# Resistive wall mode feedback stabilization in burning plasma experiments

A.M. Garofalo, Columbia University

We use a simple model [Garofalo, Jensen, and Strait, to be published in Phys. Plasmas] to analyze the systems for feedback stabilization of the resistive wall mode (RWM) in proposed burning plasma experiments. In ITER, the presence of several conducting structures close to the control coils, but far from the plasma, leads to a slow feedback response time compared to the time scale of the RWM growth. In FIRE, the copper shell passive stabilizer sets a relatively long time scale for the RWM growth, therefore the effects of higher resistivity structures close to the coils and far from the plasma are nearly negligible. RWM feedback control should be able to raise the stable $\beta_N$ up to near the ideal-wall limit in FIRE, with moderate requirements on the feedback electronics bandwidth.

## I. Introduction.

Plasma operation with high values of $\beta_N$ and of the bootstrap current fraction in the advanced tokamak requires stabilization of the low toroidal mode number *n* ideal magnetohydrodynamic (MHD) kink mode, the resistive wall mode (RWM). Advanced tokamak operation is not the design basis for nominal plasma performance in the three proposed burning plasma experiments: FIRE, IGNITOR, and ITER. However, FIRE and ITER are planning to retain the capability of accessing advanced modes of operation; these facilities have to address the problem of RWM stabilization.

Recent experiments have demonstrated sustained RWM stabilization by plasma rotation achieved with improved error field correction and sufficient angular momentum injection [1]. With *n*=1 RWM stabilization by resistive wall <u>and</u> plasma rotation, stable plasma $\beta_N$ values up to $2x\beta_N^{\text{no-wall}}$ have been achieved and maintained for as long as sufficient torque was provided. The experimental data from DIII-D is so far consistent with the RWM calculations by Bondeson and Ward [2]. The agreement between the predicted and measured rotation velocity threshold is within 50% [3]. Until the quantitative understanding of the stabilization mechanism is improved, it is not possible to extrapolate with confidence the rotation velocity threshold for RWM stabilization to ITER, FIRE, or reactor plasmas.

Active feedback stabilization of the RWM via magnetic coils is predicted to allow stable $\beta_N$ values up to near the ideal-wall limit, even in absence of plasma rotation [4]. However, without plasma rotation, we expect that the feedback will have to provide stabilization for n>1 RWMs, beside the n=1 RWM. In reality, the most likely, and most robust scenario in a fusion reactor may want to rely on both plasma rotation and active magnetic feedback to operate stably above the no-wall beta limit. In such a scenario, the feedback system corrects field asymmetries and maintains the plasma rotation necessary for RWM stability; however, if the rotation slows down for some reason and the RWM is destabilized, the active control can be used dynamically to suppress the RWM growth and recover stable high performance operation. Furthermore, the RWM feedback system may be used to obtain optimal correction of intrinsic error fields dynamically, as plasma conditions vary.

Based on our experience so far, an effective RWM feedback system requires:

1) A conducting wall close to the plasma (passive stabilizer). This has two functions:
   a) Slows down the ideal MHD kink mode growth time to the order of the conducting wall eddy current decay time, which should be manageable by the feedback system electronics.
   b) Determines the maximum theoretically achievable beta, the ideal-wall beta limit.
2) Control coils well coupled with the RWM structure, and possibly decoupled from the wall
3) Sensors that are well coupled to the RWM, highly decoupled from the control coils, and possibly insensitive to other MHD modes and noise.

In the following Section II we will introduce the characteristics of the passive stabilizer and control coil systems proposed for ITER and FIRE. In Section III, the efficacy of these systems is evaluated using a simple Smart Shell [5] feedback algorithm. This algorithm aims at making the passive stabilizers act like perfect conductors, by maintaining on their surface a zero net radial field. We will therefore assume simple radial field sensors located against the passive stabilizers. In Section IV, we will summarize the results and present our conclusions.

## II. The proposed feedback systems.

In ITER the function of the passive stabilizer could be provided by the plasma facing surfaces of the blanket modules (see Fig. 1) [6]. Each blanket module is attached to the inner shell of the double wall vacuum vessel (VV). The VV shell is 6 cm-thick stainless steel (SS 316L-IG). The control coils will be the same coils planned for correcting imperfections of the magnetic field symmetry, the Error Field Correction Coils. There are three sets of six saddle coils, around the torus, outside the vessel (see Fig. 2). This coil system should provide good coupling to poloidal mode numbers m =1,2,3,4, and to toroidal mode numbers n=1,2

In FIRE the passive stabilizers are 30 mm copper sheets bonded directly to the surface of the vacuum vessel [7]. The geometry of the passive plate system is shown in Fig. 3. Figure 3 also shows the eight pairs of control coils, located between the outboard walls of the vessel, above and below the midplane ports. This coil system should provide good coupling to m =1,2,3, and n=1,2,3.

Both in ITER and FIRE, the control coils are behind the passive stabilizer, and embedded in conducting structures. To asses the effects of the conducting structures between the control coils and the plasma, we define two time constants:

$\tau_{W,M}$ is the time constant for decay of the eddy currents that are effective at slowing down the growth rate of the RWM => only conducting structures very close to the plasma are involved.

$\tau_{W,F}$ is the time constant for the eddy currents in conducting structures close to the control coils, but far from the plasma. These eddy currents are therefore ineffective at slowing down the growth rate of the RWM, but are effective at slowing down the penetration of the feedback fields.

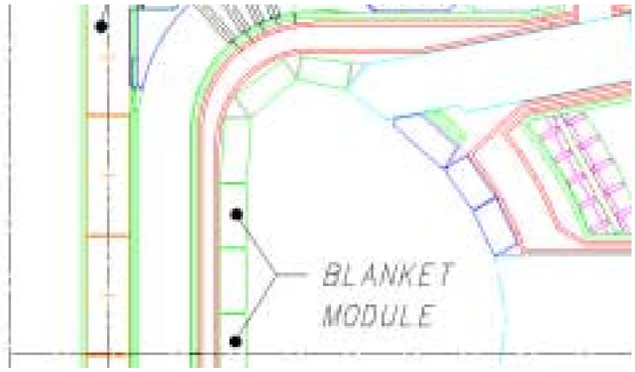


Fig. 1. Portion of a poloidal cross-section of the ITER tokamak, showing the blanket modules mounted on the inner vacuum vessel shell. The stabilizing eddy currents induced by an RWM may need to flow from module to module through the attachments to the stainless steel vessel.

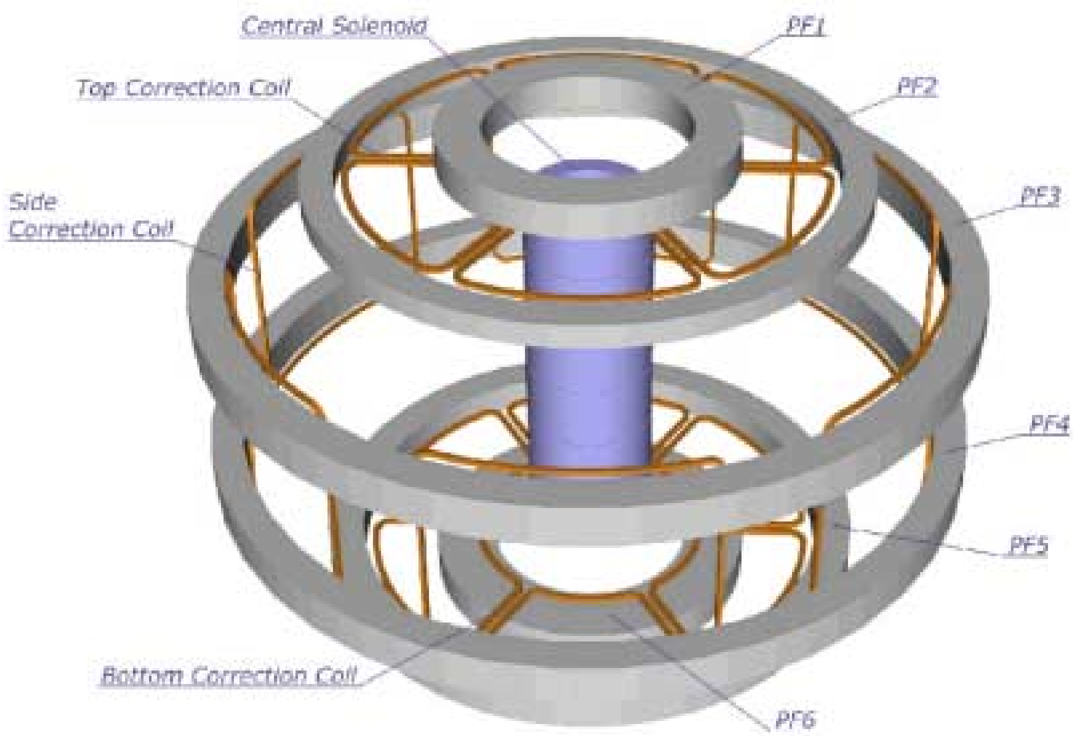


Fig. 2. ITER poloidal field coils and Error Field Correction coils.

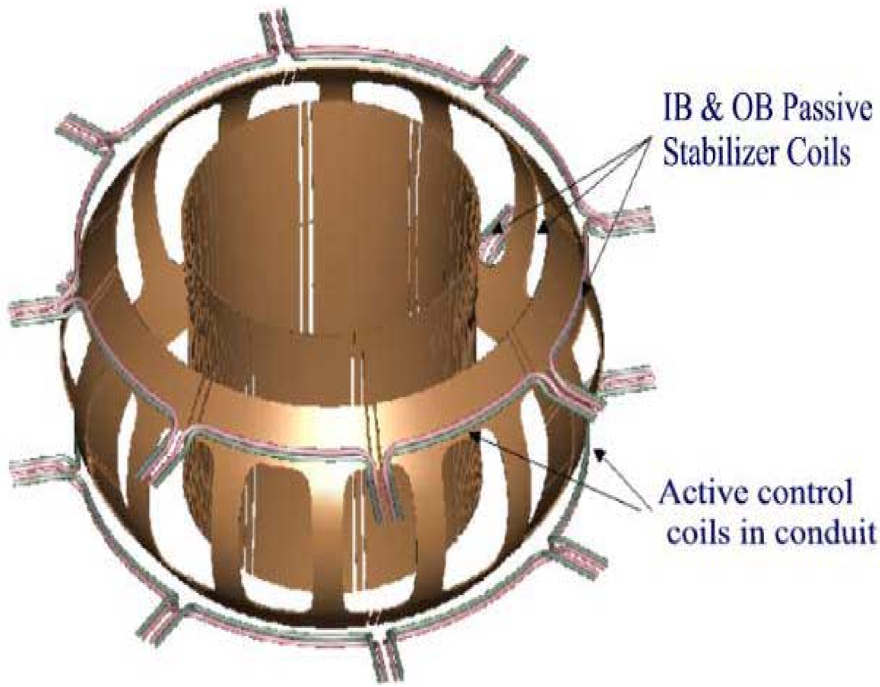


Fig. 3. Active control coils and passive stabilizing system in FIRE. The two sets of eight control coils are located between the two outboard vessel shells.

**III. Performance of Smart Shell feedback, proportional gain only.**

We have analyzed the proposed RWM feedback systems for ITER and FIRE using a model [8,9] that was successful at predicting quantitatively the RWM feedback dynamics in DIII-D. In this model, the wall time constant is defined as $\tau \equiv \dfrac{\delta\mu_0}{2k\eta}$ , where $\delta$ is the thickness of the resistive wall, $\eta$ is the resistivity of the wall material, and $k = (k_t^2 + k_p^2)^{1/2}$ is the RWM wave number. Here $k_t = n/R$ and $k_p = m/a$, where *R* is the major radius, and *a* is the minor radius, both evaluated for the wall.

For ITER, we have assumed the passive stabilizer to be the inner shell of the vacuum vessel. This assumption simplifies the calculations, and appears reasonable due to the high degree of segmentation of the plasma facing surface of the blanket modules. Our calculation gives $\tau_{W,M}$ = 33 ms. Here, we have used *m*=2 and we have reduced the actual thickness of the shell by ~0.5 to account for the numerous large ports. The outer VV shell is at too large distance from the plasma to affect the RWM growth time; therefore it is not considered part of the passive stabilizer. Note that this differs from the case of a vertical instability, which is slowed down significantly by the outer VV shell: a vertical instability has magnetic structure (*m*,*n*)=(1,0) which decays more slowly with increasing distance from the plasma than the (2,1) structure of the resistive wall mode. For $\tau_{W,F}$, the model gives $\tau_{W,F}$ = 40 ms. Here, we have simply considered the outer shell of the vacuum vessel. The space between the VV double wall also contains stainless steel, but this filler conducting material has been neglected, assuming that it has much higher resistivity.

For FIRE, we obtain $\tau_{W,M}$ = 173 ms. This high number is due to the low resistivity of copper. We have added the effects of the copper plates and the stainless steel inner VV shell. Furthermore, we have reduced the actual thickness of the shell by ~0.35, since the ports in FIRE take a high fraction of the outer midplane wall. For $\tau_{W,F}$, we find $\tau_{W,F}$ = 37 ms. This value is given by the stainless steel outer VV shell. The conducting material between the inner and outer VV shells is a mixture of stainless steel and water, and is neglected assuming it has higher resistivity.

We postulate current-controlled feedback amplifiers. Then, the dispersion relation for Smart Shell feedback is [8]:

$$\alpha - i\omega\tau_{W,M} - G(i\omega) = 0 \ , \tag{1}$$

where $\alpha$ is the plasma stability parameter, and $G$ is the overall gain of the feedback system: $G(i\omega) = G_p \times G^{open-loop}(i\omega)$. Here, $G_p$ is a simple proportional feedback gain, and $G^{open-loop}(i\omega)$ is the open-loop frequency response of the system comprising feedback amplifiers, control coils, and conducting structures between control coils and passive stabilizers.

We use a two-pole model to describe $G^{open-loop}(i\omega)$:

$$G^{open-loop}(i\omega) = \frac{\Omega_{U_1}}{\Omega_{U_1} + i\omega} \times \frac{\Omega_{U_2}}{\Omega_{U_2} + i\omega} \ . \tag{2}$$

One pole is given by the low-pass filter due to the conducting material close to the coils and far from the plasma: $\Omega_{U_1} = \dfrac{1}{\tau_{W,F}}$. The second pole can be chosen to characterize the bandwidth of the amplifiers. For example, the DIII-D RWM amplifiers could be characterized by a 100 Hz low-pass filter ($\Omega_U$~700 rad/s). We adopt this same bandwidth for the amplifiers in both FIRE and ITER: $\Omega_{U_2} = 700$. Using the dispersion relation (1), we can now calculate what is the most unstable plasma that can be stabilized by a Smart Shell feedback system in each machine.

The instability strength is expressed as the ratio of the no-feedback RWM growth time, $\tau_g$, divided by $\tau_{W,M}$. Based on VALEN calculations shown in Fig.4 [4], we estimate that:

1) In order to raise the stable plasma $\beta_N$ up to near the ideal-wall limit, a feedback system should be able to stabilize an RWM with growth time $\tau_g \geq 0.1\tau_{W,M}$.
2) In order to raise the stable $\beta_N$ up to 40% between the ideal-wall and the no-wall limits, a feedback system should be able to stabilize an RWM with growth time $\tau_g \geq 1.0\tau_{W,M}$

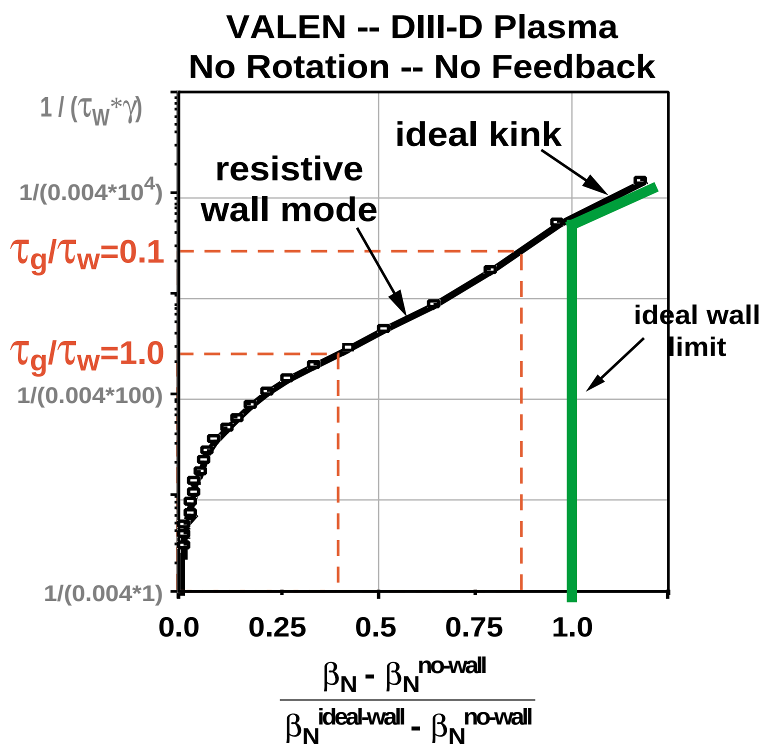


Fig. 4. RWM growth time ($1/\gamma$) vs. $\beta_N$ calculated by VALEN with no-feedback, no-rotation for a DIII-D plasma. We have normalized the y-axis to the wall time constant, while the x-axis is normalized to the $\beta_N$ range between the ideal-wall and the no-wall limits. In normalized coordinates, the VALEN curve should be a good approximation of the RWM growth time vs. $\beta_N$ for any plasma.

We solved the dispersion relation searching for just marginally stable cases of a Smart Shell feedback system in both ITER and FIRE. Figure 5 shows the associated values of the proportional gain as a function of the RWM instability drive. The lower (gray) curves can be associated with the RWM, and show that the gain has to exceed a minimum value in order to stabilize the mode. The other curves of marginal stability (black) are associated with modes of the system that come into existence because of the finite bandwidth of the electronics. These curves show that the feedback gain has to remain below a maximum value, in order to maintain stability of the feedback system. With the same amplifier bandwidth ( $\Omega_{U_2} = 700$ rad/s, or 100 Hz low-pass filter), the strongest RWMs that can be stabilized with only proportional gain in ITER have a growth time $\tau_g \geq 1.2\tau_{W,M}$, which corresponds to a $\beta_N$ 30% the way between the ideal-wall and the no-wall limits. In contrast, for FIRE the strongest RWMs that can be stabilized have a (lower) growth time $\tau_g \geq 0.2\tau_{W,M}$. This implies that the RWM can be stabilized up to a $\beta_N$ 75% the way between the ideal-wall and the no-wall limits.

Figure 5 also shows that only a small improvement in feedback performance is obtained in ITER by increasing the amplifier bandwidth by an order of magnitude (curve for $\Omega_{U_2} = 7000$ rad/s, or 1 kHz low-pass filter). More improvements in feedback performance can be expected by changing the feedback method: e.g., using Mode Control instead of Smart Shell, and adding derivative gain.

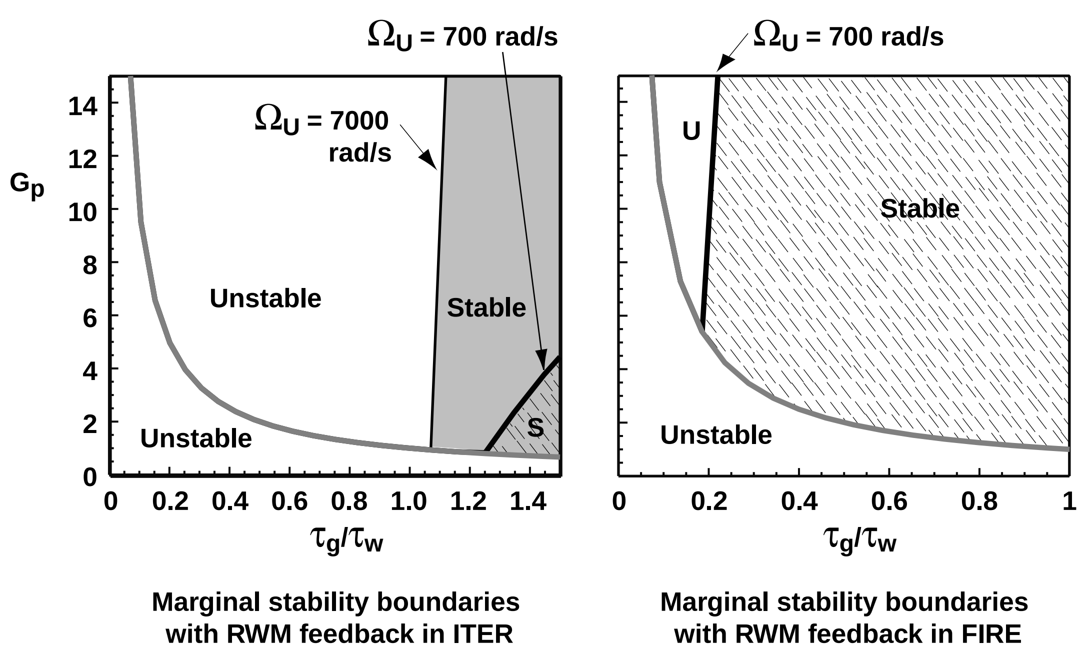


Fig. 5. Marginal stability curves for a Smart Shell RWM feedback systems in ITER and FIRE. Both machines are evaluated with an amplifier with frequency response

characterized as a 100 Hz low-pass filter. A case with significantly broader amplifier bandwidth is also shown for ITER.

## IV. Summary and conclusions

In ITER, the SS inner VV shell acts as the passive stabilizer. The outer VV shell is at too large distance from the plasma to affect the RWM growth time, but it is located between the control coils and the plasma, and it would therefore slow down the time response of the feedback system. Feedback control of the RWM would require amplifiers with good frequency response up to ~1 kHz in order to approach stable $\beta_N$ up to 40% between the no-wall and the ideal-wall limits, with the proposed feedback system geometry in this machine. On the other hand, the control coils are designed to provide best versatility for error field correction. Even a "slow" feedback system would be able to provide dynamically the optimal error field correction [1], therefore plasma rotation sustainment should be very robust in ITER. With sufficient angular momentum injection, the plasma rotation could ensure RWM stabilization up to the ideal wall $\beta_N$ limit.

In FIRE, the copper shell passive stabilizer sets a relatively long time scale for the RWM growth. The effects of higher resistivity materials close to the coils and far from the plasma, such as the SS outer VV shell and the blanket, are not very significant in this machine. With only moderate requirements on the feedback electronics bandwidth (good frequency response up to ~100 Hz) RWM feedback control should be able to raise the stable $\beta_N$ up to 75% between the no-wall and the ideal-wall limits in FIRE, even without plasma rotation.

In a new proposed control coil system for FIRE, the coils are embedded in the port shield blocks. In this case the feedback fields would couple to the plasma avoiding the shielding from the copper stabilizers. This would further improve the feedback time response, and therefore increase the maximum stable $\beta_N$. A similar configuration for the control coils in ITER would significantly diminish the shielding from the outer vessel shell, the blanket between the vessel shells, and the blanket modules. The feedback performance would be greatly enhanced. In addition, accessibility and maintenance of the coils would be improved.

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