北京大學

本科生毕业论文

题目： DIII-D 托卡马克装置中低频阿尔芬本征模的数值模拟

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摘要

在能源危机日益加重的今天，要想获得取之不尽用之不竭的清洁能源，可控核聚变几乎是唯一的方式。热核聚变是其中最重要到的一种聚变方式，而磁约束装置托卡马克又是控制住上亿度的高温等离子体目前进展最快，最有希望成功的一种装置。

托卡马克热核聚变中，辅助加热和聚变反应过程中产生的高能粒子严重影响着托卡马克装置的稳态运行。高能粒子能量密度高，能激发介观尺度的不稳定性，驱动高能粒子的径向输运，同时也深刻影响着与磁流体模式有着密切联系的微观湍流。高能粒子的损失将导致等离子体约束失效，其强烈的径向输运甚至损坏装置的第一壁。在国际热核试验聚变堆(ITER)中，高能粒子的自持加热是 ITER 点火的重要条件。因此，热核聚变中的高能粒子约束至关重要。

近年来，比压型阿尔芬声波本征模(beta-induced Alfven acoustic eigenmode, BAAE)和比压型阿尔芬本征模(beta-induced Alfven eigenmode, BAE)引起了实验人员的广泛注意，它们不仅在各个实验装置中被广泛地观察到（JET、NSTX、DIII-D），它们所在的频率段所造成的高能粒子损失甚至占到了总损失的 45%左右。根据磁流体理论，BAAE 将因为热离子的强朗道阻尼而难以存在，MHD 理论推导出的 BAAE 能否在托卡马克装置中被激发起来也一直是讨论的焦点问题。

刘雅琪博士的工作在解析圆位型的条件下验证了 BAAE 的存在，并且发现不稳定模式将随着装置尺寸增大由 BAE 过渡到 BAAE。刘雅琪博士还发现快离子的非微扰效应对 BAAE 的激发有重要作用：快离子能让 BAAE 的旁带由声波偏振变为阿尔芬波偏振，增大 BAAE 的阻尼率。另外，刘雅琪博士在圆位型的条件下验证了 BAAE 可以被非线性激发。

在本文的工作中，我将继续使用第一性原理出发的大规模并行回旋动理学代码（Gyro-kinetic Toroidal Code, GTC）,对 BAE 以及 BAAE 进行数值模拟和研究。本文的主要工作是在 DIII-D 真实实验剖面和位型下验证之前刘雅琪博士得到的结论。在线性模拟中，DIII-D 实验条件下并未找到低频本征模式。增大电子剖面梯度后，更低频的模式被激发出来，但是其模结构更像是理想气球模。因此，实验中的低频模式到底是不是 BAAE 还有待讨论。目前该工作还处于进行中。在非线性模拟中，在 DIII-D 实验条件下并未成功实现对 BAAE 的非线性激发。但是如果使用均匀背景等离子体条件，或者增大装置

尺寸，BAAE 频率模式能够在非线性阶段被激发出来。这初步证实了 BAAE 在更大装置中更容易被激发的结论，并且发现 BAAE 的激发与热等离子体梯度密切相关。

关键词：快粒子、比压型阿尔芬声波本征模、比压型阿尔芬本征模、DIII-D

Numerical Simulation of Low frequency Alfven Eigenmodes in DIII-D

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ABSTRACT

In today's increasingly worsening energy crisis, controllable nuclear fusion is almost the only way to obtain inexhaustible clean energy. Thermonuclear fusion is one of the most important fusion methods, while the device using magnetic confinement method, Tokamak, is the most promising device that can control extremely high temperature plasma of billions of degrees.

In thermonuclear fusion, energetic particles that come from auxiliary heating and fusion reactions seriously affect the steady state operation of Tokamaks. Energetic particles have super high energy density. They can excite meso-scale instabilities and drive large energetic particles transport. They will also strongly influence micro-turbulence responsible for macroscopic magnet-hydrodynamic(MHD) instabilities, which probably degrades overall plasma confinement and threaten the machine integrity. What’s more, the ignition in International Thermonuclear Experimental Reactor (ITER) relies on the self-heating by energetic fusion products, so the confinement of energetic particles is a critical issue.

In recent years, beta-induced Alfven acoustic eigenmode (BAAE) and beta-induced Alfven eigenmode (BAE) have raised attention of lots of researchers. Not only are they widely observed in various experimental devices, such as JET, NSTX and DIII-D, the frequency band in which they are is responsible for about 45% total loss of energetic particle. However, BAAE is unlikely to exist in thermal plasma due to heavy Laudau damping predicted by MHD theory. Whether it can exist in Tokamak or not is also one of the critical issues.

In Dr. Yaqi Liu’s work, she verified the existence of BAAE under the analyzed circular configuration. She found that the most unstable mode will change from BAE to BAAE as the machines size increases. Dr. Yaqi Liu also found that the non-perturbation effect of fast ions plays an important role in the excitation of BAAE. Fast ions can change the polarization of sideband of BAAE, from acoustic to Alfvenic. They can also significantly increase the damping rate of BAAE. In addition, Dr. Yaqi Liu demonstrated that BAAE can be excited nonlinearly

under analyzed circular configuration.

In this thesis, I will continue to use the first principle based large-scale parallel gyro-kinetic Toroidal Code (GTC) to do simulation and study about BAE and BAAE. The main work of this thesis is to continue Dr. Yaqi Liu's work and expand her work from analyzed circular configuration into real experimental configuration in DIII-D. In linear simulation, I did not find the targeted low frequency eigenmode in DIII-D condition. Low frequency modes appear when increases the temperature gradient of thermal electron, but it appears more like ideal ballooning mode when looking at the mode structure. Whether the low frequency mode we got in experiments is BAAE or not remains further discussion. In non-linear simulations, I failed to excite BAAE like mode in DIII-D condition. However, if I flatten the background plasma or I choose to use bigger machine size, BAAE frequency can be excited in non-linear phase. This phenomenon preliminarily verifies the conclusion that BAAE is easier excited in larger machine. This also reveals that the excitation of BAAE is closely related to the thermal plasma gradient.

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