中国科学院自然科学奖申报书（1）

项目名称 （2）	环耦合撕裂模的理论研究				
任务来源 （3）	A国家攻关、B国家高技术计划、C国家自然科学基金、D攀登计划、E国家或院重点实验室、F其他国家计划、G院或部委计划、H省、自治区、直辖市计划、I自选、J其他				
报送的学科评审组 （4）	数理天文				
研究起始时间 （5）	1992.10～1995.03		院成果登记号 （6）	113334951003	
申报日期 （7）	1995.02.10		申报等级 （8）	二等	
初评等级 （9）			审定等级 （10）		
申报单位 （11）	中国科学院等离子体物理研究所				
主要完成者人数 （12）	3		参加研究总人数 （13）	3	
项目曾获奖励情况 （14）	获奖时间	获奖种类	奖励等级	奖金数额	授奖部门

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评 审 意 见

申报单位推荐意见（17）

撕裂模通过磁场重联破坏约束高温等离子体的平衡磁场位形，能触发中止放电甚至毁坏装置的大破裂，是当代托卡马克实验中最主要的宏观不稳定性问题，也是聚变界长期的重要研究课题。撕裂模的线性和非线性经典理论采用平板和圆柱模型揭示了模的基本性质，是两项里程碑式的工作。但在托卡马克位形中，环耦合效应导致的整体结构对撕裂模的物理图象和基本性质会产生深刻的影响。国际权威学者CHT等人试图集前人一系列研究之大成，创立了环耦合撕裂模的框架理论并已被广泛应用。

然而，本项目的研究发现CHT的理论从物理假设到数学处理均有问题，重建了新的理论模型并成功地应用于分析极向旋转对稳定和约束的影响，在物理概念和处理方法上均有突破和创新。被国际同行认为"建立了能更合理地分析耦合效应的新表象，尤其是证明了环耦合总是使撕裂模退稳的结论，并改正了CHT的柱模增长率小则环耦合强的论点，并证明当相互作用模的增长率相等时环耦合很强而无论增长率大小"。这揭示了环撕裂模对聚变有不容忽视的潜在危害，因为聚变堆越紧凑则环效应越强。最近，李定在评论中论证了CHT的理论为何导致不正确的色散关系并产生定性和定量的错误后果。尽管CHT在答复中对出错的根源仍持不同意见，但承认评论"揭示了CHT的理论中色散关系在环耦合量级上的错误"。在李定获得95年国家杰出青年科学基金的各级专家评审中，本项目的研究曾获高度评价。

这些均表明本项目的研究在其领域中已达到国际先进水平，并对磁流体力学和受控聚变研究具有很高的学术价值和广泛的应用前景。学术委员会一致推荐申报院自然科学奖，申报等级二等。

单位公章

学术委员会主任（签名）：郭文康　　1996 年 2 月 7 日

学术委员会人数	13	参加讨论该项委员人数	10
同意申报等级委员人数	10		

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主要完成单位情况表(18)

序号	单位名称	承担本项目的工作内容
1	中国科学院等离子体物理研究所	全部内容
2		
3		
4		
5		

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主要完成人员情况表 (19)

序号	姓 名	单 位	性别	职 务 (职称)	对本项目做出重要贡献的内容
1	李 定	等离子体物理研究所	男	副研究员 室副主任	物理模型，数学处理，物理分析和模型应用
2	王传兵	等离子体物理研究所	男	硕 士	参与模型应用
3	霍裕平	等离子体物理研究所	男	院 士 所 长	选择研究方向，参与物理分析

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主要论著目录 (14) [不超过20篇，按下列格式列出：论文包括作者，出版年份，题名，刊名，卷（期）页，专著包括作者，出版年份，书名，出版者，页。]

1. Ding Li , Yuping Huo, 1993
Toroidal Coupling of Disparate Helical Tearing Modes.
Physics of Fluids B 5 (10), 3737.

2. Ding Li , Chuanbing Wang, 1995.
Influence of Poloidal Rotation on the Toroidally Coupled Tearing Mode.
Phys. Plasmas **2** (4), 1026.

3. Ding Li, Yuping Huo, 1993.
Coupling Effect of Resistive Tearing Modes.
Bull. Am. Phys. Soc. **38** (10), 2014.

4. Ding Li , Chuanbing Wang, 1994.
Poloidal Rotation of Toroidally Coupled Tearing Modes in Tokamak.
Presented in *the IAEA TCM on Research Using Small Tokamaks*,
IAEA, Madrid, Oct. 22-24.

5. Ding Li, Yuping Huo, 1993.
Numerical Analyses of Toroidal Tearing Modes.
Chin. Phys. Lett. **10** Supple., 154.

6. Ding Li, 1995.
Comment on "Stability of Coupled Tearing Mode and Twisting Modes in Tokamak" [Phys. Plasmas **1**, 3308 (1994)].
Phys. Plasmas 2(10), 3923. (对 CHT 的理论的评论)

附件三

引用情况影印件

附件三(A)：CHT 理论的主要论文摘要

1. Phys. Fluids B 3 (7), 1532, 1991.

Resonant magnetohydrodynamic modes with toroidal coupling. Part I: Tearing modes

J. W. Connor and R. J. Hastie
Culham Laboratory (UKAEA/Euratom Fusion Association), Abingdon, Oxfordshire OX14 3DB, England

J. B. Taylor
Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas 78712

(Received 19 July 1990; accepted 11 March 1991)

In a cylindrical plasma, tearing modes can be calculated by asymptotic matching of ideal magnetohydrodynamic (MHD) solutions across a critical layer. This requires a quantity Δ' that represents the "discontinuity" in the ideal solution across the layer. In a torus, poloidal harmonics are coupled and there are many critical surfaces for each toroidal mode number, and correspondingly many discontinuities Δ'_m. The ideal MHD solutions do not then determine the Δ'_m but only a relation between them—described by an "E matrix." The calculation of the E matrix for a large-aspect-ratio tokamak is discussed. In a weak-coupling approximation, it is tridiagonal and can be computed from integrals over the uncoupled eigenfunctions or from simple "basis functions" comprising triplets of coupled poloidal harmonics. This weak-coupling approximation fails if Δ'_m is already small for an uncoupled harmonic. An alternative strong-coupling approximation is developed for this case.

2. Phys. Fluids **31** (3), 577, 1988.

Tearing modes in toroidal geometry

J. W. Connor, S. C. Cowley,[a] R. J. Hastie, T. C. Hender, A. Hood,[b] and T. J. Martin
Culham Laboratory (EURATOM/UKAEA Fusion Association), Abingdon, Oxfordshire OX14 3DB, England

(Received 26 May 1987; accepted 16 November 1987)

The separation of the cylindrical tearing mode stability problem into a resistive resonant layer calculation and an external marginal ideal magnetohydrodynamic (MHD) calculation (Δ' calculation) is generalized to axisymmetric toroidal geometry. The general structure of this separation is analyzed and the marginal ideal MHD information (the toroidal generalization of Δ') required to discuss stability is isolated. This can then, in principle, be combined with relevant resonant layer calculations to determine tearing mode growth rates in realistic situations. Two examples are given: the first is an analytic treatment of toroidally coupled ($m = 1, n = 1$) and ($m = 2, n = 1$) tearing modes in a large aspect ratio torus; the second, a numerical treatment of the toroidal coupling of three tearing modes through finite pressure effects in a large aspect ratio torus. In addition, the use of a coupling integral approach for determining the stability of coupled tearing modes is discussed. Finally, the possibility of using initial value resistive MHD codes in realistic toroidal geometry to determine the necessary information from the ideal MHD marginal solution is discussed.

附件三(B)：CHT理论被应用及引用目录

（根据SCI检索，1995年的尚未统计在内）

1. S. C. Cowley et al., Phys. Fluids **31**, 426 (1988).
2. M. S. Chu et al., Phys. Fluids B **1**, 62 (1989).
3. J. W. Connor et al, in *Plasma Phys. Control. Nucl. Fusion Research*, IAEA, Vol. **2**, 33 (1989).
4. J. A. Holmes et al., Phys. Fluids B **1**, 788 (1989).
5. R. Fitzpatrick et al., Phys. Fluids B **1**, 2381 (1989).
6. R. Fitzpatrick et al., Plasma Phys. Control. Fusion **31**, 1127 (1989).
7. A. Rogister et al., Nucl. Fusion **29**, 1175 (1989).
8. R. Fitzpatrick et al., Phys. Fluids B **2**, 2636 (1990).
9. R. L. Dewer et al., J. Plasma Phys. **43**, 291 (1990).
10. A. Rogister et al., Phys. Fluids B **2**, 953 (1990).
11. M. S. Chu et al., Phys. Fluids B **2**, 97 (1990).
12. J. Y. Chen et al., Nucl. Fusion **30**, 2271 (1990).
13. J. W Connor et al, in *Plasma Phys. Control. Nucl. Fusion Research*, IAEA, Vol. **2**, 107 (1991).
14. R. Fitzpatrick et al., Phys. Fluids B **3**, 644 (1991).
15. A. Pletzer et al., J. Plasma Phys. **45**, 427 (1991).
16. A. Rogister et al, in *Plasma Phys. Control. Nucl. Fusion Research*, IAEA, Vol. **2**, 231 (1991).
17. K. Avinash et al., Phys. Fluids B **4**, 1671 (1992).
18. C. D. Challis et al., Nucl. Fusion **32**, 2217 (1992).
19. J. P. Christia et al., Plasma Phys. Control. Fusion **34**, 1681 (1992).
20. R. Fitzpatrick et al., Plasma Phys. Control. Fusion **34**, 1127 (1992).
21. T. R. Harley et al., J. Comput. Phys. **103**, 43 (1992).
22. H. L. Berk et al., Phys. Fluids B **5**, 3969 (1993).
23. P. M. Bellan et al., Plasma Phys. Control. Fusion **35**, 169 (1993).
24. M. S. Chu et al., Phys. Fluids B **5**, 1593 (1993).
25. J. W. Connor et al, Plasma Phys. Control. Fusion **35**, 757 (1993).
26. R. L. Dewer et al., Phys. Fluids B **5**, 4273 (1993).
27. R. Fitzpatrick et al., Nucl. Fusion **33**, 1533 (1993).
28. J. B. Wilgen et al., Phys. Fluids B **5**, 2513 (1993).
29. H. R. Wilson et al., Plasma Phys. Control. Fusion **35**, 885 (1993).
30. M. Persson et al., Phys. Fluids B **5**, 3844 (1993).
31. R. Fitzpatrick et al., Phys. Plasmas **1**, 3309 (1994).
32. G. Haqulic et al., Nucl. Fusion **34**, 1299 (1994).
33. C. C. Hegana et al., Phys. Plasmas **1**, 2308 (1994)
34. M. Persson et al., Phys. Plasmas **1**, 1256 (1994).
35. M. Persson et al., Plasma Phys. Control. Fusion **36**, 1775 (1994).

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附件三(D)：同美国«Phys. Fluids B»杂志审稿人的辩论

关于本项目研究理论模型的应用“Influnce of Poloidal Rotation on the Toroidal Coupling Tearing Mode [Phys. Plasmas 2 (4), 1025, 1995]”

本项目的研究将环耦合撕裂模的新模型成功地应用于分析极向旋转效应，澄清了旋转频率与增长率的关系。审稿人B仅一审就同意以快迅发表，建议作小修改；审稿人A则在第一次审稿意见中表示，“这篇文章本来适合于作为快迅发表，但问题在于此文断言‘以前所有这方面的工作皆以不正确的色散关系为出发点’”。

这是审稿人A的第一次审稿意见：

Dear Dr Davidson

The topic addressed in PoP-20723-L "Influence of poloidal rotation on toroidally coupled tearing mode" is suitable for submission as a lettter. The problem with the manuscript however, is that it (and its predecessor (ref 9)) assert that all previous work on this topic (refs 4-8) "employed the incorrect dispersion relation as the starting point".

In fact, the reverse is the case. In so far as the Li and Wang dispersion relation differs from that of eg ref 7, it is because of the omission by Li and Wang of $0(\epsilon^2)$ toroidal terms which modify the equilibrium and result in $0(\epsilon)^2$ corrections to the 'cylindrical' solutions. This requires the calculation of the diagonal elements in the matrix with order ϵ^2 accuracy. The method used by *Li* and Huo[9] to calculate off-diagonal terms in the matrix is different from the method employed in the earlier papers, but is, I believe, entirely equivalent. Before any application of their work can be accepted as different and correct, it would be necessary to show that their matrix elements differ from those of eg Connor, Hastie, Taylor, and that $0(\epsilon^2)$ corrections to diagonal elements are not required.

Turning to the analysis presented in this manuscript, *I* find it unsatisfactory to retain the parameter c (which is small of order ϵ^2) as though it were $0(1)$. The underlying theory is based on an expansion in the inverse aspect ratio which assumes $\epsilon \ll 1$. It is of course because of this that much earlier work focusses on cases where $\Delta_m'^{(0)}$ and/or $\Delta_{m+1}'^{(0)}$ were also small of order ϵ (or ϵ^2). Only in such optimal ordering scenarios does toroidal stability differ from cylindrical stability.

In conclusion I cannot recommend acceptance of this manuscript.

REFEREE #1

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本项目的研究人員在答复审稿人的第一次评论时详细地论证了前人的理论错在哪里和出错的根源。审稿人在第二次评论中表示，“经过研究作者对我上次评论的答复和修改稿，我相信，作者关于他们的结果和前人的结果不同的断言是正确的，我推荐发表这篇文章。”

这是审稿人A的第二次审稿意见：

MS PF 20723-L-A

I have studied the authors response to my earlier comments and their revised paper. I believe the authors are correct in their assertions concerning the difference between their results and those of ref 3, and I recommend publication of the paper.

REFEREE #1

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$$\left|\begin{pmatrix} \Delta_m^{\prime(0)} & -(C^{(1)}_{m+1,m}/C^{(0)}_{m,m})\Delta_m^{\prime(0)} \\ -(C^{(1)}_{m,m+1}/C^{(0)}_{m+1,m+1})\Delta_{m+1}^{\prime(0)} & \Delta_{m+1}^{\prime(0)} \end{pmatrix} - \begin{pmatrix} \Delta_m' & 0 \\ 0 & \Delta_{m+1}' \end{pmatrix}\right| = 0 \tag{5}$$

or

$$\begin{vmatrix} \Delta_m' - \Delta_m^{\prime(0)} & (C^{(1)}_{m+1,m}/C^{(0)}_{m,m})\Delta_m^{\prime(0)} \\ (C^{(1)}_{m,m+1}/C^{(0)}_{m+1,m+1})\Delta_{m+1}^{\prime(0)} & \Delta_{m+1}' - \Delta_{m+1}^{\prime(0)} \end{vmatrix} = 0, \tag{5'}$$

the toroidal Δ_i' in off-diagonal elements were incorrectly replaced by cylindrical $\Delta_i^{\prime(0)}$.

Second, the incorrect dispersion relation will produce qualitative and quantitative errors. By asymptotic matching, a correct dispersion relation was obtained from Eq. (2):[4]

$$A_\pm(\epsilon,k) = A_m[(1+k) \pm \sqrt{(1-k)^2 + 4k\epsilon}]/2(1-\epsilon), \tag{6}$$

where $A_m = \Delta_m^{\prime(0)}/\alpha_m$, $A_\pm = \Delta_m'/\alpha_m$, $k = A_{m+1}/A_m$, $\epsilon = \epsilon^2 F_m^{m+1+} F_{m+1}^{m-} \sim O(\epsilon^2)$ is a toroidal coupling parameter, and α_m is a constant. From

$$\frac{\partial A_\pm}{\partial \epsilon} = \pm \frac{A_m[(1+k) \pm \sqrt{(1-k)^2 + 4k\epsilon}]^2}{4(1-\epsilon)^2 \sqrt{(1-k)^2 + 4k\epsilon}}, \tag{7}$$

one can find $\partial A_+/\partial \epsilon > 0$ and $\partial A_-/\partial \epsilon < 0$ regardless of the sign of k. However, if replacing the toroidal Δ_i' by cylindrical $\Delta_i^{\prime(0)}$ in off-diagonal elements of Eq. (2), Eqs. (6) and (7) become

$$A_\pm(\epsilon,k) = A_m[(1+k) \pm \sqrt{(1-k)^2 + 4k\epsilon}]/2 \tag{8}$$

and

$$\frac{\partial A_\pm}{\partial \epsilon} = \pm \frac{A_m k}{\sqrt{(1-k)^2 + 4k\epsilon}}. \tag{9}$$

Obviously, $\partial A_\pm/\partial \epsilon$ will change sign as k from positive to negative.

Third, the $O(\epsilon^2)$ correction to diagonal elements is not important for toroidal coupling since it can only result in negligible quantitative change. The dispersion relation (6) can be straightforwardly extended to include this correction. Then, Eqs. (2) and (6), respectively, become

$$\begin{vmatrix} C_1\Delta_m' - \Delta_m^{\prime(0)} & \epsilon F_m^{m+1+}(\rho_m)\Delta_m' \\ \epsilon F_{m+1}^{m-}(\rho_{m+1})\Delta_{m+1}' & C_2\Delta_{m+1}' - \Delta_{m+1}^{\prime(0)} \end{vmatrix} = 0 \tag{10}$$

and

$$A_\pm = A_m[(c_2 + c_1 k) \pm \sqrt{(c_2 - c_1 k)^2 + 4k\epsilon}]/2(c_1 c_2 - \epsilon), \tag{11}$$

where $c_1 = 1 + \epsilon^2 G_m^{+}(\rho_m)$, and $c_2 = 1 + \epsilon^2 G_m^{-}(\rho_{m+1})$. Here $G_j^{\pm}$ are the ϵ^2 order particular solutions due to the toroidal coupling. Consequently, Eq. (7) becomes

$$\frac{\partial A_\pm}{\partial \epsilon} = \pm \frac{A_m[(1+k) \pm \sqrt{(c_2 - c_1 k)^2 + 4\epsilon k}]^2}{4(c_1 - \epsilon)^2 \sqrt{(c_2 - c_1 k)^2 + 4\epsilon k}}. \tag{12}$$

It is easy to check there is no qualitative change but only negligible quantitative change for $A_\pm$ due to $O(\epsilon^2)$ correction to diagonal elements.

Fourth, it is necessary to retain the parameter ϵ even though it is of order ϵ^2, whereas it is unnecessary for $\Delta_i^{\prime(0)}$ to be limited to small of order ϵ or ϵ^2. From the radical in Eq. (6), one can observe that the coupling term is larger than another term when $k \to 1$ even though ϵ is quite small. One can obtain $A_\pm = A_m/(1 \mp \sqrt{\epsilon})$ for $k = 1$, which means the toroidal coupling is of order ϵ regardless of the magnitude of $\Delta_i^{\prime(0)}$. On the other hand, Eq. (5) can be rewritten as

$$\begin{vmatrix} \Delta_m' - \Delta_m^{\prime(0)} & I_{m,m+1}(\Delta_m'/\Delta_m^{\prime(0)}) \\ I_{m+1,m}(\Delta_{m+1}'/\Delta_{m+1}^{\prime(0)}) & \Delta_{m+1}' - \Delta_{m+1}^{\prime(0)} \end{vmatrix} = 0, \tag{13}$$

where $I_{ij} = \Delta_i^{\prime(0)}(C_{ji}^{(1)}/C_{jj}^{(0)}) \sim O(\epsilon)$ [Eq. (B8) in Ref. 2] looks independent of $\Delta_i^{\prime(0)}$. Due to their above-mentioned error, $(\Delta_i'/\Delta_i^{\prime(0)})$ disappeared so that the off-diagonal elements looks the same order as the diagonal elements if $\Delta_i^{\prime(0)} \sim \epsilon$. Hence, they concluded incorrectly that $\Delta_i^{\prime(0)} \sim \epsilon$ is the condition for strong coupling. In fact, I_{ij} still depend on $\Delta_j^{\prime(0)}$ so that a off-diagonal element is always one ϵ order smaller than the diagonal element in the same row even if $(\Delta_i'/\Delta_i^{\prime(0)})$ disappear. From $P\int_0^b \Psi_i^{(0)} L_j \Psi_j^{(1)} dr = P\int_0^b \Psi_j^{(0)} K_j^{+} \Psi_i^{(0)} dr$ [Eqs. (6) and (A17)–(A19) in Ref. 3], it is not difficult to demonstrate this point by partial integration:

$$\begin{aligned} I_{m+1,m} &= \Delta_m^{\prime(0)} \Psi_m^{(1)}(r_m)/\Psi_{m+1}^{(0)}(r_{m+1}) \\ &= r_{m+1}\Delta_{m+1}^{\prime(0)} \Psi_{m+1}^{(1)}(r_{m+1})/r_m \Psi_m^{(0)}(r_m) \\ &\quad + \Delta_i'[\Delta_m^{\prime(0)} \Psi_{m+1}^{(0)}(r_m)/\Psi_{m+1}^{(0)}(r_{m+1}) \\ &\quad - r_{m+1}\Delta_{m+1}^{\prime(0)} \Psi_m^{(0)}(r_{m+1})/r_m \Psi_m^{(1)}(r_m)]. \end{aligned} \tag{14}$$

Therefore, $\Delta_i^{\prime(0)} \sim \epsilon$ is neither a necessary nor sufficient condition for strong coupling.

In summary, it is shown that Connor *et al.*'s dispersion relation and the strong coupling condition are incorrect. Such an incorrect dispersion relation does produce qualitative and quantitative derivation from the correct one. Hence, one cannot use it as the starting point to analyze the stability of the toroidally coupled tearing modes.

ACKNOWLEDGMENT

This work was supported by National Science Foundation of China, Contract No. 19475044.

[1] R. Fitzpatrick, Phys. Plasmas 1, 3308 (1994).
[2] J. W. Connor, R. J. Hastie, and J. B. Taylor, Phys. Fluids B 3, 1532 (1991).
[3] J. W. Connor, S. C. Cowley, R. J. Hastie, T. C. Hender, A. Hood, and T. J. Martin, Phys. Fluids 31, 577 (1988).
[4] D. Li and Y. Hun, Phys. Fluids B 5, 3733 (1993).