

# 磁约束核聚变等离子体 输运与约束研究

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核工业西南物理研究院





## 个人简介

### □ 基本情况

核工业西南物理研究院特聘研究员,博士,从事磁约束核聚变等离子体物理与诊断研究。中国环流器二号A物理实验协调人,聚变科学所青年学术交流委员会委员,中国聚变工程实验堆CFETR集成设计项目总体专家组学术秘书。

### □ 承担省部级及以上科研项目7项,人才类项目:

- 一 2016年,入选中国科协"青年人才托举工程"项目
- 2018年,入选四川省首批"天府万人计划"天府科技菁英项目
- 2018年,入选中核集团首批"青年英才"计划菁英项目
- 2019年, 获国家优秀青年基金项目

### □ 主要获奖情况

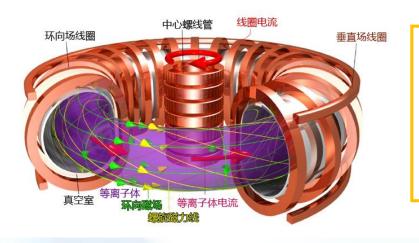
- 2016年, "蔡诗东"全国等离子体物理奖
- 2016年, 国防科技进步二等奖 (2/10)
- 2017年,四川省青年科技奖
- 2018年,亚太等离子体物理杰出青年科学家奖
- 2018年, 国防科技进步一等奖 (4/10)





# 研究背景

### 核聚变能是理想的未来能源



聚变点火条件: nTτ>5×10<sup>21</sup>m<sup>-3</sup>·keV·s

### 磁约束聚变物理研究背景:

- →提高:密度nf,温度Tf,约束τf;
- →等离子体输运是反常的,不利于nTt的提高;
- →控制输运,实现高参数稳态约束。

### 聚变物理的根本是输运与约束

### 国际共识的关键物理问题:

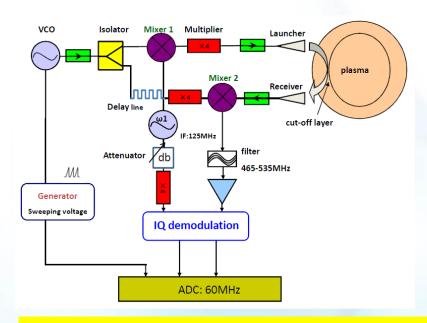
- → 反常输运是由什么决定?
- → 约束提高的障碍是什么?
- → 不稳定性如何主动控制?





# 发展先进的诊断系统

### 发展了调频连续波微波反射计诊断系统, 并提出了处理微波反射计时延的新方法

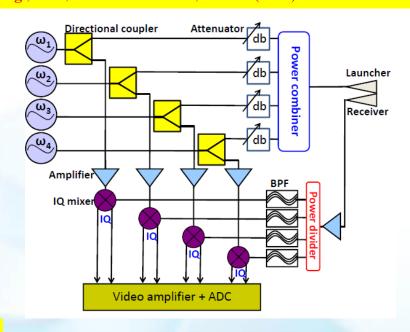


W.L. Zhong, et al., *Review of Scientific Instruments* **82**, 103508 (2011) W.L. Zhong, et al., *Review of Scientific Instruments* **85**, 013507 (2014)

- □ 2015年欧洲物理学会诊断会议最佳海报奖
- □ 2016年国防科技进步二等奖 (2/10)

### 发展多道微波多普勒反射系统,首次实现湍流三维测量

**W.L. Zhong**, *et al.*, *Journal of Instrumentation* **10**,P10014 (2015) **W.L. Zhong**, *et al.*, *Nuclear Fusion* **55**, 113005 (2015)



→ 为物理研究提供了重要数据

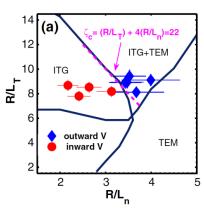


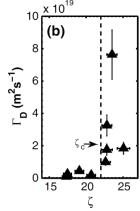


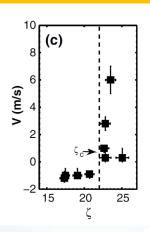
# 反常输运实验和理论模拟研究

### 首次发现了等离子体湍流模式转换与粒子对流速度反转的关系

法国Tore-Supra托卡 马克上开展实验研究







### 实验与理论模 拟直接对比

Mitsuru Kikuchi Masafumi Azumi

### Frontiers in Fusion Research II

ntroduction to Modern Tokamak Physics

7 Turbulent Transport in Tokamal

1, or goes up as well), the trapped particle pic ele contribution to the pinch dominates to h en from above formula.

 $k_s p_l \sim 1$ ), the trapped particle contribution e contribution  $(\sim 1/k_1 v_{tr})$  for  $C_T$  and  $C_p$  sinc e situation at  $s \sim 0$ . In scale drift wave turbulence is the ITG to TEM

on. Particle transport property is quite different to used to identify the mode transition. It is not the trig is inward and that by the TEM Recent modulation experiments in Tore Suprion of the convective speed across the stability TEM, which is in good agreement with the near gyrokinetic code as shown in Fig. 7.8. The of Welland fluid mode, The ITIG 4TIG 4TEM

gonal turbulent particle flux driven by dTermo-diffusion is first reported by Nagashi is also an off-diagonal turbulent particle it is price in the particle it is price in the particle it is price in the particle price price

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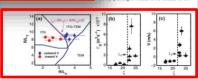


Fig. 7.8 (a) Stability diagram of ITG/TEM with experimental data of convection direction (b) Diffusive particle flux v.s. ITG/TEM boundary parameter ζ. (c) Convective speed v.s. ITG/TEM boundary parameter ζ. Reproduced with permission from Zhong 1859]. Copyright America W.L.Zhong et al., Physical Review Letters 111, 265001 (2013)

□ 12<sup>th</sup> Asia Pacific Physics Conference, Chiba, Japan, July12-19, 2013, **Oral** □ 中国物理学会2016秋季学术会议, 9.1-9.4, 2016年, 北京, **邀请报告** 



著名等离子体湍流输运模型Weiland模型的提出者,瑞典查尔姆斯理工大学Jan Weiland教授的综述文章再版

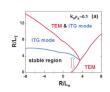
国际著名磁约束聚变专家、IAEA 聚变能大会前主席、NF前编委主席, 亚太物理学会协会等离子体物理分 会主席M. Kikuchi 教授的专著再版



and comer. The pine ITIO a worst when TITI is indicated a common the TITI is indicated a common that the title of the common that the common t

on the result (3). However, in 1977, Matter and Placke<sup>27</sup> behaved that the noisitions frequency, shift in three-wave treatestion meraged out the wave particle intraction with the result of the result of the result of the result of the state of the result of the result of the result of the result of solidors from Ref. 5. An important appect in that the defining to the result of the result of the result of the result of the lowever, here, the waves are tapped in the velocity district, however, here, the waves are tapped in the velocity district, however, here, the waves are tapped in the velocity district, however, then, the value of the result of the r

 $\left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial x}\right) f(\mathbf{x}, \mathbf{v}, t) = \frac{\partial}{\partial r} \left[\beta \mathbf{v} + D^{\mathbf{v}} \frac{\partial}{\partial v}\right] f(\mathbf{x}, \mathbf{v}, t),$   $\beta = \sum_{i} \beta_{i} [\epsilon \phi_{j} / T_{e}]^{2},$   $D^{\mathbf{v}} = \sum_{i} d_{j} [\epsilon \phi_{j} / T_{e}]^{2},$ (6)



PIG. 7. Stability of ITG and TEM modes in various regimes of density an imperature gradients. This result is taken from Ref. 22, where a line intetic code was used. In this case, the region in R/L<sub>n</sub> has been extended inverse slope. The different regimes are the same as in Fig. 5. Reproduce here, the fixtion and diffusion are due to infruithence. For contrast coefficients, (12) has an analysis estion given to Candarocachian. An example of this is shown in Fig. 8.
Chandracachian. An example of this is shown in Fig. 8.
While the contrast informer, and the contrast informer, waith for contrast confections in the Faske required increases a part of the contrast. However, we also have velocity dependence of coefficients. Thus, we have also manufacted tests. 47 the solution to the Fasker Panack equality of the contrast. However, we also have velocity dependence of coefficients. Thus, we have also manufacted tests. 47 the solution to the Fasker Panack equal to the contrast However, we also have excluded the contrast However, which we have a solution to the Fasker Panack equal to the contrast However the solution is the fasker Panack equal to the contrast tha

also made in a somewhat more pedagogical way b also made in a somewhat more pedagogical way b organea." Finally, a derivation with the method of transition behalfiles from the Bogoliubov Institute in Kiev wa Alfer having studied the coherent limit in detail, we can now understand the turbulent limit. Here, the sam

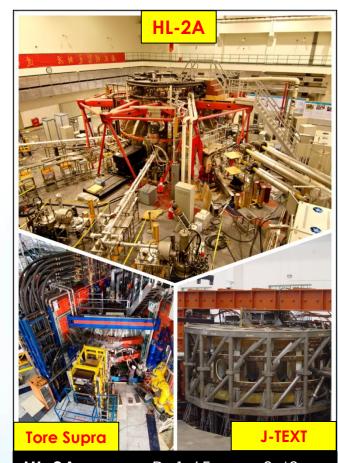
After having studied the coherent limit in detail, we can now understand the turbulent limit. Here, the sam see mixing due to oscillating nonlinear frequency shift take place. Here, we just have the additional phase mix due to several waves. We now note that (12) can also b ten in the form (10)



FIG. 8. The evolution of the mean square velocity deviation due to the Foldor-Flank equation (12). The friction,  $\beta$ , here extern as a medianer for general white, County, quantitant theory in valid for t < |S|, while the medianes thattening enters for  $t > U\beta$ . Helter, we have an exact analytical solution due to S.

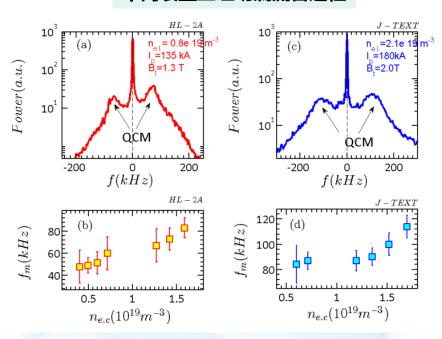


# 直接测量湍流模式转换



**HL-2A:** R=1.65m, a=0.40m **Tore Supra:** R=2.40m, a=0.72m **J-TEXT:** R=1.05m, a=0.27m

### 不同装置上证明湍流普适性



**W.L.Zhong** *et al.*, *Physics of Plasmas* (*Letter*) **23**, 060702 (2016) 入选编辑特别推荐文章

结合国内外3个托卡马克,结合理论模拟,系统地研究了TEM-ITG湍流转换,证实了其对等离子体约束与输运的影响.



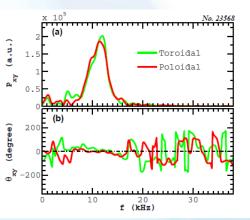
# 高约束模(H模)物理

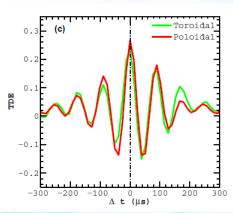
### ★ 理解了湍流驱动反常输运 →提高约束

### 提高约束的核心

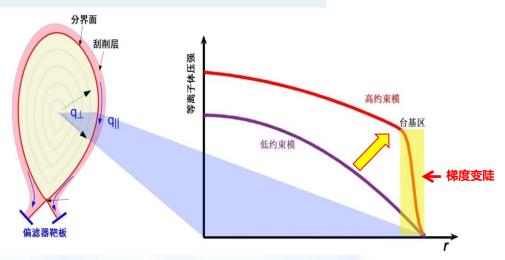
抑制湍流→降低反常输运→提高压强

- → H模是国际热核聚变实验堆(ITER)的 基本运行模式
- →高温高密度利于提高聚变反应效率
- →边缘剪切流,带状流起到关键作用









### 关键物理问题:

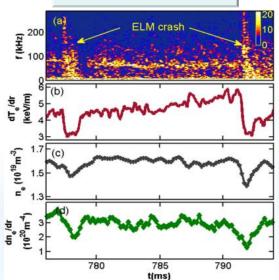
- → 剪切流如何抑制湍流?
- → 台基区湍流行为,如何影响输运?
- → 如何主动控制台基动力学?

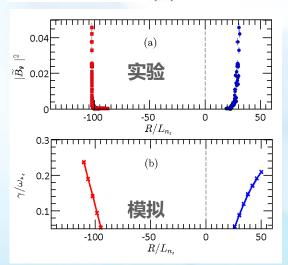




# 等离子体电磁不稳定性研究

### 台基区不稳定性模





### 证实了准相干模对台基的饱和起到限制作用

- →结合多种诊断,测量了其三维结构
- →发现其对台基饱和起到限制作用
- → BOUT++模拟与实验结果一致

W.L.Zhong et al., Plasma Physics and Controlled Fusion, **58**, 065001 (2016) (入选**2016**年度**PPCF**"高亮"文章)

- □ 第43届欧洲物理学会等离子体物理大会,邀请报告
- □ 第十八届全国等离子体科学技术会议, 大会特邀报告
- □ 首次发现激发电磁湍流的杂质密度梯度双阈值
- **」 实验和模拟定量一致,理解了杂质湍流驱动机制**
- □ 可为主动控制台基动力学实现对聚变堆第一壁材料的保护提供参考

**W.L. Zhong** *et al.*, *Physical Review Letters* **117**, 045001(2016)

**W.L. Zhong**, 1<sup>st</sup> Asia-Pacific Conference on Plasma Physics, Kanazawa, Japan,2018 **Plenary talk.** 





# 工作展望

### 瞄准聚变堆燃烧等离子体

- □ 理解高约束模下的等离子体输运,为<mark>台基结构优化和控制</mark>提供物理基础
- □ 在近堆芯等离子体中,理解等离子体电磁湍流对输运和约束的影响机制
- □ 主动控制台基动力学,<mark>控制高热负荷</mark>并减弱等离子体与壁相互作用

### 研究重点

- 电磁湍流的实验研究,推动理论模拟的发展和完善
- □ 外部杂质注入驱动台基不稳定性,实验和理论模拟
- □ 独创的掺杂超声分子束注入控制台基和靶板热负荷

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实现稳态高约束聚变等离子体



# 感谢单位、导师和合作者!感谢各位评委!感谢各位评委!

每一次进步都离不开身边良师益友给予的支持、鼓励和帮助。