel, in 4 poloidal planes. The measurements obtained from these devices can be combined in various ways to construct a signal which is proportional to $I_p z_p$ [4]. Experimentally, this can be accomplished by a "Hybrid Matrix Multiplier" [5].

2.3. Amplifier Response Time

According to JET experience [6], the power amplifier used in an active feedback system must have a response time which is less than about one half of the time constant of the unstable mode. Consequently, if we wish to stabilize all cases listed in Table 1, we need an amplifier response time of the order of 0.1ms.

2.4. Voltage, Current and Power Requirements

Coil currents and voltages which are necessary for vertical stabilization can be estimated with the numerical model described in Ref. [7]. We assume a PD controller, operating in the critically damped regime, with a time constant $2\tau_p$, and a control coil with negligible resistance R. For stabilizing an initial vertical plasma displacement Δz, the maximum value of the control coil current is approximately equal to

$$I_{max} = \frac{1.7\ I_p\,\Delta z}{K\ (1+\alpha)} \tag{1}$$

where K is the control coil efficiency and α is a parameter which measures the amount of shielding, by passive elements, between the control coil and the plasma. The minimum value of the required control coil voltage is approximately given by

$$U_{min} = \frac{1.2\ L\,I_{max}}{\tau_p} \tag{2}$$

where L is the control coil inductance. Eqns (1) and (2) are valid for $R \ll \min(U_{min}/I_{max}\ ;\ L/\tau_p)$.

In JET [6], sudden vertical displacements up to 3 cm were observed (JET pulse 20802). Numerical simulations of internal disruptions in TCV [8], assuming a single-null divertor plasma and a 20% instantaneous change in beta gave vertical displacements of the order of 0.5cm. Here, we assume a maximum initial displacement, Δz=1cm.

The parameters appearing in eqs. (1) and (2) have been evaluated for a typical TCV plasma (I_p=955kA, κ=2.5, τ_p=0.3ms), using various coil combinations for active feedback. The results are summarized in Table 2.

Table 2
Voltage, Current and Power Requirements for Sabilization of Axisymmetric Modes in TCV

Coil system	F_1+F_8	E_2+E_7	E_3+E_6	internal
K(m)	0.68	0.59	0.42	1.55
α	0.05	0.00	0.00	0.76
U_{min} (V/turn)	526	168	237	139
I_{max} (kA-turns)	22.7	27.5	38.7	6.0
P(MW)	11.9	4.6	9.2	0.83

The last line in Table 2 is the product of U_{min} and I_{max} and represents a rough estimate of the power rating of the feedback amplifier. Coil inductances are assumed as $L_E=1.53\mu H$, $L_F=L_i=5.79\mu H$.

We note that the power requirement for the inner poloidal field coils (E-coils) is considerably less than that for the outer coils (F-coils), in agreement with recent results on DIII-D [9]. However, for all external coil combinations the votages are prohibitively large (both E and F-coils have 36 turns). The voltage required on the internal coil appears to be manageable, since this coil will probably have no more than 3 turns. The main advantage of the internal coil is that it uses much less power than any of the external coils.

3. n=1 Modes

3.1. Growth Rates and Mode Structure

Growth rates of n=1 modes of elongated tokamak plasmas in resistive shells have not yet been computed. However, n=1 vacuum growth rates (without shell) have been calculated [3,10] and it is found that, in many cases of interest, their magnitude is roughly comparable to the n=0 vacuum growth rate. The stabilizing influence of the wall, which brings the growth rate down to values that can be stabilized with reasonable response time, may be quite different for n=0 and n=1. While the flux perturbation due to n=0 is primarily m=1, the n=1 mode usually involves all m's up to $m \approx q_s$. Nevertheless, it is conceivable that, in presence of a closely fitting shell, n=1 growth rates will be in a range where active stabilization experiments are possible.

3.2. Detection System

The 152 magnetic field probes in TCV are capable of detecting n=0 and n=1 modes, with any m number up to about 15.

3.3. Active Feedback Coil

It has been proposed to construct the internal coil in TCV in eight independent segments, four in the upper half and four in the lower half of the vacuum vessel. Each segment covers a toroidal angle of 90°. If all eight segments are driven independently, it is possible to provide active feedback simultaneously on all modes with $n=0,1$ and $m=1,2$. The segments can, of course, be connected in groups to stabilize particular modes or combinations of modes. Whether a successful $n=1$ stabilization experiment can be performed with these coils depends primarily on the amount of overlap between the mode structure of the instability and that of the magnetic field produced by the active coils.

4. Conclusion

In order to stabilize axisymmetric modes in TCV, at elongations up to 3, an amplifier having a response time of the order of 0.1 ms will be required. Current, voltage and power requirements for successfully controlling a 1cm sudden vertical displacement have been estimated, assuming various coil combinations for active feedback. A comparison between internal and external coils shows that the internal coil is to be preferred, since its power requirement is considerably less that that of any of the external coils.

In addition, it is shown that TCV offers the unique opportunity to investigate active stabilization of $n=1$ modes. This may give access to new domains in parameter space, i.e., higher currents, lower axisymmetric growth rates, higher elongation and higher beta values.

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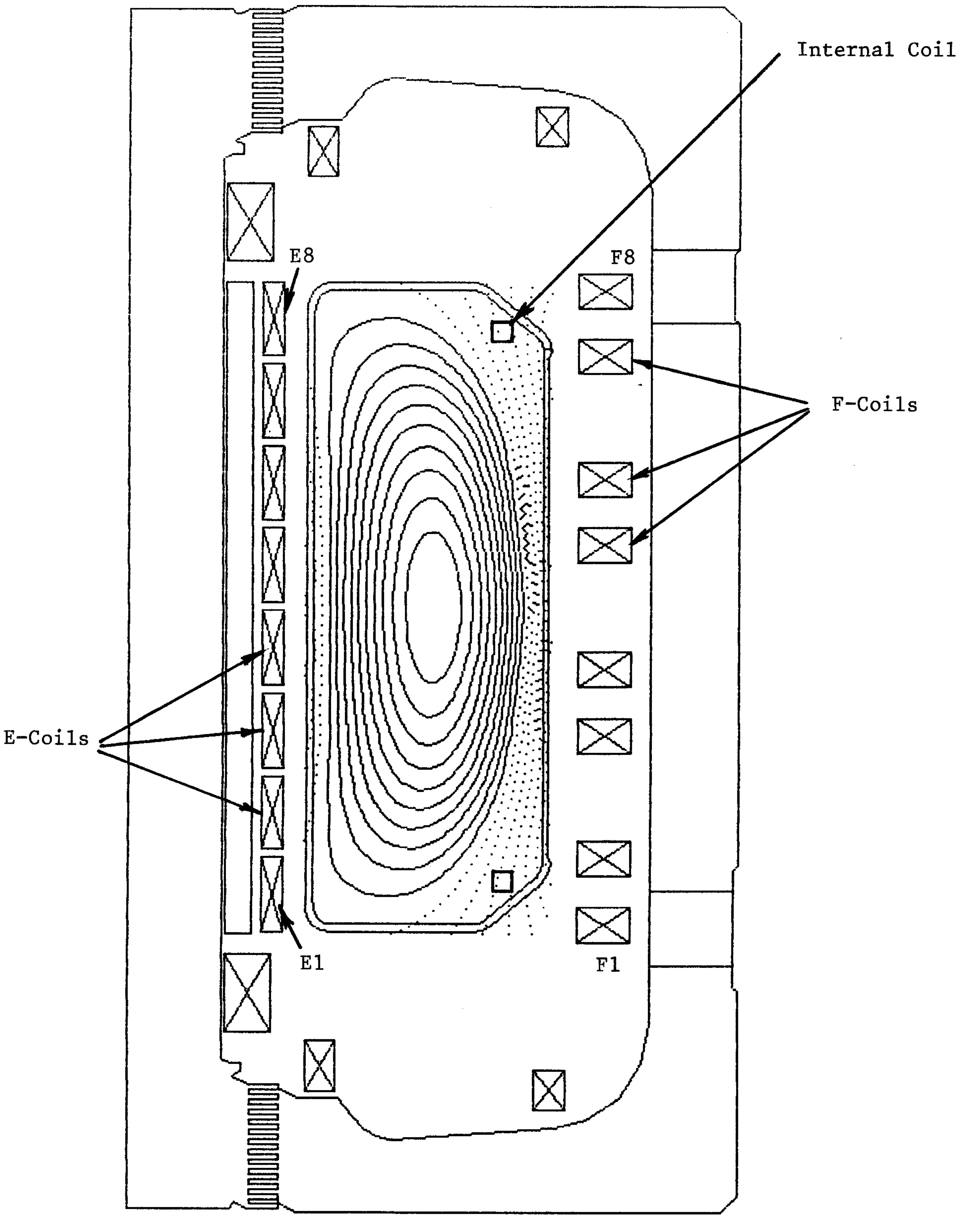
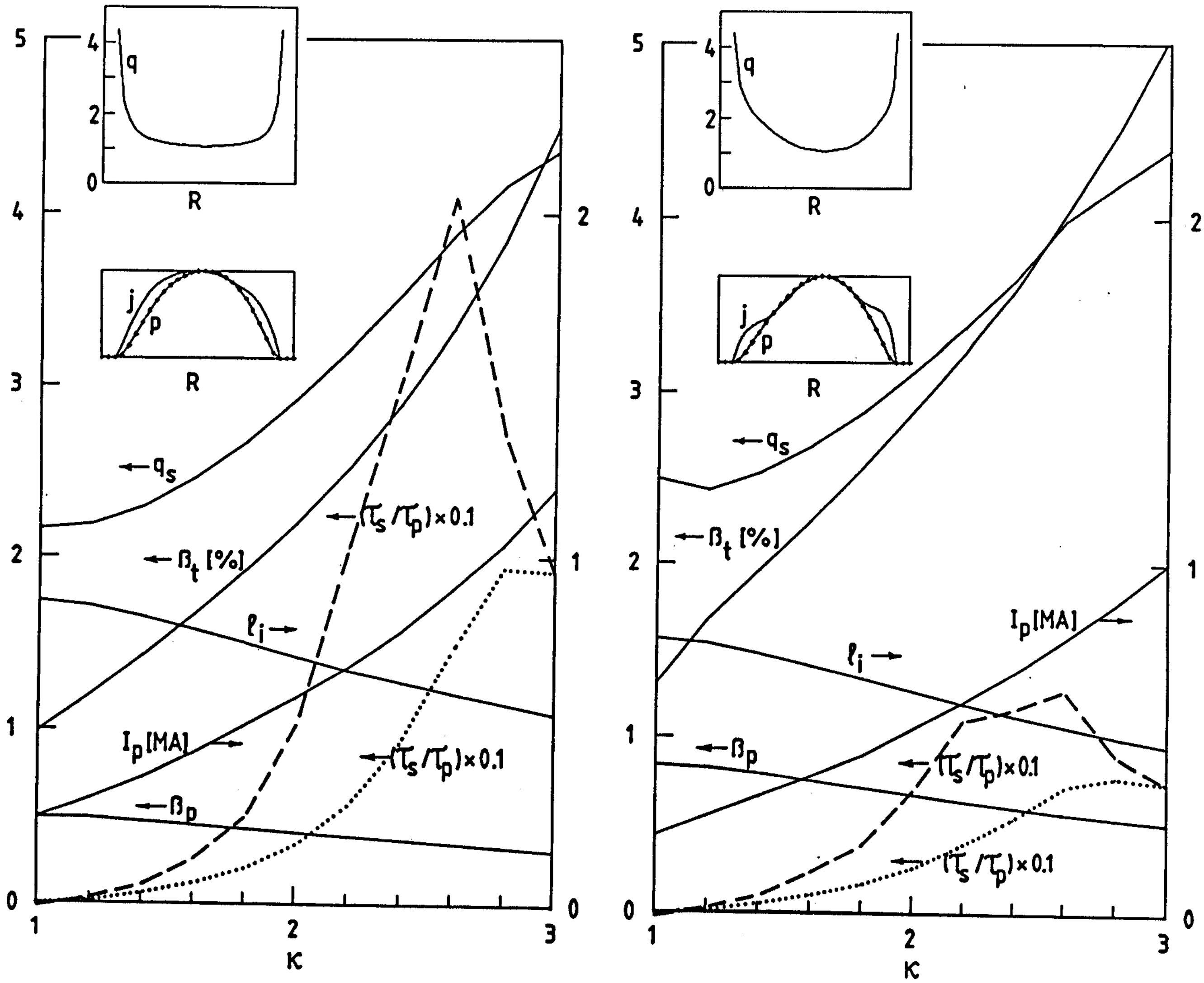


Fig.1. Cross Section of TCV Tokamak



(a) (b)

Fig.2. Global plasma parameters and vertical instability growth rates vs. elongation for up-down symmetric (dashed line) and asymmetric (dotted line) startup scenarios in TCV: (a) standard current profile, (b) bell-shaped current profile. q_0=1.05, B_0=1.5 T.