

Instabilities of Plasma in Magnetic Constraint Controlled Nuclear Fusion Devices

Jiawei Li^{1,*}

¹Institut Franco-Chinois de l'Energie Nucléaire, Université Sun Yat-sen, Zhuhai, 519082, China

*First author's e-mail: lijw259@mail2.sysu.edu.cn

*Corresponding author

Abstract

This paper investigates the plasma instability issues in magnetic confinement nuclear fusion devices and explores their impact on fusion reaction efficiency and control methods. The research aims to analyze the physical mechanisms of macroscopic and microscopic scale plasma instabilities and conclude suppression strategies. Through theoretical models, numerical simulations, and data-driven methods, a systematic study was conducted on various instabilities such as resistive wall mode, tearing mode, and edge localized mode, as well as their interactions. The research results indicate that by optimizing the magnetic field structure, employing resonant magnetic perturbation (RMP) technology, and using supersonic molecular beam injection (SMBI), instabilities can be effectively suppressed, and plasma confinement performance can be improved. Additionally, the research on high-parameter steady-state operation and the interaction between fast particles and instabilities provides important basis for the commercial operation of future fusion devices. The conclusion of this paper emphasizes the crucial role of plasma instability control in achieving controllable nuclear fusion and looks forward to the future development direction of related technologies.

Keywords

Magnetic confinement nuclear fusion; Plasma instability; macroscopic plasma perturbation; Magnetohydrodynamics; Microscopic-scale plasma perturbations.

1. INTRODUCTION

Energy issues are one of the major challenges facing today's society. With the growth of the global population and the acceleration of industrialization, energy consumption continues to rise, and the drawbacks of traditional energy usage patterns are gradually becoming apparent. The traditional energy system dominated by fossil fuels has problems of high energy consumption and high emissions. Not only is the energy utilization efficiency low, but it also causes severe pollution to the ecological environment, such as global warming caused by greenhouse gas emissions, the intensification of air pollution, and the destruction of the ocean and soil. In addition, the reserves of fossil energy are limited, and long-term reliance on non-renewable energy clearly cannot achieve sustainable development. Therefore, human society has put forward higher requirements for the development and utilization of new energy. How to find clean, efficient, and sustainable energy alternatives has become a global focus.

Among various new energy technologies (such as wind energy, solar energy, geothermal energy, etc.), controlled nuclear fusion has attracted much attention due to its unique advantages. Nuclear fusion energy has an extremely rich and almost unlimited fuel source, such as deuterium and tritium, hydrogen isotopes that are abundant in seawater, which can support

sustainable development. Its energy density is extremely high, far exceeding that of other new and traditional fossil energies. The energy density of fusion energy is approximately a million times that of hydrogen energy, and the energy released by the fusion of 1g of deuterium and tritium is equivalent to that released by the combustion of about 8 tons of fossil fuels. Nuclear fusion energy also has the advantage of stable power supply. Unlike intermittent new energies such as solar and wind energy, fusion energy can provide stable base-load power and maintain continuous power generation for 24 hours, unaffected by day and night, seasons, or weather. Moreover, unlike nuclear fission, nuclear fusion generates almost no long-term radioactive waste and does not have the risk of "core meltdown" in nuclear accidents. Therefore, it is considered a safe and environmentally friendly future energy source. If commercial application can be achieved, nuclear fusion will provide humans with long-term, stable, and efficient clean energy, completely changing the global energy landscape.

The process of nuclear fusion can be understood as the collision of atomic nuclei overcoming the potential barrier between them to generate new particles and release a large amount of energy. The temperature required for nuclear fusion reactions is extremely high, which makes the reaction occur in a plasma state. Plasma is composed of electrons, ions, and neutral particles, with approximately equal positive and negative charges. The plasma state is also known as the fourth state of matter, different from solid, liquid, and gas states, and it has unique physical properties. Although plasma usually appears as a neutral gas on a macroscopic scale, it exhibits electromagnetic properties at the microscopic level. Plasma is a mixture of charged particles, and these particles show obvious collective effects when interacting, which is one of the main differences between plasma and the other three states of matter. In nuclear fusion reactions, particles need extremely high kinetic energy to have sufficient energy to overcome the electrostatic repulsion between atomic nuclei and achieve fusion. The reaction temperature of hundreds of millions of degrees Celsius exceeds the melting point of any existing material on Earth, so the fusion reaction needs to take place in a special device. The existing confinement methods mainly include inertial confinement, magnetic confinement, and gravitational confinement. Among them, the magnetic confinement fusion scheme, with its advantages of stability and mature technical foundation, has become the most widely studied and the most likely to promote commercial fusion power generation in the future controlled fusion method. In magnetic confinement nuclear fusion, the movement of internal charged particles is constrained by a strong magnetic field. In the magnetic field, charged particles are bound to the magnetic field lines under the action of the Lorentz force and perform helical motion around the magnetic field lines, which includes both circular motion perpendicular to the magnetic field direction and linear motion along the magnetic field direction. Through a rationally designed magnetic field structure, charged particles can stay in the magnetic field for a long time, reaching sufficient temperature, density, and confinement time to trigger and maintain the fusion reaction. The core idea of these devices is to optimize the configuration of the magnetic field to reduce the contact between particles and the wall, thereby increasing the probability of fusion reactions.

Building a fusion power plant that produces substantial net energy requires effective confinement of hot plasma, so that fusion reactions occur frequently enough to generate significant power.[1] However, constrained by the current technological conditions, achieving magnetic confinement controlled nuclear fusion still faces numerous scientific and engineering challenges. In such devices, the behavior of plasma is extremely complex, especially the instabilities and turbulence caused by electromagnetic disturbances, which are key factors affecting the performance of fusion devices. In fusion physics, plasma instability mainly refers to the instability phenomenon where electromagnetic disturbances in plasma grow due to the drive of free energy sources. When the disturbance signals caused by instability are strong enough, the nonlinear interaction between disturbance signals becomes increasingly obvious,

and the system often presents a so-called turbulent state. These physical processes not only lead to the loss of energy and particles in plasma but may also affect the confinement effect and reduce the efficiency of fusion reactions. Therefore, in-depth research on the influence of different magnetic field structures on plasma performance and optimization of confinement methods to improve plasma stability are important directions for promoting the development of controlled nuclear fusion research.

2. CLASSIFICATION AND PHYSICAL MECHANISM OF PLASMA INSTABILITY

2.1. Defination of plasma instability

The formal defination of stability is based on intuitive ideas. In dynamics, there are two types of equilibrium.one called stable, any small deviation from the equilibrium point leads to small oscillations about the equilibrium. Such as a rod suspended at one end in a gravitational field. It is stable when the rod hang vertically down. On the contrast, when the rod was balanced vertically above the support, this kind of equilibrium point is unstable. Any nearby trajectories deviate from equilibrium by a distance which grows exponentially with time.

The general of stability in a confined plasma can be formally expressed in terms of an evolution equation:

$$[\frac{d}{dt}X = N(x) .] \quad (1)$$

Suppose that we have determined an equilibrium point $\chi_0, N(X_0)=0$. We considering some of the ideas and terminology when study the stability of equilibrium point[2].

The most fundamental defination of stability is *lyapunov stability*: a system is lyapunov stable if the solution $\Delta X(t)$ of

$$[\frac{d}{dt}\Delta X = N(X_0 + \Delta X)] \quad (2)$$

stays bounded for all the time.

In a stable system, the solution starting very close to χ_0 stay close, so we can expanding N about X_0 to

$$[N(X_0 + \delta X) = N'(X_0)\delta X + \dots ,] \quad (3)$$

where $N'(X_0)=L$ is a linear operator, so the equation for δX becomes

$$[\frac{d}{dt}\delta X = L\delta X .] \quad (4)$$

Thus we have, *Linear stability*: an equilibruim X_0 is linear stable if every solution to the linearized equation above is bounded as $t \rightarrow \infty$.

A slightly stronger notion of linear stability is *asmpototic linear stability*: an equilibrium has asymptotic linear stability if every solution to this eauqtion tends to zero as $t \rightarrow \infty$.

Another technique for studying linear stability is to compute the eigenvalues of the linearized operaor L . This leads to the notion of *Spectral stability*: an equilibruim is spectrally stable if every eigenvalue of the linearized operator L has a nonpositive real part.

2.2. Macroscopic plasma perturbation (magnetohydrodynamic instability)

It is triggered by the disruption of the balance between the plasma pressure gradient and the magnetic confinement force. This type of instability develops rapidly and can lead to severe degradation or even complete breakdown of plasma confinement within milliseconds. Recent studies have found that, compared with a single mode, multiple coexisting modes in plasma will more significantly affect plasma confinement performance and limit the effectiveness and application range of MHD instability control strategies. Therefore, in-depth research on the coexistence and interaction of multiple MHD instability modes and their influence on the evolution of the modes themselves and the plasma parameter profile will be of great significance for optimizing tokamak discharges [3].

2.2.1. Resistive Wall Mode

The resistive wall mode (RWM) is an external magnetohydrodynamic (MHD) instability applicable to plasmas that are stable in ideal MHD but constrained by a finite resistive wall. In an ideal scenario, plasma displacement perturbations are suppressed by a perfectly conducting wall (infinite conductivity), but in the resistive wall mode, the finite resistance of the actual wall leads to magnetic field diffusion, allowing the perturbation to grow. It is found that passive stabilization of the RWM gives a relatively small increase in normalized beta above the no-wall limit, relying on toroidal plasma flow and drift kinetic resonance damping from both thermal and The resistive effect of the wall introduces a delayed feedback, making modes that are stable in an ideal wall unstable over a longer timescale. There are two main factors which determine the stability of the RWM[4].The first factor comes from external magnetic perturbations (error fields, resistive wall, feedback coils, etc).The physics of this interaction is relatively well understood and based on classical electrodynamics. The second ingredient of RWM physics is the interaction of the mode with plasma flow and fast particles. These interactions are particularly important for nuclear devices, which have higher plasma flow and stronger trapped particle effects [5]. In this model, the linear growth rate of plasma instability lies between ideal MHD and resistive MHD. After simplification, we obtain $\gamma \approx \frac{1}{\tau_w} \left(\frac{\delta W_{\text{plasma}}}{\delta W_{\text{wall}}} - 1 \right)$, where δW_{plasma} is the plasma potential energy, δW_{wall} is the wall stabilization energy, and τ_w is the wall time (the magnetic diffusion time of the wall, $\tau_w = \mu_0 \sigma d^2$, where σ is the wall conductivity and d is the wall thickness). This model is typically applicable to large-scale distortions with low mode numbers (such as $m = 1$, $n = 1$ or $m = 2$, $n = 1$). Its stability can be judged by the plasma rotation frequency ($\omega_{\text{rot}} > \omega$). Rotation or active feedback can increase the stability threshold through the Doppler effect. Without rotation, if the plasma is close to the ideal MHD stability boundary, the instability is easily excited.

2.2.2. Interchange mode

Interchange modes have been a key limiting instability for many magnetic confinement fusion configurations [6]. Driven by an unfavorable combination of magnetic field curvature and pressure gradient, the perturbation is perpendicular to the magnetic field direction. The unfavorable curvature of the magnetic field lines causes adjacent magnetic flux tubes to exchange positions, releasing free energy and making the system unstable. This model is applicable to simple magnetic field configurations. The growth rate of the exchange mode can be classified into three cases: ideal, resistive, and toroidal configurations. The ideal exchange mode refers to the growth rate determined by the magnetic well effect in magnetic mirror

devices or low shear toroidal plasmas, which is $\gamma \sim \frac{v_A}{L_p} \sqrt{1 - \frac{1}{M}}$, in the resistive exchange mode, the growth rate is limited by the resistive effect, and the formula is $\gamma \sim \left(\frac{v_A}{L_p} \right)^{2/3} \left(\frac{\eta}{\mu_0 L_p^2} \right)^{1/3}$, in the toroidal configuration exchange mode, the growth rate can be approximated as $\gamma \sim$

$\frac{c_s}{R} \sqrt{\frac{L_p}{R} - \frac{1}{q^2}}$. The instability criteria for the exchange mode can be divided into three categories: Minimum-B Criterion, Suydam Criterion, and Mercier Criterion. The first one is applicable to simple magnetic field configurations such as magnetic mirror devices, with the criterion form being $\frac{dB}{dl} = 0$ also $\frac{d^2 B}{dl^2} > 0$, the second one is applicable to cylindrical plasmas, with the criterion form being $\frac{d \ln p}{dr} > \frac{B^2}{4\mu_0} (\mu_0 q^2 \{R\}) \cdot \frac{1}{r}$, and the third one is applicable to toroidal plasmas, with the criterion form being $D_{\text{Merc}} = \frac{r}{4} \left(\frac{dp}{dr} \right)^2 \frac{\mu_0}{B^2} - \frac{1}{q^2} \left(\frac{dq}{dr} \right)^2 > 0$.

2.2.3. Tearing mode

The tearing mode is a magnetohydrodynamic (MHD) instability caused by plasma magnetic reconnection, mainly applicable to plasmas with magnetic shear (i.e., the magnetic field direction varies with space). There is much experimental evidence that this instability is the cause of the current disruptions observed in laboratory plasma devices[7]. Due to the resistive effect of the plasma, there exists a current gradient. Resonance at rational surfaces (where the plasma safety factor $q = m/n$ is a rational number, with m being the poloidal mode number and n the toroidal mode number) weakens the magnetic shear. The combined effect leads to a change in the magnetic topology, with magnetic field lines "breaking" and reconnecting to form magnetic islands, converting magnetic energy into the internal and kinetic energy of the plasma. It is particularly important to note that both theory and experiments have shown that shear flow plays a crucial role in suppressing turbulence and the transport it drives in devices such as tokamaks for controlled fusion. In the tearing mode, it is mainly divided into two parts: the linear stage and the nonlinear stage.

The linear stage is described by resistive magnetohydrodynamic (resistive MHD) equations, with the instability growth rate $\gamma \propto S^{-3/5}$. Here, $S = \tau_R/\tau_A$, where τ_R is the resistive diffusion time and τ_A is the Alfvén time. During this stage, there are three important parameters for the tearing mode: the threshold condition, the width of the magnetic island, and the mode number. The threshold condition for linear stage requires that $\Delta' = \frac{1}{\psi} \frac{d\psi}{dr} \Big|_{r_s^+}^{r_s^-} > 0$, where Δ' characterizes the instability threshold. The saturated width of the magnetic island $w \propto (\Delta'\eta)^{1/2}$, with η being the resistivity, which is an indicator of the severity of the tearing mode, given by $W = 4 \left(\frac{\psi_1}{r_s B'_{\theta}} \right)^{1/2}$, where η is the resistivity. The mode number in this stage typically shows low mode numbers (such as $m = 2/n = 1$), and high mode number tearing modes may couple to cause turbulence or disruption. In the nonlinear stage, the magnetic island saturates, and the evolution is dominated by the Rutherford equation, involving the interaction between the magnetic island width and the current profile. The tearing mode enters the nonlinear growth stage after reaching a critical amplitude in the linear stage. When the perturbed magnetic field ($\tilde{B}_r$) exceeds a certain threshold of the background magnetic field (B_0) (such as $\tilde{B}_r/B_0 \sim \delta'a$, where δ' is the linear tearing mode parameter and a is the characteristic scale). There are three related features in this stage: scaling laws, magnetic island formation and evolution, and saturation mechanisms. The scaling law refers to the growth rate in the nonlinear stage being described by the Rutherford equation: $w \propto t^2$. Here, w is the width of the magnetic island, and η is the resistivity. The solution of this equation indicates that the width of the magnetic island grows as $w \propto t^2$ over time, which is significantly slower than the exponential growth in the linear stage. Nonlinear growth may saturate due to the following mechanisms: first, current gradient relaxation, where reconnection flattens the current distribution and reduces the instability threshold Δ' ; second, secondary effects such as polarization current, two-fluid effects (separation of electron and ion dynamics), or turbulent dissipation; and finally, external control,

actively suppressing magnetic islands through Electron Cyclotron Current Drive(ECCD) or resonant magnetic perturbations (RMP).

2.2.4. Balloon Mode and edge localized mode

On the outer side of a toroidal plasma, if the curvature direction of the magnetic field lines is the same as the direction of the plasma pressure gradient (outward bending), local expansion and contraction of the perturbation direction occur, triggering instability. In ideal MHD, its linear growth rate of instability can be approximated as $\gamma \sim \frac{v_A}{qR} \sqrt{\beta - \beta_{\text{crit}}}$; if the plasma resistance cannot be ignored, then $\gamma \sim \frac{v_A}{qR} (\beta - \beta_{\text{crit}})^{3/5} S^{-2/5}$. Its stability can be judged by β (the ratio of plasma pressure to magnetic pressure) $\beta < \beta_{\text{crit}} \propto \frac{\text{magnetic shear}}{\text{diameter ratio}}$. In the edge region, when the pressure gradient exceeds the critical threshold (ballooning mode boundary $\nabla p_{\text{crit}} \propto \frac{B^2}{\mu_0 q^2 R} \cdot S^{1/2}$), the ballooning mode may evolve into an edge localized mode (ELM). At this point, the plasma magnetic field topology changes to form magnetic islands or filamentary structures. Magnetic reconnection or turbulent transport leads to a large release of energy, and the energy loss can be calculated using the Wurden formula ($\Delta W_{\text{ELM}} \sim 0.1 \cdot W_{\text{ped}}$). During the H-mode discharge in a tokamak device, the plasma boundary is often accompanied by periodic edge localized modes (ELM). It is generally believed that the ELM instability is driven by the pressure gradient and local current at the boundary, and is classified into the ballooning mode dominated by the pressure gradient, the peeling mode dominated by the current, and the peeling-ballooning mode driven by both, depending on the strength of the driving forces of the two[8].

2.3. Microscopic-scale plasma perturbations (gyrokinetic instability)

Microscopic instabilities are driven by deviations of the plasma velocity distribution function from the Maxwellian distribution. Although these microscopic turbulence do not directly lead to the destruction of large-scale plasma structures, they significantly enhance the radial transport of energy and particles, reducing the confinement performance.

2.3.1. Electron temperature gradient mode

The electron temperature gradient couples with the magnetic field curvature. Driven by the electron pressure gradient, electrons drift along the magnetic field curvature direction, forming small-scale vortices and exciting high-frequency perturbations. Turbulence is triggered in regions with steep electron temperature gradients, with perturbation frequencies close to the electron cyclotron frequency ($\omega_{ce} = eB/m_e$). The growth rate derived from linear theory in this model is $\gamma \sim \frac{v_{te}}{L_{Te}} \left(\frac{\eta_e}{\eta_e - \eta_{\text{crit}}} \right)$; the critical gradient can be used as a stability criterion $\frac{L_{Te}}{R} < \frac{1}{2}$.

2.3.2. Ion temperature gradient mode

Ion temperature gradient as a driving force, when it exceeds a threshold, the plasma will have linear instability, that is, ion temperature gradient instability [9]. Driven by the ion pressure gradient, ions in the high-temperature region drift outward along the magnetic field curvature, while those in the low-temperature region drift inward, resulting in charge separation and exciting medium-frequency electric field perturbations. The perturbation frequency is close to the ion drift frequency ($\omega_k = \frac{k_{\perp} c T_e}{e B} \frac{\nabla n}{n}$). The growth rate under linear approximation is $\gamma \sim \frac{v_{ti}}{L_{Ti}} \sqrt{\frac{\epsilon_n}{\epsilon_T}}$, and the critical gradient can be used as a stability criterion $\frac{L_{Ti}}{R} < \frac{2}{3}$.

2.3.3. Drift wave instability

The presence of density or temperature gradients in the plasma leads to the drift motion of charged particles in the magnetic field (such as electrostatic drift and magnetic drift). The phase

matching between this drift and the wave results in the growth of wave energy, amplifying the perturbation. This perturbation belongs to low-frequency perturbations, with perturbation frequencies much lower than the ion cyclotron frequency ($\omega_{ci} = eB/m_i$). The instability growth rate is $\gamma \sim \omega_* \left(\frac{\eta_i - \eta_e}{\eta_i + \eta_e} \right)$, $\eta_{i,e} = \frac{\nabla T_{i,e}}{T_{i,e}}$. The dispersion relation ($\omega = \omega_k - i\gamma$) can describe the propagation and growth of the wave, where the real part ($\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$, $\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p$) represents the wave caused by the density and temperature gradients of the plasma, describing the wave's propagation characteristics in the plasma (such as direction and phase velocity); the imaginary part ($\gamma \sim \omega_* \left(\frac{\eta_i - \eta_e}{\eta_i + \eta_e} \right)$, $\eta_{i,e} = \frac{\nabla T_{i,e}}{T_{i,e}}$) represents the efficiency of converting free energy into perturbation energy, describing the rate of wave amplitude growth or decay over time. The stability criterion can be determined by whether the temperature gradient is unbalanced. When the temperature gradient and density gradient are in opposite directions, the drift wave tends to be unstable.

3. RESEARCH PROGRESS ON PLASMA INSTABILITY THEORY AND MODEL

Theoretical research on plasma instability is the basis for understanding and predicting complex physical phenomena in fusion devices. After experiments and research, a complete system from analytical theory to large-scale numerical simulation has been formed. These models not only provide theoretical support for various phenomena observed experimentally, but also provide scientific basis for the development of optimized control methods. Currently, the theoretical research on plasma instability mainly develops in three directions: analytical models, numerical simulations and data-driven models based on artificial intelligence.

3.1. Analytical theory and simplified model

3.1.1. Macroscopic instability

magnetohydrodynamics dynamics is the basic model for studying macroscopic instability. First, we can know from the stokes equation in fluid mechanics (realized under the assumption of non-viscosity, adiabatic process, and continuous medium), and then from the system of maxwell equations in electromagnetics, we can get the $\oint \mathbf{E} \cdot d\mathbf{S} = \frac{Q}{\epsilon_0}$, $\oint \mathbf{B} \cdot d\mathbf{S} = 0$, $\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{S}$, $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \mu_0 \epsilon_0 \frac{\partial}{\partial t} \int \mathbf{E} \cdot d\mathbf{S}$ (realized in macroscopic electromagnetic field, conservation of charge, free space or continuous medium). MHD=stokes + Maxwell, that is, magnetohydrodynamics evolved from fluid mechanics plus Lorren's magnetic coupling. Among them, the ideal linear MHD assumes that the disturbance amplitude is very small, and the higher order small amount in the coupling equation is ignored, and the first-order disturbance is retained. The control equation form is $\frac{\partial \rho_1}{\partial t} + \nabla \cdot (\rho_0 \mathbf{v}_1) = 0$, $\rho_0 \frac{\partial \mathbf{v}_1}{\partial t} = -\nabla p_1 + \mathbf{J}_0 \times \mathbf{B}_1 + \mathbf{J}_1 \times \mathbf{B}_0$, which is suitable for small amplitude fluctuations, plasma stability analysis, and linear instability threshold research; the ideal nonlinear MHD assumes that the disturbance amplitude cannot be ignored, and all nonlinear terms are retained. The control equation form is $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$, $\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mathbf{J} \times \mathbf{B}$, which is suitable for large-scale structure evolution, turbulence and energy cascade, shock wave formation and propagation. The above model is based on the assumption of an ideal fluid, that is, the plasma is an ideal conductor (resistivity $\eta=0$, magnetic field lines "freeze" in the fluid, the characteristic time is much greater than the particle collision time and meets the quasi-neutral conditions). If non-ideal fluid is considered, the influence of resistivity, Hall effect and other effects on the system of equations must also be added.

3.1.2. Triggering model of edge-localized modes

The essence of ELMs triggering is that the pressure gradient and current density in the boundary area break through the magnetofluid equilibrium threshold, resulting in the instability of the stripping-balloon mode. Through linear growth and nonlinear collapse, accumulated energy and particle flow are released to restore the constrained equilibrium. The core of the model is the combination of equilibrium stability analysis and nonlinear dynamics. Starting from the ideal linear MHD equation, first perform the equilibrium force equation analysis, and then apply disturbance to the equilibrium state (assuming that the disturbance is displacement $\xi(r,t)$), which can obtain the disturbance velocity and disturbance magnetic field, and the momentum equation is $\mathbf{F}(\xi) = \frac{1}{\mu_0} (\nabla \times \mathbf{B}_1) \times \mathbf{B}_0 + \frac{1}{\mu_0} (\nabla \times \mathbf{B}_0) \times \mathbf{B}_1 - \nabla p_1$. Coupling the peeling mode and the balloon mode to obtain $\delta W = \delta W_{\text{ballooning}} + \delta W_{\text{peeling}} + \delta W_{\text{coupling}} = \delta W = \frac{1}{2} \int \left[\frac{|\mathbf{B}_1|^2}{\mu_0} - \xi^* \cdot \mathbf{F}(\xi) \right] dV$, solve the above MHD equation, and near $r=a$ of the boundary mode, you can obtain the growth rate and stability boundary.

3.1.3. Microscopic instability

The cyclotron dynamics theory provides a more accurate physical description for the study of microscopic instability. First, the cyclotron dynamics can be simplified by the following key steps: using the rapid cyclotron motion of charged particles in a strong magnetic field, the particle's 6D phase space (position + velocity) is reduced to 5D (guiding center position + parallel velocity + magnetic moment), and the key dynamics part is retained (precisely treating the field-particle interaction after cyclotron average). On this basis, three assumptions are added, the strong magnetic field assumption (the cyclonic frequency is much higher than other dynamic time scales), the small perturbation assumption (the disturbance potential and the perturbation magnetic field are much smaller than the background field, allowing linearization or weak nonlinear processing), and the adiabatic electron assumption (the electrons meet the Boltzmann distribution along the magnetic field line), and the particle position is replaced by the guiding center, and the fast variables in the Hamiltonian are eliminated through the Lie transformation to obtain the dynamic equation of the guiding center. Finally, it is coupled with the disturbance field. Assuming that the disturbance amount $\delta f = f - f_0$, the cyclotron dynamic equation after the disturbance can be increased.

3.2. Large-scale numerical simulation technology

By using numerical simulation technology, it is possible to simulate controlled nuclear fusion more efficiently and economically, and to reproduce the behavior of plasma in experimental devices. Current numerical simulation codes can reflect the performance of plasma from the microscale to the macroscale and coupled behaviors. With the improvement of supercomputer performance and the refinement of theoretical models, first-principles numerical simulation has become an important means to study plasma instabilities. First principles refer to the calculation of the properties of objects (such as collision cross-section parameters, etc.) based on the fundamental laws of quantum mechanics without relying on empirical parameters, starting directly from the atomic structure and electron interactions.

The fully kinetic simulation of the particle-in-cell (PIC) method accurately reflects the motion of plasma in electromagnetic fields through the Newton-Lorentz equation, but it has a huge computational cost and is currently only applicable to microscale and short-time-scale physical processes. Gyrokinetic codes (such as GENE, GYRO) reduce the dimensionality of plasma motion by averaging out the gyroscopic motion phase, significantly improving computational efficiency and have been widely used in the study of microinstabilities such as ITG and ETG. Magnetohydrodynamic simulation codes (such as M3D-C1, JOREK) play an irreplaceable role in the study of macroscopic instabilities. These codes can simulate complex nonlinear processes such as the evolution of tearing modes and the interaction of magnetic islands by solving the extended MHD equations. In recent years, with the development of algorithm optimization and

parallel computing technology, the spatiotemporal resolution and physical process integrity of MHD simulations have been significantly improved, enabling three-dimensional simulations at the full device scale of tokamaks; multiscale coupling simulation is a current frontier research direction. Due to the wide range of plasma instabilities from the electron Larmor radius to the device scale, a single physical model is difficult to describe comprehensively. By developing hybrid algorithms and coupling frameworks to organically integrate different physical models, such as combining the kinetic description of the core region with the fluid description of the edge region, the experimental conditions can be more realistically reflected. The integrated simulation platform developed by the EAST team successfully predicted the suppression effect of resonant magnetic perturbations (RMP) on ELMs, providing important guidance for experiments.

3.3. Data-driven and artificial intelligence models

With the rapid growth of fusion experiment data and the advancement of machine learning technology, data-driven methods have shown great potential in the study of plasma instabilities. They can make up for the incomplete theoretical models in numerical simulation methods and directly integrate and simulate plasma instabilities through a large amount of experimental data. Artificial intelligence early warning systems based on deep learning can predict catastrophic events such as plasma disruptions by real-time analysis of diagnostic signals. Neural network models are also used to establish instability parameter space mapping, replacing some computationally expensive numerical simulations. Artificial intelligence control algorithms have become a research hotspot in recent years. Reinforcement learning algorithms are used to optimize magnetic field defect control strategies, achieving simultaneous suppression of core and edge instabilities in plasma. Multi-modal data fusion technology integrates signals from different diagnostic systems to construct a more comprehensive image of instability evolution. The EAST device has achieved the reconstruction of the three-dimensional structure of ELMs using high-speed cameras, microwave reflection, and magnetic probes, providing a new perspective for understanding their triggering mechanisms.

4. RESEARCH PROGRESS AND BREAKTHROUGHS

In recent years, magnetic confinement nuclear fusion research worldwide has made a series of major breakthroughs in the study of plasma instabilities, covering all aspects from theory to application. Major fusion research countries and regions such as China, the United States, Europe, South Korea, and Japan have continuously extended the dynamic equilibrium time of long-pulse steady-state operation through experiments on large tokamak devices, accumulating valuable experience for the construction of ITER and future fusion reactors.

4.1. Breakthroughs in edge-localized mode (ELM) control technology

Resonant magnetic perturbation (RMP) technology has become one of the most effective means to control Type-I ELMs. The EAST team of the Chinese Academy of Sciences has achieved complete suppression of ELMs under radio frequency wave-dominated heating conditions using RMP, observing the nonlinear transition process from ELM mitigation to suppression. Experiments show that the change in the boundary magnetic field topology is the key factor for complete ELM suppression. When the externally applied perturbation magnetic field resonates with the intrinsic magnetic field of the plasma, it can effectively suppress the accumulation of the boundary pressure gradient. The supersonic molecular beam injection (SMBI) technology is an original ELM control method developed by Chinese scientists. By actively injecting gas before ELM bursts, it changes the distribution of boundary plasma parameters, effectively reducing the frequency and intensity of ELM bursts. Experiments on the HL-2A device have shown that SMBI can induce small and frequent ELMs, avoiding damage to the first wall caused

by large ELMs. This method does not require additional magnetic perturbation coils and provides a simple and reliable control solution for fusion reactors. The liquid lithium limiter technology indirectly affects ELM characteristics by changing the interaction between boundary plasma and wall materials. Experiments on EAST have shown that the liquid lithium surface can not only effectively reduce hydrogen recycling but also change the transport characteristics of boundary plasma, increasing the ELM frequency while reducing its amplitude. This material engineering approach provides new ideas for ELM control, especially suitable for future long-pulse operation fusion reactors.

4.2. New strategies for magnetic field control

Three-dimensional magnetic field optimization technology has made significant progress on the DIII-D tokamak. By precisely controlling the current distribution of multiple magnetic coils, specific three-dimensional magnetic field structures can be generated, effectively suppressing the development of tearing modes and resistive wall modes. This active control strategy has been successfully applied to various plasma operation modes, providing important technical support for achieving steady-state operation. The traditional view holds that magnetic field defects (error fields) are harmful to plasma confinement, but a joint research team from the United States and South Korea has overturned this perception through experiments on the KSTAR tokamak. They achieved simultaneous management of core and edge instabilities in plasma by actively designing and regulating the "error" in the magnetic field, enabling the plasma to release accumulated energy in a controlled manner and avoiding catastrophic instabilities. The research team is planning to further optimize this "error field" control process with the aid of artificial intelligence technology to address the complexity of real-time adjustments, transforming the traditionally harmful magnetic field errors into control measures, which represents a new approach to instability control.

4.3. Breakthrough in high-parameter steady-state operation

The EAST device achieved a steady-state long-pulse high-confinement mode plasma operation at over 100 million degrees for 1066 seconds in 2025, setting a new world record for high-confinement mode operation in tokamak devices. This breakthrough was made possible by comprehensive advancements in plasma control technology, heating technology, and diagnostic technology, especially the in-depth understanding and coordinated control of multiple instability coupling effects. The DIII-D team made significant progress in breaking the Greenwald limit, achieving a plasma density 20% higher than the traditional limit while maintaining the high-confinement mode. This achievement resolves the contradiction between high density and stability in fusion reactions, but whether this technology is applicable to larger devices such as ITER still needs to be verified. After the HL-2M device was completed in 2020, the plasma current exceeded the 1MA mark, providing an important platform for studying instability behavior under high- β (plasma pressure to magnetic pressure ratio) conditions. Experiments on this device have accumulated valuable data on the interaction between fast particles and magnetohydrodynamic instabilities.

4.4. Research on the interaction between fast particles and instabilities

Alfvén eigenmode (AE) control is one of the significant challenges faced by fusion reactors, as the α particles produced by fusion may excite these instabilities, leading to premature energy loss. ITER-related research has found that fast particles can suppress the physical mechanism of tearing modes, and the use of fast ions instead of traditional external field coils to control resistive wall modes provides a new approach for stability control in fusion devices. Experiments on the KSTAR and JT-60SA devices have shown that by optimizing the heating scheme and plasma profile, a beneficial interaction between fast particles and Alfvén waves can

be achieved. When the fast particle distribution function meets certain conditions, it not only does not excite harmful instabilities but also helps suppress existing MHD disturbances.

5. DEVELOPMENT AND FUTURE

At present, the research on plasma instabilities in controllable nuclear fusion devices mainly focuses on three aspects: suppressing plasma instabilities, achieving control over the plasma profile, and developing high-precision real-time monitoring technologies. The technical challenges faced include precise measurement of relevant parameters at temperatures of over a hundred million degrees Celsius, long-pulse steady-state operation of controllable fusion devices, and the coupling and simulation of multiple physical fields. Current research aims to achieve self-sustained operation of burning plasma by enhancing confinement performance and fuel gain, thereby promoting the commercial operation of controllable fusion devices. Controllable nuclear fusion energy holds great promise as a solution to social energy problems, but plasma instabilities are a major obstacle to the stable and efficient operation of controllable fusion devices. Therefore, the necessity of researching plasma instabilities is beyond doubt. In the future, through the efforts of scientific teams and researchers, the large-scale application of controllable nuclear fusion is expected to be realized.

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