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Technical Progress Report

HIGH BETA AND SECOND STABILITY REGION TRANSPORT AND STABILITY ANALYSIS

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ABSTRACT

This report summarizes MHD equilibrium and stability studies carried out at Grumman's Corporate Research Center during the 6 month period starting March 1, 1994. Progress is reported in both ideal and resistive MHD modeling of TFTR plasmas. The development of codes to calculate the significant effects of highly anisotropic pressure distributions is discussed along with initial results from this model.

I INTRODUCTION

This report is a brief summary of work carried out at the Grumman Corporate Research Center during the 6-month period from March 1st 1994, and supported by the Department of Energy Grant #DE-FG02-89ER51124. A more detailed report will be forthcoming toward the end of the present Grant period. This summary is provided as an accompaniment to a Renewal Proposal for a further 9-month period of research starting March 1, 1995.

The Research Plan for 1994, submitted during December 1993, emphasized theoretical and computational support for the D-T phase of operation in TFTR which started towards the end of 1993 and is still in progress. The intention of our research plan was to offer assistance in interpreting the MHD equilibrium and stability properties of experimental data from these TFTR plasmas. Specifically, the program of work which we proposed was divided among three main tasks as follows:

Task 1: MHD Equilibrium and Stability Analysis of TFTR Experimental Data.

- (a) Ideal and Resistive MHD Stability Analysis of TFTR Experimental Data.
- (b) Resistive Tearing Mode Criteria.

Task 2: Transport Studies and MHD Analysis of Evolving Equilibria.

- (a) Study the effects of anisotropic pressure distributions in TFTR using $p_{||}$ and $p_{\perp}$ calculated by TRANSP.

Task 3: Implement Improvements in Equilibrium and Stability Models.

- (a) Implement Improvements in Equilibrium and Stability Models

Substantial progress is reported in each of the above topics. Specifically, Task 1(a) and (b) are discussed in §II.A and II.B while the topic of Tasks 2 is summarized in §II.C. Task 3 appears in §III. We note that part of the work discussed here has been described in two papers presented at the 1994 International Sherwood Meeting held in Dallas, Tx. and three more papers will be presented at the 1994 APS, Division of Plasma Physics Meeting to be held in Minneapolis, MN during November 1994. Two journal articles have

appeared in the literature^{1, 2}. These papers together with other associated presentations during the present period are enumerated in the Appendix to this document.

I.A Acknowledgments

It is a pleasure to acknowledge the continuing interest and cooperation of numerous colleagues at TFTR and the Theory Division at Princeton, Plasma Physics Laboratory. As in previous years, we continue to maintain and expand our interaction with various other plasma physics groups throughout the country. Their input to our work is also acknowledged.

II RESULTS

II.A Task 1(a): Ideal and Resistive MHD Stability Analysis of TFTR Experimental Data

The analysis summarized in this section concentrates attention on early, high current ($q_{\text{edge}} \sim 5$), D-T experiments in TFTR where slowly growing, coherent MHD modes were observed. The most frequently observed mode had a 4/3 structure though higher order m/n instabilities were also excited. We note that, from an MHD standpoint, these D-T supershot plasmas have essentially the same characteristics as those in deuterium only. Moreover, transport analysis of these plasmas using the TRANSP code suggest that the axial value of q was smaller than unity over a substantial fraction of the plasma radius. This computational prediction was subsequently supported by MSE diagnostic measurements of the magnetic pitch angle as these became available. The observations of q

Fig. II.A-1 Beta Limits for low -n modes in TFTR, D-T plasma.

< 1 in these and earlier supershot experiments present a significant challenge for ideal MHD theory which predicts that the 1/1 internal mode is unstable when the Bussac beta, $\beta_{p1} > 0.3$. In the experiments of interest here, $\beta_{p1} \sim 0.6$ but the ideal 1/1 mode is apparently stable. Bussac's ideal MHD criterion is invariably violated in supershots when $q < 1$ and where the central pressure gradients are believed to be large as the result of circulating hot ions produced by intense beam heating. This statement, however, is based entirely on TRANSP calculations of the neutral beam pressure and the premise that the total pressure distribution is isotropic. The possible implications of the highly anisotropic pressure distributions in TFTR is discussed in §II.C

In our previous report we noted that the stability properties of the 1/1 internal kink is sensitive to the precise details of the pressure distribution in the immediate vicinity of the $q=1$ surface. Thus, when a relatively narrow flat spot is inserted in the pressure profile near and inside the $q = 1$ surface the 1/1 mode is stabilized. Such a flat spot could be produced, for example, by a saturated 1/1 resistive mode located near $q=1$. While the existence or otherwise of flat spots in the pressure profile in supershot plasmas is a controversial topic at TFTR there is no clear experimental evidence to contradict this hypothesis. Indeed, some modification of the predicted pressure profiles obtained from TRANSP is required to stabilize the Mercier modes which are otherwise excited. When the 1/1 mode is extinguished in this way, ideal modes with $n \geq 2$ are computed whose marginal behavior depend on q_0 as indicated in Fig. II.A-1. This figure shows that, when $q_0 > 1$, the larger n -modes have lower beta limits which is characteristic of ballooning mode behavior. When $q_0 < 1$, however, the order is reversed, as is also shown Fig. II.A-1, with the $n = 2$ mode being the most unstable. It is not clear from these results why the most frequently occurring mode has a 4/3 structure, especially when $q < 1$. When the effect of finite plasma conductivity is included slowly growing resistive versions of these modes appear whose growth rates scale as $S^{-3/5}$. We are currently in the process of studying the non-linear evolution of these resistive MHD instabilities using a version of the ARES code developed recently under Grumman auspices.

II.B Task 1(b) Resistive Tearing Mode Stability Criteria

In his review of MHD stability theory Wesson³ quoted a simple formula which purports to predict the stability or instability of resistive tearing modes. Subsequently, this same formula was derived more rigorously by Strauss⁴ and, recently, by Hegna and Callen⁵. The latter derive an expression for the resistive MHD index, Δ' , treating $1/m$ as a small number, where m is the poloidal mode number. Using $\Delta' = 0$ as the threshold

condition for instability a simple stability criterion was derived. Specializing to cylindrical geometry, this stability criterion can be cast in terms of the toroidal mode number, n , to obtain

$$n < n_{\max} = \frac{r_s}{s} \cdot \left(\frac{1}{B_z/R} \right) \cdot \frac{dJ_{||}}{dr} \quad (1)$$

as the condition for instability. Here, s is the shear and $dJ_{||}/dr$ is the current density gradient both measured at the rational surface located at r_s . For given equilibrium parameters the prediction of this formula is best visualized graphically.

Fig. II.B-1 Tearing Mode Stability Diagram
This diagram illustrates the prediction of equation (1) in cylindrical geometry using $q = 1.2 \cdot (1 + (r/0.4)^8)^{1/4}$. In this example, only tearing modes with $m/n=3/2, 4/3$ and $5/4$ are unstable.

Thus, for example, Fig. II.B-1 shows a tearing stability diagram corresponding to the 'flat' current density profile of Furth, Rutherford and Selberg (FRS)⁶. This example shows how the criterion (1) predicts, in this particular case, that the 2/1 tearing mode is stable while higher order m/n modes can be unstable. Since this is precisely the behavior that is observed in TFTR, and if the prediction is correct implicitly provides information regarding the current profile, it is clearly of interest to assess the validity of the criterion (1) more closely. For this purpose, we have used ARES to calculate the stability properties of FRS profiles under various conditions and have compared these with the predictions of (1). The

details are deferred to a more complete report which will be forthcoming at the end of the current period of this Grant. The conclusion, however, is that the formula (1) does not accurately predict the onset of the low order m/n tearing modes of interest when compared with the solution of the full resistive MHD equations. In particular, the stability of the 2/1 mode, predicted by (1) and indicated in Fig. II.B-1, is not in accord with computation. In practice, we find that, using the FRS profiles, the 2/1 tearing mode is always unstable, contradicting the result exhibited in Fig. II.B-1 and, indeed, the experiment. We find that the formula is in agreement with computation only when the poloidal mode number, $m > 5$, which restricts its usefulness in modeling TFTR.

II.C Stability of Anisotropic Plasmas

During 1994 we have realized our goal of completing a comprehensive set of codes that include anisotropic pressure effects in MHD. Most major portions of the code development work was supported by Grumman Corporation. Applications of the code, benchmarking and some modification tasks were supported by this Department of Energy grant. The codes include an anisotropic equilibrium code, a ballooning code including the Mercier criterion and a low $-n$ MHD stability code.

Auxiliary heated plasmas invariably have anisotropic pressure distributions. Depending on the details of the heating scheme the plasma can have either parallel pressure dominant or perpendicular pressure dominant. High performance supershots in TFTR typically have the parallel pressure dominant. This is due to the injection angle of the neutral beams and the difference in slowing down times in the perpendicular and parallel directions. Fig. II.C-1 shows the fraction of parallel pressure compared to the total for a high powered DT supershot. The fraction of parallel pressure starts out high and drops as the particles thermalize eventually leveling off in the 20% - 30% range. The degree of pressure anisotropy is configuration dependent. For example, in contrast to the above, ICRF heated plasmas in TFTR can have the perpendicular component of the pressure largest.

Fig. II.C-1 Fraction of $\delta p_{\parallel}$ vs. time for TFTR DT supershot.

Recent DT supershots were analyzed to determine the effect, if any, of anisotropic pressure on ballooning modes. Previous analysis⁷ together with studies performed by ourselves last year demonstrated that perpendicular pressure tends to be destabilizing while parallel pressure is stabilizing. However, for low beta, circular shaped plasmas such as those in TFTR the effect is small on 1st region stability. This was confirmed by subsequent analysis of DT supershots. There is a noticeable effect on the transition region and second region boundaries and hence, on the size of the unstable region. However, there is no impact on the experiment since these supershots are solidly in the first region. In "Dee" shaped and high beta plasmas the same level of pressure anisotropy would have a more significant effect on the ballooning stability.

Although anisotropic pressure was found to have little significant effect on ballooning stability for TFTR supershots the Mercier criteria showed an interesting feature. Previous theoretical analysis by Taylor and Hastie⁸ indicated that in a plasma with the parallel pressure dominant the critical safety factor for Mercier stability could be as low as $q_0 = 0.8$. This effect was confirmed numerically for supershot equilibria where the plasma remained Mercier stable down to $q_0 \approx 0.92$ in agreement with Taylor and Hastie for this level of anisotropy. This is significant because for conditions found in supershots isotropic MHD theory typically predicts both Mercier and internal kink instabilities when $q_0 < 1$.

Experimentally these plasmas are fairly quiescent with most of the MHD activity attributed to beta dependent instabilities. Previous MHD analyses of experimental plasmas therefore artificially restricted $q_0 > 1.0$. In the last few years, though, better diagnostics and plasma equilibrium reconstruction of experiments have shown that in the high current cases q_0 is almost always less than 1. Estimates of q_0 range from 0.7 to 0.9. This could not be explained by isotropic MHD theory. Therefore, including pressure anisotropy effects brings MHD predictions more in line with the experimental observations.

Fig. II.C-2 Critical q_0 for Mercier stability for varying pressure anisotropy.

In contrast to ballooning stability, pressure anisotropy should have a significant and noticeable effect on the kink stability of TFTR. This is because the kink instability is driven by parallel current, part of which is proportional to the parallel pressure gradient. Therefore anisotropic effects should be apparent even in low beta plasmas. A low -n code has been developed based on the Kruskal-Oberman energy principle⁹ which includes pressure anisotropy. By using the Bineau form of the force balance equation¹⁰ considerable simplification can be made to the anisotropic parts of the energy principle greatly aiding numerical implementation. Initial studies were carried out for the 1/1 internal mode. A sample results for a TFTR, D-T supershot is shown in Fig. II.C-3. As can be seen parallel pressure tends to be stabilizing for the internal kink mode. These result may partially explain the experimental observations that supershot plasmas evolve without sawteeth activity although $q_0 < 1$.

Fig. II.C-3 1/1 Internal Kink Beta Limits for TFTR

The next generation tokamak experiments such as ITER and TPX will be predominately auxiliary heated and have a significantly higher beta than TFTR hence anisotropic pressure effects should be even more important. The principal result pertaining to ITER may be the ability to operate free of MHD instabilities with $q_0 < 1$. Anisotropic pressure effects on the ballooning mode and the external kink mode should prove interesting in formulating advanced operating modes for TPX.

III Implement Improvements in Equilibrium and Stability Models.

The analysis of instabilities observed in experiments continues to be an evolving area of research. This requires an on going effort to improve our analysis tools. A substantial amount of code development was performed this year in order to add new capabilities to our codes. This will allow us to address specific stability issues in TFTR and future fusion experiments. Most of the code development was supported by Grumman Corporation. We mention it here since it directly impacts our accomplishments under this contract. Our low-n stability code underwent a major update to include anisotropic pressure effects and to allow for a vacuum region and conducting wall external to the plasma. A nonlinear resistive version of ARES was developed and is now being validated. Covered under this contract were benchmarking of these codes and improvements made to the equilibrium and mapping code. A mapping code was developed for interfacing our equilibrium code to the PEST code. A non-up-down symmetric version of our ballooning subroutine was developed and installed in TRANSP. These codes were shared with several of our collaborators.

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APPENDIX

Associated Publications and Presentations

1. M.H. Hughes, M.W. Phillips and E.D. Fredrickson, *Magnetohydrodynamic Stability Studies of Supershot Plasmas*, Phys. Fluids B, 5(9), (1993), p. 3267.
2. R. Iacono, A. Bhattacharjee, C. Ronchi, J.M. Greene and M.H. Hughes, *Stability of Tearing Modes in Finite-Beta Plasmas*, Physics of Plasmas, 8, (1994), p. 2645.
3. R. Iacono, A. Bhattacharjee, C. Ronchi, J.M. Greene and M.H. Hughes, *Stability of Tearing Modes in Finite-Beta Plasmas*, 1994 International Sherwood Fusion Theory Conference, Dallas, TX, Paper 1C7
4. M.W. Phillips and M.H. Hughes, *Anisotropic Pressure Effects on Advanced Operating Regimes in Tokamaks*, 1994 International Sherwood Fusion Theory Conference, Dallas, TX, Paper 1D53
5. M.H. Hughes and M.W. Phillips, *MHD Stability Analysis of D-T Plasmas in TFTR*, 1994 International Sherwood Fusion Theory Conference, Dallas, TX, Paper 1D54
6. M.H. Hughes and M.W. Phillips, *Nonlinear MHD Studies of TFTR Plasmas*, 36th Annual Meeting, APS, Division of plasma Physics, Minneapolis, MN, November 1994
7. M.W. Phillips and M.H. Hughes, *Stability of Anisotropic Plasmas in High Beta Tokamaks*, 36th Annual Meeting, APS, Division of plasma Physics, Minneapolis, MN, November 1994
8. W. Stodiek, M.H. Hughes and M.W. Phillips, *The Nonlinear Stability of the 1/1 Mode in Tokamak Plasma Columns with $q < 1$* , 36th Annual Meeting, APS, Division of plasma Physics, Minneapolis, MN, November 1994